Piezoelectric effects in $In_{0.5}Ga_{0.5}As$ self-assembled quantum dots grown on (311)*B* GaAs substrates

A. Patanè,[a] A. Levin, A. Polimeni,[b] F. Schindler, P. C. Main, L. Eaves, and M. Henini
School of Physics and Astronomy, University of Nottingham, NG7 2RD Nottingham, United Kingdom

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Photocurrent spectroscopy is used to investigate the quantum-confined Stark shift of $In_{0.5}Ga_{0.5}As$/GaAs self-assembled quantum dots grown on (100) and (311)B planes. By comparing the Stark shift for dots grown on (100) and (311)B planes, we find that in the (311)B dots, the electron and hole wave functions are displaced by a strain-induced piezoelectric field directed from the apex to the base of the dots. © *2000 American Institute of Physics.* [S0003-6951(00)00345-4]

The effect of an electric field on the electronic properties of low-dimensional structures is of great interest for fundamental physics and device applications.[1] In particular, enhanced electro-optic and optical nonlinear effects have been predicted for quantum dots (QDs) (Refs. 2 and 3) and proposed for light modulators.[4]

A quantum-confined Stark shift [(QCSS), i.e., the redshift of the optical transition energy induced by an electric field] has been reported for CdSe nanocrystallites[5] and for III–V QDs generated by monolayer fluctuations[6] or self-assembly.[7–10] An asymmetric dependence of the QCSS with respect to the direction of the electric field has been observed by microphotoluminescence of (InAl)As/(AlGa)As self-assembled dots[7] and CdSe nanocrystallites.[5] Recently, similar behavior was observed in photocurrent (PC) spectroscopy measurements on InAs/GaAs QDs and explained in terms of a permanent electron–hole dipole in the dot.[8] However, other effects can also account for an asymmetric QCSS, for example, the presence of strain-induced electric fields associated with the dots.

In this work, PC spectroscopy is used to determine the dependence of the absorption spectrum of $In_{0.5}Ga_{0.5}As$/GaAs self-assembled quantum dots on an externally applied electric field. By comparing the QCSS for dots grown on (100) and (311)B planes, we show that the dots grown on the high-index substrate are internally biased due to a strain-induced electric field pointing from the apex to the base of the dots.

Two $p-i-n$ heterostructures were grown by molecular-beam epitaxy on (100) and (311)B GaAs substrates. The composition of the layers in order of growth on a n^+ substrate is as follows: a 0.7-μm-thick n^+-doped GaAs buffer layer ($n^+=4\times10^{18}\,\mathrm{cm}^{-3}$); a 0.1-$\mu$m-thick n-doped GaAs layer ($n=4\times10^{16}\,\mathrm{cm}^{-3}$); an undoped, intrinsic region (i), which consists, respectively, of a 0.1-μm-thick GaAs layer, an $In_{0.5}Ga_{0.5}As$ layer of thickness $L=1.4\,\mathrm{nm}$, and a 60-nm-thick GaAs layer. The growth was completed by a 0.5-μm-thick p^+-doped GaAs layer ($p^+=2\times10^{18}\,\mathrm{cm}^{-3}$). The second set of samples consists of $n-i-p$ structures, for which the growth scheme was reversed with respect to the previous one. Samples were grown at 600 °C except for the $In_{0.5}Ga_{0.5}As$ layer and the overgrown GaAs cap layer, which were both grown at 450 °C. Samples were processed into circular mesas, 200 μm in diameter. A ring-shaped electrical contact was fabricated on top of the mesa to permit optical access to the sample. For PC measurements, a tungsten–halogen lamp, dispersed by a 0.25 m monochromator, was used as the excitation source and the PC signal was measured using a standard lock-in technique. The PC spectra were measured in reverse bias as a function of the electric field $E=(V+V_0)/l$, where V is the applied voltage, V_0 is the built-in potential of the diode (~1.4 V at 200 K), and l is the thickness of the intrinsic and depleted regions of the diode (~0.16 μm). Note that E is along the direction of growth (z) in the $p-i-n$ devices and antiparallel to z in the $n-i-p$ devices. The field E does not include the piezoelectric field E_P, which is localized in strained $In_{0.5}Ga_{0.5}As$ region, and can be estimated from the dependence of the QCSS on E.

Figure 1 shows a comparison of the zero-bias PC spectra at different temperatures for the (100) and (311)B $p-i-n$ devices. At each temperature, the PC spectra show a similar line shape for the absorption of the (100) and (311)B $In_{0.5}Ga_{0.5}As$ dots. Also, as shown in the inset of Fig. 1, the peak energy of the QD PC band has the same temperature dependence for both samples and follows that of the $In_{0.5}Ga_{0.5}As$ band gap calculated according to the Varshni's relation with the $In_{0.5}Ga_{0.5}As$ parameters.[11] These data indicate that the degree of carrier confinement in the dots is comparable in the two types of structure. Also, the close agreement between the measured thermal shift and Varshni's relation indicates that the In content in the dots is approximately equal to the nominal value for all samples. In the following, we will focus on the PC spectra measured at $T=200\,\mathrm{K}$. Although our data on the QCSS do not depend on T, we have chosen this temperature to allow us to compare our results with others in the literature.[8]

Figure 2 shows a comparison of PC spectra and values of the QCSS at different electric fields E for the (100) and (311)B $p-i-n$ devices. For both samples, the dot absorption band redshifts with increasing E. The magnitude of the shift depends on the substrate orientation and is weaker for the (311)B QDs. The PC spectra shown in Fig. 2 are normalized to the peak intensity of the QD band. In general, the intensity

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[a] Electronic mail: amalia.patane@nottingham.ac.uk

[b] Permanent address: Istituto Nazionale di Fisica della Materia, Dipartimento di Fisica, Università di Roma ''La Sapienza,'' Piazzale A. Moro 2, I-00185 Roma, Italy.

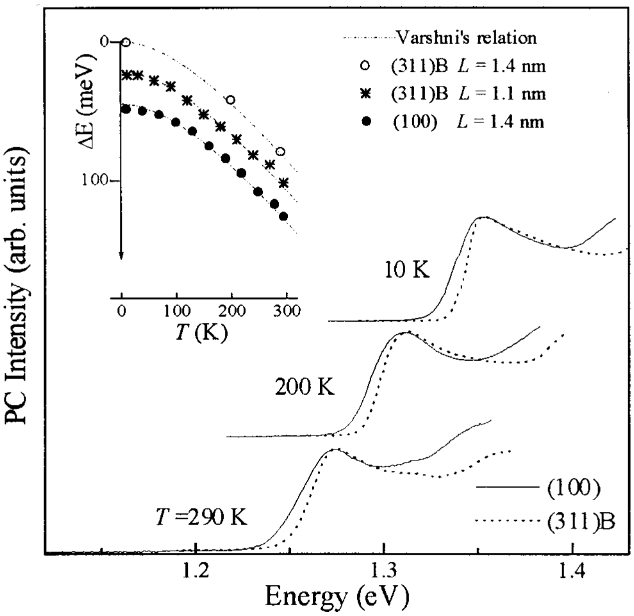

FIG. 1. Normalized photocurrent (PC) spectra at zero bias and at various temperatures for $p-i-n$ devices based on (100) (continues line) and (311)B (dotted line) $In_{0.5}Ga_{0.5}As$ quantum dots (QDs). The inset shows the thermal energy shift ΔE of the peak of the QD PC band for dots grown on different substrates and/or different $In_{0.5}Ga_{0.5}As$ layer thickness L. For clarity, the energy shifts are offset along the vertical axis. The dotted lines show the thermal shift of the $In_{0.5}Ga_{0.5}As$ band gap calculated according to Varshni's relation.

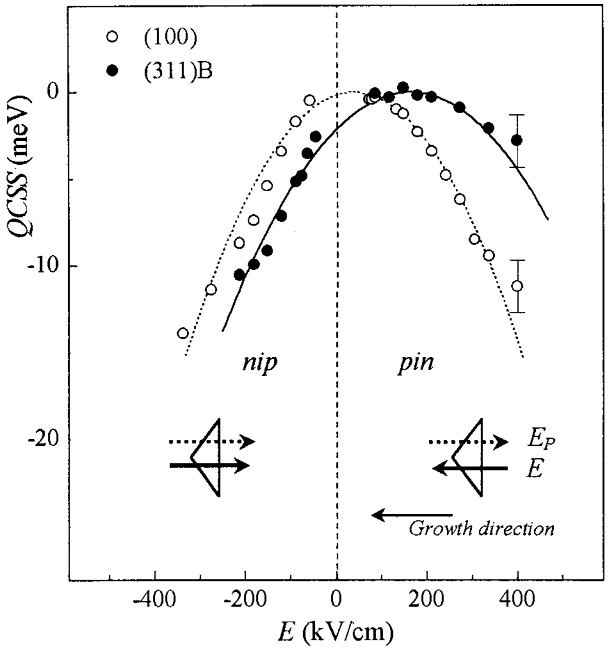

FIG. 3. Electric field E dependence of the quantum-confined Stark shift (QCSS) in the $p-i-n$ and $n-i-p$ devices, for (100) (open circles) and (311)B (full circles) $In_{0.5}Ga_{0.5}As$ dots ($T = 200$ K). Positive and negative electric fields correspond to $p-i-n$ and $n-i-p$ devices, respectively. The insets show the relative orientation of the dots with respect to E and the piezoelectric field E_P. The lines are parabolic fits to the data.

of the PC signal increases with increasing E and saturates at the highest E. This dependence can be caused by several factors, including the effect of E on the number of carriers photogenerated in the dots and the rate of escape of carriers out of the dots, which occurs by tunneling and/or thermal escape.[8] The increasing value of the PC signal with E can be related to an increasing rate of escape with E, while the saturation behavior can be caused by the reduction in the electron–hole overlap and consequent reduction of the absorption by the QDs.

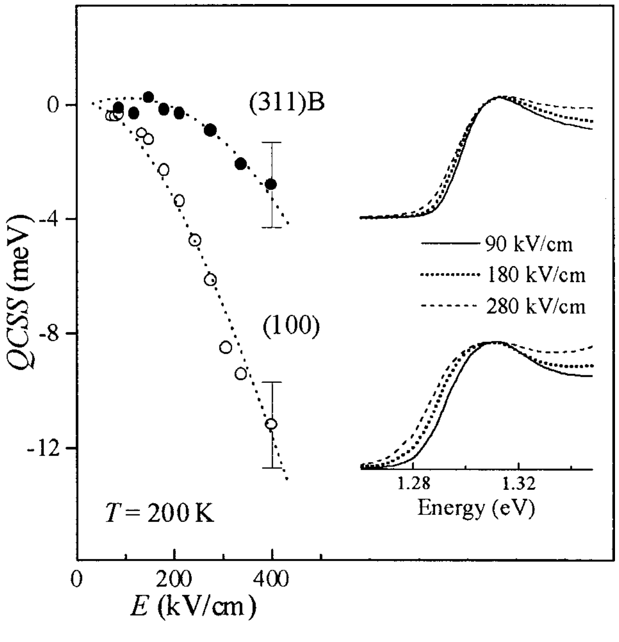

FIG. 2. Quantum-confined Stark shift (QCSS) vs electric field E of the dot absorption band measured in photocurrent (PC) for (311)B (full circles) and (100) (open circles) $In_{0.5}Ga_{0.5}As$ dots in the $p-i-n$ devices ($T = 200$ K). The dotted lines are guides for the eye. To determine the QCSS, each PC spectrum was fitted by Gaussian line shapes. The error bar represents our best estimate of the uncertainty in our fitting procedure. The inset shows the PC spectra under various electric fields for the (100) (bottom) and (311)B (top) dots.

In addition to the different magnitude of the QCSS for the (100) and (311)B dots, we also found that the two types of structure behave differently with respect to a change of direction of the electric field. We investigated the effect of electric-field reversal on the dot absorption by studying $n-i-p$ structures. Figure 3 compares the dependence on E of the QCSS for $n-i-p$ and $p-i-n$ devices. Here, the positive and negative electric fields correspond to $p-i-n$ and $n-i-p$ devices, respectively.

For the $(100)In_{0.5}Ga_{0.5}As$ dots, the QCSS is almost symmetric with respect to $E = 0$ and, to a first approximation, can be described by the parabolic relation αE^2, where α is a constant ($\sim -1.8 \times 10^{-32}\,\mathrm{F\,cm^2}$). Only a slight asymmetry of the QCSS is observed with a maximum of the QCSS parabola at $E \sim +40$ kV/cm. This result contrasts with the data reported in Ref. 8 on (100) InAs/GaAs QDs, where the center of the QCSS parabola was observed at *negative* fields ($E \sim -90$ kV/cm). The asymmetry was explained in terms of a permanent electron–hole dipole in the dot, due to the localization of the hole above the electron, i.e., further from the base of the dot. This alignment, which is inverted with respect to the predictions for a pyramidal dot with a uniform In composition,[12] was discussed in terms of In segregation effects. It was found that the actual content of In in the dot is less than the nominal value and decreases from the apex to the base of the dot. We believe these effects are weaker or even absent in our dots due to the low growth temperature used (450 °C) and the smaller nominal In content of our dots.

Consistent with this, the temperature dependence of the dot absorption measured in our samples indicates that the In content in the dots is very close to the nominal value (see Fig. 1, inset). The dipole effects may also be weaker in our QDs due to their size: atomic-force microscopy measurements on our uncapped dots show that the $In_{0.5}Ga_{0.5}As$ dots are flatter (their height, $h\sim 2$ nm) than the InAs dots ($h\sim 5$ nm) of Ref. 8. This results in a smaller relative electron–hole separation and an almost zero electron–hole dipole moment at $E=0$.

The behavior of our (311)B QDs differs substantially from that of our (100) QDs. In this case, a pronounced asymmetry of the QCSS is observed. Since the (100) and (311)B dots exhibit quantitatively similar absorption spectra, we can exclude a major difference in the confinement potential as the origin of the observed differences. However, our data are consistent with the presence of a piezoelectric field E_P in the dots grown on the high-index plane. The magnitude of this field depends on the orientation of the GaAs substrate. Its component along the growth direction is zero for the [100] growth axis, but not for the [n11] growth axis.[13,14] If we assume that the displacement of the QCSS parabola is due to the piezoelectric effect for the (311)B sample, then E_P points from the apex to the base of the dot. It is parallel and antiparallel to E in the $p-i-n$ and $n-i-p$ devices, respectively. The above discussion implies that to a first approximation, the QCSS can be described by a similar relation valid for the (100) QD sample (αE^2), but with E replaced by $(E+E_P)$. From a fit to the data using the above relation, with α and E_P as free parameters, we find $E_P=-170\,\mathrm{kV/cm}$ and $\alpha=-1.3\times 10^{-32}\,\mathrm{F\,cm^2}$. The value of E_P is comparable with the large fields found in the highly polar, nitride semiconductors[15] and those achieved in (InGa)As/GaAs quantum wells grown on (111) GaAs substrates.[16] For the (311)B case, theoretical models applied to the case of two-dimensional (InGa)As/GaAs heterostructures give piezoelectric fields of the order of 100 kV/cm.[13,14]

In conclusion, we have presented a study by PC spectroscopy of the QCSS of $In_{0.5}Ga_{0.5}As/GaAs$ QDs grown on (100) and (311)B planes. An asymmetric dependence of the QCSS with respect to the direction of the electric field has been observed and explained in terms of dipole and piezoelectric effects. We have shown that the (100) dots have an almost zero permanent electron–hole dipole moment. This result indicates that the reported[8] ''inverted electron–hole alignment'' is not a general property of QDs. Finally, by comparing the QCSS for the (100) and (311)B dots, we showed the existence of a pronounced piezoelectric field E_P in the dots grown on the high-index plane, pointing from the apex to the base of the dots.

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