Extended Abstracts of the 20th (1988 International) Conference on Solid State Devices and Materials, Tokyo, 1988, pp. 511-514 **S-IIIA-6**

Dependence of Sequential Resonant Tunneling Time on Barrier Thickness in AlAs/GaAs MQW Structures

Seigo Tarucha, Klaus Ploog*, and Fernando Miquel*

NTT Basic Research Laboratories, Musashino, Tokyo 180 Japan
* Max-Planck-Institut fur Festkorperforschung, Stuttgart 80, FRG

Tunneling time reduction induced by resonance of an electron between the ground state and first excited state in adjacent wells is studied for AlAs/GaAs multiple-quantum well structures with thin barriers ranging from 1.6 to 3.4 *nm*. The resonant tunneling times are experimentally determined using the time-resolved photocurrent measurement. These values compare favorably with those predicted by the theory of tunneling in a weakly coupled well under resonance. The theoretical calculation also predicts the significant influence of the monolayer fluctuation of barrier thickness on resonant tunneling time.

1. INTRODUCTION

Application of tunneling in quantum wells (QWs) to novel electrical devices is highly feasible because of nonlinear electric conduction. When an applied voltage (V_b) is equivalent to the energy difference between the ground state of an electron (1e) in one well and the excited state (2e, 3e, -) in the next well, electric conduction is enhanced by resonance.[1)] The resonance effect is manifested in the peaks in the cw photocurrent (PC)/voltage characteristics in multiple-quantum well structures (MQWS).[2-5)] We have recently studied time-resolved PC characteristics of AlAs/GaAs MQWS. We determined resonant tunneling (RT) times under resonance from 1e to 3e (1e-3e) and 4e (1e-4e) by analyzing the initial PC decay profile using the rate equation of electron transport for a complete RT sequence in the MQWS. Barrier thickness (L_B) is one of the most important resonance effect parameters because RT time is predicted to be strongly reduced by decreasing L_B according to the simple tunneling coefficient formula.[6)] In this paper we describe the L_B-dependence of RT time under 1e-2e resonance in AlAs/GaAs MQWS with thin barriers ranging from 1.6 to 3.4 *nm*. The time-resolved PC technique is employed to determine the RT times. We compare these RT times with those predicted by a weakly coupled well theory. The influence of monolayer fluctuation of L_B on RT time is also discussed.

2. EXPERIMENTAL

The samples are p-i-n heterostructure diodes grown by molecular beam epitaxy (MBE). The intrinsic region consists of 50-period AlAs (L_B) /GaAs (L_z) MQWS. The L_B and L_z values are listed in Table 1. L_B ranges from 1.6 to 3.4 *nm* while L_z is nearly constant between 12 and 14 *nm*. The diodes are processed into a high-mesa cylindrical geometry having a diameter of 120 μm. The dark current is less than 1 *nA* below 10 *V* at reverse bias. The cut-off frequency derived from the RC time constant is higher than 5 *GHz*. Details of the sample structures and experimental setup are the same as described previously.[4,5)]

Table 1

Sample	L_B (*nm*)	L_z (*nm*)
MQWS-1	*3.4*	*14.0*
MQWS-2	*2.2*	*12.3*
MQWS-3	*1.8*	*11.8*

3. RESULTS

3.1 cw PC/V_b

Figure 1 shows the cw PC/V_b measured under weak excitation by white light. MQWS-1 exhibits a large peak as indicated by the arrow. We assign the peak to 1e-2e resonance according to the analysis of the corresponding field. This peak is associated with quenching of excitonic recombination.[5] On the other hard, the resonance peak appears only slightly for MQWS-2 and 3 with the thinner barriers. Photoluminescence intensity, which is not shown here, is quenched at $V_b < -1$ V for these samples. These facts indicate that for MQWS-2 and 3, the carrier escape time due to tunneling is shorter than the recombination time, even under off-resonance at $V_b < -1$ V. However, the resonance effect is pronouncedly confirmed by the time-resolved PC measurements.

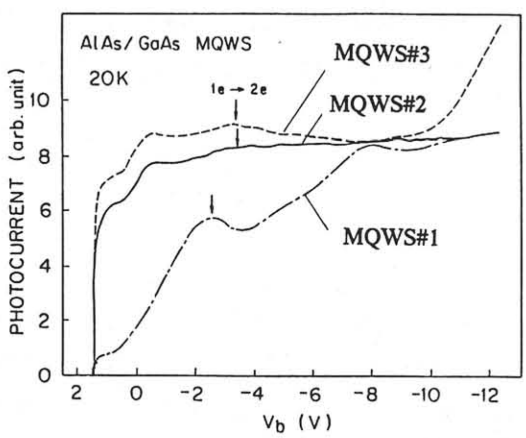

Fig. 1 --- cw PC / V_b characteristics for MQWS-1, 2, and3. The negative sign of V_b denotes the backward of the diode.

3.2 Time-resolved PC

In Figs. 2(a) and (b) we compare the time-resolved PC around V_b providing 1e-2e resonance between MQWS-1 and 2. The time-resolved PC exhibits a drastic increase of the initial decay component accompanied by a decrease of the decay time as V_b approaches the value providing 1e-2e resonance. Figure 3 shows the peak value of the time-resolved PC (PCM) as a function of V_b for MQWS-1, 2, and 3. The PCM is normalized by the maximum for each sample. The resonance-induced enhancement of PCM is even larger for MQWS-2 and 3 rather than for MQWS-1.

We determine the tunneling time τ_t under 1e-2e resonance by comparing the initial PC decay profile with the transient electron current calculated for a complete sequence of RT from 1e to 2e followed by back-relaxation to 1e as reported previously.[5] The calculated electron current to be compared with the initial PC decay profile is shown by the dotted line in Figs. 2 (a) and (b), where recombination time sufficiently longer than τ_t is assumed. The PC decay profiles under resonance are best reproduced by the calculation when τ_t = 550 ps for

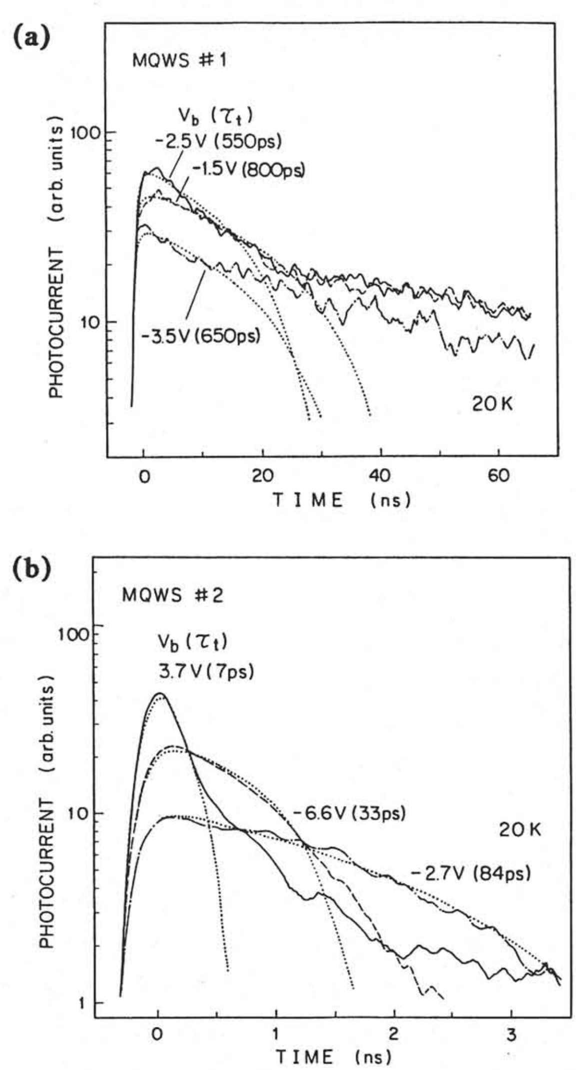

Fig. 2 --- Time-resolved PC for (a) MQWS-1 and (b) MQWS-2. 785-*nm* optical pulses of 200 *ps* duration are used for excitation. The dotted lines represent the calculated curves of electron current with tunneling time as a fitting parameter, which are convoluted with the time-resolved profile of the excitng pulse.

MQWS-1 and 7 *ps* for MQWS-2, respectively. Note that for MQWS-1 recombination cannot be neglected as mentioned previously.[5] Consideration of the recombination leads to uncertainty in the value of τ_t, which can range from 550 to 900*ps* for MQWS-1. τ_t Under resonance for MQWS-3, τ_t is too short to be determined in our analysis. The accuracy of τ_t determination is + 2 *ps,* limited by the time-resolution in our measurement. Therefore, we assume $\tau_t < 2$ *ps* under resonance for MQWS-3. These τ_t values are plotted in Fig. 5.

Our analysis of the time-resolved PC assumes that resonance-induced enhancement of electron conduction is responsible for the reduction in the decay time. Transient charge neutrality, which accompanies no carrier injection from the outside, is assumed because no significant photogain is observed in the cw PC/V_b under resonance for MQWS-2 and 3 in spite of the strong reduction of the decay time of the time-resolved PC. Transient charge neutrality suggests hole transport no later than electron transport. This may be possible if hole tunneling is associated with the light-hole band in the barrier. The effective barrier height for holes is approximately half the value for electrons, while the effective mass for the light-hole band in the barrier is comparable to that for the conduction band. This difference makes the tunneling coefficient associated with the light-hole band significantly larger than that associated with the conduction band. However, resonance of holes in QWs is not yet well understood because of the complicated valence band structure. Further investigation on this subject will be required.

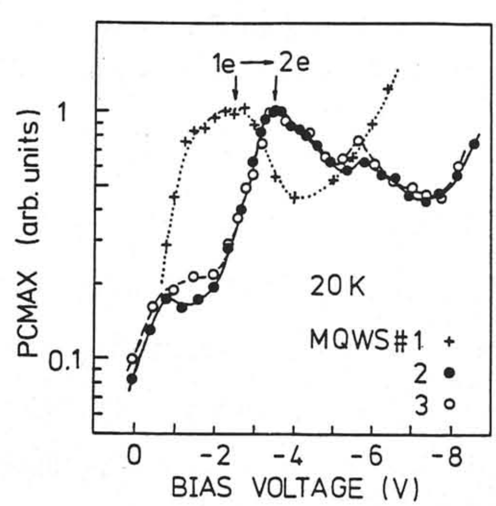

Fig. 3 --- Peak (maximum) values of the time-resolved PC as a function of V_b for MQWS-1, 2, and 3.

4. THEORETICAL CALCULATION

4.1 Weakly Coupled Well Model

Here, we compare the experimental values of τ_t under resonance with the theory for a weakly coupled well as shown in Fig. 4. The MQWS potential profile under an electric field is approximated by that of a coupled square well as shown by the broken line. This approximation is valid under a weak field as for $E > eF(L_z/2)$, where E is the confinement energy and F is the electric field. The tunneling coefficient problem under 1e-2e resonance in the present model can be solved in the same way as for a two-well model under no field.[6] Eigen states in the respective uncopled wells are given by solving the equation

$$kL_z = \tan^{-1}(\kappa/k)+(1+2n)(\pi/2), \qquad (1)$$

where

$$k = (2m^*_w E)^{1/2}/\hbar$$

and

$$\kappa = [2m^*_B(\Delta E_c - E)]^{1/2}/\hbar,$$

where m^*_w and m^*_B are the effective electron mass in the well and in the barrier, respectively, and ΔE_c is the potential barrier height. The resonance effect

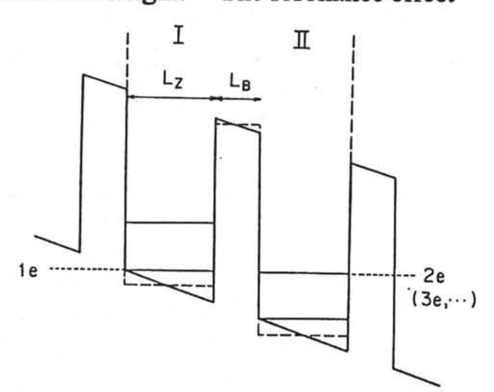

Fig. 4 --- MQWS potential profile under electric field. The broken line represent the profile assumed here.

effect in the coupled well gives rise to a split in the degenerate levels by the amount of

$$2\delta E \sim (8/\kappa L_z)(E_1E_2)^{1/2}\exp(-\kappa L_B), \qquad (2)$$

where E_1 and E_2 are the confinement energies in well I and II, respectively. An electron transfers entirely from well I to well II in a time $t = \hbar\pi/2\delta E$.[6]

Figure 5 shows the calculated τ_t under 1e-2e

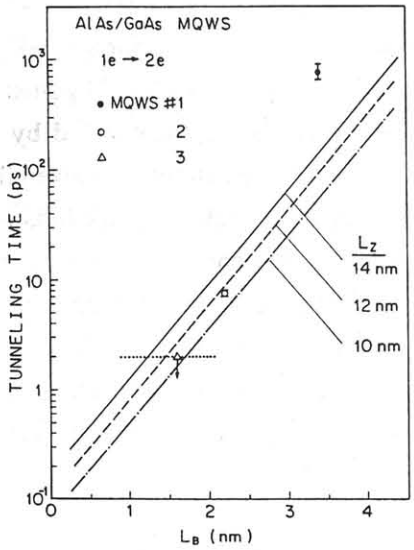

Fig. 5 --- Barrier thickness dependence of RT time under 1e-2e resonance calculated using the theory for a weakly coupled well. The dotted line represent the resolution limit. RT times determined from the time-resolved PC measurements are also plotted.

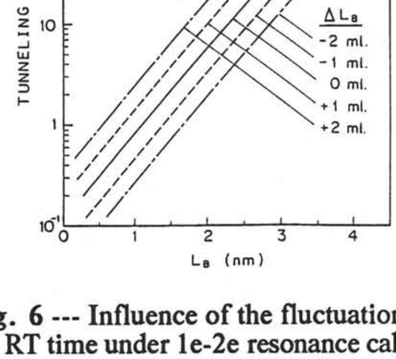

Fig. 6 --- Influence of the fluctuation of L_B on RT time under 1e-2e resonance calculated for $\Delta L_B = \pm 1$ and ± 2 monolayers with L_z = 12 *nm*.

resonance as a function of L_B for L_z = 10, 12, and 14 *nm*. The RT times obtained experimentally compare favorably with the calculated value.

4.2 Influence of Interface Roughness

Interface roughness at the heterostructure gives rise to the flucuation of L_z as well as L_B. RT time is affected by the fluctuation of L_B, ΔL_B, rather than the fluctuation of L_z as expected from eq. (2). Figure 6 shows the change of L_B-dependence of RT time when L_B is shifted by $\Delta L_B = \pm 1$ and ± 2 monolayers. ΔL_B corresponding to 1 monolayer changes RT time by a factor of 2.

5. COCLUSIONS

Barrier thickness dependence of RT time from 1e to 2e in AlAs/GaAs MQWS with thin barriers was studied both experimentally and theoretically. The experimental values of RT time are derived by analyzing the time-resolved PC. These values compare favorably with the theory of weakly coupled wells. In addition, the theoretical calculation predicts a significant fluctuation of the RT time caused by the one monolayer fluctuation of L_B.

ACKNOWLEDGEMENT

The authors are grateful to Dr. Y. Horikoshi for critical discussion on the charge neutrality problem and Dr. T. Kimura for useful suggestion concerning the influence of interface roughness on RT time. They also thank Mr. M. Hauser for the MBE growth.

REFERENCES

1) R.F. Kazarinov and R.A.Suris, Sov.Phys.Semicond. 5 (1971) 707.
2) F.Capasso, K.Mohammed, and A.Y.Cho, Appl.Phys.Lett. 48 (1986) 478.
3) T.Furuta, K.Hirakawa, I.Yoshino, and H.Sakaki, Jpn.J.Appl.Phys. 25 (1986) L151.
4) S.Tarucha, K. Ploog, and K. von Klitzing, Phys. Rev., B36 (1987) 4558.
5) S. Tarucha and K. Ploog, to be published in Phys. Rev. B
6) E. Burstein and S. Lundqvist, Tunneling Phenomena in Solids (Plenum Press, New York, 1969).