Charge separation in coupled InAs quantum dots and strain-induced quantum dots

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We present an InAs self-assembled quantum dot structure designed to spatially separate and store photo-generated electron-hole pairs. The structure consists of pairs of strain-coupled quantum dots. Separation of electron-hole pairs into the quantum dots and strain-induced quantum dots has been observed using power-dependant photoluminescence and bias-dependent photoluminescence. © *1999 American Institute of Physics.* [S0003-6951(99)04015-2]

A greater knowledge of the growth of self-assembled quantum dots (QDs) and of their electrical and optical properties is starting to yield quantum dot based devices, e.g., QD infrared detectors,[1–3] QD lasers,[4–7] and QD memory devices.[8–13] The ability to trap, localize, and store carriers within a QD makes it an attractive medium for memory applications. Such devices also offer the potential for multiple storage bits per device by utilizing the size distribution of the self-organized QDs.

In this letter we introduce a QDs device designed to spatially separate and store photo-generated electron-hole pairs. The structure consists of two GaAs quantum wells (QW) of different thicknesses, separated by a thin AlAs barrier. An InAs QDs layer is inserted in the thick QW to allow carrier localization within the device. The InAs QDs layer also creates strain-induced quantum dots (SIQDs) within the thin GaAs QW that are coupled to the InAs QDs.[14] In the structure photo-generated electrons and holes are spatially separated into the InAs QDs and SIQDs, respectively (see Fig. 1). An incident photon pulse creates electron-hole pairs within the thin QW. The thicknesses of the GaAs QWs are selected such that their first electron state is either above (for the thin QW) or below (for the thick QW surrounding the InAs QDs layer) the X-band minimum of the AlAs barrier. Electrons are able to tunnel into the InAs QDs from the thin GaAs QW through the X-band minimum, while the respective holes remain in the thin QW since there is no intermediate tunneling route available for holes.

Photoluminescence (PL) samples were grown by molecular beam epitaxy and a growth rate calibration was performed through reflection high-energy electron diffraction oscillations. After deposition of an AlAs/GaAs 40 $\times$(20 Å/20 Å) short-period supperlattice (SPS) for smoothing, a 500 Å $Al_{0.5}Ga_{0.5}As$ barrier was grown, followed by a 31 Å GaAs QW in which an InAs QDs layer (QDs samples) or wetting layer (reference samples) was inserted. Next, the 100 Å AlAs barrier was deposited, along with the thin 25 Å GaAs QW, a 500 Å $Al_{0.5}Ga_{0.5}As$ barrier, and a 50 Å GaAs capping layer. Samples used for biased photoluminescence spectroscopy (BPL) were identical to the PL samples with the addition of a n^+-GaAs back gate and a thin SPS layer above the structure to decrease the leakage current through the device. A semitransparent Cr/Au Schottky contact was thermally evaporated on the surface to provide the top contact.

A typical PL spectrum of a QDs sample is shown in Fig. 2. A QDs peak is present at about 1.32 eV in the PL spectra of the QDs sample (transition *A* of inset in Fig. 2). As expected, PL spectra from the reference sample did not contain such a peak. The strong PL lines around 1.51 eV originate from the GaAs buffer layer in the sample. The broad peak full width at half maximum [FWHM=72 meV] observed at ~1.8 eV comes from the SIQDs (transition *B*). This peak is associated with an indirect type-II recombination between electrons in the AlAs X minimum and heavy holes in the 25 Å QW. Previous PL studies on AlAs/GaAs superlattices have demonstrated strong luminescence from such a spatially indirect recombination due to the ultrafast transfer (~0.4 psec) of electrons from the GaAs QW to the X-band minimum in the AlAs.[15,16] The SIQDs arise from strain fields above the InAs QDs. The piezopotential band gap modulation[17] resulting from the strain field and the strain induced deformation potential induce carrier localization in the 25 Å QW. Results obtained from theoretical calculations of the piezoelectric and deformation potentials for a 25 Å GaAs QW located 100 Å above an InAs QD indicate a piezoelectric potential of ~30 meV for holes and electrons.

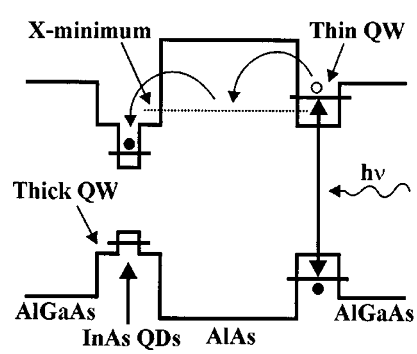

FIG. 1. Band diagram schematic of the charge separation process.

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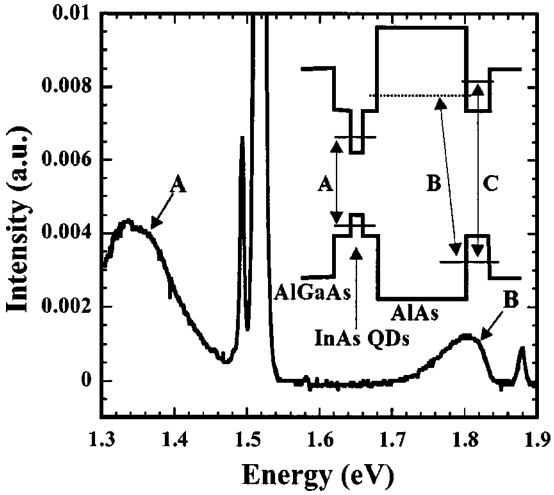

FIG. 2. PL spectrum of the QDs sample. Spectra were taken at $T=3$ K with a Ar^+ laser ($\lambda=514.5$ nm) pump power of 150 W/cm^2. Inset shows origin of PL peaks in the spectra.

These calculations are consistent with the 20–50 meV energy reductions we observe for the SIQDs, relative to an unstrained 25 Å QW. The width of the 1.8 eV PL peak is due to the SIQDs size distribution induced by the size distribution of the InAs QDs. A sharper peak (FWHM=18 meV) at 1.85 eV was observed in the reference sample PL spectra, corresponding to the same type-II recombination. The narrower line width of this peak indicates the absence of SIQDs within the reference sample, as expected.

The power dependent photoluminescence (PDPL) spectra of the SIQDs are shown in Fig. 3(a). For increasing pump powers between 12 $W/cm^2$and 3.8 kW/cm^2 the SIQDs peak blue shifts 50 meV. At a pump power of 2.2 kW/cm^2, the direct recombination of electrons and heavy holes in the 25 Å QW (transition *C* in Fig. 2) begins to dominate over the SIQDs luminescence. A similar dependence on pump power is observed in the PDPL from the reference sample [Fig. 3(b)]. The PL peak from the indirect recombination (1.8–1.84 eV) is found to shift 50 meV for increasing pump power between 12 W/cm^2 and 0.5 kW/cm^2. As observed in the PDPL of the SIQDs from the QDs sample, the direct recombination from the 25 Å QW (1.845 eV) begins to dominate at high pump powers (380 W/cm^2). The blue shift in the SIQDs peak for increasing pump powers comes from: (a) an increased filling of the higher energy SIQDs (FWHM increases from 40 to 90 meV) and (b) an increase in the band bending in the structure due to a greater number of electron-hole dipoles. In contrast, the only contribution to the blue shift in the reference sample PDPL is the increase in the number of electron-hole separations for increased pump powers. Thus, the PDPL data indicate that the structure is able to efficiently separate photo-generated electron-hole pairs into the coupled QDs.

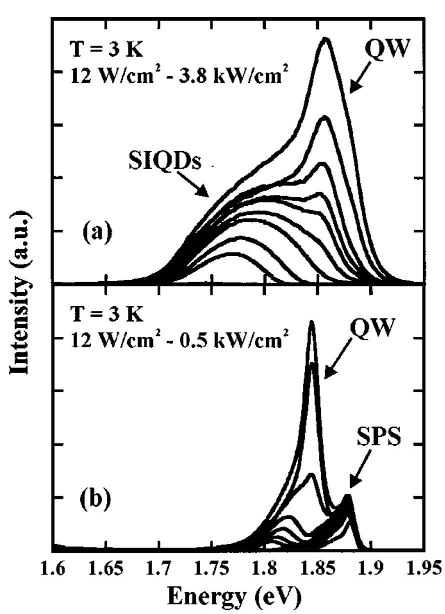

FIG. 3. Power dependent PL spectra for the QDs (a) and reference (b) samples.

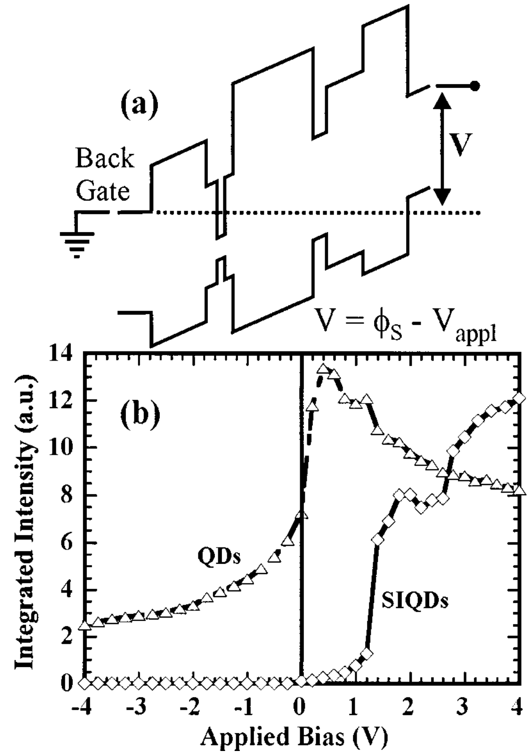

FIG. 4. Schematic of the band diagram under bias (a), and the dependence of the integrated intensities of the QDs and SIQDs PL peaks on applied bias (b). Data was taken at $T=3$ K with an Ar^+ laser power of 250 W/cm^2.

In both the QDs and reference sample PDPL spectra, a saturation of the spatially-indirect type-II recombination occurs. This is due to the dipole-induced band bending within the structure, which increases for larger pump powers. The increased dipole strength for higher pump powers causes an increased band bending which decreases the efficiency of transfer of the electrons from the 25 Å QW to the InAs QDs. At high pump powers the quasi-Fermi level in the SIQDs increases sufficiently to give rise to the direct recombination within the 25 Å QW.

In order to further investigate the carrier separation kinetics of this structure, bias dependent PL (BPL) measurements were performed. A schematic of the band diagram under bias is given in Fig. 4(a). The voltage drop, *V*, across the sample for an applied bias, V_{appl}, is simply

$$V=\phi_S-V_{appl},$$

where ϕ_S is the built-in Schottky barrier height. The integrated intensity dependence of the SIQDs and QDs peaks on applied bias is shown in Fig. 4(b). Under negative bias, no SIQDs luminescence is observed. This is due to the highly efficient transfer of electrons out of the 25 Å QW into the InAs QDs. For negative biases a PL peak is observed for the QDs. This peak increases in intensity for decreasing negative applied bias. For the negative biases, electrons and holes are swept away by the applied electric field, giving rise to a measurable photocurrent. As the negative bias is decreased towards 0.0 V, a reduced number of carriers are swept away, leading to a decreased photocurrent and an increased QDs luminescence.

As the applied bias is increased above 0.0 V, the QDs luminescence continues to increase for applied biases up to ~0.7 V, at which point it slowly drops for increased biases. Conversely, the SIQDs peak intensity rises quickly above ~0.7 V up to 1.8 V. This behavior is due to the bias-induced band bending within the structure. As stated earlier, for applied biases between −3.0 and ~0.7 V, electron transfer into the QDs from the SIQDs is very efficient. As the applied bias is increased above 0.7 V, the efficiency of the electron transfer is reduced, giving rise to an increase in the SIQDs luminescence and a reduction in the QDs PL intensity.

An interesting feature is observed for applied biases above 1.8 V. For voltages between 1.8 and 2.8 V, the integrated area of the SIQDs luminescence decreases, and then begins to increase once again. This dip in the SIQDs luminescence is associated with a change in the slope of the QDs luminescence as a function of bias. While this behavior is not fully understood, it is possible that this corresponds to the point at which holes are able to tunnel from the SIQDs into the QDs. The BPL data indicates that not only is there efficient separation of the photo-generated electron-hole pairs, but that there may also be a regime for which an applied bias pulse can be used to cause tunneling of the holes from the 25 Å QW into the QDs layer to induce the electron-hole recombination. This effect could be used for reading the stored charges in a QDs memory structure.

We have designed a QDs structure that has the ability to separate photo-generated electrons and holes into pairs of coupled QDs. Separation of the electrons and holes in the structure was demonstrated using power-dependent and biased PL spectroscopy. While the data clearly indicates the ability of the structure to efficiently separate electron-hole pairs, further investigation is required in order to access the storage capabilities of the device.

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