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Review on Nanophotonic Technologies

[1] Shagufta Khan
[1] Department Of Electronics and Communication Engineering, Galgotias University, Yamuna Expressway Greater Noida, Uttar Pradesh
[1] shagufta.khan@Galgotiasuniversity.edu.in

Abstract: Nanofabrication development has made it possible to realize optical Nano-devices capable of handling single photons and leveraging the quantum existence of single photon states. In particular, by transmitting optical pulses each containing no more than one photon, quantum cryptography (or more precisely quantum key distribution, QKD) allows unconditionally secure exchange of cryptographic keys. In addition, consistent regulation of excitonic and photonic qubits is a major step forward with potential applications in quantum computing in the field of solid−state cavity quantum electrodynamics. Here, we identify devices based on high-resolution technologies and their physical properties for realizing single photon generation and detection. Special attention will be given to the description of single−quantum dot sources based on optically and electrically driven photonic crystal micro-cavities: The electrically driven devices are an important result in the realization of a single photon source ' on demand ' A new class of single photon detectors based on superconducting nanowires, the superconducting single photon detectors (SSPDs) are also introduced: Description of the manufacturing techniques and the design proposed for large area coverage and photon number−resolving capability.

Keywords:Photonic crystal micro-cavities, Quantum dots, Single photon sources and detectors, Superconducting single photon detectors

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INTRODUCTION

A huge progress has been made in the field of nanotechnologies[1] over the past decades, opening the way to a new class of experiments involving the Nano-scale properties of light and matter. The possibility of creating Nano-structured materials on the scale of the radiation's wavelength, or even smaller, has opened access to new physical properties involving both light and matter's quantum nature. The scaling down of physical dimensions of electronic devices has been at the center of the exponential growth of semiconductor technology[2], allowing for a higher level of integration and cost reduction in fabrication. At the same time, the number of electrons used to encode a single bit in transistors and memories has dropped proportionally to the region of the unit, which naturally allows higher speed and decreases power consumption. In optical devices, too, an analogous phenomenon occurs; the number of photons involved is in continuous reduction. It would be critical to have single photon sources and detectors at telecom wavelength at our disposal in fields such as Quantum Information Processing (QIP)[3], Quantum Computing, Quantum Key Distribution, and also for fundamental studies on Quantum Electrodynamics (QED)[4].

The understanding of a single photon source requires a change of the photon number statistics from the Poisson laser light statistics to a highly non-classical statistics where the photon number is described perfectly. Single-photon signals can be obtained by thrilling single quantum systems, such as single atoms or molecules; an atom pumped to an excited state of energy relaxes to the ground by releasing a single photon if the length of the pump is much shorter than the time of relaxationAnd, theoretically, one single photon emitter will produce one photon per pulse of excitation. To classify a single photon emitter, quantum principles must be followed, and the Hanbury−Brown and Twiss (HBT) experiment is the most appropriate method to verify a single photon emission.As it is well known, in this experiment the light is split in two modes 1 and 2 by a 50/50 beam splitter, and two photon detectors are placed in the two exit arms. The autocorrelation function is measured and it can be defined as

$$g^{(2)}(\tau)= I_1(t)I_2(t+ \tau)/I^2$$

Where I_i (t) is the intensity at the time t at the place i and thebrackets denote the average over time. $I^2$is here the average intensity detected and acts as the normalization factor. In case of single photon emission, the emitted pulse will be detected at the time *t* by one of the two detectors but never in both of them.

In this paper we address the application of Nano-photonics technologies to devices aimed at producing single photons from InAs QDs in GaAs membrane, the emission of which is in the telecom window (1300 nm) and detecting them by SSPD. In order to efficiently extract the photons emitted from the InAs QDs, we need to solve the problem that photons are emitted in a very high refractive index medium (n_{GaAs} 3.5): to assume isotropic emission for simplicity, 98% of photons are fully reflected internally on a planar GaAs / air interface, and most of the out-coupled photons are deviated at angles greater than the standard numerical aperture of the array optics (0.1–0.5). A commonly exploited solution to overcoming this intrinsic limit is to increase the rate of spontaneous emission (SE)[5] at easily collected angles by inserting the QD into a micro-cavity, thus manipulating the optical modes open to the light emitted. Our research in the last years has been aimed at the optically and electrically guided realization of single−QD sources based on photonic crystal micro-cavities[6]. In the next section, we explain how the fabrication process is optimized in both optical and electrical injection, respectively. The electrically driven system, in particular, is a daunting challenge from a technical point of view and represents a revolutionary step towards achieving a single source of photons "on demand." As far as the single photon detector technology is concerned, our attention will be focused on SSPDs based on ultrathin NbN as absorbing superconductive material (NbN is used for its strong photo sensitive properties) patterned by meander-shaped electron beam lithography, To have a wide coverage of area and at the same time line widths of 100 nm or even less.In the last section along with the SSPD working theory and the fabrication process. It will also discuss the designs proposed to improve the active area of the system and to obtain PNR functionality. This emerging technology offered a crucial measurement method for the science and applications of single-photons.

Photonic Crystal Micro-Cavities as Single Photon Sources:

Numerous types of micro-and Nano-cavities were suggested and investigated. One of the most suitable optical Nano-cavity implementations with the Q factor of high quality and Volume equal to the wavelength of the light emitted can be reached by taking advantage of the unique characteristics of Photonic Crystal (PhCs)[7]. This new class of materials has been proposed and is based on the possibility of creating a periodic variation in the refractive index of dielectric materials to affect photon properties in much the same way as ordinary semiconductor crystals affect electron properties. In terms of band structures, photons can then be described, photonic band gaps are opened, and frequency ranges are prohibited for propagation. The introduction of defects like points and lines, respectively, allows the creation of Nano cavities and waveguides. Typical designs for PhCs are arrays of holes or rods arranged in square or hexagonal lattices to isotropically effect the index variation. The manufacture of these materials was only recently feasible, because the periodicity length scale is of the order of the wavelength of light to be contained, thus requiring very high resolution (down to tens of nanometers) fabrication techniques.Electron beam lithography[8] is the most suitable technique for transmitting patterning onto highly reproducible dielectric materials, and the etching processes must also be optimized to achieve vertical profiles. In fact, in the case of Nano cavities, their optical properties are strictly dependent on the geometry chosen, and accurate control during all fabrication process steps is really crucial.

Optical Excitation:

In the last decade, several studies have been reported on PhC Nano-cavity optimization, on the possibility of calculating the Purcell effect by a PhC-based Nano-cavity, and quite recently on their capacity to act as effective single photon sources. An L3 defect cavity is formed by keeping three holes untapped along a triangular PhC's u-K direction and parallel to a cleaved edge of the GaAs sample. In addition, the PhC Nano-cavities are constructed on a suspended membrane to ensure the light is transmitted in three dimensions, The in−plane confinement is due to two-dimensional PhC cavities based on a triangular lattice and the vertical one is achieved by the slab's refractive index symmetric air − semiconductor − air interfaces, which ideally produce total internal reflection.

In our studies, the point defect Nano-cavities were manufactured on heterostructures grown on a GaAs substratum: at the beginning a single layer of high-density QDs and Earlier, low-density QDs emitting at 1300 nm were grown in the 320−nm – thick GaAs diaphragm core at the top of the 1500 nm−thick Al0.7Ga0.3As a sacrificial sheet. After HF etching, a SEM image of a L3 Nano-cavity at the end of the fabrication process is shown in figure 1 & 2 along with a SEM image of a PhC structure. The membrane release is quite clearly visible. Our research on PhCs GaAs Nano-cavities as single photon sources started with a systematic cavity study based on the so-called "lithographic tuning"

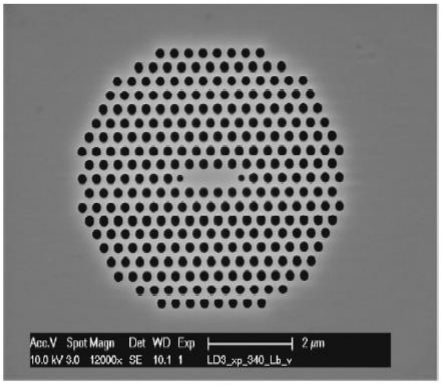

Fig.1: SEM Image of a PhC Nano-cavity: in this case $a= 340$ nm, $dL= 0.15a$, $r=8/15r_0$

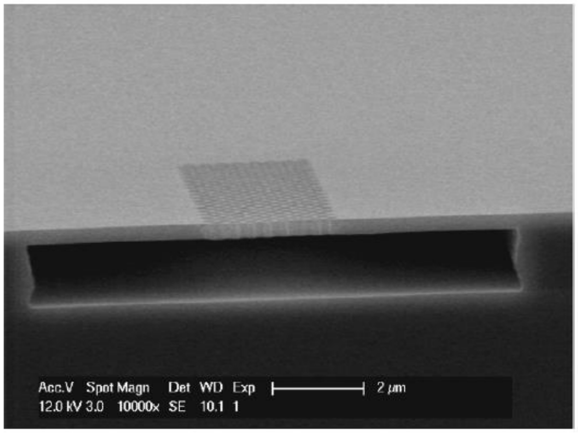

Fig.2: SEM Image of a Cleaved PhC Structure after the HF Etching of the AlGaAs Layer

Single Photon Detectors:

The advancement of realistic quantum communications and quantum cryptography[9] has generated a need for photon–counting detectors that work reliably within the optical spectrum telecommunication window. As discussed briefly in the introduction, commercial silicon APDs were used for most quantity optics experiments. They have an intrinsic peak efficiency of ~70 % and cannot discriminate between one or more photons (like photomultipliers). The InGaAs avalanche photo-diodes can be used in the telecom window (1310–1550 nm), but the practical implementation of the InGaAs APDs has been problematic due to the high level of spontaneous noise (dark count levels~10 kHz) that causes false avalanches. False avalanches are also associated with the so-called after pulsing: charge trapped when an intense avalanche current flow through the device will be released spontaneously over a period of several micro-seconds later on. False avalanches caused by noise or after-pulsing without photon detection generates errors during the protocols of the quantum key distribution.

Nanowire[10] superconducting single-photon detectors have emerged as a promising alternative approach. SSPDs offer an appealing alternative to traditional photon counting, particularly in the near infrared where photomultiplier tubes and APDs are performed above. SSPDs are promising applications candidates such as QKD, quantity emitter characterization, circuit testing, high speed optical communication, and flight laser range time. Due to their unprecedented sensitivity, temporal resolution (jitter < 100 ps), and the possibility of operating at much higher rates (> 80 MHz) than commercial APDs, they have become a key tool in characterizing single–photon sources in the telecom band. Single QDs emitting at 1300 nm were tested using SSPDs for the first time with the autocorrelation feature $g(2)(\tau)$.

The device's sensing mechanism is based on the combination of the superconductive properties and a wire's sub-micrometric thickness, generally made from NbN. The device is biased past its critical current, where the voltage across the device is zero due to superconductivity. A resistive "hot spot" is produced when a single photon is adsorbed inside the wire. This natural region, of about 20 nm size for photons with 850 nm wavelength, causes the current to flow in the wire's side regions. Because of the small width of the wire, around 100 nm, the current in this area exceeds the critical current of the material, a superconducting to normal transformation occurs so that the whole region near the hot spot becomes normal at a time of 10 ps, Create a resistive barrier throughout the nanowire cross-section. It, in effect, generates a voltage pulse. The reset mechanism of SSPD is due to the low impedance of the electromagnetic ambient. Since the superconductive film is very thin (3–5 nm), the usual part of the NbN nanowire has a high resistance of approximately 450–550 Ω/sq. The system follows a properly designed load line and enters a metastable region during the superconducting-to-normal transition; The bias current is redirected from the active part of the device to the 50-specific coaxial transmission line and 50−Ω load so that the dissipated power in the device is not sufficient to maintain a stable resistive field. With the time constant $L_{kin}/50\ \Omega$ where L_{kin} is the kinetic inductance of the nanowire, the device self-reset to its superconductive state and the current through it recovers.

NbN-based superconductive detectors operate at 2–4 K temperatures and are capable of very fast counting rates (up to GHz), low dark counts (< 1 Hz), and sensitivity from visible wavelengths to far into the infrared. While other superconducting detectors (TES) can also achieve low noise and high efficiency (88 %) based on the bolometer theory, they require cooling at much lower temperatures (~100 mK) and are much slower (kHz−MHz). NbN nanowire detectors can also be worked in a commercial cryo-cooler, by comparison. By integrating the detector into an optimized optical cavity, detection efficiencies of 67 % were achieved.

CONCLUSION

The common feature of the technologies described here is that structures with critical dimensions and tolerances of 100 nm within the nm−range are needed to achieve single photon level control over optical energies. Our progress in the development of Nano-photonic devices to be applied in the generation and detection of single photons is shown in this review. To achieve the desired performance both in single photon sources and detectors, accurate optimization of the fabrication processes is crucial. With regard to single photon sources, we successfully carry out PhC Nano-cavity electrical pumping, opening the way to the manufacture of efficient and fast electrically pumped single photon sources and the electrical control of QD−cavity coupling. In addition, optical detectors with single-photon sensitivity in the near-infrared, excellent timing resolution and a high signal-to-noise ratio, based on superconductive nanowires, were developed to meet the demands of modern quantum information applications.

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