Resonant tunneling of double-barrier quantum wells affected by interface roughness

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Resonant tunneling of double-barrier quantum wells (DBQW's) affected by interface roughness has been investigated. Our results show that interface roughness induces oscillation resonant structure around the principal resonant peak. Effects of interface roughness on the resonant bias voltage, peak-to-valley current ratio, and the width of the principal resonant peak are also investigated. Temperature effect is discussed. The results obtained here may be used to explain the oscillation or intrinsic instability observed in DBQW resonant-tunneling structures.

I. INTRODUCTION

With recent developments in semiconductor artificial structures, such as quantum wells (QW's) and superlattices (SL's), many important physical properties have been explored.[1,2] In fundamental physics, quantum-well and superlattice structures have been used to explore the physical properties of low-dimensional systems and quantum effects. Many novel phenomena in the quantum regime have been discovered, such as resonant tunneling of double-barrier quantum wells with negative differential resistance.[3,4] Applications of these quantum wells and superlattices include high-speed electronics, photoelectronics, and photonic devices such as quantum-well lasers,[5] modulation-doped field-effect transistors[6] (MODFET's), photodetectors,[7] etc.

Double-barrier quantum-well (DBQW) tunneling structures have recently drawn a great deal of attention because tunneling is the fastest charge-transport phenomenon in semiconductors.[8–10] Many important properties of resonant tunneling of electrons in DBQW's have been observed, such as negative differential resistance. Although many important properties of DBQW tunneling structures have been discovered, there are still many important questions to be answered, such as those concerning oscillation or instability in DBQW resonant-tunneling structures.[10–12]

Although molecular-beam-epitaxy (MBE) can be used to fabricate the quantum-well or superlattice structures on an atomic scale, interface roughness cannot be completely eliminated. It is important to understand how this interface roughness affects the transport properties of DBQW structures. In some cases the presence of interface roughness simply acts as a small perturbation on effects that already exist in the absence of interface roughness. In other cases it can lead to quantitative changes in phenomena that exist in the absence of interface roughness. An example of this would be the roughness-induced splitting of the surface-plasmon dispersion curve observed experimentally,[13,14] and discussed theoretically.[15,16] Overall, roughness can have a significant influence on effects occurring at interfaces. The effects of interface roughness on the optical properties of quantum wells have been studied previously.[17–19] The dominant effects observed due to interface roughness were the exciton linewidth broadening and the Stokes shift of the emission: the emission of the lowest heavy-hole exciton generally is slightly shifted to lower energy (typically a few millielectron-volts) with respect to the absorption- or excitation-spectrum maximum. Recently, dynamic processes of excitonic transitions affected by interface roughness have also been studied.[20] The exciton-transition peak shifting towards lower energy with increasing delay time caused by interface roughness has been observed.

In this paper, effects of interface roughness on the resonant tunneling in DBQW structures have been investigated. We show that interface roughness can cause multiple resonance peaks in DBQW's, and thus strongly modify the *I-V* characteristic. The *I-V* characteristic for different interface-roughness parameters as well as for different DBQW structures are studied. The effects on multiple resonance peaks are discussed. From our results, it is possible that the previously observed oscillations between the low- and high-current states in the DBQW's (Ref. 5) or intrinsic instability is induced by interface roughness.

II. CALCULATION

For a DBQW in the absence of interface roughness, the current density under a bias voltage V can be written as[3]

$$j=\frac{em^*kT}{2\pi^2\hbar^3}\int_0^\infty M^*M \times\ln\left[\frac{1+\exp[(E_F-E_l)/kT]}{1+\exp[(E_F-E_l-eV)/kT]}\right]dE_l, \tag{1}$$

where m^* is the effective mass of the electron, k is the Boltzmann constant, and T is temperature. E_F is the electron Fermi energy which depends on the concentration of electrons. E_l is the longitudinal energy of the electrons. M depends on the DBQW structure parameters (well width b and barrier width a as well as Al concentration x in GaAs-$Al_xGa_{1-x}As$ DBQW's) and the bias voltage V, which can be written as

$$M = T_{11} - T_{12}T_{21}/T_{22} , \tag{2}$$

where T_{11}, T_{12}, T_{21}, and T_{22} are the elements of the transfer matrix $T = T_1 T_2$ with

$$T_i = \frac{1}{4}\begin{bmatrix} \exp(ik_{i+2}d_{i+2}) & \exp(ik_{i+2}d_{i+2}) \\ \exp(-ik_{i+2}d_{i+2}) & -\exp(-ik_{i+2}d_{i+2}) \end{bmatrix} \times \begin{bmatrix} \exp(k_{i+1}d_{i+1}) & \exp(-k_{i+1}d_{i+1}) \\ -i(k_{i+1}/k_{i+2})\exp(k_{i+1}d_{i+1}) & -i(k_{i+1}/k_{i+2})\exp(k_{i+1}d_{i+1}) \end{bmatrix} \begin{bmatrix} 1+i(k_i/k_{i+1}) & 1-i(k_i/k_{i+1}) \\ 1-i(k_i/k_{i+1}) & 1+i(k_i/k_{i+1}) \end{bmatrix} , \tag{3a}$$

$i = 1,2$. Here d_i and k_i can be written as

$$d_{i+1} = \begin{cases} a, & i=1 \\ a+b, & i=2 \\ 2a+b, & i=3 \end{cases} \tag{3b}$$

$$k_i = [2m^*(V_i - E_l)]^{1/2}/\hbar, \quad i=1 \text{ to } 5 \tag{3c}$$

with

$$V_i = \begin{cases} 0, & i=1 \\ \Delta E_c, & i=2 \\ -V/2, & i=3 \\ \Delta E_c - (V/2), & i=4 \\ -V, & i=5 \end{cases} . \tag{3d}$$

Here ΔE_c is the conduction-band energy difference between GaAs and $Al_xGa_{1-x}As$, which has been taken to be 60% of the direct-band-gap difference between the two semiconductors. The continuity conditions of wave function $\psi(x)$ and the probability current density of the electron $(1/m^*)(d\psi(x)/dx)$, across the interface have been used to derive the expression of M. The effect of bias voltage on the conduction-band edge have been neglected for simplicity.

By considering the existence of interface roughness, the quantum-well (barrier) width of a DBQW is no longer fixed, but instead fluctuates from b_{min} to b_{max} (a_{min} to a_{max}).[21,22] In the quantum-well (barrier) plane, spatial domains induced by interface roughness with lateral sizes varying from a few hundred angstroms to a few micrometers are formed. The area of domains with well (barrier) thickness L are different from sample to sample and are determined by the growth conditions. Since the growth of a DBQW is a random process in the plane perpendicular to the growth axis, $S(L)$, the total area of all domains of well (barrier) width L, should follow a Gaussian distribution,[23] which can be written as

$$S(L) = S(L_0)\exp[-(L-L_0)^2/2\sigma^2] . \tag{4}$$

Here L_0 is the average well (barrier) thickness and σ is a fluctuation parameter which depends on the quality of sample. Therefore, the total current in the presence of interface roughness can be obtained by calculating the average current density, $\langle j \rangle$, and then multiplying by the total area of a DBQW. $\langle j \rangle$ is the quantity of a statistical average over well- (barrier-) thickness fluctuation, which can be obtained by replacing M^*M by $\langle M^*M \rangle_{av}$ in Eq. (1). $\langle M^*M \rangle_{av}$ can be written as

$$\langle M^*M \rangle_{av} = \frac{S(L_0)}{S} \sum_{l=-m}^{m} M^*M\exp(-l^2\delta^2/2\sigma^2) , \tag{5}$$

and the total area of a DBQW is

$$S = \sum_{l=-m}^{m} S(L_0 + l\delta) = S(L_0) \sum_{l=-m}^{m} \exp(-l^2\delta^2/2\sigma^2) . \tag{6}$$

In obtaining Eqs. (5) and (6), we have noticed the fact that the fluctuation in well and barrier thicknesses must be multiples of δ, 1-monolayer thickness, and that the maximum fluctuations in well and barrier thicknesses are m monolayers. From Eqs. (1)–(6), we numerically calculated the average current density $\langle j \rangle$. In the calculation, we used 1-monolayer thickness $\delta = 2.86$ Å for GaAs materials, $m_1 = 0.067m_0$ and $m_2 = (0.067 + 0.083x)m_0$ for the electron effective mass in GaAs and $Al_xGa_{1-x}As$ material, respectively, m_0 being the electron mass in free space, and the empirical expression $\Delta E_g = 1.155x + 0.37x^2$ (eV), for the direct-band-gap difference between GaAs and $Al_xGa_{1-x}As$.[24] The conduction-band offset at the interface has been taken to be 60% of the direct-band-gap difference between the two semiconductors.[25,26] The electron Fermi energy E_F has been taken as 5 meV, which corresponds to an electron concentration $n \sim 10^{17}$ cm^{-3} in the GaAs contact.

III. RESULTS AND DISCUSSIONS

Figure 1 shows the I-V characteristic of a GaAs-$Al_{0.3}Ga_{0.7}As$ DBQW at a temperature of absolute zero for three different values of interface-roughness parameter σ, with an average well width of 50 Å. The barrier thickness $a = 50$ Å is fixed. In Figs. 1–5 the units for the current density $\langle j \rangle$ are 10^3 A cm^{-2}. For simplicity, in Fig. 1, we assume the fluctuation is only caused by well thickness. From Fig. 1, we see that the predominant effect caused by interface roughness is a multiple-oscillation structure around the principal resonant-peak region. In the case of the perfect structure (without

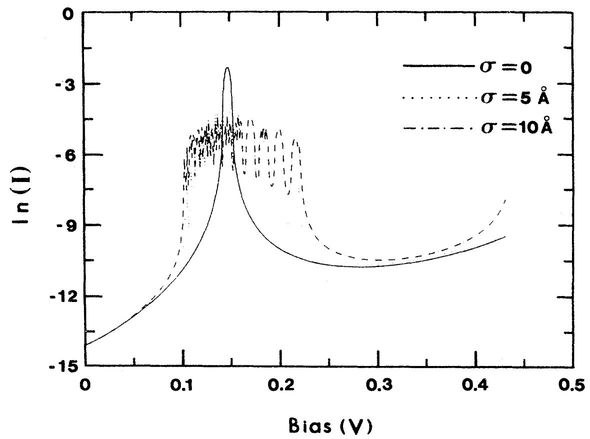

FIG. 1. Logarithm of the current density vs the bias voltage at temperature $T=0$ K for a GaAs-$Al_{0.3}Ga_{0.7}As$ DBQW for three different interface-roughness parameters σ, with an average well thickness of 50 Å. The barrier thickness, $a=50$ Å, is fixed. The units for the current density are 10^3 A cm^{-2}.

roughness), i.e., $\sigma=0$, there is only a sharp principal resonance peak appearing at a bias voltage of 0.15 V. As σ increases to 5 Å, complicated oscillation structure around the principal peak occurs. In addition, the maximum resonant current decreases and the width of resonant peak increases with increasing σ. The broadening of the resonant peak has the same origin as the broadening of exciton-transition lines[18] and x-ray-diffraction lines[27] observed in quantum wells. In a DBQW, the domains with different well thicknesses have different resonant bias voltages. This broadens the principal resonant peak. As in the cw photoluminescence, the width of resonant-tunneling peak increases with increasing σ, the degree of roughness.

The physical origin of these multiple-oscillation structures appears to be fundamentally simple. The resonant tunneling occurs when the incident electron energy coincides with the energy of the lowest quasibound energy level in the well. Because of interface roughness, there are multiple quasibound levels in the well corresponding to different well widths. Since the well width fluctuates around the average well width, interface roughness causes multiple resonant peaks in the region of the principle resonant-current maximum. As σ increases to a certain value, the quasibound energy levels for different domains will be separated, and the resonant tunneling from different domains is clearly resolved, appearing as the multiple resonant peaks in the I-V characteristic. This result shows that, under a bias voltage at one of these resonant states, the tunneling current is predominantly a contribution of the corresponding domains of well width L, and each resonant peak corresponds to resonant tunneling at quasibound energy levels $E(L_0+l\delta)$, $l=0,\pm1,\pm2,\ldots,\pm m$. In the calculation, we used $m=5$, corresponding to a maximum of 5-monolayer fluctuation in each side. From Eq. (1) the current density j has a complicated dependence on the electron Fermi energy E_F; there appears to be additional complicated structure within each of those multiple resonant peaks.

In Fig. 2, we plot the I-V characteristic at temperature $T=0$ around the principal resonant peak with average well thicknesses of 25, 35, and 45 Å, and fluctuation parameter $\sigma=5$ Å. As in Fig. 1, the barrier thickness, $b=25$ Å, is fixed here. From Fig. 2 we see that the effects of interface roughness on the I-V characteristic depend on DBQW structure. In this case, for a fixed fluctuation, $\sigma=5$ Å, the oscillation has different structures for three different well thicknesses. The peak width broadening due to interface roughness is more pronounced for narrower well widths. This observation is identical to previously reported results on cw photoluminescence and x-ray-diffraction experiments.[17,18,27] Since the fluctuation in well (barrier) thickness is a multiple of 1 monolayer, the energy difference between two quasibound levels in a quantum well induced by a 1-monolayer difference is larger for narrower wells than for wider wells. The detailed investigation into the linewidth of the resonant-tunneling current under different conditions will be shown later.

Figure 3 is the I-V characteristic of a DBQW for three different values of Al concentration x, with σ being 5 Å and the average well thickness being 50 Å. The barrier thickness, $a=50$ Å, is fixed. For a small value of x, ($x=0.1$), there is only one resonant peak which is similar to the principal resonant-tunneling peak of $\sigma=0$ (without fluctuation). As x increases ($x=0.3$), in addition to the effects of width broadening and resonant bias-voltage shifting, additional multiple resonant peaks appear. The bias-voltage differences between two adjacent resonant peaks are smaller on the lower-bias-voltage side, and become larger in the higher-bias-voltage side. This is because the difference in the resonant energy levels of electrons due to a 1-monolayer-thickness difference in narrower wells, $E(L_0-5\delta)-E(L_0-4\delta)$, is larger than that in wider wells, $E(L_0+4\delta)-E(L_0+5\delta)$. Therefore, ex-

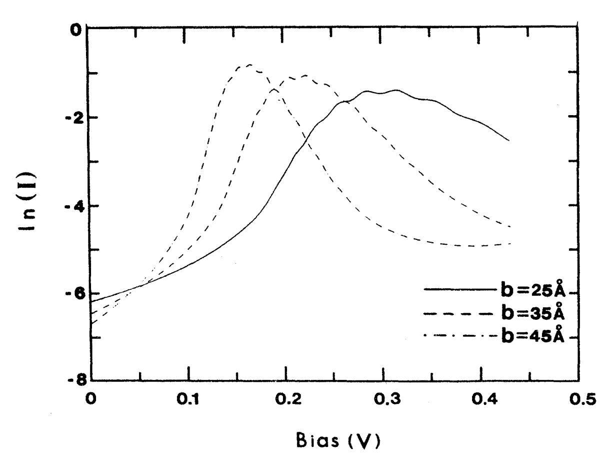

FIG. 2. Logarithm of the current density vs the bias voltage of a GaAs-$Al_{0.3}Ga_{0.7}As$ DBQW at temperature $T=0$ for three different average well thicknesses, $b=25$, 35, and 45 Å, with $\sigma=5$ Å. The barrier thickness, $a=25$ Å, is fixed.

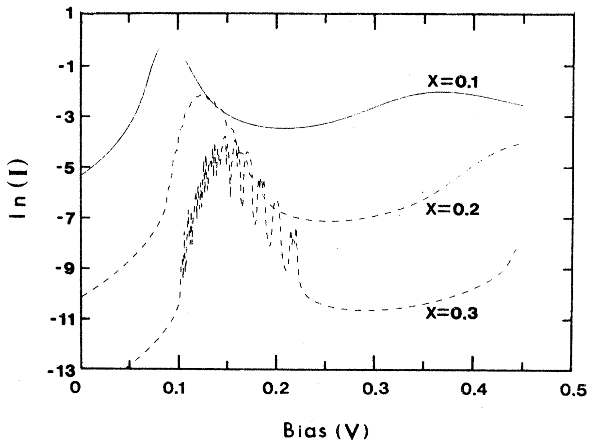

FIG. 3. Logarithm of the current density vs the bias voltage of a GaAs-$Al_xGa_{1-x}As$ DBQW at temperature $T=0$ K for three different Al concentrations x, with $\sigma=5$ Å and an average-well thickness of 50 Å. The barrier thickness, $a=50$ Å, is fixed.

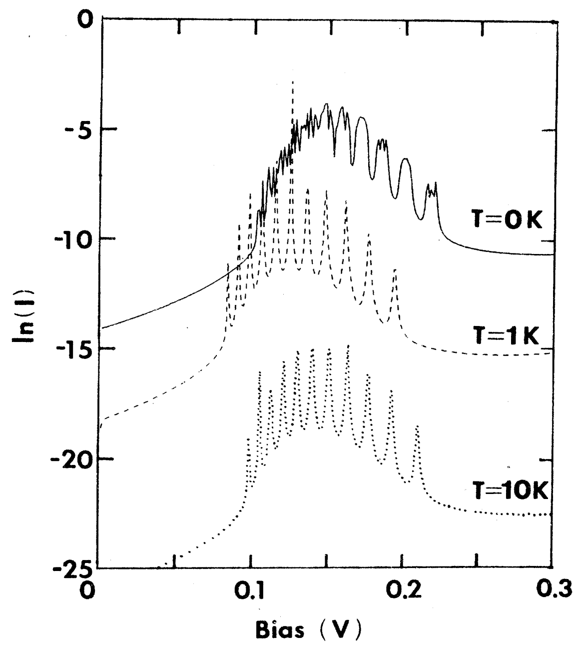

FIG. 4. Current density vs the bias voltage for three different temperatures, $T=0$, 1, and 10 K, for a GaAs-$Al_{0.3}Ga_{0.7}As$ DBQW with an average well thickness of 50 Å and $\sigma=5$ Å. The barrier thickness, $a=50$ Å, is fixed.

perimentally, the oscillation structure on the lower-bias-voltage side is more difficult to observe. One has to perform resonant-tunneling experiments with high resolution in bias voltage in order to observe this multiple resonance structure. Figure 3 shows that the multiple resonant structure can only be observed in a GaAs-$Al_xGa_{1-x}As$ DBQW with high Al concentration. For a DBQW with a larger energy-gap difference between well and barrier materials, the energy difference between quasibound levels in two domains with a well width of 1-monolayer difference is also larger. Consequently, the bias-voltage difference between two adjacent resonant peaks increases. Thus, the interface-roughness effects on resonant tunneling are easier to observe in DBQW's with a larger energy-gap difference between well and barrier materials.

Figure 4 shows the *I-V* characteristic of a DBQW with $\sigma=5$ Å at three different temperatures, $T=0$, 1, and 10 K. The average well thickness is 50 Å, and the barrier thickness is fixed at 50 Å. The results shown in Fig. 4 are surprising. As the temperature increases from 0 to 1 K, the multiple resonant peaks are more clearly resolved. Each resonant peak becomes more pronounced, in contrast to what one would expect. The width of each resonant peak is smaller at 1 K than that at 0 K. The additional complicated structure within each of those multiple resonant peaks observed at temperature $T=0$ K disappears at $T=1$ and 10 K. In general, the resonant-tunneling current decreases as temperature increases. This has been clearly demonstrated in Fig. 4. However, at $T=1$ K, the resonant-current density of the central resonant peak is even larger than the maximum resonant-current density at $T=0$ K. Compared to Fig. 1, the maximum resonant-current density at $T=1$ K with $\sigma=5$ Å is smaller than the resonant-current density at $T=0$ K with $\sigma=0$ Å, as it should be. The behavior in Fig. 4 is due to the fact that in addition to the term of $\langle M^*M\rangle_{av}$ in Eq. (5) which resolves multiple resonant peaks corresponding to different spatial domains, the temperature-dependent integrand (the Fermi distribution of electrons) in Eq. (1) further enhances these multiple resonant peaks.

We also calculated the *I-V* characteristic for higher temperatures ($T=100$ K, etc.). The basic features are similar to those in Fig. 4. The multiple resonant peaks are retained at high temperatures. Nevertheless, this does not imply that we can experimentally observe those multiple resonant peaks at high temperatures. Instead, it only means that the effect of temperature on the Fermi distribution of electrons will not smear out the multiple-resonant-peak structures. This is not a surprising conclusion. From a purely mathematical consideration, in Eq. (1), the integrand is a smooth function of T, and thus the predominant feature of the *I-V* characteristic is determined by $\langle M^*M\rangle_{av}$. We have to include electron-phonon interactions in order to obtain accurate results for high temperatures. The effects of electron-phonon interaction on resonant tunneling of a DBQW in the absence of interface roughness have been discussed recently.[28,29] Electron-phonon interaction effects on the resonant tunneling of a DBQW in the presence of interface roughness is under investigation. However, the temperature at which the multiple resonant peaks smear out can be estimated. Since the bias-voltage difference between two adjacent resonant peaks is of the order of 10 mV, these peaks are expected to be smeared out if the thermal energy kT becomes of the order of 10 meV. This gives the temperature which smears out the multiple resonant peaks at about 120 K.

Figure 5 shows the I-V characteristic of a DBQW at temperature $T=0$ for the following cases. (i) The fluctuations in both well and barrier thicknesses obey Gaussian distribution, the average well and barrier thicknesses are 50 Å, and the total thickness of the DBQW ($b+2a=150$ Å) is fixed (— — —). (ii) Only the fluctuation in well thickness follows Gaussian distribution, and the barrier thickness, $a=50$ Å, is fixed (——). Results in Fig. 5 demonstrate that the basic features of both cases are similar. This means that the effects of interface roughness on the resonant tunneling of a DBQW with fluctuations from both well and barrier thicknesses are quantitatively the same as those from only the well thickness. Thus, the results obtained in Figs. 1–4 can be used to compare with experimental results, which are obtained for the case of interface roughness present in both well and barrier thicknesses. There is one difference between the two aforementioned cases, namely that the multiple resonant peaks on the lower-bias-voltage side of the principal resonant peak is slightly more smeared out in the latter case. This is again consistent with experimental observation of hysteresis, oscillation, or intrinsic instability in DBQW's, which have been observed only on the higher-bias-voltage side.

We also calculated the resonant-tunneling linewidth under different conditions. Figure 6 is the plot of the full width at half maximum (FWHM) of the resonant-tunneling current of a DBQW as a function of Al concentration x, with fluctuation parameter $\sigma=0$ (——) and 5 Å (— — —). The average well thickness is 50 Å and the barrier thickness, $a=50$ Å, is fixed. From Fig. 6, we see that the FWHM's have different dependencies on x for the cases of $\sigma=0$ and 5 Å. In the absence of interface roughness, $\sigma=0$, the FWHM decreases as x increases. The most significant change is in the region $x<0.25$. The FWHM is almost a constant in the region $x>0.25$. In contrast, for $\sigma=5$ Å, the FWHM increases as x increases. The FWHM increases almost linearly with x in the region $0.2<x<0.35$. To see the effect of interface roughness on the resonant-tunneling-current linewidths, we define R as a ratio of the FWHM at $\sigma=5$ Å to the FWHM at $\sigma=0$, $R=[\text{FWHM } (\sigma=5 \text{ Å})/\text{FWHM } (\sigma=0)]$. R is about 2 at $x=0.15$, then increases to about 7.5 at $x=0.35$. So the effect of interface roughness becomes more important for DBQW's with higher Al concentration. The results in Fig. 6 can be understood. For $\sigma=0$, without interface roughness, increasing x will narrow the region of the quasibound levels in quantum wells which coincides with the Fermi level of electrons, and the resonant-tunneling line becomes sharper. Thus, the FWHM of the resonant-tunneling current decreases. For $\sigma=5$ Å, the dominant effect comes from the linewidth broadening by multiple resonant peaks. As we discussed above, increasing x will increase the bias-voltage difference between two adjacent resonant peaks because of the increase in the two quasibound energy-level difference between two domains of 1-monolayer difference in well thicknesses.

Figure 7 is the plot of (a) the FWHM as a function of fluctuation parameter σ with Al concentration $x=0.3$ (the average well thickness is 50 Å, and the barrier thickness, $a=50$ Å, is fixed), and (b) the FWHM as a function of average well thickness b with $\sigma=0$ (——) and $\sigma=5$

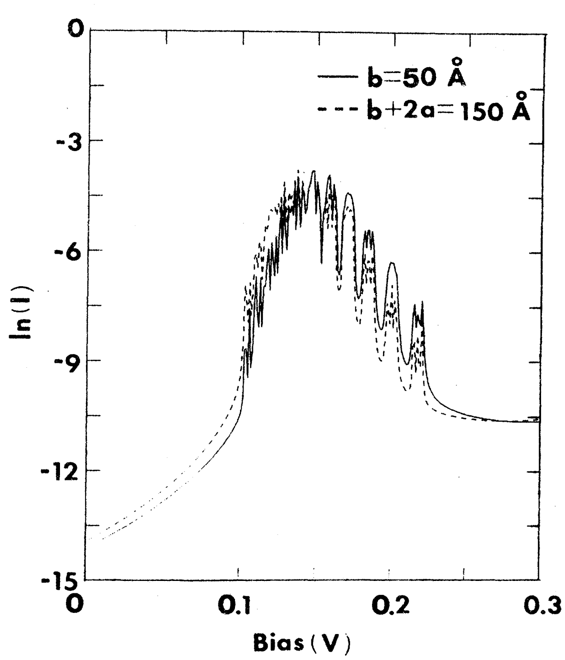

FIG. 5. Current density vs the bias voltage of a GaAs-$Al_{0.3}Ga_{0.7}As$ DBQW at temperature $T=0$ K for the following cases: (i) the fluctuation in both well and barrier thicknesses follows Gaussian distribution. Average well and barrier thicknesses are 50 Å, while the total thickness of a DBQW ($b+2a=150$ Å) is fixed (— — —). (ii) Only the well thickness is fluctuating and obeying Gaussian distribution, with an average thickness of 50 Å. The barrier thickness, $a=50$ Å, is fixed (——).

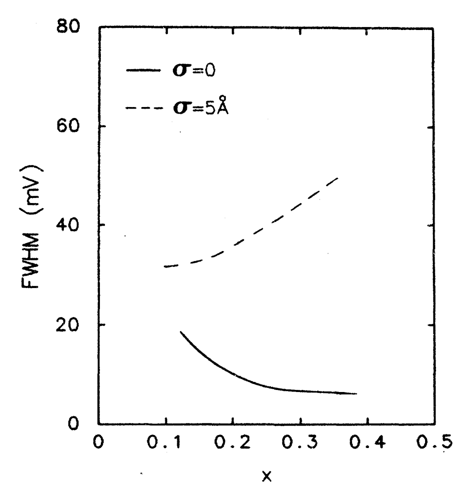

FIG. 6. Full width at half maximum (FWHM) of the resonant-tunneling current linewidth of a DBQW as a function of Al concentration x, with fluctuation parameter $\sigma=0$ (— — —) and $\sigma=5$ Å (——). The average well thickness is 50 Å and the barrier thickness, $a=50$ Å, is fixed.

Å (— — —) (the barrier thickness, $a=50$ Å, is fixed). Figure 7(a) shows that the FWHM increases with increasing σ. It changes from 8 mV at $\sigma=0$ (without interface roughness) to about 112 mV at $\sigma=20$ Å. The FWHM increases linearly with σ in the region $0<\sigma<12$ Å, then saturates at about $\sigma=20$ Å. The rate of increase of the FWHM with respect to σ in the linear region ($0<\sigma<12$ Å) is about 7.5 mV/Å. Figure 7(a) clearly demonstrates that the linewidth of the resonant-tunneling current of a DBQW is predominantly determined by the degree of interface roughness in samples. It could change by 1 order of magnitude for samples with different degrees of roughness.

Figure 7(b) shows how interface roughness affects the linewidth of the resonant-tunneling current of a DBQW with different well thickness. For the case $\sigma=0$, the FWHM increases as well thickness decreases. For $\sigma=0$, the FWHM changes from 6 mV at $b=100$ Å to about 35 mV at $b=35$ Å. For $\sigma=5$ Å, the FWHM increases much faster than for $\sigma=0$ when well thickness decreases, and changes from 10 mV at $b=100$ Å to about 120 mV at $b=30$ Å, an increase of more than 1 order of magnitude. The ratio R is about 1 at $b=100$ Å, and increases to about 4 at $b=30$ Å. Figure 7(b) shows that interface roughness affects the linewidth of resonant-tunneling current more drastically for narrower-well DBQW's.

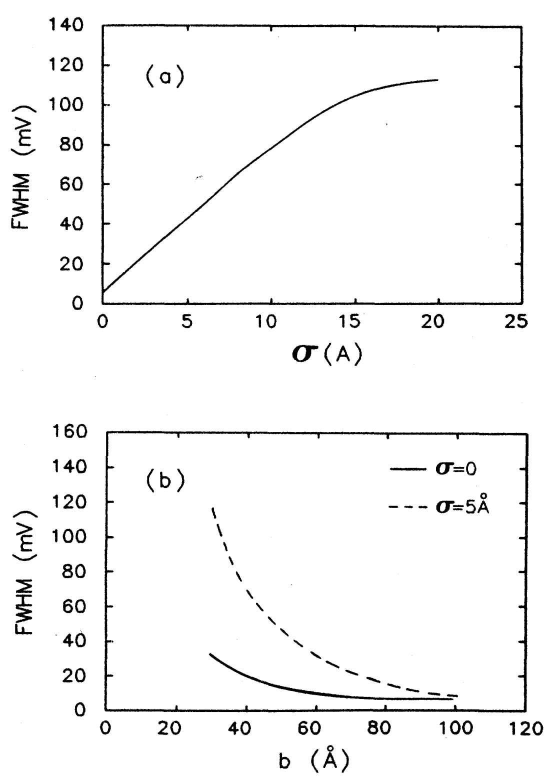

FIG. 7. (a) FWHM as a function of fluctuation parameter σ with Al concentration $x=0.3$. The average well thickness is 50 Å and the barrier thickness, $a=50$ Å, is fixed. (b) FWHM as a function of average well thickness with $\sigma=0$ (——) and $\sigma=5$ Å (— — —). The barrier thickness, $a=50$ Å, is fixed.

This is because of that the quasibound energy-level difference between domains with a 1-monolayer thickness difference is larger for narrower-well DBQW's than for wider-well DBQW's.

The results obtained here may be used to explain some experimental observations. Recently, Richard *et al.*[30] have observed the multiple-resonant-peak structure in a GaAs-$Al_{0.3}Ga_{0.7}As$ quantum-well tunneling diode. They found that, first, the difference in bias voltages between two adjacent resonant peaks, ΔV, increases with bias voltage and secondly, ΔV changes from a few millivolts to about 10 mV within the first principal resonant peak. Those are exactly what we obtained here. Additionally, the experimentally measured peak-to-valley current ratio of a DBQW is much smaller than the value calculated at $\sigma=0$. This is partly caused by contact resistance. However, from our calculation, the presence of interface roughness will also decrease this ratio. Our results may also be used to explain the oscillation or intrinsic instability around the principal resonant-peak region observed previously.[10–12] Since the bias-voltage difference between two adjacent resonant peaks is only a few millivolts, a small fluctuation in bias voltage in the resonant region will cause tunneling-current oscillation between minipeaks and minivalleys. For some DBQW's, the oscillation or instability has not been observed, which may also be accounted for by our results, because the interface-roughness-induced oscillation structure is sample dependent. Further evidence is that the previously observed oscillation or instability of resonant tunneling occurs only on the higher-bias-voltage side of the principal resonant peak. This is consistent with our calculation because the bias-voltage difference between two adjacent resonant peaks is smaller on the lower-bias-voltage side (see Figs. 1 and 3). These multiple resonant peaks on the lower-bias-voltage side will be smeared out at lower temperatures compared to those on the higher-bias-voltage side. Thus, one hardly observes this effect on the lower-bias-voltage side.

IV. CONCLUSIONS

In conclusion, we have reported the results of calculations of the I-V characteristic of DBQW's in the presence of interface roughness. We showed that interface roughness causes oscillation structure (multiple resonant peaks) around the principal resonant peak. Interface roughness will also cause width broadening in resonant tunneling, as in cw photoluminescence and x-ray scattering. Resonant-tunneling linewidths have been calculated under different conditions. The temperature dependence of this effect is also discussed. The results obtained here will be useful for fundamental understandings of charge-transport properties in quantum wells as well as DBQW device designs.

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