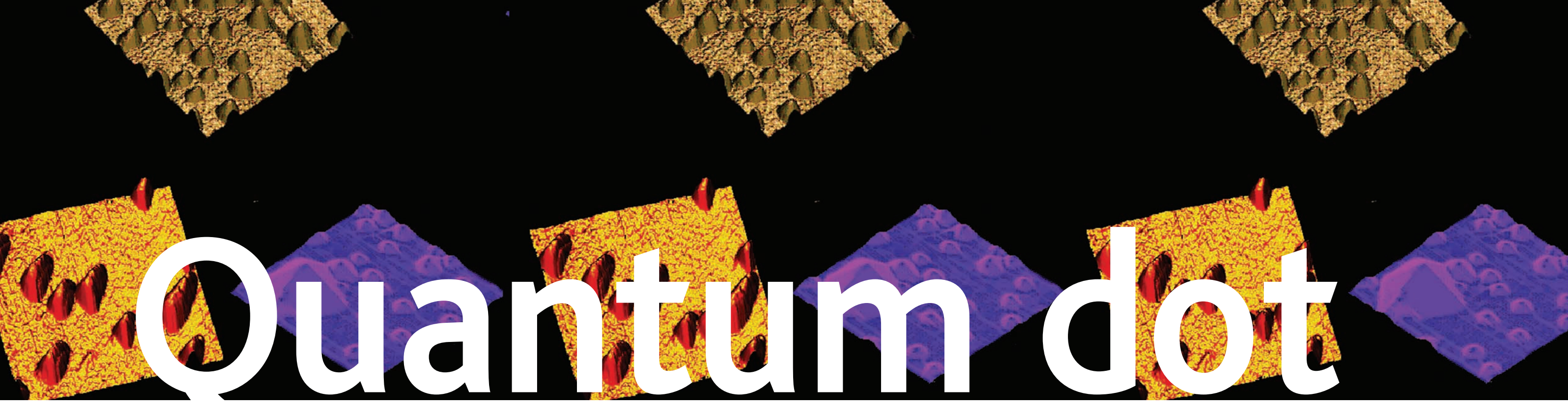

Quantum dot nanostructures

by Mohamed Henini

Low dimensional structures (LDS) form a major new branch of physics research. These semiconductor structures have such a small scale in one- or two-dimensions that their electronic properties are significantly different from the same material in bulk form. These properties are changed by quantum effects. There is increasing interest in the preparation, study, and application of LDS. Their investigation has revitalized condensed matter science, in particular semiconductor materials. Complex LDS offer device engineers new design opportunities for tailor-made new generation electronic and photonic devices. New crystal growth techniques such as molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) have made it possible to produce LDS in practice.

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These sophisticated technologies for the growth of high quality epitaxial layers of compound semiconductor materials on single crystal semiconductor substrates are becoming increasingly important for the development of the semiconductor electronics industry. This article is intended to convey the flavor of the subject by focusing on the technology and applications of self-assembled quantum dots (QDs) and to give an introduction to some of the essential characteristics.

Crystal growth and post-growth processing technologies have developed to the extent that it has become possible to fabricate semiconductor structures whose dimensions are comparable with interatomic distances in solids. In these LDS, the movement of charge carriers is constrained by potential barriers. This results in the restriction of the degrees of freedom for motion to two, one or even zero. The system becomes two-, one- or zero-dimensional depending on whether the potential barriers confine the carriers in one (layers), two (wires) or three (dots) dimensions (Fig. 1), respectively. Carriers exhibit wave-like characteristics and when the layer thickness is comparable with the carrier wavelength the carrier motion is constrained and exciting new physical properties result.

The study of LDS began in the late 1970s when sufficiently thin epitaxial layers were first produced. The layers used in the early investigations became available following developments in the technology of the epitaxial growth of semiconductors, mainly pioneered in industrial laboratories for device purposes.

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One of the main directions of contemporary semiconductor physics is the production and study of structures with a dimension less than two – quantum wires (QWs) and QDs – in order to realize novel devices that make use of low-dimensional confinement effects. During the last few years much attention has been devoted to the growth and characterization of self-assembled semiconductor QDs. The strong interest in these semiconductor nanostructures is motivated by the possibility of using them as active media in future high-speed electronic and photonic devices.

Fabrication of quantum dots

Several methods for the fabrication of QDs have been reported over the last decade, including lithography-based technologies. Although this technique is widely used to produce QDs, predominantly by the combination of high-resolution electron beam lithography and etching, the spatial resolution required for reaching the size regime where significant quantization effects can be expected tends to be larger than the desirable level. In addition, lithographic methods and subsequent processing often produce contamination, defect formation, size non-uniformity, poor interface quality, and even damage to the bulk crystal itself. A new attractive method of defect-free 10 nm scale QD fabrication is Stranski-Krastanov (SK) growth in lattice-mismatched systems. In the SK growth mode, mismatched epitaxy is initially accommodated by biaxial compression in a layer-by-layer (two-dimensional) growth region, traditionally called the wetting layer. After deposition of a few monolayers, the strain energy increases and the development of islands (three-dimensional) becomes more favorable than planar growth[1] (Fig. 2).

In III-V semiconductors, SK growth has been used to grow InAs islands on GaAs and it has been shown that the size fluctuation of dots is relatively small (<10%). The small dots and surrounding host matrix are dislocation-free and strained coherently with GaAs. It has been reported that the InAs growth mode changes from two- to three-dimensions upon the deposition of less than two monolayers of InAs, so as to reduce the strain in the grown layer, since there is about a 7% lattice mismatch in the GaAs/InAs system. The strained (In,Ga)As/GaAs material system has been the most widely studied and various quantum effects have been demonstrated. Combinations of III-V semiconductors based

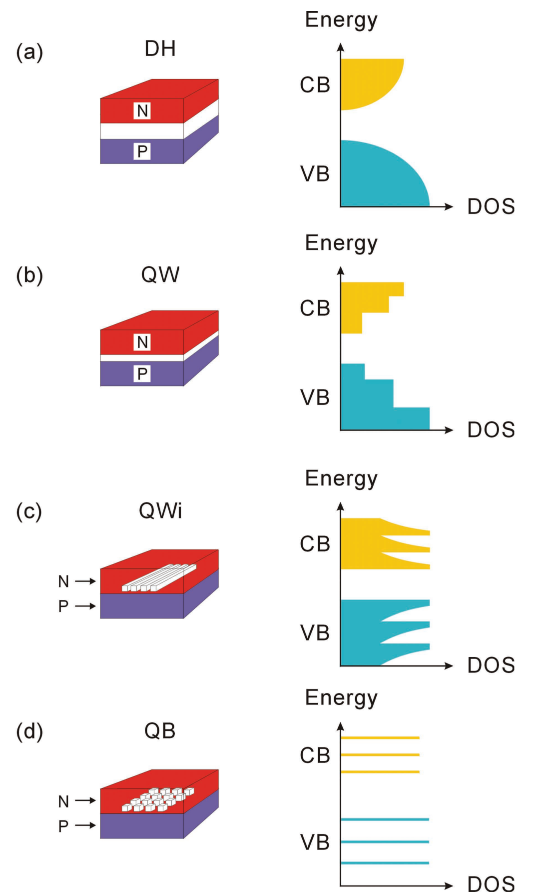

Fig. 1 Schematic diagram of the density of states (DOS) in the conduction band (CB) and valence band (VB) for (a) a double heterostructure, (b) a quantum well, (c) a quantum wire, and (d) a quantum box laser.

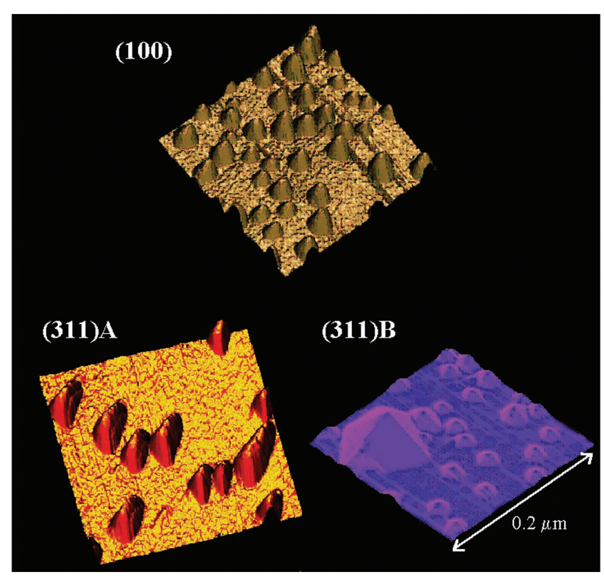

Fig. 2 Scanning tunneling microscope images (100 x 100 nm) of InAs/GaAs QDs grown by MBE on (100), (311)A, and (311)B GaAs substrates[1]. As can be seen, using substrates with different orientations can control the shape of the QDs.

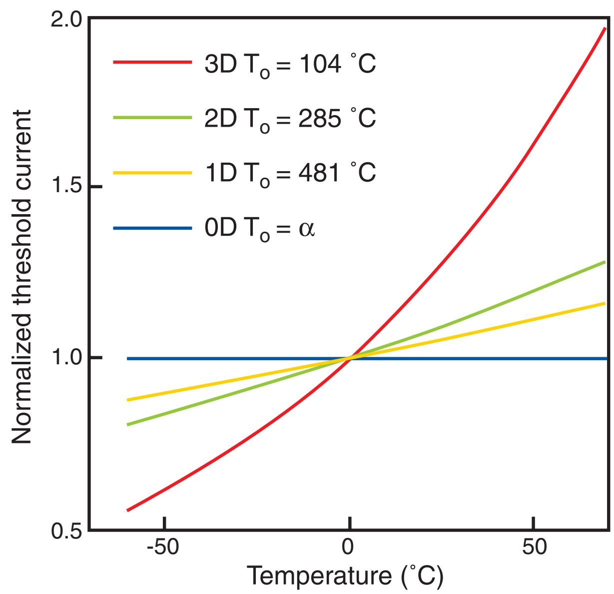

Fig. 3 Theoretical predictions of the threshold current in double heterostructure, quantum well, quantum wire, and quantum box lasers. The threshold current as a function of temperature, T, is given by: $J_{th}(T) = J_{th}(0)\exp(T/T_0)$, *where* T_0 *is the laser characteristic temperature.*

on phosphorus or antimony compounds and Si/SiGe alloys have also been studied.

The advantages of this technique of QD fabrication are that no nanotechnology and no further etch or implantation induced process is necessary. Since the dots are grown *in situ*, a homogeneous surface morphology is maintained and defect creation is avoided. However, the inherent problems associated with this method are the size non-uniformity and the lack of control of the position of the QD. Controlling the dimension and arrangement of the self-organized three-dimensional structures is believed to be very important for obtaining structures with good properties.

Quantum dot lasers

QDs are of significant interest for application in laser diodes. It is worth noting that the device which benefited most from the introduction of QWs is the injection laser. The QW laser reached mass production within a few years because of its low cost, high performance, and good reliability. QDs are believed to provide a promising way forward for a new generation of optical light sources, such as injection lasers. QD lasers are expected to have superior properties with respect to conventional QW lasers. Theoretical predictions[2] of the intrinsic properties of QD lasers include higher characteristic temperature, T_0, of threshold current, higher modulation bandwidth, lower threshold currents, and narrower linewidth (Fig. 3).

The principal advantage of using size-quantized heterostructures in lasers originates from the increase of the density of states for charge carriers near the band-edges (Fig. 1). When used as the active medium of a laser, this results in the concentration of most of the injected nonequilibrium carriers in an increasingly narrow energy range near the bottom of the conduction band and/or top of the valence band. This enhances the maximum material gain and reduces the influence of temperature on the device performance. Fig. 4 shows the development of semiconductor diode lasers in terms of threshold current density as a function of time for various heterostructures based on double heterostructures (DHS), QWs, and QDs. The recently developed QD lasers[3] based on InAs have already shown a record low threshold current density of 24 Acm^{-2} at room temperature for a wavelength of 1.28 µm. This is almost a factor of two lower than that achieved by QW lasers[4]. InAs QD laser diodes with high light output power of 3 W at 1.1 µm have also been reported[5]. Red light emitting QD lasers have also been successfully fabricated with AlInAs/AlGaAs[6] and InP/GaInP[7] QDs.

It is possible to access new energies by combining materials with different lattice constants and energy gaps. Currently, the spectral range of III–V semiconductor QD lasers extends from the near infrared (1.84 µm for InAs–(In,Ga,Al)As QD lasers on InP substrates[8]) to the visible red range[6].

Lasers based on InGaAsP/InP heterostructures emitting at 1.3 µm and 1.55 µm are currently widely used in fiber optic communication systems. These lasers, which are mainly used for long-distance data transmission, are quite expensive, however. InAs/GaAs QDs are currently considered as the most promising candidates for this wavelength range. Park *et al.*[9] reported continuous-wave (CW) lasing of a single layer 1.3 µm GaAs-based QD laser. The low CW current density of 45 Acm^{-2} demonstrates the potential of this system for eventually realizing high performance lasers and their potential application to optical interconnects.

Semiconductor lasers have opened up potentially huge markets in optical communication, compact disks and related optical data storage applications, displays, and lighting. Until a few years ago, most of these lasers were edge emitters where the lasing cavity lies horizontally in the wafer plane.

For many applications, for example those requiring a two-dimensional laser array, it is desirable to have the laser output normal to the surface of the wafer. This new breed of lasers is known as vertical-cavity surface-emitting lasers (VCSELs). Because of its unique topology, the VCSEL has some distinct advantages over conventional edge-emitting lasers. The optical beam is circular such that high coupling efficiency to optical fibers is possible. The active volume of VCSELs can be made so small that high packing density, low threshold lasers are obtained. The design of the laser allows simple monolithic integration of two-dimensional arrays of laser diodes, realizing interesting light sources for two-dimensional optical data processing. Now there is a strong motivation to create long wavelength VCSELs using QDs as the active medium. Up until now, most of the QD VCSELs have emitted near 1 μm[10]. It is worth pointing out that QD-based lasers need to be improved to achieve the necessary high output power and long lifetime.

Other applications of QDs

All important applications of infrared techniques, for both military and civil purposes (sciences, meteorology, medicine, industry, etc.) rely on the detection of radiation in the 1-3 μm, 3-5 μm, and 8-14 μm spectral range (the so-called 'atmospheric windows'). The 8-14 μm wavelength region is especially important for imaging since the temperature of the human body is around 300 K, corresponding to a peak wavelength of thermal radiation at about 10 μm. The materials that cover these wavelength regions include II-VI, III-V, and IV-VI compound semiconductors. With respect to the well-known HgCdTe detectors, GaAs/AlGaAs QW devices have a number of potential advantages including the use of standard manufacturing technology based on advanced GaAs growth and processing techniques, highly uniform and well controlled MBE growth on large GaAs wafers, high yield, greater thermal stability, and intrinsic radiation resistance.

Recently there has been significant interest in developing novel QD infrared photodetectors (QDIPs). There are two major potential advantages of QDs over QWs as photodetectors[11], namely

- Intersubband absorption may be allowed at normal incidence. In QW infrared photodetectors (QWIPs) only transitions polarized perpendicular to the growth direction are allowed, because of absorption selection rules. The selection rules in QDIPs are inherently different, and normal incidence absorption is, indeed, observed.
- Thermal generation of electrons is significantly reduced because of the energy quantization in all three dimensions. Generation by longitudinal optic (LO) phonons is prohibited unless the gap between the discrete energy levels is exactly equal to that of the phonon. This prohibition does not apply to QWs, since the levels are

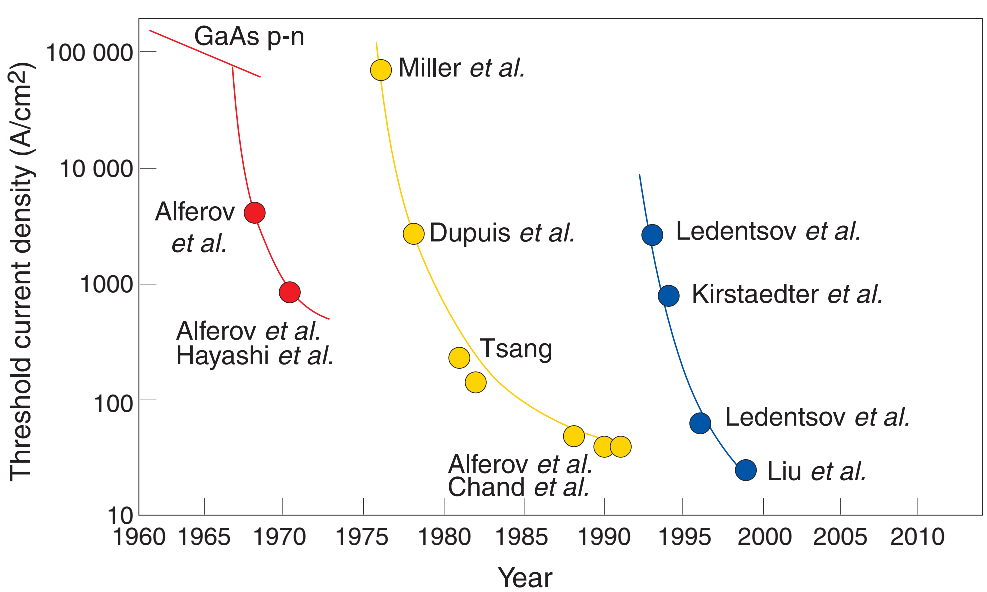

Fig. 4 Development of semiconductor diode lasers[18-29] based on DHS, QWs, and QDs.

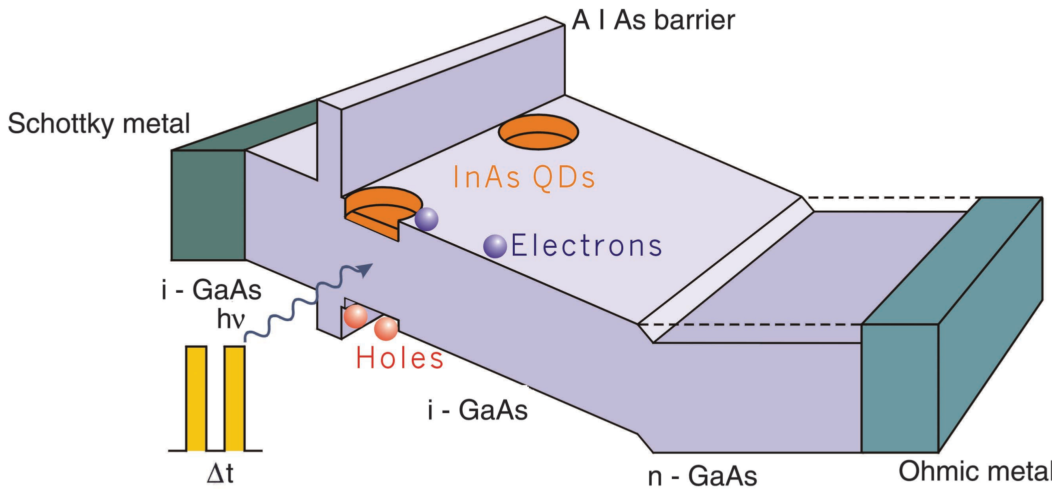

Fig. 5 Device showing memory effect in InAs quantum dots[14].

quantized only in the growth direction and a continuum exists in the other two. Hence thermal-generation or recombination by LO phonons results, with a capture time of a few picoseconds. Thus, it is expected that the signal-to-noise ratio in QDIPs will be significantly larger than that of QWIPs.

The operation of a photovoltaic QDIP fabricated from (InGa)As/GaAs heterostructures has been demonstrated by Pan *et al.*[12]. These detectors are sensitive to normal incidence light. At zero bias and low temperature (78 K), peak detectivity of 2×10^8 cm•Hz$^{1/2}$•W^{-1}, with a responsivity of 1 mAW^{-1} at a wavelength of 13 µm, was obtained. The authors claim that this is the highest detectivity achieved for a QDIP operating in the photovoltaic mode and that such a device might be attractive for focal plane array imaging applications.

Room temperature far-infrared (8-10 µm) photodetectors using self-assembled InAs QDs with high detectivity have been reported by Kim *et al.*[13]. They reported the optimized performance of a QDIP grown by MBE. In this detector, the location of InAs QDs adjacent to the channel of an AlGaAs/GaAs modulation-doped structure is adjusted to maximize the generated photocurrent and simultaneously minimize the dark current. A peak responsivity of 5.3 AW^{-1} was obtained at 9.0 µm. The high detectivities of 6×10^8 cm•Hz$^{1/2}$•W^{-1} and 5×10^{10} cm•Hz$^{1/2}$•W^{-1} were obtained at room temperature and 80 K, respectively.

QDs can be used to make better optical devices. They can also be used to make devices with a totally new functionality. For example, an optical data storage medium in which bits of information are stored as a single or few electrons within the dots. These memory devices based on QDs would require a very low switching energy because the information is stored as a single or few electrons. Optical illumination can be used to write the charge to be stored in the QDs. It is predicted that because each QD would carry a bit of information, these memory devices could potentially achieve ultra-dense storage capacities on the order of terabits per inch.

Sugiyama *et al.*[14] at Fujitsu Laboratories, Japan, observed memory effects in InAs QDs buried in Schottky barrier diodes with a memory retention time of 0.48 ms for the first time. The band diagram of their structure, which contained a single layer of QDs, is shown in Fig. 5. Two sequential laser pulses, with an interval time Δt, irradiate the diode. Electron-hole pairs are generated in the InAs QDs after the first laser pulse irradiation. The electrons escape from the QDs via tunneling or thermo-ionic emission, while the holes remain in the QD. The residual holes decrease the photocurrent when the second laser pulse irradiation occurs. The retention time of the optical memory is determined by the interval time, Δt, and the dependence of the photocurrent difference between I_{write} and I_{read}. Although these are preliminary results, the researchers believe that there is a possibility of using QDs for high density optical memory.

Some InAs QD devices in which electrons are transported in the vertical direction have shown a clear memory effect[15]. Recently, Son *et al.*[16] demonstrated the memory operation of InAs QDs in a lateral heterojunction field effect transistor (FET) structure. Lateral transport occurred through parallel conduction in the two-dimensional channel and QD layers.

This channel, which is induced by gate bias, is strongly influenced by the charge stored in InAs QD layers. The authors believe that the memory operation is caused by the charge trapping effect of InAs QDs.

QD memory devices using optical illumination to store charge in the QDs require a sensitive method of detecting the trapped photo-excited charge. Shields *et al.*[17] demonstrated that using a transistor structure (Fig. 6) allows the presence of single photo-excited carrier in a single QD to be detected. Conventional semiconductor single-photon detectors rely upon the avalanche process. However, in Shields' device, the gain derives from the fact that the conductivity of the FET channel is very sensitive to the photo-excited charge trapped in the QDs. Their FET contains a layer of InAs QDs adjacent to the channel and separated from it by a thin AlGaAs barrier. The capture of a single photo-excited carrier by a QD leads to a sizeable change in the source-drain current through the transistor, allowing the detection of a single photon.

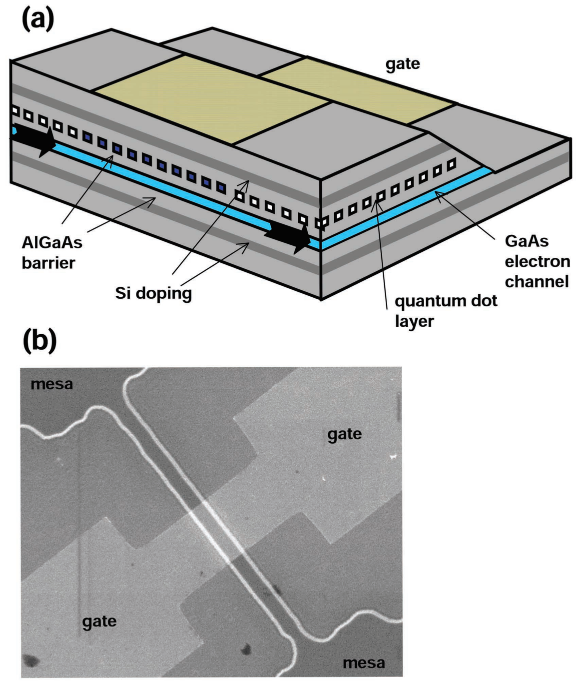

Fig. 6 (a) Cross-sectional view of a QD FET structure with a small area Schottky gate and (b) scanning electron microscope image of the gate region for an FET with a 2 μm wide mesa and 4 μm long gate. A positive gate bias charges the QDs with electrons, which limits the mobility of the adjacent electron channel. Single photons liberate a trapped electron via capture of a photo-excited hole. This results in a detectable increase in conductance of the electron channel. (Courtesy of Dr A.J. Shields, Toshiba Research Europe Ltd.)

Conclusion

This article has described the progress made on some QDs devices. Other work on QD structures is progressing in many laboratories around the world. Some of the studies cited here are still in their infancy and many challenges remain for the development of high-performance QD devices for optical and electronic applications. For the case of QD lasers, there is a consensus of opinion that they are ready for practical applications and their future is extremely promising. However, the replacement of QW with QD lasers depends on industry and its willingness to switch to a new technology. If recent history of DHS and QW lasers is any guide, it is likely that QDs will lead to entirely new classes of materials and devices. MT

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