The effect of molecular-beam-epitaxial growth conditions on the electrical characteristics of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ resonant tunneling diodes

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We have investigated the dependence of the performance characteristics of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ resonant tunneling diodes upon molecular-beam-epitaxial growth parameters. The roughness of the growth front, leading to intrawell-size fluctuations and the V/III flux ratio at a fixed growth temperature are found to be important parameters affecting the performance of these devices. By means of a simple model, we have semiquantitatively related the peak current to the interface roughness. Defects and traps in the $In_{0.52}Al_{0.48}As$ barriers, on the other hand, produced partially by nonoptimal V/III flux ratios, may produce shunt paths for tunneling, again reducing the resonant tunneling current peak-to-valley ratio. Under optimum growth conditions we have measured current peak-to-valley ratios of 6.1 and 21.6 at 300 and 77 K, respectively. These are the best values reported so far for this heterostructure system.

I. INTRODUCTION

There is considerable interest in the properties of double-barrier resonant tunneling (RT) structures since the first proposal by Tsu and Esaki.[1] Several functional devices such as RT transistors[2] and RT hot-electron transistors (RHET)[3] have been proposed for circuit applications.[4] Similarly, the application of RT diodes towards millimeter-wave sources, self-oscillating mixers, and ultrafast detectors is challenging. For the proper implementation of RT devices in circuit applications, the device should demonstrate a high- current peak-to-valley (PTV) ratio at room temperature. For example, the negative differential resistance (NDR) of RT structures needed for ultrahigh-speed operation of RHET requires a high peak current density (J_p) of 1×10^5 A/cm^2 and a large PTV ratio of ~ 10.[3] The highest PTV ratio at room temperature obtained with the GaAs/AlGaAs heterostructure system is 3.5:1.[5] Improved PTV ratio (4.0 at 300 K and 15.0 at 80 K) was demonstrated with the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ system.[6] The NDR obtained in these structures, however, are still far from the required characteristics mentioned above.

Previous investigations[7] show that design and material quality are key factors limiting the PTV ratio at room temperature. In the design aspect the parameters affecting the NDR characteristics include the effective masses and thicknesses of the barrier and well regions, and the barrier heights. These parameters have been thoroughly investigated by many authors.[5,7,8] However, the effect of material quality on the NDR is not well documented. In this paper the importance of material quality in determining the device characteristics is demonstrated by investigating the NDR of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ double-barrier RT diodes grown by molecular-beam epitaxy (MBE) under different conditions. The important parameters of the materials, needed to improve the PTV ratio, are discussed.

II. EXPERIMENT

$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ resonant tunneling structures, lattice matched to InP, were grown on a (100)-oriented S-doped InP substrate in a Varian/Gen II MBE system. Polish-induced wafer damage was etched with $H_2SO_4:H_2O_2:H_2O$:: 5:1:1, followed by etching with a 0.2% bromine-methanol solution. A special feature in our source preparation is to bake commercially available 7-N's indium ingots at 800 °C for 24 h in an ultrapure hydrogen ambient to reduce residual impurities.[9] The procedure followed for source and system preparation has been described in detail elsewhere.[10] The growth rate was about 0.7 μm/h for both $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$. A series of samples with identical structure, as shown in Fig. 1, were grown at differ-

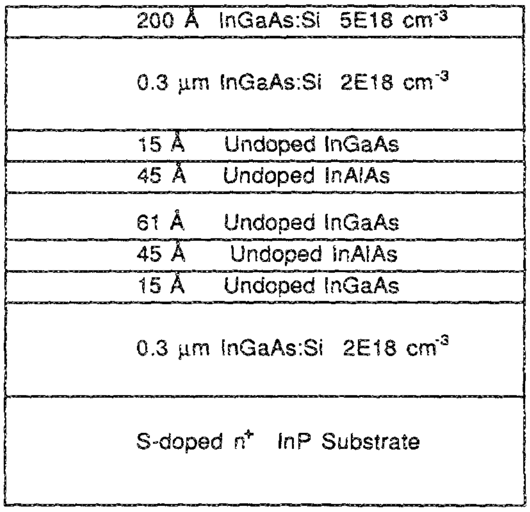

FIG. 1. Schematic of resonant tunneling diodes lattice matched to InP grown by molecular-beam epitaxy.

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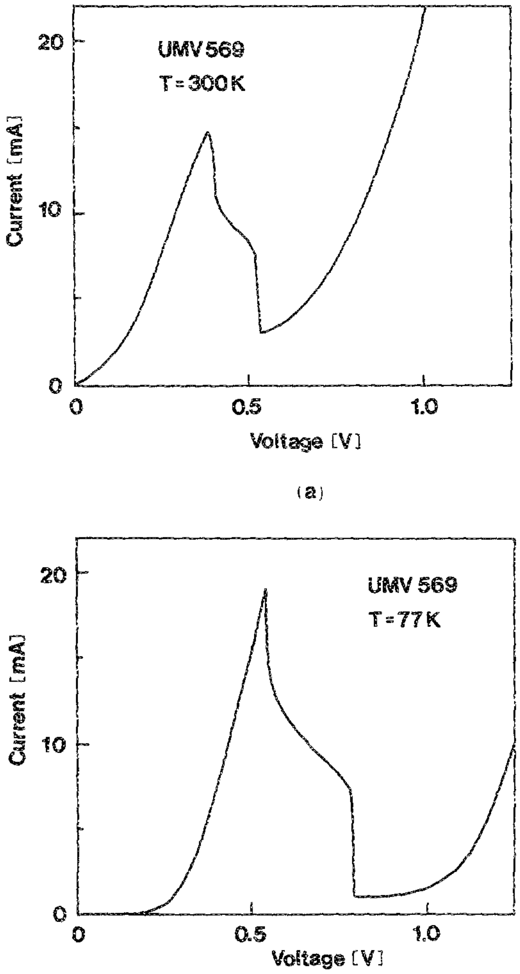
ent substrate temperatures and with varying P_{As}/P_{III} ratio. The structure consists of two undoped $In_{0.52}Al_{0.48}As$ barrier layers ($L_B = 45$ Å) on either side of an undoped $In_{0.53}Ga_{0.47}As$ well layer ($L_Z = 61$ Å). The active structure was sandwiched between two 0.3-μm-thick Si-doped $In_{0.53}Ga_{0.47}As$ ($N_D = 2\times10^{18}$ cm^{-3}) layers on either side. Undoped $In_{0.53}Ga_{0.47}As$ spacer layers of 15 Å were inserted between the barriers and the n^+ electrodes to minimize the detrimental effects due to segregation and out-diffusion of Si during epitaxy. Mesa diodes with 1, 3, 5, 10, 15, and 25 μm diameters were fabricated by conventional photolithography and wet chemical etching. The ohmic contacts on both sides of the wafers were made by electron-beam evaporation of Ni/Ge/Au/Ti/Au and subsequent alloying.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the room-temperature current-voltage characteristics for the sample grown at 500 °C with a P_{As}/P_{III} ratio of 80. As seen in this figure, the double-barrier structure exhibits a high PTV ratio of 6.1 with a peak current density of 1×10^4 A/cm^2. At 77 K the current density of this sample remained practically the same but the PTV ratio increased to about 21.6 [Fig. 2(b)]. To the best of our knowledge, these values are higher than any reported so far for $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ RT diodes. The peak in the current-voltage curve at room temperature is around 385 meV. Using a barrier height of 530 meV and an electron effective mass of $0.042m_0$, it is found[11] that the ground state is 185 meV above the quantum-well conduction band at zero bias. One would expect the peak voltage to be around 370 meV. Thus, the measured and the calculated values are reasonably close. Part of the observed discrepancy may arise from the fact that the calculations are not self-consistent and that there is some series resistance associated with the diode structure and contacts. The peak voltage at 77 K is slightly larger than that at room temperature. This is probably due to increased series resistance of the diode at lower temperatures.



(a)

(b)

FIG. 2. Measured (a) room-temperature and (b) 77-K current-voltage characteristics of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ RT diodes (sample C).

The interdependence of the growth parameters in the case of four samples is shown in Fig. 3, where the measured PTV ratios are also mentioned in the caption. We observe NDR only in the samples grown under the condition above the dotted line, even though all the samples were grown under As-stabilized conditions. Among these, sample C grown at 500 °C with a P_{As}/P_{III} ratio of 80 shows the best NDR performance. Sample B shows no NDR behavior.

To confirm the relationship between the growth condition and the device characteristics, we grew a series of undoped $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ layers with growth conditions identical to those for the RT diodes. Also, quantum wells composed of $In_{0.52}Al_{0.48}As$ barriers and $In_{0.53}Ga_{0.47}As$ wells were grown at different growth temperatures to investigate the interfacial quality at the heterointerface. Room-temperature Hall measurements were made, and from these, electron mobilities of above 10 000 cm^2/(V s) were obtained in $In_{0.53}Ga_{0.47}As$. The $In_{0.52}Al_{0.48}As$ layers showed semi-insulating characteristics. Low-temperature (10–15 K) photoluminescence (PL) measurements were performed to find the optical properties

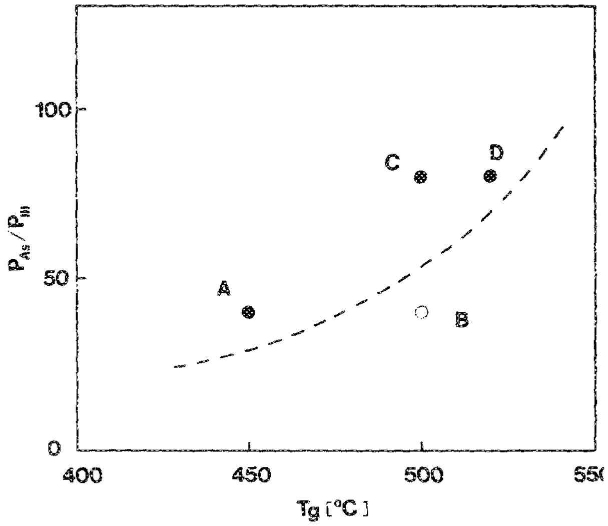


FIG. 3. Growth parameters of four resonant tunneling structures. Samples above the dashed line show NDR. The measured current peak-to-valley ratios at 300 and 77 K are, respectively, 4.8 and 18.0 for sample A, 6.1 and 21.6 for sample C, and 5.8 and 20.0 for sample D.

of bulk layers and to probe the heterointerface quality. The low-temperature PL linewidths of $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ layers were about 19 and 3 meV, respectively, weakly depending on the growth condition. However, the PL linewidths of quantum wells were quite sensitive to the growth conditions. With increase in growth temperature, the PL linewidth steadily decreased. The same characteristics have been observed by other workers.[12]

Singh *et al.*[13] reported results of a Monte Carlo computer simulation carried out to understand the molecular-beam epitaxial growth of $In_{052}Al_{048}As$. They found that a high migration rate of cations is needed to grow smooth heterointerfaces. The migration rate of cations can be enhanced by increasing the growth temperature. Smooth interfaces reduce the PL inhomogeneous line broadening due to intrawell fluctuations. We have developed a simple theory to understand the role of interfacial quality in the NDR behavior of RT diodes. The interface is described in terms of a microscopic fluctuation δ, where δ is the local fluctuation in the well width. We assumed a Gaussian distribution $G(z)$ of the well width centered at L_Z with a half-width of $\delta/2$. The modified tunneling transmission coefficient can then be calculated by convoluting the ideal transmission coefficient and the Gaussian distribution G. In other words, $T(E,V) = T_0(E,V)*G(z)$. $T(E,V)$ and $T_0(E,V)$ are functions of the electron energy and the applied bias. Figure 4 shows the dependence of the increased full width at half maximum (FWHM), ΔE, of the transmission coefficient at zero bias on well width L_Z assuming $\pm\frac{1}{2}$ monolayer (curve *a*) and ± 1 monolayer (curve *b*) interface roughness. Therefore, interface roughness reduces the peak magnitude of the transmission coefficient by a factor of $1/(\sqrt{2\pi}\,\Delta E)$. Simple qualitative expressions of the peak and valley currents derived by Collins, Lowe, and Barker[14] show that the peak current is linearly proportional to the transmission coefficient and the valley current is only dependent on nonresonant factors. Therefore, the degraded transmission coefficient due to the interface roughness reduces the magnitude of the peak current, resulting in the reduced PTV ratio. More detailed quantitative analysis is in progress. Therefore, the tendency of enhanced PTV ratios at higher growth temperatures can be explained in terms of the enhanced migration rate of cations and the resultant is the smoother heterointerfaces.

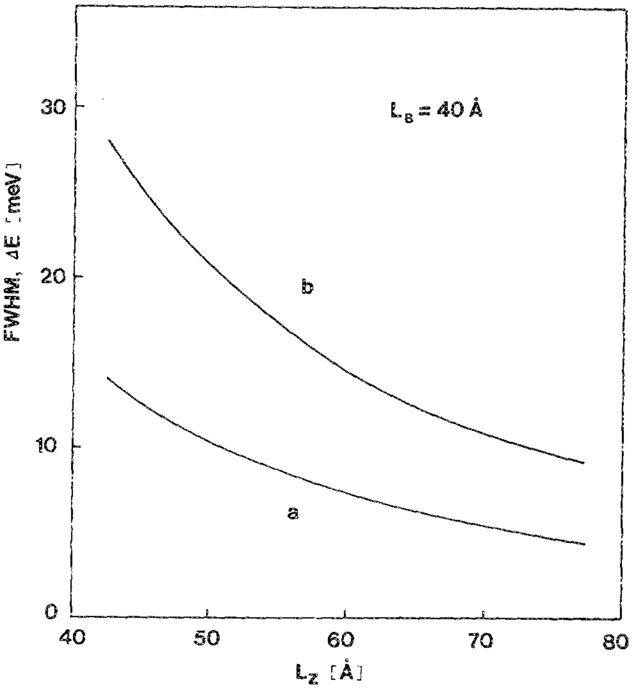


FIG. 4. Calculated increase in the linewidth (FWHM) of the transmission probability as a function of well size for $\pm\frac{1}{2}$ monolayer intrawell-size fluctuation (curve *a*) and ± 1 monolayer well-size fluctuation (curve *b*).

It was also noted that the integrated PL intensities of $In_{0.52}Al_{0.48}As$ layers were strongly dependent on the growth conditions. The integrated PL intensity of the $In_{0.52}Al_{0.48}As$ layer grown under the conditions identical to sample B is two orders lower than those for other samples. This result suggests that under relatively low As overpressures and for identical growth temperatures, the $In_{0.52}Al_{0.48}As$ layer may contain a high density of nonradiative traps, probably originating from As vacancies. Also it may arise from the preferential loss of indium under low As overpressure. At this moment it is not clear how the optically nonradiative centers affect or relate to the transport of electrons through the $In_{0.52}Al_{0.48}As$ barrier. However, we believe that these traps located in the emitter barrier provide a parallel tunneling path to carriers in nonresonant energy states, resulting in the higher valley current.

IV. CONCLUSIONS

In conclusion, we have seen that improvement of the PTV ratio can be realized by improving the material and heterointerface quality. A rough growth front can be produced by nonideal kinetics of cations on the growing surface. A higher growth temperature and a slower growth rate are necessary to enhance the mobility of cations on the growing surface. A rough growth front can cause statistical fluctuations of the well thickness, and a simple model developed here indicates that the tunneling transmission coefficient and the peak current are consequently reduced. However, it is important to realize that higher growth temperatures needed for smooth interfaces may result in segregation of dopant atoms. Also, nonideal V/III flux ratios can give rise to vacancies and/or associated defects in the $In_{0.52}Al_{0.48}As$ barriers, which can cause tunneling shunt paths. Therefore, the importance of the growth parameters in the realization of high-performance RT diodes can never be overemphasized.

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[1] R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).
[2] F. Capasso and R. Kiehl, J. Appl. Phys. **58**, 1366 (1985).
[3] N. Yokoyama, K. Imamura, T. Ohshima, H. Nishi, S. Muto, K. Kondo, and S. Hiyamizu, Jpn. J. Appl. Phys. **23**, L311 (1984).
[4] R. Bate, G. Frazier, W. Frensley, J. Lee, and M. Reed, Proc. SPIE **792**, 26 (1987).

[5] W. Goodhue, T. Sollner, H. Le, E. Brown, and B. Vojak, Appl. Phys. Lett. **49**, 1086 (1986).
[6] S. Sen, F. Capasso, A. Hutchison, and A. Y. Cho, Electron. Lett. **23**, 1229 (1987).
[7] M. Tsuchiya and H. Sasaki, Appl. Phys. Lett. **50**, 1503 (1987).
[8] D. Vakhshoori and S. Wang, J. Appl. Phys. **62**, 3474 (1987).
[9] P. K. Bhattacharya, M. V. Rao, and M.-J. Tsai, J. Appl. Phys. **54**, 5096 (1983).
[10] F.-Y. Juang, P. K. Bhattacharya, and J. Singh, Appl. Phys. Lett. **48**, 290 (1986).
[11] H. Ohnishi, T. Inata, S. Muto, N. Yokoyama, and A. Shibatomi, Appl. Phys. Lett. **49**, 1248 (1986).
[12] A. S. Brown, J. A. Henige, and M. J. Delaney, Appl. Phys. Lett. **52**, 1142 (1988).
[13] J. Singh, S. Dudley, B. Davies, and K. Bajaj, J. Appl. Phys. **60**, 3167 (1986).
[14] S. Collins, D. Lowe, and J. R. Barker, J. Appl. Phys. **63**, 142 (1988).