Topical Review

Nanowire-based sources of non-classical light

Dan Dalacu, Philip J Poole and Robin L Williams

National Research Council of Canada, Ottawa, Ontario, K1A 0R6, Canada

E-mail: dan.dalacu@nrc.ca

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Abstract
Sources of quantum light that utilize photonic nanowire designs have emerged as potential candidates for high efficiency non-classical light generation in quantum information processing. In this review we cover the different platforms used to produce nanowire-based sources, highlighting the importance of waveguide design and material properties in achieving optimal performance. The limitations of the sources are identified and routes to optimization are proposed. State-of-the-art nanowire sources are compared to other solid-state quantum emitter platforms with regard to the key metrics of single photon purity, indistinguishability and entangled-pair fidelity to maximally entangled Bell states. We also discuss the unique ability of the nanowire platform to incorporate multiple emitters in the same optical mode and consider potential applications. Finally, routes to on-chip integration are discussed and the challenges facing the development of a nanowire-based scalable architecture are presented.

Keywords: single photon sources, quantum dots, semiconductor nanowires

(Some figures may appear in colour only in the online journal)

1. Introduction

Non-classical light plays a major role in many quantum information technologies [1]. Light sources that produce single photons or entangled photon pairs are a required resource in many quantum-secured communication and quantum computing schemes. Sources based on solid-state emitters have emerged as a promising scalable solution for the generation of non-classical light and the advances in this field over the last half decade have been the subject of numerous review articles [2–10].

Depending on the application, an ideal non-classical source would generate single photons or entangled photon pairs on-demand at high repetition rates with unity efficiency. For many schemes, the sequential single photons emitted by the source are required to be indistinguishable from each other, as well as indistinguishable from photons emitted by remote sources. Such sources have proven difficult to manufacture in the solid state: there is typically no control of the emitter position, making it difficult to isolate single emitters as required to ensure high single photon purity. Spectral diffusion due to a fluctuating charge environment [11] and interaction with the phonon bath [12] lead to spectra that are not Fourier-transform limited, reducing indistinguishability. For the case of quantum dots (QDs), which offer a mechanism to produce polarization entangled pairs via the biexciton–exciton cascade [13], the phase term between the polarizations of the emitted pair due to system asymmetries makes it difficult to harness the entanglement [14]. Finally, for emitters in bulk, device efficiencies are extremely low due to the difficulty in extracting light from high index materials [15].

These limitations have, to a large extent, been mitigated by employing optical microcavities [16, 17] in conjunction with resonant excitation [18–20]. By coupling the emitter to an optical mode that is easily collected, high efficiency
devices can be obtained. For small mode volume, high quality factor \((Q)\) cavities, Purcell-enhanced spontaneous emission rates \([21]\) lead to sources that can operate at higher repetition rates. The shorter emitter lifetimes limit the time scale over which spectral diffusion \([22]\) and acoustic phonon-mediated pure dephasing \([23]\) can affect coherence. Microcavities can also enhance non-phonon-assisted emission rates whilst simultaneously frustrating phonon-assisted emission \([24]\). Using resonant excitation schemes to coherently populate optical transitions eliminates relaxation jitter \([25]\) and reduces decoherence processes \([26]\) (e.g. inhomogeneous broadening and dephasing of excitonic states) associated with above-gap excitation. Resonantly excited microcavities have been used to demonstrate near-optimal sources of indistinguishable photons \([27–31]\).

To realize these cavity-mediated performance enhancements requires both spectral and spatial matching of the emitter and cavity mode. As the near-optimal sources cited above were achieved with randomly positioned emitters, the question of yield of sites containing one and only one emitter has been used. The former have been grown using Stranski–Krastanov (S–K) growth \([86]\) whilst for the latter, background defects in bulk diamond are used \([65]\). The nanowire waveguide, shown in figure 1(f), is defined using electron-beam (e-beam) lithography and dry-etching of the host material. The conventional and well-understood processing techniques developed for fiber-based superconducting single photon detectors \([56]\), one can envision the development of high efficiency field-deployable ‘plug and play’ devices \([57,58]\).

Table 1 summarizes the different platforms that have employed the photonic nanowire approach. It includes a variety of material systems operating over a large range of emission wavelengths and shows a large variation in performance. The majority of devices listed utilized optical pumping although devices based on electrical excitation \([59]\) have also been demonstrated \([60]\). The table highlights two distinctly different approaches to photonic nanowire manufacture: a top-down approach where emitter integration is based on randomly nucleated emitters including QDs \([61–64]\) and defect centers \([65,66]\) and an approach based on bottom-up techniques, mentioned above, where the emitter is integrated deterministically and includes selective-area \([67–70]\) and vapor–liquid–solid \([44,47,48,71–76]\) growth modes.

This review focuses on nanowires as sources of quantum light as opposed to the more general photonics perspective for which the reader is directed to \([81]\). Both top-down and bottom-up approaches are included as they share the same waveguide design principles. The top-down approach is also compatible with a variety of emitters, whereas bottom-up devices are strictly QD-based. Section 2 covers device fabrication and highlights the importance of growth conditions in bottom-up nanowires in determining material properties. In section 3 we outline the key design requirements for high efficiency device operation. In sections 4, 5 and 6 we address the quantum properties of nanowire sources including single photon purity, indistinguishability of sequentially emitted photons, and entangled-pair generation. Section 7 discusses approaches to monolithic integration of nanowire sources and nanowire-microcavity coupled systems. Finally, in section 8 efforts to incorporate multiple emitters in a single nanowire are presented and possible applications are explored.

2. Fabrication and growth

There are two elements that comprise a nanowire quantum light source: the emitter, which produces the quantum light and the waveguide, which efficiently delivers the quantum light to an external optical system. As mentioned above, nanowire sources fall into two categories: bottom-up sources, where both the emitter and the waveguide are defined through growth, and top-down sources, where the waveguide is defined through etching of the bulk material that contains the emitters. These two approaches are discussed below.

2.1. Top-down nanowires

In the top-down approach emitters based on self-assembled QDs \([82,83]\) and defect centers in diamond \([84,85]\) have been used. The former have been grown using Stranski–Krstanov (S–K) growth \([86]\) whilst for the latter, background defects in bulk diamond are used \([65]\).
techniques used to control waveguide diameters and tapers, important for device efficiency (section 3), make bottom-down nanowires technologically attractive.

The number of emitters per waveguide can be controlled to a limited extent by adjusting the emitter density in the host material before etching. Typical devices contain several emitters [61] which will impact the single photon purity (section 4). As the emitters are randomly distributed in the host, there is no control of the position of the emitter within the waveguide [87] and device performance will vary from nanowire to nanowire depending on how well the emitter is coupled to the waveguide mode (section 3). There have been some recent attempts at deterministic positioning of defects in diamond nanowires using a focused ion beam (FIB) to locally generate defects, with quoted resolutions in the tens of nanometers. However, the nanowires still contain 1 to 8 defects each and the yield is low at 5% [66].

2.2. Bottom-up nanowires

For bottom-up sources, the emitters are QDs defined by the grown nanowire (i.e. they form a segment of the nanowire core) allowing for complete control of the QD geometry (i.e. diameter, height) [88]. Importantly, sources based on bottom-up nanowires inherently contain one emitter per device, and the emitter is precisely positioned on the waveguide axis. Waveguides are defined by switching from an axial (i.e. perpendicular to the growth substrate) to a radial growth mode such that the axially grown nanowire core acts as a template for the waveguide growth.

There are two basic bottom-up growth techniques: one based on selective-area (SA) epitaxy consisting of growth on a patterned substrate [89] and a second based on vapor–solid–liquid (VLS) epitaxy [90] which uses metal particles to catalyze the nanowire growth. The SA approach is by definition a site-controlled technique whereas the VLS approach was originally developed using randomly distributed particles [90–92] but is readily adapted to site-control using e-beam patterning and metal lift-off [93].

In the SA approach the growth is typically performed on single-crystal substrates or wurtzite (WZ) substrates with the polarity chosen to give vertical growth [89]. We note that the lattice-matching requirements for defect-free growth in nanowire systems are generally relaxed and growth of high quality material on dissimilar substrates, in particular III–V on silicon, has been demonstrated [94]. The substrate is coated with a mask, typically a dielectric like SiO2, which provides growth selectivity (i.e. no growth occurs on the mask). This is patterned using e-beam lithography to open up holes exposing the semiconductor surface. Under the appropriate conditions, growth on such a patterned substrate only occurs in the holes exposing the semiconductor surface, as shown in figure 1(a). Growth conditions are chosen to promote axial growth [95] and the QD inserted by switching precursors from those required for the host semiconductor to those for the dot material, e.g. from InP to InAs. The waveguide is then grown by cladding the nanowire with a shell using growth conditions that promote radial growth [95], see figure 1(d).

In the VLS approach, vertically oriented nanowires are grown on cation-terminated single-crystal substrates (e.g.
Figure 1. Upper panel: scanning electron microscopy (SEM) images of InP nanowire cores showing the different bottom-up growth modes: (a) SA—selective-area; (b) VLS—vapor–liquid–solid; and (c) SA–VLS which combines VLS growth with an oxide mask. The inset on the right shows a high resolution transmission electron microscopy (HRTEM) image of an InAsP QD embedded in an InP nanowire core. Lower panel: SEM images of nanowire waveguides based on (d) bottom-up nanowires grown using SA growth. Reproduced from [68]. © IOP Publishing Ltd. All rights reserved. (e) Bottom-up nanowires using SA–VLS growth and (f) top-down nanowires. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature [61] (2010).

(111)B / Group V-terminated) of the same material system. As above, defect-free growth on dissimilar substrates (e.g. III–V on silicon [92]) has also been demonstrated. Using appropriate conditions, growth only occurs at the metal-semiconductor interface in a layer by layer fashion [96, 97] allowing for nanowire growth with dimensions dictated by the size of the catalyst as shown in figure 1(b). QDs are included as above by switching precursors from the host to the dot material. In this way, QDs with abrupt interfaces and lateral dimensions corresponding to the nanowire core can be incorporated [34].

For completeness, we note two alternative avenues for integrating QDs in VLS-based nanowires. The first uses crystal phase (CP) QDs [78, 79] where confinement is provided by band-offsets of the same material in different CPs (e.g. ZB versus WZ), discussed below. Here, control of the number of emitters is not straightforward [98] and a route to providing lateral confinement in the case of a QD in a waveguide structure is not evident as the dots are essentially planar defects which will propagate into the cladding. The second alternative integration method relies on QD formation on the sidewalls of the nanowire in a radially grown heterostructure [77] via a strain-driven growth similar to that used to grow dots in inverted pyramids [36]. This method, however, does not provide the two major advantages normally associated with bottom-up nanowires, namely control of the number of QDs and their optimal position within the nanowire for maximum coupling to the fundamental waveguide mode.

As with SA nanowires, the VLS nanowires are clad using growth conditions that promote radial growth. In this growth mode there always exists a competition between substrate growth and VLS growth, evident in figure 1(b). As the conditions required to promote radial growth also tend to promote substrate growth, this makes it difficult to controllably clad the nanowires. A variation on the growth mode combines SA and VLS epitaxy [99]: holes are patterned in an oxide mask as in the SA approach and catalysts are deposited in the center of these holes using a self-aligned lift-off process. This growth mode can be used to control where substrate growth can occur (e.g. the annulus of exposed substrate observed in figure 1(c)), allowing for the growth of waveguides tailored to the emission wavelength of the QDs [47, 48]. Furthermore, by controlling the relative axial, radial, and substrate growth rates, waveguides with well-defined tapers can be obtained, figure 1(e). Both of these aspects play a crucial role in device efficiency, as discussed section 3.

Binary semiconductor nanowires grown using VLS epitaxy are known to exhibit a polypertic crystal structure [100]; they contain segments of both ZB and WZ CPs. WZ and ZB in the (111) direction differ only in the stacking sequence of the bilayers that make up the semiconductor and an insertion of one phase in the other constitutes a stacking fault (SF). The density of SFs will depend on nanowire diameter, growth conditions and material system [101, 102]. For example, InP, which is ZB in bulk, transitions to a WZ crystal structure for small nanowire diameters. This occurs through the appearance of WZ insertions in a predominantly ZB nanowire which, with decreasing diameter, transition to ZB insertions in a predominantly WZ nanowire shown in figure 2(a). Since the bandgaps of the two crystal phases are different, this transition can be observed in photoluminescence (PL) spectra of nanowires with different core diameter, as shown in figure 2(b).

The presence of SFs has a profound effect on the optical properties of nanowire-based quantum emitters. For example, the band alignment for the WZ InP material system (lower panel of figure 2(a)) is such that SFs (ZB insertions) act as electron traps. For above-band excitation there will be a time-varying occupation of these traps with electrons that are free to move in the cross-section of the nanowire, resulting in a fluctuating charge environment for any QD in close proximity. This will lead to significant spectral wandering of the QD emission wavelength, severely limiting two-photon
interference, discussed in section 5. The quantum emitters should therefore be incorporated in pure phase nanowires. For small diameter nanowires this is readily achieved using appropriate growth conditions [47] but becomes increasingly difficult as the diameter increases. This means that to obtain a large enough diameter nanowire for good waveguiding, see section 3, requires a core–shell approach, where a small diameter pure WZ phase nanowire core is first grown followed by radial growth to form a shell. This lateral growth is commensurate with the crystal structure of the core resulting in a large diameter, pure WZ phase nanowire waveguide.

Finally VLS epitaxy is typically performed at lower temperatures compared to conventional growth resulting in a lower quality material. Impurities and crystal defects incorporated in low temperature grown material [103] lead to shallow donor and acceptor (D–A) levels which are evident in PL (see figure 2(c)). As with SFs, the trap population dynamics limit two-photon interference by creating a varying charge environment. Growth at higher temperatures using conventional VLS epitaxy is difficult due to competition between growth at the metal-semiconductor interface and growth on the substrate. However, using SA–VLS, where substrate growth is limited, growth temperatures approaching those used in conventional high material quality epitaxy can be achieved [99].

3. Source efficiency

It is highly desirable for a quantum light source to produce a large photon flux coupled into the optical system of choice. The maximum flux will be limited by three parameters: (1) the internal quantum efficiency of the emitter, (2) the spontaneous emission rate of the emitter, and (3) the efficiency of coupling those emitted photons into the external optical system. We define the source efficiency, $\eta$, as the number of photons collected by the external optical system each time the emitter is excited. The generated photons will couple to the available photonic modes of the nanowire waveguide (figure 3(c)) with efficiency $\beta_{\text{mode}}$. For single mode operation [53] where the waveguide is designed to confine only the fundamental mode $\text{HE}_{11}$, the source efficiency can be written as

$$\eta = \alpha \beta_{\text{HE}_{11}} \eta_{\text{QE}},$$  \hspace{1cm} (1)

where $\beta_{\text{HE}_{11}}$ is the fraction of photons emitted into the $\text{HE}_{11}$ mode, $\alpha$ is the fraction of these photons that are coupled to the external optical system, and $\eta_{\text{QE}}$ is the internal quantum efficiency of the emitter. For high quality QD material $\eta_{\text{QE}}$ is close to 100%.

The maximum collection efficiency $\alpha$ will be limited to 50% using the standard nanowire geometry as half the emission is directed downwards toward the substrate. Although it entails added complexity in the fabrication, this 50% loss can largely be recovered using a back mirror deposited on the bottom of the nanowire [61, 76, 104]. Using a strictly cylindrical waveguide design will further reduce the collection efficiency due to (1) back reflections from the top of the nanowire and (2) the large divergence of the mode (i.e., losses due to limitations in the numerical aperture of the collection optics). These can both be reduced by introducing a taper along the nanowire length (see figure 3(a)) to expand the mode, limiting its divergence as it exits the nanowire [53, 105]. Alternatively, the $\text{HE}_{11}$ mode can be expanded using an inverted taper approach [63] although this then requires an antireflection coating to reduce backreflection. Together, these two design considerations provide a route to fabricating sources with near-unity collection efficiency [106].

$\beta_{\text{HE}_{11}}$ is given by the spontaneous emission rate into the fundamental mode, $\Gamma_{\text{HE}_{11}}$, relative to the emission rate into all modes:

$$\beta_{\text{HE}_{11}} = \frac{\Gamma_{\text{HE}_{11}}}{\Gamma_{\text{HE}_{11}} + \gamma},$$  \hspace{1cm} (2)
where $\gamma$ corresponds to all other modes. Calculated values for $\beta_{\text{HE}11}$, $\Gamma_{\text{HE}11}$, and $\gamma$ as a function of the normalized waveguide diameter, $D/\lambda$, are shown in figure 3(c) after [106] (see also [48]). $D$ is the waveguide diameter and $\lambda$ is the wavelength of the emitter. The emission rates are calculated at $\lambda = 950$ nm for the InP material system and have been normalized with respect to values in bulk. From the figure, it is evident that high efficiency devices can be obtained for a large range of diameters with peak values of $\beta_{\text{HE}11} = 95\%$ for $D/\lambda \sim 0.25$. The values of $\beta_{\text{HE}11}$ calculated here assumes that the QD is centered laterally in the nanowire, i.e. at the peak of the optical mode. Any off-center positioning will result in a reduction of the coupling to the HE11 mode and potential coupling to higher order modes ($\text{TE}_{01}$, $\text{TM}_{01}$), resulting in poorer efficiency.

As mentioned above, efficiency alone is not a complete measure of source performance; a high spontaneous emission rate of the emitter is also important for a high photon flux. As figure 3(c) shows, the spontaneous emission rate of the emitter is dependent on the normalized diameter via the Purcell effect [107] (i.e. the overlap of the optical mode with the emitter). In particular, the rate is inhibited for $D/\lambda < 0.24$ which results in long radiative lifetimes [108, 109] and a drop in the measured count rates [48]. Therefore, whilst a source may be very efficient over a large range of $D/\lambda$, the maximum number of photons emitted from the source per unit time will depend strongly on $D/\lambda$.

A better measure of device performance is photon number per second collected by the optical system, $\Phi_p$, $\Phi_p$ will depend not only on source efficiency but also on the spontaneous emission rate of the 2-level emitter and the probability $p_e$ that it is excited:

$$\Phi_p = \eta p_e \Gamma_{\text{HE}11} = \frac{\eta p_e}{T_1},$$

where $T_1$ is the radiative lifetime of the transition. According to equation (3), to maximize $\Phi_p$ sources should be operated at excitation powers where $p_e$ is maximum (i.e. at saturation) and, from of figure 3(c), nanowire waveguides should have normalized diameters $D/\lambda \sim 0.24$ where $\Gamma_{\text{HE}11} = 0.88\Gamma_{\text{bulk}}$ is maximum.

The optimal geometry having $D/\lambda = 0.24$ and including a tapered top (figure 3(a)) is obtained in top-down approaches using well-understood lithography and dry-etching processes [61]. It is less trivial to obtain this geometry using bottom-up growth approaches. As mentioned in section 2.2, a two-step nanowire growth process is essential, where an initial step in an axial growth mode is used to grow a nanowire core and define the QD and a second step in radial growth mode is used to grow a cladding to define the nanowire waveguide. Independent control of axial and radial growth rates and their ratio are necessary to define the core (i.e. the QD), the cladding (i.e. waveguide) and to taper the waveguide, as discussed in section 2.

The source efficiency $\eta$ can be determined from the integrated PL intensity using pulsed excitation to extract the average number of photons emitted per excitation pulse. To ensure the emitter is excited with each pulse, excitation powers that saturate the 2-level transition are used. For sources based on defects, one typically uses the integrated counts in the zero phonon line (ZPL) (e.g. $\lambda = 637$ nm at


300 K for NV centers). For QDs without charge state control [110], the ground state emission in a time-integrated photoluminescence measurement can show different excitonic charge complexes depending on the background doping and Fermi level pinning. For an accurate determination of $\beta_{\text{HE11}}$, all contributing excitonic complexes should be included.

Excitation with a continuous wave (CW) source is more appropriate for determining the maximum attainable $\Phi_p$ in that it represents the maximum pulse rate at which the source can be excited [111] (i.e. with CW excitation, the emission rate is limited by the emitter lifetime as opposed to the excitation pulse repetition rate).

An example of determining device performance is shown in figures 3(d) and (e) for a high efficiency source consisting of a tapered InP waveguide with $D/\lambda = 0.24$ with an embedded InAsP QD. Figure 3(d) shows the time-integrated PL spectrum from the dot which emits from two charge complexes: the neutral (X) and negatively charged (X⁻) exciton, distinguished by their exchange splitting [83]. Figure 3(e) shows the detected integrated intensity of the ZPL for X and X⁻ as a function of excitation power for both CW and pulsed excitation. Table 2 lists the ZPL counts at the first lens (i.e. with the spectrometer and collection optics throughput of 10% accounted for) at saturation for both charge complexes and both excitation methods.

Using the counts in the ZPL (i.e. from a lorentzian fit of the spectrally resolved PL peak) neglects emission into photon sidebands which can account for 20% of the total counts at a temperature of 4 K [3]. Alternatively, integrated counts can be determined using single-photon avalanche diodes where the fraction of phonon-assisted emission counted will depend on the width of the spectral filter used. For some applications phonon-assisted emission does not impact system performance, but where indistinguishable photons are required (section 5), performance will be degraded.

An efficiency of $\eta = 31\%$ is obtained from the ratio of the ZPL intensity of X and X⁻ combined to the pulse repetition rate of 80 MHz. This measurement is only accurate for a source where multi-photon emission is not observed up to saturation, see section 4. From equation (1), the measured collection efficiency is $\sigma = 32.6\%$, assuming $\beta_{\text{HE11}} = 0.95$ and $\eta_{\text{QE}} = 1$. The maximum collection efficiency for this device design (i.e. no back mirror) and including only the counts in the ZPL (i.e. neglecting emission in the phonon sidebands) is $\sigma_{\text{max}} = 0.4$, corresponding to a maximum efficiency for the device of $\eta_{\text{max}} = 38\%$, just 7% higher than measured.

The count rates in the ZPL using CW excitation (i.e. $\Phi_p$) increase by 3.3x for X and 1.8x for X⁻. This increase compared to pulsed excitation is consistent with the measured lifetimes of $T_1 \sim 2.5$ ns giving a decay-limited excitation rate of 400 MHz and an ultimate bound on increased intensity of 5x.

We note that this exercise is to evaluate the source design: in real devices, $\eta$ and $\Phi_p$ need to be specified for a given transition and will be lower for devices emitting from different charge complexes. This efficiency loss can be recovered using devices with charge state control [112].

Efficiencies exceeding 70% have been obtained from nanowire sources based on the top-down approach using the X transition [61] whilst bottom-up approaches have demonstrated efficiencies exceeding 40% using the X⁻ transition [45, 76]. The state-of-the-art top-down nanowire sources employed a back mirror whilst the devices in [45] did not. As such, the efficiencies demonstrated with both top-down and bottom-up approaches represents close to the ultimate performance possible. This level of performance is on par with state-of-the-art sources based on QD micropillar cavities which have achieved efficiencies of close to 80% [113]. However, there is a trade-off between the conditions which give maximum efficiency (e.g. typically above-band excitation at powers that saturate the 2-level transition) and those that optimize the quantum properties. Efficiencies and quantum properties (section 4 through section 6) both need to be specified in order to make meaningful comparisons between platforms. Ideally, a metrology-based approach should be established in order to standardize the characterization methodology of non-classical light sources and allow for a true comparison of the various platforms.

Unlike nanowire devices, sources based on micropillar cavities benefit from Purcell-enhanced emission rates. Typical lifetimes for QDs in high efficiency micropillar sources are a few hundred picoseconds [113] with shorter lifetimes possible using photonic crystal cavities [114]. These values are much lower than those reported for high efficiency nanowire devices (see table 1). Thus, cavity-based sources will greatly outperform nanowire devices in terms of emission rates (i.e. $\Phi_p$). Efforts to combine nanowires with cavities to provide Purcell enhancements and wavelength discrimination are discussed in section 7.

| Table 2. Counts at first lens in the ZPL at saturation. |
|---|---|---|---|
| Exciton | Counts (CW) (Mcps) | Counts (pulsed) (Mcps) | Efficiency, $\eta$ (%) |
| X | 15.1 | 4.6 | 5.7 |
| X⁻ | 36.6 | 20.2 | 25.3 |
| Total | 51.7 | 24.8 | 31.0 |

4. Single photon emission

High single photon purity (i.e. low probability of emitting multiple photons) is a prerequisite for any quantum light source. Ideally, the source should emit exactly one photon at a time into a given spatiotemporal mode on demand. For some quantum cryptographic communication protocols (e.g. BB84 [115]), high single photon purity is sufficient. Two photon correlation events are quantified by the second-order correlation function, $g^{(2)}(\tau)$, which, for a single mode optical field characterized by creation and annihilation operators $\hat{a}$ and $\hat{a}^\dagger$, is defined by

$$g^{(2)}(\tau) = \frac{\langle \hat{a}^\dagger(t) \hat{a}^\dagger(t + \tau) \hat{a}(t + \tau) \hat{a}(t) \rangle}{\langle \hat{a}^\dagger \hat{a} \rangle^2}.$$ (4)
where $\langle \cdot \rangle$ denotes the statistical average. In the case of photon number states, $|n\rangle$, $g^{(2)}(\tau)$ provides a measure of the multi-photon emission probability. In particular, the correlation function dips at zero delay, $g^{(2)}(\tau = 0)$, (i.e. the photon statistics display antibunching):

$$g^{(2)}(0) = \frac{n - 1}{n} = 1 - \frac{1}{n}. \quad (5)$$

Hence, for any given Fock state with $n > 1$, $g^{(2)}(0) \geq 1/2$. This is used to argue that $g^{(2)}(0) \leq 1/2$ implies single photon emission. However, practical sources require, as a minimum, $g^{(2)}(0)$ values of less than 0.1 [4].

Photon emission statistics are measured using a Hanbury Brown-Twiss (HBT) interferometer [116] where the photons are directed to the input of a beamsplitter with the outputs directed to two single photon detectors. Timing electronics are used to count and correlate detection events between the two detectors. Figure 4(a) shows the time-correlated counts from a nanowire source using CW (upper panel) and pulsed (lower panel) excitation [117]. For CW excitation, the multi-photon emission probability is determined from $g^{(2)}(\tau = 0)$ whilst the time-dependence gives the decay rate of the transition. A $g^{(2)}(0)$ derived from a CW measurement post-selects only those photons that arrive simultaneously at $\tau = 0$ convoluted with the temporal response of the detectors. To achieve on-demand operation, pulsed excitation has been proposed [118] to generate a regulated stream of single photons. The multi-photon emission probability in a pulsed $g^{(2)}(\tau)$ measurement is determined from the ratio of the area of the peak at $\tau = 0$ to that of the adjacent peaks. We will refer to this probability as $g^{(2)}(\Delta \tau_p)$. Pulsed $g^{(2)}(\tau)$ measurements provide additional information on the photon statistics, e.g. re-excitation of the emitter within the same pulse cycle [119–121] which appears as a characteristic double-peaked feature around the dip at $\tau = 0$ [119].

A prerequisite for a perfect single photon source (i.e. zero multi-photon emission) is the isolation of a single 2-level emitter. This includes both spatial isolation of a single emitter as well as spectral isolation of a single transition from that emitter. In this context, bottom-up nanowires using QD emitters are close to ideal. A single emitter is incorporated by design and in high material quality QDs at low temperatures (e.g. 4.2 K), the different excited complexes (such as $X$, $X^-$ or $XX$) do not spectrally overlap and are readily spectrally filtered. A multi-photon emission probability of $g^{(2)}(\Delta \tau_p) = 0.002$ with an efficiency of 43% has been demonstrated using the SA–VLS approach [45, 47] with InAsP QDs emitting at $\lambda = 950$ nm. This widely tunable system has also been used to demonstrate single photon emission in the telecom O-band, with a measured $g^{(2)}(\Delta \tau_p) = 0.02$ at $\lambda = 1340$ nm [48].

Isolating a single emitter when using the top-down fabrication approach with randomly nucleated self-assembled QDs is more of a challenge than for the bottom-up approach. A QD density needs to be targeted that minimizes the number of emitters per device (to limit the possibility of several emitters contributing to a non-zero $g^{(2)}$ [63]) but also minimizes the number of empty devices. This will affect device yield. Furthermore, as the position of the QD within the waveguide is random, efficiencies from device to device will vary depending on how well the emitter is coupled to the optical mode [87]. Even with these concerns, devices based on the top-down approach using self-assembled QDs have demonstrated state-of-the-art multi-photon emission of $g^{(2)}(\Delta \tau_p) = 0.008$ at an efficiency of 72% [61]. The device yield aspect distinguishes top-down and bottom-up approaches, as highlighted in figure 4. In the bottom-up approach the yield of working devices is nearly 100%: each nanowire contains a single emitter and each emitter is optimally positioned in the waveguide for maximum coupling to the HE$_{11}$ mode. Consequently, all sources show similar count rates at saturation and $g^{(2)}(\Delta \tau_p)$ values of less than a few percent.

High efficiencies have also been demonstrated using micropillar cavities when excited above-band, as mentioned in section 3. Unlike nanowires, however, these devices [113, 122] exhibit increased $g^{(2)}(\Delta \tau_p)$ values when excited at powers where $\Phi_p$ is maximum (i.e. at saturation). With above-band excitation, the system is flooded with carriers which, if they persist for times comparable to the exciton lifetime, can be captured by the QD after the first excitonic photon has been emitted [119, 120]. This will increase $g^{(2)}(\Delta \tau_p)$. Cavity
structures can promote such re-excitation by decreasing the QD exciton lifetime, (as demonstrated in a comparison of on and off resonance $g^{(2)}(\tau)$ measurements in [118] and [122]). Additionally, cavity effects may increase the lifetime of off-resonant excitons in nearby traps (e.g. in the wetting layer [122, 123]) which can also lead to re-population of the QD.

In order to achieve the high single photon purity at maximum $\Phi_p$ observed in nanowire systems, microcavity devices have employed electric fields and/or resonant excitation [27, 28]. Recent results with electric field tuned QDs in cavities [27] show improved performance at saturation with $g^{(2)}(\Delta \tau_p) = 0.024$ measured in devices operating at 65%.

This suggests that the electric field used for tuning is sweeping away excess carriers from the region around the QD that were generated by the above-band excitation.

Using resonant excitation [120], on the other hand, avoids re-population of the excited state within the same pulse cycle by directly loading the excited state. Resonant fluorescence, however, requires rejection of the pump laser and for rejection based on polarization [124] results in a 50% drop in efficiency. Hence, state-of-the-art micropillar cavities with single photon purities comparable to nanowires operate at reduced efficiencies of 15%–37% [27, 28]. Recovery of this loss should be possible with a rejection of the pump that is based on orthogonal excitation and emission directions [18, 125]. Alternatively, asymmetric microcavities systems can be employed to preferentially generate photons in a single polarization state [126].

The absence of cavity effects and wetting layers in bottom-up nanowires may contribute, together with being a uniquely single emitter device, the high single photon purity observed in nanowire systems using above-band excitation at maximum $\Phi_p$.

5. Indistinguishable photon emission

In many applications, the emitted photons from quantum sources are required to be identical in all degrees of freedom [11] (i.e. perfect overlap of the photon wave-packets in energy, time, space, polarization). Secure communication schemes such as quantum repeater-based entanglement distribution [127] and measurement-device-independent quantum key distribution [128] rely on such indistinguishable photons as do quantum computing schemes based on linear optics [129]. Factors limiting the ability to generate indistinguishable photons in nanowires, and solid state systems in general, include charge noise and interactions with acoustic phonons [130, 131]. If these decoherence mechanisms are present, the emitted photons will not be lifetime-limited and emission energies will be time-dependent (i.e. the optical linewidths will be broadened).

Charge noise can be caused by a time-dependent population of traps near the emitter which produces a fluctuating charge environment and leads to spectral wandering of the emission energy. In top-down nanowire sources based on self-assembled QDs, these traps are due to impurity-related defects, the wetting layer, or other dots. In bottom-up nanowires, charges can also be trapped in SFs, as discussed in section 2. The dramatic effect of SFs on the emission linewidth of a QD in a VLS-grown nanowire is shown in the upper panel of figure 5(a). For mixed-phase nanowires [132] having SF densities of a few tens per micron, measured linewidths are $\Delta \omega > 400 \mu$eV and vary immensely from nanowire to nanowire depending on the proximity of a SF to the QD. In pure phase nanowires [45, 47] (SF densities of less than $1 \mu$m$^{-1}$), the linewidth collapses by over two order of magnitude to $\Delta \omega \sim 4 \mu$eV, close to that expected for a radiative lifetime of $T_1 \sim 2$ ns.

The coupling of acoustic phonons to the optical transition associated with a 2-level system results in emission into sidebands around the ZPL. While phonon absorption can be eliminated at sufficiently low temperatures, the emission process will persist. At 4 K, emission into the phonon sidebands can be 20% of the total emission [3], see figure 5(b). Coupling to phonons shifts the energy of the emitted photon with a corresponding decrease in indistinguishability.

The level of indistinguishability between two photons is determined from a two-photon interference measurement [133] and for a pulsed measurement is quantified [134] by the visibility, $\nu$:

$$\nu = \frac{g^{(2)}(\Delta \tau)_{\parallel} - g^{(2)}(\Delta \tau)_{\perp}}{g^{(2)}(\Delta \tau)_{\parallel}},$$

where $g^{(2)}(\Delta \tau)_{\parallel}$ ($g^{(2)}(\Delta \tau)_{\perp}$) is the integrated probability, within a time window $\Delta \tau$ about $\tau = 0$, of detecting photons at both outputs of a beamsplitter for indistinguishable (distinguishable) photons at the two inputs. Perfectly indistinguishable photons will coalesce and exit the same output port. $g^{(2)}(\Delta \tau)_{\parallel} = 0$, whereas distinguishable photons will have equal probabilities of exiting each output port, $g^{(2)}(\Delta \tau)_{\perp} = 0.5$. An ideal source will have $\nu = 1$ over $\Delta \tau$ covering the entire repetition period around $\tau = 0$ whilst any timing jitter in the relaxation process or dephasing in the 2-level transition will result in coincidence counts for $\Delta \tau \neq 0$. Here, dephasing is any mechanism that reduces the coherence time, $T_2$, of the photon such that it is not lifetime-limited (i.e. $T_2 < 2T_1$).

To date, two-photon interference measurements on nanowires have been reported only for the bottom-up SA--VLS system [45]. Using above-band excitation from a 20 MHz pulsed source, sequential photons delayed by 50 ns show low non-post-selected visibilities of $\nu \sim 4\%$ when all the emitted photons are collected. The low value is a consequence of the presence of decoherence mechanisms discussed above. This results in a multi-peaked visibility measurement (see inset, figure 5(c)) characteristic of two-photon interference from non-lifetime-limited photons [26]. Improved visibilities can be achieved using temporal post-selection where only the photons received within a small time delay around $\tau = 0$ are used. Since many of the photons are being thrown away this results in a drop of the source efficiency (figure 5(c)). A visibility of
above-band 20MHz pulsed excitation, from Figure 5.\(^{(67)}\)\(^{(1)}\)

\[ \nu \sim 80\% \] was obtained at a device efficiency of 10\%, similar to other state-of-art broadband approaches using above-band excitation [135].

This level of performance is significantly lower than state-of-the-art QD micropillar cavities which have achieved extremely high levels of indistinguishability (\(\nu > 98\%\)) in devices operating at efficiencies of 15\%–33\% [27, 31]. Near-unity non-post-selected visibilities in these devices have only been achieved through resonant pumping schemes in combination with Purcell-enhanced spontaneous emission rates, both of which help to mitigate the decoherence mechanisms cited above. As well as reducing relaxation timing jitter, resonant pumping avoids the charge fluctuations associated with above-band excitation, where the system is flooded with carriers with each excitation pulse. For example, visibilities in micropillar devices drop to \(\nu = 53\%\) when exciting non-resonantly into the QD wetting layer [113] (where increased timing jitter in the emission process for cavity environments [26] may also contribute to the decrease in visibility). Purcell-mediated lifetime reduction may also mitigate the effects of a fluctuating charge environment by decreasing recombination times to levels potentially lower than the time scales associated with charging events. This same increase of the spontaneous emission rate into the cavity mode will also limit phonon emission and absorption processes [24].

To obtain higher visibilities in nanowire devices, higher quality material is required to reduce defect-related trap density and attain lifetime-limited emission linewidths. Improving material quality can be achieved using higher temperature growth as discussed in section 2. Alternatively, post-growth annealing-mediated intermixing has been suggested as a route to remove grown-in defects from nanowires [136]. Additionally, techniques to stabilize the charge environment can be employed, for example, 2-color excitation [113] where visibilities as high as \(\nu = 80\%\) have been achieved in devices operating at efficiencies of 79\%. Near-unity visibilities, however, will require resonant excitation to eliminate relaxation timing jitter. Resonant excitation in other broadband QD-based devices [19, 137] has demonstrated non-post-selected visibilities exceeding 90\%. Ideally, the excitation scheme would employ rejection techniques that do not sacrifice device efficiency [18, 125, 126]. Resonant excitation of nanowires [62, 138, 139] has yet to be applied to two-photon interference measurements.

High efficiency devices operating at high repetition rates will ultimately require nanowire-cavity coupled systems. Cavity structures can mitigate phonon-assisted emission [24] which is normally discarded in broadband devices through spectrally filtering. Using emitter-cavity systems will make resonant excitation mandatory in order to reduce timing jitter in the emission process due to long-lived (off-resonant) states populated at excitation powers where \(F_\nu\) is maximum [26]. Nanowire-cavity systems for generating quantum light have yet to be demonstrated (see section 7 for possible routes to on-chip nanowire integration).

Finally, two-photon interference measurements are typically quoted for sequential photons emitted from the same source, over short (a few ns) time intervals between photons. However, it is the indistinguishability on longer time scales [29, 30, 130], as well as indistinguishable photons generated by remote sources [140, 141], that are required in the applications listed above. For remote sources, tuning methods will be required as the emission energies from nominally identical nanowire devices vary by several meV as shown in figure 4(c). Tuning the emission energy of nanowire sources has been demonstrated using techniques adopted from self-assembled QDs devices and include both permanent [79, 136] and dynamic [64, 142] approaches.
6. Entangled photon pair emission

Entangled photons are required for certain quantum cryptography protocols [143, 144], quantum repeaters [127] and certain quantum computing schemes [145, 146]. Each of the degrees of freedom of a photon can be entangled (see [6]) and for two-level systems, one typically employs polarization [147] or time-bin [148] entanglement. Polarization-entanglement can be generated using post-manipulation of indistinguishable photons [149] or within the source itself (e.g. using the XX – X cascaded emission in QDs [13, 147]). In the XX – X cascade, the polarization of the photon from the biexciton decay is entangled with that from the exciton decay to form a maximally entangled Bell state i.e. \(|\psi\rangle = \frac{1}{\sqrt{2}}(|H_{\alpha}\rangle|H_{\beta}\rangle + e^{i\pi/\delta} |V_{\alpha}\rangle|V_{\beta}\rangle)\), where \(s\) is the anisotropic exchange splitting (AES) between the two intermediate exciton states (figure 6(a)) and \(\tau\) is the time interval between the biexciton and exciton emission.

The time-dependent phase factor due to a non-zero AES will limit the fidelity to a maximally entangled Bell state. AESs arise from any asymmetries in the system, for example, in the QD shape, composition, strain, or crystal structure. The bottom-up nanowire platform provides a route to the growth of highly symmetric QDs. The dot shape is dictated by the nanowire and not influenced by crystal lattice direction-dependent adatom mobilities, resulting in a highly circular in-plane geometry as shown in the inset of figure 6(b). Furthermore, VLS nanowire QDs are typically grown in the WZ CP on [0001] WZ ((111) ZB equivalent) planes without wetting layers, providing higher axial symmetry compared to ZB S–K dots grown on (001) substrates. This high symmetry is expected to manifest in a reduced AES [152]. Splittings of SA–VLS grown InAs QDs in InP nanowires range from 1 to 10 \(\mu\)eV with over 50% having splittings of \(<2 \mu\)eV [150], see figure 6(b). The likely origin of non-zero splittings is an axial inversion anisotropy [153] due to phosphorus and arsenic tailing inherent to the growth process.

The measure of entanglement is given by the fidelity to a maximally entangled state, determined from the cross-correlations between each of the transitions shown in figure 6(a) as a function of polarization basis using a polarization-resolved HBT-type measurement. The fidelity, \(F\), is calculated from \(F = \frac{1}{4}(1 + C_{\text{rectilinear}} + C_{\text{copolar}} - C_{\text{cross-polar}})\) where \(C\) is the degree of correlation for a given polarization basis denoted by the subscripts. C is given by [154]:

\[
C = \frac{\delta_{\alpha\alpha,\tau}^{(2)} - \delta_{\alpha\beta,\tau}^{(2)}}{\delta_{\alpha\alpha,\tau}^{(2)} + \delta_{\alpha\beta,\tau}^{(2)}},
\]

where \(\delta_{\alpha\alpha,\tau}^{(2)}\) and \(\delta_{\alpha\beta,\tau}^{(2)}\) are the second-order correlation functions when detecting the XX photon (e.g. \(H_{XX}\)) with a copolarized (e.g. \(H_{XX}\)) and cross-polarized (e.g. \(V_{XX}\)) photon, respectively.

Several nanowire systems have demonstrated correlated XX – X emission including devices based on SA growth [67, 68] as well as CP QDs in VLS nanowires [79]. However, to date, only the InAsP–InP system grown using the bottom-up SA–VLS technique has demonstrated entangled photon pair generation [80, 150, 155] with reported fidelities to the maximally entangled state of \(F > 80\%\) [90]. Higher fidelities should be achievable using the various AES tuning techniques developed for QDs (see [156]) in order to eliminate the small remaining splitting. Alternatively, which-path information can be eliminated even in QDs with a non-zero AES.
by tuning the biexciton binding energy to zero [157, 158], or compensating for the phase term arising from non-zero AES through the use of rotating waveplates [159].

The photon-pair source efficiency from nanowire devices, defined as the average number of photon pairs per excitation pulse collected into the first lens, is low at ~0.3%. Although this compares well with other QD-based sources (see figure 6(c), after [80]), there is much room for improvement. For a broadband device such as a nanowire this efficiency depends on the square of the single photon efficiency, \( \eta \), since it is a two photon process, and on the ability to reliably excite the XX state with every laser pulse. This is further complicated for devices using cavities where both the XX and X have to emit within a cavity mode for good collection efficiency. With a typical nanowire \( \eta \) of 31% the maximum efficiency is 9.6% compared to a measured 0.3%, implying that the above bandgap excitation used results in low biexciton population fidelity. Key to achieving higher efficiencies are excitation schemes whereby the biexciton state is populated with unity fidelity [160].

Ultimately, 2-level systems should outperform parametric down-conversion sources where efficiencies are limited due to the probabilistic emission process (i.e. higher efficiency comes at the expense of reduced fidelity due to multi-pair emission, see figure 6(c)). This was recently demonstrated in a QD system using two-photon excitation (TPE) to coherently populate the XX state with high efficiency [151]. TPE together with the broadband operation of nanowire devices (required to collect the energetically distinct X and XX photons) should enable high efficiency nanowire-based sources of entangled photon pairs in the near future.

7. On-chip integration

As highlighted in the previous sections, nanowire sources would benefit from integration with optical microcavities. Coupling to microcavities would allow for operation at higher repetition rates as well as improve the indistinguishability of the emitted photons. Nanowires are typically grown perpendicular to the substrate (i.e. in a \( <111> \) direction on a \( <111> \) substrate) and have large aspect ratios making monolithic integration difficult. This is in contrast to S–K QDs or defect-based emitters which are readily integrated on-chip using, for example, photonic crystal structures [16, 161].

Growth of SA nanowires directly on Si waveguides has been proposed as an avenue for monolithic integration using as-grown nanowires perpendicular to the substrate [162]. Although highly scalable, the coupling efficiency to the Si waveguide is low at 1%. Higher efficiencies will require growth of nanowires at non-normal directions to the substrate. This entails modification of the growth substrate to expose the appropriate facets, for example, through etching [163] or template growth. Non-normal growth has been demonstrated using ridge-type structures [164] and even nanowires [165] as the template.

In the near term, a less scalable solution involves the transfer of nanowires from the growth substrate to a new substrate with pre-patterned alignment marks. Subsequent processing is used to define appropriate photonic structures around the nanowires using the alignment marks as a reference, as shown schematically in figure 7(a), after [166]. Using this approach, VLS-grown nanowires were embedded in SiN waveguides with a measured coupling efficiency from the nanowire to the waveguide of 24%, and a measured multi-photon emission probability of \( g^{(2)}(0) = 0.07 \) [166]. Once nanowire emission is coupled to a waveguide then photonic integrated circuits are
readily envisioned. For example, dynamic routing of single photons has been demonstrated using a tunable ring resonator, as well as multiplexed single photon emission through the coupling of two nanowire sources into the same SiN waveguide [167].

An alternative approach, shown in figure 7(b), relies on evanescent coupling of the nanowire emission to a waveguide in a manner similar to that reported in [168]. There, epitaxial layers containing S–K QDs were patterned with a taper to facilitate the transfer of the optical mode to an underlying SiN waveguide. In the nanowire case, the required taper can be obtained through growth, and for taper lengths of 10 μm, coupling efficiencies of greater than 90% are predicted [169]. Importantly, combining this approach with a nanomanipulator having a sufficiently high positioning precision [170] would greatly simplify the nanowire waveguide alignment process. This corresponds to an incremental increase in scalability in that it allows for the pre-fabrication of complex photonic circuits onto which pre-selected nanowires can be placed deterministically, rather than building the photonic circuit around the already positioned nanowires. Furthermore, evanescent coupling is compatible with ring resonator structures where Purcell-mediated emission rate enhancements of ~6 are predicted from coupling to the whispering gallery modes of the resonator [168]. Alternatively, designs have also been proposed whereby nanowire sources can be coupled to photonic crystal waveguide and cavity structures [171, 172] with demonstrated eight-fold emission rate enhancements [172].

8. Multiple emitter nanowires

As mentioned in section 1, a unique feature of bottom-up nanowire growth is the ability to incorporate multiple, aligned QDs optimally coupled to the same optical mode. Such structures, an example of which is shown in figure 8(a), have been demonstrated using the different bottom-up growth modes and in different material systems [44, 70, 173, 174]. The separation between the QDs as well as their thicknesses and compositions can be reproducibly controlled through the epitaxial growth process, in contrast to results obtained when stacking S–K QDs [49].

The ability to control the composition of the individual QDs has been used to quantify the D/λ dependence of the spontaneous emission rate [48]. Using double QD structures embedded in nanowire waveguides with diameter D, the emission energy of one of the dots was progressively shifted to longer wavelengths by increasing the arsenic content. The two dots were sufficiently separated to avoid electronic coupling. The observed decrease in intensity as the dot is red-shifted, shown in figure 8(b), is consistent with the expected decrease in the spontaneous emission rate shown in figure 3(c).

Uncoupled, multidot structures also provide a route to developing sources with higher emission rates that do not rely on cavity-enhanced recombination rates. By incorporating multiple QDs in the same nanowire, each tuned to a different wavelength, sources based on wavelength division multiplexing are possible. The number of channels will be limited by the number of uncoupled QDs that can be incorporated in a single nanowire and the channel spacing will be limited by the linewidths of the emitters. A PL spectrum of a 5-channel device is shown in figure 8(c). In order to achieve linewidth-limited channel densities, charge state control will be required to avoid emission from different charge complexes (e.g. X and X−, see QD5 in figure 8(c)).

Precise control of the interdot spatial separation and the QD emission energy can also be used to study coherent

Figure 8. (a) SEM image of an InP nanowire containing four InAsP QDs selectively etched to highlight the dots. (b) Emission spectra of double QD nanowires used to quantify the D/λ dependence of waveguide-mediated spontaneous emission rates. Reprinted with permission from [48]. Copyright (2018) American Chemical Society. (c) PL spectrum of five QDs in one nanowire emitting into the same waveguide mode. (d) PL spectra from nanowire-based QD molecules as a function of the separation between the dots (R), from [175]. (e) Three-photon coincidence measurements from a QD molecule. Reproduced from [176]. CC BY 4.0.
coupling in QD molecules. Compared to molecular systems based on coupled S–K QDs [49, 177, 178], nanowire-based coupled dot systems offer better control of the alignment and separation between the two emitters [179] as well as the potential for stronger interactions mediated by the waveguide [175]. Evidence of coherent coupling has been reported in the InAsP/InP nanowire system [175] where clear spectral splitting of the uncoupled QD resonances are observed with decreasing interdot spatial separation, see figure 8(d).

A potential application of molecular QD systems is for generating multiparticle photon states without involving the excited levels of a QD. Triexcitons can be formed from the ground states of two coupled QDs, leading to the sequential emission of three strongly correlated photons. Generation of photon triplets has been demonstrated using coupled InAsP QDs in an InP nanowire [176]. The time-correlated triplet emission shown in figure 8(e) is the first step towards high efficiency sources of three-photon entangled states.

9. Conclusions and outlook

The field of nanowire-based quantum light sources has seen significant progress since the first demonstration of single photon emission from a nanowire QD in 2005 [44]. The superior scalability, in particular the near-unity yields, of bottom-up nanowire devices has been established. Importantly, pathways to eliminating existing limitations are clearly identified. Fourier-limited transitions should be possible with improved material quality available at higher growth temperatures. Two-photon interference measurements using strictly resonant excitation have yet to be performed on a nanowire device. Together, these improvements should lead to near-ideal indistinguishability independent of the temporal separation between photons and provide a pathway to generating indistinguishable photons from remote sources. They are also expected to improve the efficiency and fidelity of entangled photon pair sources.

The route to monolithic integration has yet to be clearly identified. Although the ability to pick up and position a single quantum emitter is undeniably impressive and immensely useful for development, it should not be considered a genuinely scalable solution. A scalable on-chip platform lies in growth architectures compatible with designs of photonic structures that can provide high coupling efficiencies. The growth of nanowires oriented parallel to the growth substrate will greatly facilitate progress in this area, allowing for new design concepts for coupling to waveguide and cavity structures. This geometry is also more suited to the incorporation of electrical contacts and gates, important for charge state control in nanowire QDs [112].

Ideally QD nanowires should be integrated with the silicon-on-insulator (SOI) platform and use silicon as the waveguiding material. This will entail developing sources operating at telecom wavelengths (e.g. \( \lambda = 1550 \) nm). Quantum sources in this wavelength range have been demonstrated with S–K QDs using the InAs/InP material system [180] and, in principle, should also be attainable using the nanowire platform. To date, single photon emission from the nanowire system has been demonstrated for wavelengths up to \( \lambda \sim 1350 \) nm [48], already compatible with SOI photonic circuits.

An SOI-based nanowire platform would be ideal not only for on-chip optical quantum computing [181, 182] and quantum simulation [183, 184] but will also be beneficial for quantum communication where one can envision sources integrated with on-chip measurement to test the relevant quantum properties [185] combined with efficient off-chip coupling into low-loss telecom fibers [186, 187] using fixed alignment-free techniques for field-deployable, real devices.

Finally, multiple emitters mutually coupled to the same optical mode of a nanowire waveguide is an area only recently being explored. The growth-related spectral splittings of uncoupled emitters need to be disentangled from interaction-mediated splittings [175]. This can be done, for example, with an additional tuning mechanism for controlling the resonance energy of the emitters [178]. Coupling QDs together opens up a rich field of coherent coupling effects relevant for future photonic quantum technologies that require multiple interacting emitters.

ORCID iDs

Dan Dalacu © https://orcid.org/0000-0001-6204-3952

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