

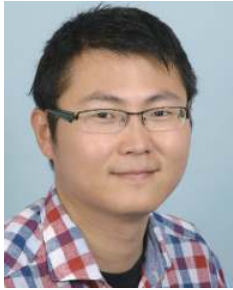
Quantum light sources from semiconductor

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ally at a low count rate imposed by Poisson statistics, QDs can generate single photons deterministically with high-purity (i.e., low multiphoton emission probability), high-brightness (i.e., short radiative lifetime and large collection efficiency), and high indistinguishability. Thanks to the rapid development of material growth and nanofabrication techniques, the figure-of-merits of these quantum emitters have been continuously improved since the first proof-of-concept demonstration of single photon emission 20 years ago^[2, 3]. By embedding a single self-assembled InGaAs/GaAs QD in a nano-pillar photonic structure, the issue of low photon-extraction efficiency from high refractive-index materials is well solved, and a benchmark extraction efficiency of 66%^[4], corresponding to a detection rate of 13 MHz, has been achieved. Moreover, Purcell effect, produced by spectrally and spatially coupling a QD to the photonic mode of a high-quality cavity, can significantly speed up the spontaneous decay, which is not only beneficial for enhancing the brightness of light source, but also favorable regarding the indistinguishability of scattered photons. By exploiting this marvelous effect, near-optimal performance of single-photon emission has been demonstrated with a purity of 0.0028 and indistinguishability of 0.996^[5], which is 20 times brighter than other source of equal quality. Further, electrical tuning of the emission wavelength has been demonstrated in such epitaxial semiconductor structures^[6] and first examples of QDs-based electrically-injected single photon sources have been already published^[7, 8].

Semiconductor provides a physics-rich environment to host various quantum light sources applicable for quantum information processing. These light sources are capable of deterministic generation of non-classical photon streams that demonstrate antibunching photon statistics, strong indistinguishability, and high-fidelity entanglement. Some of them have even successfully transitioned from proof-of-concept to engineering efforts with steadily improving performance. Here, we briefly summarize recent efforts and progress in the race towards ideal quantum light sources based on semiconductor materials. The focus of this report will be on group III–V semiconductor quantum dots, defects in wide band-gap materials, two-dimensional hosts and carbon nanotubes, as these are well-positioned to benefit from recent breakthroughs in nanofabrication and materials growth techniques.

Semiconductor quantum dots? Similar to the single atomic system, group III–V quantum dot (QD) possesses discrete energy levels owing to the three-dimensional confinement of charge carriers. Type-I band misalignment (straddling configuration) between the dot and the host materials allows the capturing of both electrons and holes in the potential well to form localized exciton, trion, or biexciton state within the nanostructure. Radiative recombination of these charge-carriers leads to single-photon emissions featuring a narrow linewidth of a few GHz at cryogenic temperature. By carefully controlling the charge and nuclear-spin environment, emission with transform-limited linewidth are demonstrated for both exciton and trion state^[1]. Comparing to the conventional SPDC quantum light source where single photons are generated probabilistic-

ally at a low count rate imposed by Poisson statistics, QDs can generate single photons deterministically with high-purity (i.e., low multiphoton emission probability), high-brightness (i.e., short radiative lifetime and large collection efficiency), and high indistinguishability. Thanks to the rapid development of material growth and nanofabrication techniques, the figure-of-merits of these quantum emitters have been continuously improved since the first proof-of-concept demonstration of single photon emission 20 years ago^[2, 3]. By embedding a single self-assembled InGaAs/GaAs QD in a nano-pillar photonic structure, the issue of low photon-extraction efficiency from high refractive-index materials is well solved, and a benchmark extraction efficiency of 66%^[4], corresponding to a detection rate of 13 MHz, has been achieved. Moreover, Purcell effect, produced by spectrally and spatially coupling a QD to the photonic mode of a high-quality cavity, can significantly speed up the spontaneous decay, which is not only beneficial for enhancing the brightness of light source, but also favorable regarding the indistinguishability of scattered photons. By exploiting this marvelous effect, near-optimal performance of single-photon emission has been demonstrated with a purity of 0.0028 and indistinguishability of 0.996^[5], which is 20 times brighter than other source of equal quality. Further, electrical tuning of the emission wavelength has been demonstrated in such epitaxial semiconductor structures^[6] and first examples of QDs-based electrically-injected single photon sources have been already published^[7, 8].

QDs are also promising platform for generating polarization-entangled photon pairs based on the radiative cascades from a biexciton state. Resonant two-photon pumping can deterministically create a biexciton in the QD, enabling on-demand generation of entanglement photon pairs at a high-yield rate^[9]. The entanglement fidelity of the photon pairs is limited by the fine structure splitting of exciton state, originating from the exchange interaction between electron and hole confined in an asymmetric QD. If the splitting is larger than the emission linewidth, which-path information may leak out by the color of the photons, and the entanglement may collapse. A direct way to improve the fidelity to recover the circular symmetry of the confinement potential. Nano-hole filling QD achieve this goal by prepatterning symmetric holes via droplet etching before filling with dot material^[10], which shows an improved entanglement fidelity of 94%^[11]. By employing active strain-tuning techniques, for example, PMN-PT/silicon micro-electromechanical system^[12], the shape of the dot can be further manipulated with fine adjustment, leading to the remark-

able entanglement fidelity of 99%^[13]. This value evenly matches the benchmark of the best probabilistic entangled photon sources. Moreover, by using bidirectional tuning of the strain, the emission wavelength of QD can be tuned by several meV without compromising the fine structure splitting^[12]. This partially alleviates the plague of inhomogeneous distribution of emission energy of semiconductor QDs. In addition, the presence of extra binding energy for bi-exciton results in an energy difference for the two emitted photons, thus a broadband antenna is needed to boost the photon extraction efficiency. Recently, by fabricating a circular-ring grating on a quantum dot membrane^[14] or utilizing a solid immersion lens to efficiently couple out the evanescent light waves^[15], an extraction efficiency of more than 60% for entangled photon pairs are demonstrated.

Since the emission wavelength of QD is determined by the physical size of the confinement potential well, which is extremely hard to control during epitaxial growth or nanohole engineering, a broad inhomogeneous distribution of photon energy is expected from an ensemble of QDs, which can be troublesome for applications requiring single photons to be indistinguishable. In addition, the shallow carrier confinement in As-based QDs limits their operation temperature to cryogenic one, rendering them cumbersome and economically unfriendly for applications in the field of quantum information processing (QIP).

Color centers in diamond? Up to date, more than 500 different optical-active impurities have been identified in diamond^[16], which are coined color centers, with emission wavelengths covering a wide range of spectrum from ultraviolet to near-infrared. Although negatively charged nitrogen vacancy (NV) center is the first color center investigated as single-photon source in diamond, its relatively poor optical properties hinder its potentials as a building block for QIP. The strong electron-phonon coupling in NV centers significantly broadens its emission spectrum leading to a weak zero-phonon-line (ZPL) at 637 nm and a strong but broad phonon sidebands (PSBs) extending up to 800 nm at room temperature. Even at 4 K, only 3% of the fluorescence is emitted into the ZPL which exhibits a lifetime-limited linewidth of 13 MHz^[17]; moreover, the emission from NV centers suffer from significant spectral diffusion^[18] and fluorescence intermittency^[19]. All these deficiencies have fueled the investigation for alternative emitters that combine bright, homogeneous, and coherent optical transitions together. Among them, silicon-vacancy (SiV) center in diamond is a promising candidate. Unlike the C_{3v} point group exhibited by NV center^[20], the molecular structure of negatively charged SiV center possesses D_{3d} symmetry, where the Si atom takes the interstitial position between two adjacent vacancies in diamond^[21]. This inversion-symmetric structure guarantees a vanishing permanent electric-dipole moment, rendering the system insensitive to the first-order Stark shift caused by the local electric-field fluctuations of the environment. This lack of susceptibility efficiently mitigates the spectral diffusion of the system, allowing for the observation of lifetime-limited linewidth^[22] and the implementation of two-photon interference by using the light from two distinct sources^[23]. Moreover, SiV center scatters 70% of photons into ZPL line^[24, 25] with a brightness of 6 million counts/s^[26]. The nearly linear polarization of ZPL fluorescence at room temperat-

ure^[24, 27] is favorable for information encoding in quantum cryptography applications. Meanwhile, SiV center can be integrated into various nano-photonic structures, including nanopillar^[28], waveguide^[29], and 2-dimensional photonic crystal cavity^[30, 31], for performance promotion or construction of quantum photonic circuits. One trade-off of choosing diamond as host material is the sacrifice of technological maturity, which would become a critical factor for any large-scale applications, such as quantum network and distributed quantum computers.

Defects in other wide-bandgap materials? Both wide bandgap materials, GaN and SiC, are backed by strong industrial supports. SiC has been used as abrasive since 1893, and made as the first light-emitting diode (LED) for electroluminescence in 1907. Shortly thereafter, SiC-based commercial LED was introduced and manufactured until 1980s, when the first GaN-based blue LED is developed and commercialized^[32]. Since then, GaN has become the second most important semiconductor worldwide in terms of business share, just behind silicon. Both materials are widely used in various applications including high-voltage power transportation, solid-state microdisplays, and high-frequency electronics, providing the needed technological maturity for scaling up the potential devices based on these two materials.

Recently, the discoveries of room-temperature optically-active emitters in standard GaN thin films with an emission wavelengths covering 1.1–1.4 μm range^[33] sheds lights on searching for telecom-band compatible, ambient, and on-demand quantum light source for long-distance quantum communication. However, the nature of these bright quantum emitters is still not clear, mainly two hypothetical mechanisms: cubic inclusions (i.e. stacking fault defects) within a GaN hexagonal matrix^[33–35]; point defects or impurities whose density is modulated by the local extended defect density^[36]. Elucidation of the nature of the defect at the origin of the single-photon emission is mandatory to push the exploitation a step further.

SiC-based single-photon emitters (SPEs) also captures significant amount of attention recently, thanks to the progress on silicon vacancies V_{Si} and di-vacancy $V_{\text{Si}}V_{\text{C}}$ defects, which have been found to be optically addressable on single defect level and behave as single photon emitters^[37, 38]. These single-photon emitters exhibited excellent photon statistics, with a typical lifetime of 1.2 ns. Combined with a high internal quantum efficiency of 0.7, the defects are amongst the brightest defect based single photon sources, with saturation count rates of up to 2 Mcps^[39]. While the high emission rates and quantum efficiencies are promising, the spectral variability makes integration into photonic circuitry and cavities challenging^[40].

Defects in two-dimensional materials? Currently, there are mainly two types of emitters prevailing in 2D material hosts. The first type is called QDs, whose emission originates from a bound exciton confined within a zero dimensional potential generated by local strain and/or a crystallographic defect. These quantum emitters, including WSe_2 ^[41–45], MoSe_2 ^[46, 47], WS_2 ^[48], and GaSe ^[49], emits a range of wavelengths from 600 to 780 nm, but operate exclusively at cryogenic temperatures due to shallow confinement potential^[50]. The second type is

single point defects or impurities in wide-bandgap materials. In the context of 2D crystal, it usually refers to hexagonal boron nitride (hBN)^[51, 52] with a bandgap of approximately 6 eV^[53], which can host a broad range of SPEs with ZPL energies covering a wide range of wavelength from UV to NIR. SPEs emitting at NIR light (1.6–2.2 eV) exhibit a range of promising properties, including room-temperature compatibility^[51], exceptional brightness of > 4 Mcps^[54] at the detector in the absence of cavity or immersion lens, linear in-plane polarization, low PSB concentration, and exceptional chemical, thermal, and photostability^[55]. Moreover, Fourier transform limited linewidths has also been observed single defect centers in layered hBN^[56], which remarkably persist all the way to room temperature when using resonant excitation^[57]. This offers new opportunities towards room temperature quantum circuitry, realization of quantum repeaters and quantum information protocols. On the other hand, the nature of these emitters is still under debate. Although theoretical studies^[58–61] over a number of defect structures suggest multiple valid possibilities, such as $V_N N_B$ ^[51], $V_N C_B$, or $V_B O_2$ configurations, experimental works are inconclusive to pinpoint the exact configuration mainly broad window of ZPLs allowed by numerous defects. Identification of the atomic structures of emitters in hBN is needed for deterministic generations and fabrications in large-scale deployment in various quantum applications. Moreover, almost all emitters in hBN studied to date have been shown to suffer from spectral diffusion, blinking, and bleaching, which indicates pronounced interactions between emitters and their local environment^[50].

Carbon nanotubes? In principle, single-photon emission requires a quantum mechanical quasi-two-level system in a single emitter, yet carbon nanotubes (CNTs)^[62] conflicts this major requirement by exhibiting one-dimensional freedom. Fortunately, recent developments in low-level covalent functionalization chemistry of CNTs provide a route to get around this issue. These include functionalization of the nanotube sidewall with oxygen groups via ozonation chemistry^[63], or by using diazonium-based reactions to introduce aryl sp³ defects within the continuous sp² structure of the nanotube^[64]. Both routes generate exciton localization at these synthetic defect sites with well depths of 100 meV or greater^[65], allowing to achieve single-photon emission at telecom wavelengths up to room-temperature^[66, 67] along with an enhanced apparent quantum yield (10%–30%)^[63, 64]. Thereby, CNTs are another promising single-photon source capable of telecom-wavelength emission, room-temperature operation, and electric injection^[68, 69]. Further, the use of individual nanometric emitting objects open very interesting perspectives in terms of miniaturization^[69], but it obviously brings about enormous challenges in terms of device fabrication and electronic-environment isolation: in this sense, while proof-of-concept devices can be envisaged and have been indeed recently realized^[70], the issues of scalability and fabrication yield remain very challenging. Similarly, the compatibility of carbon nanotubes with materials necessary to fabricate photonic devices (e.g. Si, SiO₂, Si₃N₄) and their detrimental impact on quantum yield remains problematic^[71].

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