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# Quantum Dots in Semiconductors for Coming Optical Applications

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**Abstract.**
Review of semiconductor quantum dots (QDs) development and research for optical applications. The QDs are tiny crystals, around 10 nm in size, made of semiconductors III-V, II-VI, IV, and IV-VI. They are divided into two categories. The self-assembled QDs, which are grown epitaxially on a semiconductor substrate, are one type. The other type is colloidal QDs, which are chemically produced in a solvent. Due to the fact that both QDs' emission wavelengths span a broad spectrum, from visible to infrared, the QDs are appealing to a variety of application domains. In the areas of replacing current devices, quantum information devices, and solar energy conversion devices, research on both epitaxial QDs and colloidal QDs has advanced. The QD devices will be crucial to the 21st century's large-capacity information-oriented civilization and the solution to the energy crisis. The three application sectors, namely the replacement of current products, quantum information devices, and solar cells, are the main topics of this article.

**Keywords:** quantum dot, nano crystal, semiconductor laser, quantum information, solar cell

## Introduction

The quantum dots (QDs), which have an average size of around 10 nm, are tiny crystals made of semiconductors III-V, II-VI, IV, and IV-VI. QDs are divided into two groups. One type is epitaxial QDs, which self-assemble on single-crystal semiconductor substrates by using well-known epitaxial growth techniques including metalorganic vapor phase deposition (MOCVD) and molecular beam epitaxy (MBE). The other is colloidal QDs, which are created using a chemical process in a flask and a solvent. The most interesting finding is that both QDs emit light with a broad spectrum of wavelengths, ranging from visible to infrared. As a result, both are very desirable materials for use in many optical device applications.

Since epitaxial QDs are manufactured using the same equipment as semiconductor devices today, they can be simply incorporated into semiconductor device fabrication procedures. Actually, the active layer of semiconductor laser diodes for the optical communication system already uses QDs. Because of the crystal strain energy caused by the substrate's lattice mismatch, the epitaxial QDs self-assemble. Hence the self-assembled QDs' form cannot completely shield them from the effects of substrate orientation. This has advantages for managing QD location and disadvantages for producing isotropically shaped QDs, as will be discussed later.

The cost of producing colloidal QDs is exceptionally low since they may be produced in large quantities without the use of expensive equipment. Since they are not attached to a substrate, QDs are often symmetrical. The utilization of biomarkers is attracted by their excellent chemical stability. Colloidal QDs are assembled into solid devices using a polymer matrix that maintains QD functionality. In the area of optical quantum information technology, for instance quantum processing and communication, both types of QDs have advanced. The two QDs have already achieved the single photon emission. In order to achieve optical quantum repetition and optical quantum operation, the creation of the quantum-entangled photon pair is still a research goal. A significant problem for the generation is the symmetry of the QD structure. In order to construct the QD circuit for the quantum operation, it is also necessary to regulate the size, position, and connectivity of QDs.

Recent years have seen a keen demand for innovations in green nanotechnology. It has been demonstrated that the QD solar cell offers a significant solution. The intermediate energy band will be created if QDs can be stacked thickly in three dimensions, much like an artificial crystal. With the QDs' intermediate band, it is expected that the photoelectric conversion efficiency will be greater than 70%, which is significantly higher than the efficiency of the existing silicon-based solar cell. A current crucial topic is how to realize the intermediate band. This study examines semiconductor QD research and development, including our contributions, in the three areas of product replacement, quantum information devices, and solar cells.

## Materials and methods

The primary application of quantum dot technology, which was the initial motivation for studying it, is still replacement of existing devices. The semiconductor laser diode is the most popular and sophisticated QD technology. Since it is sufficient to develop a QD layer as an active region in place of a quantum well (QW) layer, epitaxial QDs are simple to incorporate into the laser diode construction process. Thus, using QDs does not increase the price of manufacturing semiconductor lasers,

as was previously believed. Since in paper researchers (Arakawa et al., 1982) suggested that the performance of a QD laser would be significantly better than a QW laser, numerous researchers have worked to make the QD laser a reality (Mukai et al., 1998, Huffaker et al., 1998, Murray et al., 1999). Despite having to overcome numerous practical obstacles, QD lasers are now on the market thanks to QDLaser Inc., a spin-off business initiative of Fujitsu Lab. QD lasers have advanced significantly over the past several years. The realization of high modal gain, high speed modulation, and high temperature functioning was made possible by the high density of QD layers. Direct modulation at a speed of 25 Gbit/s is offered. Because the threshold current is steady between -10 and 85°C, it was possible to create a high-bit-rate, temperature-unrestricted communications transmitter. Even at 220 °C, the QD laser functions (Figure. 1).

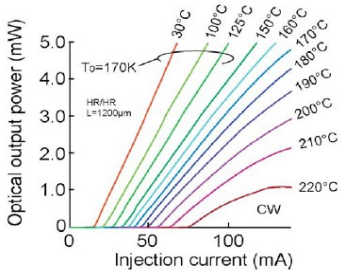


**Figure 1.** QD laser parameters of optical output power against injection current from 30 and 220°C.

Compared to epitaxial QDs, colloidal QDs have a number of advantages. Since they are cheap, the cost of QD items can be reduced. The colloidal QDs' band gap energy is depicted in Figure 2 (Rogach et al., 2007). Each bar shows the changeable energy range.

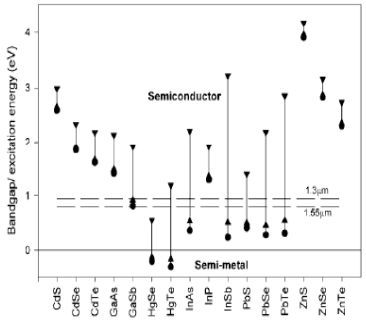


**Figure 2.** Band gap energies for bulk materials and nano crystals with diameters of 10 nm and 3 nm are displayed.

There are numerous component material options available to obtain the visible emission. The use of QDs luminescence at visible wavelengths advances the bio marker application (Michalet et al., 2005). They are suitable for use in security ink or light emitting diodes (LED) due to their chemical stability (Craig et al., 2012). Although the electronics applications are still being researched, it has been established that they function well enough for everyday use. The spectral purity of QDs permits a color gamut wider than the HDTV (High Definition Television) standard, as shown by the CIE chromaticity diagram in Figure 3. PbS, PbSe, InAs, and InSb are the materials of choice for invisible light, notably in telecommunication wavelengths.

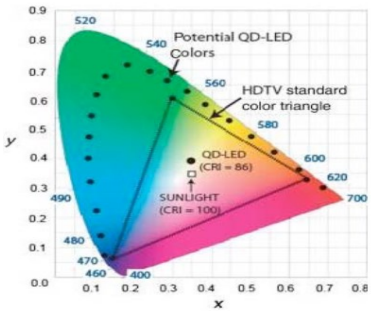


**Figure 3.** CIE chromaticity diagram displaying the QD LED's potential.

## 3. Quantum information devices

The quantum information device, which will enable entirely safe communication and incredibly rapid processing, is another significant application of QD. QDs have been researched as a source material for the single photon emitter and the entangled photon pair generator in the quantum communication technology. QDs and microcavity are integrated for the goal. QDs are employed in quantum computation as a qubit storage or a waveguide for a quantum optical circuit. In the early 2000s, epitaxial QDs produced their first single photon (Santori et al., 2002). By using HBT conFigureuration, anti-bunching of the photon count was shown as the evidence. Following that, the quantum cryptography-based communication investigations have been proven at the specific communication wavelength, as illustrated in Figure 4 (Miyazawa et al., 2005).

These emitters were created by fusing microcavity and QD. The ideal microcavity for controlling single photon properties is a three-dimensional photonic crystal (Nomura et al., 2010). Numerous researchers have attempted to combine these two ultimate artificial materials since QD can predict the single electron characteristics.

One of these final structures is depicted in Figure 5 (Tandaechanurat et al., 2009). In the manufacturing process, the stack of woodpile structures was put together on top of the active layer with the defect nanocavity sitting on top.

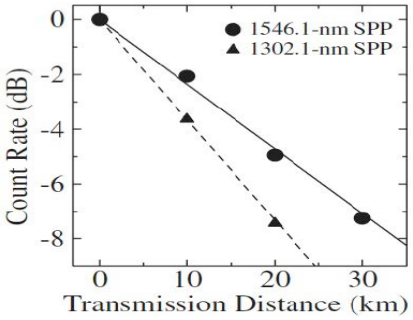


**Figure 4.** C- and O-band single photon transmission rates across the long single mode fiber.

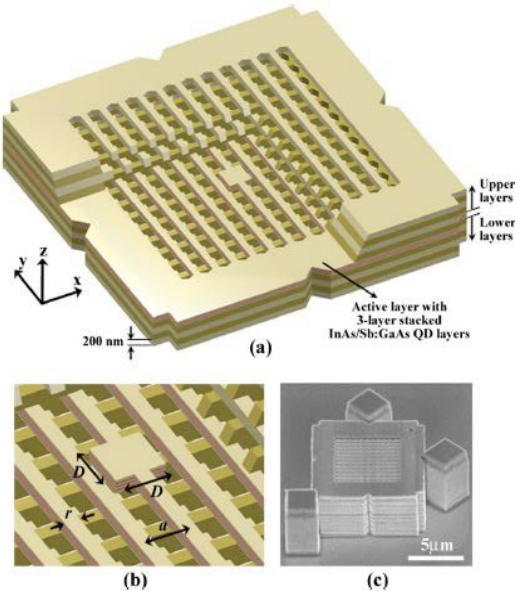


**Figure 5.** (a) Three-dimensional cavity structure schematic. (b) A cavity that has been magnified. The 25-layer woodpile structure may be seen in the (c) SEM image.

The colloidal QD has also achieved single photon emission. At visible wavelengths, the antibunching was seen (Pisanello et al., 2010). QD was placed in the straightforward cylindrical polymer microcavity for the intended use. We are also looking at the Figure 6 colloidal QD-containing simple polymer microcavity in three dimensions (Mukai et al., 2007).

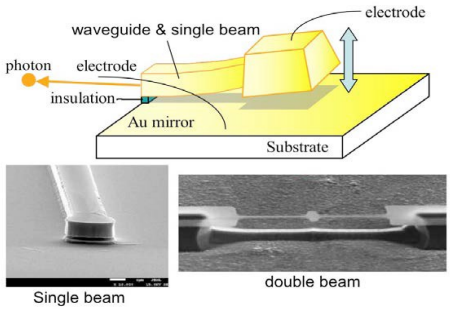


**Figure 6.** (a) Waveguide-equipped tunable photonic dot schematic. The photonic dot's head portion contains a QD. (b) A product composed of III-V compound semiconductor; (c) a product with two polymethylmethacrylate waveguides (PMMA).

QD is installed in the photonic dot portion of the microcavity head, which is supported by one or two beams. The beam serves as a waveguide guiding a photon into the planar photonic circuit, while the QD serves as a photon source. Instead of using high reflection multilayers, the upper wall, sidewalls of the head, and substrate surface are simply coated with gold. The timing of the QD's photon spontaneous emission is controlled by adjusting the distance between the head and the substrate using the micromachine approach. There have been several suggestions for employing QDs to build quantum circuits (Khan., 2006, Vartuli et al., 1994). The most fundamental concept uses QDs as the photon source, and photonic crystal waveguides are utilized to connect QDs to other optical elements like optical couplers and detectors. Another concept uses a QD waveguide to drive the quantum signal (Huang et al., 2007). The quantum circuit device cannot be created without the QD positioning technique. In this realm of study, epitaxial QD has also advanced. The groundbreaking study's two-dimensional arrangement of size-controlled QDs was depicted as qubit cells in Figure 7 (Okubo et al., 2017).

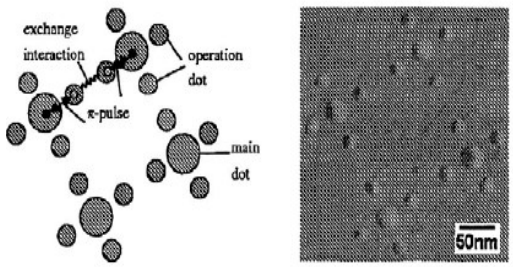


**Figure 7.** Quantum circuit arrangement in two dimensions created through SPM oxidation and subsequent epitaxial growth.

In this manufacturing, nano-sized holes on the substrate were first created by nano-spot oxidation using scanning probe microscopy (SPM), and then the oxides were selectively etched away. The preferred QD development in the holes was caused by epitaxial growth on the patterned substrate. The holes were followed by the QD position as well as the QD size. In another instance, the QD array as depicted in Figure 8 (Ohkouchi et al., 2009) was drawn using the cantilever source dropper.

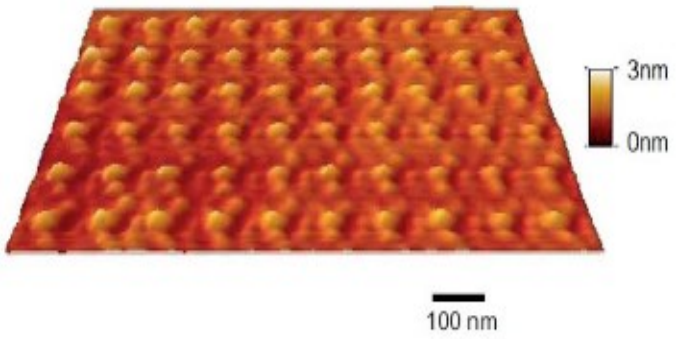


**Figure 8.** By using a nano-jet probe, a QD array was drawn.

With the help of epitaxial growth on a prepared substrate, the astounding 3D arrangement of QDs was made possible (Figure 9) (Atkinson et al., 2008). The method is based on the observation that crystal deformation causes QD nucleation to happen. It needs to be emphasized, nonetheless, that these QDs still struggle with low quantum efficiency and poor size homogeneity for use in real devices.

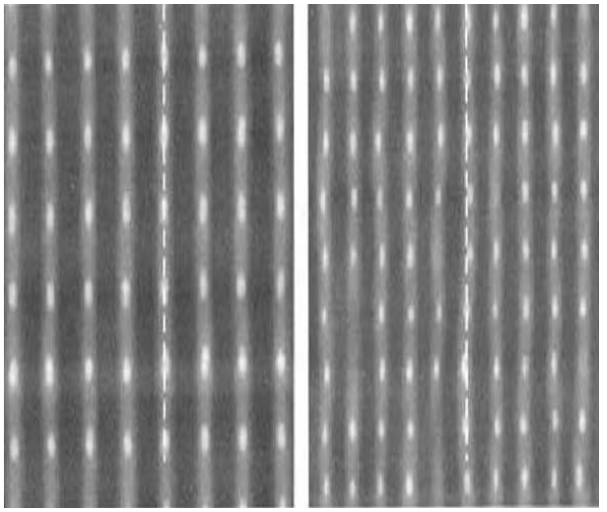

**Figure 9.** Epitaxial QDs produced in lines on a patterned substrate.

Since it is required for optical quantum repetition and optical quantum processing, the creation of the entangled photon pair is a crucial analyze topic in the field of quantum information technology. The photon pair emitted from the exciton molecules in QD has the potential to be in the polarization-entangled condition. When an exciton molecule is excited, it produces a photon that converts it into a single exciton, and the single exciton subsequently releases a second photon with a typically slightly different energy (Moreau et al., 2001). The reliability of nuclear power generation has recently been questioned, and the development of energy sources other than oil is urgently needed. The so-called "green technology" may provide several solutions, one of which is the QD solar cell. Two different forms of QD solar cells have received a lot of attention. One method includes epitaxial QDs as the compound semiconductor cell's intermediate-band photon absorber (Figure 10).

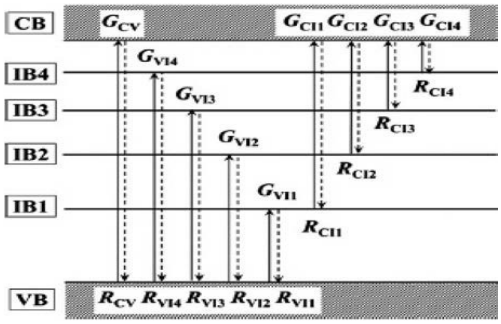


**Figure 10.** Carrier transitions and energy levels of the several QD intermediate bands are shown schematically.

The sensitizer in the organic solar cell of the other type uses colloidal QDs. The latter style of cell was anticipated to have a maximum photoelectric conversion efficiency of more than 70% (Nozawa et al., 2011). Although the latter form of cell is more readily adapted to practical use, its conversion efficiency is less than 10%. The epitaxial growth equipment has been used to study the production of the intermediate band solar cell (Ahsan et al., 2012). To create the intermediate energy band, the QDs must be packed tightly in three dimensions, but this is challenging. Existing QDs influence the development of new QDs because the crystal distortion energy serves as the basis for epitaxial QD production. As a result, it's imperative that the growth of multiplied layers be coordinated with the continual modification of the growth surface circumstances. In addition to the QD-sensitized cell, the Schottky cell or the depletion hetero junction cell has also been studied using colloidal QDs (Figure 11) (Zhou et al., 2011). In the QD layers, the QDs are accumulated at random. PbSe and CdSe QD Schottky cells still only have a 10% conversion rate. The challenges are still being solved through research and advancement. As an illustration, the ligands

around QDs serve to electrically isolate them to some extent. To increase conductivity, it has been researched how to substitute the ligands with shorter ones.

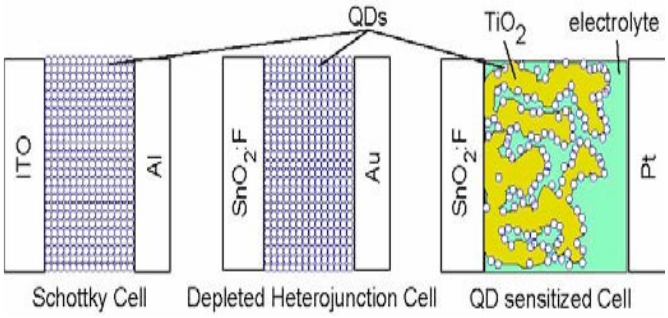


**Figure 11.** Schematic of the colloidal QD-based solar cells.

The production of a low-cost solar cell with a benefit of an intermediate band will be possible without trouble if QD superlattice is produced utilizing colloidal QDs.

## Conclusion

Overview of semiconductor QD research & innovation with an eye toward diverse applications of its optical features. Because QDs' emission wavelength spans the visual to infrared spectrum, they are appealing to a variety of application domains. In the areas of replacing current devices, quantum information devices, and solar energy conversion devices, research on both epitaxial QDs and colloidal QDs has advanced. The QD devices will be crucial to the 21st century's large-capacity information-oriented civilization and the solution to the energy crisis.

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