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Effects of Impurity Scattering on Resonant Transmission Coefficients in GaAs/AlAs Double Barrier Structures

Hiroyuki FUKUYAMA, Takao WAHO and Takashi MIZUTANI

NTT LSI Laboratories
3-1, Morinosato Wakamiya, Atsugi, Kanagawa 243-01, Japan

The resonant transmission coefficients in GaAs/AlAs double barrier structures are estimated from the d^2I/dV^2-V characteristics of resonant tunneling diodes using a recently introduced method. Comparing the I-V curves reproduced from the estimated coefficients with the measured ones shows that the method gives reliable transmission coefficients. The effect of impurities doped either in the wells or in the barriers on transmission coefficients is also studied. The two peaks observed in the coefficients of the well-doped samples are probably attributable to tunneling through the quasi-bound state as a result of impurities and tunneling through the resonant state.

1. Introduction

Since the pioneering study by Tsu and Esaki,[1] resonant tunneling in double barrier (DB) structures has been studied intensively, providing new and attractive devices, such as a resonant tunneling diode with cutoff frequencies above 700 GHz.[2] However, our understanding of scattering effects such as impurity scattering[3-6] has been quite limited because there are few tools for investigating them experimentally. Recently an interesting method was proposed[7] for estimating the transmission coefficient, which directly reflects scattering effects. In this paper, we examine the suitability of the method by reproducing I-V curves from measured coefficients. We then analyze the impurity effect on the resonance level in the GaAs/AlAs DB structures.

2. Experimental

The sample structures were grown on n^+-GaAs (001) substrates by molecular beam epitaxy (MBE). First, a 300-nm n-GaAs buffer layer (doped with Si to 5×10^{17}cm^{-3}) was grown. Then, the AlAs/GaAs/AlAs DB structure was grown with undoped spacer layers at both ends. The thicknesses of the upper and lower spacer layers were 1.4 nm and 5 nm, respectively. At the end of the growth sequence, a 270-nm n-GaAs layer (doped with Si to 5×10^{17} cm^{-3}) and a 50-nm n^+-GaAs layer (doped with Si to 1×10^{19} cm^{-3}) were grown as cap layers.

Diodes were fabricated using conventional photolithography, wet-etching and metallization. Mesa structures were formed by wet-etching to isolate the devices. AuGe/Ni/Ti/Pt/Au was deposited on the top and the bottom of the wafers, which were then annealed to form ohmic contacts.

To evaluate the resonant transmission coefficient, we employed the method proposed by Tsuchiya and Sakaki, in which the coefficient is derived from the second derivative (d^2I/dV^2) of the I-V curves at low temperature as follows:[7]

$$TT^*(E) = \frac{1}{\alpha^2}\frac{2\pi^2\hbar^3}{e^3m^*}\frac{d^2I}{dV^2}, \qquad E = E_F + \alpha eV. \tag{1}$$

Here α is the ratio of the potential difference between the emitter electrode and the well to that between the emitter electrode and the collector electrode. In this study, α is assumed to be 0.5. To obtain the second derivative of the current density (d^2I/dV^2), the applied dc voltage was modulated with a low frequency, ω, and the 2ω component of current density was measured with lock-in amplifiers.

3. Results and Discussion

3.1 *Comparing reproduced and measured I-V curves*

The transmission coefficients were estimated from d^2I/dV^2-V characteristics at 4.2 K for two types of undoped DB structures with a 7-nm GaAs well. One had 4-nm AlAs barriers and the other had 2-nm AlAs barriers. Figure 1 shows the transmission coefficients for the sample with thick (4 nm) barriers, which shows relatively small current density (I_p=340 A/cm^2) and small charge accumulation in the well. Although the peak energy agreed well with the theoretically predicted value, the resonant peak was lower (2.5×10^{-5}) and broader

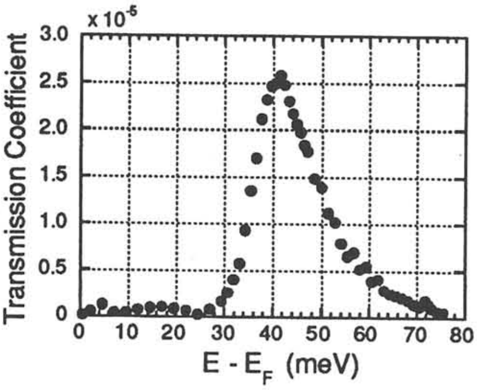


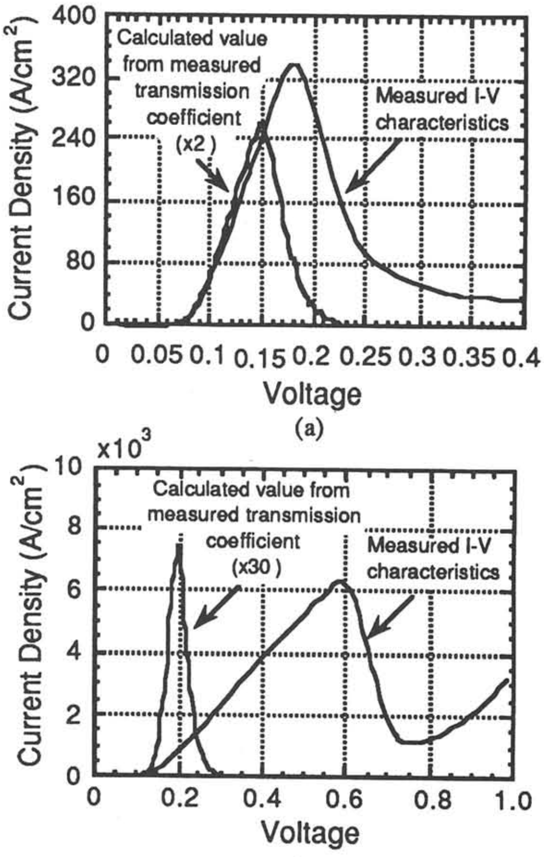
Fig. 1. The transmission coefficients of a double barrier structure which consists of two 4-nm undoped AlAs barriers separated by a 7-nm undoped GaAs well. The theoretical peak height and width are 0.7 and 5 μeV.

(16 meV) than the predicted values (0.7 and 5 μeV). However, using these coefficients and Tsu-Esaki's formula, we succeeded in reproducing the measured *I-V* characteristics within an error of factor 2 (Fig. 2(a)). This reasonable agreement proves the reliability of the coefficients obtained here. The lower and broader peak is probably due to the potential fluctuation caused by interface roughness.[7,8]

For the sample with thin (2 nm) barriers, which shows relatively large current density (I_p=6400 A/cm^2) and large charge accumulation, the reproduced currents were only one-thirtieth of the measured values (Fig. 2(b)). This means that serious errors were contained in the coefficients. In addition, the peak voltage is three times the value predicted by Tsu-Esaki's formula. The difference in the peak voltage suggests that there is a large band bending caused by accumulated charges in the well. It should be noted that in this calculation the band bending is omitted and α is set to 0.5. If this is taken into account, α in Eq. (1) is less than 0.5. The decrease in α increases the transmission coefficients, as shown in Eq. (1), and also increases the reproduced current values, which would lead to better agreement. To estimate the transmission coefficient quantitatively for DB structures with considerable charge accumulation, therefore, one should determine α properly, for example, by a self-consistent potential calculation.

3.2 *The impurity effect*

As mentioned above, quantitative investigation of the transmission coefficients is relatively easily carried out by using thick barriers to reduce the accumulation effect. Keeping this in mind, we prepared three samples with 4-nm AlAs/6-nm GaAs/4-nm AlAs DB structures, two of which were planar-doped at the center of the well with 5×10^{10}-cm^{-2} Si and 1×10^{11}-cm^{-2} Si. The other was planar-doped at the center of both the barriers with 5×10^{10}-cm^{-2} Si. The transmission coefficients estimated from d^2I/dV^2-V characteristics at 4.2 K are



(b)

Fig. 2. Comparison of the measured *I-V* characteristics and those calculated from the estimated transmission coefficients for (a) 4-nm AlAs/7-nm GaAs/4-nm AlAs and (b) 2-nm AlAs/7-nm GaAs/2-nm AlAs double barrier structures. It should be noted that there is a large difference in peak current and voltage between the calculated and measured values in (b), where the band bending effect is not negligible.

shown in Fig. 3.

For the well-doped samples, double-peaked structures were observed. For the peaks on the higher energy side, the peak widths of 15 meV were independent of Si concentration. This indicates that the peak broadening probably has the same origin as for the undoped samples, i.e., interface roughness, since the width is almost equal to that for the undoped sample shown in Fig. 1. The peak energies of 55 meV were also independent of Si concentration. Since the peak energies were close to the calculated resonance levels, these peaks are probably attributable to the resonance levels for undoped samples.

For the lower energy peaks, the peak widths and the peak energies from the Fermi energy were 12 meV and 37 meV for the 5×10^{10}-cm^{-2}-doped sample, and 17 meV and 35 meV for the 1×10^{11}-cm^{-2}-doped sample. Being estimated to be 10 nm, the Bohr radius for the impurity state is smaller than the average distance ($\geq$30nm) between doped impurities for the samples

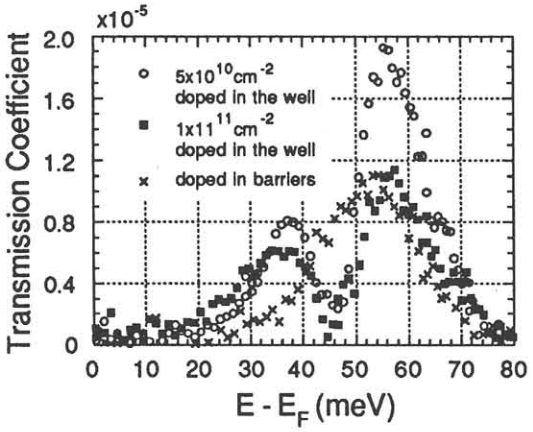


Fig. 3. The energy dependence of transmission coefficients on different impurity profiles.

studied here. Hence, some electrons can be transmitted through impurity quasi-bound states, while others can be transmitted without being influenced by the impurity field (Fig. 4). Furthermore, the bound energy of Si impurity would increase up to about 18 meV as a result of the confinement effect by the two barriers.[9] It is highly likely that the peaks with lower energies, therefore, result from the tunneling through the quasi-bound states introduced by impurities. The peak broadening observed for samples with thin barriers[10] is probably due to tunneling through quasi-bound states of impurities.

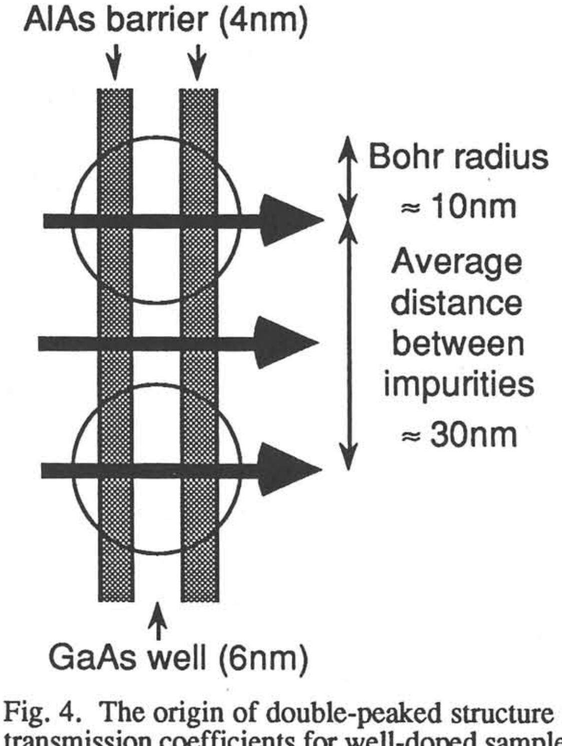


Fig. 4. The origin of double-peaked structure in transmission coefficients for well-doped samples. The average distance is estimated for the 1×10^{11}-cm^{-2} doped sample. Some electrons can be transmitted through the quasi-bound states caused by impurities.

For the barrier-doped samples, a single-peaked structure was observed. The peak energy was 54 meV, which is close to the resonance energy calculated for the undoped samples. The lower-energy-side peak was absent and the peak width of 20 meV was wider than for the well-doped samples. These results are explained if we take shallower quasi-bound states into account. In the case of barrier layer doping, the quasi-bound states are likely to be formed close to the resonance level because of the small electron-impurity coupling, which results from a small electron wave amplitude in the barrier layer.

4. Conclusion

We investigated the resonant transmission coefficients in GaAs/AlAs double barrier structures. The derivation method previously proposed gives reliable transmission coefficients, but for the DB structure with thin barrier layers, the effect of electron accumulation in the well must be taken into account. We observed the effect of impurities doped either in the wells or in the barriers on resonance level. For the well-doped samples, two peaks were observed in the transmission coefficients. These correspond to tunneling though the quasi-bound state due to impurities and tunneling through the resonant state.

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