Hybrid Quantum Photonics
Junyi Lee,1 Victor Leong,1 Dmitry Kalashnikov,1 Jibo Dai,1 Alagappan Gandhi,2 and Leonid Krivitsky1
1) Institute of Materials Research and Engineering, Agency for Science, Technology and Research (A*STAR), 2 Fusionopolis Way, #08-03 Innovis, 138634 Singapore
2) Institute of High Performance Computing, Agency for Science, Technology and Research (A*STAR), 1 Fusionopolis Way, #16-16 Connexis North, 138632 Singapore
(Dated: 25 May 2020)

The realization of scalable devices for quantum information processing and networking is of utmost importance to the quantum information community. Building such devices is difficult because of challenges in achieving all the necessary functionalities on a unified platform. However, the consolidation of unique experimental and theoretical capabilities in quantum physics and integrated photonics can provide a promising solution. Hybrid quantum photonics systems, in which solid-state based quantum registers are integrated with on-chip photonic structures and devices, are attractive candidates for such scalable devices. Such systems allow efficient processing, storage, and readout of the quantum information. Here we discuss practical efforts in the implementation of hybrid quantum devices. We review solid-state candidates for quantum registers and their integration with photonic structures with a particular emphasis on their coupling with resonant nanostructures. Our work contributes to further development and realization of quantum networking protocols and quantum logic on a scalable and fabrication-friendly platform.

I. INTRODUCTION

Quantum information networks are at the forefront of practical applications of quantum technology1. These networks employ stationary quantum systems as nodes, which process and store quantum information. The nodes are connected by quantum links, which transfer quantum information from one node to another. Deployment of quantum networks enables the acceleration and scaling-up of processing along with the distribution of quantum information. The number of accessible states in the quantum network grows exponentially with the number of nodes, while in conventional networks, it scales linearly. Besides, connecting quantum nodes allows secure and private communication as well as distributed quantum computation2,3.

In physical implementations of quantum networks, the nodes are realized as stationary quantum systems (quantum dots, atomic defects in solids, atoms etc.). Solid-state systems possess outstanding quantum optical properties that can be used as building blocks for quantum networks. Quantum information can be stored, for example, in the electron spin of a defect and the nuclear spin of nearby atoms with relatively long coherence times (a few ms) even at room temperature. During this time, it is feasible to record, manipulate, and readout quantum information. Quantum logic can be implemented with incident microwave and RF fields, driving transitions between electron and nuclear sublevels. These blocks can interact with each other via photon-mediated interaction. Optical links connect the nodes as they enable reliable and fast transfer of quantum information.

Two of the biggest challenges in the development of quantum networks are, (1) Efficient connection between stationary nodes and their optical links, which provide high fidelity transmission, and (2) A scalable and fabrication-friendly platform, which accommodates both stationary nodes and their optical links. Any platform built to overcome these challenges needs to satisfy compatibility requirements for different materials, operation wavelengths, and temperatures.

A practical approach towards implementing scalable quantum networks is to employ integrated photonics technologies. The quantum information can be encoded, for example, in spin states of atomic defects in diamonds or quantum dots, which are used as stationary nodes. Then the stationary nodes are interconnected via optical waveguides made of low-loss materials. Optically-resonant nanostructures are used to enhance the coupling of photons emitted from the stationary nodes into waveguides. Photons can then be distributed to different nodes on the same chip or between different chips to create quantum entanglement between the nodes. Furthermore, for the readout of quantum information, one can use compact single-photon sensitive photodetectors fabricated on the same chip. Generation, transport, manipulation and detection of quantum information can all be accomplished on this scalable, intrinsically stable and fabrication-friendly platform.

The physics concepts, developed for quantum networks, can be further applied in quantum metrology and sensing3,4. Combining quantum systems with compact photonic devices will lead to the development of a new family of highly sensitive temperature, stress, inertia, electric and magnetic field sensors with high spatial resolution. These sensors will find applications in microelectronics, bio-chemical, and healthcare industries.

In this review, we discuss practical efforts by many groups in implementing essential elements of quantum networks using integrated photonics technologies. Following a brief theoretical introduction (Section II), we review the integration of various solid-state quantum systems with on-chip optical structures. We discuss photonic integration of color centers in bulk diamonds and diamond nanocrystals (Sections III and IV), quantum
dots (Section V), and 2D materials (Section VI).

II. THEORETICAL BACKGROUND

A necessary requirement for many quantum computing, quantum information or nano-scale sensing applications is a stable, scalable quantum system with discrete energy levels. Discrete energy levels within a solid-state system normally described by valence and conduction bands might seem at odds with intuition but they can exist under special circumstances near a lattice defect or in quantum dots where electrons are physically confined to such small spatial volumes that their eigen-energies are discrete. Here we briefly review the nitrogen vacancy defect in diamond, a well studied qubit candidate with many potential nano-sensing applications, to illustrate how such discrete states may arise in the band gap of diamond, and motivate the benefits of integrating such qubits to photonic structures. We note that although defects and quantum dots may have discrete energy levels for somewhat different reasons, yet they must nevertheless overcome similar challenges before they can be used as practical qubits on a solid state platform and these challenges can be similarly mitigated by their integration with photonic structures.

A. The NV− center as an illustrative qubit

A nitrogen vacancy (NV) center in diamond consists of a nitrogen atom (a substitutional defect) that is paired together with a neighboring vacant site. The substitution-vacancy pair can be aligned along any of the equivalent <111> directions in the crystal and typically, all four possible orientations of the NV centers are found in equal proportions although we note that relatively recent work have successfully created preferentially oriented NV centers5–7. Although NV centers are known to exist in two distinct states (traditionally labeled as NV0 and NV−)8, it is the NV− state that has of late received the most attention due to its attractive optical and spin properties that have made it amenable to a variety of technological applications including quantum computation9, quantum information10 and microscopic magnetic11, electric12, stress13, inertia14 and even thermal15 sensing. For this reason, we shall focus exclusively on NV− for the rest of this section although we remark here that the NV0 state can affect the dynamics of NV− in important ways. For example, despite the excellent photostability of the NV− center (which is another reason for its popularity), it is known that the fluorescence of NV− can be significantly (but mostly reversibly) quenched16–19 when probed at high (typically pulsed) laser intensity and that this has been partially attributed to a spin-dependent ionization of NV− to NV020. Moreover, oscillations between NV− and NV0 have been observed as a function of the excitation wavelength21 and it is estimated that the NV center can be in the NV0 state for ~ 30% of the time under usual operating conditions22. Nevertheless, we also note that these effects may be mitigated by further annealing at 1200 °C23,24, and more generally, the equilibrium concentration25 and stability of the NV− state depends on the Fermi level, which may be altered, among other things, by doping (N is itself a deep donor), irradiation, heating, photo-excitation, surface-termination, and annealing conditions8,26–30.

1. Energy levels of NV−

The NV center has a C3v point symmetry with 2 one-dimensional irreducible representations (A1 and A2), and a two-dimensional irreducible representation (E)31,32. Consequently, theoretical studies of the NV center often begin by building one-electron molecular orbitals (MO) from a linear combination of carbon and nitrogen sp3 atomic orbitals31 that conserve C3v symmetry. Ab initio calculations33–38 suggest that there are 3 such MOs which lie within the band gap of diamond while 1 MO was found to lie in the valence band. These MOs can be labeled {a1′, a1, εx, εy} according to whether they transform as A1 or E under C3v and are listed in ascending energy order as determined by symmetry/charge considerations31,39. Since the ground-state of NV− is a spin triplet39, which requires an even number of electrons, and considering that a substitutional nitrogen atom has 2 valence electrons that are not involved in covalent bonding while its neighboring vacancy defect has 3 “dangling” electrons, NV− is typically modeled as a 5 + 1 = 6 electron system, where the extra electron is assumed to have been captured by the center from another impurity in the lattice37,41,42. In a six electrons model, the electronic configuration of the ground state is a2g a1g e2 (a′1 lies within the valence band) while that of the first excited state is a2g a1g e3.39 Since the NV center has C3v symmetry, it is convenient to use basis states that are C3v invariant. Given a particular electronic configuration, basis states of the full 6-electron wavefunction may be obtained by taking tensor products of the C3v invariant MOs with C3v invariant linear combinations of the [1/2, ±1/2] spin states. The resulting basis states may then be classified according to whether they transform as A1, A2 or E under C3v. It turns out that the ground state configuration (a2g a1g e2) consists of an orbital-singlet spin-triplet 32A2 state, an orbital-doublet spin-singlet 1E state, and an orbital-singlet spin-singlet 1A1 state, while the excited state configuration (a2g a1g e3) consists of an orbital-doublet spin-triplet 32E state and an orbital-doublet spin-singlet 1E state.

Turning on multi-electron Coulomb repulsion splits the degeneracy of the 32A2, 1A1 and 1E levels in the ground state configuration as well as the degeneracy of 32E and 1E in the excited state configuration39. This is in agreement with measurements involving electron para-
magnetic resonance (EPR) in the dark\textsuperscript{40}, optical hole burning\textsuperscript{43}, optically detected magnetic resonance\textsuperscript{44,45} (ODMR), and Raman heterodyne measurements\textsuperscript{46}, that all point towards a spin triplet \(^3\)A\(_2\) ground state. Moreover, the excited state has been determined via ODMR measurements\textsuperscript{47,48} to be a spin triplet \(^3\)E state in line with the above theoretical expectations. Earlier uniaxial stress studies\textsuperscript{49}, together with the results above, indicate that the prominent zero-phonon line (ZPL) observed at 1.945 eV (637 nm) is due to a \(^3\)A\(_2\) \rightarrow \(^3\)E transition.

The ordering of the singlet \(^1\)E and \(^1\)A\(_1\) states were the subject of much controversy over the years but recent \textit{ab initio}\textsuperscript{38,50} calculations and observations of the zero-phonon line under application of uniaxial stress\textsuperscript{51} have resolved that the \(^1\)E singlet state is the lower energy state. Earlier detection of infrared emission from the NV\(^-\) center that was anti-correlated with visible fluorescence at 637 nm and confirmed by uniaxial stress measurements to be associated with a A\rightarrow\(E\) transition gives a splitting of 1046 nm between the \(^1\)E and \(^1\)A singlet states\textsuperscript{52}. We note that the relatively weak infrared emission at 1046 nm suggests that there are probably additional non-radiative decay pathways between \(^1\)E and \(^1\)A\textsuperscript{52}. It is also worth pointing out that the results of an \textit{ab initio} calculation\textsuperscript{48} and measurements of non-radiative inter-system crossing (ISC) rates\textsuperscript{53} suggest that an additional third singlet state might exist between the ground \(^3\)A\(_2\) and excited \(^3\)E states.

Spin-spin interactions\textsuperscript{31,41,42} further split the ground \(^3\)A\(_2\) state into a spin singlet A\(_1\) (with \(m_s = 0\)) and spin doublet \(E_xE_y\) (with \(m_s = \pm 1\)) state so that there is a finite splitting between \(m_s = 0\) and \(m_s = \pm 1\) states at zero magnetic field. Early EPR\textsuperscript{54} and hole burning experiments\textsuperscript{43} measured this zero-field splitting \(D_{xy}\) to be \(\approx 2.88\) GHz. Similarly, spin-spin and spin-orbit interactions\textsuperscript{31} further split the excited \(^3\)E state into \(E_xE_y\) states with \(m_s = 0\), and \(A_1A_2E_x\) and \(E_y\) states with \(m_s = \pm 1\) (see Fig. 1). Compared to the ground state however, the excited state is considerably more sensitive to shifts induced by lattice strains\textsuperscript{47,48,55} and the exact ordering of its states are less certain. Nevertheless, it is clear from EPR measurements that the zero-phonon line at 637 nm is associated with a spin-triplet excited state and that the triplet state consists of a spin-singlet (i.e. the \(E_xE_y\) states with \(m_s = 0\)) and spin-doublet (consisting of \(A_1, A_2, E_x\) and \(E_y\) states with \(m_s = \pm 1\)) state that are separated by a zero-field splitting \(D_{xx}\) of \(\approx 1.42\) GHz\textsuperscript{47,48}. We note that \(D_{yy}\) is temperature dependent and that this can potentially be a significant problem for magnetometry applications\textsuperscript{56} although it also conversely allows the NV\(^-\) to be used as a nano-scale temperature sensor\textsuperscript{15}.

Besides spin-spin and spin-orbit interactions, there is of course a Zeeman shift for states with \(m_s = \pm 1\). EPR measurements have shown that the \(g\)-factors for both ground and excited states are close to 2, indicating that there is likely to be negligible orbital angular momentum in either states\textsuperscript{47,48}. Moreover, since both \(^{14}\)N \((I = 1)\) and \(^{15}\)N \((I = 1/2)\) have non-zero nuclear spin \(I\), there is in addition a measurable hyperfine shift due to the nitrogen nucleus\textsuperscript{57}. For the case of \(^{14}\)N with \(I = 1/2\), there is also a shift due to the nuclear electric quadrupole moment\textsuperscript{32}. Furthermore, electric fields in the crystal leads also to a Stark shift in the ground state energies and uniaxial strain, which can be unambiguously parametrized as an effective electric field, affects the NV center in a similar way\textsuperscript{39}. Since most applications of the NV\(^-\) center requires a manipulation of the ground state spin, we summarize this section by giving the spin Hamil-

![FIG. 1. Energy levels of the ground and first excited MO configuration of the NV\(^-\). States labeled here with a \(|n, m_s\rangle\) notation are spin-orbit states that transform according to a particular row of an irreducible representation of \(C_3v\) (labeled by \(n\))\textsuperscript{31,39}, which are the convenient basis states to use in the presence of spin-orbit/spin-spin interactions. Note that they are linear combinations of states with definite azimuthal spin quantum numbers \(m_s\) and can hence have \(m_s = \pm 1\). PSB denotes the phonon side band. Solid lines with single arrow heads denote optical transitions, while solid lines with double arrow heads denote microwave transitions. Non-radiative ISCs are denoted by dashed lines. A darker ISC line between the \(m_s = \pm 1\) states of \(^2\)E to \(^1\)A\(_1\) is used to illustrate the faster ISC rate for that transition. Spacing of the energy levels are not drawn to scale.](image-url)
ton of the ground state:

\[
\frac{H_{gs}}{\hbar} = D_{gs}(T) \left( S_z^2 - \frac{S_z^2}{3} \right) + A_{gs}^\parallel S_z I_z + A_{gs}^\perp S_\perp \cdot I_\perp \\
+ P_{gs} \left( I_z^2 - \frac{I_z^2}{3} \right) + d_{gs}^\parallel (E_z + \delta_z) \left( S_z^2 - \frac{S_z^2}{3} \right) \\
+ d_{gs}^\perp (E_z + \delta_z)(S_y^2 - S_z^2) \\
+ d_{gs}(E_y + \delta_y)(S_z S_y + S_y S_z) \\
+ \frac{g_{gs} \mu_B}{\hbar} \mathbf{B} \cdot \mathbf{S},
\]

where \( \mathbf{S} \) and \( \mathbf{I} \) are the electron and nuclear spin operators respectively, and \( \mathbf{B}, E, \) and \( \delta \) are the magnetic, electric and strain (parametrized as an effective electric field) fields respectively. \( D_{gs}(T) \) is the temperature dependent zero-field splitting of the ground state due to spin-spin interactions that reduces to \( \approx 2.88 \) GHz at room temperature while \( A_{gs}, P_{gs}, d_{gs} \) and \( g_{gs} \) are the hyperfine constant, nuclear electric quadrupole constant, electric dipole moment, and \( g \)-factor of the ground state respectively. \( \parallel \) components are aligned along the \( (z) \) axis of the NV center, while \( \perp \) components are transverse to it. As usual, \( \hbar \) is Planck’s constant and \( \mu_B \) is the Bohr magneton. For the convenience of the reader, we have listed the measured values of these parameters in Table I.

| Parameter | Isotope | Value |
|-----------|---------|-------|
| \( d_{gs} \) | \( ^{14}\text{N},^{15}\text{N} \) | 17±3 (Hz cm/V) \(^{58} \) |
| \( d_{gs} \) | \( ^{14}\text{N},^{15}\text{N} \) | 0.35 ± 0.02 (Hz cm/V) \(^{58} \) |
| \( g_{gs} \) | \( ^{14}\text{N},^{15}\text{N} \) | 2.0028 ± 0.0003 \(^{54} \) |
| \( A_{gs} \) | \( ^{14}\text{N} \) | -2.70 ± 0.07 (MHz) \(^{57} \) |
| \( A_{gs} \) | \( ^{14}\text{N} \) | -2.162 ± 0.002 (MHz) \(^{59} \) |
| \( P_{gs} \) | \( ^{14}\text{N} \) | -4.945 ± 0.005 (MHz) \(^{59} \) |
| \( A_{gs} \) | \( ^{15}\text{N} \) | 3.65 ± 0.03 (MHz) \(^{57} \) |
| \( A_{gs} \) | \( ^{15}\text{N} \) | 3.03 ± 0.03 (MHz) \(^{57} \) |

TABLE I. NV\(^{-}\) ground-state spin Hamiltonian parameters.

2. Spin initialization and read out

A key reason for the popularity of the NV\(^{-}\) center in technological applications ranging from quantum computing to nano-scale sensing is the ease in which its spin state may be prepared and read out. To obtain a typical two-level system, a magnetic field is typically applied to lift the degeneracy between the ground \( m_s = \pm 1 \) states and either a \( \{ |m_s = 1 \rangle, |m_s = 0 \rangle \} \) or \( \{ |m_s = -1 \rangle, |m_s = 0 \rangle \} \) basis is used. The NV\(^{-}\) center is typically initialized by optically pumping it into the \( ^3A_2 \) state by illuminating the NV\(^{-}\) center with linearly polarized light at 532 nm, which non-resonantly depopulates the \( ^3A_2 \) states into the phonon sidebands of the \( ^3E \) states. Although both the (spin) singlet and doublet in the excited state can decay back to the ground state via (mostly spin-conserving\(^{49,60}\)) radiative transitions, the doublet with \( m_s = \pm 1 \) can also decay via an ISC to the \( ^1A_1 \) singlet at a significantly higher rate, and consequently, fluorescence at the 637 nm ZPL is due mostly to radiative decays from the \( m_s = 0 \) singlet in the excited state, thereby allowing for easy spin-sensitive photoluminescence measurements (see Fig. 1). \( Ab \) initio calculations suggest that the much faster ISC from the \( m_s = \pm 1 \) doublet to the \( ^1A_1 \) state is due to both a level crossing between the \( ^3E \) and \( ^1A_1 \) states as well as spin orbit interactions that preferentially couple part of the \( ^3E \) state with \( A_1 \) representation \( (m_s = \pm 1) \) to the \( ^1A_1 \) state\(^{61} \).

Fig. 2 shows an averaged fluorescence trace of a NV\(^{-}\) center after it has been initialized to either a \( m_s = 0 \) or \( m_s = 1 \) state. Evidently, fluorescence from a \( m_s = 0 \) and \( m_s = 1 \) state is markedly distinct at early times although they both eventually settle to the same constant level at late times. This may be understood by first noting that since the radiative lifetime of the NV\(^{-}\) center’s ZPL is \( \approx 13 \) ns\(^{63} \), the trace in Fig. 2 comprises of multiple optical cycles. At early times, the fluorescence for the NV\(^{-}\) center initialized to both the \( m_s = 0 \) and \( m_s = 1 \) states rapidly increase after the onset of the excitation laser, but as explained above, the \( m_s = 1 \) state emits less fluorescence due to a non-radiative ISC decay to the \( ^1A \) singlet state. The fluorescence for the \( m_s = 1 \) state then decreases to a minimum, which corresponds to a period when there is high occupancy of the intermediate non-radiative singlet states before decay to \( ^3A_2 \) occurs. However, at later times, the fluorescence increases again as these singlet states decay back to the ground \( ^3A_2 \) state, populating both the \( m_s = 0 \) and \( m_s = \pm 1 \) states. Assuming two singlet levels, there are two possible routes for this decay: 1) an ISC from \( ^3A_2 \) to \( ^3A_2 \) and/or 2) a decay (through radiative and non-radiative channels) from \( ^1A_1 \) to the \( ^1E \) state, followed by an ISC to \( ^3A_2 \) (see Fig. 1). Measurements of ISC rates from the singlets \( ^1A_1, ^1E \)
and possibly an additional singlet) indicate that decays from all the singlets to $^3A_2$ is largely not spin-selective and therefore both $m_s = 0$ and $m_s = \pm 1$ states in the $^3A_2$ ground state are populated from the singlets’ decay. Nevertheless, due to spin-selective depopulation of $^3E$ to $^1A_1$, there is typically a $\sim 80\%$ polarization of the ground state in $m_s = 0$ after equilibrium under optical pumping has been reached$^{53,64}$. This procedure therefore allows for both the read-out and re-initialization (with $\sim 80\%$ polarization of the $m_s = 0$ state) of the NV$^-$ center. To prepare a state in $m_s = \pm 1$, a typical procedure is to first initialize it to the $m_s = 0$ state before performing a microwave $\pi$ pulse to transfer the $m_s = 0$ state to $m_s = \pm 1$.

The utility of the ZPL’s transition in reading out the ground state spin of a NV$^-$ center is obvious, and although there are other more sophisticated techniques for single-shot read-out of the NV$^-$ spin using low temperature resonant excitations$^{65}$ or coupling to the nuclear spin of a nearby $^{13}C$ or $^{15}N$ atom$^{66}$, they all also require the above spin-dependent fluorescence. More generally, transitions at the ZPL allow for coherent spin-photon couplings and is desirable for many quantum applications. Conversely, phonon side band emissions are undesirable for many quantum photonic applications since they are incoherent and will degrade the indistinguishability of the emitted photon, which is for example required for two-photon interference used in quantum teleportation$^{67–69}$ and entanglement swapping$^{70,71}$. We note that there are several other common factors that can contribute to the degradation of an emitted photon’s indistinguishability. In general, fast interactions (compared to the radiative lifetime) with the solid-state environment through, for example, phonons and charge (if in a semiconductor)/spin noise$^{72,73}$ will induce dephasing of the optical transitions and decrease the indistinguishability of emitted photons. On the other hand, slower interactions (relative to the radiative lifetime) will induce spectral diffusion of the emission wavelength (see Fig. 21a).

Ideally, all of the NV$^-$’s fluorescence would be due to a ZPL transition, but since it is embedded within a solid, phonon interactions can significantly broaden the ZPL transition and in reality, only a fraction of its fluorescence (quantified by the Debye-Waller factor$^{74,75}$ is due to a ZPL transition. This is an especially severe problem for the NV$^-$, which has a Debye-Waller factor of only $\sim 0.04$.$^{74,75}$ Although other quantum systems embedded within solid-state materials may have higher Debye-Waller factors, they will all likewise benefit from enhanced ZPL emission. Fortunately, integrated photonics can, besides the obvious advantages of providing stable and scalable waveguiding to quantum nodes on a chip, help quantum emitters embedded within solid-state materials to enhance their ZPL emission through the Purcell effect, which we review below.

### B. Enhancement of ZPL emission through the Purcell effect

To begin with, let us first review the derivation of the expression for a power radiated by a dipole emitter. Maxwell’s equations in the source free region can be casted as$^{76}

\begin{align}
\nabla \times \mathbf{E}(r, t) &= -\mu_0 \frac{\partial \mathbf{H}(r, t)}{\partial t} \\
\nabla \times \mathbf{H}(r, t) &= \mathbf{J}(r, t) + \epsilon(r) \frac{\partial \mathbf{E}(r, t)}{\partial t},
\end{align}

where $\mathbf{E}$, $\mathbf{H}$ and $\mathbf{J}$ are position $r$ and time $t$ dependent electric field, magnetic field and free current density vectors. In equations (2) and (3), $\mu_0$ and $\epsilon(r)$ are the vacuum permeability, and position dependent (absolute) permittivity respectively. For a time-harmonic electric field, we may write

\[
\mathbf{E}(r, t) = \frac{1}{2} \left( \mathbf{E}(r)e^{-i\omega t} + \mathbf{E}^*(r)e^{i\omega t} \right),
\]

where $\omega$ is the angular frequency of light. Similar expression holds for all the other time dependent fields in equations (2) and (3). In terms of the time-harmonic fields equations (2) and (3) may be written as

\[
\nabla \times \mathbf{E}(r) = i\omega \mu_0 \mathbf{H}(r) \\
\nabla \times \mathbf{H}(r) = \mathbf{J}(r) - i\omega \epsilon(r) \mathbf{E}(r).
\]

The Poynting vector $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ denotes the power propagated per unit area. Taking the divergence on both sides of this expression, applying the vector identity

\[
\nabla \cdot (\mathbf{E} \times \mathbf{H}) = \mathbf{H} \cdot \nabla \times \mathbf{E} - \mathbf{E} \cdot \nabla \times \mathbf{H},
\]

and using equations (2) and (3), we can show that$^{77}

\[
\nabla \cdot \mathbf{S} = -\dot{\mathbf{J}} \cdot \mathbf{E},
\]

where we have assumed the medium is linear so that the time varying terms $\mathbf{H} \cdot (\partial \mathbf{B}/\partial t)$ and $\mathbf{E} \cdot (\partial \mathbf{D}/\partial t)$ may be dropped. The time-averaged version of equation (8) can be obtained using the time-harmonic fields (4) as

\[
\nabla \cdot \mathbf{S} = -\frac{1}{2} \text{Re}[\mathbf{J}^*(r) \cdot \mathbf{E}(r)].
\]

By integrating equation (9) over the volume, we can show that the time-averaged radiated power is $-\int \text{d}^3 r \text{Re}[\mathbf{J}^*(r) \cdot \mathbf{E}(r)]/2$. For a radiating dipole at position $r = r_0$, the current density is modeled via$^{77}

\[
\mathbf{J}(r) = -i\omega \mathbf{p} \delta(r - r_0),
\]

where $\mathbf{p}$ is the dipole moment vector and $\delta(r)$ is the Dirac delta function. Substituting (10) into the expression for...
the time-averaged radiated power, we get that the averaged power radiated by the dipole is

\[
P = \frac{\omega}{2} \text{Im}[|\mathbf{p}^* \cdot \mathbf{E}(r_0)|].
\]  

(11)

The Purcell factor \( F \) of a dipole emitter represents the normalized emission rate when the emitter is placed in an optical cavity. The rate is normalized with respect to the emission rate in free space (i.e., in the absence of the cavity). The power radiated by a dipole in a homogeneous dielectric medium is \( P_0 = \omega \text{Im}[|\mathbf{p}^* \cdot \mathbf{E}_0(r_0)|]/2 \), where \( \mathbf{E}_0(r_0) \) is the dipole field in the homogeneous dielectric medium. Using the well-known expressions for \( \mathbf{E}_0(r_0) \), it can be shown that \( P_0 \) may be succinctly written as

\[
P_0 = \mu_0 |\mathbf{p}|^2 n \omega^3/(12\pi c),
\]

where \( n \) is the refractive index of the dielectric medium and \( c \) is the speed of light. With these expressions for \( P \) and \( P_0 \), the Purcell factor is given by \( F = P/P_0 \). One can also derive similar expressions for \( P \) and \( P_0 \) using Fermi’s golden rule. The quantum derivations will have an additional factor of 4, and this is related to fields from vacuum fluctuations. Nevertheless, the factor cancels out in the ratio of \( F \) so that both classical and quantum derivations yield the same result.

When a dipole is placed in a structured dielectric medium like photonic crystal cavities, the corresponding electric field can be expressed as a sum of the dipole’s own field \( \mathbf{E}_0(r) \) and the scattered field \( \mathbf{E}_{s}(r_0) \). Using \( F = P/P_0 \) and the expression for \( P_0 \), it can be shown that

\[
F = 1 + \frac{6\pi c}{\mu_0 n |\mathbf{p}|^2 \omega^3} \text{Im}[|\mathbf{p}^* \cdot \mathbf{E}_{s}(r)|].
\]  

(12)

Equation (12) may be evaluated by numerically simulating a dipole source in a finite-difference time-domain (FDTD) simulation of Maxwell’s equations where in general the field created by the dipole consists of its own field and the scattered field, but the scattered field \( \mathbf{E}_{s}(r) \) may be obtained by Fourier transforming the electric fields after the dipole excitation is switched off.

The fields \( \mathbf{E}(r) \) and \( \mathbf{H}(r) \) are the total fields in the presence of the dipole emitter with current density \( \mathbf{J}(r) \) (10). All \( \mathbf{E}, \mathbf{H} \) and \( \mathbf{J} \) fields obey equations (5) and (6). Let us assume the fields may be expanded using the quasi-normal modes of the optical cavity. Under single-mode conditions the expansions can be written as

\[
\mathbf{E} = \sum \alpha_n \mathbf{E}_n = \alpha_0 \mathbf{E}_0 \quad \text{and} \quad \mathbf{H} = \sum \alpha_n \mathbf{H}_n = \alpha_0 \mathbf{H}_0,
\]  

(13)

(14)

where \( \alpha_0 \) is the expansion coefficient for the single mode. \( \mathbf{E}_0 \) and \( \mathbf{H}_0 \) are the electric and magnetic field of the quasi-normal single mode and they obey (in the absence of free currents)

\[
\nabla \times \mathbf{E}_0(r) = i \omega_0 \mu_0 \mathbf{H}_0(r),
\]  

\[
\nabla \times \mathbf{H}_0(r) = -i \omega_0 \epsilon(r) \mathbf{E}_0(r),
\]  

(15)

(16)

where \( \omega_0 \) is the complex frequency of the quasi-normal mode. Applying, Lorentz reciprocity theorem to the set of fields \( (\mathbf{E}, \mathbf{H}) \) and \( (\mathbf{E}_0, \mathbf{H}_0) \), we have \( \int d^3r \nabla \cdot (\mathbf{E} \times \mathbf{H}_0 - \mathbf{E}_0 \times \mathbf{H}) = 0 \). Subsequently, equations (5), (6), (15) and (16) can be combined as \( i(\omega - \omega_0) \int d^3r (\mathbf{E} \cdot \mathbf{r}) \mathbf{E}_0 - \mu_0 \mathbf{H} \cdot \mathbf{H}_0) = \int d^3r \mathbf{J} \cdot \mathbf{E}_0 \). Using this result and equations (10), (13) and (14), it can be shown that the complex expansion coefficient \( \alpha_0 \) is

\[
\alpha_0 = -\frac{\omega \mathbf{p} \cdot \mathbf{E}_0(r_0)}{(\omega - \omega_0) I},
\]  

(17)

where \( I \) is given by

\[
I = \int d^3r (\mathbf{E}_0 \cdot \epsilon(r) \mathbf{E}_0 - \mu_0 \mathbf{H}_0 \cdot \mathbf{H}_0).
\]  

Using this integral, a mode volume \( V \) for the single mode can be defined as

\[
V = \frac{I}{2 \epsilon_0 \omega \mu_0 |\mathbf{E}_0(r_0) \cdot \mathbf{p}|^2},
\]  

(19)

where \( \epsilon_0 \) is the vacuum permittivity and \( n^2 \) is the square of the refractive index.

For cavities with high quality factor, the quasi-normal modes can be approximated to be normal modes where the integral \( I \) and the mode volume \( V \) are real-valued. If we assume that \( \mathbf{E}_0 \in \Re \), we see from equations (15) and (16) that \( \mathbf{H}_0 \in \text{Im} \), and therefore \( I = \int d^3r (\epsilon |\mathbf{E}_0|^2 + \mu_0 |\mathbf{H}_0|^2) = 2 \int d^3r \epsilon |\mathbf{E}_0|^2 \), where we have used the fact that \( \int d^3r \epsilon |\mathbf{E}_0|^2 = \int d^3r \mu_0 |\mathbf{H}_0|^2 \), which follows from equation (7) and the requirement that \( \int d^3r \nabla \cdot (\mathbf{E}_0 \times \mathbf{H}_0) = 0 \) for normal modes in which there is no out flow of energy from the cavity. By assuming a real \( I \) and using equations (13) and (11), it may be shown that the maximum Purcell factor on resonance (i.e. \( \omega = \omega_0 = \Re[\omega_0] \)) is given by

\[
F_c = \frac{P}{P_0} = \frac{3}{4\pi^2} \left( \frac{\lambda_0}{n} \right)^3 \frac{Q}{V},
\]  

(20)

where \( Q = \text{Im}[\omega_0]/(2\Re[\omega_0]) \) and \( \lambda_0 = c/(2\pi \omega_0) \). In the case of a slight deviation off resonance, it is straightforward to show that \( F = F_c L_s(\omega) \), where \( L_s(\omega) \) is the Lorentzian line shape function

\[
L_s(\omega) = \frac{\omega_0^2}{\omega^2} \frac{\omega_0^2}{\omega^2 + 4Q^2(\omega - \omega_0)^2}.
\]  

(21)

Sauvan et al. showed that for cavities with small quality factors, it is important to include the leakage part of the fields in the integral of \( I \). Consequently, this leads to a complex volume, and in this case one can obtain a generalized \( F \)

\[
F = F_c L_s(\omega) \left( 1 + 2Q \frac{\omega - \omega_0}{\omega_0} \frac{\text{Im}[V]}{2\Re[V]} \right),
\]  

(22)

where \( F_c \) is now

\[
F_c = \frac{3}{4\pi^2} \left( \frac{\lambda_0}{n} \right)^3 \frac{Q}{\Re[V]}.
\]  

(23)
C. Advantages of hybrid quantum photonics

Equations (20) and (23) indicate that to maximize the spontaneous emission at the ZPL, it is necessary to achieve a high Q/V ratio at the ZPL wavelength. Typical cavity structures include microdisks, micropillars, nanopockets, and photonic crystals. The whispering gallery modes of microdisk cavities can have very high quality factors of $Q \sim 10^5$, but relatively large mode volumes. For micropillar resonators with integrated Bragg mirrors, very high $Q > 250,000$ and small $V < (\lambda/n)^3$ can be achieved, where $\lambda$ is the wavelength and $n$ is the refractive index. Nanowires and micropillars, like micropillars, are also efficient vertical-emitting photon sources when coupled with a quantum emitter such as a quantum dot or NV center. Yet although they are useful for applications requiring outcoupling of light from the plane of the device, they are not as well suited for planar routing of light. Photonic crystal cavities (PCCs) present an appealing compromise between high $Q$, low $V$, and efficient in-plane coupling. PCCs commonly take the form of a membrane of material with a periodic lattice of air holes, where selected holes have been displaced to form a defect in the photonic crystal bandgap. A prominent example is the L3 cavity with three missing holes in a line (see Fig. 8 for an example), which supports polarized single modes with a relatively wide spectral margin.

For fabricated L3 cavities with embedded quantum dots (QDs) on a GaAs platform, $Q \sim 10^4$ and $V \sim (\lambda/n)^3$ has been demonstrated.

For optimal coupling to the cavity, it is important for the quantum emitters, which may be modeled as dipole emitters, to be correctly oriented and positioned to match the cavity’s mode and polarization. For example, light emission from a strain-free NV− center has a single ZPL transition that may be modeled using a pair of orthogonal dipoles (with equal strength of dipole moment) perpendicular to the NV axis while SiV centers, which have four ZPL transitions at cryogenic temperatures, may be modeled as single dipole emissions. A misalignment of the optical dipole’s orientation with respect to the cavity can significantly affect the modes it excites as Fig. 3 shows.

Cavities are not only useful for enhancing spontaneous emission but they are also useful in enhancing absorption, which can be beneficial under certain spin-to-charge, spin-to-photoocurrent and magnetometry read-out schemes. Besides enabling enhanced emission/absorption and out-of-plane waveguiding of quantum emitters, integrated photonic structures can also of course provide for in-plane waveguiding through conventional waveguides or line-defect PCC waveguides. In the following sections, we review various fabrication techniques for quantum emitters and their integration with different photonic structures.

III. NV− CENTERS IN BULK DIAMOND

The NV− center introduced in section II A is a particular example of a defect center in diamond. However, there are many other defects in diamond and more generally, defects that give rise to discrete energy levels with optical transitions in the visible are frequently labeled color centers since they give color to the diamond when excited. Although we shall in this section focus on the NV− center in bulk diamond, we note that many of the fabrication techniques reviewed here can also be, by substituting nitrogen for the appropriate impurity element, analogously applied to other color centers. In section IV, we shall review a few other color centers in nanodiamonds and their integration with various photonics structures.

Since the NV center consists of a substitutional nitrogen atom adjacent to a vacancy, there are two necessary ingredients to the making of a NV center: nitrogen impurities and vacancy defects. There are therefore various ways a NV center can be assembled depending on the diamond sample that is being worked with.

Diamonds can be classified into either type I (natural abundance of ~95%) or II depending on their optical absorption properties. Optically, the key difference between type I and II diamonds is that whereas both type I and II diamonds have absorption bands in the 2–6 µm region, type I diamonds have an additional absorption band from ~6–13 µm which has been attributed to nitrogen impurities with number densities of ~10¹⁹ cm⁻³. In other words, type II diamonds are almost nitrogen-less whereas type I diamonds contain significant amounts of nitrogen impurities. This suggests two broad pathways to fabricating NV centers: 1) start with a type I diamond and create vacancies next to a single nitrogen impurity, or 2) start with a type II diamond, implant a nitrogen impurity, and then create a vacancy next to it. We begin by briefly summarizing the standard classification schemes for diamonds and then delve into various schemes for creating NV centers in diamond.
A. Fabrication of NV centers

Type I diamonds, which have significant nitrogen impurities, can be further classified into type Ia or Ib. If the nitrogen impurities in type I diamonds aggregate together and are non-paramagnetic, they are classified as type Ia\(^{109}\). On the other hand, if the impurities are paramagnetic and singly dispersed\(^{110,111}\), they are labeled as type Ib\(^{109}\). Moreover, type Ia diamonds can still be further classified into either type IaA or IaB depending on the structure of the nitrogen aggregates, which also affect their optical properties\(^{112}\). In type IaA diamonds, the nitrogen aggregate is a pair of nitrogen atoms substituting for two carbon atoms\(^{113}\), whereas in type IaB, the nitrogen aggregate is thought to consist of four nitrogen atoms arranged tetrahedrally around a vacancy\(^{114}\). Evidently, neither type IaA nor IaB diamonds with their aggregate nitrogen impurities will be desirable for the formation of NV centers. On the other hand, it is clear that NV centers can form in type Ib diamonds if a vacancy happens to be adjacent to a single nitrogen impurity, and indeed, NV centers do exist in naturally occurring type Ib diamonds\(^{115}\) but of course, a more deterministic positioning of NV centers is required for practical applications. Most synthetic High-Pressure High-Temperature (HPHT) diamonds are type Ib\(^{109}\).

Similarly, Type II diamonds can be (and are often) further classified into type IIa and IIb. The defining feature of type IIb diamonds is that they are doped to further classify into type IIa and IIb. The defining

24 diamonds than in the bulk was found closer to the surface (\(\sim \mu \text{m}\)) of type IIa diamonds. Implantation and annealing approach\(^{118,122,123}\) that seem to defy the simple \(l_\Delta \sim \sqrt{D\Delta t}\) estimate, we note that this could potentially be explained by the scattering of ions/electrons on masks\(^{131–134}\) if they were used on the diamond’s surface\(^{135}\). Nevertheless, we note that if the mask is carefully designed, transverse spatial resolution in the tens of nanometers can be achieved using an implantation and annealing approach\(^{136}\) (see Fig. 4 and section III A 2). Furthermore, we note that the choice of radiation used can significantly affect the vertical distribution of vacancies. In general, the heavier ions deposit most of their energy within a narrow band and creates vacancies at a more well defined depth whereas the lighter electrons tend to create a more uniform depth profile of vacancies\(^{137}\).

2. Implantation and annealing

A slightly different approach is to start with a type IIa diamond which does not contain significant amounts of nitrogen impurities and to introduce both the vacancy and nitrogen impurity at the same time by implanting N\(^+\) (or N\(^\text{II}\)) with a focused ion beam and then annealing at \(\gtrsim 600 \degree C\). Using this approach, it is possible to fabricate single NV\(^-\) centers with transverse spatial resolution of tens of nm and a yield of \(\sim 50\%\) using 2 MeV N\(^+\) ions with a beam diameter of 300 nm\(^{138}\). The NV\(^-\) yield, which is defined as the ratio of active NV\(^-\) centers to the number of implanted N\(^+\) ions, is proportional to the ion beam’s energy with a particularly strong slope in the keV region\(^{139}\). This is most likely due to the fact that the number of vacancies an ion generates is also proportional to its energy and SRIM\(^{140}\) calculations show that the NV\(^-\) yield show a very similar energy dependence\(^{139}\). A more energetic beam should therefore be used to increase the NV\(^-\) yield but a more energetic beam also results in deeper NV\(^-\) centers within the diamond, which is undesirable for many applications that require them to be close to the surface. This problem can
be mitigated however by irradiating the diamond first with a low energy N$^+$ ion implantation beam, followed by a higher dose $^{12}$C “damage” beam at the appropriate energy to produce the necessary vacancies at the desired depth.$^{144}$ Another advantage of using two separate irradiation doses is that a lower energy N$^+$ dose causes less ion straggling in both the vertical and transverse directions, which further improves the spatial resolution of the technique.$^{139}$ We note however that there is a maximum damage threshold of about 10$^{22}$ vacancies/cm$^3$ above which the diamond no longer anneals into diamond (graphitization) and care should therefore be taken to not subject the diamond sample to overly large doses of damaging irradiation.$^{129,142}$ Moreover, a large number of vacancies does not necessarily lead to more NV centers since the vacancies can also combine with each other or other impurities to form a different vacancy complex.$^{115,137}$ We note that another plausible approach to obtaining shallow NV centers is to first implant them deeper (by using a higher energy beam) and then etching down to that depth.$^{128,143,144}$

For diagnostic purposes, it can also be helpful to distinguish between NV centers formed by native nitrogen impurities (which might still be significant even in type IIa diamonds over the volume traced by the implanted ion) versus nitrogen ions implanted by the ion beam. This may be accomplished by using $^{15}$N (0.4% natural abundance) ions for the implantation instead and conducting hyperfine resolved ODMR.$^{145}$ Indeed, a recent statistical study of NV centers using such a technique found that implanted $^{15}$NV centers had significantly broader optical linewidths compared to native $^{14}$NV centers and that this was correlated to larger energy shifts in the $^{15}$NV centers due to increased lattice strain that has been attributed to lattice damage from the implanted ion.$^{146}$

Besides strains due to lattice damage, there can be a host of other contributing factors that lead to an undesirable broadening of the optical linewidth or a shortening of the spin coherence time $T_2$, which is of crucial importance in practical applications. For example, $^{13}$C, which has a non-zero nuclear spin, is known to be a primary source of decoherence in NV centers of ultra-pure type IIa diamonds$^{147,148}$, whereas other paramagnetic impurities, including nitrogen impurities, are also significant sources of decoherence in type Ib diamonds$^{11,149,150}$. Therefore, although both type Ib and type IIa diamonds can be used for creating NV centers, it is advantageous for practical applications requiring long coherence times to use type Ib diamonds that have significantly less impurities. Nevertheless, we acknowledge that HTHP type Ib diamonds can have significantly inhomogeneous concentration of nitrogen on different growth regions$^{128}$ and that the (inhomogeneously broadened) zero-phonon line (ZPL) linewidths of NV$^-$ centers in a low nitrogen sector can be only $\approx 15$ GHz, which is significantly lower than the typical value of 750 GHz$^{151}$. Moreover, it was also found that a secondary high temperature annealing ($\gtrsim 1000$ °C) can further narrow the linewidths of NV$^-$ centers and increase the equilibrium ratio of NV$^-$/NV$^0$, albeit at the cost of overall decreased NV$^-$ concentration$^{24}$ and perhaps a lack of compatibility with other processing steps. We note that besides post-annealing at high temperatures, there has also been speculations that performing the implantation at cryogenic temperatures could potentially result in higher NV$^-$/NV$^0$ ratios but unfortunately, experiments at cryogenic temperatures have found no obvious dependence between the NV$^-$/NV$^0$ ratio and the implantation temperature$^{24}$.

3. CVD, irradiation and annealing

An alternate pathway to creating NV$^-$ centers with long coherence times is to grow an isotopically pure $^{12}$C (which has no nuclear spin) diamond layer on an ex-
the growth rate down to nitrogen doped layer, which determines the depth of the NV centers created in this way at a depth of 52 nm exhibited a Hahn-echo $T_2$ coherence time of 765 $\mu$s at room temperature. Using a similar procedure, Ref. 152 achieved a $T_2$ of $\approx 1.7$ ms in isotopically enriched $^{13}C$ diamond. Reprinted from Ref. 153, with the permission of AIP Publishing.

FIG. 5. Top: NV$^-$ centers created by CVD growth and nitrogen delta doping of a bulk diamond substrate. Vacancies were created by electron irradiation at 2 MeV. Bottom: NV$^-$ centers created in this way at a depth of 52 nm exhibited a Hahn-echo $T_2$ coherence time of 765 $\mu$s at room temperature. Using a similar procedure, Ref. 152 achieved a $T_2$ of $\approx 1.7$ ms in isotopically enriched $^{13}C$ diamond. Reprinted from Ref. 153, with the permission of AIP Publishing.

existing substrate using plasma assisted CVD, and then introducing nitrogen gas during the last stages of the growth$^{152-154}$ (see Fig. 5). It is possible using this procedure to make single NV$^-$ centers with a long spin coherence time of $T_2 \approx 1.7$ ms$^{152}$. To achieve 3-D localization of NV$^-$ centers using such an approach, the depth of the nitrogen doped layer, which determines the depth of the NV centers, can first be carefully controlled by slowing the growth rate down to $\approx 0.1$ nm/min$^{153}$, which allows a depth precision of a few nm (delta doping). Transverse localization ($\lesssim 450$ nm) of long coherence NV$^-$ centers with $T_2 \approx 1$ ms can then be achieved by using a Transverse Scanning Microscope (TEM) to create vacancies within the nitrogen doped layer followed by annealing$^{155}$. The long coherence time of those NV centers are not limited by either $^{13}C$ nuclear spins or lattice damage induced by the electrons (which is thought to be small compared to ion implantation) but rather the presence of other nitrogen impurities that were not converted into NV centers$^{155}$. For most applications, it is desirable to have a dense ensemble of NV centers with coherence times that are limited by NV-NV dipole interactions and it is possible, using a TEM irradiated nitrogen doped CVD grown diamond, to achieve magnetic sensitivities of a NV ensemble that is a factor of two away from that limit$^{156}$. A variation to using electron irradiation via a TEM is to use implantation of $^{12}C$$^{157}$ or $^{40}He^+$$^{158}$ ions to create vacancies. Compared to electron irradiation, using ions allows for a more localized layer of vacancies, which will reduce the unwanted creation of NV centers in the substrate of the CVD grown diamond. However, we note that using such an approach can possibly decrease the $T_2$ of the NV centers due to increased lattice damage caused by the ions.

4. Laser writing and annealing

While traditional irradiation or implantation of particles typically create a trail of vacancies following the implanted particle’s path (with increased straggling for lighter particles), irradiation of the diamond by focused femtosecond (fs) laser pulses can create vacancies at a more localized depth. Moreover, their transverse spatial resolution can be better than the diffraction limit due to the non-linear processes involved. In addition, fs laser pulses from the same optical system can also be used to fabricate other photonic structures on the same diamond, opening a convenient avenue of integrating photonic structures with NV centers on the same diamond. We give here a brief introduction to fs machining before discussing its application in creating NV centers below.

Femtosecond laser machining, which has many applications spanning the writing of photonic structures like waveguides$^{159,160}$ and Bragg gratings$^{161,162}$ in glass to nano-surgery involving the ablation of cell organelles within living cells$^{163}$, works in transparent materials where there is ordinarily no linear absorption in the wavelengths of interest by a non-linear multi-photon ionization process$^{164,165}$. Valence electrons that are thus ionized into the conduction band rapidly accelerate in the intense electric field and further liberate other electrons through collisions (collisional or avalanche ionization$^{166}$) to form a plasma that strongly absorbs the laser pulse. Experimental evidence suggests that when $\approx 10\%$ of the valence electrons become ionized, it sufficiently weakens bonds and results in a disordered of the lattice (and the creation of vacancies) without a corresponding increase in the lattice temperature$^{167}$. This is a distinct physical mechanism from damage caused by longer pulses ($\gtrsim 1$ ps) where the disordering is due to a rise in lattice temperature that results in melting as electrons excited by the laser pulse relax and transfer their energy to the lattice$^{167}$. An important consequence of this distinction is that since the damage from fs pulses are not due to an increase in lattice temperature that can diffuse beyond the laser’s focal volume to cause melting in nearby regions, vacancies created by fs pulses are considerably more localized and are in fact only limited to areas where the laser intensity was sufficiently high to generate an in-situ plasma$^{164}$.

Implementing fs laser machining in diamond is complicated by the fact that there is a significant mismatch between the refractive indices of diamond ($\approx 2.4$ at 790 nm) and air or (more commonly) immersion oil ($\approx 1.5$). This can result in considerable aberration of the focal point within diamond and cause a significant elongation of the focal volume (which reduces the peak field intensity and localization of vacancies) in the beam’s direction of propagation. Indeed, an early experiment attempting...
to create NV centers using fs lasers focused the beam above the diamond’s surface instead of within it and relied on the ionization of O₂ and N₂ molecules in air to generate free electrons and ions that are subsequently accelerated by the light’s electric field into the diamond. This approach is therefore conceptually similar to irradiation followed by annealing as discussed above, although the source of electrons/ions is admittedly different. A recent variation of this technique is to focus the laser on Si nanoballs placed on the diamond’s surface, which aids in enhancing the yield of NV centers through irradiation of Si ions from the nanoballs into the diamond via Coulomb explosion that also generates sufficient heat locally for the created vacancies to diffuse and be captured by native (or implanted from the air) nitrogen impurities. We note that there exists another conceptually similar work in which a Scanning Electron Microscope (SEM) is used to irradiate the diamond with free electrons/ions ionized from molecules in the air. Since the physical mechanism of vacancy creation using fs pulses focused above the diamond’s surface is similar to that of electron irradiation, we do not discuss it further here but instead draw attention to efforts relying on focused fs pulses within the diamond.

Aberrations caused by refractive index mismatch between diamond and air (or immersion oil) may be corrected by using adaptive optics such as membrane deformable mirror (DM) and/or spatial light modulators (SLM) that modify the light’s wavefront to compensate for the refractive index mismatch. Indeed, NV centers have been successfully created using focused fs laser pulses with a SLM that had a transverse spatial resolution of ≈200 nm that was limited by the diamond’s nitrogen concentration. More recently, it was demonstrated that the same fs laser system may be used to both create a vacancy and anneal the diamond (locally) by careful control of the laser pulse energy. Coupled together with real-time monitoring of the fluorescence, NV centers at a single site could be generated with near-unity yield and statistically selective generation of NV centers with a particular orientation is even possible by monitoring the polarization pattern of the fluorescence (which is correlated with the NV center’s orientation) and keeping the annealing pulse on until a desired polarization pattern is generated (NV centers with the “wrong orientation” can be destroyed after creation by keeping the annealing pulses on) (see Fig. 6).

### B. Integration with photonic structures

For many practical quantum computing or nanosensing applications, it is desirable for NV− centers to be coupled with on-chip photonic structures so that a dense network of NV− centers coupled through photonic structures can be realized. Besides reasons of scalability, integration with on-chip photonic structures can also address certain disadvantages with using NV− centers. For example, although many quantum processing schemes make use of the NV− center’s spin-dependent ZPL fluorescence to read-out its spin state, the NV− center has a Debye-Waller factor of only ~0.04, which means that only about 4% of its fluorescence is at its useful ZPL (the rest are due to phonon assisted transitions). However, emission at the ZPL can be enhanced by increasing the local density of (optical) states/modes at the ZPL (the Purcell effect), which may be accomplished by placing the NV− center in a high Q cavity with small mode volume. The enhancement can be quantified by the Purcell factor and is proportional to the $Q/V_{mode}$ ratio. Coupling NV− centers with resonant on-chip photonic structures therefore opens the possibility of enhancing its ZPL emission through the Purcell effect and a 70 fold enhancement has been observed by placing a NV− center in a photonic crystal cavity. Besides enhancing the NV− center’s ZPL emission, integration with on-chip...
photonic structures can possibly enable efficient in and out-coupling of light that is otherwise difficult to achieve due to the large refractive index mismatch between diamond ($n \approx 2.4$) and air although we acknowledge that there are other strategies such as the use of solid immersion lenses\cite{173,174} that may also ameliorate this problem. The integration of NV$^-$ centers with photonic structures may be broadly divided into two categories: 1) integration on an all-diamond platform, or 2) integration with structures on a hybrid platform.

1. All diamond platforms

There has been considerable work on fabricating photonic structures on bulk all-diamond platforms that are integrated with NV$^-$ centers using various fabrication techniques. For fabricating diamond photonic structures that contain only a single mode around the NV$^-$ center's ZPL wavelength (637 nm), it is necessary to use thin membranes of diamond ($n \approx 2.4$ at 637 nm) that are $\sim 200$ nm thick. Although such membranes may be obtained from nanocrystalline diamond films grown on a substrate\cite{175,176}, their optical quality is typically worse compared to bulk single-crystal diamonds due to increased absorption and scattering\cite{175}. It is therefore preferable to obtain such thin diamond membranes from bulk single-crystal diamonds. Early attempts to do so relied on a focused ion beam (FIB) assisted, ion irradiated lift-off technique\cite{177–179} where ions of the appropriate energies (calculated using SRIM\cite{140}) are implanted at the desired depth to create a relatively localized heavily damaged layer, which is then connected to the surface by employing a FIB to mill trenches of a desired shape. The heavily damaged layer then undergoes graphitization following a high temperature anneal that makes it susceptible to a variety of etching reagents even as the non-damaged diamond layer above it remains etch resistant. The desired membrane can then be formed by selectively etching away the graphitized region by using a boiling acid mix\cite{177–179}. Using this technique, a photonic crystal consisting of air holes milled using FIB in such a membrane was fabricated, and the Q-factor of a 3-hole defect in the crystal was measured to be $\approx 500$, which suggests that the diamond membrane has relatively low optical losses since the expected Q was only 700\cite{180}.

Although diamond membranes fabricated using the FIB assisted ion-irradiated lift-off method described above had relatively low optical losses compared to nanocrystalline diamond films grown on substrates, damage in the lattice due to ion irradiation resulted in an undesirable significant change of the fluorescence spectrum with most of the NV$^-$ centers being converted to NV$^0$\cite{180,181}. To avoid such an undesirable outcome, new methods of obtaining a thin diamond membrane were pioneered that did not require ion irradiation to create a heavily damaged layer. One such method used a FIB to mill away three sides of a rectangular area on the single-crystal diamond before performing an undercut by milling at 45° degrees to the normal on the last side. The wedge shaped sample is then lifted off from the bulk by attaching a probe to the sample's surface through platinum deposition on both the probe and surface\cite{182}. By using a similar technique, it is possible to fabricate a triangular nanobeam (using two 45° degrees undercuts instead of one) on an all-diamond platform with a photonic crystal consisting of air holes (milled out by FIB\cite{183} (see Fig. 7). Quality factors of up to 221 were measured and considering an expected value of $\approx 274$, it appears that these diamond also have reasonably good optical qualities. Moreover, it appears that the underlying photoluminescence spectrum did not change appreciably from that of an unprocessed diamond\cite{183}, which makes it bode well for NV$^-$ related applications.

Nevertheless, residual lattice damage as measured using Raman spectroscopy can still be observed in thin diamond membranes obtained using angled FIB milling as compared to those obtained using (typically inductively coupled plasma (ICP)) reactive ion etching (RIE)\cite{184}, which is a fabrication process that has been demonstrated to be compatible with moderately long NV$^-$ spin coherence lifetimes of $\gtrsim 100 \mu s$\cite{185} while also being consistent with low optical losses\cite{93,172}. Moreover, RIE (with oxygen plasma) can be used to create surface-termination of the diamond membrane that encourages the conversion of NV$^0$ to NV$^-$ states\cite{39}. By using RIE in an oxygen plasma to create 300 nm thin diamond membranes and a FIB to
mill out air holes in them, a Q factor of 400 was obtained in a 2-D photonic crystal defect and a spontaneous emission enhancement of 2.4 was observed for a coupled silicon vacancy defect center (no NV− center was found to have coupled with the photonic crystal)\textsuperscript{186}. The Q factor in this case was limited by geometric imperfections of the fabricated photonic crystal such as non-vertical walls in the air holes\textsuperscript{186}, which are known to reduce the quality factor in such photonic crystals\textsuperscript{181,187}. Moreover, geometric imperfections also results in an undesirable shift of the cavity’s resonance wavelength, although this may be partially compensated by carefully oxidizing the membrane in air at 480 °C, which results in a blueshift of the resonance due to a slightly decreased membrane thickness and an increased air hole diameter\textsuperscript{186}. We note that the use of FIB milling to create air holes in the membrane creates a layer of implanted ions in the diamond which may adversely affect the properties of NV− centers. To mitigate this, the sample may be annealed at 1000 °C for 2 hours to remove the implanted ions\textsuperscript{186}. Moreover, annealing can also help to repair ion-induced damage within the diamond\textsuperscript{186}.

Nevertheless, although careful oxidization of the membrane can mitigate a shift of the crystal’s resonance, it is still desirable to achieve tighter fabrication tolerances that can enable higher quality factors. Compared to FIB milling, other pattern writing technologies such as electron beam lithography (EBL) can achieve tighter fabrication tolerances and it is therefore not surprising that there has been a number of work on all-diamond photonic cavities fabricated using EBL followed by a RIE etch step. For example, by using EBL to write patterns on a polymethyl methacrylate (PMMA) resist atop a silicon nitride and single crystal diamond membrane thinned via RIE, a triangular lattice all-diamond photonic crystal with a three hole linear defect\textsuperscript{188} was fabricated after transferring the EBL written pattern to the diamond membrane with two additional RIE etch steps\textsuperscript{172}. The final device was measured to have a quality factor of ∼3000 that gave a NV− ZPL enhancement of ∼70\textsuperscript{172} (see Fig. 8). Similarly, a micro-ring resonator was fabricated out of a single crystal diamond membrane using the aforementioned fabrication technique and was coupled to a NV− center where a ZPL enhancement of ∼12 was observed\textsuperscript{169} (see Fig. 9). We note that for both these works, the measurements were conducted at cryogenic temperatures (< 10 K) and that the cavity’s resonance wavelengths were tuned to the NV−’s ZPL by flowing xenon into the cryostat, which altered the resonance wavelength as it condensed on the resonant structure\textsuperscript{190}. To further illustrate the potential of this fabrication procedure, we point out that race-track resonators (see Fig. 10) fabricated from a single diamond crystal has been demonstrated with quality factors of up to ∼250 000 at telecommunication wavelengths\textsuperscript{191}.

Larger scale integration of NV− centers with photonics structures on a single crystal all-diamond platform also have been demonstrated using a similar RIE thinning, EBL and RIE etch procedure. Indeed, out-coupling of single photons from a single NV− center coupled with a micro-ring resonator (with a loaded Q-factor of ∼3000 and up to 12600 for a bare ring) and waveguide with grating couplers has been demonstrated at room temperature\textsuperscript{192}. Similar quality factors (∼5500 for a coupled ring and 12000 for an uncoupled ring) and a NV− ZPL enhancement of ∼12 (resonance tuned with flowing xenon)\textsuperscript{186} were also observed in another work that likewise fabricated all-diamond micro-ring resonators that...
were coupled with all-diamond waveguides\textsuperscript{193}.

It is also possible to fabricate free-standing all-diamond structures from a single diamond crystal. This is typically accomplished using the fabrication procedure described above with the added prior step of first mounting the diamond (before thinning by RIE etching) on a sacrificial substrate and including a final isotropic etch step that removes the substrate under the area of interest (after RIE etching to transfer the resist’s pattern to the diamond membrane). Free standing photonic structures benefit from having a larger refractive index contrast between diamond and air (as compared to the substrate). Examples of free standing all-diamond photonic structure fabricated using this procedure include the aforementioned triangular lattice photonic crystal with a three hole linear defect\textsuperscript{172} and a suspended one-dimensional photonic crystal nanobeam\textsuperscript{194} (similar in structure to Fig. 7). The suspended 1-D photonic crystal nanobeam achieved a quality factor of \( \approx 1600 \) and a \( \text{NV}^+ \) ZPL enhancement of \( \approx 7 \)\textsuperscript{194} after its resonance was tuned by blueshifting it with controlled oxygen plasma etch steps\textsuperscript{196} and redshifting it with flowing xenon at cryogenic temperatures\textsuperscript{190}.

Free standing all-diamond structures can also be created by using angular RIE etching, which involves enclosing the diamond sample in an appropriately shaped Faraday cage with a mesh of roughly 2\text{mm} \times 2\text{mm} pitch that alters the electric potential so that ions are only accelerated perpendicular to the cage’s surface\textsuperscript{195}. A variety of freestanding all-diamond photonic and mechanical structures including cantilevers, waveguides, photonic crystal nanobeams, racetrack resonators, and microdisk cavities can be fabricated using this technique\textsuperscript{195,196} (see Fig. 11). All-diamond suspended racetrack resonators thus fabricated have been realized with loaded quality factors reaching up to \( \sim 151,000 \) at 1648 nm and photonic crystal defects on a suspended 1-D nanobeam have achieved loaded quality factors of up to 59,000 at around 637 nm\textsuperscript{196}. A variation to using angular RIE etching for undercutting is to, after a typical anisotropic RIE etch step, use a further quasi-isotropic RIE etch step, where the plasma is operated with zero RF power and the main etching mechanism is not due to mechanical acceleration of ions into the substrate but from chemical action with slightly different etch rates along distinct crystal planes. All-diamond suspended waveguides\textsuperscript{197}, micro-disk resonators\textsuperscript{87} (see Fig. 12) and suspended nanobeam photonic cavities\textsuperscript{398} have been fabricated using quasi-isotropic RIE etching. The micro-disk resonators have demonstrated loaded quality factors of up to \( \sim 109,000 \) that is thought to be limited mainly by a non-cylindrical pedestal due to dissimilar etching rates in distinct crystal planes\textsuperscript{87} while a instrument resolution limited quality factor of \( > 14,000 \) at \( \approx 637 \) nm was obtained for the 1-D nanobeam photonic cavities\textsuperscript{198}.

In addition, FIB milling can also be used to undercut an all-diamond cylinder (first defined by a photolithography step followed by RIE etching of a diamond plate) to form a free-standing micro-ring resonator. Nevertheless, it appears that the quality factor of such a FIB undercut micro-ring resonator (\( Q \sim 5720 \) at 1492 nm)\textsuperscript{199} is still significantly less compared to suspended resonators fabricated using EBL and angular RIE etching\textsuperscript{196} due, it seems, to surface roughness caused by FIB milling since various precautions to mitigate \( \text{Ga}^+ \) induced dam-

![FIG. 11. Schematic of angular RIE with a Faraday cage. (a, i) An etch mask is defined by coating the sample with resist, writing it with EBL, and developing the resist. (a, ii) The pattern is transferred into the diamond substrate using anisotropic top down plasma etching. (a, iii) Angular RIE etching (using the Faraday cage in (b)) is used to undercut the structure to form a suspended triangular nanobeam. (a, iv) Etch mask is removed. (b) Schematic of the Faraday cage which modifies the electric field so that the ions are accelerated at an angle defined by \( \theta \). (c) Illustration of angular RIE undercutting a structure to form a suspended nanobeam. Reprinted with permission from Ref. 195. Copyright 2012 American Chemical Society.](image1)

![FIG. 12. (a) Schematic of a quasi-isotropic RIE process, where \( \text{O}_2 \) plasma is used with zero RF power to quasi-isotropically undercut areas of the substrate that is not protected by a \( \sim 200\text{nm} \) conformal coating of plasma enhanced chemical vapor deposited PECVD Si\textsubscript{3}N\textsubscript{4}. Consistent with a predominantly chemical etch, the etch direction is defined by crystal planes. Black and red arrows denote etching along the \{100\} and \{111\} families of crystal planes. (b) SEM image at \( 60^\circ \) of the fabricated diamond micro-disk resonator. (c) Top-down SEM image of the micro-disk. Reprinted with permission from Ref. 87. Copyright 2015 American Chemical Society.](image2)
age, including applying an aluminum and chromium coating, and various annealing plus acid cleaning treatments, were already taken and energy-dispersive X-ray spectroscopy (EDX) did not reveal the presence of any Ga in the final sample.\textsuperscript{199}

Most of the work discussed above which demonstrated coupling of NV\textsuperscript{−} centers to all-diamond photonic structures relied on randomly positioned native NV\textsuperscript{−} centers within the diamond even though deterministic placement of them are crucial to optimum performance. Nevertheless, we note that spatial positioning of NV\textsuperscript{−} centers to about \(\sim 10\) nm in all three dimensions\textsuperscript{136} has already been separately demonstrated and the coupling of NV\textsuperscript{−} centers that were placed at deterministic depths (via delta-doping\textsuperscript{153} as described in section III A 3) with a nanobeam photonic crystal has been demonstrated with a measured Q factor of \(\sim 7000\) and ZPL enhancement of 20 times\textsuperscript{200}. Separately, deterministic placement of NV\textsuperscript{−} centers using ion-implantation with a FIB milled aperture in an atomic force microscopy (AFM) tip in a 2-D photonic crystal fabricated from a single crystal diamond and FIB milling recently reported a signal-to-noise enhancement of 3 in the NV\textsuperscript{−} center’s spin read out (via spin-dependent fluorescence) but only a meager NV\textsuperscript{−} ZPL enhancement of 1.224\textsuperscript{201}.

An alternative to using EBL to write patterns on a resist atop a diamond membrane is to first write the patterns on a reusable Si membrane that is then transferred onto a diamond membrane using either a micro-polydimethylsiloxane (PDMS) adhesive attached to a tungsten probe tip or by stamping the Si membranes onto the diamond with a polytetrafluoroethylene (PTFE) sheet\textsuperscript{202} (see also section V B 4 for an application of this technique to the positioning of quantum dots). Once transferred onto the diamond membrane, the Si membrane then serves as a mask for pattern transfer to the diamond via RIE (see Fig. 13). A 2-D photonic crystal with a seven hole linear defect fabricated using this technique in a single-crystal diamond membrane yielded a quality factor of 4700\textsuperscript{202}. One significant advantage of this mask transfer technique is that the diamond membrane is never exposed to damaging irradiation that can adversely affect the NV\textsuperscript{−} centers’ properties. Indeed, using such a fabrication procedure, spin coherence lifetimes of \(\sim 200\) \(\mu\)s were measured for NV\textsuperscript{−} centers coupled to suspended 1-D photonic crystals defects, which are similar to lifetimes measured in their parent CVD crystals\textsuperscript{203}. Moreover, quality factors of \(\sim 3300\) at \(\approx 637\) nm were achieved and a 62 times resonant enhancement of the NV\textsuperscript{−} center’s ZPL emission was obtained\textsuperscript{203}. Suspended 1-D nanobeam photonic crystal defects and waveguides can also be fabricated using a Si membrane transfer followed by RIE anisotropic etching and then undercutting with an angular RIE etch using a Faraday cage\textsuperscript{204}. The resulting 1-D photonic crystal defect had a measured quality factor of \(\sim 1200\) at \(\approx 688\) nm and up to 98.78\% transmission was reported for optimized waveguides although it is not entirely clear what is the propagation loss per unit length\textsuperscript{204}.

Finally, we note that there has been work towards an all-diamond platform using fs-laser writing. As discussed in section III A 4, fs laser pulses are capable of creating NV\textsuperscript{−} centers in diamond. Moreover, as in the case of crystals like LiNbO\textsubscript{3}\textsuperscript{205,206} and sapphire\textsuperscript{207}, it is possible to inscribe waveguides in diamond with fs laser writing. This may by accomplished by writing two parallel lines in diamond that results in graphitization of material within the focus leading to a decreased refractive index that in turn enables the confinement of an optical mode between the two laser written lines. In addition, the graphitized material, which has lower density, expands and causes stress-induced modification to the refractive index of the surrounding diamond that leads to vertical confinement of the optical mode\textsuperscript{208}. Importantly, the laser inscribed waveguides in diamond survive annealing at 1000 °C\textsuperscript{209}, which is commonly required for the formation of NV\textsuperscript{−} centers, but is not necessarily guaranteed as in the case of laser inscribed waveguides in sapphire\textsuperscript{207}. Since the same fs laser system can be used to both create NV\textsuperscript{−} centers and write waveguides within bulk diamond, sub-micron relative positioning accuracy is possible between the NV\textsuperscript{−} center and waveguide. Using this technique, single NV\textsuperscript{−} centers were successfully incorporated into the midst of laser written diamond waveguides and waveguiding of their spontaneous emission was confirmed\textsuperscript{210} (see Fig. 14).
Generally, NV\textsuperscript{−} centers in GaP-diamond hybrid platforms are evanescently coupled to the GaP photonic structures. For example, in the first demonstration of a coupled NV-GaP waveguide system\textsuperscript{219}, NV\textsuperscript{−} centers created by ion implantation in HPHT type Ib diamonds (at a depth of \(\approx 100\) nm) were evanescently coupled to a 120 nm thick GaP rib waveguide that was transferred onto diamond via epitaxial liftoff\textsuperscript{220} after removal from its underlying Al\textsubscript{0.8}Ga\textsubscript{0.2}P sacrificial layer atop a GaP substrate. The evanescent coupling requires that NV\textsuperscript{−} centers are created close to the diamond’s surface and for gaps between GaP and the diamond substrate to be minimized. Indeed, a significant disadvantage of a (bulk) hybrid platform compared to an all-diamond one is that the NV\textsuperscript{−} centers cannot generally be placed in a maximum of the optical mode that would otherwise enable good optical coupling and an enhancement of spontaneous emission rates. To mitigate this, NV\textsuperscript{−} centers may be coupled to optical resonators such as microdisks with sufficiently high quality factor\textsuperscript{221} and light within these resonators may then be outcoupled via coupling with another waveguide\textsuperscript{222,223}. Despite the high refractive index of GaP, wavguideing in a GaP waveguide atop a diamond substrate can still be significantly lossy due to the reduced effective index of the guided mode and the moderately high refractive index of diamond. To enable waveguiding and to reduce losses due to mode leakage into the substrate, it is common to decrease the effective index of the substrate (from its bulk value) by etching it so as to create a diamond pedestal beneath the resonator\textsuperscript{221−225}. Hybrid GaP-diamond architecture have to date successfully coupled NV\textsuperscript{−} centers with GaP based resonators, waveguides, as well as directional/grating couplers on the same chip\textsuperscript{222,223} (see Fig. 16).

Besides a GaP-diamond hybrid platform, it is also possible to couple NV\textsuperscript{−} centers with other material systems. For example, by pre-selecting single NV\textsuperscript{−} centers in bulk diamond and fabricating single-mode tapered waveguides from them, it is possible to, with near-unity yield, couple single NV\textsuperscript{−} centers in single-mode diamond waveguides to low loss single-mode SiN waveguides\textsuperscript{218} (see Fig. 15). A similar work couples single NV\textsuperscript{−} centers in tapered diamond waveguides to commercially available tapered optical fibers\textsuperscript{226}. Other examples of a non-GaP hybrid

![FIG. 14. Raman and NV fluorescence for various excitation (E)/collection (C) modes of an integrated laser written diamond waveguide and NV\textsuperscript{−} center. (a) Raman scattered light collected above the waveguide after butt-coupled excitation of the waveguide, demonstrating waveguiding within the diamond. (b) Fluorescence of NV\textsuperscript{−} above the waveguide after sending in excitation light from the end of the waveguide, demonstrating that the NV\textsuperscript{−} is sufficiently close to the optical mode of the waveguide to interact with it. Fluorescence was measured using a home-built confocal microscope. (c) Same as in (b) but the fluorescence is measured using an electron multiplying charged coupled detector (EMCCD). (d) Fluorescence of the NV\textsuperscript{−} measured at the end of the waveguide using an EMCCD after the NV\textsuperscript{−} center was excited from above. Reprinted with permission from Ref. 210 © The Optical Society.

2. Hybrid platforms

Much of the work on hybrid platforms have revolved around a GaP-diamond hybrid platform due to both the high refractive index of GaP (\(\approx 3.3\) at 637 nm) (compared to diamond \(\approx 2.4\) at 637 nm), and its relative ease of fabrication using standard semiconductor processing technology. In addition, unlike an all (bulk) diamond platform, which by inversion symmetry has a zero second-order non-linear susceptibility (\(\chi^{(2)}\)) (we note however, that diamond has a non-zero third-order non-linear susceptibility \(\chi^{(3)}\) and that it has a relatively high non-linear refractive index that allows it to be harnessed for non-linear four-wave mixing processes\textsuperscript{211}), GaP possesses a relatively large \(\chi^{(2)}\) that allows it to be used in non-linear processes such as second harmonic generation\textsuperscript{212}. Moreover, unlike diamond which is forbidden by symmetry to have a bulk linear electro-optic coefficient\textsuperscript{213}, GaP has a non-zero linear electro-optic coefficient (\(r_{41}\approx -0.97\) pm/V at 633 nm\textsuperscript{214}) that enables it to be used for active electro-optic switching applications (as has been demonstrated in AlN material systems\textsuperscript{215,216}), and as a III-VI semiconductor, GaP can potentially host on-chip integrated single-photon detectors as demonstrated on GaAs waveguides\textsuperscript{217}.

Generally, NV\textsuperscript{−} centers in GaP-diamond hybrid platform
FIG. 16. Examples of integrated hybrid GaP-diamond systems where a thin 125 nm film of GaP was epitaxially grown and transferred onto a diamond substrate before being patterned with EBL and RIE. Above: schematic view overlaid with FDTD simulations, bottom: SEM images of integrated devices. (a) waveguide-coupled disk resonators, (b) directional coupler, (c) grating coupler. Reprinted with permission from Ref. 223 © The Optical Society.

diamond platform include a Ag-diamond system where diamond nano-pillars enclosed within an Ag film exhibited enhanced spontaneous emission of up to 4.6 times due to coupling of NV\textsuperscript{−} centers within the pillars to the plasmonic cavity formed by the encasing Ag film\textsuperscript{227}. The directivity of the spontaneous emission can be enhanced by surrounding the nano-pillars with concentric, circular SiO\textsubscript{2} gratings\textsuperscript{228}.

IV. COLOR CENTERS IN NANO DIAMONDS

As discussed in the preceding section, NV centers are not the only defects in diamond that exhibit discrete energy levels with optical transitions although they are arguably the most studied defect. Recently, defect centers consisting of group-IV elements such as silicon vacancy (SiV)\textsuperscript{229,230}, germanium-vacancy (GeV)\textsuperscript{231} and tin-vacancy (SiV)\textsuperscript{232,233} centers in diamond have been of particular interest due to symmetries in their configuration that leads to a higher Debye-Waller factor and narrower spectral lines that increases the indistinguishability of their emitted photons. Moreover, although there has, as the preceding section shows, been a great deal of work in bulk diamond, there has also been considerable work in integrating color centers in nanodiamonds to hybrid photonic structures. We note however, that NV centers in nanodiamonds are less photo-stable and tend to have significantly larger inhomogeneously broadened ZPL linewidths as compared to their bulk counterparts. Although this makes them less suitable for many quantum computing/processing applications, nanodiamonds are more suited for bio-sensing/labeling applications\textsuperscript{234–236}, and interestingly enough, the spontaneous emission rates of NV centers in nanodiamonds can also be enhanced by encasing them in phenol-ionic complexes\textsuperscript{237}. Moreover, nanodiamonds with a high concentration of SiV centers can also be used as temperature sensors\textsuperscript{238}. In this section, we give examples of other color centers in nanodiamonds that have been coupled to photonic structures.

A. Fabrication

Nanodiamonds are synthesized by various techniques such as detonation, laser assisted synthesis, HPHT high energy ball milling of microcrystalline diamond, hydrothermal synthesis, CVD growth, ion bombardment on graphite, chlorination of carbides and ultrasonic cavitation\textsuperscript{239}. In the laboratory, the detonation method and HPHT growth are commonly employed to synthesize NV containing nanodiamonds on a large scale\textsuperscript{240}. CVD growth is another promising technique that has successfully synthesized single NV centers in nanodiamonds\textsuperscript{241}. More recently, a new metal-catalyst free method to syn-
thesize nanodiamonds with varying contents of NV and SiV centers produced high-quality color centers with almost lifetime-limited linewidths.\textsuperscript{242,243}

In Ref. \textsuperscript{244}, the authors reported the first direct observation of NV centers in discrete 5 nm nanodiamonds at room temperature. Although the luminescence of those NV centers was intermittent (i.e. they undergo blinking), the authors were able to modify the surface of the nanodiamonds to mitigate the undesirable blinking. In another work, the authors showed the size reduction of nanodiamonds by air oxidation and its effect on the nitrogen-vacancy centers that they host.\textsuperscript{245} The smallest nanodiamond in their samples that still hosted a NV center was about 8 nm in size.

SiV centers in nanodiamonds have subsequently been investigated.\textsuperscript{246–248} Ref. \textsuperscript{246} describes the first ultra-bright single photon emission from SiV centers grown in nanodiamonds on iridium. The SiV centers were grown using microwave-plasma-assisted CVD and those single SiV\textsuperscript{−} defects achieved a photon count rate of about 4.8 Mcounts/s (at saturation). Bright luminescence in the 730-750 nm spectral range were observed using confocal microscopy. No blinking was observed but photobleaching occurred at high laser power. Enhanced stability might be gained by controlling the surface termination of the nanodiamonds, as was shown for the case of NV centers.\textsuperscript{249}

Residual silicon in CVD chambers often results in the formation of SiV\textsuperscript{−} centers in most CVD-grown nanodiamonds.\textsuperscript{243,246} Likewise, due to silicon-containing precursors, many HPHT-synthesized nanodiamonds also include SiV\textsuperscript{−} centers.\textsuperscript{240} In Ref. \textsuperscript{248}, the authors demonstrated optical coupling of single SiV\textsuperscript{−} centers in nanodiamonds and were able to manipulate the nanodiamonds both translationally and rotationally with an AFM cantilever.

Fabrication of other color centers such as GeV centers in nanodiamond were also recently demonstrated. For example, single GeV centers in nanodiamonds were successfully fabricated by the authors in Ref. \textsuperscript{250} after they introduced Ge during HPHT growth of the nanodiamonds. More generally, in Ref. \textsuperscript{251}, the authors studied a larger variety of group IV color centers in diamond, including SiV, GeV, SnV and PbV centers.

We note that it is possible to control the size and purity of the HPHT nanodiamonds down to 1 nm.\textsuperscript{252} In other works, the size of nanodiamonds are typically tens of nanometers,\textsuperscript{253–255} which make nano manipulation of them feasible. For example, emission from single NV centers hosted in uniformly-sized single-crystal nanodiamonds with size 30.0 ± 5.4 nm have been reported.\textsuperscript{255}

Although high count rates are in general achievable for NV and SiV color centers in nanodiamonds,\textsuperscript{256} these high count rates were sometimes reported to be correlated to blinking.\textsuperscript{173} Compared to SiV centers in the bulk, SiV centers in nanodiamonds have significantly less reproducible spectral features and can feature a broad range of ZPL emission wavelengths and linewidths.\textsuperscript{257} More generally, the linewidths of SiV centers in nanodiamonds have been shown to depend on the strain of the diamond lattice.\textsuperscript{257} Nevertheless it is sometimes possible to obtain nearly lifetime-broadened optical emission in SiV centers in nanodiamonds at cryogenic temperatures,\textsuperscript{242,258} and indeed nearly lifetime limited zero-phonon linewidths have been obtained in both NV and SiV centers in nanodiamonds. For example, despite spectral diffusion and spin-nonconserving transitions, zero-phonon linewidths as small as 16 MHz has been reported for NV centers in type Ib nanodiamond at low temperature.\textsuperscript{259}

For GeV centers in HPHT nanodiamond, the stability of its ZPL emission wavelength and linewidth has been attributed to the symmetry of its molecular configuration, although a large variation of lifetimes was also reported.\textsuperscript{260} The authors there estimate a quantum efficiency of about 20% for GeV centers in HPHT nanodiamonds.

\section{B. Integration with photonic structures}

As mentioned in section \textsuperscript{III B 2} above, a hybrid GaP-diamond platform is attractive for multiple reasons and there has been work involving not just bulk GaP-diamond systems but also hybrid GaP-nanodiamond systems. For an extensive review, see Ref. \textsuperscript{240}. Purcell enhancement of the ZPL emission by a factor of 12.1 has been reported in a hybrid nanodiamond-GaP platform where the ZPL of an NV center is coupled to a single mode of a PCC.\textsuperscript{261} In that work, both the nanodiamond and cavity are first pre-selected and the resonance of the cavity is then tuned to the ZPL of the NV center by locally oxidizing the GaP with a focused blue laser.\textsuperscript{261} Finally, the pre-selected nanodiamond is then transferred to the GaP cavity using a pick-and-place technique\textsuperscript{262,263} (see Fig. 17). Alternatively, a GaP PCC may be transferred using a micro-PDMS adhesive on a tungsten probe (briefly discussed and illustrated in section \textsuperscript{III B 1} and Fig. 13) to a pre-selected nanodiamond containing a NV\textsuperscript{−} center of desirable properties.\textsuperscript{264}

Nanodiamonds were also integrated with silica micro-resonators to achieve cavity QED (cQED) effects. In one early attempt, diamond nanocrystals were attached to silica micro-resonators by dipping silica micro-disks with diameters of 20 \textmu m into an isopropanol solution containing suspended nanodiamonds with a mean diameter of 70 nm.\textsuperscript{254} Initially, the micro-disks had a quality factor of $Q = 40000$ at room temperature, but after deposition of the nanodiamonds, low temperature measurement showed that the quality factor decreased significantly to around 2000 – 3000. By condensing nitrogen gas to tune the cavity modes, the authors observed that a single NV center could couple to two cavity modes simultaneously. However, there was no significant change in the spontaneous emission rate, which was probably due to, in addition to the emitters’ large linewidth, the resonator’s large mode volume and limited quality factor. In Ref. 265...
FIG. 17. (a) AFM image of the core of a photonic crystal fiber. (b) A pre-selected nanodiamond is then transferred to center of the photonic crystal fiber using a pick-and-place technique. (c) A nanodiamond in the center of a gallium phosphide photonic crystal membrane cavity. Reprinted from Ref. 262, with the permission of AIP Publishing.

265, a tapered fiber is used to both pick up and position NV containing nanodiamonds onto a high-Q SiO$_2$ micro-disk cavity. The same tapered fiber could then also be used to characterize light transmission through the system. Coupling in the strong cQED regime has also been achieved between NV centers in nanodiamonds and silica micro-spheres resonators.

Besides silica resonators, there has also been work on polystyrene micro-sphere resonators. Nanodiamonds with a mean diameter of 25 nm can be attached to polystyrene micro-spheres with diameters of $\sim 5 \mu$m by first dispersing both on a cover slip and then using near-field scanning optical microscopy (NSOM) tips to bring the micro-spheres close to a pre-selected nanodiamond containing a single NV$^-$ center. Touching a nanodiamond with a micro-sphere then attaches the former to the latter. Using this technique, the authors demonstrated coupling of two single NV centers found in two different nanodiamonds to the same micro-sphere resonator.

Silicon carbide is another material that can be integrated with diamond due to its similarity with diamond. For example, the authors in Ref. 240 developed a scalable hybrid photonics platform which integrates nanodiamonds with 3C-SiC micro-disk resonators fabricated on a silicon wafer. By condensing argon gas on the structure, the authors were able to continuously red shift the resonator’s resonance and tune it to the color center’s emission to observe an enhancement of the center’s spontaneous emission.

It is also possible to enhance the spontaneous emission rate of a quantum emitter coupled to waveguiding structures like dielectric-loaded surface plasmon polariton waveguides (DLSPPWs) where the significantly confined mode volume of the surface plasmon polariton can enable Purcell factors above unity (see Fig. 18). Experiments involving embedded nanodiamonds with NV centers in a DLSPPW consisting of a HSQ waveguide on top of a silver film demonstrated a spontaneous emission enhancement of up to 42 times. In a similar vein, a GeV center embedded within a similar DLSPPW was successfully excited by 532 nm light propagating within the waveguide and achieved a three-fold enhancement in its spontaneous emission rate due to the small mode volume within the waveguide.

Although likely to be less useful than coupling to DLSPPWs due to higher losses, coupling of single NV centers in nanodiamonds to silver nanowires can enable interesting studies of surface plasmon polaritons (SPP) as in Ref. 269 where a wave-particle duality was demonstrated for SPPs excited by single photons from a nanodiamond.

The spontaneous emission rate of a quantum emitter can be significantly enhanced when coupled to a plasmonic nano-antenna. For example, enhancement factors of up to 90 times was observed for a NV center within a nanodiamond that was coupled to a nanopatch antenna. Even higher enhancement of up to 300 times has been theoretically proposed by coupling SiV centers in a nanodiamond to a specific geometry of gold dimers.

Besides static resonators such as micro-disks and
A. Introduction to Quantum Dots

A quantum dot (QD) is a small nanometer-sized three-dimensional inclusion of a narrower bandgap material within a wider bandgap matrix. The 3D confinement potential of the QD leads to a discretization of energy levels and gives it localized, atom-like properties. By controlling and manipulating these properties, QDs can be utilized in many aspects of quantum technologies, such as quantum light sources or as qubit systems. QDs have also been studied extensively and developed for numerous optoelectronic applications, including light-emitting diodes (LEDs), photovoltaic devices, and flexible displays.

Compared to other atomic systems (e.g., trapped ions) used in early experimental realizations of quantum logic, QDs are embedded within a solid-state medium and thus do not require bulky and complicated vacuum systems and optical trapping setups. Moreover, QD-based devices can take advantage of well-established growth techniques, e.g., molecular beam epitaxy (MBE) or metalorganic vapor phase epitaxy (MOVPE), which allow for monolithic growth with monolayer precision. Coupled with the ability to electrically control these devices, QDs have attracted extensive research efforts in developing and realizing QD photonic devices.

The most common QD growth approach uses the Stranski-Krastanov mechanism, as QD material is successively deposited and reaches a critical thickness, strain energy from mismatched lattice constants drive the formation of 3D nano-islands through a self-assembly process which allows for more efficient strain relaxation. Common QD materials systems include both III-V (typically In(Ga)As in (Al, Ga)As matrices) GaAs/InGaAs) and Group IV (Si).

QD devices have numerous applications in quantum integrated photonics. They can serve as tunable, high-quality single-photon sources that can be integrated into nanophotonic structures. To complement this, photonic device components for photon manipulation, such as modulators, frequency sorters, and frequency converters, have been developed. High-speed near-infrared (NIR) detectors based on QDs have also been demonstrated in recent years. By controlling the QD spin, spin-photon interfaces can also be realized, allowing the QD to be used as a quantum memory, as well as a range of additional applications such as single-photon switching.

B. Integration Strategies for Quantum Dots

While QDs can be integrated with photonic circuits and operated in their as-grown state or as dispersed colloidal nanoparticles, it is often desirable, as discussed in section II C, to embed or integrate QDs within cavity devices where they can, among other things, benefit from enhanced spontaneous emission and increased coupling efficiency to the rest of the photonic circuit. In this section, we will review the major approaches for integrating QDs with photonic circuits, and highlight the recent advances in these areas. A detailed reference on integration methods for hybrid quantum photonics can be found in Ref. 301.

1. Random Dispersion

A simple integration method is to forego deterministic positioning, and randomly disperse colloidal QDs as nanoparticles onto photonic structures via drop casting or spin coating. However, such nanoparticles have a large surface area, which may lead to optical instabilities such as blinking or bleaching, due to the stronger influence of surface states and enhanced Auger recombination. Moreover, such methods are not suitably scalable for quantum photonic applications where efficient, deterministic coupling between QDs and the photonic circuit is crucial.

To improve the positioning precision, and thus the coupling efficiency, a lithography-based masking method can be used to selectively deposit dispersed QDs on top of the photonic structures (Fig. 20a). Despite its limitations, randomly dispersed QDs can still be a useful
method to rapidly prototype hybrid quantum photonics platforms.

2. In-situ Lithography

Photonic structures can be fabricated on adjacent layers to a QD sheet where the self-assembled QDs are randomly located\textsuperscript{309}. However, the QDs would not be optimally placed with respect to the photonic structures for efficient coupling. To circumvent this problem, the QDs can first be located and pre-selected, e.g. via cathode luminescence, and the waveguide structures can then be patterned and etched via an in situ lithography technique. This has been demonstrated, for example, with the deterministic integration of InAs QDs into a GaAs photonic circuit\textsuperscript{303} (Fig. 20b).

3. Wafer Bonding

Quantum emitters embedded in a high-quality bulk crystalline material are able to produce stable single-photon emission with high purity and indistinguishability. Ideally, hybrid heterostructures of QDs and photonic components can be grown directly on a single wafer. However, growing such heterostructures directly often results in poor crystal quality due to the formation of antiphase boundaries and large mismatches in material lattice constants, thermal coefficients, and charge polarity\textsuperscript{310}.

Wafer-to-wafer bonding is a method for integrating
dissimilar material platforms\textsuperscript{311}. Consider the transfer of a III-V material onto a silicon nitride photonics circuit: Each material is grown separately with optimized substrates and conditions, thus maintaining high crystal quality for both compounds. The III-V wafer is flipped and bonded onto the top surface of the photonic wafer; subsequent removal of the substrate of the transferred wafer leaves a thin membrane structure on top of the photonic circuit. Photonic structures are then patterned using lithographic techniques; for example, the coupling of the emission from InAs QDs in a GaAs waveguide cavity structure into an underlying silicon nitride waveguide has been observed, with an overall coupling efficiency of \(\sim 0.2\textsuperscript{304} \) (Fig. \textit{20c}).

However, random positioning of QDs with respect to the photonic structures will result in non-optimal coupling, leading to a low yield of efficiently coupled devices across the wafer. This can be improved via \textit{in situ} lithography around pre-identified QDs after the wafer bonding step\textsuperscript{303}.

The wafer bonding can also be performed orthogonally (Fig. \textit{20d}), to allow the QDs optimized for out-of-plane emission (e.g. with distributed Bragg reflector cavities\textsuperscript{305}) to be efficiently coupled into photonic waveguides. However, since only devices at the wafer edge can be integrated (as opposed to across the entire wafer for non-orthogonal bonding), this approach is less scalable.

4. Pick-and-place

Another approach that allows for precise positioning of QDs on the photonic circuit is to pick-and-place individual QD-embedded structures instead of having a single wafer-scale integration step. QDs can be pre-characterized and pre-selected, and then selectively integrated at desired positions on the photonic circuit. For example, they can be either placed on top of existing waveguides\textsuperscript{296,312}, or at specific points relative to a marker for subsequent waveguide encapsulation, i.e. waveguide material is deposited and patterned over the deposited QD structure\textsuperscript{313}. Besides ensuring optimal coupling of the QDs to the photonic circuit, this method also allows for a greater flexibility in the choice of transferred QD material and device geometry.

There are two common techniques for performing the pick-and-place transfer. The transfer printing method typically uses a stamp made of a material such as polydimethylsiloxane (PDMS) that is adhesive and transparent, such that precise alignment of the structures can be monitored under an optical microscope during the transfer\textsuperscript{306,314,315} (Fig. \textit{20e}). With the aid of additional alignment markers, positioning accuracies better than 100 nm have been achieved\textsuperscript{314}. Different strategies to control the adhesion of the stamp are detailed in a separate review paper\textsuperscript{316}. However, there are several challenges in using the transfer printing technique. The stamping process induces a force over a large sample area and may damage parts of the fragile photonic circuit, although this may be mitigated by using a sufficiently small stamp not much larger than the transferred material\textsuperscript{317}. Moreover, it is difficult to re-position the emitters as the adhesion between the integrated structures is typically much stronger than their adhesion to the stamp.

An alternative is to perform the pick-up and transfer using a sharp microprobe (Fig. \textit{20f}). A small amount of adhesive (e.g. PDMS) can be added to the probe tip to aid the transfer, analogous to a micro-stamp\textsuperscript{302}. Although this technique requires precise control of the microprobe, it is able to transfer small, fragile structures such as single nanowires with high accuracy and controllability when aided by an optical microscope\textsuperscript{296,313,318}, and especially so when using an electron microscope\textsuperscript{319}.

Currently, the manual transfer of individual devices one by one can be very time-consuming, but there is great potential in automating the process and allowing for scalable fabrication of many integrated devices.

C. As a single-photon source

Single-photon sources can be realized from QDs by utilizing the radiative recombination from an excitonic state of a single QD\textsuperscript{322,323}. QD-based single-photon sources have been extensively studied, and in-depth discussions can be found in other review articles\textsuperscript{294,324}. A pure single-photon light field consists solely of single-photon Fock states, and its purity can be verified by measuring its second-order intensity correlation function \(g^\text{(2)}\) via a Hanbury Brown and Twiss (HBT) experiment\textsuperscript{125}. For a single photon source, the average number of additional photons arriving at the same time as another “heralding” photon at \(t = 0\) should be zero and consequently, the measured \(g^\text{(2)}(0)\) value can be taken as a measure of the source’s single-photon purity. The first demonstrations of single-photon emission from QDs were performed under optical pumping\textsuperscript{322}, and then by electrical pumping\textsuperscript{326}. The photon statistics of QD single-photon sources can be degraded by imperfections such as multi-photon emission from multi-exciton states, or if light is also collected from nearby QDs. For non-resonant excitation, obtaining a low \(g^\text{(2)}(0)\) generally requires that carriers are not captured and that they undergo recombination after a first exciton emission. Therefore, relaxation into the QD and the radiative cascade causing recombination should occur on a longer timescale than the decay of the initial carriers\textsuperscript{327,328}. With resonant, pulsed excitation, \(g^\text{(2)}(0)\) values very close to zero have been demonstrated for QD single-photon sources\textsuperscript{329–331}.

In addition to the mechanisms described in section II A 2 that degrade the indistinguishability of the QD’s emitted photon, the radiative cascade of high-energy carriers results in a temporal uncertainty (i.e. jitter) of photon emission\textsuperscript{327}, and results in decreasing indistinguishability for higher excitation powers\textsuperscript{332}. However, we note that this can be overcome with strictly resonant
pumping schemes. Moreover, resonant pumping and adding a weak auxiliary continuous wave reference beam to the excitation beam of the QD can help to suppress charge fluctuations that would otherwise lead to spectral diffusion. To suppress the effects of phonon interactions, one can operate at cryogenic temperatures although we acknowledge that for InGaAs QDs at 4 K, PSB emissions can still represent ~10% of emission (see Fig. 21a). Also, spectral filtering of the QD ZPL can yield high indistinguishability close to unity, albeit at the expense of photon rates. Since the first Hong-Ou-Mandel (HOM) two-photon interference experiment with QDs reported indistinguishabilities of ~70%, near-unity values (e.g., 0.995±0.007, Ref. 333) have been consistently achieved. Recent research efforts have also focused on demonstrating high indistinguishabilities of photons from QDs embedded in nanophotonic waveguides with temporal delays of up to 14.7 µs.

D. Interfacing multiple QDs

Hybrid quantum photonics platforms aim to integrate multiple quantum sources, including dissimilar quantum systems, onto the same device. Two-photon interference has been demonstrated between QDs and other quantum emitters, including atomic vapors, a Poissonian laser, parametric down-conversion source, and frequency combs. The rest of this section will focus on the interfacing of multiple QDs on the same photonics circuit.

To obtain high interference visibility, the emitted photons have to be identical, but it is experimentally challenging to find two QDs with almost identical emission energies, linewidths, and polarization. While much effort has been invested in fabricating highly reproducible QDs, it is often necessary to employ tuning mechanisms, both for the QDs and the cavity structures they are embedded in, to match the emission properties and ensure a high indistinguishability of the photons. A scalable solution for fully integrated quantum photonics would require that the tuning can be applied locally and independently to individual QD devices.

a. Temperature Temperature tuning can affect the bandgap structure, which strongly tunes the QD energy; it can also alter the refractive index and cause physical expansion, which would shift the resonances of a cavity device coupled to the QD. The simplest way to achieve this is to change the sample temperature in the cryostat, but this does not allow for the tuning of individual devices. Instead, local temperature changes can be applied via electrical heaters or laser irradiation (see Fig. 22a). A recent report has also employed temperature tuning of two QDs in a nanophotonic waveguide to achieve superradiant emission.

b. Strain QD energy is sensitive to strain tuning, and strain sensors have been demonstrated by detecting energy shifts at the μeV level for InGaAs QDs embedded in a photonic crystal membrane. However, to achieve larger tuning ranges, strain can be induced via piezoelectric crystals, and a tuning rate of ~1 pm/V has been achieved (see Fig. 22b). A difficulty with this approach is the relatively large fabrication overhead of integrating piezoelectric materials. However, another recent work has shown that strain tuning can be achieved via laser-induced local phase transitions of the crystal structure, which circumvents this issue.

c. Electric field The application of electric fields across the QD can be used to control the energy of the QD excitonic lines via the quantum-confined Stark effect. The application of a forward bias voltage leads to a blue-shift of the QD emission wavelength of several nm. This can be complemented by independently tuning the cavity mode of the photonic crystal structure, e.g., via electromechanical actuation (see Fig. 22c).

d. Frequency conversion An alternative strategy is to tune the emitted photons via on-chip quantum frequency conversion (QFC). Ref. 342 performs QFC

FIG. 21. (a) The bottom part shows a typical spectrum of InAs/GaAs QDs. The top part shows the temporal evolution of the spectrum showing spectral wandering of the QD transitions. Reprinted figure with permission from Ref. 320. Copyright 2005 by the American Physical Society. (b) Calculated absorption spectra of an InAs QD. At lower temperatures, the broadband phonon interactions are suppressed, while the zero-phonon line (ZPL) is asymmetrically broadened. The inset compares the calculated broadening with experimental data (circles). Reprinted figure with permission from Ref. 321. Copyright 2004 by the American Physical Society.
separately on the output of two QDs to convert them from 904 nm to the telecom C-band, achieving a two-photon interference visibility of $29 \pm 3\%$ (see Fig. 22d).

### E. Spin-photon interfaces

By accessing and manipulating the their spin, QDs can provide not only photonic qubits, but spin qubits as well. Various level structures can be exploited for qubit encoding, and rapid spin initialization, manipulation, and read-out can be achieved with short optical pulses (in the nanosecond range)\textsuperscript{360}. Such spin-photon interfaces can enable many quantum information processing tasks, such as deterministic spin-photon entanglement and mediating strong photon-photon interactions.

The strong nonlinearity at a single-photon level has led to demonstrations of photon blockade\textsuperscript{361} and tunable photon statistics via the Fano effect\textsuperscript{362}. Single-photon switches and transistors have been realized via a QD spin\textsuperscript{96,363,364} (see Fig. 23a). Coherent control of the QD spin has also been achieved, with Ref. 365 demonstrating Ramsey interference with a dephasing time $T_2^* = 2.2 \pm 0.1$ ns (see Fig. 23b).

The strong light confinement in nanophotonic cavities also opens up the possibilities of chiral, or propagation-direction-dependent, quantum optics\textsuperscript{366}. This can be used to deterministically induce unidirectional photon emission from quantum dot spin states, i.e. $\sigma_\pm$ transitions emit in different directions\textsuperscript{367,368} (see Fig. 23c).
FIG. 23. (a) Schematic of the single-photon switch and transistor. A gate photon controls the state of the spin, and then the spin determines the polarization of the signal field. From Ref. 363. Reprinted with permission from AAAS. (b) Ramsey interference of a QD spin embedded in a nanobeam waveguide, with a dephasing time $T_2^* = 2.2 \pm 0.1$ ns, and a contrast of 0.04 for the first period. Reprinted figure with permission from Ref. 365. Copyright 2019 by the American Physical Society. (c) [Left] QD level scheme featuring two circularly polarized exciton transitions. [Right] Calculated directional emission patterns of $\sigma^+$ and $\sigma^-$ transitions. Reprinted with permission of Springer Nature Customer Service Center GmbH from Ref. 367, Copyright 2015.

This can help to realize complex on-chip non-reciprocal devices such as single-photon optical circulators\textsuperscript{369}.

VI. 2-D MATERIALS

A. Introduction into 2D Materials

Single photon sources in 2D materials have unique advantages compared to other quantum emitters in 3-D bulk material. Confined in atomically thin material, they can potentially have high photon extraction efficiencies and their emission properties can be controlled by a variety of effects including strain, temperature, pressure and applied electric and magnetic field. Indeed, single photon sources in monolayered 2D material can have almost unity out-coupling efficiency as none of the emitters are surrounded by high refractive index material and their emitted light are consequently not affected by Fresnel or total internal reflection\textsuperscript{370,371}. In addition, 2D materials can be easily transferred and integrated with photonic structures or other 2D materials to form synergistic heterostructures that combine the advantages of various materials together in one unified structure\textsuperscript{372}. In this review of single photon sources in 2D materials we restrict ourselves to transitional metal dichalcogenids (TMDC) and hexagonal boron nitride (hBN) although we acknowledge that there are other important examples of 2D materials including graphene, anisotropic black phosphorus and borophene\textsuperscript{373–375}. An important feature of single photon emitters in these 2D materials is that similar to NV$^-$ centers in diamonds and QDs, their optical properties can be interfaced with spin transitions to realize spin polarization and optical spin readout systems\textsuperscript{376,377}. The zero field splitting in TMDC materials can be up to $\sim 0.7$ meV, which is about 50 times higher than InAs/GaAs self-assembled quantum dots, and it has a surprisingly large anomalous g-factor of $\sim 8.7$ that can potentially allow for extremely fast coherent spin coupling\textsuperscript{378}. On the other hand, hBN has a considerably smaller zero-field splitting of 0.00145 meV and a more modest g-factor of 2\textsuperscript{379}.

B. Single photon emitters in Transitional Metal Dichalcogenides (TDMC)

A monolayer of TMDC can be described as a $MX_2$ sandwich structure with M being a transition metal atom (e.g., Mo, W) enclosed between two lattices of chalcogen atom X (e.g., S, Se, Te)\textsuperscript{381,382}. Depending on the choice of elements and the number of layers present, TMDC materials can have widely varying electrical, optical, chemical, thermal and mechanical properties\textsuperscript{383–388}. Although TMDCs have strong in-plane covalent bonds, they are only weakly bonded in between the layers by Van der Waals forces, which allows them to be easily exfoliated to form monolayer flakes. Alternatively, single layer TMDCs can be fabricated using CVD or MBE\textsuperscript{389,390}. Despite the fact that multilayer TMDCs have indirect bandgaps, monolayer TMDCs are actually direct bandgap semiconductors, which enables them to have enhanced interactions with light\textsuperscript{383,391–393}. There are two distinctive properties that are associated with monolayer TMDCs: strong excitonic effects and valley/spin-dependent properties. The latter can be attributed to the fact that there is no inversion center for a monolayer structure, which opens up a new degree of freedom for charge carriers, i.e. the $k$-valley index, that brings new valley-dependent optical and electrical properties into play\textsuperscript{387,394–396}. In contrast, TMDC’s strong
excitonic effects is due to strong Coulomb interactions between charged particles (electrons and holes) and reduced dielectric screening, which result in the formation of excitons with large binding energies (0.2 to 0.8 eV), charged excitons (trions), and biexcitons. These manifest themselves by broadband photoluminescence (tens of nanometers) in the visible and near-IR ranges at room and cryogenic temperatures. At the same time, TMDCs can possess quantum-dot like defects, which exhibit themselves in the photoluminescence spectrum as a series of sharp peaks with peak intensities up to several hundred times larger than the excitonic photoluminescence. For exfoliated samples these defects are usually associated with local strain and typically appear at cracks or edges of the flake while for grown samples they are mostly due to impurities and can appear everywhere. A number of works have shown that these defects emit in the single photon regime and can be controlled by induced strain, applied temperature, electric and magnetic fields. However, a significant drawback is that the single photon emission quenches at temperatures above 20 K although some recent research have shown that special treatment of TMDC flakes can lead to a redistribution of the energy levels and enable emission at room temperature.

C. Single photon emitters in Hexagonal Boron Nitride (hBN)

hBN monolayers are structurally similar to TDMC but whereas single photon emitters (SPEs) in TMDCs are associated with localized excitons, SPEs in insulating hBN are, similar to color centers in diamond, attributed to atomic-like defects of the crystal structure. These defects in hBN are some of the brightest single photon sources in the visible spectrum and have large Debye-Waller factors with good polarization contrasts. Like NV$^-$ centers, their electronic levels are within the band gap ($\sim 6$ eV), resulting in stable and extremely robust emitters at room temperature over a wide spectral bandwidth ranging from green to near infrared with most emitters emitting around the yellow-red region. These SPEs in hBN are generally characterized by short excited state lifetime, narrow linewidth, absolute photon stability, and high quantum efficiency. Recent research indicates that various types of defects are responsible for the multiplicity of observed ZPL emissions, including nitrogen vacancy defects (NV), carbon substitutional (of a nitrogen atom) defects, and oxygen related defects. Interestingly, the asymmetric linewidths of some of these ZPLs have been attributed to the existence of two independent electronic transitions.
FIG. 26. Deterministic creation of single photon emitters by strain: a) SEM image of nanopillar substrate, fabricated using electron beam lithography, black scale bar corresponds to 2 µm; b) illustration of the fabrication method; c) dark-field optical image of mono-layer WSe$_2$ flake on top of nanopillar array. Green rectangle indicates the 6 adjacent nanopillars where single photon emitters were measured; d) examples of measured spectras at different pillars demonstrating narrow emission lines; e) measurements of $g^2(0)$ for the emission lines in (d). Reprinted from Ref. 406 under the CC BY 4.0 license.

D. Deterministic Creation and Control of Single Photon Emitters in 2D Materials

The random distribution of SPEs in 2D materials is a significant obstacle that prevents their integration with photonic structures. Deterministically creating SPEs in 2D materials is therefore an important technological goal. One way to do so is to induce SPEs by introducing strain to the material. This concept was successfully realized by several groups that transferred 2D materials onto the tops of metallic or dielectric nanopillar arrays$^{405,406,415}$ (Fig. 26). The SPE (as confirmed by measured $g^2(0)<0.1$) yield of this technique exceeds 90 % and the quality of these engineered SPEs was reported to be even higher than naturally occurring defects with 10 times less spectral diffusion ($\sim 0.1$ meV)$^{406}$. An even simpler (but less scalable) way to create SPEs with strain was suggested by Rosenberger et al.: place a deformable polymer film below the 2D material of interest and apply mechanical force to the film using an atomic force microscopy (AFM) tip$^{416}$. Although this approach is less scalable, it can enable one to tune the SPE’s optical properties through careful strain engineering with the AFM tip.

Remarkably, emission from SPE in 2D material defects can be controlled through the application of a voltage$^{403,404}$. For example, in Ref. 404, photo and electro-luminescence were observed from point defects in a 2D material (WSe$_2$) sandwiched between hBN layers that served as tunnelling barriers between WSe$_2$ and its graphene electrodes. Moreover, Schwarz et al. showed that it was possible to tune the emission wavelength of the SPE ($\sim 0.4$ meV/V) by changing the applied bias voltage, which makes the platform amenable to a host of technological applications.

E. Enhancement of Emission from 2D Materials by Coupling into Resonant Modes

Although the tunability and large oscillator strengths of SPEs in 2D materials make them attractive in photonic applications, their sub-nanometer thickness results in a small light-matter interaction length that limits their efficiency. However, as noted in section II C, this disadvantage may be mitigated by coupling them with resonant photonic structures where both their absorption and emission can potentially be enhanced$^{418}$. Fortunately, the atomic thickness of 2D materials makes them especially amenable to integration with photonic structures such as planar photonic crystal cavities, ring resonators, and optical microcavities.

The first demonstration of this came from the coupling of photoluminescence from SPEs in TMDC materials to dielectric and plasmonic nanocavities$^{417,420-422}$ (Fig. 27, a - c). In Ref. 420, a coupling efficiency of over 80% was demonstrated and a spontaneous emission enhancement of over 70 times was reported. Intriguingly, the photoluminescence enhancement can be controlled via an optical spin orbit coupling, which depends on both the resonant nanoparticles’ geometry as well as the incident laser’s polarization and power$^{417}$ (Fig. 27, a, b). Subsequently, single photon emission from a single emitter in a hBN nanoflake was successfully coupled to both one and two resonant gold nanospheres$^{419}$ (Fig. 27, d - g). These nanospheres were brought into close proximity with a pre-characterized SPE (verified by measuring $g^{(2)}(0)$ < 0.5) by means of an AFM tip and the emitter was observed to have a photon flux of about 6 MHz that corresponded with a 3-fold Purcell enhancement$^{419}$.

A natural structure for SPEs in 2D materials to couple to are noble metal nanopillars since they can kill two birds with one stone by first facilitating the deterministic creation of SPEs (as discussed in section VI D above), and then enhancing the created SPEs’ spontaneous emission through the SPEs’ coupling with surface plasmon resonances of the metallic nanopillars. This has been successfully implemented for both TDMCs and hBN at
cryogenic and room temperatures where increased brightness, shorter lifetimes and enhanced spontaneous emission of the SPEs were all reported.\textsuperscript{423–426} Coupling of the emitter to plasmonic modes results in linearly polarized emission that depends on the geometry of the nanopillars and the orientation of the optical dipole.\textsuperscript{424} A record high Purcell enhancement of 551 times was achieved with metallic nanocubes.\textsuperscript{425}

F. Coupling and Transfer of Emission from 2D Materials into Photonic Structures

To fully integrate SPEs in 2D materials onto an on-chip photonic platform, it is also necessary to couple emission from SPEs into waveguiding photonic structures. To this end a few groups have successfully coupled emission from SPEs in 2D materials into the surface plasmon polariton modes of silver based waveguides. For example, localized SPEs formed from the intrinsic strain gradient formed along a WSe\textsubscript{2} monolayer when it was deposited on top of a silver nanowire were efficiently coupled to the guided surface plasmon modes of the nanowire.\textsuperscript{427} A coupling efficiency of 39\% was measured for a single SPE by comparing the intensity of the laser excited SPE and the emission intensities at both ends of the silver nanowire.\textsuperscript{427} Separately, S. Dutta et al. demonstrated the coupling of single emitters in WSe\textsubscript{2} to propagating surface plasmon polaritons in silver-air-silver, Metal-Insulator-Metal (MIM) waveguides\textsuperscript{428} (Fig. 28, a – d). The waveguides were fabricated using EBL, followed by metal deposition of Cr and Ag, and then a lift-off in acetone with subsequent protection by a 4 nm buffer layer of oxide. As before, strain gradients on the monolayer due to the waveguide generated sharp localized SPEs that were intrinsically close to the plasmonic mode. Due to the sub-wavelength confinement of the surface plasmon polariton modes, a 1.89 times enhancement of the SPE’s radiative lifetime was observed under illumination at 532 nm at cryogenic (3.2 K) temperatures and bright narrow lines associated with the SPE’s emission were measured.

Although surface plasmon polariton modes on silver waveguides may help to enhance the spontaneous emission of a SPE, the metal interface results in significantly lossy propagation that is undesirable. Such high propagation losses can be circumvented by using dielectric
measurements of the background subtracted 702 nm also produces less background fluorescence. Mea-
surement laser. Besides enabling brighter emission, excitation at a critical wavelength (≈ 702 nm) with a tunable Ti:Sapphire laser. Besides enabling brighter emission, excitation at 702 nm also produces less background fluorescence. Measurements of the background subtracted $g^{(2)}$ correlation function revealed a clear anti-bunching dip below 0.5 that confirmed the existence of a SPE.

Finally, we note that there has been successful integration of SPEs in 2D materials to an on-chip beamsplitter in the form of a lithium niobate directional coupler,430 (Fig. 28, e - f). Indeed, emission from an excited SPE in a strain engineered WSe$_2$ monolayer was coupled into one input port of the directional coupler and its photo-
luminiscence, which consisted of strong emission lines corresponding to emission from the WSe$_2$ flake, was suc-
cessfully measured at the other output port of the di-
rectional coupler (Fig. 28e), demonstrating the desired operation of the beam splitter and showing that an on-
chip Hanbury Brown and Twiss measurement is possible.

VII. CONCLUSION AND OUTLOOK

In this paper we have reviewed a variety of quantum systems with discrete-energy levels that are conveniently embedded within a solid. These systems, which range from color centers in diamond to semiconductor quantum dots and defects in 2D materials, have promising properties and can potentially be used to form the building blocks of future quantum networks. A feasible way to realizing these quantum networks is to integrate them with on-chip optical structures and devices. Such interfaces are capable of enhancing the light-matter interaction of these quantum systems and allow efficient interaction between the nodes. However, translation from proof-of-concept laboratory demonstrations of individual components to full-scale quantum devices is still quite immature. Considerable efforts are required to overcome issues associated with the material incompatibility of quantum registers, photonic circuits and other required components on the same chip. We propose the following four critical steps to address this challenge:

First, quantum photonic devices should be thoroughly designed, fabricated and tested since quantum information processing imposes stringent demands on loss and fabrication accuracy. These demands, which are at the limits of conventional silicon photonic technology, might require fabrication for quantum applications to be achieved at the expense of scalable fabrication by, for example, using time-consuming electron beam lithography instead of photolithography.

Second, the coupling between quantum systems and resonant photonic cavities should be optimized through the accurate positioning of the emitter in the cavity. This calls for further improvements in the reliability and throughput of methods such as AFM manipulation, nano-patterning, and various transfer techniques that have been employed for accurate positioning of these quantum emitters.

Third, full scalability implies integration with on-chip single-photon sensitive detectors and lasers on-chip. The development of on-chip active devices would eliminate the need for using bulk optics and allow a significantly smaller footprint for the photonic platform. Design, fab-
rication, and characterization of on-chip photodetectors and lasers operating at desired performance levels is a chal-
enging task since it involves multiple fabrication steps involving various materials that require state-of-
the-art cleanroom facilities and a comprehensive strate-
gy for heat management and integrating associated optoelectronics.

Fourth, a crucial building block for quantum networks is the realization of quantum-mechanical interaction between two separate quantum nodes on the same optical chip. Photons emitted by two independent nodes should be able to coherently interfere on a beamsplitter and pro-
duce an interference signal. This task requires demand-
ing control of quantum emitters and photonic elements but demonstration of such an interaction would lead to more complicated schemes of quantum networking, in-
cluding the interaction of a large number of quantum emitters on the same chip.

Clearly, a consolidation of new technologies is re-
quired to address these challenges and to demonstrate a platform for quantum networking that is scalable and amenable to mass manufacturing. This program should leverage on a broad collaboration between experts in quantum physics, integrated photonics, material science, and electronics.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.
FIG. 28. Coupling and transport of single photon emission from 2D materials in photonic structures: (a) Scheme of an MIM waveguide covered by a WSe$_2$ monolayer. The yellow dipole is a quantum emitter, the blue arrows denote the excitation and collection points; (b) The spectra of the defect with the excitation spot fixed at the location of the defect at the waveguide and collection spot moved to the far end of the waveguide; (c) and (d) Lifetime measurements for emitters located on the MIM waveguide and out of it. Figures (a) – (d) were reprinted from Ref. 428, with the permission of AIP Publishing. (e) Scheme of Ti in diffused lithium niobate directional coupler with a WSe$_2$ flake at the input facet. Emitters are excited in confocal geometry. Their emission is detected by a confocal microscope and through the two output ports (Port 1 and Port 2); (f) The spectra measured through the waveguide output port and confocally when the emitter is excited at the facet. Figure (e) and (f) were reprinted from Ref. 430 under the CC BY 4.0 license. (g) Illustration of the Si$_3$N$_4$ photonic device with a WSe$_2$ flake integrated on top of a 220 nm thick single mode Si$_3$N$_4$ waveguide, separated by 2 air trenches from the bulk Si$_3$N$_4$; (h) Confocal and waveguide-coupled spectrum of the emitter excited by 702 nm pump. The waveguide spectrum is multiplied by 10 and offset by 2000 cts/sec for improved visualization. The inset shows confocal spectra obtained by either green excitation at 532 nm (green curve) or excitation at 702 nm (blue curve); (i) Background-corrected measurements of g$^2$(0) for the coupled emitter made in confocal geometry. Figures (g) – (i) were reprinted from Ref. 429 under the CC BY 4.0 license.

ACKNOWLEDGMENTS

This work was supported by NRF-CRP14-2014-04, “Engineering of a Scalable Photonics Platform for Quantum Enabled Technologies” and the Quantum Technologies for Engineering program of A*STAR.

REFERENCES

1. H. J. Kimble, “The quantum internet,” Nature 453, 1023–1030 (2008).
2. N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, “Quantum repeaters based on atomic ensembles and linear optics,” Rev. Mod. Phys. 83, 33–80 (2011).
3. J. R. Maze, P. L. Stanwix, J. S. Hodges, S. Hong, J. M. Taylor, P. Cappellaro, L. Jiang, M. V. G. Dutt, E. Togan, A. S. Zibrov, A. Yacoby, R. L. Walsworth, and M. D. Lukin, “Nanoscale magnetic sensing with an individual electronic spin in diamond,” Nature 455, 644–647 (2008).
4. G. Balasubramanian, I. Y. Chan, R. Kolesov, M. Al-Hmoud, J. Tisler, C. Shin, C. Kim, A. Wojcik, P. R. Hemmer, A. Krueger, T. Hanke, A. Leitenstorfer, R. Bratschitsch, F. Jelezko, and J. Wrachtrup, “Nanoscale imaging magnetometry with diamond spins under ambient conditions,” Nature 455, 648–651 (2008).
5. A. M. Edmonds, U. F. S. D’Haenens-Johansson, R. J. Crudace, M. E. Newton, K.-M. C. Fu, C. Santori, R. G. Beausoleil, D. J. Twitchen, and M. L. Markham, “Production of oriented nitrogen-vacancy color centers in synthetic diamond,” Phys. Rev. B 86, 035201 (2012).
6. L. M. Pham, N. Bar-Gill, D. Le Sage, C. Belthangady, A. Stacey, M. Markham, D. J. Twitchen, M. D. Lukin, and R. L. Walsworth, “Enhanced metrology using preferential orientation of nitrogen-vacancy centers in diamond,” Phys. Rev. B 86, 121202 (2012).
7. T. Fukui, Y. Doy, T. Miyazaki, Y. Miyamoto, H. Kato, T. Matsumoto, T. Makino, S. Yamasaki, R. Morimoto, N. Tokuda, M. Hatano, Y. Sakagawa, H. Morishita, T. Tashima, S. Miwa, Y. Suzuki, and N. Mizuochi, “Perfect selective alignment of
nitrogen-vacancy centers in diamond,” Applied Physics Express 7, 055201 (2014).
8 G. Davies, S. C. Lawson, A. T. Collins, A. Mainwood, and S. J. Sharp, “Vacancy-related centers in diamond,” Phys. Rev. B 46, 13157–13170 (1992).
9 F. Jelezko, T. Goy, I. Popa, M. Domhan, A. Gruber, and J. Wrachtrup, “Observation of Coherent Oscillation of a Single Nuclear Spin and Realization of a Two-Qubit Conditional Quantum Gate,” Phys. Rev. Lett. 93, 130501 (2004).
10 B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau, and R. Hanson, “Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres,” Nature 526, 682–686 (2015).
11 J. M. Taylor, P. Cappellaro, L. Childress, L. Jiang, D. Budker, P. R. Hemmer, A. Yacoby, R. Walsworth, and M. D. Lukin, “High-sensitivity diamond magnetometer with nanoscale resolution,” Nature Physics 4, 810–816 (2008).
12 F. Dolde, H. Fedder, M. W. Doherty, T. Nöbauer, F. Rempp, G. Balasubramanian, T. Wolf, F. Reinhard, L. C. L. Hollenberg, F. Jelezko, and J. Wrachtrup, “Electric-field sensing using single diamond spins,” Nature Physics 7, 459–463 (2011).
13 P. Kehayias, M. J. Turner, R. Trubko, J. M. Schloss, C. A. Hart, M. Wesson, D. R. Glenn, and R. L. Walsworth, “Imaging crystal stress in diamond using ensembles of nitrogen-vacancy centers,” Phys. Rev. B 100, 174103 (2019).
14 A. Ajoy and P. Cappellaro, “Stable three-axis nuclear-spin gyroscope in diamond,” Phys. Rev. A 86, 062104 (2012).
15 P. Neumann, I. Jakobi, F. Dolde, C. Burk, R. Reuter, G. Waldherr, J. Honert, T. Wolf, A. Brunner, J. H. Shim, D. Suter, H. Sumiya, J. Boya, and J. Wrachtrup, “High-Precision Nanoscale Temperature Sensing Using Single Defects in Diamond,” Nano Letters 13, 2738–2742 (2013).
16 T. Plakhotnik and R. Chapman, “Nitrogen-vacancy centers in nano-diamond reversibly decrease the luminescence quantum yield under strong pulsed-laser irradiation,” New Journal of Physics 13, 045001 (2011).
17 R. Chapman and T. Plakhotnik, “Anomalous saturation effects due to optical spin depolarization in nitrogen-vacancy centers in diamond nanocrystals,” Phys. Rev. B 86, 045204 (2012).
18 N. D. Lai, O. Faklaris, D. Zheng, V. Jacques, H.-C. Chang, J.-F. Roch, and F. Treussart, “Quenching nitrogen-vacancy center photoluminescence with an infrared pulsed laser,” New Journal of Physics 15, 033030 (2013).
19 Y. Dumeige, F. Treussart, R. Allaume, T. Gacoin, J.-F. Roch, and P. Grangier, “Photo-induced creation of nitrogen-related color centers in diamond nanocrystals under femtosecond illumination,” Journal of Luminescence 199, 61 – 67 (2004).
20 R. P. Roberts, M. L. Juan, and G. Molina-Terriza, “Spin-dependent charge state interconversion of nitrogen vacancy centers in nanodiamonds,” Phys. Rev. B 99, 174307 (2019).
21 K. Beha, A. Batalov, N. B. Manson, R. Bratschitsch, and A. Leitenstorfer, “Optimum Photoluminescence Excitation and Recharging Cycle of Single Nitrogen-Vacancy Centers in Ultra-pure Diamond,” Phys. Rev. Lett. 109, 097404 (2012).
22 G. Waldherr, J. Beck, M. Steiner, P. Neumann, A. Gali, T. Frauenheim, F. Jelezko, and J. Wrachtrup, “Dark States of Single Nitrogen-Vacancy Centers in Diamond Unraveled by Single Shot NMR,” Phys. Rev. Lett. 106, 157601 (2011).
23 B. Naydenov, F. Reinhard, A. Lmmle, V. Richter, R. Kalish, U. F. S. DHaenens-Johansson, M. Newton, F. Jelezko, and J. Wrachtrup, “Increasing the coherence time of single electron spins in diamond by high temperature annealing,” Applied Physics Letters 97, 242511 (2010).
24 J. O. Orwa, C. Santori, K. M. C. Fu, B. Gibson, D. Simpson, I. Aharonovich, A. Stacey, A. Cimmino, P. Balog, M. Markham, D. Witchen, A. D. Greentree, R. G. Beausoleil, and S. Prawer, “Engineering of nitrogen-vacancy color-center states in high purity diamond by ion implantation and annealing,” Journal of Applied Physics 109, 083530 (2011).
25 A. Wotherspoon, J. Steeds, B. Catmull, and J. Butler, “Photoluminescence and positron annihilation measurements of nitrogen doped CVD diamond,” Diamond and Related Materials 12, 652 – 657 (2003).
26 Y. Mita, “Change of absorption spectra in type-Ib diamond with heavy neutron irradiation,” Phys. Rev. B 53, 11360–11364 (1996).
27 A. T. Collins, “The Fermi level in diamond,” Journal of Physics: Condensed Matter 14, 3743–3750 (2002).
28 B. T. Webber, M. C. Per, D. W. Drumm, L. C. L. Hollenberg, and S. P. Russo, “Ab initio thermodynamics calculation of the relative concentration of NV− and NV0 defects in diamond,” Phys. Rev. B 85, 014102 (2012).
29 K.-M. C. Fu, C. Santori, P. E. Barclay, and R. G. Beausoleil, “Conversion of neutral nitrogen-vacancy centers to negatively charged nitrogen-vacancy centers through selective oxidation,” Applied Physics Letters 96, 121907 (2010).
30 M. V. Hauf, B. Grotz, B. Naydenov, M. Dankerl, S. Poggaz, J. Meijer, F. Jelezko, J. Wrachtrup, M. Stutzmann, F. Reinhard, and J. A. Garrido, “Chemical control of the charge state of nitrogen-vacancy centers in diamond,” Phys. Rev. B 83, 081304 (2011).
31 A. Lenev and S. C. Rand, “Electronic structure of the N-V center in diamond: Theory,” Phys. Rev. B 53, 13441–13455 (1996).
32 M. W. Doherty, N. B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup, and L. C. Hollenberg, “The nitrogen-vacancy colour centre in diamond,” Physics Reports 528, 1 – 45 (2013).
33 J. P. Goss, R. Jones, S. J. Breuer, P. R. Briddon, and S. Öberg, “The Twelve-Line 1.682 eV Luminescence Center in Diamond and the Vacancy-Silicon Complex,” Phys. Rev. Lett. 77, 3041–3044 (1996).
34 M. Luszczek, R. Laskowski, and P. Horodecki, “The ab initio calculations of single nitrogen-vacancy defect center in diamond,” Physica B: Condensed Matter 348, 292 – 298 (2004).
35 J. A. Larsson and P. Delaney, “Electronic structure of the nitrogen-vacancy center in diamond from first-principles theory,” Phys. Rev. B 77, 165201 (2008).
36 C.-K. Lin, Y.-H. Wang, H.-C. Chang, M. Hayashi, and S. H. Lin, “One- and two-photon absorption properties of diamond nitrogen-vacancy defect centers: A theoretical study,” The Journal of Chemical Physics 129, 124714 (2008).
37 A. Gali, M. Fyta, and E. Kaxiras, “Ab initio supercell calculations on nitrogen-vacancy center in diamond: Electronic structure and hyperfine tensors,” Phys. Rev. B 77, 155206 (2008).
38 Y. Ma, M. Rohlfing, and A. Gali, “Excited states of the negatively charged nitrogen-vacancy color center in diamond,” Phys. Rev. B 81, 041204 (2010).
39 M. W. Doherty, N. B. Manson, P. Delaney, and L. C. L. Hollenberg, “The negatively charged nitrogen-vacancy centre in diamond: the electronic solution,” New Journal of Physics 13, 025019 (2011).
40 D. A. Redman, S. Brown, R. H. Sands, and S. C. Rand, “Spin dynamics and electronic states of N-V centers in diamond by EPR and four-wave-mixing spectroscopy,” Phys. Rev. Lett. 67, 3420–3423 (1991).
41 J. Martin, “Fine structure of excited 3E state in nitrogen-vacancy centre of diamond,” Journal of Luminescence 81, 237 – 247 (1999).
42 N. B. Manson, J. P. Harrison, and M. J. Sellars, “Nitrogen-vacancy center in diamond: Model of the electronic structure and associated dynamics,” Phys. Rev. B 74, 104303 (2006).
43 N. Reddy, N. Manson, and E. Krausz, “Two-laser spectral hole burning in a colour centre in diamond,” Journal of Luminescence 88, 46 – 47 (1997).
44 E. van Oort, N. B. Manson, and M. Glasbeek, “Optically detected spin coherence of the diamond N-V centre in its triplet ground state,” Journal of Physics C: Solid State Physics 21, 4385–4391 (1988).
J. Brossel and F. Bitter, “A New ‘Double Resonance’ Method for Investigating Atomic Energy Levels. Application to Hg$^2$Pt,” Phys. Rev. 86, 308–316 (1952).

N. B. Manson, X.-F. He, and P. T. H. Fisk, “Raman heterodyne detected electron-nuclear-double-resonance measurements of the nitrogen-vacancy center in diamond,” Opt. Lett. 15, 1094–1096 (1990).

G. D. Fuchs, V. V. Dobrovitski, R. Hanson, A. Batra, C. D. Weis, T. Schenkel, and D. D. Awschalom, “Excited-State Spectroscopy Using Single Spin Manipulation in Diamond,” Phys. Rev. Lett. 101, 117601 (2008).

P. Neumann, R. Kolesov, V. Jacques, J. Beck, J. Tisler, A. Batrov, L. Rogers, N. B. Manson, G. Balasubramanian, F. Jelezko, and J. Wrachtrup, “Excited-state spectroscopy of single NV defects in diamond using optically detected magnetic resonance,” New Journal of Physics 11, 013017 (2009).

G. Davies and M. F. Hamer, “Optical studies of the 1.945 eV vibronic band in diamond,” Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences 348, 285–298 (1976).

P. Delaney, J. C. Greer, and J. A. Larsson, “Spin-Polarization Mechanisms of the Nitrogen-Vacancy Center in Diamond,” Nano Letters 10, 610–614 (2010).

L. J. Rogers, M. W. Doherty, M. S. J. Barson, S. Onoda, T. Ohshima, and N. B. Manson, “Singlet levels of the NV$^-$ centre in diamond,” New Journal of Physics 17, 013048 (2015).

L. J. Rogers, S. Armstrong, M. J. Sellars, and N. B. Manson, “Infrared emission of the NV centre in diamond: Zeeman and uniaxial stress studies,” New Journal of Physics 10, 103024 (2008).

L. Robledo, H. Bernien, T. van der Sar, and R. Hanson, “Spin dynamics in the optical cycle of single nitrogen-vacancy centres in diamond,” New Journal of Physics 13, 025013 (2011).

J. H. N. Loubser and J. A. van Wyk, “Electron spin resonance in the study of diamond,” Reports on Progress in Physics 41, 1201–1248 (1978).

P. Tamarat, N. B. Manson, J. P. Harrison, R. L. McMurtie, A. Nizovtsev, C. Santori, R. G. Beausoleil, P. Neumann, T. Gaebel, F. Jelezko, P. Hemmer, and J. Wrachtrup, “Spin-flip and spin-conserving optical transitions of the nitrogen-vacancy centre in diamond,” New Journal of Physics 10, 045004 (2008).

V. M. Acosta, E. Bauch, M. P. Ledbetter, A. Waxman, L.-S. Bouchard, and D. Budker, “Temperature dependence of the nitrogen-vacancy magnetic resonance in diamond,” Phys. Rev. Lett. 104, 070801 (2010).

S. Felton, A. M. Edmonds, M. E. Newton, P. M. Martinneau, D. Fisher, D. J. Twitchen, and J. M. Baker, “Hyperfine interaction in the ground state of the negatively charged nitrogen vacancy center in diamond,” Phys. Rev. B 79, 075203 (2009).

E. V. Oort and M. Glasbeek, “Electric-field-induced modulation of spin echoes of N-V centers in diamond,” Chemical Physics Letters 168, 529 – 532 (1990).

B. Smeltzer, J. McIntyre, and L. Childress, “Robust control of individual nuclear spins in diamonds,” Phys. Rev. A 80, 050302 (2009).

K.-M. C. Fu, C. Santori, P. E. Barclay, L. J. Rogers, N. B. Manson, and R. G. Beausoleil, “Observation of the Dynamic Jahn-Teller Effect in the Excited States of Nitrogen-Vacancy Centers in Diamond,” Phys. Rev. Lett. 103, 256404 (2009).

S. Choi, M. Jain, and S. G. Louie, “Mechanism for optical initialization of spin in NV$^-$ center in diamond,” Phys. Rev. B 86, 041202 (2012).

A. Gupta, L. Hacquebard, and L. Childress, “Efficient signal processing for time-resolved fluorescence detection of nitrogen-vacancy spins in diamond,” J. Opt. Soc. Am. B 33, B28–B34 (2016).

A. T. Collins, M. F. Thomaz, and M. I. B. Jorge, “Luminescence decay time of the 1.945 eV centre in type Ib diamond,” Journal of Physics C: Solid State Physics 16, 2177–2181 (1983).

G. D. Fuchs, V. V. Dobrovitski, D. M. Toyli, F. J. Heremans, C. D. Weis, T. Schenkel, and D. D. Awschalom, “Excited-state spin coherence of a single nitrogen-vacancy centre in diamond,” Nature Physics 6, 668–672 (2010).

L. Robledo, L. Childress, H. Bernien, B. Hensen, P. F. A. Alkemade, and R. Hanson, “High-fidelity projective read-out of a solid-state spin quantum register,” Nature 477, 574–578 (2011).

L. Jiang, J. S. Hodges, J. R. Maze, P. Maurer, J. M. Taylor, D. G. Cory, P. R. Hemmer, R. L. Walsworth, A. Yacoby, A. S. Zibrov, and M. D. Lukin, “Repetitive readout of a single electronic spin via quantum logic with nuclear spin ancillae,” Science 326, 267–272 (2009).

C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, “Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels,” Phys. Rev. Lett. 70, 1895–1899 (1993).

D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, “Experimental quantum teleportation,” Nature 390, 575–579 (1997).

F. De Martini, V. Buzek, F. Sciarrino, and C. Sias, “Experimental realization of the quantum universal NOT gate,” Nature 419, 815–818 (2002).

M. Žukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, “‘Event-ready-detectors’ Bell experiment via entanglement swapping,” Phys. Rev. Lett. 71, 4287–4290 (1993).

J.-W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, “Experimental Entanglement Swapping: Entangling Photons That Never Interacted,” Phys. Rev. Lett. 80, 3891–3894 (1998).

A. V. Kuhlmann, J. Houel, A. Ludwig, L. Greuter, D. Reuter, A. D. Wieck, M. Poggio, and J. R.Warburton, “Charge noise and spin noise in a semiconductor quantum device,” Nature Physics 9, 570–575 (2013).

A. Bertholot, I. Favero, G. Cassabois, C. Voisin, C. Delalande, P. Roussignol, R. Ferreira, and J. M. Gérard, “Unconventional motional narrowing in the optical spectrum of a semiconductor quantum dot,” Nature Physics 2, 759–764 (2006).

I. Aharonovich, S. Castelletto, D. A. Simpson, C.-H. Su, A. D. Greentree, and S. Prawer, “Diamond-based single-photon emitters,” Reports on Progress in Physics 74, 076501 (2011).

H.-Q. Zhao, M. Fujiwara, and S. Takeuchi, “Suppression of fluorescence phonon sideband from nitrogen vacancy centers in diamond nanocrystals by substrate effect,” Opt. Express 20, 15628–15635 (2012).

D. J. Griffiths, Introduction to Electrodynamics, 4th ed. (Cambridge University Press, 2017).

L. Novotny and B. Hecht, Principles of Nano-Optics (Cambridge University Press, 2006).

W. L. Barnes, S. A. Horsley, and W. L. Vos, “Classical antennae, quantum emitters, and densities of optical states,” Journal of Optics (2020).

A. Tallove and S. C. Haggens, Computational Electro-optics: The Finite-Difference Time-Domain Method, 2nd ed. (Artech House, 2000).

R.-C. Ge and S. Hughes, “Design of an efficient single photon source from a metallic nanorod dimer: a quasi-normal mode finite-difference time-domain approach,” Opt. Lett. 39, 4235–4238 (2014).

P. T. Kristensen and S. Hughes, “Modes and Mode Volumes of Leaky Optical Cavities and Plasmonic Nanoresonators,” ACS Photonics 1, 2–10 (2014).

P. T. Leung, S. Y. Liu, and K. Young, “Completeness and orthogonality of quasinormal modes in leaky optical cavities,” Phys. Rev. A 49, 3057–3067 (1994).

E. A. Muljarov and W. Langbein, “Exact mode volume and Purcell factor of open optical systems,” Phys. Rev. B 94, 235438 (2016).

C. Sauvan, J. P. Hugonin, I. S. Maksymov, and P. Lalanne, “Theory of the Spontaneous Optical Emission of Nanosize Photonic and Plasmon Resonators,” Phys. Rev. Lett. 110, 237401 (2013).
101. A. Brenneis, L. Gaudreault, M. Seifert, H. Karl, M. S. Brandt, H. Huebl, J. A. Garrido, F. H. L. Koppens, and A. W. Holleitner, “Ultrafast electronic readout of diamond nitrogen-vacancy centers coupled to graphene,” Nature Nanotechnology 10, 135–139 (2015).

102. B. Khanalillo, M. Mitchell, A. C. Hryciw, and P. E. Barclay, “High-Q/V Monolithic Diamond Microdisks Fabricated with Quasi-isotropic Etching,” Nano Letters 15, 5131–5136 (2015).

103. H.-Z. Song, W. Zhang, L.-B. Yu, and Z. M. Wang, “Microcavity Cavity Design for 1.55-μm Quantum-Dot Single-Photon Sources,” Journal of Electronic Science and Technology 17, 221–230 (2019).

104. G. Alagappan, L. A. Krivitsky, and C. E. Png, “Diamond in a Nanopocket: A New Route to a Strong Purcell Effect,” ACS Omega 3, 4733–4742 (2018).

105. G. Alagappan, L. A. Krivitsky, and C. E. Png, “Purcell enhancement of light emission in nanodiamond using a trenched nanobeam cavity,” Journal of Optics 22, 025401 (2020).

106. J. E. Frch, S. Kim, C. Stewart, X. Xu, Z. Du, M. Lockrey, M. Toth, and I. Aharonovitch, “Photonic Nanobeam Cavities with Nanopockets for Efficient Integration of Fluorescent Nanoparticles,” Nano Letters In print. null (2020).

107. W. Fan, Z. Hao, E. Stock, J. Kang, Y. Luo, and D. Bimberg, “Comparison between two types of photonic-crystal cavities for single-photon emitters,” Semiconductor Science and Technology 26, 014014 (2010).

108. T. M. Babinec, B. J. M. Hausmann, M. Khan, Y. Zhang, J. R. Maze, P. R. Hemmer, and M. Loncar, “A diamond nanowire single-photon source,” Nature Nanotechnology 5, 195–199 (2010).

109. E. Neu, P. Appel, M. Ganzhorn, J. Miquel-Sanchez, M. Lesik, V. Mille, V. Jacobs, A. Tallaire, J. Achard, and P. Maletinsky, “Photonic nano-structures on (111)-oriented diamond,” Applied Physics Letters 104, 153108 (2014).

110. K. G. Lagoudakis, K. Fischer, T. Sarmiento, A. Majumdar, A. Rundquist, J. Lu, M. Bajcsy, and J. Vuckovic, “Deterministically charged quantum dots in photonic crystal nanoresonators for efficiently charged quantum dots in photonic crystal nanoresonators,” New Journal of Physics 15, 113056 (2013).

111. Z. Luo, S. Sun, A. Karasahin, A. S. Bracker, S. G. Carter, M. K. Yakes, D. Gammon, and E. Waks, “A Spin-Photon Interface Using Charge-Tunable Quantum Dots Strongly Coupled to a Cavity,” Nano Letters 19, 7072–7077 (2019).

112. M. Jamali, I. Gerhardt, M. Rezai, K. Frenner, H. Fedder, and J. Wrachtrup, “Microscopic diamond solid-immersion-lenses fabricated around single defect centers by focused ion beam milling,” Review of Scientific Instruments 85, 123703 (2014).

113. C. Hemp, T. Müller, W. Wasilewski, J. N. Becker, B. Pingault, H. Sternschulte, D. Steinmüller-Nethl, A. Gali, J. R. Maze, M. Atatüre, and C. Becher, “Electronic Structure of the Silicon Vacancy Color Center in Diamond,” Phys. Rev. Lett. 112, 036405 (2014).

114. E. Neu, M. Fischer, S. Gsell, M. Schreck, and C. Becher, “Fluorescence and polarization spectroscopy of single silicon vacancy centers in heteroepitaxial nanodiamonds on iridium,” Nature 450, 862–865 (2007).

115. B. J. Shields, Q. P. Unterreithmeier, N. P. de Leon, H. Park, and M. D. Lukin, “Efficient Readout of a Single Spin State in Diamond via Spin-to-Charge Conversion,” Phys. Rev. Lett. 114, 136402 (2015).

116. D. A. Hopper, R. R. Grote, A. L. Exarhos, and L. C. Bassett, “Near-infrared-assisted charge control and spin readout of the nitrogen-vacancy center in diamond,” Phys. Rev. B 94, 241201 (2016).

117. E. Bourgeois, A. Jarmola, P. Siyushev, M. Gulk, J. Hruby, F. Jelezko, D. Budker, and M. Nesladek, “Photoelectric detection of electron spin resonance of nitrogen-vacancy centres in diamond,” Nature Communications 6, 8577 (2015).
121. Wee, Tse-Luen and Tzeng, Yan-Kai and Han, Chau-Chung and Chang, Huan-Cheng and Fann, Wunshain and Hsu, Jui-Hung and Chen, Kuan-Ming and Yu, Yueh-Chung, “Two-photon Excited Fluorescence of Nitrogen-Vacancy Centers in Proton-Irradiated Type Ib Diamond,” The Journal of Physical Chemistry A 111, 9079–9086 (2007).

122. I. Kiflawi, A. T. Collins, K. Jakoubkovskii, and D. Fisher, “Electron irradiation and the formation of vacancy–interstitial pairs in diamond,” Journal of Physics: Condensed Matter 19, 046216 (2007).

123. S. Becker, N. Raatz, S. Jankuhn, R. John, and J. Meijer, “Nitrogen implantation with a scanning electron microscope,” Scientific Reports 8, 32 (2018).

124. A. Mainwood, “Nitrogen and nitrogen-vacancy complexes and their formation in diamond,” Phys. Rev. B 49, 7934–7940 (1994).

125. A. T. Collins and I. Kiflawi, “The annealing of radiation damage in type Ia diamond,” Journal of Physics: Condensed Matter 21, 364209 (2009).

126. G. Davies, “Charge states of the vacancy in diamond,” Nature 269, 498–500 (1977).

127. X. Hu, Y. Dai, R. Li, H. Shen, and X. He, “The diffusion of vacancies near a diamond (001) surface,” Solid State Communications 121, 45–48 (2002).

128. C. Santori, P. E. Barclay, K.-M. C. Fu, and R. G. Beausoleil, “Vertical distribution of nitrogen-vacancy centers in diamond formed by ion implantation and annealing,” Phys. Rev. B 79, 125313 (2009).

129. A. Gippius, R. Khmelnitskiy, V. Dravin, and S. Tkachenko, “Formation and characterization of graphitized layers in ion-implanted diamond,” Diamond and Related Materials 18, 1631–1634 (1999).

130. J. W. Steeds, W. Sullivan, A. Wotherspoon, and J. M. Hayes, “Long-range migration of intrinsic defects during irradiation or implantation,” Journal of Physics: Condensed Matter 21, 364219 (2009).

131. D. M. Troyli, C. D. Weis, G. D. Fuchs, T. Schenkel, and D. D. Awschalom, “Chip-Scale Nanofabrication of Single Spins and Spin Arrays in Diamond,” Nano Letters 10, 3168–3172 (2010).

132. P. Spinicelli, A. Dréau, L. Rondin, F. Silva, J. Achard, S. Xavier, S. Banravon, T. Debuisschert, S. Pezzagna, J. Meijer, V. Jacques, and J.-F. Roch, “Engineered arrays of nitrogen-vacancy color centers in diamond based on implantation of CN-molecules through nanoapertures,” New Journal of Physics 13, 025014 (2011).

133. S. Pezzagna, D. Rogalla, H.-W. Becker, I. Jakobi, F. Dolde, B. Naydenov, J. Wrachtrup, F. Jelezko, C. Trautmann, and J. Meijer, “Creation of colour centres in diamond by collimated ion-implantation through nano-channels in mica,” physica status solidi (a) 212, 1791–1795 (2015).

134. D. Scarabelli, M. Trusheim, O. Gaathon, D. Enghard, and S. J. Wind, “Nanoscale Engineering of Closely-Spaced Electronic Spins in Diamond,” Nano Letters 16, 4982–4990 (2016).

135. V. M. Acosta, E. Bauch, M. P. Ledbetter, C. Santori, K.-M. C. Fu, P. E. Barclay, R. G. Beausoleil, H. Linget, J. F. Roch, F. Treussart, S. Chemerisov, W. Gawlik, and D. Budker, “Diamonds with a high density of nitrogen-vacancy centers for magnetometry applications,” Phys. Rev. B 80, 115202 (2009).

136. J. Meijer, B. Burchard, M. Domhan, C. Wittmann, T. Gaebel, I. Popa, F. Jelezko, and J. Wrachtrup, “Generation of single color centers by focused nitrogen implantation,” Applied Physics Letters 87, 261909 (2005).

137. P. Spinicelli, C. Trautmann, M. Markham, A. M. Edmonds, A. Denisenko, and J. Wrachtrup, “Effect of low-damage inductively coupled plasma on shallow nitrogen-vacancy centers in diamond,” Applied Physics Letters 105, 082413 (2014).

138. M. Loretz, S. Pezzagna, J. Meijer, and C. L. Degen, “Nanoscale nuclear magnetic resonance with a 1.9 nm-deep nitrogen-vacancy sensor,” Applied Physics Letters 104, 033102 (2014).

139. F. Fvaro de Oliveira, S. A. Momenzadeh, Y. Wang, M. Konuma, M. Markham, A. M. Edmonds, A. Denisenko, and J. Wrachtrup, “Enhanced generation of single optically active spins in diamond,” Applied Physics Letters 110, 172102 (2017).

140. S. B. van Dam, M. Walsh, M. J. Degen, E. Bersin, S. L. Mouradian, A. Galiliun, M. Ruff, M. Ispeet, T. H. Timianu, R. Hanson, and D. R. Englund, “Optical coherence of diamond nitrogen-vacancy centers formed by ion implantation and annealing,” Phys. Rev. B 99, 165203 (2019).

141. L. Childress, M. V. Gurudev Dutt, J. M. Taylor, A. S. Zibrov, F. Jelezko, J. Wrachtrup, P. R. Hemmer, and M. D. Lukin, “Coherent Dynamics of Coupled Electron and Nuclear Spin Qubits in Diamond,” Science 314, 281–285 (2006).

142. G. Balasubramanian, P. Neumann, D. Twitchen, M. Markham, R. Kolosov, N. Mizuochi, J. Isoya, J. Achard, J. Beck, J. Tissler, V. Jacques, P. R. Hemmer, F. Jelezko, and J. Wrachtrup, “Ultralong spin coherence time in isotopically engineered diamond,” Nature Materials 8, 383–387 (2009).

143. J. A. van Wyk, E. C. Reynhardt, G. L. High, and I. Kiflawi, “The dependences of ESR line widths and spin – spin relaxation times of single nitrogen defects on the concentration of nitrogen defects in diamond,” Journal of Physics D: Applied Physics 30, 1790–1793 (1997).

144. J. Achard, G. Balasubramanian, P. Neumann, C. Santori, B. A. Fairchild, J. Wrachtrup, K. Ganesan, K.-M. C. Fu, R. G. Beausoleil, A. D. Greentree, and S. Prawer, “Producing optimized ensembles of nitrogen-vacancy color centers for quantum information applications,” Journal of Applied Physics 106, 124904 (2009).

145. C. Santori, D. Fattal, S. M. Spillane, M. Fiorentino, R. G. Beausoleil, A. D. Greentree, P. Olivero, M. Draganski, J. R. Rabeau, P. Reichart, B. C. Gibson, S. Rubanov, D. N. Jamieson, and S. Prawer, “Coherent population trapping in diamond N-V centers at zero magnetic field,” Opt. Express 14, 7986–7994 (2006).

146. T. Ishikawa, K.-M. C. Fu, C. Santori, V. M. Acosta, R. G. Beausoleil, H. Watanabe, S. Shikata, and K. M. Itoh, “Optical and Spin Coherence Properties of Nitrogen-Vacancy Centers Placed in a 100 nm Thick Isotopically Purified Diamond Layer,” Nano Letters 12, 2083–2087 (2012).

147. K. Ohno, F. Joseph Heremans, L. C. Bassett, B. A. Myers, D. M. Troyli, A. C. Bleszynski Jayich, C. J. Palmstrm, and D. D. Awschalom, “Engineering shallow spins in diamond with nitrogen delta-doping,” Applied Physics Letters 101, 092413 (2012).

148. K. Ohashi, T. Rosskopf, H. Watanabe, M. Loretz, Y. Tao, R. Hauer, T. Tomizawa, T. Ishikawa, J. Ishi-Hayase, S. Shikata, C. L. Degen, and K. M. Itoh, “Negatively Charged Nitrogen-
Vacancy Centers in a 5 nm Thin 12C Diamond Film,” Nano Letters 13, 4733–4738 (2013).

C. A. McEllan, B. A. Myers, S. Kraemer, K. Ohno, D. D. Awschalom, and A. C. Bleszynski Jayich, “Patterned formation of highly coherent nitrogen-vacancy centers using a focused electron irradiation technique,” Nano Letters 16, 2450–2454 (2016).

T. R. Eichhorn, C. A. McEllan, and A. C. Bleszynski Jayich, “Optimizing the formation of depth-confined nitrogen vacancy center spin ensembles in diamond for quantum sensing,” Phys. Rev. Materials 3, 113802 (2019).

K. Ohno, F. Joseph Heremans, C. F. de las Casas, B. A. Myers, B. J. Alem, A. C. Bleszynski Jayich, and D. D. Awschalom, “Three-dimensional localization of spins in diamond using 12C implantation,” Applied Physics Letters 105, 052406 (2014).

E. E. Kleinsasser, M. M. Stanfield, J. K. Q. Banks, Z. Zhu, W.-D. Li, V. M. Acosta, H. Watanabe, K. M. Itoh, and K.-M. C. Fu, “High density nitrogen-vacancy sensing surface created via He+ ion implantation of 12C diamond,” Applied Physics Letters 108, 202401 (2016).

K. M. Davis, K. Miura, N. Sugimoto, and K. Hiroa, “Writing waveguides in glass with a femtosecond laser,” Opt. Lett. 21, 1729–1731 (1996).

K. Miura, J. Qiu, H. Inouye, T. Mitsuyu, and K. Hiroa, “Photonic via networks on various glasses with ultraviolet pulse laser,” Applied Physics Letters 71, 3329–3331 (1997).

H. Zhang, S. M. Eaton, J. Li, and P. R. Herm, “Femtosecond laser direct writing of multilength Bragg grating waveguides in glass,” Opt. Lett. 31, 3495–3497 (2006).

M. Thiel, G. Flachenecker, and W. Schade, “Femtosecond laser writing of Bragg grating waveguide bundles in bulk glass,” Opt. Lett. 40, 1266–1269 (2015).

N. Shen, D. Datta, C. B. Schaffer, and E. Mazur, “Ablation of cytoskeletal filaments and mitochondria in live cells using a femtosecond laser nanoscissors,” Molecular & Cellular Biomechanics 2, 17–26 (2005).

B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore, and M. D. Perry, “Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses,” Phys. Rev. Lett. 74, 2248–2251 (1995).

B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry, “Nanosecond-to-femtosecond laser-induced breakdown in dielectrics,” Phys. Rev. B 53, 1749–1761 (1996).

E. Yablonovitch and N. Bloembergen, “Avalanche Ionization and the Limiting Diameter of Filaments Induced by Light Pulses in Transparent Media,” Phys. Rev. Lett. 29, 907–910 (1972).

S. K. Sundaram and E. Mazur, “Inducing and probing non-thermal transitions in semiconductors using femtosecond laser pulses,” Nature Materials 4, 217–224 (2005).

Y. Liu, G. Chen, M. Song, X. Ci, B. Wu, E. Wu, and H. Zeng, “Fabrication of nitrogen vacancy color centers by femtosecond pulse laser illumination,” Opt. Express 21, 12843–12848 (2013).

Y.-C. Chen, B. Griffiths, L. Weng, S. S. Nicley, S. N. Ishmael, Y. Lekhai, S. Johnson, C. J. Stephen, B. L. Green, G. W. Morley, M. E. Newton, M. J. Booth, P. S. Salter, and J. M. Smith, “Laser writing of individual nitrogen-vacancy defects in diamond with near-unity yield,” Optics 6, 662–667 (2019).

Y.-C. Chen, P. S. Salter, S. Kraemer, L. Weng, A. C. Frangeskou, C. J. Stephen, S. N. Ishmael, P. R. Dolan, S. Johnson, B. L. Green, G. W. Morley, M. E. Newton, J. G. Rarity, M. J. Booth, and J. M. Smith, “Laser writing of coherent colour centres in diamond,” Nature Photonics 11, 77–80 (2017).

E. M. Purcell, “Proceedings of the American Physical Society: Spontaneous Emission Probabilities at Radio Frequencies,” Phys. Rev. 69, 674–674 (1946).

A. Faraon, C. Santori, Z. Huang, V. M. Acosta, and R. G. Beausoleil, “Coupling of Nitrogen-Vacancy Centers to Photonic Crystal Cavities in Monocrystalline Diamond,” Phys. Rev. Lett. 109, 033604 (2012).

T. Schrader, F. Gdeke, M. J. Banholzer, and O. Benson, “Ultra-bright and efficient single-photon generation based on nitrogen-vacancy centres in nanodiamonds on a solid immersion lens,” New Journal of Physics 13, 055017 (2011).

H. W. Choi, E. Gu, C. Liu, C. Griffin, J. M. Girkin, I. M. Watson, and M. D. Dawson, “Fabrication of natural diamond microcavities by plasma etching,” Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena 23, 130–132 (2005).

C. F. Wang, Y-S. Choi, J. C. Lee, E. L. Hu, J. Yang, and J. E. Butler, “Observation of whispering gallery modes in nanocrystalline diamond microdisks,” Applied Physics Letters 90, 081110 (2007).

C. F. Wang, R. Hanson, D. D. Awschalom, E. L. Hu, T. Feygelson, J. Yang, and J. E. Butler, “Fabrication and characterization of two-dimensional photonic crystal microcavities in nanocrystalline diamond,” Applied Physics Letters 91, 201112 (2007).

P. Olivero, S. Rubanov, P. Reichart, B. Gibson, S. Huntington, J. Rabeau, A. Greenstreet, J. Salzman, D. Moore, D. Jamieson, and S. Prawer, “Ion-Beam-Assisted Lift-Off Technique for Three-Dimensional Micromachining of Free-Standing Single-Crystal Diamond,” Advanced Materials 17, 2427–2430 (2005).

P. Olivero, S. Rubanov, P. Reichart, B. Gibson, S. Huntington, J. Rabeau, A. D. Greenstreet, J. Salzman, D. Moore, D. Jamieson, and S. Prawer, “Characterization of three-dimensional microstructures in single-crystal diamond,” Diamond and Related Materials 15, 1614 – 1621 (2006).

B. A. Fairchild, P. Olivero, S. Rubanov, A. D. Greenstreet, F. Waldernann, R. A. Taylor, I. Walsmsley, J. M. Smith, S. Huntington, B. C. Gibson, D. N. Jamieson, and S. Prawer, “Fabrication of Ultrathin Single-Crystal Diamond Membranes,” Advanced Materials 20, 4793–4798 (2008).

I. Bayn, B. Meyer, J. Salzman, V. Richter, and R. Kalish, “Single crystal diamond photonic crystal nanocavity: Fabrication and Initial Characterization,” in Conference on Lasers and Electro-Optics 2010 (Optical Society of America, 2010) p. QThL7.

I. Bayn, B. Meyer, A. Lahav, J. Salzman, R. Kalish, B. A. Fairchild, S. Prawer, M. Barth, O. Benson, T. Wolf, P. Siyushev, F. Jelezko, and J. Wrachtrup, “Processing of photonic crystal nanocavity for quantum information in diamond,” Diamond and Related Materials 20, 937 – 943 (2011).

D. P. Hickey, E. Kuryliw, K. Siebein, K. S. Jones, R. Chodrela, and R. Elliman, “Cross-sectional transmission electron microscopy method and studies of implant damage in single crystal diamond,” Journal of Vacuum Science & Technology A 24, 1302–1307 (2006).

I. Bayn, B. Meyer, J. Salzman, and R. Kalish, “Triangular nanobeam photonic cavities in single-crystal diamond,” New Journal of Physics 13, 025018 (2011).

L. Li, M. Trusheim, O. Gaathon, K. Kisslinger, C.-J. Cheng, M. Lu, D. Su, X. Yao, H.-C. Huang, I. Bayn, A. Wolcott, R. M. Osgood, and D. Englund, “Reactive ion etching: Optimized diamond membrane fabrication for transmission electron microscopy,” Journal of Vacuum Science & Technology B 31, 05FP02 (2013).

J. S. Hodges, L. Li, M. Lu, E. H. Chen, M. E. Trusheim, S. Allegri, X. Yao, O. Gaathon, H. Bakhru, and D. Englund, “Long-lived NV-spin coherence in high-purity diamond membranes,” New Journal of Physics 14, 093004 (2012).

J. Riedrich-Möller, L. Kipstuhl, C. Hepp, E. Neu, C. Pauly, F. Mücklich, A. Baur, M. Wandt, S. Wolf, M. Fischer, S. Gsell, M. Schreck, and C. Becher, “One- and two-dimensional photonic crystal microcavities in single crystal diamond,” Nature Nanotechnology 7, 69–74 (2012).

T. M. Babinec, J. T. Choy, K. J. M. Smith, M. Khan, and M.Lonar, “Design and focused ion beam fabrication of single crystal diamond nanobeam cavities,” Journal of Vacuum Science
193. D. Fattal, and R. G. Beausoleil, “Quantum photonic devices for quantum information processing,” New Journal of Physics 12, 18582 (2012).

194. A. Faraon, C. Santori, Z. Huang, K.-M. C. Fu, V. M. Acosta, J. Giero, J. Salzman, R. Kalish, and D. Englund, “Fabrication of single-crystal diamond,” Applied Physics Letters 87, 141105 (2005).

195. B. J. M. Hausmann, I. B. Bulu, P. B. Deotare, M. McCutcheon, V. Venkataraman, M. L. Markham, D. J. Twitchen, and M. Loncar, “Integrated High-Quality Factor Optical Resonators in Diamond,” Nano Letters 13, 1898–1902 (2013).

196. B. J. M. Hausmann, B. Shields, Q. Quan, P. Maletinsky, M. McCutcheon, J. T. Choy, T. M. Babinec, A. Kabanek, A. Yacoby, M. D. Lukin, and M. Loncar, “Integrated Diamond Networks for Quantum Nanophotonics,” Nano Letters 12, 1578–1582 (2012).

197. A. Faraon, C. Santori, Z. Huang, K.-M. C. Fu, V. M. Acosta, D. Fattal, and R. G. Beausoleil, “Quantum photonic devices for quantum information processing,” New Journal of Physics 15, 025010 (2013).

198. B. J. M. Hausmann, B. J. Shields, Q. Quan, Y. Chu, N. P. de Leon, R. Evans, M. J. Burek, A. S. Zibrov, M. Markham, D. J. Twitchen, H. Park, M. D. Lukin, and M. Loncar, “Coupling of NV Centers to Photonic Crystal Nanobeam in Diamond,” Nano Letters 13, 5791–5796 (2013).

199. M. J. Burek, N. P. de Leon, B. J. Shields, B. J. M. Hausmann, Y. Chu, Q. Quan, A. S. Zibrov, H. Park, M. D. Lukin, and M. Loncar, “Free-Standing Mechanical and Photonic Nanostructures in Single-Crystal Diamond,” Nano Letters 12, 6084–6089 (2012).

200. M. J. Burek, Y. Chu, M. S. Z. Liddy, P. Patel, J. Rochman, S. Meesala, W. Hong, Q. Quan, M. D. Lukin, and M. Loncar, “High-quality-factor optical nanocavities in bulk single-crystal diamond,” Nature Communications 5, 5718 (2014).

201. B. Khanaliloo, H. Jayakumar, A. C. Hryciw, D. P. Lake, H. Kaviani, and P. E. Barclay, “Spin of long-lived quantum memories into a photonic circuit,” Phys. Rev. Lett. 111, 241103 (2013).

202. T. Graziosi, S. Mi, M. Kiss, and N. Quack, “Single crystal diamond micro-disk resonators by focused ion beam milling,” APL Photonics 3, 126101 (2018).

203. C. Xiong, W. H. P. Pernice, X. Sun, C. Schuck, K. Y. Fong, and H. X. Tang, “Aluminum nitride as a new material for chip-scale optoelectronics and nonlinear optics,” Applied Physics Letters 105, 261106 (2014).

204. T. Jung, J. Grütz, B. Kambs, C. Pauly, N. Raatz, R. Neul, E. Neu, A. M. Edmonds, M. Markham, F. Meckel, J. Meier, and C. Becher, “Spin measurements of NV centers coupled to a photonic crystal cavity,” Applied Physics Letters 105, 121105 (2014).

205. L. Li, I. Bayn, M. Lu, C.-Y. Nan, T. Schröder, A. Stein, N. C. Harris, and D. Englund, “Fabrication of triangular nanobeam waveguide networks in bulk diamond using single-crystal silicon hard masks,” Applied Physics Letters 105, 211101 (2014).

206. J. Burghoff, C. Grebing, S. Nolte, and A. Tünnermann, “Efficient frequency doubling in femtosecond laser-written waveguides in lithium niobate,” Applied Physics Letters 89, 081108 (2006).

207. J. Burghoff, S. Nolte, and A. Tünnermann, “Origins of waveguiding in femtosecond laser-structured LiNbO3,” Applied Physics A 89, 127–132 (2007).

208. A. Benayas, D. Jaque, B. McMillen, and K. P. Chen, “Thermal stability of microstructural and optical modifications induced in sapphire by ultrafast laser filamentation,” Journal of Applied Physics 107, 033522 (2010).

209. B. Sottilo, A. Chiappini, V. Bharadwaj, J. P. Hadden, F. Bosia, P. Olivero, M. Ferrari, R. Ramponi, P. E. Barclay, and S. M. Eaton, “Polarized micro-raman studies of femtosecond laser written stress-induced optical waveguides in diamond,” Applied Physics Letters 112, 031109 (2018).

210. B. Sottilo, V. Bharadwaj, J. P. Hadden, S. Rampini, A. Chiappini, T. T. Fernandez, C. Armellini, A. Serpengzel, M. Ferrari, P. E. Barclay, R. Ramponi, and S. M. Eaton, “Visible to Infrared Diamond Photonics Enabled by Focused Femtosecond Laser Pulses,” Micromachines 8 (2017), 10.3390/mi8020060.

211. J. P. Hadden, V. Bharadwaj, B. Sottilo, S. Rampini, R. Osel-lane, J. D. Witmer, H. Jayakumar, T. T. Fernandez, A. Chiappini, C. Armellini, M. Ferrari, R. Ramponi, P. E. Barclay, and S. M. Eaton, “Integrated waveguides and deterministically positioned nitrogen vacancy centers in diamond created by femtosecond laser writing,” Opt. Lett. 43, 3586–3589 (2018).

212. B. J. M. Hausmann, I. Bulu, V. Venkataraman, P. Deotare, and M. Loncar, “Diamond nonlinear photonics,” Nature Photonics 8, 369–374 (2014).

213. K. Rivoire, Z. Lin, F. Hatami, W. T. Masselink, and J. Vucković, “Second harmonic generation in gallium phosphide photonic crystal nanocavities with ultralow continuous wave pump power,” Opt. Express 17, 22609–22615 (2009).

214. E. Anastassakis and E. Burstein, “Second-Order Electro-Optic Effect in Diamond,” J. Opt. Soc. Am. 61, 1618–1621 (1971).

215. D. F. Nelson and E. H. Turner, “Electrooptic and Piezoelec- tric Coefficients and Refractive Index of Gallium Phosphide,” Journal of Applied Physics 39, 3337–3343 (1968).

216. C. Xiong, W. H. P. Pernice, X. Sun, C. Schuck, K. Y. Fong, and H. X. Tang, “Aluminum nitride as a new material for chip-scale optomechanics and nonlinear optics,” New Journal of Physics 14, 095014 (2012).

217. C. Xiong, W. H. P. Pernice, and H. X. Tang, “Low-Loss, Silicon Integrated, Aluminum Nitride Photonic Circuits and Their Use for Electro-Optic Signal Processing,” Nano Letters 12, 3562–3568 (2012).

218. J. P. Sprengers, A. Gaggero, D. Sahin, S. Jahanmirinejad, G. Frucci, F. Mattioli, R. Leoni, J. Beetz, M. Lermer, M. Kamp, S. Hilling, R. Sanjines, and A. Fiore, “Waveguide superconducting single-photon detectors for integrated quantum photonic circuits,” Applied Physics Letters 99, 181110 (2011).

219. S. L. Mouradian, T. Schröder, C. B. Poirtras, L. Li, J. Goldstein, H. E. Chen, M. Walsh, J. Cardenas, M. L. Markham, D. J. Twitchen, M. Lipson, and D. Englund, “Scalable integration of long-lived quantum memories into a photonic circuit,” Phys. Rev. X 5, 011009 (2015).

220. K.-M. C. Fu, C. Santori, P. E. Barclay, I. Aharonovich, S. Prawer, N. Meyer, A. M. Holm, and R. G. Beausoleil, “Coupling of nitrogen-vacancy centers in diamond to a GaP waveguide,” Applied Physics Letters 93, 234107 (2008).

221. E. Yablonovitch, D. M. Hwang, T. J. Gmitter, L. T. Florez, and J. P. Harbison, “Van der Waals bonding of GaAs epitaxial liftoff films onto arbitrary substrates,” Applied Physics Letters 56, 219–221 (1990).

222. P. E. Barclay, K.-M. C. Fu, C. Santori, and R. G. Beausoleil, “Chip-based microcavities coupled to nitrogen-vacancy centers in single crystal diamond,” Applied Physics Letters 95, 191115
A. W. Schell, G. Kewes, T. Schröder, J. Wolters, T. Aichele, and O. Benson, “Fiber-integrated diamond-based single photon source,” Nano Letters 11, 198–202 (2011).

T. Schröder, M. Fujitawa, T. Noda, H.-Q. Zhao, O. Benson, and S. Takeuchi, “A nanodiamond-tapered fiber system with high single-mode coupling efficiency,” Opt. Express 20, 10490–10497 (2012).

L. Liebermeister, F. Petersen, A. v. Muchow, D. Burchardt, J. Hermelbracht, T. Tashima, A. W. Schell, O. Benson, T. Meintricht, A. Krueger, A. Stiebeiner, A. Rauschenbeutel, H. Weinhaber, and M. Weber, “Tapered fiber coupling of single photons emitted by a deterministically positioned single nitrogen vacancy center,” Applied Physics Letters 104, 033210 (2014).

V. Y. Shen, T. M. Sweeney, and H. Wang, “Zero-phonon linewidth of single nitrogen vacancy centers in diamond nanocrystals,” Phys. Rev. B 77, 033201 (2008).

M. Nguyen, N. Nikolay, C. Bradać, M. Kianinia, E. A. Ekimov, N. Mendelson, O. Benson, and I. Aharonovich, “Photodynamics and quantum efficiency of germanium vacancy color centers in diamond,” Advanced Photonics 77, 1–7 (2019).

J. Wolters, A. W. Schell, G. Kewes, N. Nese, M. Schoengen, H. Dschier, T. Hamnappel, B. Lchel, M. Barth, and O. Benson, “Enhancement of the zero phonon line emission from a single nitrogen vacancy center in a nanodiamond via coupling to a photonic crystal cavity,” Applied Physics Letters 97, 141108 (2010).

A. W. Schell, G. Kewes, T. Schröder, J. Wolters, T. Aichele, and O. Benson, “A scanning probe-based pick-and-place procedure for assembly of integrated quantum optical hybrid devices,” Review of Scientific Instruments 82, 073709 (2011).

O. Benson, “Assembly of hybrid photonic architectures from self-assembled nanophotonic constituents,” Nature 480, 193–199 (2011).

D. Englund, B. Shields, K. Rivoire, F. Hatami, J. Vuković, H. Park, and M. D. Lukin, “Deterministic Coupling of a Single Nitrogen Vacancy Center to a Photonic Crystal Cavity,” Nano Letters 10, 3922–3926 (2010).

P. E. Barclay, C. Santori, K.-M. Fu, R. G. Beausoleil, and O. Painter, “Coherent interference effects in a nano-assembled diamond NV center cavity-QED system,” Opt. Express 17, 20891–20897 (2009).

Y.-S. Park, A. K. Cook, and H. Wang, “Cavity QED with Diamond Nanocrystals and Silica Microspheres,” Nano Letters 6, 2075–2079 (2006).

H. Siampour, S. Kumar, and S. I. Bozhevolnii, “Nanofabrication of Plasmonic Circuits Containing Single Photon Sources,” ACS Photonics 4, 1879–1884 (2017).

H. Siampour, S. Kumar, and S. I. Bozhevolnii, “Chip-integrated plasmonic cavity-enhanced single nitrogen-vacancy center emission,” Applied Physics Letters 103, 263108 (2013).

R. Kolesov, B. Grotz, G. Balasubramanian, R. J. Stöhr, A. A. L. Collet, P. R. Hammer, F. Jelezko, and J. Wrachtrup, “Wave-vector multiplicity of single surface plasmon polaritons,” Nature Physics 5, 470–474 (2009).

S. I. Bogdanov, M. Y. Shalaginov, A. S. Lagutchev, C.-C. Chiung, D. Shah, A. S. Baburin, I. A. Ryzhikov, I. A. Rodionov, A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, “Ultra-bright Room-Temperature Sub-Nanosecond Emission from Single Nitrogen-Vacancy Centers Coupled to Nanopatch Antennas,” Nano Letters 18, 4837–4844 (2018).

X. Meng, S. Liu, J. I. Dadap, and R. M. Osgood, “Plasmonic enhancement of a silicon-vacancy center in a nanodiamond crystal,” Phys. Rev. Materials 1, 015202 (2017).

H. Kapp, C. Deutsch, H.-C. Chang, J. Reichel, T. W. Hänsch, and D. Hunger, “Scaling laws of the cavity enhancement for nitrogen-vacancy centers in diamond,” Phys. Rev. A 88, 053812 (2013).

R. Albrecht, A. Bonmer, C. Deutsch, J. Reichel, and C. Becher, “Coupling of a Single Nitrogen-Vacancy Center in Diamond to a Fiber-Based Microcavity,” Phys. Rev. Lett. 110, 243602 (2013).

H. Kapp, T. Hümmer, M. Mader, B. Schlederer, J. Benedikter, P. Haeusser, H.-C. Chang, H. Fedder, T. W. Hänsch, and D. Hunger, “Purcell-Enhanced Single-Photon Emission from Nitrogen-Vacancy Centers Coupled to a Tunable Microcavity,” Phys. Rev. Applied 6, 054010 (2016).

J. Benedikter, H. Kapp, T. Hänsch, Y. Liang, A. Bonmer, C. Becher, A. Krueger, J. M. Smith, T. W. Hänsch, and D. Hunger, “Cavity-Enhanced Single-Photon Source Based on the Silicon-Vacancy Center in Diamond,” Phys. Rev. Applied 7, 024031 (2017).

T. Schröder, A. W. Schell, G. Kewes, T. Aichele, and O. Benson, “Fiber-integrated diamond-based single photon source,” Nano Letters 11, 198–202 (2011).

T. Schröder, M. Fujitawa, T. Noda, H.-Q. Zhao, O. Benson, and S. Takeuchi, “A nanodiamond-tapered fiber system with high single-mode coupling efficiency,” Opt. Express 20, 10490–10497 (2012).

L. Liebermeister, F. Petersen, A. v. Muchow, D. Burchardt, J. Hermelbracht, T. Tashima, A. W. Schell, O. Benson, T. Meintricht, A. Krueger, A. Stiebeiner, A. Rauschenbeutel, H. Weinhaber, and M. Weber, “Tapered fiber coupling of single photons emitted by a deterministically positioned single nitrogen vacancy center,” Applied Physics Letters 104, 033210 (2014).

V. V. Vorobyov, S. V. Soschenko, V. V. Bel'shedevski, J. Javadzade, N. Lebedev, A. N. Smolyaninov, V. N. Sorokin, and A. V. Akimov, “Coupling of single NV center to adiabatically tapered optical single mode fiber,” The European Physical Journal D 70, 269 (2016).

M. R. Henderson, B. C. Gibson, H. Ebendorff-Heidepriem, K. Kuan, S. Aishar V., J. O. Orwa, I. Aharonovich, S. Tomilinovic-Hanic, A. D. Greentree, S. Prawer, and T. M. Monroe, “Diamond in Tellurite Glass: a New Medium for Quantum Information,” Advanced Materials 23, 2896–2891 (2011).

W. Wood and V. Bulović, “Colloidal quantum dot light-emitting devices,” Nano Reviews 1, 5202 (2010).

H. S. E. Sargent, “Colloidal quantum dot solar cells,” Nature Photonics 6, 133–135 (2012).

M. K. Choi, J. Yang, T. Hyeon, and D.-H. Kim, “Flexible quantum dot light-emitting diodes for next-generation displays,” npj Flexible Electronics 2, 10 (2018).

C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland, “Demonstration of a Fundamental Quantum Logic Gate,” Phys. Rev. Lett. 75, 4714–4717 (1995).

S. C. Snyder, B. G. Orr, D. Kessler, and L. M. Sander, “Effect of strain on surface morphology in highly strained InGaAs films,” Phys. Rev. Lett. 66, 3032–3035 (1991).

S. H. Xin, P. D. Wang, A. Yin, C. Kim, M. Dobrowolska, J. L. Merz, and J. K. Furdy, “Formation of self-assembling CdSe quantum dots on ZnSe by molecular beam epitaxy,” Applied Physics Letters 69, 3884–3886 (1996).

T. S. Faafard, Z. Wasilewski, J. McCaffrey, S. Raymond, and S. Charbonneau, “InAs selfassembled quantum dots on InP by molecular beam epitaxy,” Applied Physics Letters 68, 991–993 (1996).

J. Oshinowo, M. Nishioka, S. Ishida, and Y. Arakawa, “Highly uniform InGaAs/GaAs quantum dots (15 nm) by metalorganic chemical vapor deposition,” Applied Physics Letters 65, 1421–1423 (1994).

F. Heinrichsdorff, M.-H. Mao, N. Kirsainted, A. Krost, D. Binberg, A. O. Kosogov, and P. Werner, “Room-temperature continuous-wave lasing from stacked InAs/GaAs quantum dots grown by metalorganic chemical vapor deposition,” Applied Physics Letters 71, 22–24 (1997).

S. W. Kim, S. Fujita, and S. Fujita, “Self-organized ZnO quantum dots on SiO2/Si substrates by metalorganic chemical vapor deposition,” Applied Physics Letters 81, 5036–5038 (2002).

E. Kawakami, P. Scarlino, D. R. Ward, F. R. Braakman, D. E. Savage, M. G. Lagally, M. Frisens, S. N. Coppersmith, M. A. Eriksson, and L. M. K. Vandersypen, “Electrical control of a long-lived spin qubit in a Si/SiGe quantum dot,” Nature Nanotechnology 8, 713–717 (2013).
290. P. Mirin, J. P. Ibbetson, K. Nishi, A. C. Gossard, and J. E. Bowers, “Electrically controlled spontaneous emission in colo-
ral quantum dots,” Science Advances 5 (2019), 10.1126/sci-
dia.abc1140.

291. R. P. Mirin, J. P. Ibbetson, K. Nishi, A. C. Gossard, and J. E. Bowers, “1.3 μm photoluminescence from InGaAs quantum dots on GaAs,” Applied Physics Letters 67, 3795–3797 (1995).

292. R. P. Mirin, J. P. Ibbetson, K. Nishi, A. C. Gossard, and J. E. Bowers, “1.3 μm photoluminescence from InGaAs quantum dots on GaAs,” Applied Physics Letters 67, 3795–3797 (1995).

293. P. Senellart, G. Solomon, and A. White, “High-performance semiconductor quantum-dot single-photon sources,” Nature Nanotechnology 12, 1026–1039 (2017).

294. P. Bhasker, J. Norman, J. Bowers, and N. Dagli, “Intensity and phase modulators at 1.55 μm with InAs/InGaAs quantum dots epitaxially grown on silicon,” in Conference on Lasers and Electro-Optics/Pacific Rim (Optical Society of America, 2018) pp. ThJ2J–3.

295. A. W. Elshaarai, I. E. Zadeh, A. Fognini, M. E. Reimer, D. Dalacu, P. J. Poole, V. Zwiller, and K. D. Jøns, “On-chip single photon filtering and multiplexing in hybrid quantum photon-
tic circuits,” Nature Communications 8, 379 (2017).

296. A. Singh, Q. Li, S. Liu, Y. Yu, X. Lu, C. Schneider, S. F. Hølbling, J. B. Pollard, V. Verma, R. Mirin, S. W. Nam, J. Liu, and K. Srini-
vasan, “Quantum frequency conversion of a quantum dot single-
photon source on a nanoporphic chip,” Optica 6, 563–569 (2019).

297. T. Umezawa, K. Akahane, A. Kanno, and T. Kawanishi, “Investi-
gation of a 1.5-μm-wavelength InAs/quantum-dot absorption layer for high-speed photodetector,” Applied Physics Express 7, 032201 (2014).

298. Y. Yan, Z. Zhang, R. Chao, J. Norman, D. Jung, C. Shang, Q. Li, M. Kennedy, D. Liang, C. Zhang, J.-W. Shi, A. C. Gossard, K. M. Lau, and J. E. Bowers, “Monolithically inte-
grated InAs/InGaAs quantum dot photodetectors on silicon substrates,” Opt. Express 25, 27715–27723 (2017).

299. P. Lodahl, “Quantum-dot based photonic quantum networks,” Quantum Science and Technology 3, 013001 (2017).

300. J.-H. Kim, S. Aghaeeimibodi, J. Carolan, D. Englund, and E. Waks, “Hybrid integration methods for on-chip quantum photonic-
tors,” Optica 7, 201–208 (2020).

301. Y. Chen, A. Ryou, M. R. Friedfeld, T. Fryett, J. Whitehead, B. M. Cossairt, and A. Majumdar, “Deterministic Positioning of Coloalnd Quantum Dots on Silicon Nitride Nanobeam Cavi-
ties,” Nano Letters 18, 6404–6410 (2018).

302. P. Schnauber, A. Singh, J. Schall, S. I. Park, J. D. Song, S. Rodt, K. Srinivasan, S. Reitzenstein, and M. Danvano, “Indistinguish-
able photons from deterministically integrated single quantum dots in heterogeneous gaa/sbn4 quantum photonic circuits,” Nano Letters 19, 7164–7172 (2019).

303. M. Danvano, J. Liu, L. Sapienza, C.-Z. Zhang, J. V. De Mi-
randla Cardoso, V. Verma, R. Mirin, S. W. Nam, L. Liu, and K. Srinivasan, “Heterogeneous integration for on-chip quantum photon-
tic circuits with single quantum dot devices,” Nature Communications 8, 889 (2017).

304. E. Murray, D. J. P. Ellis, T. Meany, F. F. Floetner, J. P. Lee, J. P. Griffiths, G. A. C. Jones, I. Farrer, D. A. Ritchie, A. J. Bennett, and A. J. Shields, “Quantum photonics hybrid inte-
gration platform,” Applied Physics Letters 107, 171108 (2015).

305. R. Katsumi, Y. Ota, A. Osada, T. Yamaguchi, T. Tajiri, M. Kakuda, S. Iwamoto, H. Akiyama, and Y. Arakawa, “In situ wavelength tuning of quantum-dot single-photon sources integrated on a CMOS-processed silicon waveguide,” Applied Physics Letters 116, 041103 (2020).

306. C. Linghu, S. Zhang, C. Wang, and J. Song, “Transfer printing techniques for flexible and stretchable inorganic electronics,” npj Flexible Electronics 2, 26 (2018).

307. J. Lee, I. Karnadi, J. T. Kim, Y.-H. Lee, and M.-K. Kim, “Printed Nanolaser on Silicon,” ACS Photonics 4, 2117–2123 (2017).

308. A. W. Elshaarai, E. Bykzer, I. E. Zadeh, T. Pettner, P. Zhao, E. Schll, S. Gyger, M. E. Reimer, D. Dalacu, P. J. Poole, K. D. Jns, and V. Zwiller, “Strain-Tunable Quantum Integrated Photonic-
tors,” Nano Letters 18, 7969–7976 (2018).

309. J.-H. Kim, S. Aghaeeimibodi, C. J. K. Richardson, R. P. Leavitt, D. Englund, and E. Waks, “Hybrid Integration of Solid-State Quantum Emitters on a Silicon Photonic Chip,” Nano Letters 17, 7394–7400 (2017).

310. S. Rodt, A. Schliwa, K. Fötschke, G. Gufrath, and D. Bimberg, “Correlation of structural and few-particle properties of self-
organized InAsGaAs quantum dots,” Phys. Rev. B 71, 155325 (2005).

311. E. A. Muljarov and R. Zimmermann, “Dephasing in Quantum Dots: Quadratic Coupling to Acoustic Phonons,” Phys. Rev. B 93, 237401 (2001).

312. M. Pichler, A. Kiraz, C. Becker, W. V. Schoenfeld, P. M. Petroff, L. Zhang, E. Hu, and A. Imamoglu, “A Quantum Dot Single-
Photon Turnstile Device,” Science 290, 2282–2285 (2000).

313. C. P. Dietrich, A. Fiore, M. G. Thompson, M. Kamp, and S. Hfling, “GaAs integrated quantum photonics: Towards com-
pact and multi-functional quantum photonics integrated cir-
tuits,” Laser & Photonics Reviews 10, 907–911 (2016).

314. A. J. Shields, “Semiconductor quantum light sources,” Nature Photonics 9, 215–221 (2007).

315. R. Hanbury Brown and R. Q. Twiss, “A Test of a New Type of Stellar Interferometer on Sirius,” Nature 178, 1046–1048 (1956).

316. Z. Yuan, B. E. Kardynal, R. M. Stevenson, A. J. Shields, C. J. Lobo, K. Cooper, N. S. Beattie, D. A. Ritchie, and M. Pepper, “Electrically Driven Single-Photon Source,” Science 295, 102–105 (2002).

317. E. B. Flagg, S. V. Polyakov, T. Thomay, and G. S. Solomon, “Dynamics of Nonclassical Light from a Single Solid-State Quantum Emitter,” Phys. Rev. Lett. 109, 163601 (2012).

318. V. Giesz, O. Gazzano, A. K. Nowak, S. L. Portalupi, A. Lema-
tre, I. Sagnes, L. Lanco, and P. Senellart, “Influence of the Purcell effect on the purity of bright single photon sources,”
B. V. Kuhlmann, I. Söllner, M. C. Löbl, R. J. Warburton, and R. Schott, A. Ludwig, A. D. Wieck, S. I. Park, J. D. Song, T. Pregnolato, L. Midolo, P. Tighineanu, A. Javadi, S. Stobbe, G. Kirsanske, H. Thyrrestrup, R. S. Daveau, C. L. Dreesen, photon sources,” Optica 3 (2016).

I. Sagnes, A. Lemaitre, A. Auffeves, P. Senellart, M. P. Almeida, V. Giesz, T. Grange, M. A. Broome, O. Gazzano, G. Coppola, J. C. Loredo, M. P. Almeida, A. Auffeves, P. Senellart, “Near-optimal single-photon sources in the solid state,” Nature Photonics 10, 340–345 (2016).

O. Gazzano, S. Michaelis de Vasconcellos, C. Arnold, A. Nowak, E. Galopin, I. Sagnes, L. Lanco, A. Lemaitre, and P. Senellart, “Bright solid-state sources of indistinguishable single photons,” Nature Communications 4, 1425 (2013).

A. Thoma, P. Schnauber, M. Gschrey, M. Seifried, J. Wolters, J.-H. Schulze, A. Strittmatter, S. Rodt, A. Carabia, A. Knorr, T. Heindel, and S. Ritztenhaus, “Exploring Dephasing of a Solid-State Quantum Emitter via Time- and Temperature-Dependent Hong-Ou-Mandel Experiments,” Phys. Rev. Lett. 116, 033601 (2016).

C. Santori, D. Fattal, J. Vuckovic, G. S. Solomon, and Y. Yamamoto, “Indistinguishable photons from a single-photon device,” Nature 419, 594–597 (2002).

M. Reindl, J. H. Weber, D. Huber, C. Schimpf, S. F. Covre da Silva, S. L. Portalupi, R. Trotta, P. Michler, and A. Rastelli, “Highly indistinguishable single photons from coherently excited quantum dots,” Phys. Rev. B 100, 155420 (2019).

H. Wang, Z.-C. Duan, Y.-H. Li, S. Chen, J.-P. Li, Y.-M. He, M.-C. Chen, Y. He, X. Ding, C.-Z. Peng, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, and J.-W. Pan, “On-Demand Single Photons with High Extraction Efficiency and Near-Unity Indistinguishability from a Resonantly Driven Quantum Dot in a Micropillar,” Phys. Rev. Lett. 116, 020401 (2016).

N. Somaschi, V. Giesz, L. De Santis, C. Arnold, A. Nowak, E. Clarke, I. E. Itskevich, A. M. Fox, M. S. Skolnick, and E. Van Keuren, A. Migdall, P. Petroff, “Local quantum dot tuning on photonic crystal cavities,” Applied Physics Letters 88, 131101 (2006).

A. Faraon, D. Enghild, I. Fushman, J. Vukovi, N. Stoltz, and P. Petroff, “Local quantum dot tuning on photonic crystal chips,” Applied Physics Letters 90, 213110 (2007).

A. Faraon and J. Vuckovic, “Local temperature control of photonic crystal devices via micron-scale electrical heaters,” Applied Physics Letters 95, 043102 (2009).

J.-H. Kim, S. Aghaeimeibodi, C. J. K. Richardson, R. P. Leavitt, and E. Waks, “Super-Radiant Emission from Quantum Dots in a Nanophotonic Waveguide,” Nano Letters 18, 4734–4740 (2018).

D. G. Gevaux, A. J. Bennett, R. M. Stevenson, A. J. Shields, P. Atkinson, J. Griffiths, D. Anderson, G. A. C. Jones, and D. A. Ritchie, “Enhancement and suppression of spontaneous emission by temperature tuning InAs quantum dots to photonic crystal cavities,” Applied Physics Letters 88, 131101 (2006).

T. Yoshie, A. Scherer, J. Hendrickson, G. Khitrova, H. M. Gibbs, G. Rupper, C. Ell, O. B. Shchekin, and D. G. Deppe, “Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity,” Nature 432, 200–203 (2004).

S. M. Thon, H. Kim, C. Bonato, J. Gudat, J. Hagemeier, M. Petroff, and D. Bouwmeester, “Independent electrical tuning of separated quantum dots in coupled photonic crystal cavities,” Applied Physics Letters 99, 161102 (2011).

J. Q. Grim, A. S. Bracker, M. Zalalutdinov, S. G. Carter, A. C. Kouzen, M. Kim, C. S. Kim, J. T. Mack, M. Yakes, B. Lee, and D. Gammon, “Sensitiv fluxing motion of a photonic crystal membrane with InGaAs quantum dots,” Applied Physics Letters 111, 183101 (2017).

J. Q. Grim, A. S. Bracker, M. Zalalutdinov, S. G. Carter, A. C. Kouzen, M. Kim, C. S. Kim, J. T. Mack, M. Yakes, B. Lee, and D. Gammon, “Scalable in operando strain tuning in nanophotonic waveguides enabling three-quantum-dot-superradiance,” Nature Materials 18, 963–969 (2019).

M. Reindl, J. H. Weber, D. Huber, C. Schimpf, S. F. Covre da Silva, S. L. Portalupi, R. Trotta, P. Michler, and A. Rastelli, “Highly indistinguishable single photons from coherently excited quantum dots,” Phys. Rev. B 100, 155420 (2019).

H. Wang, Z.-C. Duan, Y.-H. Li, S. Chen, J.-P. Li, Y.-M. He, M.-C. Chen, Y. He, X. Ding, C.-Z. Peng, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, and J.-W. Pan, “Near-transform-limited single photons from an efficient solid-state quantum emitter,” Phys. Rev. Lett. 116, 213601 (2016).

J. C. Loredo, N. A. Zakaria, N. Somaschi, C. Anton, L. de Santis, V. Giesz, T. Grange, M. A. Broome, O. Gazzano, G. Coppola, I. Sagnes, A. Lemaitre, A. Auffeves, P. Senellart, M. P. Almeida, and A. G. White, “Scalable performance in solid-state single-photon sources,” Optica 3, 433–440 (2016).

G. Kiršanské, H. Thyrrestrup, R. S. Daveau, C. L. Dreèlen, T. Pregnolato, L. Midolo, P. Tighineanu, A. Javadi, S. Stobbe, R. Schott, A. Ludwig, A. D. Wieck, S. I. Park, J. D. Song, A. V. Kuhlmann, I. Söllner, M. C. Löbl, R. J. Warburton, and P. Loidl, “Indistinguishable and efficient single photons from a quantum dot in a planar nanobeam waveguide,” Phys. Rev. B 96, 165306 (2017).

M. Petruzzella, S. Birindelli, F. M. Pagliano, D. Pellegrino, Z. Zobenica, L. H. Li, E. H. Linfield, and A. Fiore, “Quantum photonic integrated circuits based on tunable dots and tunable cavities,” APL Photonics 3, 106103 (2018).

J. H. Weber, B. Kambs, J. Kettler, S. Kern, J. Maisch, H. Virtal, M. Jetter, S. L. Portalupi, C. Becher, and P. Michler, “Two-photon interference in the telecom C-band after frequency conversion of photons from remote quantum emitters,” Nature Nanotechnology 14, 23–26 (2019).
P. Schneeweiss, J. Volz, H. Pichler, and P. Zoller, “Chiral quan-
11
Waveguide-Based Spin-Photon Interface,” Phys. Rev. Applied

Coherent Optical Control of a Quantum-Dot Spin-Qubit in a
R. Schott, C. Papon, T. Pregnolato, L. Midolo, A. D. Wieck,
D. Ding, M. H. Appel, A. Javadi, J. Marcus, P. Kozacki, and M. Potemski,
“Single photon emitters in exfoliated WSe$_2$ structures,” Nature
Nanotechnology 10, 503–506 (2015).

Q. H. Wang, K. Kalantar-Zadeh, A. Kis, J. N. Coleman, and M. S. Strano, “Electronics and optoelectronics of
two-dimensional transition metal dichalcogenides,” Nature Nanotechnology 7, 699–712 (2012).

K. F. Mak and J. Shan, “Photonics and optoelectronics of 2D semiconductor transition metal dichalcogenides,” Nature Photonics 7, 57–60 (2018).

A. Splendiani, L. Sun, Z. Zhang, T. Li, J. Kim, C.-Y. Chim, G. Galli, and F. Wang, “Emerging Photoluminescence in Mono-
layer MoS$_2$,” Nano Letters 10, 1271–1275 (2010).

J. S. Ross, F. Klement, A. M. Jones, N. J. Ghimire, J. Yan, D. G. Mandrus, T. Taniguchi, K. Watanabe, K. Kitamura, W. Yao, D. H. Cobden, and X. Xu, “Electrically tunable excitonic light-emitting diodes based on monolayer WSe$_2$ p-n junctions,” Nature Nanotechnology 9, 268–272 (2014).

C. Lee, H. Yan, L. E. Brus, T. F. Heinz, J. Hone, and S. Ryu, “Anomalous Lattice Vibrations of Single- and Few-
Layer MoS$_2$,” ACS Nano 4, 2695–2700 (2010).

K. F. Mak, K. He, J. Shan, and T. F. Heinz, “Control of val-
ley polarization in monolayer MoS$_2$ by optical helicity,” Nature Nanotechnology 7, 494–498 (2012).

A. M. Jones, H. Yu, N. J. Ghimire, S. Wu, G. Alivisatos, J. S. Ross, B. Zhao, J. Yan, D. G. Mandrus, D. Xiao, W. Yao, and X. Xu, “Optical generation of excitonic valley coherence in monolayer WSe$_2$,” Nature Nanotechnology 8, 634–638 (2013).

C. Chiriteescu, D. G. Cahill, N. Nguyen, D. Johnson, A. Boda-
pati, P. Kebinski, and P. Zschack, “Ultralow Thermal Conduc-
tivity in Disordered, Layered WSe$_2$ Crystals,” Science 315, 351–353 (2007).

S.-Y. Kim, J. Kwak, C. V. Ciobanu, and S.-Y. Kwon, “Recent Developments in Controlled Vapor-Phase Growth of 2D Group 6 Transition Metal Dichalcogenides,” Advanced Materials 31, 1804988 (2019).

Y. Zhang, T.-R. Chang, B. Zhou, Y.-T. Cui, H. Yan, Z. Liu, F. Schmitt, J. Lee, R. Moore, Y. Chen, H. Lin, H.-T. Jeng, S.-K. Mo, Z. Hussain, A. Bansil, and Z.-X. Shen, “Direct observation of the transition from indirect to direct bandgap in atomically thin epitaxial MoSe$_2$,” Nature Nanotechnology 9, 111–115 (2014).

T. Li and G. Galli, “Electronic Properties of MoS$_2$ Nanoparti-
cles,” The Journal of Physical Chemistry C 111, 16192–16196 (2007).

T. Cheiwchanchamnij and W. R. L. Lambrecht, “Quasiparticle band structure calculation of monolayer, bilayer, and bulk mo$_2$,” Phys. Rev. B 85, 205302 (2012).

K. F. Mak, C. Lee, J. Hone, J. Shan, and T. F. Heinz, “Atom-
ically Thin MoS$_2$: A New Direct-Gap Semiconductor,” Phys. Rev. Lett. 105, 136805 (2010).

D. Xiao, G.-B. Liu, W. Feng, X. Xu, and W. Yao, “Cou-
piled Spin and Valley Physics in Monolayers of MoS$_2$ and Other Group-VI Dichalcogenides,” Phys. Rev. Lett. 108, 196802 (2012).
Materials
Y. You, X.-X. Zhang, T. C. Berkelbach, M. S. Hybertsen, D. R. Pan, “Single quantum emitters in monolayer semiconductors,” Nature Nanotechnology 10, 497–502 (2015).

Chakraborty, L. Kinnischtez, K. M. Goodfellow, R. Beams, and A. N. Vannikavak, “Voltage-controlled quantum light from an atomically thin semiconductor,” Nature Nanotechnology 10, 507–511 (2015).

Schwarz, A. Koizikov, F. Withers, J. K. Maguire, A. P. Foster, S. Dufferwiel, L. Hague, M. N. Makhonin, L. R. Wilson, A. K. Geim, K. S. Novoselov, and A. I. Tartakovskyi, “Electrically pumped single-defect light emitters in WSe2,” 2D Materials 3, 020308 (2016).

A. Branny, S. Kumar, R. Proux, and B. D. Gerardot, “Deterministic strain-induced arrays of quantum emitters in a two-dimensional semiconductor,” Nature Communications 8, 15053 (2017).

C. Palacios-Berraquero, D. M. Kara, A. R. P. Montblanch, M. Barbone, P. Latawiec, D. Yoon, A. K. Ott, M. Loncar, A. C. Ferrari, and M. Atatüre, “Large-scale quantum-emitter arrays in atomically thin semiconductors,” Nature Communications 8, 15903 (2017).

T. T. Tran, S. Choi, J. A. Scott, Z.-Q. Xu, C. Zheng, G. Senutiunas, A. Bendavid, M. S. Fuerher, M. Toth, and I. Aharonovich, “Room-Temperature Single-Photon Emission from Oxidized Tungsten Disulphide Multilayers,” Advanced Optical Materials 5, 1600939 (2017).

Y. Luo, N. Liu, X. Li, J. C. Hone, and S. Strauf, “Single photon emission in WSe2 up 160 K by quantum yield control,” 2D Materials 6, 035017 (2019).

T. T. Tran, K. Bray, M. J. Ford, M. Toth, and I. Aharonovich, “Quantum emission from hexagonal boron nitride monolayers,” Nature Nanotechnology 11, 37–41 (2016).

T. T. Tran, C. Elbadawi, D. Totonjian, C. J. Lobo, G. Grosso, H. Moon, D. R. Englund, M. J. Ford, I. Aharonovich, and M. Toth, “Robust Multicolor Single Photon Emission from Point Defects in Hexagonal Boron Nitride,” ACS Nano 10, 7331–7338 (2016).

F. Hayee, L. Yu, J. L. Zhang, C. J. Ciccarino, M. Nguyen, A. F. Marshall, I. Aharonovich, J. Vuckovic, P. Naranag, T. F. Heinz, and J. A. Dionne, “Revealing multiple classes of stable quantum emitters in hexagonal boron nitride with correlated optical and electron microscopy,” Nature Materials (2020), 10.1038/s41563-020-0616-9.

X. Liu and M. C. Hersam, “2D materials for quantum information science,” Nature Reviews Materials 4, 669–684 (2019).

D. Wong, J. Velasco, L. J. Lu, J. Lee, S. Kahn, H.-Z. Tsai, C. Germany, T. Taniguchi, K. Watanabe, A. Zettl, F. Wang, and M. F. Crommie, “Characterization and manipulation of individual defects in insulating hexagonal boron nitride using scanning tunneling microscopy,” Nature Nanotechnology 10, 949–953 (2015).

A. Bommer and C. Becher, “New insights into nonclassical light emission from defects in multi-layer hexagonal boron nitride,” Nanophotonics 8, 2041 – 2048 (2019).

V. Proscia, Z. Shotan, H. Jayakumar, P. Reddy, C. Cohen, M. Dollar, A. Alkauskas, M. Doherty, C. A. Meriles, and V. M. Menon, “Near-deterministic activation of room-temperature quantum emitters in hexagonal boron nitride,” Optica 5, 1128–1134 (2018).

M. R. Rosenberger, C. K. Dass, H.-J. Chuang, S. V. Sivaram, K. M. McCready, J. R. Hendrickson, and B. T. Jonker, “Quantum Calligraphy: Writing Single-Photon Emitters in a Two-Dimensional Materials Platform,” ACS Nano 13, 904–912 (2019).

Z. Li, Y. Li, T. Han, X. Wang, Y. Yu, B. Tay, Z. Liu, and Z. Fang, “Tailoring MoS2 ExcitonPlasmon Interaction by Optical SpinOrbit Coupling,” ACS Nano 11, 1165–1171 (2017).

G. M. Akselrod, T. Ming, C. Argyropoulos, T. B. Hoang, Y. Lin, X. Ling, D. R. Smith, J. Kong, and M. H. Mikkelsen, “Leveraging Nanocavity Harmonics for Control of Optical Processes in 2D Nanodevices,” Nano Letters 15, 3578–3584 (2015).

M. Nguyen, S. Kim, T. T. Tran, Z.-Q. Xu, M. Kianinia, M. Toth, and I. Aharonovich, “Nanomasking of quantum emitters in hexagonal boron nitride and gold nanospheres,” Nanoscale 10, 2267–2274 (2018).

X. Gan, Y. Gao, K. Fai Mak, X. Yao, R.-J. Shuie, A. van der Zande, M. E. Trusheim, F. Hatami, T. F. Heinz, J. Hone, and D. Englund, “Controlling the spontaneous emission rate of monolayer MoS2 in a photonic crystal nanocavity,” Applied Physics Letters 103, 181119 (2013).

G. Wei, T. K. Staney, D. A. Czaplewski, I. W. Jung, and N. P. Stern, “Silicon-nitride photonic circuits interfaced with monolayer MoS2,” Applied Physic Letters 107, 091112 (2015).

H. Chen, S. Nanz, A. Abas, J. Yan, T. Gao, D.-Y. Choi, Y. S. Kvishar, C. Rockshtul, and D. N. Neshev, “Enhanced Directional Emission from Monolayer WSe2 Integrated onto a Multiresonant Silicon-Based Photonic Structure,” ACS Photonics 4, 3031–3038 (2017).

T. Cai, J.-H. Kim, Z. Yang, S. Dutta, S. Aghaeimeibodi, and E. Waks, “Radiative Enhancement of Single Quantum Emitters in WSe2 Monolayers Using Site-Controlled Metallic Nanopillars,” ACS Photonics 5, 3466–3471 (2018).

O. Iff, N. Lundt, S. Betzold, L. N. Tripathi, M. Emmerling, S. Tongay, Y. J. Lee, S.-H. Kwon, S. Höfling, and C. Schneider, “Deterministic coupling of quantum emitters in WSe2 monolayers to plasmonic nanocavities,” Opt. Express 26, 25944–25951 (2018).

Y. Luo, G. D. Shepard, J. V. Ardelean, D. A. Rhodes, B. Kim, K. Barmak, J. C. Hone, and S. Strauf, “Deterministic coupling of site-controlled quantum emitters in monolayer WSe2 to plasmonic nanocavities,” Nature Nanotechnology 13, 1137–1142 (2018).

N. V. Proscia, R. J. Collison, C. A. Meriles, and V. M. Menon, “Coupling of deterministically activated quantum emitters in hexagonal boron nitride to plasmonic surface lattice resonances,” Nanophotonics 8, 2057 – 2064 (2019).

T. Cai, S. Dutta, S. Aghaeimeibodi, Z. Yang, S. Nah, J. T. Fourkas, and E. Waks, “Coupling Emission from Single Localized Defects in Two-Dimensional Semiconductor to Surface Plasmon Polaritons,” Nano Letters 17, 6564–6568 (2017).

S. Dutta, T. Cai, M. A. Buyukkaya, S. Barik, S. Aghaeimeibodi, and E. Waks, “Coupling quantum emitters in WSe2 monolayers to a metal-insulator-metal waveguide,” Applied Physics Letters
F. Peyskens, C. Chakraborty, M. Muneeb, D. Van Thourhout, and D. Englund, “Integration of single photon emitters in 2D layered materials with a silicon nitride photonic chip,” Nature Communications 10, 4435 (2019).

D. White, A. Branny, R. J. Chapman, R. Picard, M. Brotons-Gisbert, A. Boes, A. Peruzzo, C. Bonato, and B. D. Gerardot, “Atomically-thin quantum dots integrated with lithium niobate photonic chips (Invited),” Opt. Mater. Express 9, 441–448 (2019).