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Characterization of electron emission from relaxed InAs quantum dots capped with InGaAs

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The effect of strain relaxation in a relaxed InAs quantum dot (QD) capped with InGaAs is investigated by admittance and deep-level transient spectroscopy (DLTS). Strain relaxation markedly increases the emission time in the QD region and extends carrier depletion to the bottom GaAs layer. The experimental data show the presence of relaxation traps in the QD region and the neighboring bottom GaAs layer. The electron emission from the QD region is governed by a trap located at 0.17–0.21 eV below the QD ground state. The electron-escape process is identified as thermal activation at high temperatures and direct tunneling at low temperatures from the trap. In the bottom GaAs layer near the QD, DLTS reveals a relaxation trap at 0.37–0.41 eV relative to the GaAs conduction band. The energy difference between these two traps is comparable to the QD ground-state energy relative to the GaAs conduction-band edge, suggesting that the two traps may be the same trap which is pinned to the GaAs conduction band. The considerable difference between their properties may result from different atoms surrounding the trap. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1957124]

I. INTRODUCTION

InAs/GaAs self-assembled quantum dots[1–9] (QDs) have attracted considerable attention because they have promising technological applications.[10–14] Electron emission from QDs (Refs. 15–18) has interesting features for fundamental studies. Kapteyn *et al.*[15] proposed a two-step electron emission process from the QDs: thermal activation from the ground to the first-excited state and subsequent tunneling to the GaAs conduction band. However, when the InAs thickness is increased beyond a critical thickness, strain relaxation[19] occurs. Strain relaxation is expected to alter the properties of the QDs. However, little is known about the relaxation process and its effect. The authors have previously investigated the strain relaxation in InAs QDs capped with GaAs (Ref. 19) and found that relaxation causes carrier depletion in the QDs. The carrier depletion is so drastic that it extends to the neighboring GaAs layers on both sides. Accordingly, the details of the properties of electron emission from relaxed QDs could not be studied. Capping the QDs with an InGaAs layer has been shown to reduce the strain, yielding an emission of over 1.5 μm.[20] Therefore, in this work, strain relaxation in InAs QDs capped with InGaAs was characterized. The thickness of InAs was carefully controlled. The relaxation-induced carrier depletion was found to extend only to the bottom GaAs layer. The photoluminescence (PL) quality of the relaxed QDs is comparable to that of nonrelaxed QDs. The effects of relaxation on the carrier distribution and emission in the QDs and neighboring GaAs bottom layer are presented.

II. EXPERIMENTS

The studied samples were grown on n^+-GaAs (100) substrates by solid source molecular-beam epitaxy in a Riber Epineat machine. The QDs were formed in the Stranski-Krastanow growth mode by depositing InAs layers of different thicknesses at a substrate temperature of 490 °C. The QD formation was controlled *in situ* by monitoring the diffraction pattern of high-energy electrons. The QDs were then capped with a 60-Å-thick $\mathrm{In}_{0.15}\mathrm{Ga}_{0.85}\mathrm{As}$ layer. The QDs which were sandwiched between two 0.2-μm-thick Si-doped GaAs $[(6-10)\times 10^{16}\ \mathrm{cm}^{-3}]$ layers were positioned outside the depletion region at zero bias. Details of the growth of the QD samples can be found elsewhere.[21] A QD sheet density of about $3\times 10^{10}\ \mathrm{cm}^{-2}$ was observed by atomic field microscopy (AFM) images. Schottky diodes were realized by evaporating Al onto the sample with a dot diameter of 1500 μm. The PL measurements were made using a double-frequency yttrium-aluminum-garnet (YAG):Nd laser at 532 nm. An HP 4194A gain phase analyzer was employed to perform capacitance-voltage ($C-V$) profiling and admittance spectroscopy.

III. MEASUREMENT AND RESULTS

A. Carrier distribution in nonrelaxed QD

The PL spectra show that the InAs critical thickness is between 2.7 and 3.06 monolayers (MLs). Below the critical

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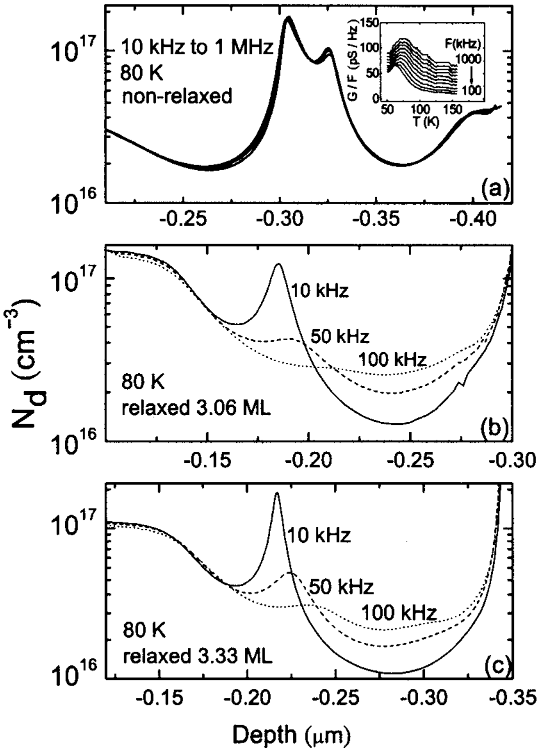

FIG. 1. (a) Carrier-concentration profiles of a typical nonrelaxed sample converted from the $C-V$ spectra at 80 K. A strong accumulation peak at 0.305 μm and a weak peak at 0.325 μm are visible. The inset shows the G-T spectra measured at the capacitance plateau. Carrier-concentration profiles of (b) the relaxed 3.06–and (c) 3.33-ML samples.

thickness, a redshift of the QD ground-state emission is observed as the thickness of the InAs layer is increased. Deep-level transient spectroscopy (DLTS) measurements show no traps in these samples, indicating coherent QD formation. However, beyond the critical thickness, the QD ground-state peak is blueshifted and the linewidth considerably broadened. This sudden transition from redshift to blueshift and the broadening of the linewidth are indicative of strain relaxation. Figure 1 compares the carrier distributions of nonrelaxed and relaxed QD. Figure 1(a) shows the typical carrier distribution at 80 K for a nonrelaxed sample (2.4-ML InAs) under various frequencies. The QD ground state emits at 1300 nm at 300 K. Two accumulation peaks at about 0.305 and 0.325 μm are clearly seen. The magnitude of the large peak (0.305 μm) increases as the temperature decreases, which trend is characteristic of a Debye-length effect in a quantum structure. No attenuation of this peak is seen up to 1 MHz at 10 K, indicating a very fast emission whose time constant cannot be determined at the available frequencies. This peak is not related to any confined states of the InGaAs cap layer since it is also observed in similar QDs capped with GaAs. This peak is attributed to the emptying of the electrons from the QD excited states. Direct tunneling previously proposed[15–17] for the emission from the first-excited state to the GaAs conduction band can explain the very fast emission for this peak.

The small peak (at 0.325 μm) is visible when the temperature is lowered below 100 K. It shows frequency-dependent attenuation at $T < 100$ K, suggesting relatively slow emission. The emission time can be obtained by measuring the conductance that probes the carrier exchange rate between the QD and the GaAs electrode. The conductance reaches a peak when the measuring frequency is comparable to the carrier emission rate, according to the relation $2\pi f\tau \cong 2$. The inset of Fig. 1(a) shows the conductance-temperature (G/F-T) spectra measured at the capacitance plateau at several frequencies. These spectra reveal that the typical emission time was about 10^{-6} s at 75 K. Figure 2 displays Arrhenius plots (indicated by "G-T nonrelaxed") of emission times versus temperatures. An activation energy (capture cross section) of 57.2±5 meV$(1.4\times10^{-14}\ \mathrm{cm}^2)$ is determined. This activation energy is similar to the PL energy spacing between the ground and first-excited states so this peak is ascribed to the thermal excitation from the ground to first-excited state. The electron will subsequently tunnel to the GaAs conduction band. These data are consistent with the two-stage emission process proposed by Kapteyn *et al.*[15] The fact that the tunneling peak is much stronger than the thermal excitation peak suggests that the QDs are charged up to higher states than the first-excited state.

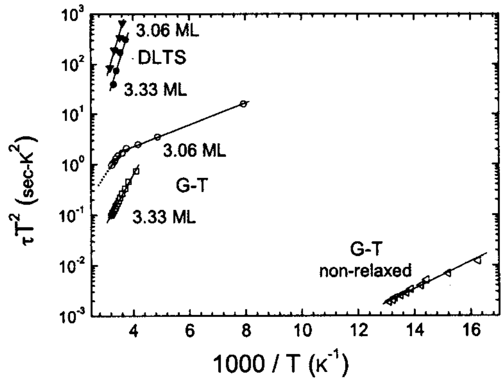

FIG. 2. Arrhenius plots of the emission times from the QD region (indicated by G-T) and from the bottom GaAs layer (DLTS) for the relaxed 3.06- and 3.33-ML samples. The emission time from the QDs in a nonrelaxed sample is included.

B. Carrier distribution in relaxed QD

Figures 1(b) and 1(c) show the 80-K carrier distribution for the relaxed 3.06- and 3.33-ML samples. In each case, an accumulation peak can be seen in the QD region. Notably, the peak shows a long emission time, as evidence by its attenuation as the frequency increases. This long emission time is characteristic of the emission of electrons from traps in the QD region. Additionally, the carrier depletion on both sides of the QD is not symmetric. The carrier depletion drastically extends far to the bottom GaAs layer. Such extended carrier depletion is attributed to relaxation-induced traps which have been previously reported to be acceptorlike.[21] The evidence of the presence of the traps in the extended depletion region is the irregular and large peak at 0.3–0.34 μm. This peak cannot be interpreted as electron accumulation at that depth. The long emission time prevents electrons that are emitted from the traps from following ac probing signal. However, the trapped electrons are eventually

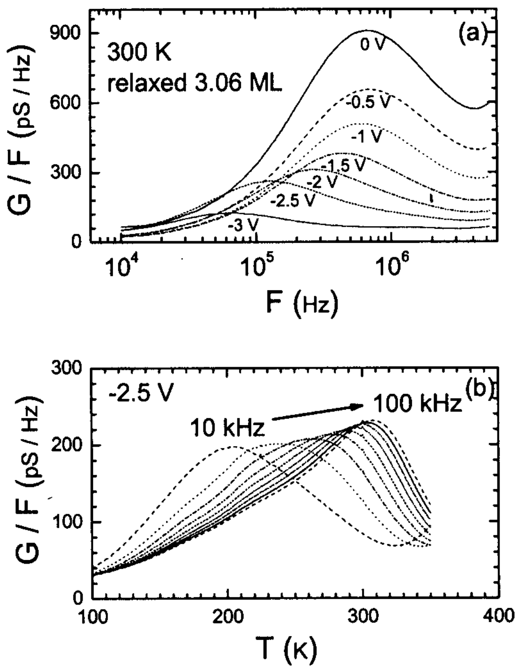

FIG. 3. (a) G/F-F spectra for the 3.06-ML sample at several dc biases. (b) G/F-T spectra at −2.5 V measured from the 3.06-ML sample. The inverse of the frequency is the emission time.

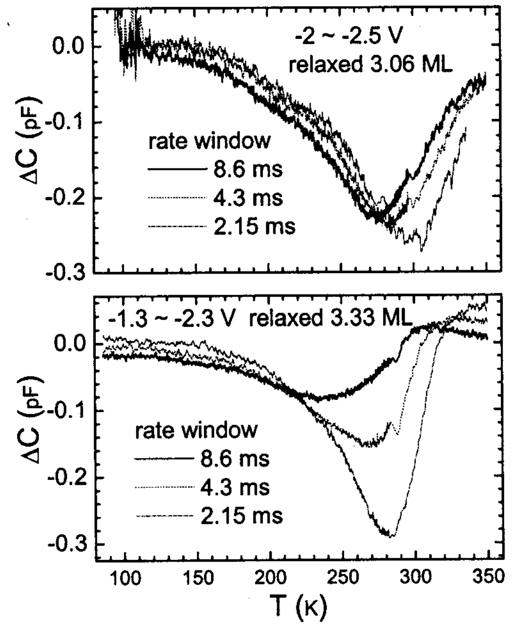

FIG. 4. DLTS spectra for the bottom GaAs region in the 3.06- and 3.33-ML samples. A dominant relaxation-induced trap at around 250–300 K is clearly seen.

swept out when dc bias moves Fermi level well below the traps. This fact explains why such a peak appears after the extended depletion region and is independent of frequency.

C. Carrier emission in relaxed QD

The long emission time in the relaxed samples can be obtained from the G/F-F spectra in Fig. 3(a) derived from the 3.06-ML sample at several dc biases. At small reverse voltages (0 to −1 V), a nearly voltage-independent peak position can be seen, which is due to the free electrons in the top GaAs layer that are emitted to the GaAs bottom electrode. The emission time is short and unaffected by voltage. At small voltages, the QDs do not donate electrons to the conduction band until the Fermi level crosses the QD quantum states or the defect levels because of the application of more reverse voltage. At large reverse voltages (−1.5 to −3 V), a voltage-dependent peak is seen. The peak moves toward low frequency, suggesting an increase in the emission time. The voltage of −1.5 V marks the beginning of the capacitance plateau, indicating that the ac probing signal modulates the electrons in the QDs. The quantum emission is very short, so this long emission time must be associated with relaxation-induced traps. The increase in emission time with the decrease in reverse voltage suggests that the trap has a broad energy distribution, probably because the sizes of the QDs fluctuate. When the voltage is decreased beyond −2.5 V, the magnitude of the peak decreases considerably, indicating that the trap is nearly empty of electrons. Therefore, a voltage of −2.5 V is chosen for G-T measurements to obtain the emission time from the trap.

Figure 3(b) shows the G/F-T spectra obtained from the 3.06-ML sample. The curve displays a peak at each frequency. Figure 2 presents the Arrhenius plots of the emission times (indicated by "G-T"). As shown, the plots are not linear. At high temperatures, the emission time (indicated by the dotted lines) displays appreciable dependence on temperature at activation energies E_a (capture cross sections σ) of 0.17 eV (3.1×10^{-18} cm^2) and 0.20 eV (6.0×10^{-16} cm^2) for the 3.06- and 3.33-ML samples, respectively. These values are smaller than the estimated QD ground-state energy of about 0.25 eV (Ref. 17) below the GaAs conduction band, predicted from the QD size and PL wavelength. The relaxation trap is tentatively located at 0.17–0.20 eV below the QD ground state from which the electrons are thermally activated (at high temperatures) out of the QD region. After they are excited to the QD ground state, the electrons are thermally activated to the first-excited state and subsequently tunnel to the GaAs conduction band in the two-stage process described for the nonrelaxed case. This subsequent two-stage process is a relatively fast process that was not observed herein. Figure 2 shows that, at low temperatures, the emission times depend weakly on temperature. This fact can be explained by direct tunneling from the trap to the QD ground state. Based on the assumption that the barrier is triangular,[15] the saturated tunneling rate of 10^5 s^{-1} yields a tunneling barrier height of about 0.20 eV. This value is similar to the measured activation energies at high temperatures.

D. Carrier emission in the bottom GaAs

The extended carrier depletion in the bottom GaAs, as shown in Figs. 1(b) and 1(c), suggests the presence of relaxation traps. The irregular peak at 0.3–0.34 μm provides further evidence of the presence of the traps. The emission time is too long to be resolved at available frequencies by admittance spectroscopy. The DLTS measurement is more effective in revealing the traps. Figure 4 shows the DLTS spectra of the bottom GaAs region in the 3.06- and 3.33-ML samples, respectively. A trap at around 250–300 K is clearly observed at activation energies (capture cross sections) of 0.37 eV (5.45×10^{-17} cm^2) and 0.41 eV (9.78×10^{-16} cm^2) for the 3.06- and 3.33-ML samples, respectively. This trap is found only in the bottom GaAs region and in the relaxed samples; it must therefore be responsible for the extended carrier depletion. As shown, this trap is rather broad, probably because of the localized residual strain. The fact that the top GaAs layer is free of this trap indicates that the relaxation occurs in the QD bottom interface. Figure 2 presents the Arrhenius plots of these traps (indicated by "DLTS"). Their emission times are two orders of magnitude longer than those from the QD region (indicated by G-T). This result may suggest either that the relaxation traps in the QD region differ from those in the neighboring GaAs bottom layer or that they are the same traps but the difference originates from different atoms surrounding the trap. We have no conclusive evidence but we think that they are likely the same trap. The atoms that surround the trap are In and As in the QD, but Ga and As in the bottom GaAs layer. The considerable difference between their atomic characters suggests very different emission times: the covalent radii of In and Ga are 1.44 and 1.26 A.[22] The data show that this trap displays quick emission with $E_{\mathrm{ac}}=0.17-0.20$ eV in the QD region and slow emission with $E_{\mathrm{ac}}=0.37-0.41$ eV in the neighboring bottom GaAs layer. The energy differences in the 3.06- and 3.33-ML samples are 0.20 and 0.21 eV, respectively. These values are similar to the estimated QD ground-state energy relative to the GaAs conduction-band edge. Kapteyn *et al.*[15] and Chang *et al.*[17] reported values of 0.195 and 0.25 eV, respectively, for this energy difference for QDs that emit similar wavelength to those herein. This result suggests that the traps in the QDs and in the neighboring bottom GaAs layer might be the same trap, which to some extent is pinned to the GaAs conduction band. More work must be conducted to make a more conclusive argument.

The DLTS spectra of the 3.33-MLs sample (in Fig. 4) show a strong dependence of the peak height on the rate window, suggesting the presence of a large capture barrier. The capture barrier height can be obtained by changing the filling pulse width. Figure 5(a) reveals that the peak height increases with the filling pulse width and finally saturates in the 3.06-MLs sample. The 3.33-MLs sample exhibits a similar trend, as presented in Fig. 6(a). The capture barrier can be obtained from the capture rate c, as in Ref. 23, and can be expressed by the following kinetics:

$$S(t_p)=S(\infty)[1-\exp(-ct_p)],$$

where $S(t_p)$ is the peak height, $S(\infty)$ the saturated peak height, and t_p is the filling pulse width. The capture rate can be obtained from the slope of $\ln[1-S(t_p)/S(\infty)]$ vs t_p as plotted in Figs. 5(b) and 6(b) for the 3.06- and 3.33-ML samples, respectively. The capture rates at different temperatures are obtained by changing the rate window. The capture rate yields the capture cross section σ, according to $c=\sigma v n$ where v is the mean thermal velocity and n is the free-electron concentration. The capture cross section is related to the capture barrier height by $\sigma=\sigma_0\exp(-E_\sigma/k_BT)$ where σ_0 is a constant, E_σ is the capture barrier height, and k_B is the Boltzmann constant. Figure 7 presents the measured capture cross sections as a function of inverse temperatures, from which the capture barrier heights of 0.10 and 0.22 eV are obtained for the 3.06- and 3.33-ML samples, respectively. The higher capture barrier of the 3.33-ML sample may be caused by the higher degree of relaxation. If the capture barrier is caused by the electrical field created by the already captured electrons, then the barrier height will be propor-

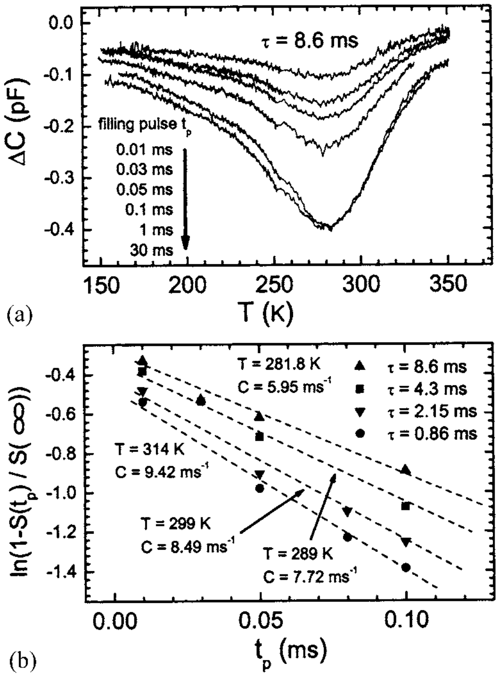

FIG. 5. (a) DLTS spectra for different filling pulse widths in the 3.06-ML sample. (b) $\ln[1-S(t_p)/S(\infty)]$ vs t_p. The capture rate can be obtained from the slope.

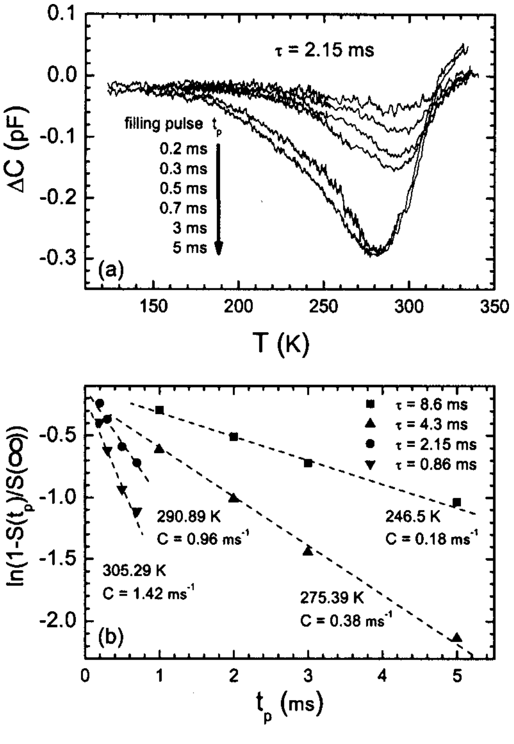

FIG. 6. (a) DLTS spectra for different filling pulse widths in the 3.33-ML sample. (b) $\ln[1-S(t_p)/S(\infty)]$ vs t_p.

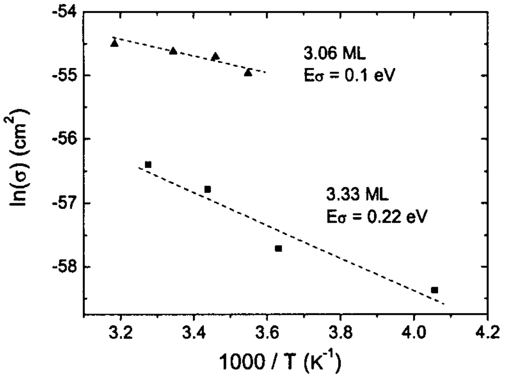

FIG. 7. Capture cross sections at various inverse temperatures for the 3.06– and 3.33-ML samples. Capture barrier heights of 0.10 and 0.22 eV in the 3.06–and 3.33-ML samples, respectively, are determined.

tional to the number of captured electrons. The results herein show that the relaxation-induced trap is located at 0.37–0.41 eV below the GaAs conduction-band edge and has a significant capture barrier height of 0.10–0.22 eV. The Arrhenius plots reveal that this trap is the relaxation-induced trap at 0.33 eV (Ref. 24) in relaxed GaAs/InGaAs/GaAs quantum-well (QW) structures.

IV. CONCLUSIONS

The properties of a relaxation-induced trap in InAs QDs capped with InGaAs are investigated. The $C-V$ profiling shows that relaxation extends carrier depletion to the bottom GaAs layer. Traps are observed in the QD region and the neighboring bottom GaAs layer. In the QD region, the electrons are thermally activated at high temperatures (and undergo direct tunneling at low temperatures) from the trap at 0.17–0.20 eV. In the bottom GaAs, the electrons are emitted from a trap at 0.37–0.41 eV below the GaAs conduction-band edge. The energy difference is similar to the difference between the QD ground state and the GaAs conduction-band edge, suggesting that the traps are likely to be the same trap which is pinned to the GaAs conduction band.

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