Conduction- and valence-band offsets in GaAs/$Ga_{0.51}In_{0.49}P$ single quantum wells grown by metalorganic chemical vapor deposition

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We have independently estimated the conduction- and valence-band offsets ΔE_c and ΔE_v in GaAs/$Ga_{0.51}In_{0.49}P$ quantum wells by measuring the capacitance transient resulting from thermal emission of carriers from the respective wells. The heterostructure samples were grown by low-pressure metalorganic chemical vapor deposition. The band offsets are extrapolated from the emission activation energies with appropriate corrections. The estimated values of ΔE_c and ΔE_v are 0.198 and 0.285 eV, respectively.

The lattice-matched GaAs/$Ga_{0.51}In_{0.49}P$ heterojunction is emerging as an important alternative to the GaAs/AlGaAs system for potential application to modulation-doped field-effect transistors[1] and heterojunction bipolar transistors.[2,3] In particular, the heterojunction is believed to have a larger valence-band offset ΔE_v than the conduction-band offset ΔE_c,[4] which makes it attractive also for logic applications. However, there is quite a bit of discrepancy in the values of these parameters reported by the different groups,[4,5] and it is crucial that the proper values are established. We have used a different technique, the measurement of thermal emission rates from a specially designed quantum well, to estimate ΔE_c and ΔE_v independently.

The potential variation of a quantum well is similar to that of a deep trap in the forbidden energy gap of a semiconductor with some obvious and important differences. Therefore, a detailed balance between thermal capture and emission rates of electrons from such wells is valid. From such detailed balance, the emission rate of electrons is given by[6]

$$e_n = (16\pi^{3/2}/3h^3) m_B^* \chi (kT)^{1/2} (\Delta E_e)^{3/2} \exp(-\Delta E_e/kT), \quad (1)$$

where ΔE_e is the electron emission energy for the conduction-band well, m_B^* is the effective mass in the well material, and χ is a parameter related to the capture of carriers by the wells. An equation similar to (1) is valid for hole emission from a valence-band well. The thermal emission energy of carriers from a quantum well is related to the appropriate band offset.

Next, consider a single quantum well in the depletion region of a Schottky barrier. 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

$$W^2 = W_0^2 (1 + 2n_w L L_w / N_D W_0^2), \quad (2)$$

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 $V = V_{\rm app} + V_{\rm bi}$. The transient capacitance ΔC is then given by

$$\Delta C / C(W) \simeq n_w L L_w / N_D W_0^2. \quad (3)$$

The diode samples were grown by low-pressure metalorganic chemical vapor deposition on n^+ and p^+ substrates. Details of the growth procedure have been described elsewhere.[7] Essentially, the structures are grown at low pressure ($P = 76$ mbar) using triethylgallium, trimethylindium, and pure phosphine in a hydrogen carrier gas. The schematics of the grown layers are shown in Fig. 1. The region in which the quantum well is placed is uniformly doped n or p type to a level of 2×10^{16} cm^{-3}. Deep level transient spectroscopy (DLTS) measurements were made with a variable-temperature cryostat, a 1 MHz Boonton capacitance meter, and a signal analyzer for providing the rate windows and processing the capacitance-difference signals with varying temperatures.

It is important to verify that the thermal emission signals from the quantum well and from deep levels in the material are separated. For this purpose, DLTS and optical DLTS measurements were first made with Schottky diodes on n-GaInP with the GaAs well removed. Majority- and minority-carrier filling pulses were provided with a pulsed bias source and a pulsed intrinsic optical source, respective-

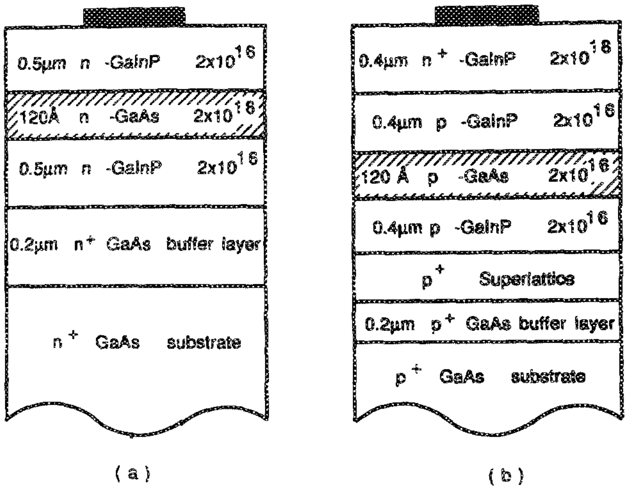

FIG. 1. Schematic diagrams of the diode structures containing the single quantum wells with (a) uniform n doping and (b) uniform p doping.

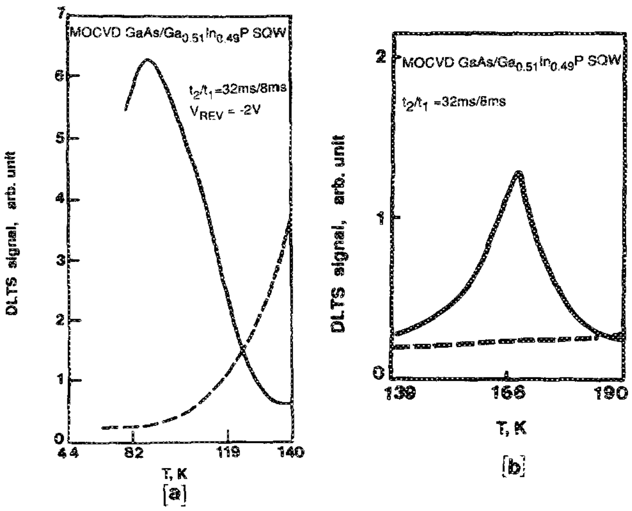

FIG. 2. DLTS signals resulting from thermal emission of (a) electrons and (b) holes from conduction- and valence-band quantum wells, respectively. The dashed profiles are the DLTS signals for $Ga_{0.51}In_{0.49}P$ with the quantum wells removed.

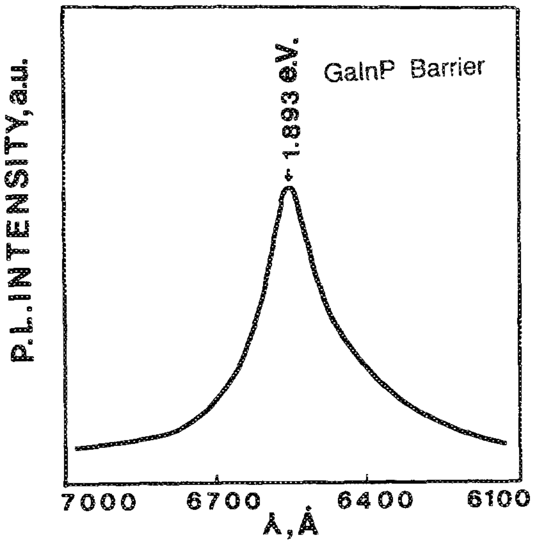

FIG. 4. Room-temperature photoluminescence of $Ga_{0.51}In_{0.49}P$.

ly. The activation energies of the electron and hole traps range from 0.34 to 1.10 eV. As will be evident shortly, the purpose of the trap characterization was to differentiate the quantum well emissions of interest from the emissions originating from deep levels.

With measurements on GaInP Schottky or junction diodes with GaAs quantum wells in the depletion region, additional prominent peaks are obtained in the DLTS temperature scans. These peaks, believed to originate from the conduction- and valence-band quantum well carrier emissions, are shown in Figs. 2(a) and 2(b), respectively. Note that these peaks are significantly absent from the DLTS data for electron and hole traps in GaInP, shown by the dashed profiles. By repeating the DLTS temperature scans with different rate windows, Arrhenius plots in accordance with Eq. (1) are obtained. These plots are shown in Fig. 3, from which electron and hole emission energies of 0.17 and 0.275 eV, respectively, are derived. The room-temperature photoluminescence emission corresponding to the band edge of GaInP is shown in Fig. 4. From this, and the known band gap of GaAs, a band-gap difference, $\Delta E_g = 0.48$ eV, is derived.

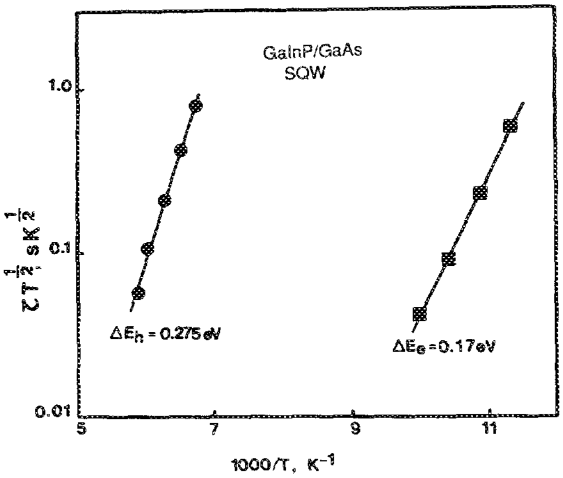

FIG. 3. Arrhenius plots corresponding to emission of electrons and holes from quantum wells.

Our main objective is to estimate the band offsets ΔE_c and ΔE_v from the DLTS measurements. The band offset is the sum of the thermal emission energy, the subband energy, and the band bending in the well due to the applied bias. There are obvious sources of error in this simple assumption, the principal ones being the spread in the subband energies and the excess energy of carriers above the barrier during emission, or reduced energy due to tunneling. The values of ΔE_c and ΔE_v derived from this simple formulation are 0.198 and 0.285 eV, respectively. Also, $\Delta E_c + \Delta E_v = \Delta E_g \simeq 0.48$ eV, which agrees well with the measured value from photoluminescence. The values of ΔE_c and ΔE_v estimated in this study also agree reasonably well with the measured values reported by Watanabe and Ohta.[5] Disorder at the quantum well heterointerfaces and trapped charge in these regions can give rise to errors. However, using identical growth techniques, modulation-doped heterostructures with $\mu = 780\,000$ cm^2/V s (under illumination) have been produced. Also, interface states usually give a broad background signal in the DLTS temperature scan, which was also absent in our data.

In conclusion, we have measured the band offsets ΔE_c and ΔE_v for the GaAs/$Ga_{0.51}In_{0.49}P$ heterostructure by doing DLTS measurements on properly designed single quantum well structures. The estimated values of ΔE_c and ΔE_v are 0.198 and 0.285 eV, respectively.

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