

# Transient capacitance spectroscopy on large quantum well heterostructures

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We report transient capacitance measurements on  $\text{Al}_x\text{Ga}_{1-x}\text{As}-\text{GaAs}-\text{Al}_x\text{Ga}_{1-x}\text{As}$  ( $x \sim 0.35$ ) double heterojunctions with a large quantum well active region ( $L_z \sim 800 \text{ \AA}$ ). It is suggested that the thin GaAs layer acts as a "giant" artificial deep level. It follows then that the band edge discontinuity  $\Delta E_c$  determines the electron emission rates (from the thin layer), thus making it possible for  $\Delta E_c$  to be determined by transient capacitance measurements.

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As part of a larger effort, we have been employing deep level transient spectroscopy<sup>1</sup> to examine thin GaAs layers as well as quantum well heterostructure layers.<sup>2</sup> The intent of these measurements has been to determine how the emission rate of electrons (holes) at interfaces or from quantum wells differs from the behavior of bulk crystals. These changes have been anticipated to arise from changes in the energy levels of deep traps close to interfaces and from the two-dimensional final density of states in the quantum well.<sup>3,4</sup> Preliminary experimental results, however, have exhibited peculiarities which, in our opinion, require a very different explanation: the GaAs thin layers *themselves* behave like big traps. We have reported earlier on the dynamics of capture and emission of hot electrons in quantum wells.<sup>5,6</sup> Deep-level transient spectroscopy adds new perspective to this problem and, based on the model employed earlier,<sup>5,6</sup> opens a new method or opportunity to determine band-edge discontinuities. We note that the nature and role of the interface band-edge discontinuities are among the most fundamental problems in the physics of semiconductor heterojunctions,<sup>7</sup> and hence are of much interest.

The experimental samples of the present work have been grown by metalorganic chemical vapor deposition and are nominally doped *n*-type with Se ( $\sim 2 \times 10^{15} \text{ cm}^{-3}$ ). The double heterojunction (DH) samples consist of a buffer layer of GaAs grown on top of a GaAs substrate, followed by a 1.0- $\mu\text{m}$  confining layer of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  ( $x \sim 0.35$ ), a GaAs well ( $L_z \sim 800 \text{ \AA}$ ), and another confining layer of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  ( $x \sim 0.35$ ) that is  $\sim 0.3 \mu\text{m}$  thick.

For preparation into diodes the DH wafer is first lapped to 5 mil, and Au-Sn is electroplated and alloyed on the substrate side of the wafer. Schottky barriers are then formed on the top AlGaAs confining layer by electroplating 2  $\mu\text{m}$  of Au in a pattern of 11-mil-diam. dots defined by  $\sim 1200 \text{ \AA}$  of  $\text{SiO}_2$ . The Au is applied after the surface has been mildly etched with a dilute solution of 1 HF:7  $\text{NH}_4\text{F}$ . The resulting devices are separated and attached with silver-filled epoxy to TO-18 headers, and a wire bond to the Schottky barrier completes the diode. These diodes have a forward turn-on voltage of 0.5–0.7 V and a reverse breakdown voltage which varies from diode to diode and is greater than 3 V.

Deep level transient spectroscopy (DLTS) has been performed using a system described elsewhere.<sup>8</sup> In the present work a parallel-plate capacitor was used in place of the sec-

ond diode. For the DLTS measurements a reverse bias of 1 V is used and 20- $\mu\text{s}$  pulses of varying magnitudes are superimposed on the bias. Two deep levels have been observed (Fig. 1). One, which we label E2, exhibits an energy level at 0.88 eV, a capture cross section of  $7.0 \times 10^{-13} \text{ cm}^2$  and a concentration (corrected for the effect of the edge region<sup>9</sup>) of about  $5 \times 10^{13} \text{ cm}^{-3}$ . E2 behaves as predicted by DLTS analysis and does not show any significant dependence of the signal peak with temperature and the peak height on bias pulse voltage. It is therefore easily attributed to a deep level in the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ . We have, however, no straightforward explanation of the other peak (E1). The second level, which we label E1, exhibits a peculiar dependence on the forward-bias pulse height and width. This makes fitting to the conventional detailed balance expressions a questionable procedure.

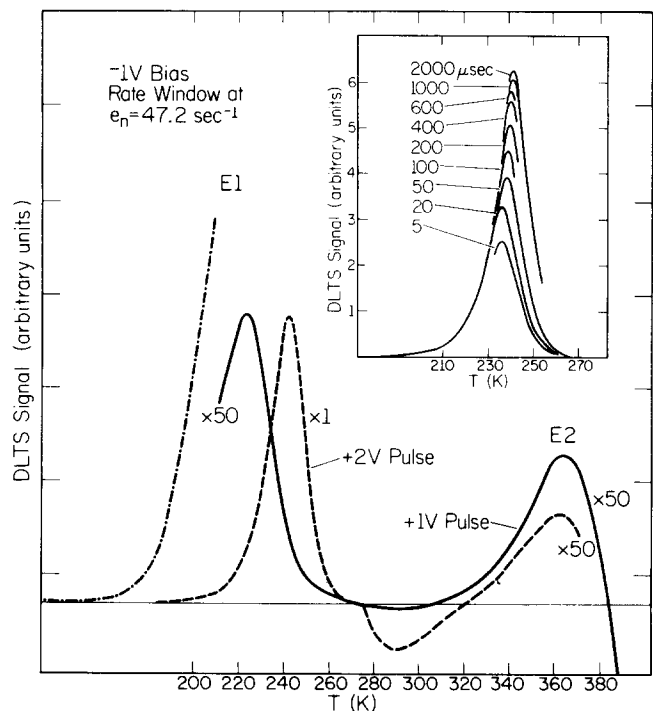


FIG. 1. DLTS scan for 1 V reverse bias with two different bias pulse voltages, showing variation in the height and temperature of the low-temperature peak, E1. The apparent decrease in the signal strength of the second peak (E2) as the bias pulse is increased to 2 V is due to a superimposed minority carrier trap. Inset: variation of peak E1 with bias pulse duration.

The magnitude of the DLTS peak E1 and the temperature at which the peak occurs increases as the pulse voltage is increased from +1 to +7 V as shown in Figs. 2(a) and 2(b). Using conventional DLTS analysis, we observe a large uncertainty in the trap's apparent energy level, concentration, and capture cross section. Data obtained with 2-V pulses yield an activation energy  $\Delta E = 0.35$  eV, a capture cross section  $\sigma \approx 3.7 \times 10^{-15}$  cm<sup>2</sup>, and an effective trap concentration of  $4.5 \times 10^{12}$  cm<sup>-3</sup> (assuming uniformity in the depletion region); data obtained with 3-V pulses yield  $\Delta E = 0.53$  eV,  $\sigma \approx 1.8 \times 10^{-13}$  cm<sup>2</sup>, and an effective trap density of  $4.5 \times 10^{14}$  cm<sup>-3</sup>. The activation energies could be with respect to either the conduction band of the AlGaAs or that of the GaAs. We do not have sufficient profiling information to fix the location of the defect.

The shift in the temperature of the DLTS signal peak E1 with pulse voltage is opposite to that observed for field-enhanced electron emission.<sup>10</sup> We expect the DLTS peaks to

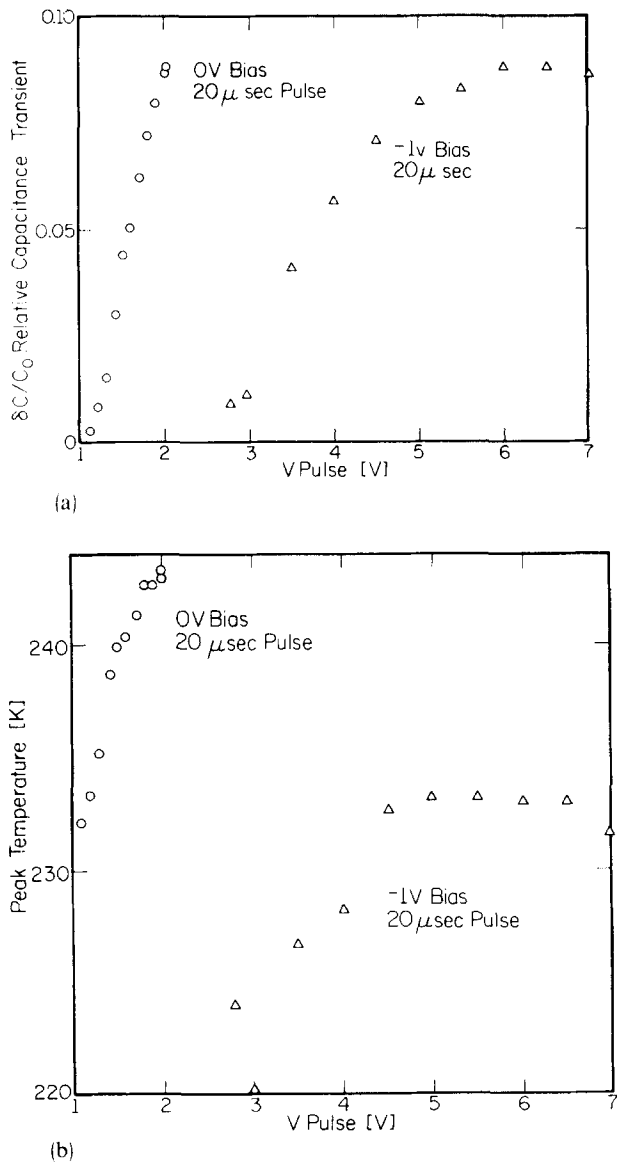


FIG. 2. Dependence of the magnitude (a) and peak temperature (b) of the transient signal for the low temperature level E1.

occur at lower temperatures when the pulse magnitude is increased, because traps in regions of higher field (and therefore faster emission rates) are being filled. If this level corresponded to interface states, it would be possible to explain the rise in apparent concentration with increasing pulse magnitude as due to the partial filling of the interface states (near the edge of a residual depletion region) at high forward bias. This still does not explain, however, the shift in the temperature of the DLTS peak E1.

The capture process of E1 has been studied by biasing the diode at 0 V and varying the pulse width. With 3-V pulses the capture process is highly nonexponential and very similar to some observations of McAfee *et al.*<sup>11</sup> The filling of the trap is logarithmic in time rather than exponential. McAfee *et al.* have attributed this to capture from the Debye tail of carriers in the depletion width. In the present experiment, capture from the Debye tail at 3 V forward bias could only be explained by the filling of interface states in the presence of a residual depletion region. With the pulse magnitude increased to 4 V, the capture appears to be exponential with a rate of  $5.0 \times 10^6$  s<sup>-1</sup>, and with 5-V pulses the rate is  $1.3 \times 10^7$  s<sup>-1</sup>. At each pulse voltage the temperature of the signal peak shifts slightly to higher values as the pulse width is increased. The total shift in the peak is 4 to 5° and is shown in detail in Fig. 1, which also displays the form of the spectra.

*C-V* analysis shows that the GaAs well is within the zero-bias depletion region. Because of this we are unable to sweep the depletion region through the well by varying the reverse bias applied to the diode. Nonuniform carrier concentration introduces some uncertainty in the extrapolated measurement of the Schottky barrier height, which we estimate to be 1.5 V.

Figure 3 shows the band-edge discontinuity of a quantum well in the reverse biased space-charge region of a Schottky barrier (or *p-n* junction). The close analogy to a "big trap" is clear. Below we assume that the quantum well is a "trap" and calculate the approximate capture and emission rates. The emission of electrons over a heterojunction barrier has been discussed previously for the case of elec-

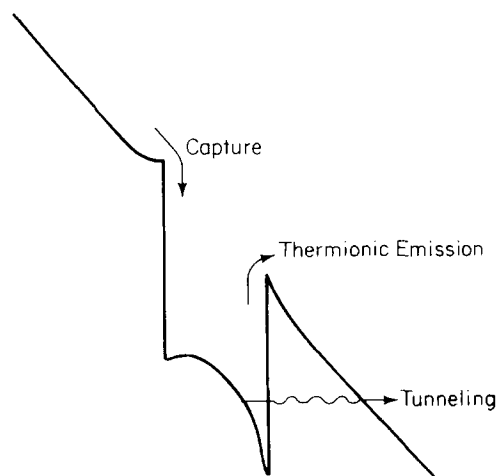


FIG. 3. Band-edge discontinuity of a quantum well in the space-charge region of a reverse biased Schottky barrier.

trons heated by an electric field, i.e., real space transfer<sup>5</sup>; capture has been discussed also in the case of hot-electron radiative recombination in a quantum well laser.<sup>6</sup> We now consider the same processes when caused by lattice heating. The rate at which electrons transfer from  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  to GaAs, assuming band bending of total voltage  $\varphi$ , is given as:

$$c_n = \frac{A^* T^2 m^*}{e N_c L_D m_0} \exp(-e\varphi/kT), \quad (1)$$

where we have assumed that charge transfer is governed by thermionic emission of electrons over the barrier  $\varphi$  caused by ionized donors in the depleted AlGaAs.  $A^*$  is the Richardson constant internal to the crystal,  $T$  is the lattice temperature,  $m^*$  is the electron effective mass in the AlGaAs,  $e$  is the electronic charge,  $N_c$  is the effective density of states at the AlGaAs conduction band edge,  $L_D$  is the width of the AlGaAs depletion region, and  $m_0$  is the free electron mass. Since  $\varphi$  is a function of the electron concentration in the well,  $c_n$  will vary strongly with time. We expect the initial capture from undepleted AlGaAs to be very fast ( $\varphi \simeq 0$ ), and subsequently to slow down by orders of magnitude as the system approaches equilibrium.  $L_D$  varies with time as well, but it is present in Eq. (1) by virtue of the approximation  $\partial J/\partial x = J/L_D$  in the continuity equation. A numerical calculation of  $c_n(t)$  should include a better estimate of this derivative.

Similarly, the emission rate out of the low-gap material (GaAs) is given by

$$e_n = \frac{1}{L_z} \left( \frac{kT}{2\pi m^*} \right)^{1/2} \exp(-e\Delta E_c/kT), \quad (2)$$

where we have eliminated the dependence on the effective density of states and assume the quasi-Fermi level is constant, which results in the  $T^{1/2}$  dependence. Due to the long capture times involved in the final capture process, the system may not reach equilibrium during the bias pulses of a DLTS experiment. We must therefore allow for the possibility of partial filling of the well and a discontinuous Fermi level across the interface.

Further complications include band bending and electron redistribution in the well, quantized energy levels for emission from a thin quantum well [in which case the effective  $\Delta E_c$  in Eq. (2) is reduced by the difference in energy

between the  $n = 1$  electron state and  $E_c$  (GaAs)] and enhancement of the emission rate by the large electric field at the heterojunction. Using Eqs. (1) and (2), we can qualitatively explain the emission and capture rates of the E1 peak. The temperature range of the signal peak at varying pulse magnitudes corresponds to a band-edge discontinuity of 0.35 eV  $< \Delta E_c < 0.52$  eV. The conduction band discontinuity  $\Delta E_c \simeq 0.38$  eV for the alloy composition  $x = 0.35$  of this work and the range of measured capture cross sections follow naturally from Eqs. (1) and (2). However, the variation of the temperature of the signal peak with pulse width and pulse magnitude remains a puzzle and does not seem to have a straightforward explanation in terms of a simple large trap model.

In summary, we have reported unusual DLTS spectra measured for Schottky barriers which involve double heterojunctions. We have shown that some aspects can be explained by assuming that the well in the DH behaves as a big trap. Based on this interpretation, DLTS may prove to be a useful tool in determining heterojunction band-edge discontinuities.

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