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Resonant Tunneling Electron Dynamics in Semiconductor Heterostructures

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This paper reports an experimental investigation of resonant tunneling (RT) electron dynamics in semiconductor heterostructures. We first estimate the resonance state lifetime from the peak width of the transmission coefficient measured for RT diodes. The RT transit time across double-barrier structures is then studied in terms of cutoff frequency of quantum-well-base RT transistors. Comparing these times to theoretical predictions, we confirm that RT times in real systems are reasonably well described by theoretical models of the ideal system.

1. Introduction

The resonant tunneling (RT) effect is attracting increasing attention because of its potential to play a key role in future nanoscale semiconductor devices.[1), 2), 3)] To clarify the intrinsic response time of these devices, it is necessary to answer the fundamental question: How long does it take for an electron to tunnel through the double-barrier structure?

A simple theoretical approach is to introduce the resonant state lifetime τ_{life} (i. e., the escape time for an electron from the well) determined by the energy level width Γ:

$$\tau_{life} = \frac{\hbar}{\Gamma}. \qquad (1)$$

In addition, when an electron is incident on a double-barrier (DB) structure, one should consider the build-up process of electron wave in the well. Various theoretical models have been proposed up to now, and it is difficult to choose the one that best describes tunneling dynamics in general. On the other hand, no contradictions seem to exist for resonant tunneling in an ideal system[4), 5)] where double-barriers are symmetric, interfaces are atomically flat, and no inelastic scatterings exist. The RT transit time is then

$$\tau_{trans} \approx \frac{2\hbar}{\Gamma} = 2\,\tau_{life}. \qquad (2)$$

This has been a useful guideline for designing high-speed RT devices. However, since real semiconductor heterostructures are probably not nearly as simple as the ideal system because of barrier asymmetricity induced by bias voltages, interface roughness and inelastic scatterings, experimental studies are required to clarify how much we can rely on theoretical predictions.

The first experimental approach was performed by Tsuchiya *et al.*[6)] They estimated the tunneling escape rate from the time-resolved photoluminescence (PL) measurement and showed a good agreement with Eq. (1). Although this study and several experiments which followed using ultra-short laser pulses have revealed some significant aspects of RT dynamics, they are mainly concerned with electrons flowing from the 2D to 3D states or between the 2D states. It seems difficult to observe the build-up process from the 3D emitter to the 2D well, which would critically influence high-frequency performance of RT diodes and transistors. It is thus desirable to analyze RT dynamics in these devices in terms of their electrical characteristics. In addition to the CR-type equivalent circuit usually used,[3), 7)] Brown *et al.*[8)] proposed quantum inductance to represent current delay due to the build-up and escape processes. However, the time delay due to RT is not fully understood yet. Moreover, how to incorporate the quantum effect into classical parasitic effects needs to be clarified.

In this paper, we will first describe the resonance state lifetime estimated from the transmission coefficient for RT diodes. This is an alternative to the time-resolved PL measurement. The RT transit time will then be discussed in terms of the RT current response to high-frequency modulation applied directly to a quantum-well potential. We have successfully realized the thought experiment by fabricating RT transistors with a quantum-well base. These times will be compared with theoretical predictions.

2. Resonance Level Width and Lifetime

The resonance state lifetime is related to the energy level width as shown in Eq.(1). If it is possible to measure the resonance transmission coefficient, one can estimate the lifetime. We derived the lifetime by employing the method introduced by Tsuchiya and Sakaki[9)] for evaluating the coefficient. The coefficient is obtained from the second derivative d^2I/dV^2 as follows:

$$TT^*(E) = \frac{1}{\gamma^2}\frac{2\pi^2\hbar^3}{e^3m^*}\frac{d^2I}{dV^2} \text{ and } E = E_F + \gamma eV. \quad (3)$$

Here, γ is the ratio of the applied voltage to the potential difference between the emitter and the quantum well, and assumed to be 0.5. Figure 1 shows the transmission coefficients obtained for an AlAs (4 nm) / GaAs (7 nm) /

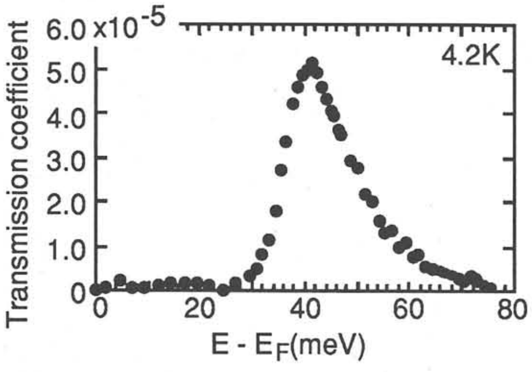

Fig. 1 The transmission coefficients of a double-barrier structure of AlAs(4 nm)/GaAs(7 nm)/AlAs(4 nm) at 4.2 K.

AlAs (4 nm) DB structure. By successfully reproducing the original I-V characteristics with the Tsu-Esaki formula, we have confirmed that TT* thus obtained is appropriate.[10] This leads us to apply measured TT* to the lifetime estimation.

According to Stone and Lee[11], the transmission coefficient in the presence of inelastic scattering is

$$TT^* \cong \left(\frac{\Gamma_e}{\Gamma_i}\right) \frac{\left(\frac{\Gamma_i}{2}\right)^2}{(E - E_r)^2 + \left(\frac{\Gamma_i}{2}\right)^2}, \qquad (4)$$

if $\Gamma_i >> \Gamma_e$. Here, Γ_e and Γ_i are elastic (intrinsic) and inelastic resonance widths, respectively. By fitting this equation to the obtained TT* profile, we obtained the ratio Γ_e/Γ_i of 5×10^{-5} and Γ_i of 16 meV. The intrinsic resonance width Γ_e was then calculated to be 0.8 μeV. The lifetime is thus estimated as

$$\tau_{life}^{exp} = \frac{\hbar}{\Gamma_e} \cong 0.7 \text{ ns.} \qquad (5)$$

This is close to the calculated lifetime of 0.3 ns using Eq. (1). Tewordt *et al.* [12] estimated the lifetime in a similar manner, but they confined tunneling electrons to quasi-1D structures. The present estimation is suitable for commonly used diode structures.

3. Resonant Tunneling Transit Time

The basic idea of estimating the RT transit time across the DB structure is schematically shown in Fig. 2. We fabricated a transistor with a quantum-well base, applied high-frequency modulation ω to the base potential and observed the response of the collector current I_C.[13] The transistor structure we used (Fig. 3) is similar to conventional HBTs except for the quantum-well base. Two types of quantum-wells were used as the base: a single-QW (SQW) of 2-nm AlAs barriers and a 15-nm GaAs well and a coupled-QWs (CQW) with extra 1-nm inner barriers dividing the well into three 5-nm wells. Every well was δ-doped with Be, which allowed the alloy-type base ohmic contacts to directly control the QW-base potential.

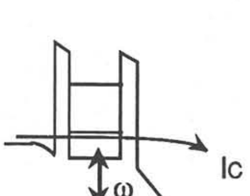

Fig.2
Schematic showing the measurement principle.

Fig. 4 shows the collector current as a function of the base-emitter voltage. Resonance peaks corresponding to the energy states in the QW-base were clearly observed.[14] Two peaks in the SQW-base transistor indicate the RT current through the first (n = 2) and second (n = 3) excited states. Resonant tunneling via the ground state (n = 1) was not observed because the state was below the conduction band edge of the wide-gap emitter. For the CQW-base transistor, the current peaks corresponding to the three states (n = 1, 2, 3) could not be resolved, but one single peak was observed. These peak structures clearly indicate that the collector current is the RT current flowing through the resonance states and that it is controlled by the base-emitter voltage.

We assumed that the RT transit time causes the signal delay time as follows:

$$\frac{I_{nc}}{I_{ne}} = \frac{\alpha_0}{1 + j\omega\tau_{RT}}. \qquad (6)$$

Here, I_{ne} and I_{nc} are ac-current amplitudes respectively flowing into and out of the quantum-well base, α_0 is the base transport efficiency, j is the imaginary unit and τ_{RT}

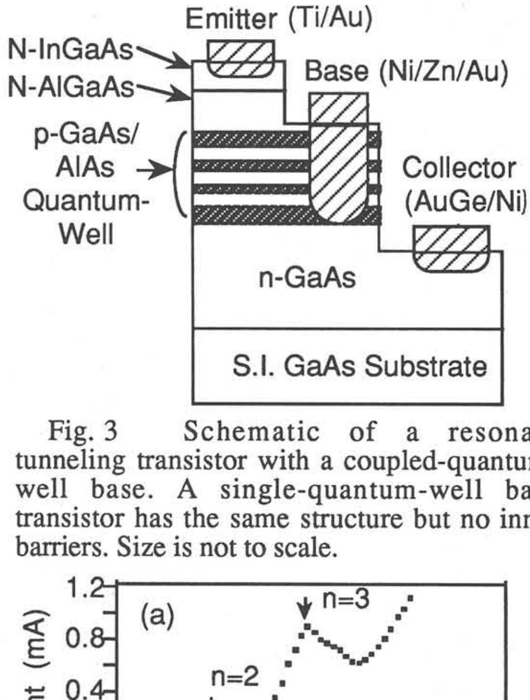

Fig. 3 Schematic of a resonant tunneling transistor with a coupled-quantum-well base. A single-quantum-well base transistor has the same structure but no inner barriers. Size is not to scale.

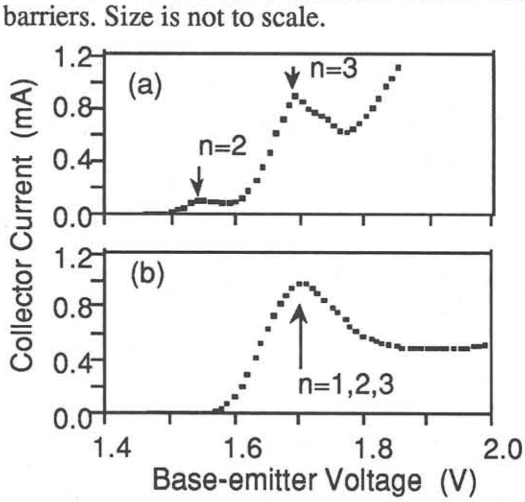

Fig. 4 Resonance peaks observed in collector currents at 77 K in resonant tunneling transistors with (a) a single-quantum-well base and (b) a coupled-quantum-well base. The emitter is 1×10 μm^2.

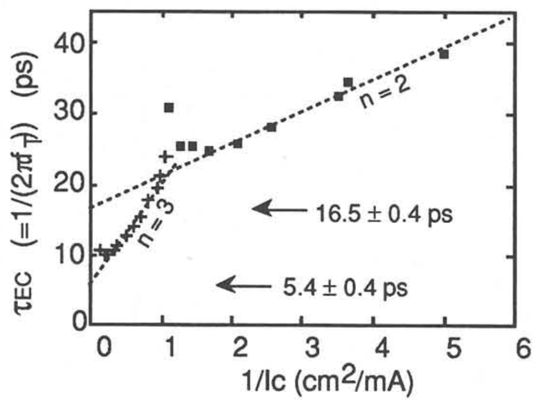

Fig. 5 The total signal delay for the collector currents flowing through the n = 2 and 3 resonance states in the SQW-base transistor.

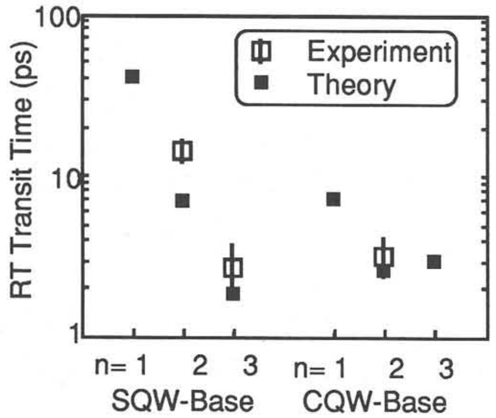

Fig. 6 Experimentally derived RT transit times with theoretical predictions.

is the delay time due to resonant tunneling. It should be noted that τ_{RT} corresponds to base transit time due to diffusion and/or drift in conventional bipolar transistors. The cutoff frequency f_T giving the unity current gain in the common-emitter configuration is then obtained by a similar procedure to conventional transistors[15] as

$$\frac{1}{2\pi f_T} = \tau_{EC} = \tau_{RT} + \tau_e + \tau_c + \tau_{cc}, \qquad (7)$$

where τ_{EC} is the total signal delay time from the emitter to the collector, and τ_e, τ_c and τ_{cc} are the emitter charging time, the collector depletion layer transit time and the collector capacitance charging time, respectively. If f_T, τ_e, τ_c and τ_{cc} are measured, then we are able to derive the resonant tunneling transit time τ_{RT}.

The current gain β of these RT transistors for various frequencies was obtained from S parameter measurements. Cutoff-frequency f_T was then estimated from β. Fig. 5 shows the τ_{EC} (= $1/2\pi f_T$) dependence on the collector current obtained from the cutoff frequency of the SQW-base. To eliminate τ_e, we plotted τ_{EC} as a function of $1/I_C$, and extrapolated the plots to infinitely large collector current and obtained $\tau_{EC}{}^0$ (= τ_{EC} - τ_e = $\tau_{RT} + \tau_c + \tau_{cc}$). Two times of 16.5±0.4 ps and 5.4±0.4 ps were distinguished for two resonant states (n = 2 and 3) in the SQW-base. It should be noted that since the dc-bias conditions for these two resonances differ only in the base-emitter voltage by 0.17 V (see Fig. 4 (a)), they cause virtually no changes in τ_c and τ_{cc}. Therefore, the difference in $\tau_{EC}{}^0$ for the n = 2 and 3 states should reflect the transit time difference through these states.

We estimated τ_c and τ_{cc} by a similar technique usually employed to analyze HBT characteristics and subtracted them from $\tau_{EC}{}^0$.[13] Fig. 6 summarizes the estimated τ_{RT} and compares them with theoretical predictions based on the phase time model.[4] We used

$$\tau_{CAL} = \tau_{PH} + \frac{L_B}{v_g} \quad \text{and} \quad \tau_{PH} = \hbar\,\frac{d\phi}{dE} \approx \frac{2\hbar}{\Gamma}, \qquad (9)$$

where ϕ is the phase difference between incoming and outgoing electron waves calculated using the Schrödinger equation and L_b and v_g are the QW-base width and the electron group velocity. The agreement between theory and experiments is quite satisfactory.

4. Concluding Remarks

Resonant tunneling electron dynamics have been investigated from electrical characteristics of RT diodes and transistors. Our experimental study confirmed that the theoretical prediction describes the experimental results quite reasonably in spite of non-ideal factors such as inelastic scatterings and interface roughness, which are usually overlooked in simple theories. However, there still are small deviations, indicating the needs for further investigation to clarify the RT dynamics in real double-barrier structures.

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