REVIEWS

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Electrically driven single-photon sources

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Abstract: Single-photon sources are building blocks for photonic quantum information processes. Of the many single-photon generation schemes, electrically driven single-photon sources have the advantages of realizing monolithic integration of quantum light sources and detectors without optical filtering, thus greatly simplify the integrated quantum photonic circuits. Here, we review recent advances on electrically driven single-photon sources based on solid-state quantum emitters, such as semiconductor epitaxial quantum dots, colloidal quantum dots, carbon nanotubes, molecules, and defect states in diamond, SiC and layered semiconductors. In particular, the merits and drawbacks of each system are discussed. Finally, the article is concluded by discussing the challenges that remain for electrically driven single-photon sources.

Key words: single photon sources; electrically driven; integrated quantum photoncs

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1. Introduction

Quantum information techniques are recognized to have greatly enhanced performance in communication, computation, and measurement over the classical ones[1]. Optical qubits based on single-photons have been widely used due to the ability to preserve their quantum states over long distances and to propagate at the speed of light[2]. Additionally, optical qubits can be coherently controlled by standard optical components such as beam splitters, waveplates and mirrors. However, with the increasing size and complexity of the experimental realizations, the optical systems based on bulk optical components suffer from the difficulties of stability and scalability[3]. Integrated quantum photonics is one of the most promising approaches to address these problems. Core components such as on-chip single-photon sources (SPSs)[4], circuit-based quantum gates[5, 6], thermos or electro-optic phase shifter[7], single-photon buffers[8] and single-photon detectors[9, 10] have been demonstrated in various material platforms. Virtually a complete toolbox is ready to develop fully integrated quantum photonic circuits. Nevertheless, functional circuit integrated with single-photon generation, manipulation and detection on a single chip has not been realized. The main challenge comes from the fact that in most cases, single-photons are prepared using optical excitation schemes, either via nonlinear optical parametric processes or from the emission of single quantum emitters[11]. Particularly, the numerous remaining pump photons are difficult to be filtered out on chip, which overwhelm the single-photon signals.

Electrically driven SPS based on semiconductor p–n structure is a straightforward solution to this problem. Once a voltage is applied on such device, carriers can be injected into a single quantum emitter buried in the junction region and single-photons can be generated. Thus, the lack of optical pumping renders the monolithic integration of SPSs and detectors without optical filtering possible. However, additional sophisticated growth and fabrication processes are usually needed to ensure efficient electrical excitation comparing to the optical excitation schemes. Nevertheless, electrically driven SPSs have been realized in various semiconductor systems based on quantum dots (QDs)[12–18], carbon nanotubes[19], organic molecules[20] and defect states[21–24]. Majority of these devices are working at cryogenic condition, while the few room-temperature demonstrations shed light on the practical quantum information applications, even though several challenges have to be dealt with in both cases.

We organize this review as follows: In the second part, we introduce the important properties of a SPS for practical applications, and the ways to characterize them. In the third part, we review recent progresses in electrically driven SPSs based on different solid-state quantum emitters, including quantum confined materials such as semiconductor QDs and carbon nanotubes, single molecules and defect states. Finally, remaining challenges for electrically driven SPSs are discussed.

2. The basics of single-photon sources

An ideal SPS emits exactly one photon at a given time into a particular polarization and spatial mode. From a practical point of view, the most important factors that evaluate the performance of a SPS are single-photon purity, determinacy and brightness. While in many quantum information applications, indistinguishability is also required so that single-photons are identical to each other in all their freedom of degrees.

Single-photon purity denotes how well the source satisfies the SPS criterion that each light pulse generated contains no more than one photon. This property can be characterized by the second-order intensity correlation function $g^{(2)}(\tau)$ in term of the classical intensity of the light field as[25]:

$$g^{(2)}(\tau) = \frac{< I(t+\tau)I(t) >}{< I(t) >^2}, \qquad (1)$$

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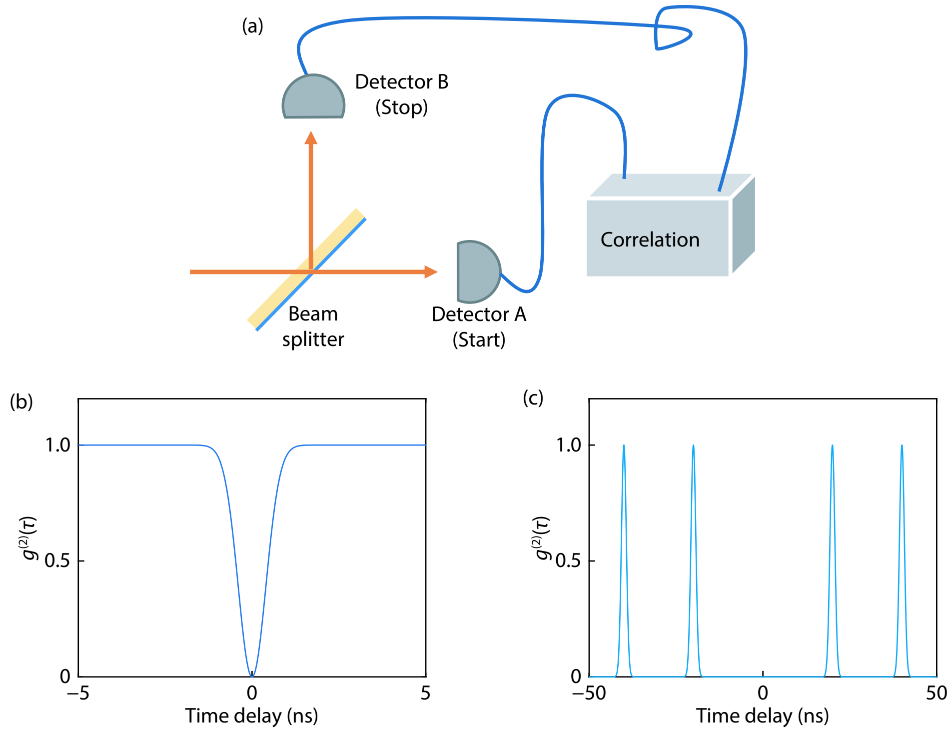

Fig. 1. (Color online) (a) Schematic diagram of a Hanbury Brown and Twiss experiment. Second-order correlation function $g^{(2)}$ (τ) of an ideal SPS working in continuous wave mode (b) and pulse mode (c).

While in quantum mechanics, it can be expressed as:

$$g^{(2)}(\tau)=\frac{<\hat{a}^{+}(t)\hat{a}^{+}(t+\tau)\hat{a}(t+\tau)\hat{a}(t)>}{<\hat{a}^{+}(t)\hat{a}(t)>^{2}}, \tag{2}$$

where $\hat{a}$ ($\hat{a}^{+}$) is the photon annihilation (creation) operator. When $\tau=0$, $g^{(2)}(0)$ reflects the statistics property of the light source. For a coherent light (laser) source, the number of photons follows Poisson distribution, which results in $g^{(2)}(0)=1$. And a conventional incoherent source, or thermal light, follows super-Poisson distribution and has $g^{(2)}(0)=2$. In contrast, a nonclassical sub-Poisson light satisfies $g^{(2)}(0)<1$, and particularly, for an ideal SPS $g^{(2)}(0)=0$. $g^{(2)}(0)$ can be measured using a Hanbury Brown and Twiss (HBT) setup experimentally[26], as shown in Fig. 1. $g^{(2)}(0)=0$ indicates that the possibility of two or more photons to be detected simultaneously by the two detectors is zero.

As mentioned above, SPSs can not be prepared from a classical light source, as either a coherent or a thermal light source will always generate multi-photons at the same time with certain probability, no matter how such a source is attenuated. There are mainly two ways to generate single-photons. The most widely used SPSs are based on spontaneous parametric down-conversion or spontaneous four-wave mixing. However the nonlinear optical processes occur randomly, and single-photons are generated in a probabilistic way. On the other hand, quantum emitter based on a single two-level system can generate single-photons in a deterministic way (on-demand) under certain excitation condition[27].

However, in the real world, there always exists loss in the system. Even an deterministic source will be probabilistic when the optical loss increases. The property of brightness implies the overall probability of collecting photons when the loss of a the system is considered. Together with the source repetition rate, brightness determines the speed of quantum information process, which is critical for system scaling.

Indistinguishable single-photons are essential for many quantum applications, especially in constructing quantum gates. The property that photons hardly interact with each other hinders the implement of nonlinear optics schemes in scalable quantum information processes. The linear optical protocol which uses linear optical elements, single-photons and photon detectors can solve this problem, however requiring the single-photons to be indistinguishable. Indistinguishability can be characterized by Hong-Ou-Mandel (HOM) interference[28], as shown in Fig. 2. When two indistinguishable photons hit on the beam splitter with perfect spatial and temporal overlap, there are four possible outcomes. However, the destructive interference cancels the probabilities of two events. As a result, both photons scatter into the same output.

The degree of indistinguishability can be evaluated by HOM visibility. In practice, the HOM visibility may not reach unity due to the coupling between the quantum emitter and environment, especially for a solid-state system. Phonon interaction and fluctuating electric/magnetic field will introduce dephasing that shorten the coherence time of the photon, and thus lower the degree of indistinguishability of generated single-photons.

Other than the factors discussed above, for practical applications, there also exist other essential standards for SPSs like working at room temperature, pump by electricity, emission spectral range and so on.

3. Electrically driven single-photon sources

SPSs based on the optical pump are more mature than those driven by electricity. However, the demands of fully integ-

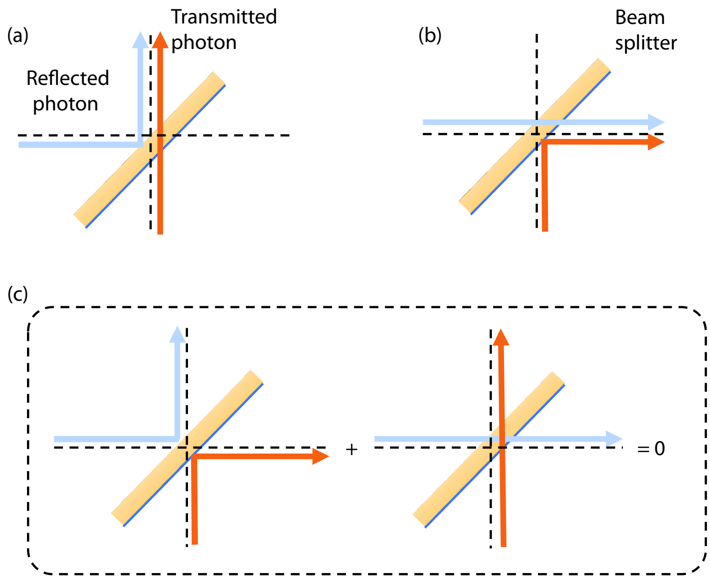

Fig. 2. (Color online) When two indistinguishable photons encounter a beam splitter simultaneously, the two paths in (a) and (b) are observable, while the two paths in (c) interfere destructively and cancel each other.

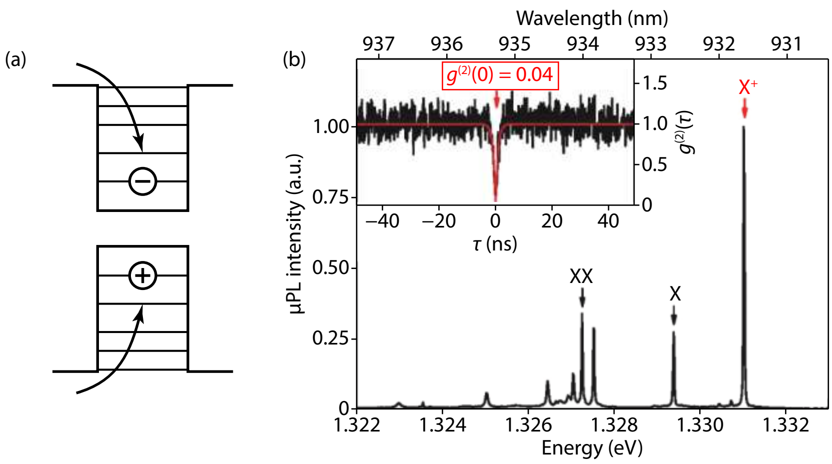

Fig. 3. (Color online) (a) Schematic diagram of forming an exciton state in a QD. (b) Spectrum of a single QD. The exciton (X), biexciton (XX) and singly charged exciton (X^+) emission lines were identified at 10 K[30]. Panel (b) adapted with permission from Ref. [30]. Copyright 2013, American Institute of Physics.

rated quantum photonic circuits promote the development of electrically driven SPSs. Of the two schemes that may generate single-photons, the nonlinear optical processes can not be realized by electrical pumping. For a two-level like system, the spontaneous relaxation from excited state to the ground state will emit one, and only one, photon at a time. SPSs based on single quantum emitters have been demonstrated in systems such as atoms, ions, molecules, defect states and semiconductor QDs. Fortunately, most of the solid-state emitters are compatible with electrical excitation scheme. To efficient inject carriers into a electrically driven SPS and populate the excited state, the device usually incorporates a p–n junction to form a single-photon emitting diode. In the following part, we explore realizations of electrically driven SPSs based on various solid-state systems in detail.

3.1. Semiconductor quantum dots

An early proposal on electrically driven SPS was utilizing the Coulomb blockade and quantum confinement effects based on a mesoscopic semiconductor p–i–n heterostructure[29]. However, extreme cryogenic temperature ($T = 0.1$ K) was required for this structure. A more promising semiconductor candidate is QD. QD is often referred to as “artificial atom”, as strong three-dimensional spatial confinement results in discrete energy-level spectrum, like that of an atom. As shown in Fig. 3(a), when an electron and a hole are injected into a QD, they quickly relax nonradiatively into exciton state. Radiative decay of this exciton results in single-photon emission.

There are a couple of types of QDs that can be used as solid-state SPSs. Epitaxial QDs grown by molecular beam epitaxy (MBE) or metal-organic chemical vapour deposition (MOCVD) in the Stranski-Krastanov mode are the most widely studied ones. A lattice-mismatched material is firstly grown on a semiconductor substrate to form an epitaxial wetting layer. When the thickness of this layer reaches a critical value, tiny self-assembled islands start to form in order to minimize the surface strain. Various material systems have been investigated as candidates for epitaxial QDs, such as III–V arsenide, phosphide or nitride based QDs, II–VI telluride or selenide based QDs, with

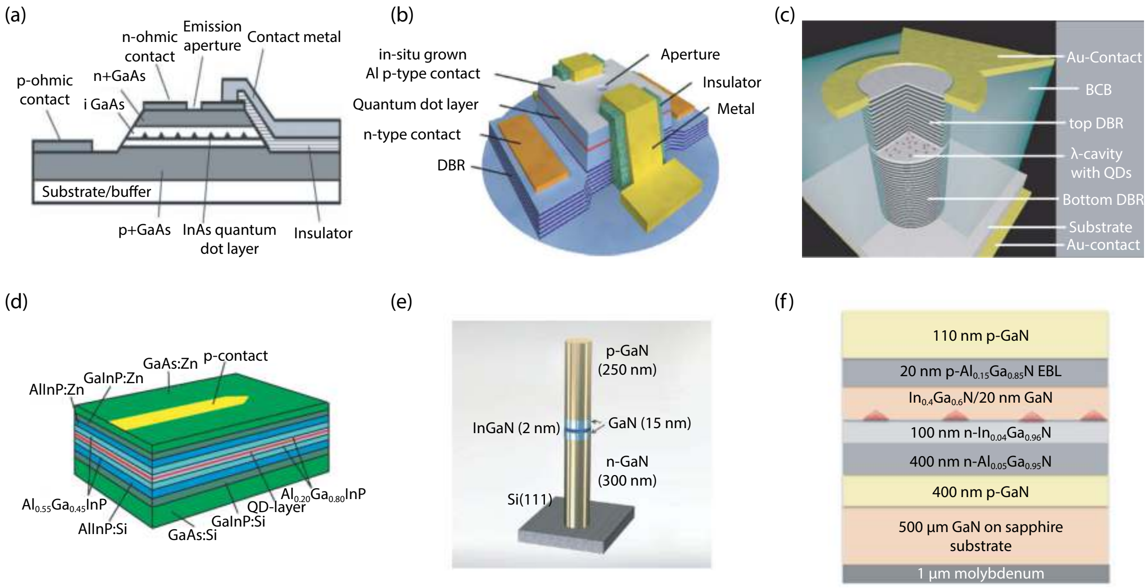

Fig. 4. (Color online) (a) Schematic of a single-photon emitting diode in cross section[12]. (b) Improved device structure by integrating with a planar cavity. The lateral dimensions of the mesa are 60×40 μm^2[13]. (c) Illustration of the indistinguishable-photon emitting diode based on a QD micropillar cavity structure[17]. (d) Structure of an electrically driven SPS based on InP QDs[32]. (e) Schematic of an InGaN dot-in-GaN nanowire p–n junction grown on (111) silicon by MBE. A 2-nm quantum dot is placed at the center of doped GaN regions[14]. (f) Schematic of the heterostructure grown on GaN-on-sapphire by MBE to form a single-photon diode[15]. Panel (a) adapted with permission from Ref. [12]. Copyright 2002, American Association for the Advancement of Science. Panel (b) adapted with permission from Ref. [13]. Copyright 2007, American Institute of Physics. Panel (c) adapted with permission from Ref. [17]. Copyright 2010, American Institute of Physics. Panel (d) adapted with permission from Ref. [31]. Copyright 2008, The Optical Society. Panel (e) adapted with permission from Ref. [14]. Copyright 2013, Springer Nature Publishing AG. Panel (f) adapted with permission from Ref. [15]. Copyright 2014, American Institute of Physics.

emission wavelengths ranging from ultraviolet to telecom wavelength. Though many of the epitaxial QDs work at cryogenic temperature, QDs based on wide band gap semiconductors may operate at high or room temperature.

At present, the best-performing QD-based SPSs are made of InAs/GaAs QDs. Fig. 3(b) shows a typical low temperature photoluminescence spectrum of a single QD. Here multiple excitation states can be observed, which may degrade the single-photon properties. Fortunately due to Coulomb interaction, photons from exciton state (X), biexciton state (XX) and charged exciton (X^+, exciton with an extra hole) have distinct energies. Thus a spectral filtering mechanism is usually needed to single out just one emission line, either externally or via microcavity resonance. SPSs with high single-photon purity and indistinguishability have been reported based on InAs QDs, though via optical excitation[27, 31].

The epitaxial growth procedure of QDs makes them feasible to be integrated in conventional p–i–n light emitting diode (LED) structure. In 2002, shields *et al.* presented the first electrically driven SPS, as shown in Fig. 4(a). The semiconductor layer was grown by MBE and the InAs QDs were inserted into the intrinsic region. Working at 5 K, the single QD emission exhibited two sharp emission lines, which respectively represented exciton and biexciton peaks. By extracting the exciton electroluminescence, the clear anti-bunching of the second-order correlation function under continuous or pulse drive indicated single-photon generation. Due to the high refractive index of GaAs material, the single-photon extracting efficiency was very low. This structure was subsequently improved by integrating a planar cavity with the LED, as shown in Fig. 4(b)[13]. By cavity enhancement, the collection efficiency was increased. Under 10 K temperature and 1.4 V voltage, the electroluminescence spectra showed a peak around 1.3 μm and the second-order correlation was measured as $g^{(2)}(0) = 0.28$ which indicated the suppression of multiphoton. By coupling a single QD to a vertical micro-pillar cavity, the single-photon collection efficiency was greatly enhanced, as shown in Fig. 4(c)[17]. With larger quality factor and small mode volume of the microcavity, the Purcell effect promoted the overall single-photon extraction efficiency to (34 ± 7)%. This value was almost doubled several years later by the same group. Overall single-photon extraction efficiency reached (61 ± 11)% with electrical excitation repetition rates up to 1.2 GHz. Moreover, a photon-indistinguishability of (41.1 ± 9.5)% was measured by the HOM experiment, with a single-photon emission rate of (92 ± 23) MHz[33].

Though the performance of InAs QD based SPSs at low temperature are promising via either optical or electrical excitation, their applications at higher or room temperature are difficult due to the low exciton bondage energy. III–V epitaxial phosphide or nitride based QDs that possess larger exciton bondage energies have been explored with blue shifted working wavelength range. Electrically driven SPS based on InP QDs working at 80 K was demonstrated, and the emission was in the red spectral range (670 nm)[32], as shown in Fig. 4(d). Nitride based QDs are expected to be able to operate at ambient condition. The first work was demonstrated from a InGaN QD in a GaN nanowire, as shown in Fig. 4(e)[14]. Single-photon emission at 435 nm was measured when the sample was cooled to 10 K. Shortly after that, the working temperature in-

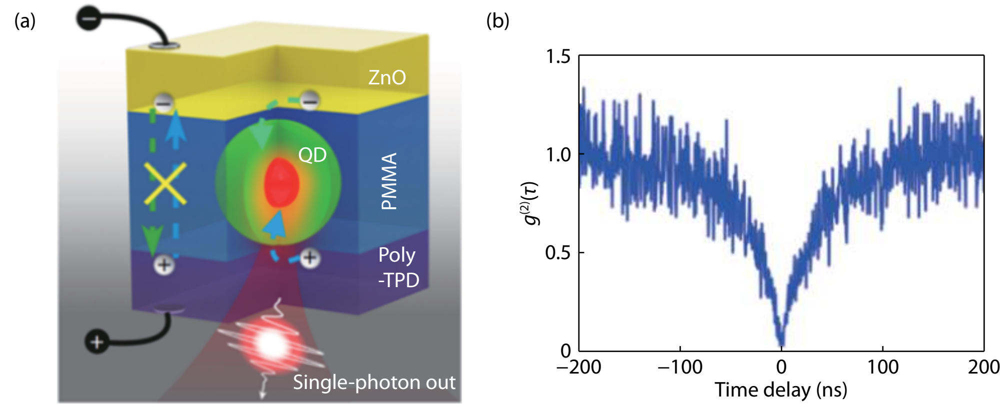

Fig. 5. (Color online) (a) Schematic diagram of the key components of a electrically driven SPS based on CQD. (b) $g^{(2)}(\tau)$ curve of a quantum-dot driven at 2.6 V indicates the generation of single-photons with high purity[18]. Panel (a) and (b) adapted with permission from Ref. [18]. Copyright 2017, Springer Nature Publishing AG.

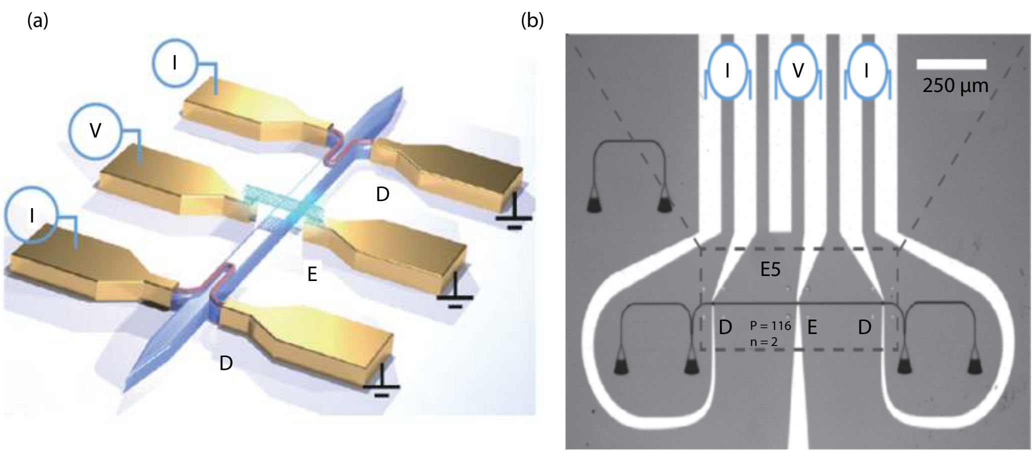

Fig. 6. (Color online) (a) Schematic view of a waveguide with integrated single carbon nanotube and two SNSPDs. (b) Optical micrograph of the metallic contacts and the waveguide. The positions of the detectors and emitter are denoted by D and E, respectively[19]. Panel (a) and (b) adapted with permission from Ref. [19]. Copyright 2016, Springer Nature Publishing AG.

creased to 150 K, while the single-photons was at 520 nm[34]. A later demonstration from the same group showed a room temperature (280 K) electrically driven SPS at 630 nm[15], as shown in Fig. 4(f). The fast recombination lifetime of 1.3 ns and 200 MHz excitation repetition rate promise the potentiality on high-speed quantum communication and computation. Other than III–V epitaxial QDs, II–VI based epitaxial QDs also have the potential to work at room temperature. Epitaxial CdSe/ZnSSe single quantum dot embedded into a p–i–n diode with single-photon emission at 200 K was demonstrated when a DC bias of 5.8 V was applied[35].

Semiconductor colloidal QDs (CQDs), or nanocrystals, synthesized by wet chemical approaches are another kind of QDs that have been studied extensively as room-temperature sources of single-photons since the first report in 2000[36]. Different from the strain induced self-assembled process of epitaxial QDs that causes randomness in QD sizes, the monodisperse size of the CQDs can be controlled with almost atomic precision. Near-unity photoluminescence quantum yield is confirmed for a number of material systems of CQDs at room temperature, while the troublesome photoluminescence blinking of a CQD is greatly suppressed. Besides, wet-chemistry syntheses of CQDs and inherent property of solution-based process grants the CQDs the flexibility for low-cost device fabrication, including thin-film assembly process. Recently, electrically driven SPS at room temperature based on CdSe/CdS core/shell CQDs was demonstrated with high single-photon purity[18]. The device structure and fabrication process were similar to those of ordinary CQD LEDs, however the isolated CQDs as quantum emitters were buried in an insulating layer that was sandwiched between electron and hole-transport layers, as shown in Fig. 5(a). This insulating layer played an critical role in generation high-purity single-photons, as it greatly suppressed the background emission from carrier-transport layers. Such devices with virtually background free single-photon signals are suitable for room-temperature fully integrated quantum photonic circuit as no spectral filtering is needed.

3.2. Carbon nanotubes

Other than the three-dimensionally confined (or zero-dimensional material) QDs, two-dimensionally confined (or one-dimensional material) semiconductors such as single-walled carbon nanotubes have been reported as single-photon emitters at low temperature[37]. Due to the Auger processes, the photoluminescence from a single nanotube exhibited photon antibunching.

The first full integrated quantum photonic circuit was demonstrated in carbon nanotube system[19]. As shown in Fig. 6,

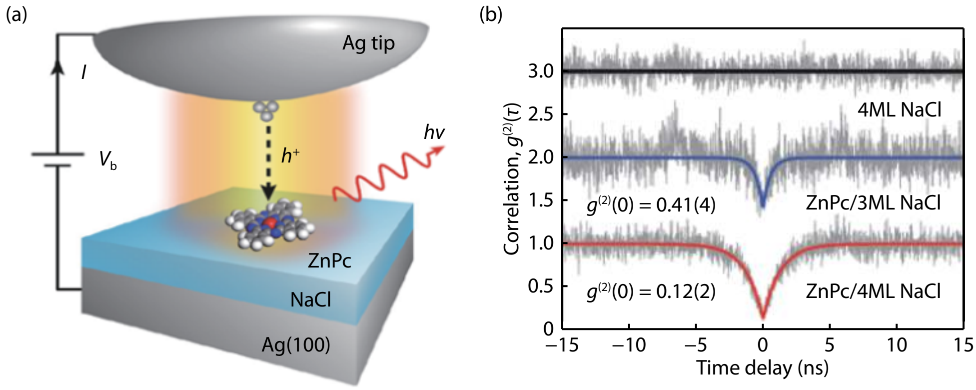

Fig. 7. (Color online) (a) Schematic diagram of STM-induced fluorescence from a single molecule. Molecular fluorescence was generated by the excitation of highly localized tunneling electrons over a single ZnPc molecule that was decoupled by NaCl layers from the Ag(100) substrate. (b) Second-order correlation measurements of single-molecule electroluminescence[20]. Panel (a) and (b) adapted with permission from Ref. [20]. Copyright 2017, Springer Nature Publishing AG.

a single carbon nanotube was coupled to an on-chip waveguide, so that the generated electroluminescence was collected by the waveguide. With two superconducting nanowire single-photon detectors (SNSPDs) integrated at both ends of the waveguide to construct HBT configuration, photon correlation was measure directly on chip. Without any optical filtering, pronounced photon antibunching was observed when a DC voltage was applied, and emission count rate was above $1{\times}10^5$. To enable reliable operation of the SNSPDs, the experiment was carried out at 1.6 K.

3.3. Single molecules

Unlike quantum confined semiconductor systems whose emission energies can be tuned by the sizes of nanostructures, molecules are atomic like systems with fixed electronic states. Different from atom systems, vibrations and phonons are usually strongly involved in luminescence of molecular systems. The excitation of phonon states are strongly dependent on temperature. At low temperature, only the lowest lattice vibration is excited. So the transition between the ground electronic state and excited electronic state shows a very narrow line which is called the zero-phonon line[38]. However, at room temperature, thermal fluctuation causes fast dephasing of the electronic oscillations which broaden the width lines, as many of the higher phonon levels are involved. Nevertheless, the adequate exciton binding energies of organic molecules make them feasible for room temperature operation.

Organic fluorescent molecules have for a long time served as a tool for imaging and lighting. And the optically excited dye molecule SPS demonstrated in 2000 is the poineering work for room-temperature SPSs based on quantum emitters[39]. While the organic LED (OLED) have been developed for decades with successful applications in portable electronic devices, electrically driven SPS based on OLED structure has not been demonstrated yet. A not very successful approach was using a single phosphorescent $Ir(piq)_3$ molecule imbedded in a solid-state matrix which achieved sub-Poisson photon statistics with $g^{(2)}(0)$ slightly smaller than 1[40]. This is probably because of the lack of an effective mechanism to suppress the background emission in the device.

Interestingly, the first demonstration of electrically driven molecule SPS was based on a technique called scanning tunneling microscope (STM) induced luminescence[20]. As shown in Fig. 7, a zinc-phthalocyanine (ZnPc) molecule was deposited on a Ag substrate yet with a thin sodium chloride (NaCl) spacer layer in between to suppress fluorescence quenching. A silver tip was used to provide tunneling electrons to excite the molecular fluorescence, meanwhile, provided strong resonant plasmonic enhancement. Without any complex electrode structures as OLEDs, the single-photon purity was measured down to $g^{(2)}(0) = 0.09$, yet under ultra-high vacuum (1×10^{-10} Torr) and cryogenic temperature (8 K) experimental condition. Moreover, with the capability of manipulating single molecules with sub-nanometer precision by STM, a single-photon emitter array at nanoscale was also demonstrated with nearly identical feature in the spectral and single-photon emission properties.

3.4. Defect states

A defect state in a crystal, either a missing atom or an impurity atom, introduces a narrow level within bandgap of the crystal material. If transition between such defect level and the ground level absorbs or emits a photon in visible spectrum, the crystal that is usually transparent becomes colored. So defect states are sometimes called color centers in wide bandgap semiconductors. Similar as single molecule, radiative relaxation from a defect state to the ground electronic state will generate sharp ZPL, while broad phonon sideband may show up at room temperature.

Color centers in diamond, particularly nitrogen-vacancy (NV) centers, are prominent candidates for SPSs due to their excellent photostability at room temperature[41]. Though the luminescence spectrum of an NV center is much broader than that of a CQD, the NV center represents other merits of excellent spin characteristic, long coherence time and fast manipulation rate that grant it one of the most favorable room temperature quantum emitters.

The difficulties of realizing electrically driven SPSs based on color centers lie on the synthesis of the electron (n-type) and hole (p-type) conducting materials as well as an ultra-pure intrinsic (i) layers to build up p–i–n diode structures. The first approach was reported in 2011, where the in-plane diodes were fabricated on a high quality single crystal diamond grown by chemical vapor deposition, with implantation of boron and phosphorus ions to form doping p-type and n-type areas, respectively[21]. NV centers were formed during the growth as re-

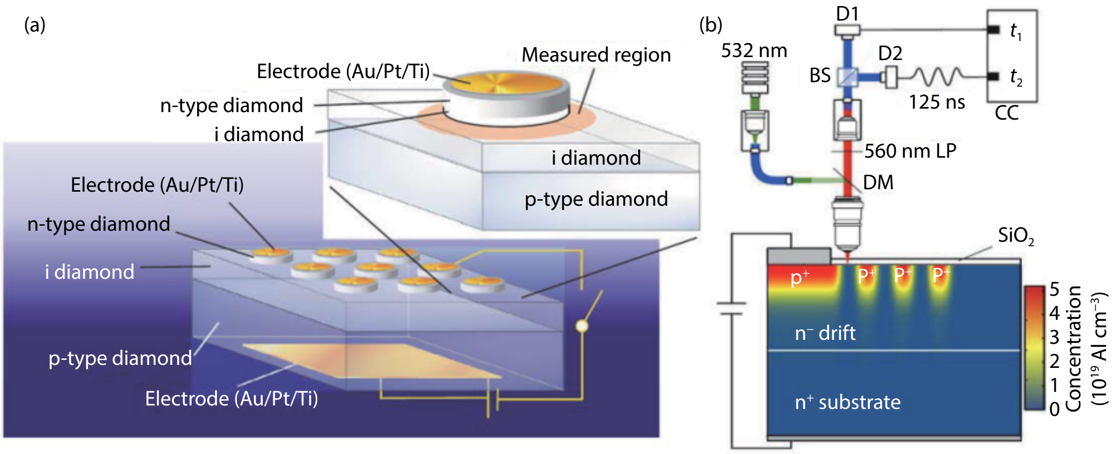

Fig. 8. (Color online) (a) Schematic diagram of the single-photon emitting diode based on NV centers in diamond[22]. (b) Schematic diagrams of SiC SPS and optical measurement setup[24]. Panel (a) adapted with permission from Ref. [22]. Copyright 2012, Macmillan Publishers Limited. Panel (b) adapted with permission from Ref. [24]. Copyright 2015, Springer Nature Publishing AG.

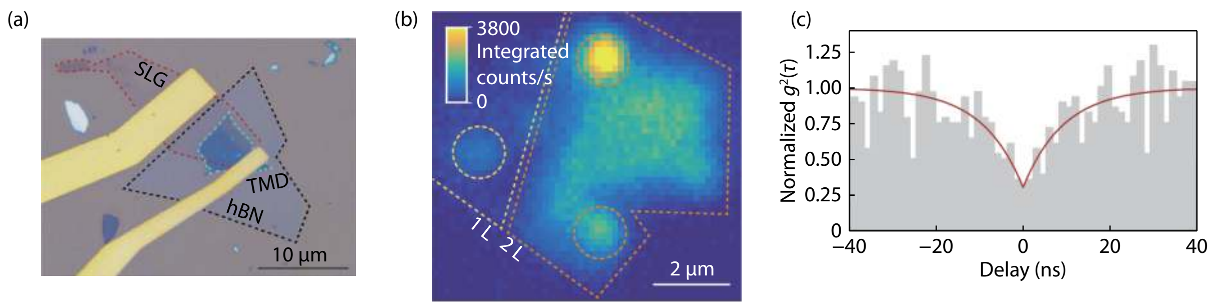

Fig. 9. (Color online) (a) Optical microscope image of a LED device by vertical stacking of thin layer semiconductors. (b) Confocal microscope image of the electroluminescence from monolayer and bilayer WSe_2 areas with an injection current of 3 μA (12.4 V). The dotted circles highlight the submicron localized emission in this device. (c) Second-order correlation measurement of electroluminescence from a single quantum emitter with $g^{(2)}(0) = 0.29 \pm 0.08$[50]. Panel (a), (b) and (c) adapted with permission from Ref. [50]. Copyright 2016, Springer Nature Publishing AG.

sidual nitrogen impurities. Photon antibunching was observed from an isolated NV defect which implied single-photon generation at room temperature, yet with large background. A different diode structure was demonstrated shortly after, where the ultra-pure intrinsic layer and n-type layer were independently grown by CVD on a p-type diamond substrate, as shown in Fig. 8(a)[22]. After growth, round mesa structures were fabricated and nitrogen was subsequently implanted to introduce NV centers in the intrinsic layer. The single-photon purity as $g^{(2)}(0) = 0.45$ and the emission rates of 4×10^4 photon/s was observed when a DC voltage around 30 V was applied. Based on the same structure, deterministic electrical control on the single negatively charge state NV and neutral state NV^0 was reported, which provides an essential role for spintronics and sensing applications[23]. A theoretical work on the single-photon emission dynamics in an electrically pumped system based on NV centers in diamond was reported recently, which was helpful to understand single electron and single-photon processes in semiconductors[42].

Similar to color centers in diamond, single defects in other wide-bandgap semiconductors such as silicon carbide (SiC) and zinc oxide (ZnO) are also possible solutions for room-temperature electrically driven SPSs. ZnO has attractive emission range in ultraviolet and visible spectral with the high exciton binding energy (60 meV)[43]. Localized defects in n-ZnO/p-Si heterojunctions based on ZnO nanoparticles or film were demonstrated, and photon antibunching was observed from an optically excited single defect. However, the photon statistics of electroluminescence was not shown in this report[44]. SiC is compatible with well-developed complementary metaloxide semiconductor (CMOS) processing protocols for on-chip photonic and electronic devices. By using photolithography, ion implantation and annealing, as shown in Fig . 8(b), single defect was integrated in a SiC p-n junction diode and emission at visible spectrum was observed at room temperature. With a long-pass filter to suppress the background luminescence, the photon antibunching with $g^{(2)}(0) < 0.1$ confirmed excellent single photon purity[24]. A theoretic work predicted that the photon emission rate from a p–i–n SiC SPS might exceed 5 G count/s, which was superior to other quantum emitters such as NV centers and epitaxial QDs[45].

Thin layers of semiconducting transition-metal dichalcogenides (TMDs) are emerging platforms for both scientific study and technological applications, providing the potential to be integrated into conventional optoelectronic systems[46]. Single-photon emission from single QDs/defects in TMDs by optical excitation have been demonstrated in 2015[47–49]. And shortly after that, electrically excited ones were reported from

WSe_2 and WS_2 thin films[50]. The LED structure was realized by vertical stacking of a single layer of graphene, a thin sheet of hBN and a mono/bilayer of TMDs on a silicon/silicon dioxide substrate, as shown in Fig. 9. Though these demonstration were all performed at cryogenic temperature, the defects in wide-bandgap thin layer semiconductors such as hexagonal boron nitride show potential of electrically driven SPS at room temperature[51].

4. Summary and outlook

In summary, we have overviewed recent progresses in electrically driven solid-state SPSs for integrated quantum photonics. For all of the realizations, epitaxial InAs QDs exhibit the best performance in terms of single-photon purity and indistinguishability, however, cryogenic environments are usually needed. Wide bandgap epitaxial QDs, colloidal QDs, molecules and many defect states based SPSs show the ability to operate at room temperature, which are favorable for practical applications. Quantum emitters in their freestanding form have the flexibility to integrate with other structures and devices on various substrates, as single carbon nanotubes have demonstrated the monolithic integration of SPS with single-photon detectors.

Despite many remarkable progresses have been done so far, the complex mesoscopic environment of the p-n junction structure entails numerous challenges. Suppressing background emission from auxiliary structures and other excited states is the key to generate single-photons with high purity from integrated SPSs. Fluctuating charges around a quantum emitter can create a fluctuating electric field that gives rise to photon distinguishability from the same emitter under electrical excitation, though such effect can be suppressed to a certain extent by incorporating a microcavity. Moreover, unlike the optical π pulse that flips the state of quantum emitter deterministically under resonant excitation, the electrical excitation process lacks a mechanism that can coherent control the excited state, even though the resonant electrical injection may suppress the background light[52]. In short, to take the advantages of electrical excitation scheme in integrated quantum photonics, more investigations are demanded to make it competitive with optical excitation one.

Acknowledgments

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