SINGLE-PHOTON SOURCES

Quantum-dot-based single-photon sources are fast and efficient and remain at the forefront of candidates for use in quantum information schemes.

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Much as the laser dramatically changed the telecommunications industry and led to rapid scientific progress in many fields, a single-photon source (SPS) would push photonics to its fundamental limit—control of single quanta—and lead to major advances. While many of those advances are not immediately obvious, there are, even now, three uses for an SPS.

First among these is in quantum cryptography, which promises unconditionally secure communications.[1] Second, an SPS could be applied to quantum computation following the ingenious scheme of Knill, Laflamme, and Milburn, which requires only a source of indistinguishable single photons, high-efficiency photon detectors, and linear optical elements to carry out such tasks as Shor's algorithm for factoring large numbers in finite time and Grover's algorithm for searching an unordered database.[2] These algorithms promise to speed up difficult computational problems. Third, an emerging application of an SPS is to drive a different system such as an atom or even a mechanical oscillator. While these applications are driving development of SPSs across institutions, researchers will certainly find abundant unforeseen uses for these sources.

There have been several proposed sources of single photons and proof-of-principle demonstrations in many systems.[3] These systems fall into four rough categories. The first two are based on attenuated laser pulses and spontaneous parametric downconversion in nonlinear crystals, respectively. While much research has been put into developing these sources and even implementing them in cryptography schemes, they both suffer from the fact that the emission is inherently classical and composed of a broad distribution of photon numbers, which leads to a non-negligible number of multiphoton events, reducing the level of security in a quantum cryptography scheme. In practice, these events can be reduced by further attenuation, but only at the cost of a reduced bit-rate. The third category of SPSs uses a collective excitation of a cold, atomic vapor. This technique produces highly indistinguishable photons, but is difficult to implement because it requires trapping and cooling of the atoms in addition to multiple-pulse laser preparation sequences. The probabilistic nature of creating the excitation as well as the lack of optical confinement has limited the largest measured single-photon rate to 100 s^{-1}.

The fourth category of SPS is based on a single quantum emitter like an atom, molecule, defect center or quantum dot. These sources rely on the fact that when these optically active emitters are excited, they decay primarily by the emission of a single photon. A wide range of these types of sources have been demonstrated, including using single molecules, single atoms trapped in cavities, single self-assembled quantum dots, single nitrogen-vacancy centers in diamond, and recently single carbon nanotubes. The primary limitation and difficulty in working with these systems is the ability to observe and collect emission from a single emitter. Typically, this is performed in condensed matter systems with microphotoluminescence (PL) spectroscopy, which uses a combination of spectral filtering and confocal microscopy techniques to eliminate emission from nearby emitters (see Fig. 1, left). The emission is then analyzed using a Hanbury-Brown and Twiss (HBT) interferometer to verify single photon emission (see Fig. 1, right).

Self-assembled quantum dots (QDs) have emerged as a very attractive candidate due to the ease of incorporating them into existing optoelectronic semiconductor technology. In addition, QDs have a near perfect quantum efficiency and a fast (1 ns) radiative lifetime at low temperature. Quantum dots can also be excited non-resonantly by carrier relaxation from nearby quantum wells or from the bandgap of the host semiconductor. Proof of single photon emission in QDs was first demonstrated in 2000 using a low density of cadmium selenide (CdSe) quantum dots on a glass substrate and since then the field has progressed rapidly. The most commonly used system is comprised of indium arsenide (InAs) QDs embedded in a gallium arsenide (GaAs) matrix.

Advances in nanofabrication techniques have led to development of various semiconductor microcavities such as micropillars, microdisks, and 2-D photonic-crystal defect cavities. Embedding the QDs inside a microcavity offers four important and interrelated benefits for their use as single-photon sources. First, the cavity size limits the number of QDs that can participate and effectively acts as a spatial filter that is at least equal to, if not better, than the diffraction-limited spot achieved by a good microscope objective. Second, the small mode volume and high quality factor lead to an increase in the spontaneous emission rate, a phenomenon known as the Purcell Effect. Third, the Purcell effect combined with the small size of the cavity force the single-photon emission dominantly into one mode of the cavity. Fourth, since the single photon emission is now directed into an optical mode of the cavity it is easier to extract than if it were emitted in all directions. Of course, the ease with which this is done depends critically on the type of cavity mode, but a tapered optical fiber can be used to efficiently extract photons from the cavity mode in microdisks without introducing significant parasitic loss and even direct coupling of micropillars to optical fibers has been demonstrated.[4]

We recently demonstrated a QD-based SPS with a measured single-photon count rate of $4x10^6$ s^{-1} and a photon capture efficiency of 38 % using 80 MHz pulsed excitation at the University of California Santa Barbara.[5] This constituted a 20-fold improvement over the previous record of $2x10^5$ s^{-1} achieved by researchers at Stanford. The mechanism used to make this advance was the implementation of intracavity electrical gates to control the charge state of the QD, which prevented formation of the optically dark states that ultimately limit the efficiency of QD-based SPSs (See Fig. 2). Furthermore, the fundamental optical mode of our cavity naturally couples efficiently to our experimental setup due to its Gaussian-like transverse profile. In this way, almost all of the single photons emitted by the QD are directed to the measurement path. Using a similar design, we have also demonstrated fast electrical control of the single-photon polarization with polarization switching rates up to 1 MHz.[6]

There are three natural directions to pursue to improve QD-based SPSs; new cavity geometries, mode-coupling strategies, and changing the way the QD is excited. Recent progress has been made at the University of Texas at Austin using QDs excited resonantly via a laser source that is waveguided perpendicular to the collection direction.[7] This is the most efficient excitation mechanism because the carriers are excited directly into the QD rather than having to cascade down. In addition, since each QD has a different emission energy, resonant excitation selectively excites a single QD and reduces background emission.

Another approach is to create an all-electrical ("plug-in") device that would not require an additional excitation laser. This strategy is based on electro-luminescence of a quantum dot whereby carriers are electrically injected from nearby charge reservoirs. At its simplest, such a device comprises a QD layer in the intrinsic region of a *p-i-n* LED structure. Once the forward bias becomes large enough and current flows through the intrinsic region, carriers can radiatively recombine in the QDs and emit single photons (see Fig. 3). The first such device was demonstrated in 2002 by researchers at Toshiba and recently these LED structures have been combined with micropillar cavities to create an all-electrical SPS operating with a photon capture efficiency of 14 %.[8] Because of the Purcell effect in these devices, the SPS count rate could in principle increase to more than 1 GHz.

Until recently, a further limitation to QD-based SPSs was the degree of indistinguishability present in the single photons. While not important for quantum cryptography, indistinguishability is an important criterion of SPSs for use in quantum computing. Because QDs are embedded within a crystalline matrix, the wavefunctions of carriers are perturbed (dephased) on timescales as short as 100 ps due to interaction with nearby atoms and carriers. This limits the overall coherence length of photons and makes photons from subsequent excitation events distinguishable from one another. One solution to this problem is to use a cavity to decrease the spontaneous-emission time to roughly the dephasing time—in this way researchers were able to achieve an indistinguishability of 75 %.[9] More recently, a 64 % indistinguishability was demonstrated using electrically generated single photons by a post-selection technique.[10]

Quantum dot-based SPSs have made substantial progress over the last few years and remain a leading candidate for use in quantum information schemes. Future developments should enable creation of single-photon sources capable of gigahertz repetition rates with negligible multiphoton pulses and nearly indistinguishable photons. Such a source will lead to ultrafast bit rates with unprecedented security in quantum cryptography and will provide a necessary component to quantum computation with linear optics.

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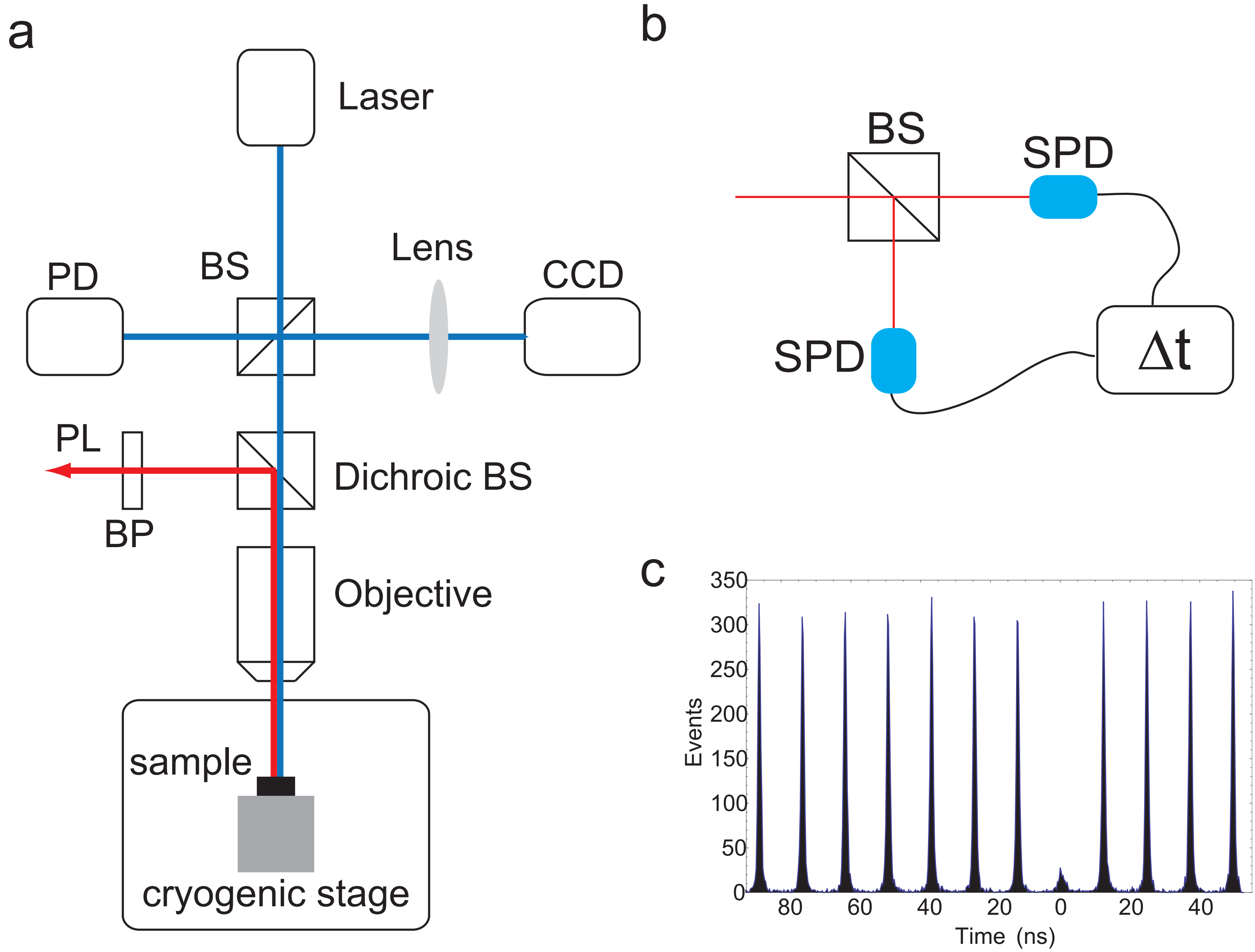
FIGURE 1. In a microphotoluminescence spectroscopy setup laser light is directed through a microscope objective and focused onto the sample (left). The sample rests in a cryogenic environment and is mounted to a cryogenic compatible stage. The photoluminescence (PL) is collected by the objective and separated from the laser light by a dichroic beamsplitter (BS). The PL is then spectrally filtered by a bandpass filter (BP). The location on the sample surface is monitored by an imaging charge-coupled device (CCD) camera and the excitation power is monitored at the photodiode (PD). A Hanbury-Brown and Twiss (HBT) interferometer with a time correlator is used to verify single-photon emission. Photons are separated at the 50:50 beamsplitter (BS) and detected by the single photon detectors (SPDs). The time between successive arrival times, Δt, is tabulated by the time correlator (upper right). A histogram of detection events using the HBT setup with a quantum-dot SPS under pulsed excitation shows a dramatic lack of events at $\Delta t = 0$, which indicates the single-photon character of the emission (lower right).

FIGURE 2. Image reproduced from Reference 5, copyright 2007 by the Nature Publishing Group. In the trench-etched oxide-apertured micropillar cavity that was used to generate a high rate of single photons from a quantum dot, the QD region is bounded by two *n*-type gating layers that enable charging of the QD and prevent formation of optically dark states. The cavity is formed by the top and bottom distributed-Bragg-reflector (DBR) and the oxide aperture (top). The SEM micrographs show different trench geometries used in the experiments (bottom).[5]

FIGURE 3. Simplified band structure of a QD embedded in the intrinsic region of a *p*-*i*-*n* diode under no applied bias (a). With bias applied to enable a current to flow right-to-left carriers are captured by the QD where they recombine creating single photons (b). A density plot of the electroluminescence (EL) spectrum as a function of applied bias for a *p*-*i*-*n* device measured at UCSB. Once the bias is large enough (as in (b) near 3 V), carriers recombine inside of the QDs and photons are emitted. The thicker, black regions correspond to emission into one of the cavity modes (c). For a cavity of type A in Fig. 2b, a CCD image shows EL from the cavity region (center of circle) as well as at the trench interfaces (d).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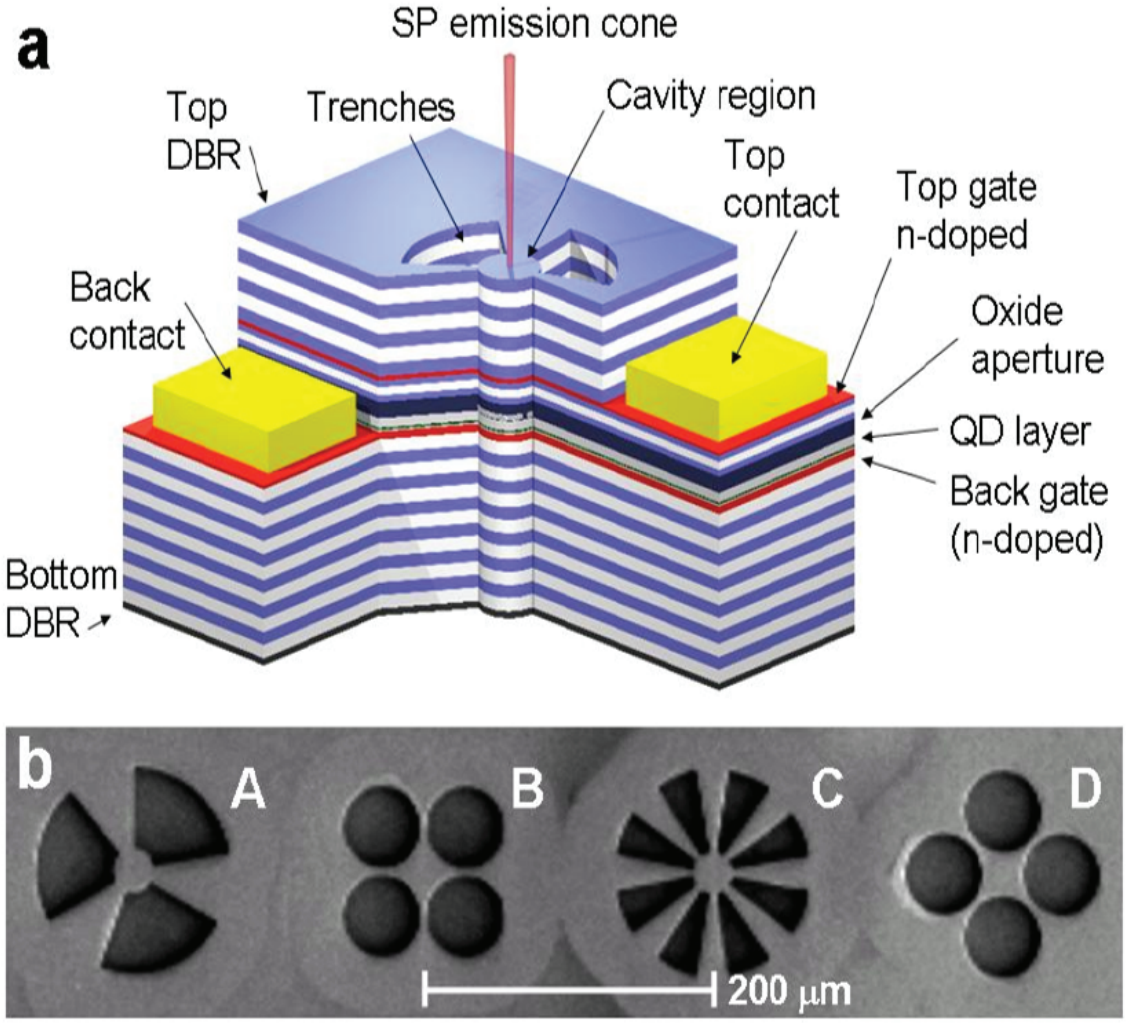
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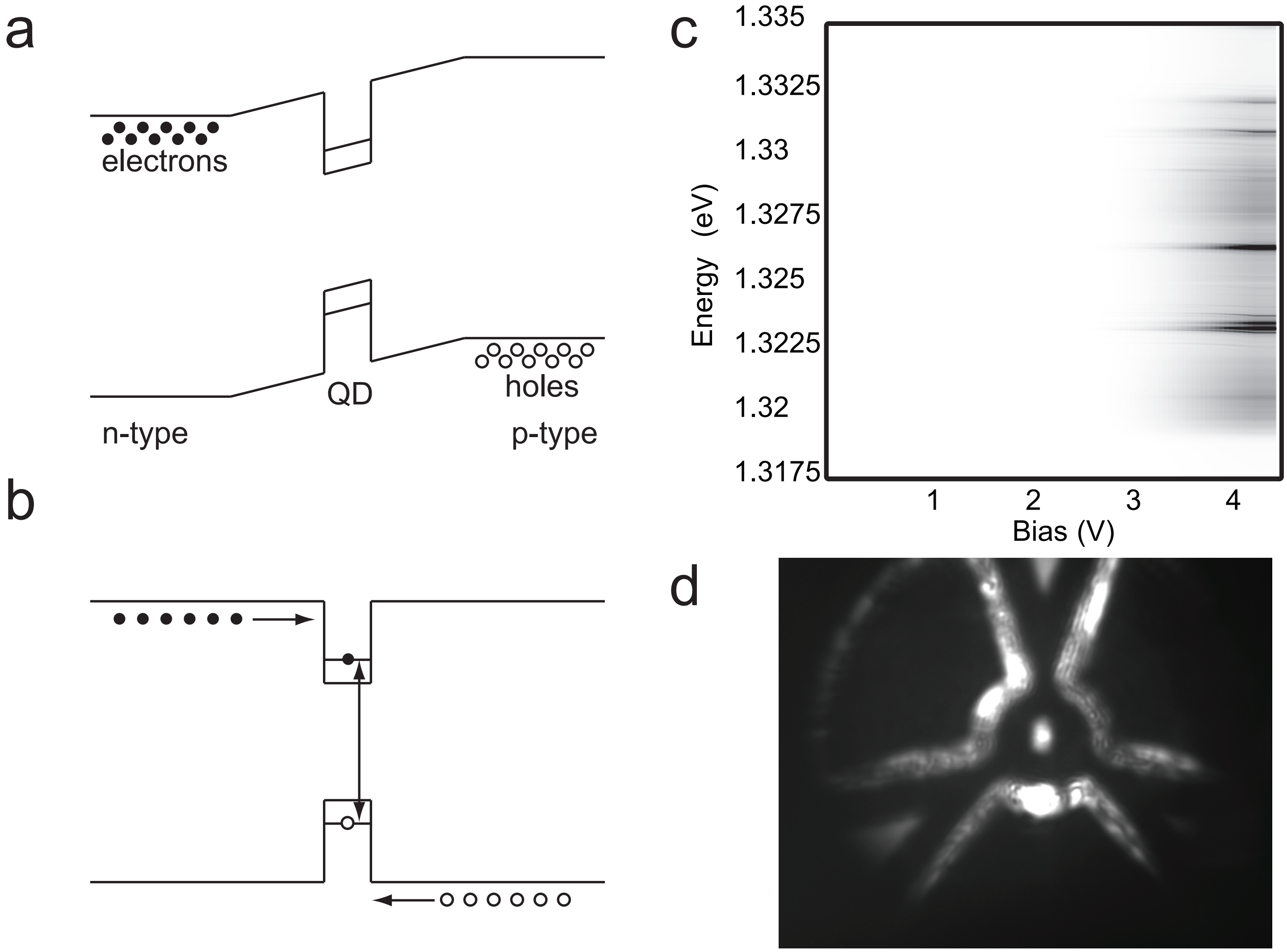

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