Phonon assisted tunneling in lattice-matched and pseudomorphic resonant tunneling diodes

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(Received 13 September 1989; accepted 15 November 1989)

MBE grown resonant tunneling diodes based on the lattice matched AlAs/GaAs and the pseudomorphic AlGaAs/InGaAs systems are investigated. In the presence of quantizing magnetic field, a large number of tunneling peaks in the valley region of the current–voltage curves are observed. The dependence of the peak positions on magnetic field is used to distinguish direct tunneling between Landau levels from that due to phonon assisted tunneling. Shubnikov de-Haas measurements show the evidence of a two-dimensional quasibound state in the accumulation layer of the emitter and LO phonon assisted tunneling through the Landau levels in the well.

I. INTRODUCTION

Resonant tunneling diodes (RTDs) have been widely studied because of their potential high speed device applications and their physical interest.[1,2] Considerable progress has been made in both fabrication and understanding the physics of RTDs with the advent of modern epitaxial growth techniques. In this paper we report on electrical and magnetic field studies of lattice matched RTDs based on AlAs/GaAs and pseudomorphic RTDs based on $Al_{0.4}Ga_{0.6}As/In_{0.1}Ga_{0.9}As$. All RTDs were grown by molecular beam epitaxy on silicon ($n = 2\times 10^{18}$ cm^{-3}) doped ⟨100⟩ GaAs substrates.

The lattice matched AlAs/GaAs RTD comprises the following layers, in order of growth from the $n+$ GaAs substrate: 1.0 μm of $n = 2\times 10^{18}$ cm^{-3} GaAs buffer layer, 250 Å of $n = 2\times 10^{18}$–1×10^{16} cm^{-3} linearly graded GaAs, 150 Å of undoped GaAs (referred to as the spacer layer), 35 Å undoped AlAs barrier, 85 Å undoped GaAs well, 35 Å undoped AlAs barrier, 150 Å of undoped GaAs spacer layer, 250 Å of $n = 1\times 10^{16}$–2×10^{18} cm^{-3} linearly graded GaAs layer and 0.5 μm of $n = 2\times 10^{18}$ cm^{-3} GaAs top contact.

The pseudomorphic RTD consists of the following layers, in order of growth from the $n+$ GaAs substrate: 1.0 μm of $n = 2\times 10^{18}$ cm^{-3} GaAs buffer layer, 500 Å of undoped GaAs spacer, 85 Å of $Al_{0.4}Ga_{0.6}As$ barrier, 50 Å of undoped $In_{0.1}Ga_{0.9}As$ well, 85 Å of undoped $Al_{0.4}Ga_{0.6}As$ barrier, 500 Å of undoped GaAs spacer and 0.4 μm of $n = 2\times 10^{18}$ cm^{-3} top contact layer.

After epitaxial growth of the structures described above, the bottom Ohmic contact area was etched and Ni/Au–Ge/Au Ohmic contacts which serve as an etching mask, were made for the top and bottom contacts. Mesas were etched using a solution of $NH_4OH(1) + H_2O_2(1) + H_2O(5)$ followed by SiO_2 deposition for device passivation using the plasma enhanced chemical vapor deposition (PECVD). The Ohmic contact area under SiO_2 was etched and Ti/Au were evaporated for bonding pads. Finally the RTDs were mechanically diced and wire bonded in an IC package for measurement.

II. LATTICE-MATCHED AlAs/GaAs RTD

A. *I–V* characteristics

Typical current-voltage (*I–V*) characteristics of the AlAs/GaAs RTD measured at 1.8 K are shown in Fig. 1. The device size used for the measurements is 16×16 μm^2. The dashed and the solid lines are the *I–V* curves when the magnetic field perpendicular to the barrier is 0 and 8 T, respectively. The peak to valley current ratio (PVCR) of the RTD at 1.8 K is 10.8 and 11.2:1 without and with ($B = 8$ T) magnetic field, respectively. The inset of the Fig. 1 shows the forward (top side is biased negatively with respect to sub-

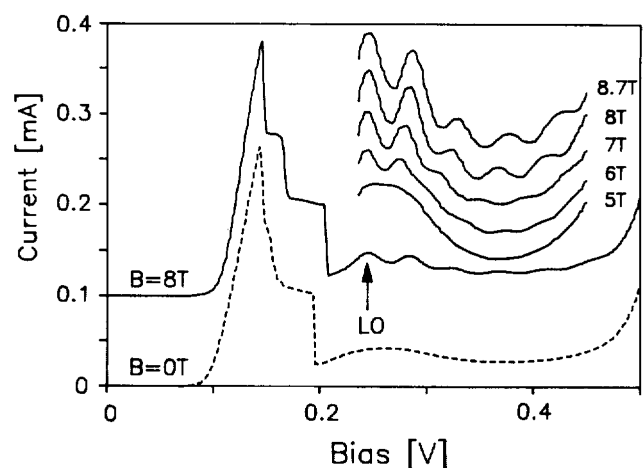

FIG 1. *I–V* characteristics of the AlAs/GaAs RTD at 1.8 K. The solid and the dashed lines are for $B = 8$ ($B \parallel J$) and 0 field, respectively. The inset figure shows the valley region of the *I–V* curve at different magnetic fields ($B \parallel J$).

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strate side) I–V characteristics of the RTD in the valley region under different magnetic fields.

The RTD exhibits a main resonant peak (V_p) at 144 mV and a first subsidiary peak marked as LO at 245 mV. Goldman *et al.*[3] have attributed this subsidiary peak to tunneling assisted by LO phonon emission. The phonon related peak and the valley current due to inelastic scattering are revealed more clearly by applying a magnetic field B perpendicular to the barrier ($B \| J$) as shown in the inset of the Fig. 1. The LO phonon related first subsidiary peak after the main resonance splits into two peaks as the applied magnetic field becomes > 6 T. The first subsidiary peak does not shift while the other peaks move to higher bias as the magnetic field increases.

The application of a magnetic field perpendicular to the barrier quantizes the energies of electrons in the quantum well and in the accumulation layer. The energy levels in the accumulation layer (E_a) and the quantum well (E_q) in an applied magnetic field are given by

$$E_a = \hbar eB/m^*(n + 1/2) + E_{a0},$$

$$E_q = \hbar eB/m^*(s + 1/2) + E_{q0},$$

where m^* is an effective mass and n and s are the Landau level indices in the accumulation layer and the quantum well, respectively. E_{a0} and E_{q0} are the quantized energy in the accumulation layer and the quantum well without magnetic field. The energy selection rule for tunneling is $E_a = E_q\ (+\hbar\omega_L)$ and the conservation of $k_\perp$ momentum for $B = 0$ corresponds to Landau level indices $n = s$ in the presence of the quantizing magnetic field. The $\hbar\omega_L$ in the parenthesis allows for transitions in which $k_\perp$ is not conserved ($n \neq s$). The $\hbar\omega_L$ can correspond either to an LO phonon or an acoustic phonon emission.

The fan chart of the Fig. 2 shows the evolution of the measured magneto-quantum peaks in the presence of the quantizing magnetic field. Electron transitions in the presence of the magnetic field with LO phonon emission is given by

$$\Delta N \times B = [\Delta E - \hbar\omega_L]m^*/\hbar e,$$

where $\Delta N = (s - n)$, $\Delta E = (E_{a0} - E_{q0})$ and rest of the symbols have the same meaning as before. The squares and the triangles are the maximum ($\Delta N =$ integer) and the minimum ($\Delta N =$ half-integer) of the magneto-quantum peaks, respectively and the solid lines are the results of the least-square fit of these peaks. The extrapolation of the least square fit intersects the bias point at 245 mV marked as LO in Fig. 1. Thus, we interpret the magneto-quantum peaks in the valley region of the I–V curve as a result of a tunneling current through different Landau levels ($\Delta N = 1,2,3,4$) with the GaAs LO phonon emission.

The inset of Fig. 2 is a plot of the slope of the least square fit as a function of Landau level index, ΔN. The slope of the inset figure is 5.07 meV/T which corresponds to $\hbar e/m^*\alpha$, where α is the relative voltage drop between the lowest bound state in accumulation layer of the emitter and the half-well width. We obtain α of 0.34 when the device is biased in the valley region of the I–V curve. The voltage difference between the main and the LO phonon satellite peak is 101 mV so the phonon energy measured is 101 mV$\times$0.34 = 34.3 meV which is in good agreement with the LO phonon energy of GaAs, 36.25 meV.[4] We assumed the effective mass of GaAs, $m^* = 0.067$ in our analysis which is different from the value of 0.063 ± 0.002 of Mendez *et al.*[5] or 0.07 of Goldman *et al.*[6]

B. Shubnikov-de Hass measurement

Figure 3 is the differential conductance of the RTD at a fixed bias as a function of the magnetic field ($B \| J$). The sample does not show strong magneto-oscillations when biased before resonance. The three sets of oscillations shown in this figure are taken in the valley region of the I–V curve. The magneto-oscillations at each bias show more than one period in $1/B$. The periodicity in $1/B$ is conventionally defined in

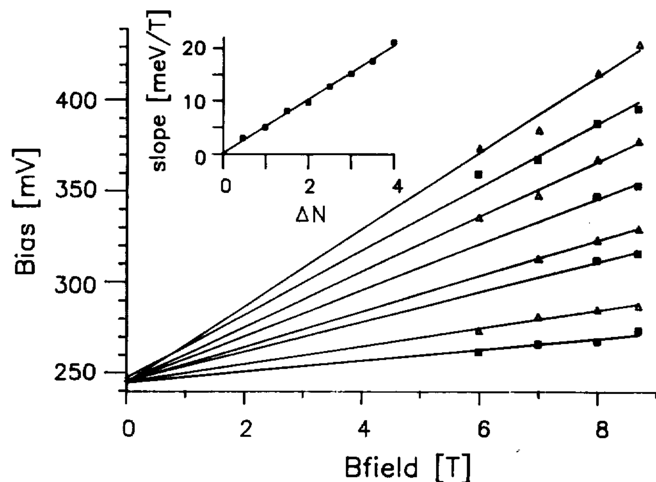

FIG. 2. Evolution of the magneto-quantum peaks as a function of applied magnetic field ($B \| J$). The squares and the triangles correspond to the maximum and minimum of the magneto-quantum peaks, respectively. The inset figure is a result of the slope of the least square fit as a function of Landau level indices.

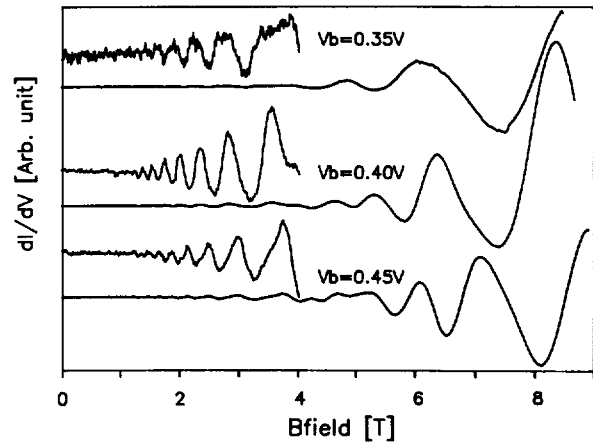

FIG. 3. Differential conductance of the AlAs/GaAs RTD as a function of magnetic field ($B \| J$) at $V_{bias} = 0.35, 0.40, 0.45$ V. The inset figures are the magnified differential conductance at low magnetic field.

terms of a fundamental field, $B_f = [\Delta(1/B)]^{-1}$. The lower series of B_f's are $\simeq 13$–16 T (for B below $\simeq 4$ T) while the higher are $\simeq 30$–45 T (for B above $\simeq 5$ T) for applied biases of 0.35, 0.4, and 0.45 V.

The multiple periodicity in magneto-quantum oscillation was also reported with 1000 Å thick spacer layers adjacent to the (AlIn)As barriers on lattice matched InP substrate.[7] They interpret the multiple periodicity as due to two occupied 2D bound state in the emitter accumulation layer and transition between two quasibound states in the well with LO phonon emission.

We assume a single quasibound state in the accumulation layer of the emitter considering the different oscillation features from theirs. The oscillations in Ref. 7 seem to be a combination of multiple periods while this paper presents a clear separation between the low and the high periods. The B_f below $B \approx 4$ T is small and above $B \approx 5$ T is large with some transition regions.

The lower series of B_f's are believed to be a result of the Fermi energy of the emitter side passing through the Landau levels of the quasibound state of the emitter. The higher series of B_f's are due to the electrons tunneling into a Landau level in the well and scattering into another Landau level with a LO phonon emission. The lower series of B_f's ranging from 13 to 16 T gives the equivalent 3D density of $5–7 \times 10^{17}$ cm^{-3} which agrees reasonably with the emitter doping concentration.

III. PSEUDOMORPHIC $Al_{0.4}Ga_{0.6}As/In_{0.1}Ga_{0.9}As$ RTD

A. *I–V* characteristics

Figure 4 is the *I–V* characteristics of the pseudomorphic RTD measured at 1.8 K for $B = 8$ T (—) and 0 (- -) field. The size of the device is 50×50 μm^2. It is interesting to compare the *I–V* characteristics of the pseudomorphic RTD with the lattice matched AlAs/GaAs RTD discussed previously. Similar trends are observed such as the enhancement of the PVCR at higher magnetic field and the existence of an LO phonon satellite peak in the valley region of the *I–V* curve which also enhances its peak height with increased magnetic field. In the pseudomorphic case however, no additional peaks in the valley region of the *I–V* curve were observed up to 8.5 T.

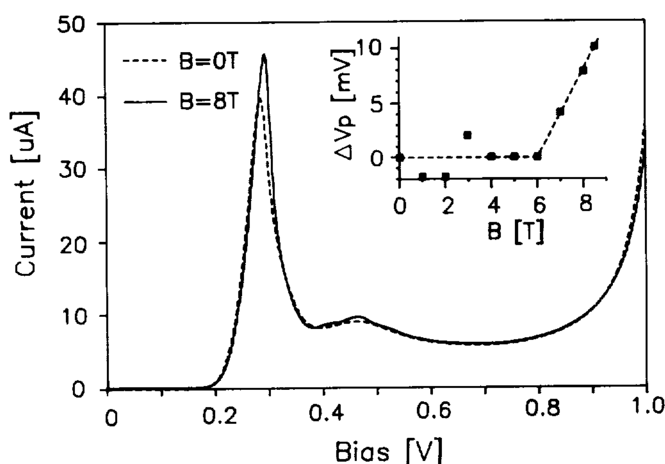

FIG. 4. *I–V* characteristics of the pseudomorphic $Al_{0.4}Ga_{0.6}As/In_{0.1}Ga_{0.9}As$ RTD at 1.8 K. The solid and the dashed lines are for $B = 8$ ($B \| J$) and 0 field, respectively. The inset figure shows the change of the main resonance peak as a function of magnetic field.

The PVCR's of the RTD is 8:1 and 7:1 at 8 T and 0 field, respectively. The magnetic field applied perpendicular to the barrier gives rise to sharp peaks in the density of states. The sharp density of states increases the electron population in the well at resonance and in the accumulation layer of the emitter off resonance.[8] This explains the enhancement of the PVCR and LO phonon satellite peak under magnetic field. The same phenomenon was also reported by Eaves *et al.*[9]

The occurrence of no additional subsidiary peaks except the LO phonon peak in the valley region of the *I–V* curve is believed to be due to the presence of the InGaAs in the well. InGaAs grown on GaAs substrates tends to increase scattering due to surface segregation and the evaporation of indium[10] which enhances the interface roughness and the random alloy scattering. Scattering in the InGaAs well makes the mean free path of an electron smaller than the cyclotron orbital length, which makes the energy separation between the Landau levels in the InGaAs well unresolvable. Thus there are no additional peaks present even at 8 T.

The separation in bias voltage between the V_p and the LO phonon peak is 167 mV and LO phonon energy of the $In_{0.1}Ga_{0.9}As$ is 36 meV.[11] Thus the relative voltage drop between the lowest bound state in accumulation layer of the emitter and the half-well width α is 0.22. The smaller α of this device compared to the previous lattice matched AlAs/GaAs RTD is due to the much wider spacer and barrier thicknesses causing a smaller portion of the applied voltage to drop across the two layers.

The nonlinear behavior of the V_p shift and stationary behavior of the LO phonon satellite peak as a function of magnetic field are observed in both samples. The main resonance peak changes nonlinearly while the LO phonon peak does not change with the magnetic field applied perpendicular to the barrier. The inset of Fig. 4 shows the main resonance peak change of the pseudomorphic $Al_{0.4}Ga_{0.6}As/In_{0.1}Ga_{0.9}As$ RTD as a function of the magnetic field. The closed squares are the measured values of ΔV_p $[= V_p(B) - V_p(0)]$ and the dashed line is a result of two step piecewise linear approximation. The ΔV_p of the pseudomorphic $Al_{0.4}Ga_{0.6}As/In_{0.1}Ga_{0.9}As$ RTD increases linearly above 6 T and shows oscillatory behavior below 6 T. The similar behavior was also observed in the lattice matched AlAs/GaAs RTD. The interesting behavior of the ΔV_p and LO phonon peak as a function of magnetic field is not well understood yet.

B. Shubnikov-de Hass measurement

Magneto-quantum oscillations of the pseudomorphic $Al_{0.4}Ga_{0.6}As/In_{0.1}Ga_{0.9}As$ RTD at the three different biases are shown in Fig. 5. The oscillations are taken the same way as the lattice matched AlAs/GaAs RTD described previously.

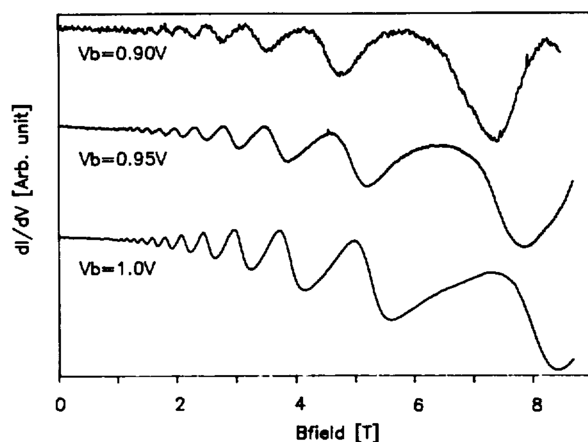

FIG. 5. Differential conductance of the pseudomorphic $Al_{0.4}Ga_{0.6}As$/$In_{0.1}Ga_{0.9}As$ RTD as a function of magnetic field ($B \| J$) at V_{bias} = 0.90, 0.95, 1.0 V.

The oscillation shows a single period in $1/B$ and B_f's are 13.2, 14.3, and 16.2 T for applied biases of 0.90, 0.95, and 1.0 V. The oscillations are due to the Fermi level of the emitter contact passing through the Landau levels of the accumulation layer of the emitter side. We interpret these oscillations are the evidence of a two-dimensional quasibound state in the accumulation layer of the emitter.

The oscillation periods which are comparable to those of the AlAs/GaAs RTD suggest that the doping concentration at the emitter contact of the two RTDs are comparable which is consistent with the device parameters. The increased scattering in the InGaAs well broadens the density of state and makes the energy separation between the Landau levels unresolvable. Thus the LO phonon assisted tunneling features in magneto-quantum oscillations are suppressed.

IV. CONCLUSIONS

Electric and magnetic field study of the lattice matched AlAs/GaAs and the pseudomorphic $Al_{0.4}Ga_{0.6}As$/$In_{0.1}Ga_{0.9}As$ RTDs grown by molecular beam epitaxy are presented. The I–V curve of the valley region in the presence of the quantizing magnetic field ($B \| J$), show a large number of tunneling peaks which can be distinguish tunneling between Landau levels from those due to phonon assisted tunneling. The former changes its peak position while the latter does not as a function of a magnetic field.

Shubnikov-de Haas measurements show the evidence of a two-dimensional quasibound state in the accumulation layer of the emitter and LO phonon assisted tunneling through the Landau levels in the well.

ACKNOWLEDGMENTS

Some of the authors (H.M.Y., S.M.G., and J.R.A.) thank J. Ebner and J. Lary for discussions related to the work and S.B. Kim for deposition of the PECVD oxide. We acknowledge partial support from ONR Contract No. N00014-89-J-1894.

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