

# Single-photon Source Based on Self-Assembled Quantum Dots and Its Applications

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**Abstract.** Over the past few decades, extensive exploration has been conducted on quantum dot light sources. Researchers have continuously improved the synthesis techniques of quantum dots, developing various materials and structures to enhance their optical performance and stability. This has also led to the expansion of application fields for quantum dot light sources. This paper provides a concise overview of the fundamental background knowledge on self-assembled quantum dot (QD) single-photon sources. Additionally, it explores the techniques for evaluating the standards of single-photon sources through two-photon suppression and the second-order correlation function. It reviews common self-assembled quantum dot growth methods, focusing on molecular beam epitaxy (MBE) technology and the introduction of Distributed Bragg Reflectors (DBR). Finally, this article introduces the research history of enhancing single-photon performance by modifying the quantum dot system structure. The primary measure involves enhancing single-photon emission using microcavity structures. By leveraging the tight coupling between the photons radiated by atoms, quantum dots, and other structures with the microcavity field modes, significant improvements in single-photon characteristics are achieved. Researchers have already obtained single-photon emission streams with well-regulated time intervals and time-controllable quantum dot single-photon sources. Additionally, they have been able to fabricate high-quality quantum dot light sources that exhibit high efficiency, indistinguishability, and single-photon purity.

**Keywords:** Semiconductor; Self-Assembled Quantum Dots; Single-photon Source; Two-photon suppression; Microcavity.

## 1. Introduction

Since the concept of quantum information was first introduced in 1982, significant progress has been made in high-speed information processing and other related fields. Among these advancements, quantum light sources have garnered widespread research interest because they provide essential physical foundations for quantum information processing. In terms of quantum computing, quantum light sources play a crucial role in producing the essential qubits for computation, thereby enhancing the performance of quantum computers. Similarly, within the context of quantum communication, quantum light sources are fundamental for enabling secure and efficient communication protocols. For quantum sensing, these sources facilitate the excitation of relevant sensor quantum states. Among various types of quantum light sources, single-photon sources possess the advantages of reliability and ease of access, and are considered promising candidates for overcoming technical bottlenecks. Consequently, the development and research of high-quality single-photon sources are of utmost importance.

Self-assembled quantum dots are nanoscale semiconductor structures formed through a self-organizing process, typically grown on semiconductor substrates. Quantum dots exhibit quantum confinement effects due to their small size, where electrons and holes are confined within a minuscule space, leading to the splitting of energy levels into discrete states. This energy level structure resembles that of atomic energy levels, hence self-assembled quantum dots sometimes mean "artificial atoms." Self-assembled quantum dots possess numerous superior properties. By altering growth conditions, the size of the quantum dots can be controlled; simultaneously, self-assembled quantum dots can generate highly pure single-photon sources, since the emitted photons have an extremely narrow spectral width with minimal energy fluctuations. Consequently, this article will



explore the implementation and advancement of single-photon sources based on self-assembled quantum dots, emphasizing their exceptional properties and potential applications.

## 2. Single-photon Source

### 2.1. Criterion for single-photon source

#### 2.1.1. Two-photon suppression

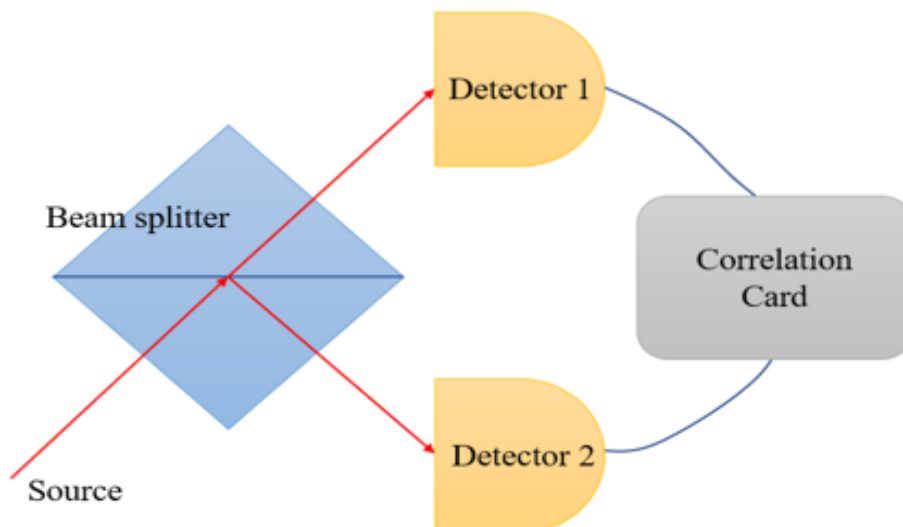
The term "two-photon suppression" refers to a mechanism that reduces or inhibits two-photon processes like two-photon absorption or fluorescence within materials or systems. To judge whether a light source qualifies as a single-photon source, the  $g^{(2)}(\tau)$  parameter acts as a crucial criterion. Also named as the second-order correlation function,  $g^{(2)}(\tau)$  is expressed as:

$$g^{(2)}(\tau) = \frac{\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau)\hat{a}(t+\tau)\hat{a}(t) \rangle}{(\langle \hat{a}^\dagger(t)\hat{a}(t) \rangle)^2} \quad (1)$$

This function reflects the possibility of detecting a photon at both time  $t$  and time  $t+\tau$  [1]. For a Fock state which has  $n$  photons, the value of  $g^{(2)}(0)$  is equal to  $1 - 1/n$ .  $g^{(2)}(0) = 0$  only occurs in the superposition state of a single-photon state and the vacuum state. Otherwise, this value is positive. Consequently, this value serves as a criterion for single-photon character, with closer proximity to zero indicating superior single-photon quality, which implies fewer multiphoton events. In many previous applications, it is believed that when  $g^{(2)}(0) < 1/2$ , the source field signifies a single-photon source. However, numerous studies continue to strive for reducing this value to zero [2].

#### 2.1.2. Scheme to measure second-order correlation function

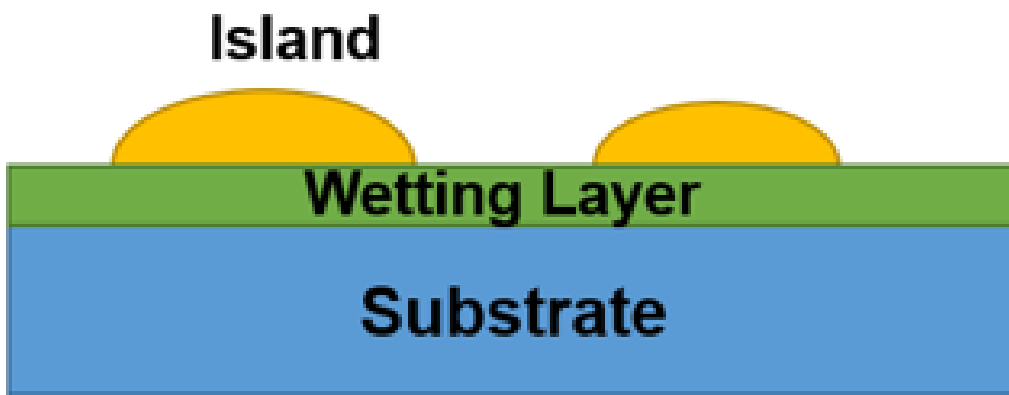
In academic research, the Hanbury Brown and Twiss (HBT) interferometer is commonly used to measure the second-order correlation function of photons. The HBT effect is a fundamental phenomenon in quantum mechanics that describes the particle properties of light fields. The physical principle underlying this effect is based on the second-order coherence of light fields. When two detectors each receive photons from the same source, if these photons are emitted within the same time interval, the difference in their arrival times will be small. This temporal proximity leads to an increase in the correlation of signal intensities between the detectors, even though the two photons themselves are not coherent (Figure 1). Based on this principle, classical HBT devices have been devised to measure second-order correlation functions [3].



**Figure 1.** Scheme of a HBT interferometer, monitoring the second-order correlation coefficient (Photo/Picture credit: Original).

## 2.2. Methods to form self-assembled semiconductor quantum dots

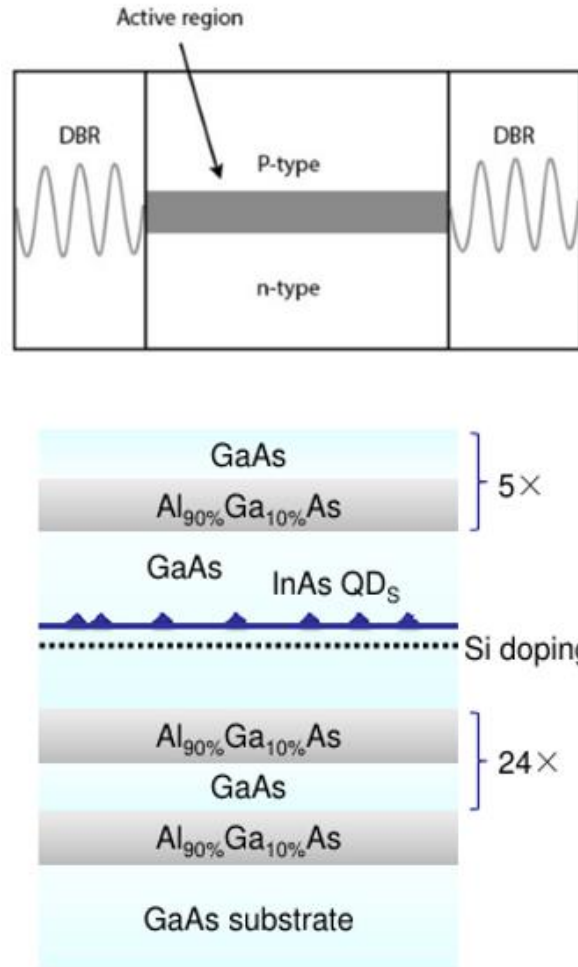
The formation of self-assembled quantum dots is often driven by intermolecular interactions, including van der Waals forces, hydrogen bonding, and electrostatic interactions. Under suitable conditions, these molecules autonomously arrange into distinct nanostructures, giving rise to quantum dots. This process does not necessitate external fine control and is therefore termed self-assembly. The formation of self-assembled quantum dots has reached a certain level of maturity, with molecular beam epitaxy (MBE) being the predominant method employed today. Molecular beam epitaxy technology facilitates the growth and deposition of various semiconductor nanomaterials on substrate surfaces at the monolayer atomic scale, enabling strain-induced growth and epitaxial processes. Specifically, in lattice-mismatched heteroepitaxy, an initial wetting layer is formed, leading to increased stress. Subsequently, to minimize the interfacial energy, strain energy, and surface energy, nano-scale islands are formed. This mechanism is called the Stranski-Krastanow growth, or SK growth, mode (Figure 2). These islands eventually transform into quantum dots when materials of larger bandgaps cover them [4].



**Figure 2.** Mechanism of Self-Assembly Quantum Dot Growth (Photo/Picture credit: Original).

The growth of self-assembled quantum dots in the InAs/GaAs system was successfully realized, and to date, this system remains the most widely used for self-assembling quantum dots [5]. This system forms InAs quantum dots on GaAs substrates using the SK mode. Due to the approximately 7% difference in lattice constant between GaAs and InAs, the InAs undergoes elastic deformation to accommodate the lattice mismatch, initially forming a wetting layer on GaAs. As wetting layer thickness increases, so does the stress. When the InAs grown on GaAs exceeds about 1.7 monolayers, the stress is relieved by the formation of island-like structures on the GaAs surface, which are referred to as quantum dots [6]. Previous research has demonstrated techniques for controlling nucleation sites, such as employing localized surface chemical potential engineering and utilizing localized surface strain engineering to create ordered arrays of quantum dots [7].

Another commonly employed structure for the formation of self-assembled quantum dots is known as the Distributed Bragg Reflector (DBR), which is a periodic structure capable of achieving near-total reflection within a certain frequency range. The upper and lower DBRs form a microcavity where quantum dots are grown using MBE. In a previous experimental work, the researchers designed a structure for growing quantum dots in DBR systems using MBE. For a DBR with a thickness of  $d$ , when the working wavelength is  $\lambda$  ( $d = \lambda / 4$ ), the two reflections will produce an optical path difference of  $0.5\lambda$  and a phase change of  $\pi$ . As a result, the reflected light from both reflections becomes in phase and their superposition is enhanced, leading to an overall increase in reflection coefficient. This configuration enhances both the luminescence efficiency of the quantum dots and the collection efficiency of their fluorescence, Figure 3 shows the basic structure of a DBR and the specific application of InAs quantum dots in a Al-mixed GaAs system [8].



**Figure 3.** (Top) Scheme of the operation principle of DBR; (Bottom) The layered structure of the QD sample.[8].

### 2.3. Modulation of single-photon performance in self-assembly semiconductor quantum dots.

To amplify the single-photon emission performance of self-assembled semiconductor quantum dots, various artificial microstructures have been proposed to improve their luminescence index. The aforementioned Distributed Bragg Reflector (DBR) serves not only as a critical optical component but also as an effective modulation technique in its own right. In addition, microcavity structures have been widely employed to enhance the purity, indistinguishability, and efficiency of single-photon sources.

The principle underlying microcavity-enhanced single-photon emission is rooted in cavity quantum electrodynamics. In this phenomenon, atoms, quantum dots, and other microscopic entities, once coupled to a microcavity, experience a tight coupling of their radiated photons with specific microcavity field modes, leading to a significant enhancement in emission efficiency and a considerable improvement in the directional propagation of photons. Furthermore, through the Purcell effect, by adjusting the coupling strength between a two-level system and a single-mode microcavity field, one can either enhance or suppress the spontaneous emission rate of that system, thereby effectively controlling the radiation process [9][10]. Employing the Purcell effect, by carefully designing the microcavity parameters and integrating them with semiconductor growth and processing conditions, it is possible to fabricate microcavity structures capable of efficiently coupling with quantum dots, thereby enabling the effective modulation of the luminescence performances of these quantum dots.

The origins of research on microcavity-enhanced single-photon emission can be traced back to 1999. Kim J. and his team discovered a stream of single-photon emission which has achieving well-

regulated time intervals within a pillar microcavity system composed of a GaAs/AlGaAs three-quantum well sandwich structure at a mere 50 millikelvin [11]. This study quickly garnered widespread attention, and shortly thereafter, in 2001, Moreau et al. successfully achieved a time-controllable quantum dot single-photon source by employing a cylindrical DBR microcavity. At a temperature maintained at 8K, when the quantum dots were excited with pulsed laser light, the measured  $g^{(2)}(0) = 0.19$ , indicating that this quantum dot could be regarded as an efficient single-photon source [12]. During the period from 2002 to 2003, Pelton, Santori, Vučković, and their respective teams successively investigated InAs quantum dots embedded within cylindrical DBR microcavities, all achieving highly efficient single-photon emission. They separately accomplished a 38% efficiency for single-mode transverse electromagnetic wave single-photon emission, a single-photon indistinguishability of 0.81, and  $g^{(2)}(0) = 0.02$  for emitted photons when the quantum dot luminescence was brought into resonance with the microcavity optical field mode by controlling the temperature. These results collectively demonstrated that the single-photon source possesses high efficiency, indistinguishability, and single-photon purity [13] [14] [15].

Besides cylindrical microcavities, researchers have explored other structural semiconductor microcavities to see if they can modulate the single-photon emission performance of quantum dots. In 2000, Michler et al. successfully achieved an InAs quantum dot coupled with whispering gallery cavity modes in a microdisk microcavity to obtain a single-photon source. By adjusting the temperature, this system enables the neutral exciton emission from quantum dots to couple with whispering gallery cavity modes possessing higher quality factors, thereby realizing single-photon emission [16].

The experiments described above convincingly demonstrate that semiconductor microcavities significantly enhance the performance of quantum dot single-photon emission, specifically including efficiency, two-photon suppression, and photon indistinguishability. These breakthroughs set the stage for the application of controllable, stable, and high-speed single-photon sources.

### 3. Conclusion

Quantum dots single-photon sources possess excellent optical properties and promising application prospects, attracting widespread attention from researchers. To evaluate the quality of these sources, it is essential to focus on two-photon suppression and calculate  $g^{(2)}(\tau)$ . The closer  $g^{(2)}(0)$  approaches zero, the better the single-photon performance. Utilizing the HBT effect, HBT interferometers have been designed to measure this function..

Regarding the formation of self-assembled quantum dots, MBE is commonly used. It allows for the growth and deposition of various semiconductor nanomaterials on substrate surfaces at the monolayer atomic scale, forming island-like structures on the substrate surface that eventually transform into quantum dots. The InAs/GaAs system is the most thoroughly researched self-assembled quantum dot system. InAs forms island-like structures on GaAs substrates through the Stranski-Krastanow growth mode, ultimately releasing stress to form quantum dots. DBR can also be used to efficiently grow quantum dots by inverting the phase by  $\pi$  during two light reflections, thereby enhancing luminescence efficiency.

Besides DBR, more advanced research on enhancing the emission performance of quantum dot with microcavities is also conducted. Researchers have utilized the Purcell effect to carefully design critical microcavity parameters and combine them with semiconductor growth and processing conditions, successfully fabricating achieving effective modulation. Currently, the most common system is the multi-system cylindrical microcavity, which can produce a high-quality single-photon emission stream. Under specific temperature control, it significantly enhances the ability to suppress two-photon emission, resulting in a light source with excellent single-photon purity. Other shapes of semiconductor microcavities are also being studied, and single-photon sources of high quality have been achieved in some other shapes of microcavities, such as disk-shaped ones.

## References

- [1] Fischer, K. A., Müller, K., Lagoudakis, K. G., Vučković, J. Dynamical modeling of pulsed two-photon interference. *New J. Phys.* 18 (2016) 113053.
- [2] Schweickert, L., et al. On-demand generation of background-free single photons from a solid-state source. *Appl. Phys. Lett.* 112 (2018) 093106.
- [3] Hanbury Brown, R., Twiss, R. Q. A test of a new type of stellar interferometer on Sirius. *Nature* 178 (1956) 1046–1048.
- [4] Petroff, P. M. Semiconductor self-assembled quantum dots: present status and future trends. *Adv. Mater.* 23 (2011) 2372-2376.
- [5] Leonard, D., Krishnamurthy, M., Reaves, C. M., Denbaars, S. P., Petroff, P. M. Direct formation of quantum-sized dots from uniform coherent islands of InGaAs on GaAs surfaces. *Appl. Phys. Lett.* 63 (1993) 3203–3205.
- [6] Stranski, I. N., Krastanow, L. Zur Theorie der orientierten Ausscheidung von Ionenkristallen aufeinander. *Mon. Chem. Verwandte Teile And. Wiss.* 71 (1937) 351–364.
- [7] Lee, H., Johnson, J. A., Speck, J. S., Petroff, P. M. Controlled ordering and positioning of InAs self-assembled quantum dots. *J. Vac. Sci. Technol. B* 18 (2000) 2193–2196.
- [8] He, Y. M., He, Y., Wei, Y. J., et al. On-demand semiconductor single-photon source with near-unity indistinguishability. *Nat. Nanotechnol.* 8 (2013) 213–217.
- [9] Sauvan, C., et al. Theory of the spontaneous optical emission of nanosize photonic and plasmon resonators. *Phys. Rev. Lett.* 110 (2013) 237401.
- [10] Purcell, E. M. Spontaneous emission probabilities at radio frequencies. *Confined Electrons and Photons.* Springer, Boston, MA, 340 (1995) 839-839.
- [11] Kim, J., Benson, O., Kan, H., Yamamoto, Y. A single-photon turnstile device. *Nature* 397 (1999) 500–503.
- [12] Moreau, E., et al. Single-mode solid-state single photon source based on isolated quantum dots in pillar microcavities. *Appl. Phys. Lett.* 79 (2001) 2865–2867.
- [13] Pelton, M., et al. Efficient Source of Single Photons: A Single Quantum Dot in a Micropost Microcavity. *Phys. Rev. Lett.* 89 (2002) 233602.
- [14] Santori, C., et al. Indistinguishable photons from a single-photon device. *Nature* 419 (2002) 594–597.
- [15] Vučković, J., et al. Enhanced single-photon emission from a quantum dot in a micropost microcavity. *Appl. Phys. Lett.* 82 (2003) 3596–3598.
- [16] Michler, P., et al. A Quantum Dot Single-Photon Turnstile Device. *Science* 290 (2000) 2282-2285.