

Single Photon Source

Xiaoshu Chen*

Department of Mechanical Engineering, University of Rochester, NY, 14623

Abstract

Single photon sources are introduced as emitters which deliver one photon at one time. The necessity of developing single photon sources, related principles and the development of single photon sources are also discussed in this essay.

Keywords: Single photon source, antibunching

1. Necessities of Single Photon Sources

A single photon source is a light source that emits one photon one time. Reliable and bright single photon sources would open up many applications in quantum optics. Currently, the main proposed applications and recent progresses in single photon sources are: quantum cryptography, random number generation and weak absorption measurement. These applications are of great motivation for developing efficient single photons sources.

Quantum cryptography, also called quantum key distribution, is one of the earliest examples of quantum processing. It was initially proposed in 1984 [1] and it is now commercially available [2] with weak coherent pulse (an approximation of single photon pulses). And the first complete of realized quantum cryptography with a true single photon source was realized in 2002 [3]. The security of quantum cryptography is based on the fact that each bit of information is coded on a single quantum object, like a single photon. Due to the quantum theory, it is impossible to intercept and duplicate complete quantum state of a single particle without been noticed by the receiver. So the classical photon source cannot guarantee the safety of quantum cryptography.

Random numbers are very important to many information processing. Like Monte Carlo simulation, it is often used in simulating physical and mathematical systems and dealing with problems of larger number of degrees of freedom. The basic of Monte Carlo simulation relies on the repeated random sampling. Usually, there are two ways to generate random numbers: pseudorandom generators upon numerical algorithms and physical random generators use the randomness or noise of physical phenomenon. Both ways are suffer from systematic errors and perturbations. While combining single photon source and a 50/50 beam splitter has been proposed as a physical quantum mechanical random generator [4]. The behavior of each photon at the beam splitter regarding the "which way" information is truly random according to quantum theory.

Single photon source can also be used for weak absorption measurement, because it delivers amplitude-squeezed light, so the fluctuations of a given quadrature will be reduced [5]. The noise of the absorption signal with a single photon source is much less than that of the noise of a coherent light source.

2. Observation of Single Photon Sources

As stated above, single photons have many possible applications. Photon, as the oldest and most widely known quantum object was first evidenced by photoelectric effect in 1905 by Albert Einstein. The method to determine whether a light source is single photon source was proposed by Hanbury Brown and Twiss in 1956 [6]. They studied the second time correlation $g^{(2)}$ of photons. The Hanbury Brown and Twiss setup is showed in Figure 1 (Fig. 1). The correlation between the intensities of the transmitted beams I_T and the reflected beams I_R are given by the amplitude of second-order (temporal) correlation,

$$g^{(2)}_{T,R}(\tau) = \frac{\langle I_T(t+\tau)I_R(t) \rangle}{\langle I_T(t)I_R(t) \rangle} \quad (1)$$

When the time delay between I_R and I_T is 0 (simultaneous), Equation (1) can be written as:

$$g^{(2)}_{T,R}(0) = \frac{\langle [I_T(t)]^2 \rangle}{\langle [I_T(t)] \rangle^2} = g^{(2)}(0) \quad (2)$$

It was found out that $g^{(2)}(0)$ of classical source equals to or larger than one for all classical light, and $g^{(2)}(0)$ equals to 1 for perfect coherent light source [7]. In this case, the photons tend to come in bunches. First observation of “antibunching” effect was by Kimble and his co-workers at the University of Rochester in 1977 [8]. Because one photon can only be detected in the reflection arm or in the transmission arm, so when the source gives out one photon, then the detected correlation will be zero when delay time is zero, which proves that photons come one by one, with the same time interval. So the single photon source is unbunched, as opposed to bunched classical light source.

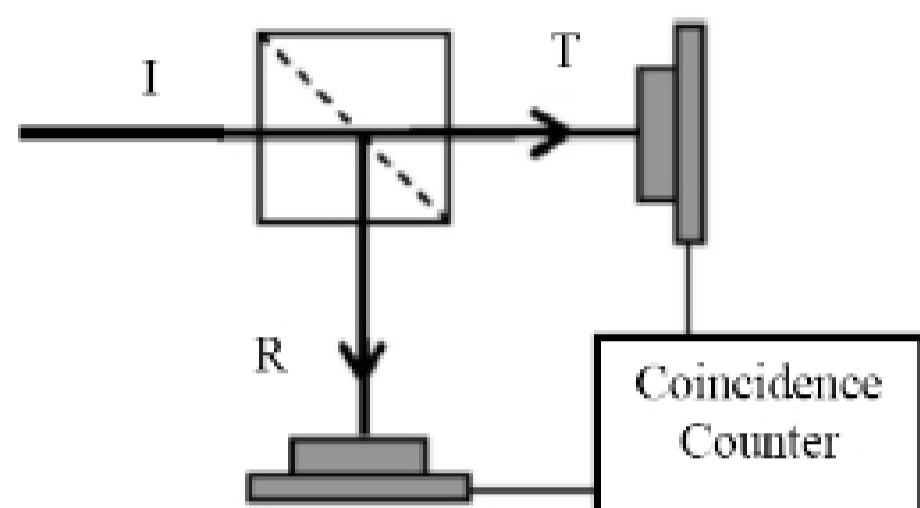


Fig. 1 Hanbury Brown and Twiss setup.

The development of single photons source also depends on the development of single photon detectors. Currently, the single photon avalanche photon detectors are available from visible to near-infrared regions and communication band in fiber 1550nm.

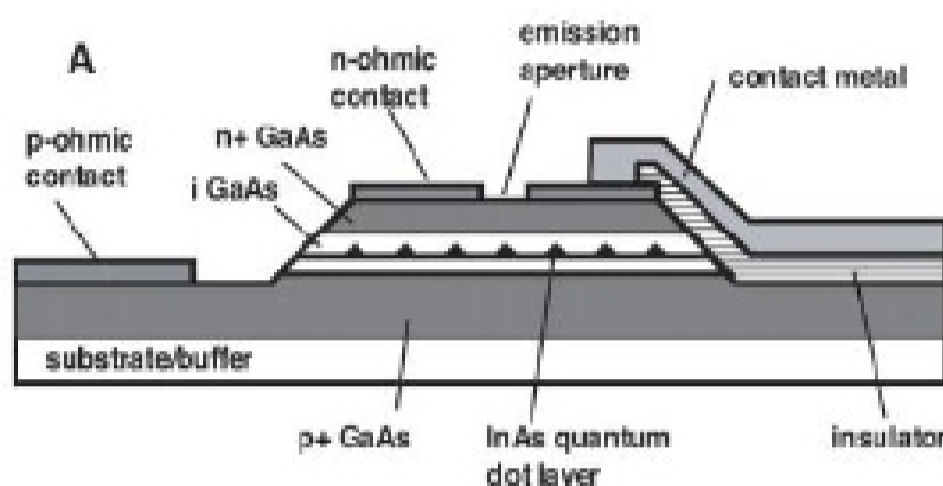


Fig. 2 Electrically driven p-i-n quantum dots single photon source

3. Single Photon Sources

Two basic criterions for single photon are getting single emitters and fluorescence lifetime. To get single emitters, the emitters must be distributed separately at a very low density. This can be realized by spin coating, or implantation and self-assembling. Fluorescence lifetime is the average time a system stays in its excited state before emitting a photon. Within the fluorescence lifetime, the system can excite one and only one photons, which guarantee that the system only emits one photon at one time.

Now, there are two types of single photon sources, optically and electrically driven single photon sources, which are classified by their pump methods. Or the single photon sources can be classified by the materials, currently, widely used single photon sources are color center in nanodiamonds, quantum dots, and single molecules.

The single photon sources using nitrogen-vacancy color centers in the diamond or nanodiamonds are probably the simplest single photon sources. In 2000, Grangier et al. reported the first observation of antibunching in nitrogen-vacancy color centers in a single crystal diamond at room temperature [9]. In their experiment, the color centers are formed by electrons irradiation and then annealing, and it is a four level energy system with fluorescence lifetime of 11.6ns. According to them, the merit of color center is that there is no photobleaching: fluorescence level remains unchanged with long time laser irradiation. Later, they developed their idea by using color center in nanodiamonds (50nm is size) [10]. They found that colors centers in nanodiamonds preserved important features of that in the bulk diamonds, and each nanodiamonds can be treated as a single photon emitter. It can be easily put into cavities or on the fiber tip for better photon efficiency and energy collection.

In 2000, Moerner et al. realized a controllable source of single photons from a single molecule in a solid. The molecular is a four level system. They used p-terphenyl molecular crystals, which has extremely high photostability, and solved the photobleaching problem [11].

Colloidal quantum dots are another kind of optically driven single photon source. They are bright and emit a broad range of wavelengths and operate at room temperatures, but they are blinking with time. Now, the non-blinking colloidal quantum dots are available [12], which will be better single photon source.

Above mentioned are optically driven single photon source, however, from a view point of real application, electrically driven single photon sources are more practical than optically driven single photon sources. Quantum dots have been widely used as electrically driven single photon emitters, such as InAs quantum dots. First electroluminescence from a single quantum dot at room temperature as an electrically driven single-photon source has been proposed by Yuan et al in 2002 [13]. Their device is showed in Fig. 2, the p-i-n diode containing a layer of InAs self-organized quantum dots in the intrinsic region. This kind of quantum dots, unlike the colloidal quantum dots, is small regions of one material

buried in another material with a larger band gap. Due to the very small size of quantum dots, there are only one or two pairs of electro-holes in the conductance and valance band of quantum dots. To avoid the nonradiative recombination, large mesas were prepared containing many quantum dots and the surface is aperture to allow collecting emission from one dot. And pulsed electrical injection leads to the pulsed emission from the dot. Another improvement of quantum dots is changing to nitride semiconductor quantum dots. With gallium nitride quantum dots, Kako et al. reported single photon source operating at 200K [14], and this wide gap material opens a new wavelength region in the blue and near – ultraviolet portions of the electro-magnetic spectrum.

Nowadays, for real applications of single photons, lots of work is still being done towards to making more applicable single photon sources, like realizing room temperature working, averaging distribution of emitters and increasing photon emission and collecting efficiency. Usually, researches use micro cavities to get higher photon emission efficiency, as shown in Fig. 3 (a) and (b). It has been approved that the cavity structures is able to enhance spontaneous emission if the emitters' energy coincidences with the energy of cavity mode. Besides the cavity, photonic crystal and liquid crystal can also be used as cavity to enhance photon emission, because the emission at the band edge of band gap will be enhanced.

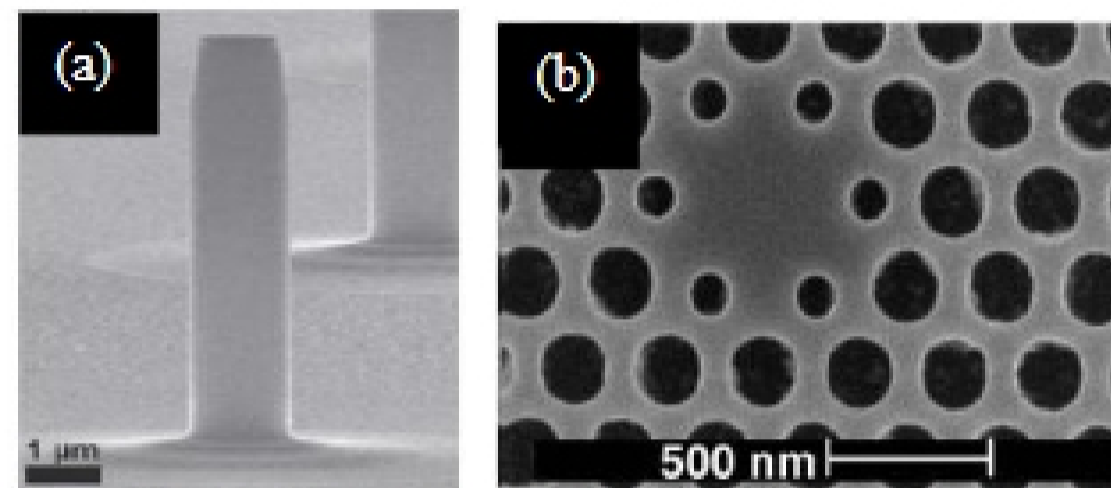


Fig. 3 (a) Scanning electron micrograph of a 1.2 μm diameter pillar cavity [15]; (b) SEM image of photonic bandgap structures [16].

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5. References

1. C. H. Bennett and G. Brassard, in Proceedings of the International Conference on Computers, Systems and Signal Processing, Bangalore, India, 1984 (IEEE, Piscataway, NJ, 1984), p. 175.
2. Id Quantique SA, <http://www.idquantique.com>
3. Alexios Beveratos, Rosa Brouri, Thierry Gacoin, et al. "Single photon quantum cryptography", *Phys. Rev. Lett.* Vol. 89, 187901-1-4 (2002)
4. J. G. Rarity, Owens and P. R. Tapster, "Quantum random number generation and key sharing", *J. Mod Opt.* 41 2435-44(1994)
5. Min Xiao, Ling-An Wu, and H. J. Kimble, "Precision measurement beyond the shot-noise limit", *Phys. Rev. Lett.* Vol. 59, 278-281 (1987)
6. R. Hanbury Brown, R. Q. Twiss, "The question of correlation between photons in coherent light rays", Vol. 178, 1447-1448(1956).
7. Mark Fox, *Quantum Optics: An introduction*, Oxford, 2006
8. H. J. Kimble, M. Dagenais, L. Mandel, "Photon antibunching in resonance fluorescence". *Phys. Rev. Lett.* 39, 691-695 (1977).
9. Rosa Brouri, Alexios Beveratos, Jean-Philippe Poizat, and Philippe Grangier, "Photon antibunching in the fluorescence of individual colored centers in diamond", *Opt. Lett.* 25, 1294-1296, 2000.
10. A. Beveratos, S. Kuhn, R. Brouri, T. Gacoin, J.-P. Poizat, and P. Grangier, "Room temperature stable single-photon source". *Eur. Phys. J. D*, 18, 191-196 (2002)
11. B. Lounis, W. E. Moerner, "Single photons on demand from a single molecule at room temperature", 407, 491-493(2000)
12. Zhiliang Yuan, Besta E. Kardynal, R. Mark Stevenson, Andrew J. Shields, Charlene J. Lobo et. al. "Electrically driven single-photon source", Vol. 29, 102-104(2002).
13. Satoshi Kako, Charles Santori, Katsuyuki Hoshino et al, "A gallium nitride single-photon source operating at 200K", *Nature Materials*, Vol. 5, 887-892(2006)
14. Press, D. et al, "Photon antibunching from a single quantum dot-microcavity system in the strong coupling regime". *Phys. Rev. Lett.* 98, 117402(2007)
15. Gevaux, D. G. et al. Enhancement and suppression of spontaneous emission by temperature tuning InAs quantum dots to photonic crystal cavities. *Appl. Phys. Lett.* 88, 131101 (2006).
16. B. Mahler, P. Spincelli, S. Buil, X. Quelin, J. P. Hermier, B. Dubertret, "Towards non-blinking colloidal quantum dots", *Nature Materials*, 7, 659-664(2008)