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Phonon Assisted Tunneling and P/V-Ratio in a Magnetic Confined Quasi 0D InGaAs/InAlAs Resonant Tunneling Diode

Christoph WIRNER*, Yuji AWANO, Toshiro FUTATSUGI† and Naoki YOKOYAMA
Fujitsu Ltd., Fujitsu Laboratories Ltd.† 10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-01, Japan
Tadashi NAKAGAWA and Hiroshi BANDO
Electrotechnical Laboratory, Tsukuba, Ibaraki 305, Japan
Shunichi MUTO
Hokkaido University, Faculty of Engineering, Sapporo, Japan

We studied phonon assisted tunneling and P/V-ratio of magnetic confined "dot-like" electron systems in an InGaAs/InAlAs triple barrier resonant tunneling diode. We clearly observe phonon bottleneck effects, i.e. suppression of the phonon assisted valley current and two mode narrow band GaAs- and AlAs-like LO-phonon assisted tunneling peaks. In addition, we measure very weak peaks at the InAs-LO-phonon energy at intermediate magnetic fields. The P/V-ratio increases to high values with increasing magnetic confinement having maxima each time a multiple Landau-level spacing matches the LO-phonon energy.

KEYWORDS: Resonant tunneling diode, zero dimensional electron gas, phonon relaxation

1. Introduction

Tunnel devices based on the quantum mechanical tunneling effect have attracted much interest since the invention of the tunneling diode by Esaki in 1958[1]. In 1985 Yokoyama et al.[2] proposed a hot electron transistor where electrons are injected through a resonant tunneling barrier (RHET). The high functionality of the RHET makes the device a promising candidate for application in ultra large scale integrated circuits[3]. An important issue is to increase the peak-to-valley ratio (P/V-ratio) of the resonant tunneling current.

In this paper we investigate the feasibility to improve the P/V-ratio by confining the electrons to quantum dot systems. Theory predicts that in a quantum dot inelastic phonon scattering is suppressed due to the discreteness of the atom-like dot density of states[4]. LO-phonon relaxation is restricted to a narrow energy regime where the subband energy difference exactly matches the LO-phonon energy [5]. Both effects are called phonon bottleneck effect[6]. In a tunneling device composed of quantum dot systems the phonon bottleneck effect may suppress the non resonant valley tunneling current hence increasing the P/V-ratio. Confinement of the electrons by a magnetic field in direction of the tunneling current is an elegant experimental tool to study electron tunneling in the transition regime from a two-dimensional to a magnetic confined dot-like system with so called Landau-energy states[7,8,9].

2. Experimental results

The InGaAs/InAlAs triple barrier tunneling diode used in the experiments is shown in Figure 1. It isgrown by molecular beam epitaxy. On an InP substrate an n-type InGaAs layer($N_D=2\cdot10^{18}cm^{-3}$), an undoped InGaAs layer (300Å), an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ triple barrier structure having a center InAlAs barrier of 80Å, InGaAs wells of 100Å and end barriers of 40Å, an undoped InGaAs layer (50Å) and an n-type InGaAs toplayer ($N_D=2\cdot10^{18}cm^{-3}$) are successively grown.

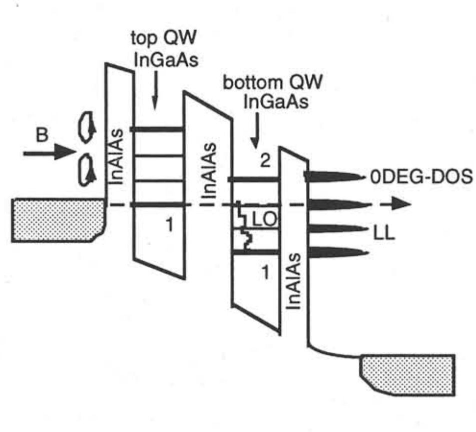

Figure 1
Conduction band of the InGaAs/InAlAs triple barrier tunneling diode. A magnetic field in direction of the tunneling current creates "dot-like" Landau-Level states.

Figure 2 shows the valley current of the triple barrier diode at injection energies between the first (1-1 resonance) and the second (1-2 resonance) energy level of the bottom quantum well (T=300mK). At zero magnetic field the valley current exhibits a maximum at 190mV and a broad band tail extending to the 1-2 resonance. By applying a magnetic field the valley current changes and narrow tunnel peaks appear increasing strongly in intensity at magnetic fields higher than 3T. The remarkable feature is the decrease of the valley current between the 1-1 resonance peak and the peak at 190mV at high magnetic field.

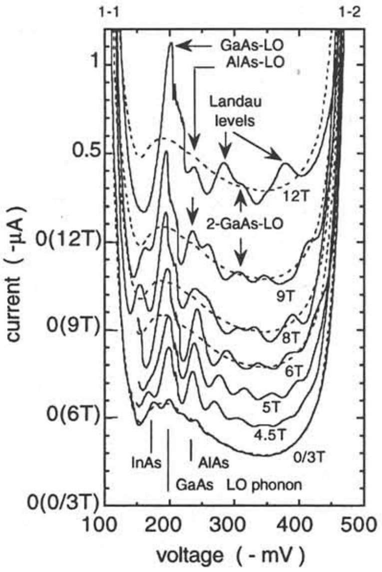

Figure 2
Tunneling current of the InGaAs/InAlAs triple barrier resonant tunneling diode as a function of applied voltage for various magnetic fields recorded at 300mK.

Figure 3 shows the position of the measured tunneling peaks as a function of the applied magnetic field. Peaks fanning out with linear dispersion from the 1-1 resonance correspond to tunneling through the Landau-level states. By comparing the theoretical Landau-spacing (solid lines) to the experimental data (closed circles) we obtain a relation between the external applied voltage ΔV and the energy difference between the two quantum wells ΔE:

$$\Delta E\,[\text{meV}] = 0.38 \cdot \Delta V\,[\text{mV}] \qquad (1)$$

Using equation (1) the two dispersionless peaks at voltages 190mV and 225mV are assigned to GaAs-like (36.6±0.5 meV) and AlAs-like (47.5±0.5 meV) LO-phonon assisted tunneling in excellent agreement with literature data[10]. The dispersionless peak at a voltage of 300mV is then attributed to tunneling involving emission of two GaAs-like LO-phonons. Each LO-phonon peak is the origin of a new series of peaks corresponding to LO-phonon assisted tunneling accompanied by a change in the Landau quantum number. In addition we observe peaks fanning out with negative dispersion from the GaAs-like LO-phonon peak becoming dispersionless at intermediate magnetic fields of around 4T and disappearing at higher magnetic fields (Double arrow in Figure 3). The peaks at 4T correspond to an energy of 30.5±0.5 meV which agrees well with the InAs-LO-phonon energy[10]. Accordingly we attribute the peak to InAs-like LO-phonon assisted tunneling. At the maximum available field of 12 Tesla the Landau-level energy spacing equals the GaAs-LO phonon energy. All peaks at this magnetic field are related to LO-phonon assisted tunneling.

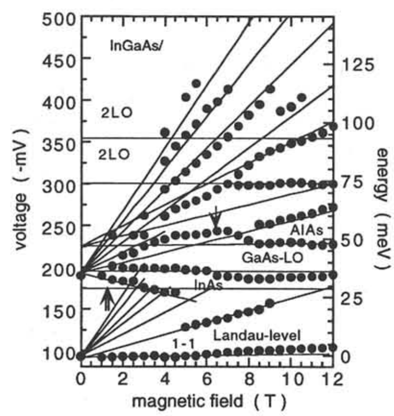

Figure 3
Peak position and energy difference relative to the 1-1 resonance peak as a function of the applied magnetic field.

3. Discussion

The results show significant changes of the tunneling characteristics in magnetic confined dot systems. Narrow band GaAs-like LO-phonon assisted tunneling is dominant with peak heights increasing continuously with increasing magnetic field. We attribute the relative weakness of the AlAs-like LO-phonon peak to the small overlap of the electronic wave functions in the InAlAs tunneling barrier. At intermediate magnetic fields electrons tunnel more likely via GaAs-LO-phonon assisted inter Landau-level tunneling in the wells than via AlAs-LO-phonon assisted tunneling in the barriers resulting in deviations of the peaks at the AlAs-LO phonon energy (arrow in Figure 3).

InAs-LO-phonon relaxation could so far only be detected in photoluminescence experiments[11]. The small scattering probability is explained by the weak electrostatic coupling of the electrons prefering the phonon mode with higher energy[12]. In our experiment the weak peaks at intermediate magnetic fields (double arrow in Figure 3) might be related to InAs-LO-phonon assisted tunneling. The results agree with photoluminescence experiments by Skolnick et al. who could resolve InAs-LO phonon relaxation only at magnetic fieldsd of around 4T[13]. At this field Landau-level energy spacing exactly matches the energy difference between the GaAs- and the InAs-LO-phonon energy. However, further experiments have to be carried out in order to exclude effects of carrier injection from higher energy Landau states in the injection quantum well resulting in the branch with negative dispersion.

Figure 4(a) shows the valley current between the 1-1 resonance peak and the LO-phonon peak as a function of the applied magnetic field. It continously decreases with increasing magnetic field having minima each time a multiple Landau-level spacing matches the GaAs-LO-phonon energy. In this case the discreteness of the system is maximal resulting in maximum phonon bottleneck effect. Corresponding maxima are found in the peak-to-valley ratio of the 1-1 resonance peak displayed in Figure 4(b). The value of the peak-to-valley ratio at the highest magnetic field of 12T is more than twice the zero magnetic field value. The results indicate that for achieving an optimum P/V-ratio the subband energy spacing in a quasi zero dimensional tunneling diode should be designed in resonance with the GaAs-LO phonon energy.

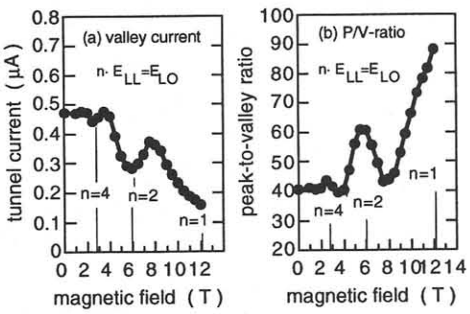

Figure 4
(a) Valley current between the 1-1 resonance peak and the GaAs-LO-phonon peak as a function of the applied magnetic field, (b) Peak-to-valley ratio of the 1-1 resonance peak as a function of the applied magnetic field. (n=n-th Landau-Level in resonance with the GaAs-LO-phonon energy)

4. Conclusion

In conclusion we have investigated phonon assisted tunneling and peak-to-valley ratio of magnetic confined quasi zero dimensional electron systems in an InGaAs/InAlAs triple barrier resonant tunneling diode. We observe clear phonon bottleneck effects i.e. significant reduction of the phonon assisted valley current and narrow band GaAs- and AlAs-like LO-phonon assisted tunneling peaks. While GaAs-LO phonon relaxation is dominant, InAs-LO-phonon assisted tunneling might be detected only at intermediate magnetic fields. The P/V-ratio increases with increasing magnetic confinement having maxima each time a multiple Landau-level spacing matches the LO-phonon energy.

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*NEDO Industrial Technology Researcher

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