Carrier dynamics in quantum wells behaving as giant traps

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An Arrhenius-type of expression is derived for the emission rate of electrons from a quantum well on the basis of detailed balance principles. The formulation is applied to a 150-Å $In_{0.2}Ga_{0.8}As/Al_{0.16}Ga_{0.84}As$ strained single quantum well grown by molecular beam epitaxy. From an analysis of the data it is possible to estimate the conduction band offset ΔE_c, which may be extremely useful for strained systems.

I. INTRODUCTION

The potential variation of a quantum well is similar to the potential of a deep trap. There are, however, important differences. Quantum wells in which electrons can be reasonably confined are $\geqslant 50$ Å, whereas the equivalent distance in the atomic potential distribution is $\sim$3–5 Å. The wave-function localization of the trapped carrier is, therefore, very different in the two cases. Second, deep traps have a three-dimensional potential, whereas the quantum well potential is a two-dimensional variation, usually in the growth direction. Finally, in a quantum well, the density of states is a step distribution, while it is usually discrete for a deep trap, localized at the trap energy level. In spite of these differences, quantum wells can thermally emit and capture carriers in much the same way as deep traps and, therefore, can behave as "giant" trapping centers. In fact, at least two groups of authors[1,2] have reported deep-level transient spectroscopy (DLTS) data from $Al_xGa_{1-x}As/GaAs$ ($x \geqslant 0.3$) quantum well structures, and they indicated that the measured DLTS signal is due to traplike emission from the quantum well. However, the emission energy derived from an Arrhenius plot has a value very different from the conduction band discontinuity ΔE_c. Furthermore, the emission energy was very sensitive to filling pulse amplitude and duration.

We have investigated the electron emission properties from single quantum wells in the GaAs/AlGaAs, InGaAs/InAlAs, and the pseudomorphic InGaAs/AlGaAs systems in order to understand the process and get some quantitative description of the quantum wells. The parameter of interest is the band-edge discontinuity ΔE_c. It was clear to us, on repeating the emission experiments with Schottky barriers on $Al_{0.3}Ga_{0.7}As/GaAs$ quantum wells, that the main transient capacitance signal is not due to emission of well electrons, but to the *DX* center,[3] a deep electron trap, in the $Al_{0.3}Ga_{0.7}As$ barriers. In fact, the anomalous movement of the DLTS peak to higher temperatures on increasing the bias pulse, which is opposite to that due to a well-behaved trap, can be explained by considering the capacitance due to the modulation-doped quantum well in series with the depletion-layer capacitance of the Schottky diode. This analysis and the results obtained from GaAs/AlGaAs modulation-doped heterostructures have been reported by us.[4] It is, therefore, important that in order to study quantum well emissions one must have samples in which there are no traps in the wells and barrier regions that can thermally emit in the same temperature range as the quantum well itself. Even then, there is always the uncertainty due to interface states. In this paper we present an analysis of the thermal emission and capture rates from quantum wells on the basis of detailed-balance principles, and the well parameters obtained from transient-capacitance data using this analysis.

II. THEORY

Drawing an analogy between an electron quantum well and a giant electron trap, a detailed balance between thermal capture and emission rates of electrons is valid. The capture rate of electrons into the well, r_{cn}, is proportional to the electron concentration in the barrier, n_B, and to the empty states in the well, $\bar{n}_w$,

$$r_{cn} = \langle v_{\rm th} \rangle \chi n_B \bar{n}_w \,, \tag{1}$$

where $\langle v_{\rm th} \rangle$ is the average thermal velocity of electrons, and χ (cm^2) is a capture cross section related to the scattering rate of carriers into the well. It is, therefore, closely related to the quantum well parameters. By using a three-dimensional density of states in the well, which is approximately valid for $L_w \geqslant 150$ Å,

$$\bar{n}_w = (8\pi/3h^3)(2m_w^*)^{3/2}\Delta E^{3/2} \,, \tag{2}$$

where ΔE is the difference in energy between the first electron subband and the top of the well. Similarly,

$$n_B = N_{CB} \exp[(E_f - E_{CB})/kT] \,, \tag{3}$$

where N_{CB} is the three-dimensional density of states in the barrier material. Similarly, the emission rate of electrons from the well is given by the product of the emission probability e_n and the number of electrons, n_W, in the well. In other words,

$$r_{en} = e_n \frac{4\pi}{h^3}(2m_w^*)^{3/2}\frac{\sqrt{\pi}}{2}(kT)^{3/2}\exp\left(\frac{E_f - E_{CW}}{kT}\right). \tag{4}$$

In thermal equilibrium,

$$r_{en} = r_{cn} \,. \tag{5}$$

By substituting Eqs. (1)–(4) in (5),

$$e_n = \frac{16\pi^{3/2}}{3h^3} m_B^* \chi (kT)^{1/2}(\Delta E)^{3/2}\exp\left(-\frac{\Delta E}{kT}\right). \tag{6}$$

It is important to note that the emission rate of electrons can

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also be derived from the thermionic emission current due to electrons emitted from the well to the barrier region. The emission rate is given by[1]

$$e_n = \left(\frac{kT}{2\pi m_w^*}\right)^{1/2} \frac{1}{L_w} \exp\left(-\frac{\Delta E_c}{kT}\right). \tag{7}$$

It is clear that although the exponential dependence is identical in Eqs. (6) and (7), there are important differences in the prefactor. This difference comes mainly from the fact that in the thermionic emission model, the electrons in the wells must have an energy greater than ΔE_c to be thermally emitted over the barrier. By equating the prefactors in Eqs. (6) and (7), the following expression is obtained for the capture cross section:

$$\chi = 3h^3/[16\times 2^{1/2}\pi^2 L_w m_w^{*1/2} m_B^* (\Delta E)^{3/2}]\,. \tag{8}$$

Finally, we turn to the electrostatics of the problem. Consider a single quantum well (SQW) in the depletion region of a Schottky barrier, as shown in Fig. 1. The existence of confined electrons in the well changes the depletion width W. Solution of Poisson's equation in the well and barrier regions with the appropriate boundary conditions gives[2]

$$W^2 = W_0^2(1 + 2n_w L L_w / N_D W_0^2)\,, \tag{9}$$

where $W_0^2 = (2\epsilon/qN_D)\,V$ is the depletion region width in the absence of the well. N_D is the net donor density in the barrier, and $V = V_{\text{app}} + V_{\text{bi}}$. The transient capacitance ΔC is then given by

$$\Delta C / C(W) \simeq n_w\, L\, L_w / N_D W_0^2\,, \tag{10}$$

which was also derived by Hamilton, Singer, and Peaker.[2] The DLTS signal for rate windows t_1 and t_2 (Ref. 5) is then given by

$$s(t) = C(t_2) - C(t_1)$$
$$= C_0 \frac{n_{w0}}{N_D} \frac{L L_w}{W_0^2} [\exp(-e_n t_1) - \exp(-e_n t_2)]\,. \tag{11}$$

III. SAMPLE PREPARATION

We will now describe the measurements made on 150-Å $Al_{0.16}Ga_{0.84}As/In_{0.2}Ga_{0.8}As$ quantum wells and the results obtained by using the analysis described above. The sample was grown by molecular beam epitaxy (MBE) on n^+ GaAs substrates and was uniformly doped to a level of $n \sim 5\times 10^{16}\ \text{cm}^{-3}$ with Si. The schematic of the structure is shown in the inset of Fig. 2. This structure has the following advantages: $Al_xGa_{1-x}As$ with $x < 0.24$ does not have the DX center, and we have established the traps in strained $In_{0.2}Ga_{0.8}As$[6]. None of the identified centers occurs in the temperature range where well emissions are expected. Gold Schottky diodes with an area of $2.2\times 10^{-3}\ \text{cm}^2$ were formed on the heterostructures by evaporation. The doping and thickness of the heterostructure layers were carefully controlled so that the quantum well is outside the zero-bias depletion region, but is within it at the quiescent reverse bias at which the experiments were done. The diodes typically have a reverse breakdown voltage of 12–15 V, and capacitance-voltage measurements give a value of $N_D = 1.5\times 10^{16}\ \text{cm}^{-3}$ in the $Al_{0.16}Ga_{0.84}As$ barriers. The depletion-accumulation regions due to the SQW are observed in the capacitance-voltage data and are shown in Fig. 3.

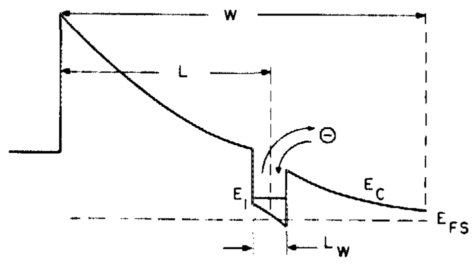

FIG. 1. Band diagram of a reverse-biased Schottky diode with a SQW in the depletion region.

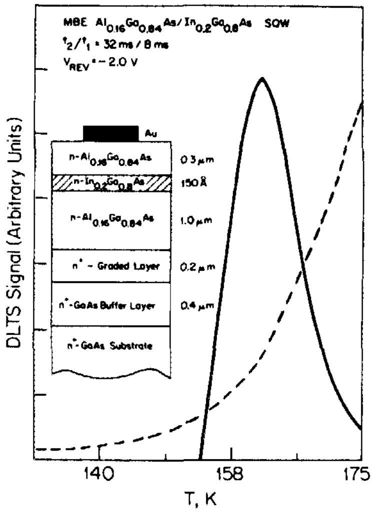

FIG. 2. DLTS signal believed to result from thermal emission of electrons from the quantum well. The schematic of the heterostructure sample is shown in the inset. The dashed profile indicates DLTS data obtained from the same sample with the quantum well removed.

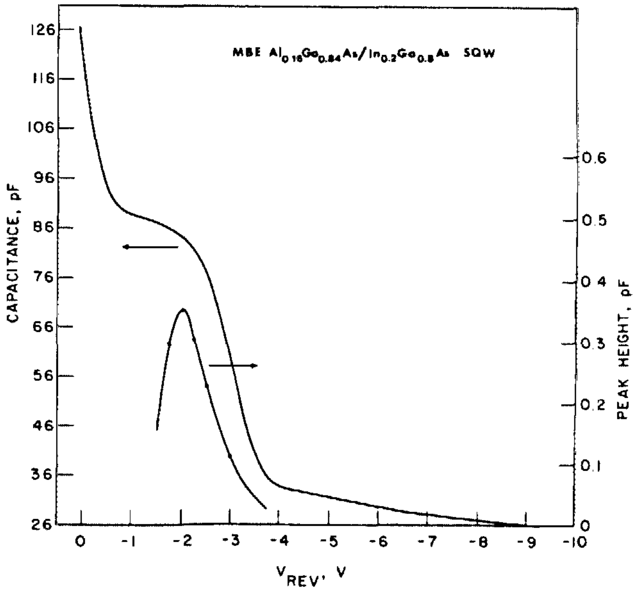

FIG. 3. Variation of depletion layer capacitance and DLTS peak height of the quantum well emission with bias applied to the diode.

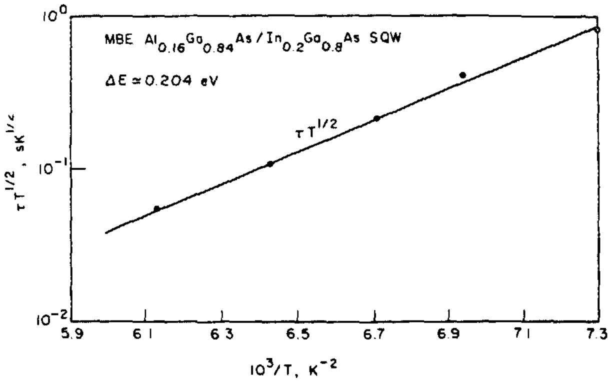

FIG. 4. Arrhenius plot corresponding to emission from the $Al_{0.16}Ga_{0.84}As/In_{0.2}Ga_{0.8}As$ SQW, in accordance with Eq. (6).

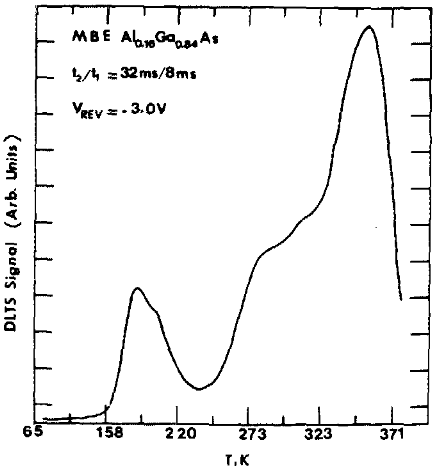

FIG. 5. DLTS data of MBE $Al_{0.16}Ga_{0.84}As$ obtained with a Schottky diode reverse biased at ~3 V.

IV. RESULTS AND DISCUSSION

The prominent peak obtained in the DLTS temperature scan, which we believe originates from quantum well emission, is shown in Fig. 2. An important observation was the fact that the height of this peak goes through a maximum at nearly the same quiescent reverse bias at which the depletion-accumulation region is observed in the capacitance-voltage data. This is shown in Fig. 3. By repeating the experiment with different rate windows, an Arrhenius plot in accordance to Eq. (6) can be obtained. This plot is shown in Fig. 4, from which $\Delta E = 0.204$ eV is estimated. By adjusting the quiescent reverse bias, it was possible to observe emissions from traps in the $Al_{0.16}Ga_{0.84}As$ barriers only, and these traps were essentially the same as those observed by us and other authors.[4,7,8]

We further repeated the DLTS measurements with Schottky diodes made on the same samples after removing the quantum well by chemical etching. The data are shown in Fig. 5, in which the peak, believed to be due to quantum well emissions, is significantly absent. It may be noted that the DLTS data over the entire temperature of the samples with the quantum well are very similar to that shown in Fig. 5, except the presence of the low-temperature peak of Fig. 2. The only difference is that the background trap level concentration in these samples is higher over the entire temperature range. This is typical of emissions from surface and interface states, which typically have a distributed density of states in the energy scale and usually do not show a sharp peak. For a lattice-matched quantum well, the conduction band offset ΔE_c is approximately equal to 0.6 times the band-gap difference. Under an electric field F, which bends the bands in the well and barrier regions, the emission energy will be given by $\Delta E_c - (E_{1c} + L_w F)$, where E_{1c} is the subband energy. For our case of the pseudomorphic well, $\Delta E = 0.192$ eV is derived. This is about 12 meV smaller than the measured value of 0.204 eV. It is, therefore, apparent that the lattice mismatch effects tend to increase the value of ΔE_c, as suggested by recent theoretical work.[9]

We repeated the measurements with a similar structure, having a 250-Å SQW and uniformly n doped at a level of 6×10^{17} cm^{-3}. The emission peak in the DLTS signal is almost absent, as expected from Eq. (10). It may be noted that a 250-Å $In_{0.2}Ga_{0.8}As/Al_{0.16}Ga_{0.84}As$ quantum well may produce a larger density of interface states than a 150-Å well. In fact, the background-trap-density level over the entire temperature does increase slightly, as discussed above. We therefore believe that the low-temperature emission peak characterized here is a true quantum well emission.

V. CONCLUSION

We have analyzed electron emission and capture from a quantum well using a detailed balance approach. Careful DLTS measurements done on $Al_{0.16}Ga_{0.84}As/In_{0.2}Ga_{0.8}As$ quantum wells indicate that the technique can be used to estimate the conduction band discontinuity ΔE_c and may be very useful for determining this parameter in strained systems.

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