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Citation	Chua, S. J., Xu, S. J., Zhang, X. H., Wang, X. C., Mei, T., Fan, W., Wang, C. H., Jiang, J., & Xie, X. G. (1998). Polarization dependence of intraband absorption in self-organized quantum dots. <i>Applied Physics Letters</i> , 73(14), 1997.
Date	1998
URL	http://hdl.handle.net/10220/17881
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Polarization dependence of intraband absorption in self-organized quantum dots

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(Received 30 March 1998; accepted for publication 30 July 1998)

Photoluminescence and intraband absorption were investigated in *n*-doped self-organized InAs and In_{0.35}Ga_{0.65}As quantum dots grown on a GaAs substrate. Intraband absorption of the dots is strongly polarized along the growth axis in the mid infrared spectral range. The absorption is maximum at around 120 meV for InAs dots and at 130 meV for In_{0.35}Ga_{0.65}As dots. The experimental results on InAs dots are in agreement with published theoretical calculations. © 1998 American Institute of Physics. [S0003-6951(98)00740-2]

In the past several years there has been a surge of interest in structures that exhibit quantum confinement in three dimensions, commonly known as quantum dots (QDs). Stranski–Krastanov growth of highly mismatched semiconductors can lead to the spontaneous formation of islands.¹ The nucleation of the pseudomorphic islands is driven by strain, and results in the formation of the so-called self-organized quantum dots.² The optical properties of these quantum dots is of increasing interest due to their original atomic-like properties. The interband optical properties of quantum dots have been widely studied, both for the physical aspect^{3–5} and for device applications.^{6,7} In addition, the quantum dots are also expected to exhibit optical absorption and emission between states lying in the same band, i.e., intraband transitions either in the conduction band or in the valence band. The intraband absorption of quantum dots could be of practical interest for the development of the photon detector. For this application, one of the advantages of quantum dots as compared to quantum wells is the predicted slowing of the intersubband relaxation process due to the reduced electron–phonon interaction.⁸ Moreover, unlike quantum wells, quantum dots are expected to be sensitive to normal incidence photoexcitation. The intraband absorption of quantum dots has been reported^{9–13} using a variety of techniques. Drexler *et al.*⁹ studied the intraband absorption of quantum dots using a capacitance spectroscopy technique coupled with a far-infrared spectrometer. Phillips *et al.*¹⁰ studied the far-infrared absorption of Si-doped InAs quantum dots with GaAs and Al_{0.15}Ga_{0.85}As as the barrier materials using a Fourier transform infrared (FTIR) spectrometer. Sauvage *et al.*^{11,12} studied the intraband absorption of undoped and doped InAs quantum dots using a photoinduced infrared absorption technique and a FTIR spectrometer. Berryman

*et al.*¹³ also studied the intraband absorption in self-organized InAs/In_xGa_{1-x}As clusters using midinfrared photoconductivity measurements. Recently, normal incidence infrared absorption in an InGaAs/GaAs quantum dot superlattice has been reported,¹⁴ but the origin of the absorption (quantum dots or quantum wells) was not clear. In this letter, we investigate the polarization dependence of the intraband absorption in *n*-doped InAs and InGaAs quantum dots embedded in a GaAs matrix using a FTIR spectrometer. We found that the intraband absorption is strongly polarized along the growth axis, and there is no clear normal incidence intraband absorption in our samples in the spectral range investigated.

A series of InAs and InGaAs dot samples with different Si doping densities, grown by molecular beam epitaxy on a (001) oriented GaAs substrate, were investigated. They have the same structure except for the doping density. A 30 nm thick, nominally undoped, GaAs layer was first grown, followed by a 700 nm thick Si-doped layer with nominal doping concentration $n = 1.0 \times 10^{18} \text{ cm}^{-3}$. Next, 20 layers of InAs or In_{0.35}Ga_{0.65}As dots separated by 30 nm GaAs barriers were grown. Finally, a 500 nm cap layer was grown over the layers with Si doping concentration $n = 1.0 \times 10^{18} \text{ cm}^{-3}$. Silicon was continuously supplied during the InAs and In_{0.35}Ga_{0.65}As layer growth. Details of the growth are described elsewhere.¹⁵ The samples were examined with high-resolution transmission electron microscopy (TEM) that indicated evidence of the existence of dots¹⁵ as shown in Fig. 1. Our high-resolution TEM observation shows that the InAs dots have a typical pyramidal shape with a base length of around 110 Å and a height of around 45 Å.

Photoluminescence (PL) measurements of the samples were carried out with an argon ion ($\lambda = 488 \text{ nm}$) laser, lock-in phase amplification, a 0.75 m monochromator, a liquid-nitrogen-cooled Ge detector for detection. Figure 2 shows the typical PL spectra of the InAs and InGaAs dots at 10 K. The Si doping densities of the InAs dots and InGaAs dots in

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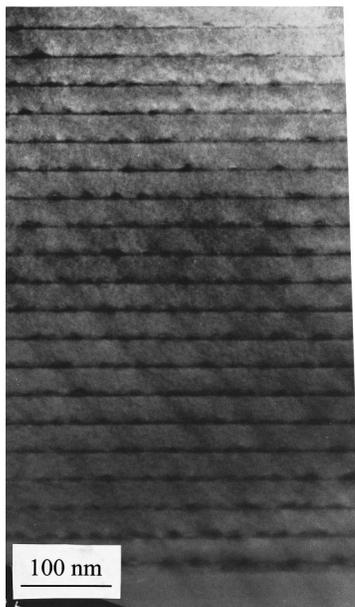


FIG. 1. Cross-sectional TEM picture of sample 215. The quantum dots can be seen clearly.

Fig. 2 are 6.4×10^{18} and $6.0 \times 10^{17} \text{ cm}^{-3}$, respectively. For the InAs dots, the PL spectrum consists of two emissions. With an increase in exciting power, the lower energy emission gets saturated whereas the intensity of higher energy emission increases. For the $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}$ dots, the only PL peak is around 1.22 eV with a full width at half maximum (FWHM) of 50 meV. The PL spectrum of the InAs dots can be fitted very well using two Gaussian functions while the PL spectrum of the InGaAs dots can be fitted using one Gaussian function. For the PL spectrum of the InAs dots, the first fitting peak has a position of 1.191 eV and a FWHM of 86.6 meV while the second fitting peak has a position of 1.315 eV and a FWHM of 121.1 meV. The energy separation between the two fitting peaks is 124 meV. Very recently, Jiang and Singh¹⁶ calculated the electronic structure of InAs/GaAs dots with similar size pyramidal shapes using an eight-band $\mathbf{k} \cdot \mathbf{p}$ model rather than a simple effective mass

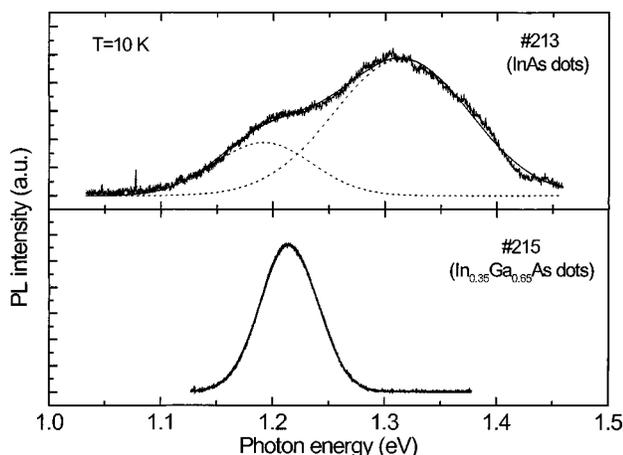


FIG. 2. Ten K photoluminescence of the self-organized InAs and $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}$ quantum dots excited with an argon ion laser. The PL spectrum of the InAs dots can be fitted very well with two Gaussian functions (dotted lines) while the PL spectrum of the $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}$ dots is fitted with only one Gaussian function (solid line).

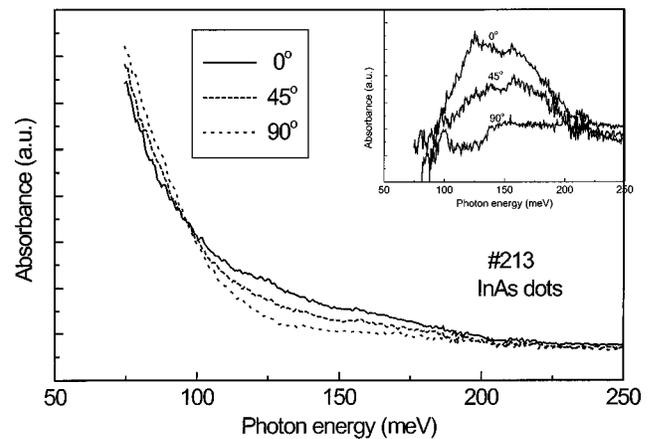


FIG. 3. Room temperature infrared absorption spectra of the InAs dots under different polarization directions of light. The inset shows the baseline corrected spectra.

approach.¹⁷ They found that there were at least three bound states in the conduction band of the InAs/GaAs dots. According to their calculation, the energy separation between the lowest state and the second state in the conduction band is 114 meV. Therefore, we attribute the second PL peak in the PL spectrum of the InAs dots to be due to the transition from the first electron excited states to the ground heavy-hole state. Further evidence of this is suggested by the fact that the first peak saturates and the second peak grows in intensity as the PL excitation source is increased, as mentioned earlier.

For infrared measurements, the samples were polished into multireflection waveguides with 45° facets in order to increase net absorption, as shown schematically in Fig. 4. The polarization of the incoming infrared beam was set in 0° (p -polarization), 45° (50% of the p -polarization component and 50% s -polarization component), and 90° polarizations (s polarization), which, in turn, corresponds to normal incidence. The measurements were performed with a Nicolet 850 FTIR system.

The measured infrared absorption spectra of the InAs and InGaAs dots at room temperature are shown in Figs. 3 and 4, respectively. A strong polarization dependence feature in the spectra is observed. For 0° polarization, a broad ab-

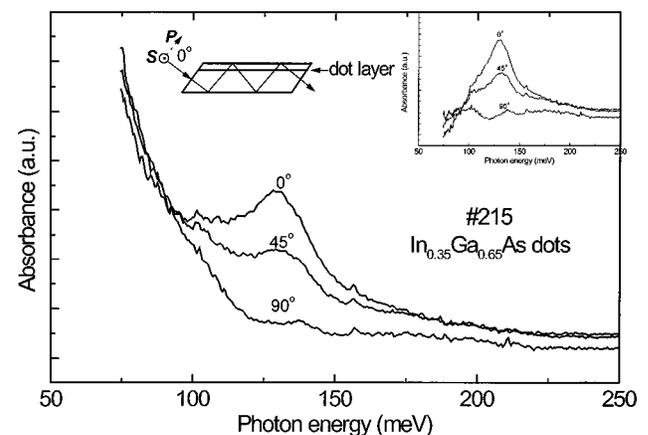


FIG. 4. Room temperature infrared absorption spectra of the InGaAs dots under different polarization directions of light. The inset shows the baseline corrected spectra.

sorption peak is observed around 125 meV for the sample with InAs dots, while a strong peak is around 130 meV for the sample with $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}$ dots. It should be noted that the position of the infrared absorption peak of the InAs dots almost equals the energy separation between the lowest state and the second state in the conduction band determined from its PL spectrum. Moreover, it is in good agreement with the calculated value by Jiang and Singh.¹⁶ A more interesting result is that they predicted a strong dependence of the intraband optical transition matrix between the lowest state and the second state in the conduction band upon polarization of light. This is also in agreement with our observation. For example, intraband absorption is strongest for 0° polarization; for 45° polarization, the absorption peak intensity is decreased and is about half that for 0° polarization; for 90° polarization, no clear absorption is observed in the infrared spectral range investigated, except for the free carrier absorption which stems from the carriers in the GaAs matrix. We thus attribute the infrared absorption observed to the intraband transition within the conduction band of the quantum dots. The polarization dependence reported in the present work is also in agreement with that observed in the Si modulation-doped InAs dots in Ref. 12, although only the ratio $1-T_p/T_s$ of the transmissions of the sample in p and s polarizations was given in the literature. Moreover, our experiments on polarization dependence of the intraband transitions in the self-organized quantum dots also demonstrate that the selection rule is similar to that of the intraband transitions in the conduction band of quantum wells.

The broadening of the intraband absorption in Figs. 3 and 4 is large (about 150 meV for the InAs dots and about 50 meV for the InGaAs dots) and of the same order of magnitude as the FWHM of the PL spectra shown in Fig. 2. This fact also confirms that the infrared absorption we observed stems from the intraband transitions in quantum dots and not from quantum wells. The large broadening of the intraband absorption and interband transition (PL) is mainly attributed to the size distribution of the self-organized quantum dots.¹²

In conclusion, we have shown that the intraband absorption in n -doped self-organized InAs/GaAs and $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}/\text{GaAs}$ quantum dots is strongly polarized along the growth axis in the spectral range investigated. The intraband absorption is attributed to electron bound-to-bound transition and the large broadening of absorption spectra is

due to the fluctuations in the dot size. The polarization selection rule of the intraband transitions within the conduction band of the quantum dots is similar to the polarization selection rule of intersubband transitions in the conduction band of quantum wells.

The authors would like to acknowledge C. H. Tung, T. T. Sheng, K. Pan, Y. H. Zhang, and J. L. Wang of the Failure Analysis and Reliability Department of the Institute of Microelectronics, Singapore, for providing the TEM measurements.

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