Diamond as a Platform for Integrated Quantum Photonics

Francesco Lenzini, Nico Gruhler, Nicolai Walter, and Wolfram H. P. Pernice*

1. Introduction

Integrated quantum photonics enables the generation, manipulation, and detection of quantum states of light in miniaturized waveguide circuits. Implementation of these three operations in a single integrated platform is a crucial step toward a fully scalable approach to quantum photonic technologies. In this context, diamond has emerged as a particularly promising material as it naturally combines a large transparency range for the fabrication of low-loss photonic circuits, and a variety of optically active defects for the realization of efficient single-photon emitters. Furthermore, its high Young’s modulus makes it ideal for the implementation of tunable optomechanical devices for active quantum state manipulation. This review reports recent progress on the realization of the main components required for a diamond-based integrated quantum photonic architecture: single-photon emitters, static and actively tunable waveguide circuits, and, as a last building block, integrated superconducting single-photon detectors.

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1. Introduction

Integrated photonics has emerged as a leading platform for optical quantum technologies[1,2] including secure quantum communication,[3] enhanced quantum sensing,[4] and quantum information processing.[5] Implementation of linear optical circuits in lithographically patterned waveguides has offered a scalable approach for the manipulation of quantum states of light,[6] as well as an improvement in the fidelity of quantum operation thanks to an augmented stability and overlap between interacting modes in interferometric processes.[7] Furthermore, integrated optics provides a scalable way for the generation of nonclassical light[8] and its characterization on chip using integrated single-photon detectors.[9] Integration of these three classes of devices on a common platform enables a continuous increase in complexity of quantum photonic circuits,[10,11] and enhances the stability and scalability of quantum photonic technologies. A key question to date is the selection of an optimal material platform for this endeavor. Among the many different options diamond offers significant advantages which have contributed to the attractiveness of this material choice and are thus the subject of this review.

Diamond exhibits an outstanding combination of optical and mechanical properties, which makes it a promising platform for integrated photonic circuits and especially quantum information technologies. Many applications have been enabled by the ongoing progress in the synthesis and processing of chemical vapor deposition (CVD) diamond, which provides a material platform of high quality with reproducible properties.[12] A large refractive index and a wide transparency window are essential properties which make diamond an attractive candidate as a basic material platform for integrated photonic circuits. The refractive index of around 2.4 in the visible and near-infrared (NIR) spectral regime provides a large index contrast to surrounding optical buffer layers and enables tight light confinement in diamond waveguides.[13,14]

A large bandgap of 5.5 eV gives rise to a transmission window starting in the ultraviolet (UV) and stretching to the very far infrared.[15–17] The large bandgap also prevents two-photon absorption even in the visible and NIR regime. Furthermore, its high thermal conductivity and low thermo-optic coefficient allows to use extreme levels of optical power.[18] In combination with a relatively high nonlinear refractive index[19,20] (n2 = 1.3 × 10−19 m2/W−1 for visible wavelengths) this also renders diamond an attractive platform for nonlinear optics.[21–23]

Additionally, optically active defect centers attract intense research attention. Currently there are over 500 so-called color centers known in diamond with their emission wavelengths covering a wide range from the UV to NIR region.[24] Color centers can exhibit highly stable fluorescence of single photons and supply a controllable coherent electron spin.[25,26] Color centers in diamond, such as the nitrogen- or silicon-vacancy center (NV, SiV), are of particular interest as they are long-term stable and a low density of phonon states (diamond provides the highest Debye temperature of ~2000K) causes low electron–phonon coupling, which makes their usage viable even under ambient conditions.[27–29] By combining color centers with nanophotonic circuits, diamond can provide a single material platform for quantum photonic applications.

Besides its versatile optical properties, diamond also offers outstanding mechanical properties, in particular an exceptionally high Young’s modulus of 1100 GPa. Together with low thermelastic dissipation due to its high thermal conductivity,[30] this enables mechanical resonators operating at high frequencies without suffering from significant damping.[31–33] In particular, for high precision sensing applications this is of utmost interest.[34,35] Moreover, joining optical and mechanical elements in one device enables tunable parts in integrated photonic circuits by using opto-mechanical components. Based on the
displacement of a movable strip next to a waveguide the effective refractive index of the waveguide mode is altered and a phase shift is induced.\cite{36,37} Such phase shifters are an additional essential element for the development of diamond-based quantum photonic circuits.\cite{3,38}

As a final building block, superconducting films can be deposited on top of diamond waveguides and used for the realization of integrated superconducting nanowire single-photon detectors (SNSPDs).\cite{39} Combined with the above mentioned devices, this provides a complete toolbox for a diamond-based integrated quantum photonic architecture. The current progress in the development of all the contributing components is discussed in this review article.

The review is structured as follows: in Sections 2 and 3 we introduce single-photon emitters based on diamond defects and discuss different approaches for their coupling to photonic structures; in Sections 4 and 5 we describe static and actively tunable optical circuits and currently employed fabrication methods; finally, in Section 6 we discuss the performance of single-photon detectors integrated with diamond waveguides.

2. Single-Photon Emitters in Diamond

Optically active defects in diamond, commonly referred to as color centers, have attracted increasing attention from the quantum optics community in the last two decades. Color centers are defects of the diamond crystal structure consisting in a vacancy of the carbon lattice coupled with an adjacent non-carbon atom.\cite{24} Such modifications of the crystal lattice induce the creation of localized energy states in the band structure of the material which, effectively, act as isolated artificial atoms embedded in a solid state system.

More than 500 color centers have been identified in diamond, and more than ten have demonstrated single-photon emission.\cite{65} Remarkably, these systems show stable photo-emission even at room temperature and, due to the extremely high Debye temperature of diamond, a low probability for phonon-induced dephasing and phonon-assisted emission. Thus, color centers have emerged as unique candidates for the implementation of solid-state single-photon emitters without need for cryogenic operation.\cite{25,66}

Additional interest in color centers stems from the availability of optically addressable electronic and nuclear spin states with long coherence times even at room temperature.\cite{67-69} Notably, this has enabled the use of color centers as quantum memories for the realization of quantum networks mediated by spin-photon entanglement,\cite{70-74} and holds promise for the realization of solid-state quantum registers for quantum information processing.\cite{75,76} A comprehensive discussion on diamond spins and their entanglement to photons for quantum computing and quantum networks can be found in two excellent review articles (see ref. [77,78]).

In this section we focus on the properties of color centers as single-photon emitters and describe recent progress in their realization. Table 1 summarizes the performance of diamond-based single-photon sources and provides a comparison with various other platforms.

2.1. NV Centers

The negatively charged NV center has been the first and most extensively studied color center for the realization of single-photon sources.\cite{25,66} NV centers occur natively in bulk diamond, homoepitaxially grown diamond, and diamond nanocrystals, with a density which is low enough to isolate single-photon emitters.
Native NV centers have been the most widely used system for carrying out quantum photonic experiments with diamond in early years. More recently major effort has been devoted to their artificial generation for deterministic placement inside photonic structures, a crucial step toward the development of a fully scalable platform for diamond quantum photonics.

Implantation with focused ion beams has been the first studied technology, and enabled maskless positioning of NV centers with a precision better than 100 nm. A further enhancement in spatial resolution can be obtained by irradiating a nanoscopic hole in an atomic force microscope tip, with a positioning accuracy of up to ±25 nm. After annealing treatment, NV centers generated by ion implantation have shown high coherence properties with near lifetime-limited optical transitions.

Placement of NV centers inside non-diamond photonic structures, as required for the assembly of hybrid photonic architectures, is achieved by picking and placing pre-characterized diamond nanocrystals containing a single defect. This can be accomplished by the use of a nanomanipulator in a scanning electron microscope or with the aid of an atomic force microscope tip. Although these techniques can achieve near-deterministic positioning with nanometer-scale precision, nanodiamonds with diameter smaller than 100 nm are often affected by deteriorated optical coherence properties as well as “blinking” (luminescence intermittency) behavior and thus require accurate individual screening before assembly.

NV centers are typically excited off resonance with a 532 nm laser light. The emission spectrum of native defects in bulk diamond shows an optical transition centered at a wavelength of 637 nm (ZPL: zero phonon line) with a Fourier transform-limited 13 MHz linewidth—corresponding to a lifetime of 11.5 ns—at a temperature of 4 K. The highest single-photon count rate measured to date from a NV center was reported in ref. [41] using a circular bullseye grating fabricated around a native defect in a diamond membrane. Under continuous excitation, this work reported a single photon count rate up to 4.56 MHz at saturation power with a second-order correlation function $g^{(2)}(0) ≈ 0.3$.

Indistinguishability between single photons emitted from different NV centers is strongly limited by spectral inhomogeneities due to random variations—mainly strain—of the local environment. Emission lines of defects with different spectral properties can be brought into resonance by tuning the frequency of the optical transition via the DC Stark effect, and enabled to achieve a visibility up to 80% for two-photon interference between remote native NV centers.

Table 1. Comparison of the performance of diamond-based single-photon sources with different platforms.

| Source                        | Maximum count rate | Emission efficiency | Lifetime | $g^{(2)}(0)$ | Indistinguishability between different emitters | Ref. |
|-------------------------------|--------------------|---------------------|----------|-------------|-----------------------------------------------|------|
| NV centers                    | 4.56 MHz           | ≈ 18%**             | 1.15 ns  | ≈ 0.1 (low excitation power) ≈ 0.3 (saturation power) | 80% (with electric frequency tuning) | [40–42] |
| SiV centers (single crystalline diamond) | 0.73 MHz           | ≈ 15%               | 1.2–1.7 ns | ≈ 0.1       | 72% (no frequency tuning)                      | [43–46] |
| SiV centers (nanodiamond)     | 6.2 MHz            | ≈ 9%                | 1.2–1.7 ns | 0.05        | N/A                                           | [47–48] |
| GeV centers                   | 0.56 MHz           | ≈ 10%               | 1.4–5.5 ns | 0.08        | N/A                                           | [49–50] |
| Electrically driven NV centers| 0.04 MHz           | N/A                 | 13.2 ns   | 0.45        | N/A                                           | [51] |
| InGaAs/GaAs and InAs/GaAs quantum dots | ≈ 9 MHz           | 65% (NRE)           | 1 ns     | 0.025 (NRE) | 33% (with electric frequency tuning) | [52–55] |
| quantum dots                  |                    |                     |          | 0.0028 (RE) |                                               |      |
| DBT molecules                 | ≈ 1 MHz            | ≈ 20%               | 4–5 ns   | ≈ 0.2       | N/A                                           | [56–58] |
| Carbon nanotubes              | 0.92 MHz           | ≈ 10%               | 0.4 ns   | ≈ 0.03      | N/A                                           | [59–61] |
| Silicon carbide defects       | 4.3 MHz            | N/A                 | 1–4 ns   | ≈ 0.2       | N/A                                           | [62,63] |
| Nonlinear optics (SPDC/SFWM)  | 2.1 MHz            | ≈ 1%**              | 1 ps**   | <0.05**     | 97% (no frequency tuning)                     | [64] |

N/A: not available; NRE: non-resonant excitation; RE: resonant excitation. *Estimated in ref. [40] on a ≥200 nm broad spectrum. For applications requiring pure ZPL emission this value is strongly reduced. ** For SPDC and SFWM, the $g^{(2)}(0)$ value can be made arbitrarily small by reducing the emission efficiency. An emission efficiency <1% is required to get highly pure single-photon emission with a $g^{(2)}(0)$ < 0.05. ***Here defined as the coherence time of the emitted photons. – All the reported count rates are affected by system detection inefficiencies and can be improved by optimizing the experimental setup. Emission efficiency is the probability of emitting one photon in the desired optical mode per excitation. Lifetime is one of the bulk single-photon source without Purcell enhancement. Indistinguishability is the visibility for two-photon interference between different emitters.
Figure 1. Emission spectrum of NV and SiV centers. a) Typical emission spectrum of a NV center at room temperature. Besides the ZPL, a large phonon side-band causes a broad emission spectrum. Reproduced with permission. Copyright 2015, American Physical Society. b) ZPL of SiV centers (left image) and fine structure of the electronic energy levels (right image). \( \Delta_g \approx 50 \text{ GHz} \) and \( \Delta_e \approx 250 \text{ GHz} \) are the fine splitting values of ground and excited energy levels. Reproduced with permission. Copyright 2014, Springer Nature.

A major limitation of single emitters based on NV centers is that, even at cryogenic temperature, they present a broad phonon side-band with only 3% of the total radiation emitted into the ZPL (see Figure 1a).\(^{[97]}\) For applications requiring high indistinguishability of the emitted photons this strongly reduces the maximum attainable brightness. Although this problem can be overcome by the use of optical microcavities (see Section 2.4), this has motivated the study of alternative active defects—most prominently SiV centers—with different optical properties.

2.2. SiV Centers

The negatively charged SiV center has emerged as an ideal candidate for the realization of diamond-based single photon sources thanks to its outstanding optical properties. Unlike NV centers, even at room temperature more than 70% of the radiated light is emitted into the ZPL.\(^{[47]}\) Furthermore, the electronic structure of SiV centers possesses an inversion symmetry which, at cryogenic temperatures, protects their optical transitions from charge noise and prevents them from spectral diffusion.\(^{[98]}\) This has enabled to measure a spectral overlap between different emitters larger than 90%,\(^{[43]}\) and to observe two-photon interference between remote SiV centers with a 72% visibility without any need for frequency tuning.\(^{[44]}\) An additional advantage SiV defects emit almost completely polarized light,\(^{[99]}\) an important requirement for several quantum computing and communication protocols.

SiV centers occur very rarely in natural diamond, and are usually incorporated by in situ doping during CVD growth.\(^{[47,99,100]}\) Focused ion beams can also be employed for their artificial creation,\(^{[101,102]}\) and recently enabled the generation of high quality defects with nearly lifetime-limited optical transitions, <50 nm position accuracy, and a \( \approx 2.5\% \) fabrication yield.\(^{[102]}\) An additional increase by one order of magnitude in fabrication yield was reported in this same work after electron beam irradiation.

The ZPL of SiV centers is split into four distinct emission lines centered at a wavelength of \( \approx 737 \text{ nm} \) (see Figure 1b), which are commonly attributed to the fine structure of the electronic energy levels.\(^{[103]}\) At a temperature of 4 K, \( \approx 70\% \) of the total light emitted into the ZPL is contained in the C line. For SiV centers generated by in situ doping\(^{[48]}\) or ion implantation\(^{[102]}\) in single crystalline CVD diamond, this transition shows a 1.7 ns lifetime with a \( \approx 130 \text{ MHz} \) linewidth, which is equal to \( \approx 1.4 \) times the Fourier transform-limited value.

The brightest diamond-based single-photon sources reported to date have been obtained using SiV centers in CVD grown nanodiamonds (NDs) and nanoislands (NIs) on iridium films.\(^{[47,48]}\) These systems have shown single photon count rates up to 6.2 MHz under continuous excitation, with a \( g(2)(0) \approx 0.1 \) even at saturation power.\(^{[48]}\) However, defects in NDs and NIs are affected by high levels of strain, which broaden their transitions and limit their indistinguishability.\(^{[48]}\) On the other hand, defects in single crystalline diamond show a reduced brightness (maximum count rates of \( \approx 700 \text{ kHz} \)) despite their excellent optical coherence properties. As the excited state lifetime shows a strong dependence to temperature variations, this is likely due to the presence of thermally activated non-radiative decay paths. Individuation of single emitters combining high levels of brightness and indistinguishability is thus an open problem which requires further study.

2.3. Other Color Centers

Besides NV and SiV centers, different diamond defects have demonstrated single-photon emission in a broad range of wavelengths spanning from the UV\(^{[106]}\) to the NIR\(^{[107]}\) region. In particular, nickel\(^{[107]}\) and chromium\(^{[108]}\) related centers and, more recently, the negatively charged germanium vacancy (GeV) center,\(^{[49,109]}\) have been identified as promising single-photon emitters thanks to their weak coupling with phonons and strong ZPLs.

The NE8 color center, consisting of one Ni atom surrounded by four N atoms, is the only Ni-related defect known to exhibit single-photon emission. Approximately 70% of the radiated light is concentrated in the ZPL, which shows a narrow peak with 1.2 nm linewidth centered at a wavelength of \( \approx 800 \text{ nm} \).\(^{[107]}\)
Cr-related centers, instead, display single-photon emission in a broad range of wavelengths spanning from 740 to 770 nm, with excited states lifetime in the range of 1–14 ns.\(^\text{[108]}\)

NEB and Cr-related defects have shown quantum efficiencies comparable to NV and SiV centers, with measured single-photon count rates exceeding 1 MHz for both systems.\(^\text{[107,108]}\) A common problem of these defects is the lack of efficient techniques for their generation by ion implantation, which are affected by extremely low fabrication yields\(^\text{[110,111]}\) and limit their usability in combination with photonics structures.

The GeV center has been identified as a new optically active defect in diamond only in recent years.\(^\text{[49,109]}\) Interestingly, the electronic structure of this defect possesses an inversion symmetry similar to the one of SiV centers,\(^\text{[49]}\) making it a promising candidate for the realization of highly indistinguishable single-photon emitters.\(^\text{[45]}\)

The ZPL of GeV centers displays a maximum centered at a wavelength of \(\approx 602\, \text{nm}\), containing approximately 60\% of the total emitted light, with an excited state lifetime estimated in the range of 1.4–5.5 ns.\(^\text{[49]}\) GeV centers have been successfully generated in single crystalline diamond by both microwave plasma CVD and ion implantation techniques.\(^\text{[49,30]}\) Recently, a single-photon count rate up to 0.56 MHz, with a \(g^{(2)}(0) = 0.08\), has been measured from a GeV center coupled to a nanoscale diamond waveguide.\(^\text{[50]}\) This work also reported a negligible dependence of the GeV excited lifetime to temperature variations, indicating the absence of thermally activated non-radiative decay paths. This gives strong evidence that GeV centers should possess a much higher quantum efficiency than the one obtained for SiV defects in single crystalline diamond.\(^\text{[43]}\)

Other defects which received recent attention are the tin vacancy (SnV) color center (emission wavelength \(\approx 620\, \text{nm}\)),\(^\text{[112]}\) the neutral SiV\(^0\) center (emission wavelength \(\approx 950\, \text{nm}\)),\(^\text{[113]}\) and Pb-related color centers (emission wavelength \(\approx 520–560\, \text{nm}\)).\(^\text{[114,115]}\) Particular interest in these defects stems from the fact that they are expected to possess all the favorable optical properties of negative SiV and GeV centers because of the equivalent inversion symmetry of their electronic structures but much longer spin coherence times (with an electronic spin coherence time \(\approx 1\, \text{ms}\) already measured for the SiV\(^+\) center\(^\text{[113]}\)), making them attractive candidates for the realization of long-distance quantum networks.

### 2.4. Electrically Driven Single-Photon Emitters

One of the main challenges for monolithically integrated quantum photonics technologies is that, when optically exciting a single-photon emitter, the pump light needs to be efficiently filtered out on chip. Because the pump light is many orders of magnitude brighter than the single-photon emitter, optical filtering needs to deliver typically \(\approx 100\, \text{dB}\) suppression while introducing minimal losses on the emitted photons.\(^\text{[116,117]}\) Electrically driven single-photon emitters, first demonstrated for quantum dot sources,\(^\text{[118]}\) can overcome the problem of pump filtering in integrated optics. Furthermore, they eliminate the need of external pump sources and enhance the scalability of quantum photonics circuits.

p-i-n diodes can be fabricated in single crystalline diamond by boron and phosphorus doping during CVD growth, and have been first investigated for the realization of UV-light emitting devices taking advantage of the large (\(\approx 5.5\, \text{eV}\)) diamond bandgap.\(^\text{[119,120]}\) Fabrication of p-i-n diodes around active defects was first demonstrated in ref. \([121]\) for the Xe color center, and later on, for NV centers generated by nitrogen doping\(^\text{[51]}\) or ion implantation\(^\text{[122]}\) in the intrinsic region (see Figure 2). Both groups observed electroluminescence only from neutral NV centers with sub-Poissonian light statistics, demonstrating electrically driven single-photon emission from a diamond defect for the first time.

Reference \([51]\) reported a single-photon count rate up to \(\approx 40\, \text{kHz}\) for a 14 mA injection current, with a \(g^{(2)}(0) = 0.45\). Importantly, this work confirmed that single-photon emission was caused by electron-hole recombination at the defect and excluded the possibility of electroluminescence caused by absorption of photons generated by surrounding impurities.

Electroluminescence from diamond defects has been also demonstrated for negatively charged SiV centers generated by ion implantation\(^\text{[123]}\) or silicon doping\(^\text{[124]}\) in the intrinsic region. Although these works did not report actual single-photon emission, count rates up to 4 kHz were obtained for a 2.5 mA injection current.\(^\text{[123]}\)

Diamond-based electrically driven single-photon emitters are currently affected by low count rates and large spectral shifts due to instability of the charge state during emission.\(^\text{[125]}\) A further challenge is achieving precise charge recombination only at defect location, which otherwise results in large background emission from surrounding impurities and high \(g^{(2)}(0)\) values. As the electroluminescence mechanism of color centers has not been yet fully elucidated, further theoretical research is on the way\(^\text{[126,127]}\) and holds promise for improving their performance in the near future.

### 3. Coupling Color Centers to Photonic Structures

Coupling of color centers to photonic structures has been first employed to enhance the collection efficiency of the radiated light to free-space optics, which, for defects in bulk diamond, is strongly limited by the steep (\(\approx 25^\circ\)) total internal reflection angle of the diamond–air interface. Different photonic structures, including solid immersion lenses, nanopillars,\(^\text{[130,131]}\) and circular bullseye gratings\(^\text{[41]}\) have been investigated, providing up to a 15-fold enhancement in the detection rate.\(^\text{[41]}\)

Of particular interest for this review is the coupling of color centers to optical cavities and waveguides monolithically integrated in diamond, whose fabrication method will be described in detail in Section 4. Hybrid architectures, where color centers are integrated with non-diamond photonic structures, are briefly discussed in Section 3.2.

### 3.1. Coupling to Diamond Photonic Structures

Coupling of NV centers to optical cavities is necessary in order to enhance their emission rate into the ZPL via the Purcell effect.\(^\text{[97]}\)
It has been theoretically demonstrated that, by the use of high-Q resonators, NV centers can potentially achieve pure ZPL emission with a near-unity efficiency and an excited state lifetime smaller than 100 ps.\cite{132} A useful figure of merit is the Purcell factor $F_P$, defined as the enhancement in emission rate induced by the cavity structure. In the case of an emission dipole perfectly aligned and in resonance with the cavity field mode, this factor is given by the relation\cite{133}

$$F_P = \frac{3}{4\pi^2} \left( \frac{\lambda}{n} \right)^2 \frac{Q}{V} \tag{1}$$

where $V$ is the modal volume, $n$ is the effective index, and $Q$ is the cavity quality factor.

Planar photonic crystal cavities, thanks to their small volume, have enabled the highest Purcell enhancement reported to date for NV centers (see Figure 3c,d). A record Purcell factor $F_P = 70$, corresponding to $\approx 70\%$ of the total photons emitted in the ZPL, was reported in ref. [134] using a planar cavity fabricated around a native defect. Waveguide-based optical cavities, including microring resonators\cite{133,135} and 1D photonic crystal (nanobeam) cavities\cite{136,137} have been also investigated (see Figure 3a,b,e). The latter systems have enabled to obtain a Purcell enhancement factor $F_P = 62$,\cite{137} corresponding to more than 50% of the radiated field emitted into the ZPL, which is comparable to the best value reported for planar cavities.

The achievement of higher Purcell factors is currently limited by difficulties in obtaining perfect alignment between the emission dipole of NV centers and the cavity field mode. All the experiments reported so far were performed in (100)-oriented diamond, the most commonly used crystal axis, where NV centers display a random orientation. A promising approach is the fabrication of photonic structures in CVD grown (111)-oriented diamond, already reported for nanopillars,\cite{138} where NV centers have shown almost perfect ($\approx 95\%$) preferential orientation.\cite{139,140}

While all the experiments described above made use of photonic structures fabricated around native defects, ref. [141] recently demonstrated coupling of an ion implanted NV center to a 1D photonic crystal cavity. To achieve precise positioning of the defect in the center of the cavity, this work made use of the same lithography mask for targeted nitrogen ion implantation and dry etching of photonic structures. An enhancement in the ZPL intensity up to a factor $\approx 5$ was reported, which is close to the values obtained using native NV centers.

Another route was recently reported using deterministic positioning of a laser-written NV center inside a buried waveguide generated by laser writing in bulk diamond.\cite{142} However, the large mismatch between waveguide mode ($\approx 5.8 \mu m$) and the focused laser excitation spot ($\approx 0.6 \mu m$) on the NV center limited the measured count rate to $\approx 10$ counts per second.

While SiV centers already naturally emit a large portion of the radiated light into the ZPL, coupling to optical cavities can be employed to improve their quantum efficiency by enhancing their emission rate and reducing the probability of non-radiative decays.\cite{134} Purcell enhancement experiments have been demonstrated using either photonic structures fabricated around defects generated by in situ doping,\cite{46,141,144} or SiV centers generated by focused ion beams in the center of the cavity.\cite{100,145} A record Purcell factor $F_P \approx 26$, corresponding to a 42-fold enhancement in emission intensity, has been recently reported in ref. [46] using a 1D photonic crystal cavity.

For GeV centers, coupling of ion implanted defects to photonic structures has been recently demonstrated using a nanoscale diamond waveguide with a partially reflective Bragg mirror.\cite{96} Remarkably, this work estimated a probability of emitting one photon into the waveguide per excitation equal to at least 10%, enabled by the large overlap of the defect’s cross section with the waveguide mode ($\approx 400 nm$) as well as the high quantum efficiency of this single emitter.

We conclude remarking that, as preliminary demonstrated for SiV and GeV centers,\cite{50,145} coupling diamond defects to integrated circuits is also a promising path for achieving strong light–matter interaction at the single photon level. In the future this technique may be employed for the implementation of deterministic two-photon gates for optical quantum computing as well as for the realization of scalable quantum networks.\cite{146}

Figure 2. Electrically driven neutral NV center. a) Schematic picture of a p-i-n diode fabricated in single crystalline diamond. b) Measured $g^{(2)}(\tau)$ from an electrically driven neutral NV center. Reproduced with permission.\cite{51} Copyright 2012, Springer Nature.

3.2. Hybrid Architectures

Instead of using monolithic all-diamond platforms, hybrid systems consisting of diamond and a different material have been explored for the implementation of integrated quantum photonic circuits. The advantage of such a hybrid system is that diamond
Figure 3. Color centers coupled to different photonic structures. a) SEM images of a microdisk resonator used for Purcell enhancement of NV centers. b) Scheme for laser excitation and fluorescence collection. (a,b) Reproduced under the terms of a Creative Commons Attribution 3.0 Unported licence. Copyright 2013. c) SEM image of a planar photonic crystal cavity used for Purcell enhancement of SiV centers. d) SEM image of a planar photonic crystal cavity overlapped with the fluorescence scan of SiV centers. e) SEM images of a nanobeam cavity used for Purcell enhancement of SiV centers. (c–e) Reproduced with permission. Copyright 2011, Springer Nature.

can be used for single-photon generation exploiting a plethora of color centers while established photonic platforms can be employed for the routing of light, thus playing the strengths of both systems.  

One system which received particular attention is gallium phosphide bonded to a diamond substrate (GaP-on-diamond). GaP as a photonic platform has several attracting features: GaP provides a higher refractive index compared to diamond thus enabling waveguiding in the GaP layer. GaP features electro-optic properties which enable optical on-chip modulation and well-established fabrication processes allowing wafer-scale processing with a high yield. Based on the GaP-on-diamond hybrid system, coupling of NV centers to waveguides and to optical resonators has been demonstrated. An integrated system combining waveguide-coupled microdisk resonators and grating couplers to couple out photons from NV centers have been published, demonstrating the potential of this hybrid platform for quantum communication applications (see Figure 4a,b).

Hybrid systems based on the silicon nitride (SiN) platform have also been proposed. SiN features a large bandgap, allowing operation in the emission wavelength of color centers, with a fabrication process compatible with silicon nanofabrication processes. Deterministic coupling of a single nanodiamond to an integrated SiN cavity was first demonstrated in ref. 154 by the use of a pick-and-place technique. A further enhancement in coupling efficiency was demonstrated in ref. 155 by placing a tapered diamond microwaveguide containing a single NV center over an integrated SiN cavity. To this end a novel pick-and-place technique was applied, which allowed the pre-characterization of the color center and a deterministic integration into the desired structure (see Figure 5c,d). A drawback of the SiN material system is strong fluorescence emission in the visible wavelength range which is excited during optical pumping.

Another system which can be combined with diamond is aluminum nitride (AlN). AlN features a large band-gap and thus a transparency window starting in the UV, as well as optical nonlinear and piezoelectric properties. This allows to create active components (see Section 5) which makes this hybrid system an attractive alternative to all-diamond photonic platforms.

4. Fabrication of Integrated Photonic Circuits

Mainly two types of diamond platforms are in use for realizing nanophotonic circuits. On the one hand there is bulk single crystalline diamond (SCD), typically offering a high material quality
Figure 4. Examples of various hybrid architectures. a, b) Integrated GaP-on-diamond devices. a) Schematic for the collection of the ZPL of one NV center using a grating coupler and a waveguide coupled microdisk resonator. b) SEM image of waveguide coupled microdisk resonators. (a, b) Reproduced with permission.\textsuperscript{[152]} Copyright 2016, American Physical Society. c–f) Silicon nitride–diamond hybrid system. c) Schematic of device geometry showing a diamond microcavity containing a single NV center bridging a SiN waveguide. d) Cross section and FDTD simulated electrical field transferred from the diamond waveguide mode to the SiN waveguide. e) SEM image of a diamond microcavity (μWG) bridging a silicon nitride waveguide. f) Confocal photoluminescence map of the diamond waveguide showing the NV center emission. (c–f) Reproduced under the terms of a Creative Commons Attribution 3.0 Unported licence.\textsuperscript{[155]} Copyright 2015.

Figure 5. Passive integrated devices implemented on a diamond platform. In a–c) devices fabricated by angled reactive ion etching are shown: a) Racetrack resonator; b) 1D nanobeam and its triangular cross section c) obtained by the angled etching. In d) a part of a photonic crystal cavity is presented, which is directly carved from a SCD slab by FIB milling. e) On the left side the output facet of a type II waveguide fabricated by DLW with femtosecond pulses in a bulk SCD slab is shown. On the right side the near-field mode obtained from this facet is shown. f) A focusing grating coupler is used for out-of-plane access to a circuit. g) Optical micrograph of some directional couplers with the SEM inset showing the start of the coupler region. EBL and dry etching are used for structuring of devices in (f) on PCD and in (g) on thinned down SCD. (a) Reproduced under the terms of a Creative Commons Attribution 4.0 International licence.\textsuperscript{[176]} Copyright 2017. (b, c) Reproduced with permission.\textsuperscript{[175]} Copyright 2012, American Chemical Society. (d) Reproduced with permission.\textsuperscript{[179]} Copyright 2011, Elsevier. (e) Reproduced with permission.\textsuperscript{[183]} Copyright 2016, AIP Publishing. (g) Reproduced with permission.\textsuperscript{[191]} Copyright 2018, IEEE.
at the cost of more challenging fabrication procedures. On the other hand, there is polycrystalline diamond (PCD) with a better availability of wafer-scale thin films for easier nanofabrication processes. Because SCD has to be grown on existing SCD template, no wafer-scale substrates with thin SCD films are currently available. Thus, instead thick slabs of SCD are obtained with a limited size of typically below 1 cm² and more advanced transfer and etching methods have to be applied for the fabrication of integrated circuits. On the other hand, in SCD high material quality can be achieved with, for example, a low concentration of color centers and a low background fluorescence.\cite{51, 160}

Even though most of the outstanding properties of diamond are preserved for the polycrystalline case, the transparency range and the thermal conductivity are reduced because of the grain boundaries, which incorporate sp²-carbon and additional dopants.\cite{18, 24} The grain boundaries also contribute to additional scattering losses, and impurities as well as induced strain deteriorates the color center properties.\cite{17} Nevertheless, in contrast to bulk SCD slabs, thin PCD films can be grown by CVD on different insulating substrates such as SiO₂ and thereby provide a fabrication friendly platform for large-area circuits.\cite{161}

In order to fabricate integrated optical devices and circuits from diamond a wide range of different methods are employed depending on the specific material platform. Especially the fabrication of rather thin nanophotonic devices from bulk SCD slabs led to the development of many different strategies varying in their complexity. These methods as well as the comparatively simple fabrication of devices from PCD are discussed in the next section.

### 4.1. SCD Nanophotonic Fabrication

There are mainly two approaches for structuring photonic components from bulk diamond: i) either a thin diamond film or membrane is obtained from a thick diamond piece and subsequently processed or ii) structures are directly carved out from bulk diamond.

In order to realize thin SCD films different methods are employed. The thin down approach uses dry etching to reduce the thickness of a diamond piece from tens of microns to some hundreds of nanometers, but is often limited in size or suffers from thickness variations of the bulk slab, which requires further precautions.\cite{162–166} The challenge of thickness variations can be avoided by using a lift-off procedure in which a damaged layer is implanted in diamond by ion irradiation. This layer graphitizes during an annealing step and can be selectively removed via wet etching.\cite{165–167} As crystal damage is inevitably caused in the membrane, additional diamond overgrowth is used and the damaged layer is removed in a dry etching step.\cite{168–170} One alternative could be heteroepitaxial growth of diamond that can lose its polycrystalline character within a few to tens microns due to a high density and initial alignment of the diamond nucleation on specific substrates.\cite{171, 172} A thin film is then obtained by removing the substrate and buffer layers, followed by dry etching the PCD backside.\cite{141} In general, such thin SCD membranes can subsequently be processed by electron beam lithography (EBL) or ion milling methods. Alternatively, in order to avoid the exposure and potential spin-coating of, for example, very small samples, a pre-patterned transferable silicon mask can be directly used as an etching mask for structuring thin as well as bulk diamond samples.\cite{117, 173, 174}

By using an etching mask, bulk diamond is structured in the following way. In the angle etching technique an angled anisotropic dry etching step is used for creating triangular freestanding devices.\cite{173, 175, 176} Opposed to this, vertical side walls can be maintained by using the undercut etching procedure. First, an anisotropic plasma etching step is used followed by a Si₃N₄ protecting coating and a quasi-isotropic reactive ion etching undercut.\cite{177, 178} A racetrack resonator and a nanobeam (including its cross section) made with this fabrication method are shown in Figure 5a–c. Without the need for generating a mask, focused ion beam (FIB) milling using typically Ga⁺-ions allows for directly cutting and structuring any given material including diamond.\cite{179, 180} However, the scalability of the progress is limited and the material is damaged during structuring. Future direct patterning by electron-beam induced etching (EBIE) might circumvent this issue.\cite{181–183} A part of a photonic crystal cavity fabricated by ion milling is presented in Figure 5d.

Recently, a further promising structuring method emerged without using material ablation. By direct laser writing (DLW) ultrashort laser pulses are used to modify the material. Thus in diamond the lattice is damaged yielding a slightly decreased refractive index, which can be used for writing buried 3D waveguides in bulk SCD slabs (see also Figure 5e).\cite{184–186} This method also brings the advantage of generating and coupling to color centers in diamond as outlined above.

### 4.2. PCD Nanophotonic Fabrication

Differing from SCD, wafer-scale availability of thin film polished PCD \cite{187, 188} makes this material very fabrication friendly in terms of available methods and scalability. Only standard lithography, dry and wet etching fabrication techniques are required to structure full photonic circuits from PCD.\cite{161} Also further progress in high purity diamond deposition might enhance the PCD quality in terms of transparency and, for example, for the incorporation of color centers.\cite{189, 190}

### 4.3. Passive Components

For the realization of full quantum photonic circuits on a diamond platform a toolbox of components is required. The most basic but important building blocks are waveguides required to route light across a chip and connect all devices. Second, waveguide couplers are needed for transferring light into and out of the waveguides in order to connect for example off-chip components such as light sources or detectors, if they are not co-implemented on-chip. These components employ in-plane coupling from a fiber or free space beam to the end facet of a waveguide.\cite{192, 193} Alternatively, out-of-plane coupling can be achieved via reflection at angled total internal reflection mirrors\cite{184} or via tapered fiber coupling.\cite{194} In addition, a very convenient method in terms of simple fabrication and fast out-of-plane access to many different
circuit is the use of grating couplers (see Figure 5f). \[195,196\] Furthermore, beam splitters such as y-splitters\[31,185\] and directional couplers (see Figure 5g)\[191\] are implemented as a basic part for Mach–Zehnder interferometers and quantum photonic circuits.

Additional essential devices are optical resonators or cavities. Especially in the case of color centers in diamond, they play an important role for the Purcell enhancement of the photon emission,[46,143,197] but are also used as narrow-band filters, for signal routing and waveguide characterization. A wide range of cavities are in use which are characterized by their optical quality factor (Q-factor). These include 1D photonic crystal cavities (highest Q up to 9900 (18 300) in the visible (NIR) regime for SCD),\[137,194\] 2D PhC (highest Q up to 4700 in the visible regime for SCD and up to 600 (6500) for PC in the visible (NIR) regime),\[165,174,198,199\] disk resonators (highest Q up to 3000 (115 000) in the visible (NIR) regime for SCD),\[165,178,198,199\] as well as ring and racetrack resonators (highest Q up to 59 000 (1 000 000) in the visible (NIR) regime for SCD and up to 30 000 for PC in the NIR).\[22,176,194,200\] A selection of passive devices fabricated by a variety of different techniques is presented in Figure 5, including a racetrack resonator in a) and part of a photonic crystal cavity in d). These integrated photonic diamond circuits can also be compared in terms of their respective propagation losses. Waveguides fabricated in PCD by DLW with ultrashort pulses exhibit losses of 8–16 dB cm\(^{-1}\) in the visible regime.\[184,185\] By angled dry etching of triangular waveguides in PCD an attenuation of 1.5 dB cm\(^{-1}\) was achieved for near-IR wavelengths.\[194\] Very low losses of down to 0.3–0.6 dB cm\(^{-1}\) were accomplished also in the near-IR regime using a thin down approach of bulk SCD slabs to thin membranes.\[22,196\] In PCD waveguides with near-IR propagation losses down to 4 dB mm\(^{-1}\) were achieved using standard EBL and dry etching procedures\[201\] and the circuit quality was further improved by reactive ion beam angled etching.\[176\]

Besides the above discussed performance of diamond integrated photonic structures in the visible and NIR regime, the large transparency window of diamond also opens the door to mid- and long-wavelength infrared devices for sensing applications in the very interesting fingerprint region of many molecules, illustrating the versatile application opportunities of diamond photonic circuits.\[193,202,203\]

5. Active Components

In addition to the passive devices reported in the previous section, active components are required to tune the optical properties of integrated quantum photonic circuits after their fabrication. For applications where quantum interference from different single-photon emitters is used, it is of paramount importance to achieve high emission efficiency from each single-photon emitter while overlapping all their emission wavelengths to make the photons indistinguishable. The emission efficiency can be boosted via Purcell enhancement by coupling the emitter to an optical cavity. Unfortunately, fabrication inhomogeneities across a chip make it difficult to fabricate cavities with exactly the same resonance wavelength. Therefore, techniques are required to actively tune the resonances of individual cavities to match each other. The same holds for the light emitters. The wavelengths of single photons emitted from different color centers differ because of variations in slightly different electric environments. In order to increase the indistinguishability of the emitted photons additional tuning knobs are needed to move each emitter to exactly the same frequency. Importantly, active tuning is also required to change the functionality of an integrated circuit, for example, for controlling the routing of single photons through the chip or to perform reconfigurable linear optical operations on quantum states of light.

In order to achieve active control of cavities or light routing on chip, the effective refractive mode index has to be locally altered in a controllable way. In semiconducting materials such as SOI or GaAs systems this can be done by free-carrier injection, for example, electrically\[204\] or by two-photon absorption.\[205\] However, this approach is not viable in diamond because of its large bandgap. Furthermore, injection of free carriers would also perturb the charge state of color centers.

In diamond devices methods based on gas adsorption to shift the resonance to higher wavelengths\[133,137,143\] were demonstrated. Other approaches, albeit non-volatile, use the deposition and etching of an additional material, for example, HfO\(_2\), to shift the resonance frequency.\[206\] While this is a viable option for one cavity, both methods affect the complete chip and allow no tuning of a specific cavity.

Another approach is to place a resistive heater in the vicinity of a device and use the temperature-dependence of the refractive index for local tuning.\[207–209\] This technique has enabled the realization of reconfigurable circuits on several material platforms\[210–212\] but comes with the disadvantage of thermal cross talk and large power dissipation (approximately 10 mW for a π-phase shift\[207\]). Both limit the integration density while the latter also interferes with the operation of cryogenic devices such as integrated superconducting single-photon detectors.

An alternative way to actively tune the effective index of a waveguide relies on electro-mechanical tuning.\[36\] The effective refractive index can be locally altered by bringing a movable arm in the vicinity of the waveguide (see Figure 6). Depending on the material system, the actuation of the moving arm can be achieved by electrostatic forces\[36,213–215\]—for all-diamond photonic platforms—or by the piezoelectric effect\[159,216\]—for hybrid AlN/diamond systems.

For all-diamond photonic platforms, electro-mechanical tuning is an essential feature for the realization of variable phase-shifters. Such a phase shifter can be used in a Mach–Zehnder interferometer configuration to switch between constructive interference (transmission) and destructive interference (reflection) at the output, thus enabling the routing of light inside a waveguide network.\[217\] or for the implementation of arbitrary linear optics transformations for photonic quantum information processing.\[6,218\] The experimental implementation of an optical-mechanical phase shifter was demonstrated in ref.\[37\] on a diamond on insulator platform (see Figure 6), providing an additional important building block for a diamond-based integrated quantum photonic architecture. Thanks to the high Young’s module of diamond, excitation of mechanical modes with mechanical resonance frequency up to 115 MHz was reported, demonstrating the potential of this material platform for fast routing applications.\[219,220\]

Electro-mechanical tuning can also be employed to change the resonance of an optical cavity to the desired wavelength. A design
for an electro-mechanically tunable optical cavity was recently proposed in ref. [221] for the hybrid AlN/diamond platform (see Figure 7a–c).

Finally, electro-static tuning can be employed to increase the indistinguishability of single-photon emitters with different spectral properties. The patterning of electrodes around a single emitter makes it possible to compensate for local charge inhomogeneities in the vicinity of the color center by tuning its emission wavelength via the DC Stark effect. Using this technique, dynamic stabilization of the emission wavelength of NV centers in the range of minutes was shown [223] and two-photon interference from two different NV centers [42, 224] was achieved. Electrical tuning and stabilization of NV centers in an integrated optical circuit has been recently demonstrated in ref. [225] on the hybrid GaP-on-diamond photonic platform (see Figure 7d,e).

6. Integrated Single-Photon Detectors

Availability of efficient single-photon detectors is a further essential requirement for the development of optical quantum technologies. For instance, single-photon detectors are needed to measure the state of a photonic qubit in quantum computing and communication protocols, or to take advantage...
of measurement-induced nonlinearities for generation of two-photon entanglement.\textsuperscript{[218]} Typically, such measurements are performed by out-coupling the light from the chip with subsequent detection by an external single-photon detector, for example, an avalanche photodiode (APD). This has several disadvantages such as the introduction of additional losses to the system and the requirement of special coupling structures including gratings, or tapers which limit the scalability of the system.

A straightforward way to circumvent these problems is the integration of detectors directly on chip. SNSPDs\textsuperscript{[226]} patterned on top of optical waveguides have emerged as the technology of choice for the implementation of high performance integrated single-photon detectors featuring detection efficiencies in excess of 90%.\textsuperscript{[9]} Besides their potential for scalability, integrated SNSPDs have shown superior performance over all their competing platforms, including dark-count rates lower than 10 Hz,\textsuperscript{[227]} and GHz count rates at low timing jitter ($\approx 32$ ps).\textsuperscript{[218]}

A typical SNSPD detector is a thin (width $< 100$ nm) nanowire patterned from a superconducting thin film (thickness $\approx 5$ nm). Such a nanowire becomes superconducting if cooled below its critical temperature. For sufficiently narrow wires the absorption of one-single photon leads to the breakdown of the superconducting state, resulting in a voltage spike which can be amplified and detected by counting electronics (see, e.g., ref. \textsuperscript{[229]} for a general review on SNSPDs).

On the diamond platform SNSPDs have been demonstrated based on different superconducting films. Niobium titanium nitride (NbTiN) thin films deposited on a specially polished single crystalline diamond substrate have been reported to show similar performances to other substrate materials.\textsuperscript{[210]} SNSPDs fabricated on top of diamond waveguides (see Figure 8) made from polycrystalline diamond have been demonstrated using niobium nitride (NbN) thin films.\textsuperscript{[19,231]} These detectors showed an on-chip detection efficiency up to $\approx 50\%$, count rates in the MHz regime, and a time jitter $< 30$ ps.\textsuperscript{[231]} Somewhat lower performances compared with state-of-the-art detectors are likely due to surface roughness of the diamond substrate used in the experiment, which reduces the quality of the deposited superconducting film. Nevertheless, these results show that SNSPDs prove a viable option for developing fully integrated quantum photonic circuits based on the diamond platform.

7. Conclusion

Since the first demonstrations of single-photon emission from single NV centers,\textsuperscript{[25,66]} tremendous progress has been made in the field of diamond quantum photonics. Efficient coupling of color centers to integrated optical cavities has been achieved using several photonic structures; low loss static and actively tunable waveguide circuits, as well as integrated single-photon detectors, have been demonstrated, providing a complete toolbox for the development of a diamond-based integrated quantum photonics architecture.

Future challenges toward the realization of fully integrated quantum photonic circuits on a diamond platform will include
the development of efficient techniques for pump filtering in integrated optically pumped color centers, the achievement of high indistinguishability between multiple single-photon emitters coupled to an integrated waveguide network, as well as an improvement in the performance of single-photon detectors by the use of specially polished diamond films. Nevertheless, diamond-based integrated quantum photonics is now a mature technology able to compete with other platforms, such as silicon quantum photonics, which received higher attention in past years. All the necessary components required for linear optical quantum computing (LOQP), that is, single-photon sources, linear circuits, and single-photon detectors, have been already separately demonstrated on diamond devices. Integration of these elements on a single platform is a promising approach for the development of large-scale LOQP, and, in the near future, may play a central role for the demonstration of intermediate quantum computing protocols, such as boson sampling, which received higher attention in past years. Besides their excellent properties as single-photon emitters, color centers coupled to nanophotonic structures have recently emerged as promising candidates for achieving nonlinear interactions at the single-photon level. In the future they may be employed for the implementation of deterministic two qubit gates and drastically reduce the number of resources needed for LOQP.

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Conflict of Interest

The authors declare no conflict of interest.

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