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Negative Differential Resistance Characteristics of an $In_{0.53}Ga_{0.47}As/In_{1-x}Al_xAs$ Pseudomorphic Resonant Tunneling Barrier Grown by MBE

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We have studied the effect of barrier height on the negative differential resistance characteristics of $In_{0.53}Ga_{0.47}As/In_{1-x}Al_xAs$ ($0.65 \leq x \leq 1$) pseudomorphic resonant tunneling barriers (RTBs) grown by MBE. A peak-to-valley current (J_p/J_v) ratio of 14 (300K) and 35 (77K) with a high peak-current density (J_p) of 2.3×10^4 A/cm^2 was achieved for a resonant tunneling barrier structure of $In_{0.53}Ga_{0.47}As$ (15 atomic layers)/AlAs (9 atomic layers). These J_p/J_v values are almost three times larger than the largest J_p/J_v ratio with a compatible J_p observed so far for any RTB structure at both 300K and 77K.

1. Introduction

Great improvements[1-7] have been made in the negative differential resistance (NDR) characteristics of the resonant tunneling barrier (RTB) structure, since it was first demonstrated in 1973 by Tsu and Esaki.[8] However, its characteristics, such as peak-current density and peak-to-valley current ratio, are not yet of a high enough level to allow its application to new functional devices, such as the resonant-tunneling hot electron transistor (RHET)[9] and the resonant-tunneling bipolar transistor.[10] We recently reported the barrier-width[11] and well-width[12] dependence of the NDR of InGaAs/InAlAs RTB structures, lattice-matched to InP, and demonstrated a NDR, much improved over conventional $GaAs/Al_xGa_{1-x}As$ RTBs. The potential barrier height is another important parameter affecting RTB structures. In fact, an improved room-temperature NDR of $GaAs/Al_xGa_{1-x}As$ RTBs was achieved by Tsuchiya et al[2], using an AlAs barrier layer. In this paper, we report on our studies on the effect of barrier height on the NDR characteristics of $In_{0.53}Ga_{0.47}As/In_{1-x}Al_xAs$ pseudomorphic RTBs.

2. Experimental

The $In_{1-x}Al_xAs/In_{0.53}Ga_{0.47}As/In_{1-x}Al_xAs$ pseudomorphic RTB structure was grown on a n^+-InP (100) substrate at 470°C by MBE. Figure 1 shows a schematic cross-section of an $In_{0.53}Ga_{0.47}As/In_{1-x}Al_xAs$ RTB diode and its energy band diagram. It consists of a Si-doped n-$In_{0.53}Ga_{0.47}As$ (1×10^{18} cm^{-3}) layer, an undoped $In_{0.53}Ga_{0.47}As$ spacer-layer (15 Å), an undoped $In_{1-x}Al_xAs$ (x=0.65, 0.74, 1) barrier-layer (9 atomic layers), an undoped $In_{0.53}Ga_{0.47}As$ well-layer (15 atomic layers), an undoped $In_{1-x}Al_xAs$ (x=0.65, 0.74,

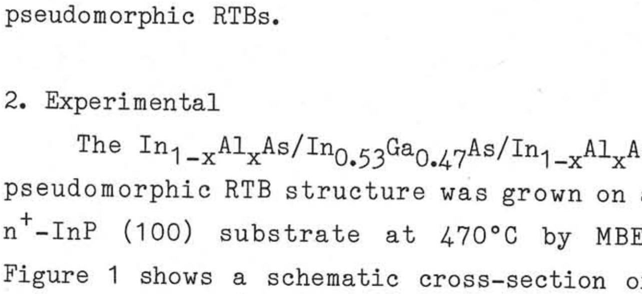

Figure 1 Schematic cross-section of an $In_{0.53}Ga_{0.47}As/In_{1-x}Al_xAs$ pseudomorpic RTB grown on an n^+-InP substrate and its energy band diagram.

1) barrier-layer (9 atomic layers), an undoped $In_{0.53}Ga_{0.47}As$ spacer-layer (15 Å) and a Si doped n-$In_{0.53}Ga_{0.47}As$ (1×10^{18} cm^{-3}) layer. The n-InGaAs layers far from the RTB were highly doped with Si to 2×10^{19} cm^{-3}, and the top and bottom electrodes of the diodes were formed using Au non-alloyed ohmic contacts. The thickness of the pseudomorphic layer $In_{1-x}Al_xAs$ barriers (about 24 Å for AlAs) is much less than the critical thickness (about 100 Å for AlAs) given by Matthews[13] for the formation of misfit dislocations in strained multilayers.

3. Results and Discussion

The current-voltage characteristics at room-temperature of the $In_{0.53}Ga_{0.47}As$/AlAs pseudomorphic RTB structures are shown in figure 2. For the $In_{0.53}Ga_{0.47}As$/AlAs pseudomorphic RTB with a higher barrier height, an excellent peak-to-valley current ratio of 14 with a peak-current density of 2.3×10^4 A/cm^2 was obtained at room-temperature, and the peak-to-valley current ratio further increased with decreasing temperature and reached a maximum of 35 at 77K with $J_p=2.3\times10^4$ A/cm^2. The peak-to-valley current ratio of the $In_{0.53}Ga_{0.47}As$/AlAs RTB is the best obtained for any RTB.

Figure 3 shows the dependence of the peak-current density (J_p) and peak-to-valley current ratio (J_p/J_v) of the NDR region at both 300K and 77K, as a function of the x-value of the $In_{1-x}Al_xAs$ barrier layer. At 300K, the peak-current density decreases from 7.2-8.9×10^4 A/cm^2 to 1.7-2.7×10^4 A/cm^2 as the x-value increases from 0.65 to 1. However, the J_p/J_v ratio increases linearly from 5.5-6.1 to as high as 13.0-14.3 as the x-value increases. The excellent peak-to-valley current ratio at room-temperature can be attributed to the large potential barrier height at the InGaAs/$In_{1-x}Al_xAs$ interface because a higher barrier height is effective in reducing the non-resonant, thermionic component[2] of the valley-current due to thermally excited electrons both tunneling through higher quantum levels and surmounting the barrier. The peak-current density is almost independent of the temperature. The valley-current density, however, is strongly temperature-dependent and the resultant peak-to-valley current ratio increased by 2-2.5 times as the temperature was decreased to 77K. The reason for the high peak-to-valley current ratio at 77K is

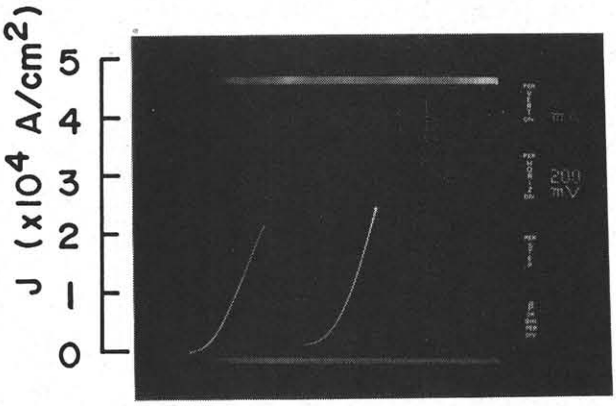

Figure 2 Current-voltage characteristics at 300K for an $In_{0.53}Ga_{0.47}As$/AlAs pseudomorpic RTB.

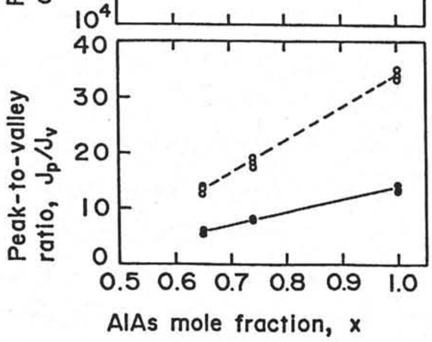

Figure 3 Peak-current density (J_p) and peak-to-valley current ratio (J_p/J_v) of an $In_{0.53}Ga_{0.47}As$/$In_{1-x}Al_xAs$ resonant tunneling barrier at 300K and 77K as function of the AlAs mole fraction, x.

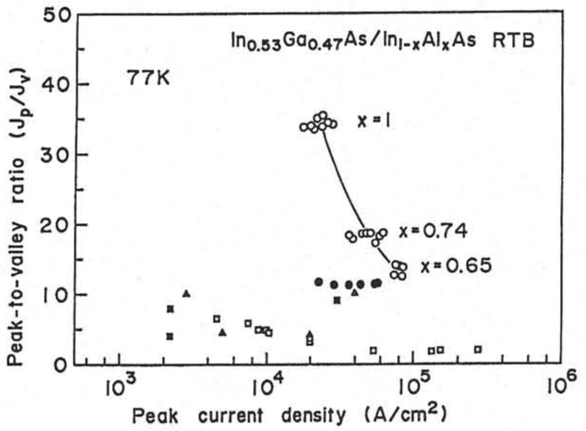

Figure 4 Peak-to-valley current ratio in the negative differential resistance region of $In_{0.53}Ga_{0.47}As/In_{1-x}Al_xAs$ pseudomorpic RTB at 77K as a function of the peak-current density. Data for GaAs/ $Al_xGa_{1-x}As$ and $In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$ RTB structure is also plotted: (▲) after ref.2,3,4; (■) after ref.5,6; (△) after ref.7; (●) after ref.11,12; (□) after ref.14.

as yet not understood. Although the large barrier-height might still be effective in reducing the thermionic current at 77K, it is hard to believe that the thermionic current is the main component of the valley-current at such a low temperature.

Figure 4 shows the peak-to-valley current ratio at 77K as a function of the peak-current density observed in $In_{0.53}Ga_{0.47}As$/ $In_{1-x}Al_xAs$ RTBs, compared with previous data of GaAs/AlGaAs[2-7,14] and $In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$[11,12] RTBs. It can been seen that the InGaAs/AlAs pseudomorphic RTBs exhibit both a remarkably high peak-to-valley current ratio and a high peak-current density.

Our result indicates that the stress in $In_{0.53}Ga_{0.47}As$/AlAs has no adverse effect on the peak-to-valley current ratio. On the contrary, the stress is expected to enhance electron tunneling of the RTB through reduction of both the electron effective mass and barrier height of the AlAs barrier layer.

Table 1. Measured and calculated peak-current density (77K) of a pseudomorphic InGaAs/AlAs RTB structure with parameters used for the calculation.

	Peak-current density (J_p)
Calculated	2.2×10^4 A/cm^2
Measured	1.7-2.7×10^4 A/cm^2

Parameters:	
Conduction-band discontinuity	1.20 eV
Electron effective mass (AlAs)	$0.14m_0$
(InGaAs)	$0.042m_0$
Barrier width	23.7 Å
Well width	44.0 Å

If the stress at the InGaAs/AlAs interface due to a lattice-mismatch of 3.7% is accommodated completely by tensile strain in the thin AlAs layers, the lattice constant parallel to the interface, $a^{\parallel}_{AlAs}$, is equal to $a^{\parallel}_{InGaAs}$ ($=a_{InP}=5.86$ Å). The lattice constant in the z-direction (normal to the interface), a^{z}_{AlAs}, becomes 5.46 Å by the relation of $(a^{z}_{AlAs}-a_{AlAs})/a_{AlAs}=-2C_{12}/C_{11}\cdot(a^{\parallel}_{AlAs}-a_{AlAs})/a_{AlAs}$, where $C_{11}=1.202\times10^{12}$ dyne/cm^2, and $C_{12}=0.570\times10^{12}$ dyne/cm^2 are the elastic stiffnesses of AlAs. According to a tight-binding calculation[15], such strain results in the lowering of the Γ-band minimum by 0.166 eV and a reduction in the electron effective mass from $0.15m_0$ (the unstrained case) to $0.14m_0$. The calculation also indicates a raising of the X-band minimum near $(0,0,2\pi/a)$ by 0.148 eV. By assuming a conduction-band (Γ) discontinuity of $\Delta E_c=0.6\,\Delta E_g$ ($\Delta E_g=E^{\Gamma}_{gAlAs}-E^{\Gamma}_{gInGaAs}=3.03$ eV-0.76 eV$=2.27$ eV) for the unstrained AlAs/InGaAs interface, we obtained a much larger potential barrier height of 1.2 eV for the Γ-band and 0.65 eV for the X-band, with an AlAs barrier. Table 1 shows the peak-current density, J_p, obtained by a simple resonant tunneling calculation[12] using the parameters given above for an InGaAs/AlAs pseudomorphic

RTB. The calculated J_p value of $2.2x10^4$ A/cm^2 agrees well with the observed value of $1.7\text{-}2.7x10^4$ A/cm^2, in spite of the crude assumption used.

The strained AlAs is still an indirect band-gap material, and recently the effect of the indirect valleys of the AlAs barrier layer has been pointed out for GaAs/AlAs RTBs.[16] It should be noted, however, that the barrier height (0.65 eV) corresponding to the indirect (x) AlAs valley in InGaAs/AlAs RTBs is higher than that for GaAs/AlAs RTBs (0.2 eV), primarily because of the narrower band-gap of InGaAs. Thererfore we believe that the tunneling current through the upper valley becomes less for InGaAs/AlAs RTBs than for GaAs/AlAs RTBs.

4. Summary

We studied the effect of barrier height on the negative differential resistance characteristics of $In_{0.53}Ga_{0.47}As/In_{1-x}Al_xAs$ pseudomorphic RTBs, and found that a high barrier-height plays an important role in obtaining an exceedingly high peak-to-valley current ratio, while maintaining a high peak-current density, not only at 300K but also at 77k. Dramatically improved negative differential resistance characteristics, $J_p/J_v=14$ with $J_p=2.3x10^4$ A/cm^2 at 300K and $J_p/J_v=35$ with $J_p=2.3x10^4$ A/cm^2 at 77K, have been obtained by preparing a large barrier-height $In_{0.53}Ga_{0.47}As$ (15 atomic layers)/AlAs (9 atomic layers) pseudomorphic RTB grown on an InP substrate. These J_p/J_v values are almost three times larger than the largest peak-to-valley current ratio with a compatible peak-current density observed so far for any RTB structure at both 77K and 300K.

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