5 Self Assembled Quantum Dot Devices

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In this paper we review some three novel semiconductor devices which are made possible by the unique electronic properties associated with quantum dots. We also discuss the prospects for the commercial applications of quantum dot devices.

INTRODUCTION

Novel quantum dots (QDs) devices are making use of the physical properties of the self assembled quantum dots (QDs) [1] and have been developed rapidly. Among the important QDs characteristics [2] which should provide new advances in semiconductor optoelectronic devices we find: a) the three dimensional quantum confinement of carrier and excitons which bring into play important many body effects, b) an ultra sharp density of states which confer to the QD "atom like properties" and c) carrier and excitons localization which reduce their interactions with the surrounding material.

A wide variety of optoelectronic QDs devices have already been investigated. We cannot in this paper give an exhaustive review of all of them. For example, we omit to cover the QDs laser [3] and infrared detector devices which have made rapid progress. Instead we provide and discuss three examples of QDs devices which make use of some of their characteristics. These are:

a) An exciton storage which uses carrier localization in quantum dots to write information using photons to store the dissociated excitons (electron hole pairs) for long time periods (minutes) and to read the information as emitted photons at low temperature.
b) A novel quantum dot spin injection light emitting diode which shows magnetically controlled circular polarization of its electroluminescence.
c) A single photon quantum dot generator which produces a single photon on command.

I) INFORMATION STORAGE USING QUANTUM DOTS

Trapping of carriers and excitons in a QD drastically reduces their recombination rate with ionized impurities or other defects in the surrounding material. This quantum dot characteristic can be used for a memory device in which information is written and read by controlling charge storage in quantum dots [4,5]. In the

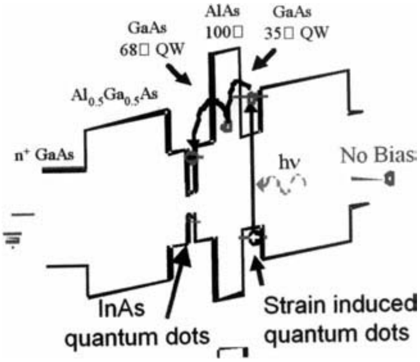

Figure 1 Band structure of the quantum dot device.

example discussed here, light is used to write and read the information. As shown schematically in Figure 1, an exciton is dissociated by the internal field in the structure and the corresponding electron and hole are stored in a pair of strain coupled closely spaced quantum dots. After storing, the exciton is reassembled by using an applied electric field to drive the hole into the quantum dot that contains the stored electron. The recombination of the exciton is then read using standard photon detection techniques. The relevant band structure and the device are schematically shown in Figure 1.

In the device, we make of the strain field associated with the InAs QDs. A GaAs quantum dot is induced in a narrow GaAs quantum well adjacent to the InAs QDs [6]. An electron hole pair is generated in the GaAs QD through a short light pulse. The InAs and GaAs QDs layers are separated by a thin AlAs layer which provides a very fast (≈0.5 ps) electron transfer from the strain induced GaAs quantum dot into the InAs quantum dot. The electron and hole are then spatially confined into an adjacent pair of InAs-GaAs QDs.

The external electric field required to separate the electron-hole pair and bring them back together, is produced by locating the quantum dot layers inside a field effect structure which includes an n+ doped GaAs back gate and a semi-transparent Schottky front contact. The charge separation takes place only if the electron energy level in the strain induced quantum dot is higher than the X valley minima level in the AlAs barrier layer. The stored carriers are recombined by applying an electric field which tilts the band in the opposite direction from that shown in Figure 1.

As shown in Figure 2, very long storage times (well over 10 seconds) can be achieved with this device. These storage times are remarkably long when compared to the exciton lifetime in quantum dots (≈1 ns). The temperature dependence of the light storage is preserved up to 120 K. Above this temperature, thermal ionization of carriers out of the QDs is occurring and destroys the light storing properties of the device.

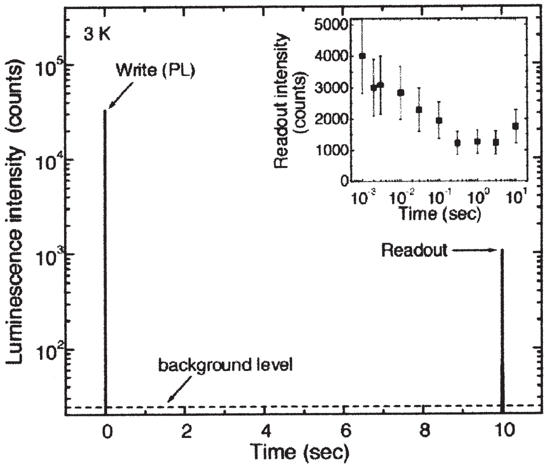

Figure 2 Luminescence intensity from the peak of the InAs QDs line (1.25 eV) as function of time. A 100 μs optical pulse excites the sample at t = 0, and a 10 μs bias pulse (3 V) is applied at t = 10 sec. The dash line represents the average background signal. The inset shows the readout integrated intensity as a function of delay time. The loss of signal as a function of storage time may be related to the presence of hole trapping centers in the AlAs layers.

II) A SPIN POLARIZED QUANTUM DOT LIGHT EMITTING DIODE

A critical element to the implementation of spintronics is based on the efficient transfer of spin-polarized electrons through interfaces between different materials. The recent demonstration of surprisingly long decoherence times in III-V compounds semiconductors [7,8] and the possible use of spins for implementing quantum computing have greatly stimulated the research in spin based electronics and optoelectronics using hybrid ferromagnetic-semiconductor structures. The introduction of magnetic semiconductors [9,10] as spin aligners to demonstrate coherent spin transfer across heterojunctions has led to the development of spintronics-based light-emitting diodes (LEDs). These all-semiconductor devices emit circularly polarized light as a direct consequence of polarized spin injection through the interface between the magnetic semiconductor (spin filter) into the non-magnetic one. Understanding further the spin alignment process in the magnetic semiconductors [11] and coherent spin transfer processes from a ferromagnetic film into a semiconductor [12] or across semiconductor hetero-junctions [13] are essential to further progress in the field of spintronics.

The possibility of injecting polarized spins into QDs is attractive since the lateral quantum confinement of carriers broadens the selection rule for emitting circularly polarized and should lead to longer spin coherence times because carriers are confined and interact less with their surrounding. Here we discuss a quantum dot light emitting diode (QDLED) which emits circularly polarized with a magnetic field dependent polarization. The device is a hybrid structure composed of a GaMnAs magnetic semiconductor layer and GaAs (i)/InAs(i)/GaAs(n) semiconductor QD layers. Under forward bias electrons and spin polarized holes are injected into the QDs.

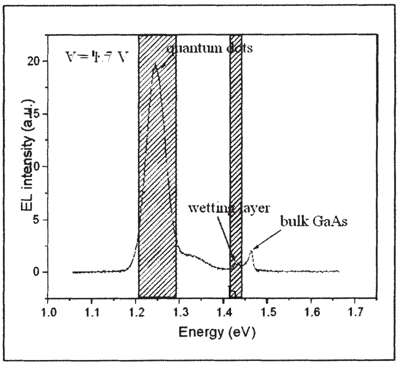

Figure 3 Electroluminescence spectrum of the QDLED at a forward bias of 1.7 V at 5 K. The quantum dot and emission wetting layer are indicated. The shaded area correspond to the energy range over which the circular polarization is measured.

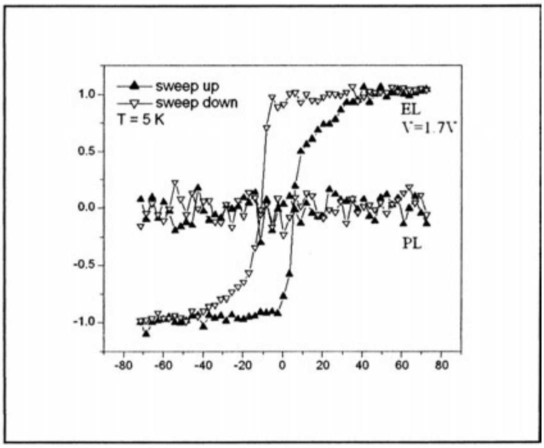

Figure 4 Circular polarization of the EL for a QDLED as a function of the in plane magnetic field at T=5 K. The circular polarization of the photoluminescence for the same device is also shown as a function of magnetic field.

The electroluminescence (EL) circular polarization is analyzed as a function of the in plane magnetization of the GaMnAs layer and temperature. The magnetic field is applied along the <110> easy magnetization axis and the emitted light is collected from the edge of the QDLED. Figure 3 shows the EL spectrum of the QDs at T=5 K for a forward bias of 1.7 V.

The EL circular polarization at 5 K is shown in Figure 4. The magnetic field dependence of the circular polarization shows a clear hysteresis loop which coincides well with that of the GaMnAs measured using a SQUID magnetometer. On the other hand the polarization measurement of the photoluminescence (PL) of the same QDLED does not show a measurable magnetic field dependence (Figure 4). This result provides a clear indication that the injected spin polarized holes are responsible for the EL circular polarization.

The measured temperature dependence of the EL circular polarization shown in Figure 5 gives also a clear indication that the holes spin polarization in the GaMnAs layer is responsible for the magnetic field dependence of the polarization. Indeed, above the Curie temperature ($T_c \approx 70$ K) of the GaMnAs, the measured circular polarization disappears completely.

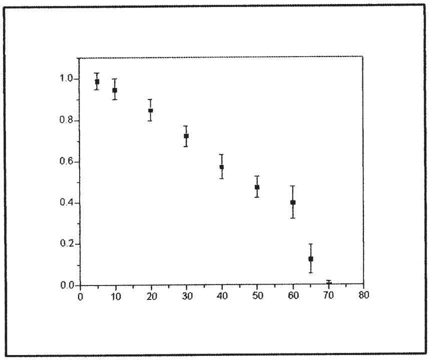

Figure 5 EL circular polarization of the QDLED as a function of the temperature.

These results point out the potential applications spin polarized devices based on QDs to the field of spintronics. The new challenge will be the development of room temperature devices using hybrid structures with ferromagnetic layers having a Curie temperature above 300 K.

III) SINGLE PHOTON GENERATION USING A SINGLE QUANTUM DOT

Excitons in QDs constitute an ideal two-level system for cavity-QED applications. The excitons are trapped by the surrounding high bang-gap energy semiconductor. Using a semiconductor microdisk which contains a layer of QDs, it is possible to support high Q modes and couple these with QDs [14].

This coupling makes use of the Purcell effect and the high-Q values of the whispering gallery modes in microdisk structures should favor a strong coupling regime in the microdisk. These effects have been already demonstrated in microdisks and micro-pillars [15,16].

The principal application of QD cavity-QED has been the realization of a QD single photon turnstile device, which has demonstrated the great potential of self-assembled QDs have for applications in quantum information technology. Photon correlation measurements (Figure 6) carried out on a single QD embedded in a microdisk have revealed that a saturated QD generates one-and-only-one photon (at the fundamental exciton transition) for every excitation pulse from a mode-locked laser.

Optical pumping of a single QD in a micro-disk containing a very low density of QDs allows to find the QD in resonance with a cavity mode near the edge of the microdisk by observing the full width at half maximum of the fundamental exciton line. The second order correlation (intensity) function of a single QD emitter fluorescence is measured. These measurements have clearly shown that the presence of photons antibunching. The value of the correlation function changes from 0 to 1 in a time scale determined by the single exciton recombination time.

Through the Purcell effect, the radiative recombination time is shortened when the QD fundamental exciton line is on resonance with a cavity mode. Experiments on QDs embedded in microdisk microcavities already reveal some of these features [17]. This approach provides a means of producing single photon on command. The collection efficiency of the photon is still very low and structures with micro-pillars should be superior for device applications. Positioning a single quantum dot into a micro-pillar will remain a formidable challenge. However, the QD positioning described in a preceding chapter could be useful for this.

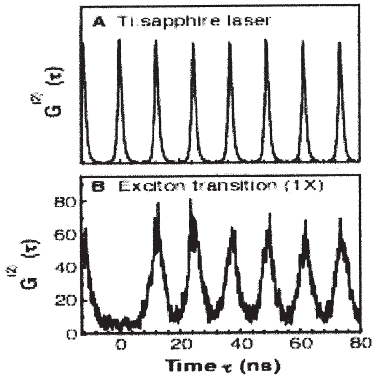

Figure 6 Intensity correlation function for the Ti-Sapphire laser (upper curve) and for the exciton transition as a function of the time delay between the photon arrival times τ. The absence of a peak at τ = 0 ns in the lower curve proves that none of the pulses contain more than one photon [17].

This type of single photon turnstiles have potential applications to the field of quantum cryptography and quantum computing.

CONCLUSIONS

QDs properties are making possible the realization of new optoelectronic devices. We have described here only a few of them. It is clear that one of the remaining challenge to bring these devices into the realm of commercial products is to develop a QD material system which eliminates carrier thermal ionization out of the QDs at room temperature. A promising system is the GaN/AlN system where the band offsets for the electrons and holes are much larger than for the InAs/GaAs system. The development of such a QD system should offer new possibilities for commercial applications and the development of novel QD devices.

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