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Intersubband absorption in annealed InAs/GaAs quantum dots: a case for polarization-sensitive infrared detection

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Abstract

We have studied the characteristics of intersubband absorption of polarized infrared (IR) radiation in as-grown and annealed self-organized InAs/GaAs quantum dots. It is observed that with the increase of annealing time and temperature, the dots tend to flatten and behave more like quantum wells. As a result, their sensitivity to TE (in-plane)-polarized light decreases and that to TM (out-of-plane)-polarized light increases. The effect could be utilized for the realization of polarization-sensitive IR detectors.

Self-organized Ga(In)As/Ga(Al)As quantum dots studied extensively and incorporated in the active region of electronic and optoelectronic devices [1–9]. Quantum dot infrared photodetectors (QDIPs) [2–6], have emerged as potentially important devices for the following two attractive features, both arising from the three-dimensional quantum confinement of carriers: first, low dark current which, in part, is due to the large band offsets, and second, the possibility of normal incidence. In an ideal spherical quantum dot, one would not expect any polarization dependence. However, the Ga(In)As/Ga(Al)As self-organized quantum dots are very asymmetric, with a near-pyramidal shape. The base dimension is almost three times that of the height [10]. The intersubband transition matrix element is found to be very strong for in-plane (TE)-polarized light [11] in these dots for two reasons: a very high biaxial strain field which causes a strong s–p intermixing of the conduction band states and the dot shape which alters the electronic wavefunction envelope function. Consequently, TE-polarized light is preferentially emitted or absorbed in self-organized quantum dots via intersubband transitions [9].

We have calculated the strength of the TE- and TM-polarized intersubband absorption for dots of varying height-to-base ratio. These calculations are based on an 8-band k.p model with the strain determined by the valence force field formulation [11]. We find that for as-grown pyramidal dots, absorption of TM polarization is essentially zero. However, as the dots 'flatten' out, to become more like wells, the TE-polarization absorption decreases while the TM polarization absorption increases. It is well-known that in a quantum well the TM polarization absorption dominates. The exact value of the absorption depends strongly on the shape and size of the dots; the following values will provide a guideline for the trend. The results below are for a dot of height $h = 62$ Å. The base-to-height (b/h) ratio is then varied. The absorption can be written as:

$$\alpha\ (\mathrm{TE}) = \frac{\alpha_p\ (\mathrm{TE})}{\sigma\ (\mathrm{meV})}, \qquad \alpha\ (\mathrm{TM}) = \frac{\alpha_p\ (\mathrm{TM})}{\sigma\ (\mathrm{meV})} \qquad (1)$$

where α_p is the peak absorption coefficient and σ is the linewidth (dominated by inhomogeneous broadening) in millielectronvolt. Assuming a value of 30 meV for the linewidth, we calculated the following values: for $b/h = 2$, $\alpha_p\ (\mathrm{TE}) = 3.3 \times 10^5\ \mathrm{cm}^{-1}$ and $\alpha_p\ (\mathrm{TM}) = 6.0 \times 10^3\ \mathrm{cm}^{-1}$ and for $b/h = 8$, $\alpha_p\ (\mathrm{TE}) = 3 \times 10^4\ \mathrm{cm}^{-1}$ and $\alpha_p\ (\mathrm{TM}) = 3.6 \times 10^4\ \mathrm{cm}^{-1}$. Therefore, light of TM polarization is preferentially absorbed as the dots become flatter.

It has been observed that thermal annealing of In(Ga)As/Ga(Al)As self-organized quantum dots led to several changes in their properties, mainly due to In–Ga interdiffusion and an overall change in dot size and shape. This is accomplished by a predominant blue-shift of the ground-state intersubband transition energy [12]. The dots become flatter, and more like quantum wells [13]. It is therefore expected that intersubband absorption of out-of-plane TM-polarized light would become more favourable. This modification presents the interesting possibility of polarization-sensitive detection with QDIPs, hitherto not possible with HgCdTe (MCT) detectors or quantum well infrared photodetectors (QWIPs). It is known that the light reflected by geometric objects is polarized [14], whereas the background is unpolarized. Therefore, a polarization-sensitive detection scheme, wherein both TE- and TM-polarized light can be simultaneously detected and the corresponding photoresponse subtracted, would enhance the detectivity and improve the resolution. There is, to date, no report on polarization-sensitive absorbance measurements in self-organized In(Ga)As/Ga(Al)As quantum dots. In this study, we have grown multi-dot layer heterostructures by molecular beam epitaxy (MBE) and have measured the intersubband absorption of TE- and TM-polarized light at room temperature in these samples after varying amounts of thermal annealing.

The quantum dot heterostructures were grown by solid-source MBE on (001) semi-insulating GaAs substrates. Multiple (20–70) dot layers were incorporated to increase the intersubband absorption for normally incident light. The heterostructure is schematically shown in figure 1(*a*). The growth of the GaAs barrier in between the dot layers was accomplished in two steps. The first 250 Å of the barrier were grown by ramping the temperature of the substrate from 500˚C to 590˚C. The growth was then paused for a minute. The remaining 250 Å of the barrier were grown by ramping down the substrate temperature from 590˚C to 500˚C. The InAs QDs were grown at 500˚C at a rate of 0.1 monolayers s^{-1}. The InAs charge was varied from 2.0 to 2.2 monolayers for different heterostructures. Of this, the wetting layer consisted of 1.7 monolayers and the rest formed the quantum dot. With these growth conditions, the samples were almost defect-free, as observed by cross-sectional transmission electron microscopy (XTEM). The quantum dots were selectively doped with Si to provide approximately two electrons per dot. One set of samples was rapid-thermal annealed (RTA) with a GaAs cap under flowing nitrogen at temperatures of 700˚C, 750˚C, 800˚C and 850˚C for 30 s. Another set of samples was annealed in an open quartz furnace tube at 700˚C for time intervals ranging from 30 to 120 min.

Infrared (IR) absorption measurements were made with a Nicolet MAGMA-IR 560 Fourier transform IR (FTIR) spectrometer with a globar source and a liquid nitrogen cooled wideband HgCdTe detector. IR polarizers were placed between the source and the sample, for measurements with polarized light. Absorbance was determined by

$$A = \log\left(\frac{S_{\mathrm{GaAs}}}{S_{\mathrm{Sample}}}\right), \quad (2)$$

where S_{sample} and S_{GaAs} are the single beam outputs of the sample to be measured and a GaAs substrate identical to the one on which the sample was grown. A comparison was also made with the absorbance of the GaAs substrate with respect to air. Typical absorbance data for normally incident unpolarized light on a 20 dot layer sample is shown in figure 1(*b*). It is observed that the peak absorption occurs at ~8 μm. In order to verify the trend in variation of the intersubband absorption of the quantum dots with polarization of incident light, we varied the angle of incidence of the incident plane-polarized radiation from zero to nearly 70˚. Beyond this angle the interferogram was not very clear. In doing so, the nature of the polarization changes from pure TE- to TM-like. As illustrated in figure 2, the peak absorbance decreases as the incident polarization becomes more TM-like. Conversely, with unpolarized radiation, the peak absorbance

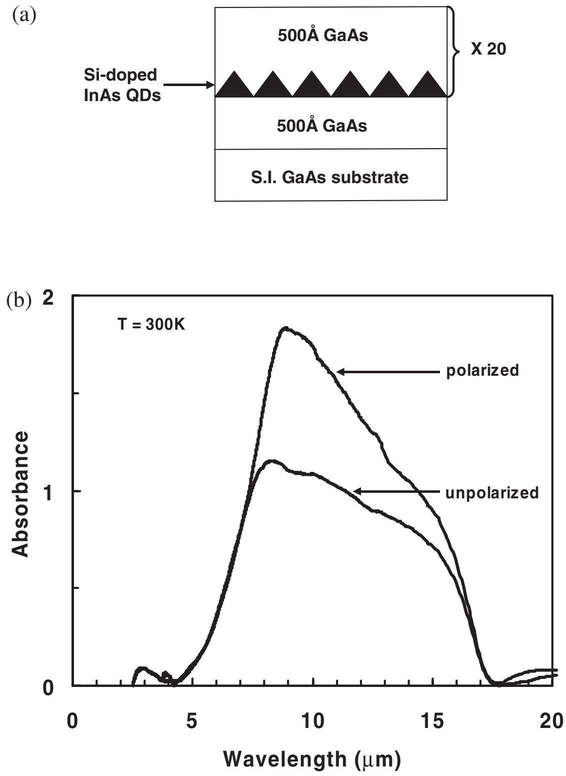

Figure 1. (*a*) Schematic of the 20-layer quantum dot heterostructure; (*b*) measured absorbance spectra of the heterostructure at room temperature with in-plane TE-polarized and unpolarized light.

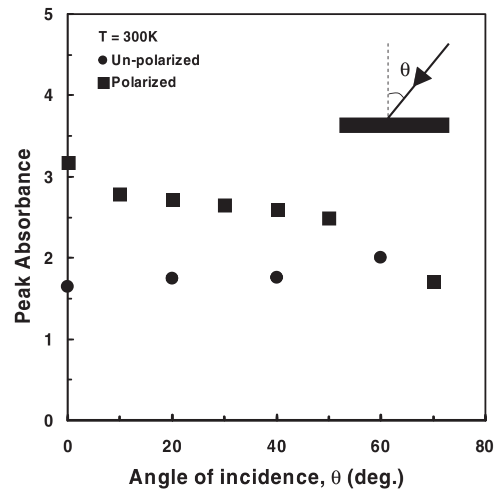

Figure 2. Variation of measured peak absorbance at room temperature with the angle of incidence of polarized light for as-grown quantum dots. A similar variation with unpolarized light has been shown for comparison.

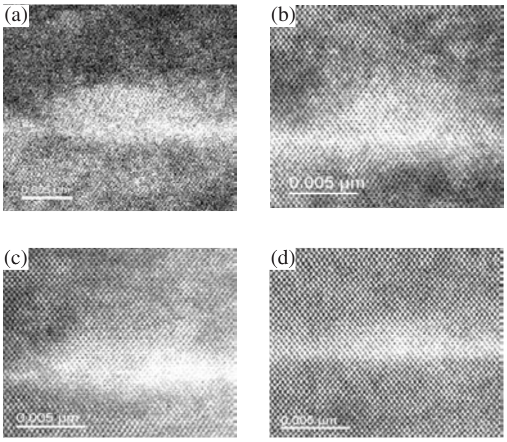

Figure 3. XTEM images of self-organized InAs/GaAs quantum dots as-grown (*a*) and RTA at 700˚C (*b*), 750˚C (*c*) and 800˚C (*d*).

remains almost constant and exhibits a slight increase at larger angles. This is expected, since with an increase in the angle of incidence, the effective absorption thickness increases.

The XTEM images of the dots annealed at different temperatures are shown in figure 3. The number density of the dots remained almost constant over the entire range of annealing temperatures. Upon annealing at 700˚C for 30 s, the average size of the dots increased, as reported earlier [13]. At higher annealing temperatures, the average dot size decreases due to outdiffusion of In from the dots [13]. It is important to note that these dots become flatter with annealing and there is no evidence of defect or cluster formation. The average aspect ratio (b/h) of the dots as a function of annealing temperature is plotted in figure 4(*a*). The measured peak absorbance in the same annealed samples with normally incident TE-polarized light are shown in figure 4(*b*). The trend in the data corresponds to that of the data in figure 4(*a*) and clearly elucidates the relationship of the dot shape with absorption of polarized light.

We next investigated the variation of absorbance to TE and TM radiation with annealing time. The annealing temperature was fixed at 700˚C and the time was varied from 0 to 120 min. XTEM data, similar to those shown in figure 3 confirm that dots become flatter and behave more like quantum wells. For example, the dot b/h changes from 2.67 in the unannealed dots to 3.3 in dots annealed at 700˚C for 60 min. Normal incidence was employed for in-plane (TE)-polarized light, while 65˚ incidence was used for out-of-plane or TM-like polarization. A guided-wave measurement could have been used in the latter case, but we chose to confine the measurements to surface photoexcitation. The data are shown in figure 5. Similar data were recorded for higher annealing temperatures.

In conclusion, we have investigated the intersubband absorption of polarized light in self-organized InAs/GaAs quantum dots. It is observed that there is preferential increased absorption of TM-polarized light and decreased absorption of TE-polarized light with increase in temperature and annealing time. XTEM measurements confirm that the observed trend in absorption is due to flattening of the dots, which then behave electronically more like quantum wells. These results suggest the interesting possibility of polarization-sensitive detection, featuring vastly improved signal-to-noise ratio, with quantum

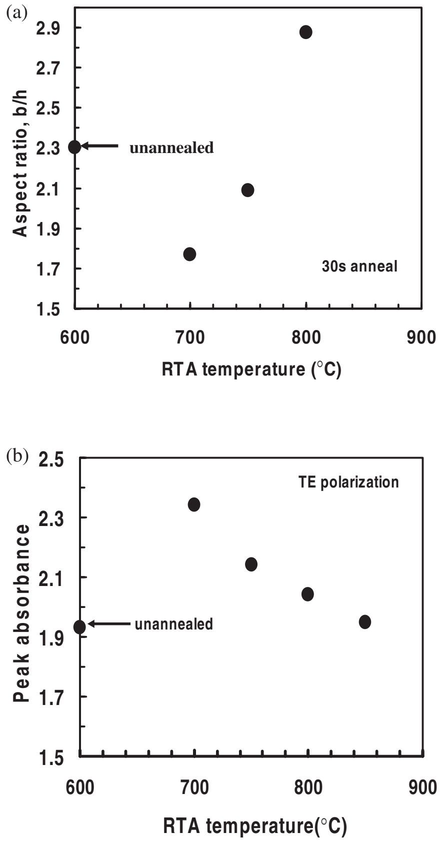

Figure 4. (*a*) Variation of the aspect ratio of the quantum dots with rapid-thermal annealing temperature, and (*b*) variation of peak absorbance at room temperature with annealing temperature for TE polarization.

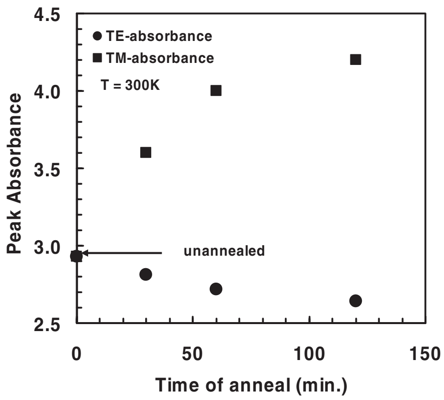

Figure 5. Variation of measured peak absorbance at room temperature with 700˚C isothermal anneal duration for normally incident TE- and TM-polarized light incident at 70˚ to the normal.

dots in a single device. In such a scheme, TE- and TM-polarized radiation would be simultaneously incident on the devices with quantum dots suitably annealed such that both polarizations are equally absorbed. Appropriate algorithms can be used to compute the difference signal.

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