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Nanoelectronic devices—resonant tunnelling diodes grown on InP substrates by molecular beam epitaxy with peak to valley current ratio of 17 at room temperature

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This paper reports that InAs/$In_{0.53}Ga_{0.47}As$/AlAs resonant tunnelling diodes have been grown on InP substrates by molecular beam epitaxy. Peak to valley current ratio of these devices is 17 at 300K. A peak current density of 3kA/cm^2 has been obtained for diodes with AlAs barriers of ten monolayers, and an $In_{0.53}Ga_{0.47}As$ well of eight monolayers with four monolayers of InAs insert layer. The effects of growth interruption for smoothing potential barrier interfaces have been investigated by high resolution transmission electron microscope.

Keywords: resonant tunnelling diode, InP substrate, molecular beam epitaxy, high resolution transmission electron microscope

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1. Introduction

To increase the density of integrated circuits, the conventional method has tried to continually decrease the minimum device size. This approach places increasing demands on the device of wafer processing, such as pattern-defining lithography. An alternate approach is to increase device functionality with constant device size by including quantum functional devices, of which resonant tunnelling diodes (RTDs) are the most promising for ultrahigh frequency, ultrahigh speed and low power consumption devices.[1−3] The use of quantum devices places stringent demands on epitaxial growth, because of the extreme sensitivity of these devices to variations in layer thickness and composition. For the above applications the peak current and the current peak-to-valley ratio (PVR) of RTDs are the two major figures of merits.[4,5] So the choice of material system is of great importance. $In_{0.53}Ga_{0.47}As$/AlAs/InP material system shows the highest peak to valley current ratio and the highest speed at room temperature due to the large increase in the conduction band discontinuities of potential barrier, electron mobility of emitter and collector, and allows a nonalloyed ohmic contact with contact resistivity as low as $1.7\times10^{-8}\Omega\cdot$cm^2[6,7] relative to the GaAs material system. This is an important point since the extrinsic voltage drop at the ohmic contact could be serious with ρ_c of 10^{-6} to $10^{-5}\Omega\cdot$cm^2 when the current density of the RTD is as high as 10^5A/cm^2. The use of a low band gap material like InAs in the well is expected to reduce the well width required for a given well energy level with respect to the $In_{0.53}Ga_{0.47}As$ emitter conduction band. RTD structures are grown by molecular beam epitaxy for abrupt heterointerfaces and precise control of ultrathin layers. We report the typical I-V characteristics of InAs/$In_{0.53}Ga_{0.47}As$/AlAs/InP RTDs with good PVR and atomically flat interfaces.

2. Material growth and device fabrication

The RTDs were grown in an EPI GEN II MBE system by using individual In, Ga, Al, As and Si effusion cells, all of 7N's purity. Polished (100) Fe-doped

semi-insulating 2-inch InP substrates were used in this work. Native oxides on InP substrates were removed in the cleaning chamber by heating to 500°C under As_4 pressure of about 133×10^{-5}Pa. The growth rate for lattice-matched $In_{0.53}Ga_{0.47}As$ was 3.07Å/s and that for AlAs, InAs was 1.65Å/s and 1.69Å/s respectively. Silicon was used as the n-type dopant. The substrate holder was rotated at 10r/min during the growth. Growth interruptions and an *in situ* reflection high energy electron diffraction (RHEED) intensity oscillation technique were used to aid the growth of the thin barrier and well layers. The substrate temperature during the growth of $In_{0.53}Ga_{0.47}As$ and AlAs was maintained at 480°C. However, the substrate temperature was lowered to 420°C when the InAs well was grown.

Figure 1 shows a schematic cross-section of InAs/$In_{0.53}Ga_{0.47}As$/AlAs RTD structure and its energy band diagram. Two Si-doped n-$In_{0.53}Ga_{0.47}As$ buffer layers of 0.2 μm thickness each with doping concentrations of $5\times10^{18}cm^{-3}$ and $2\times10^{17}cm^{-3}$ respectively were grown on InP substrate. The double barrier structure is sandwiched between 6 monolayers (ML) thick, undoped spacer layer. The undoped $In_{0.53}Ga_{0.47}As$ spacer layers are introduced to suppress the possible diffusion of Si. The thickness of the top and bottom AlAs barrier is 10 ML. The well consists of 4 ML lattice matched $In_{0.53}Ga_{0.47}As$, 4 ML of strained InAs, and 4 ML of lattice matched $In_{0.53}Ga_{0.47}As$. The active region is covered with three 100-nm-thick $In_{0.53}Ga_{0.47}As$ layers with Si-doping concentrations of $2\times10^{17}cm^{-3}$, $2\times10^{18}cm^{-3}$, $2\times10^{19}cm^{-3}$ respectively. Growth interruptions before and after each AlAs layer, allowed smoothing the AlAs barrier interfaces but did not fully compensate for effusion cell flux transient effects[8,9] which caused growth rate variations during the short growth times of ultrathin layers. After the epitaxial growth, Mesa diodes, with device areas ranging from 6×6 μm^2 to 6×10 μm^2, were fabricated by using conventional photolithographic techniques. Nonalloyed ohmic contacts of Cr/Au=50/100 nm which were deposited at 200°C were used for the topside and bottom side.

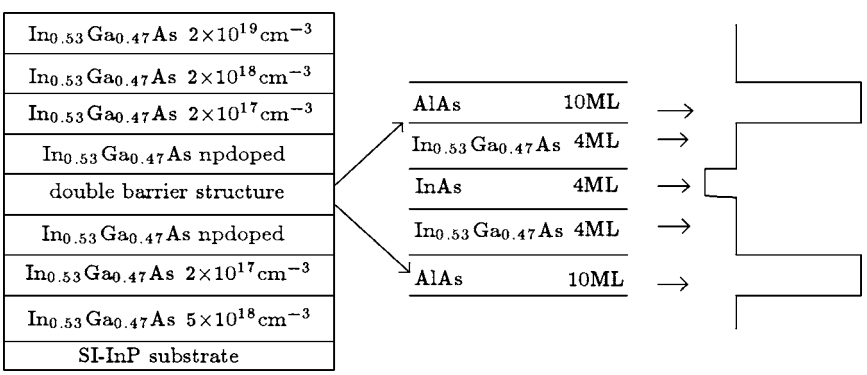


Fig.1. Cross-sectional layer structure of a AlAs/$In_{0.53}Ga_{0.47}As$ double barrier RTD grown on InP substrate, and its energy band diagram.

3. Results and discussions

The DC current–voltage (I–V) characteristics were measured with a KEITHLEY4200 semiconductor parameter analyser. Figure 2 shows the I-V characteristics of a typical device with a peak-to-valley current ratio of 17 and a peak current density of approximate 3kA/cm^2 in positive bias (corresponding to electron flow from the substrate contact towards the top contact).

'Plateaulike'[10–13] structures can be seen in Fig.2 and are due to the intrinsic instability of RTDs in the negative differential resistance region. Bistability can also been observed, and is found to be dependent in some extent on external circuit parameters.

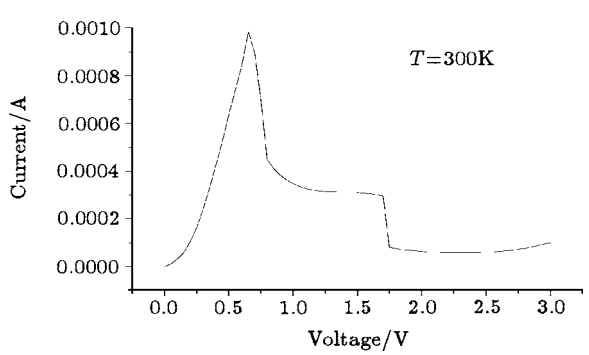


Fig.2. I–V characteristics of a $6\times6\mu m^2$ InAs / $In_{0.53}Ga_{0.47}As$ / AlAs RTD at T=300K with J_p/J_v= 17 (V_p= 0.65 V, V_v= 2.29 V).

With regard to PVR and J_p's imperfection, there are many possible reasons, such as inferior crystal quality inducing electron mobility to decrease, growth rate too fast resulting in atoms clustering during the growth, growth interruptions at AlAs barrier interfaces too short causing to less flat interfaces and barrier thickness asymmetry, etc. In our experiments, $In_{0.53}Ga_{0.47}As$ epitaxial crystal quality might be the main reason because the electron mobility of $In_{0.53}Ga_{0.47}As$ measured by Hall measurement was not very satisfactory. According to improving growth conditions and adjusting parameters, we believe that a better PVR and J_p will be attained. This attempt is now in progress.

We have also investigated the influence of growth interruptions for smoothing potential AlAs barrier interfaces by high resolution transmission electron microscope (HRTEM). The samples were measured by JEM-2010 HRTEM for which the resolution was 0.2 nm. Figure 3(a) and 3(b) show micrographs with $AlAs/In_{0.53}Ga_{0.47}As$ potential barrier interface interruptions of 15 and 40 s respectively. In Fig.3(a), $AlAs/In_{0.53}Ga_{0.47}As$ interfaces are quite rougher than that in Fig.3(b). From these micrographs, with prolonging growth interruptions before and after AlAs barriers, barrier interfaces would be flatter. Sufficient time allows Al atoms to migrate along the surface adequately for smoothing interfaces and avoids clustering during the growth interruptions. With different growth interruptions at double potential barrier interfaces, we have fabricated corresponding devices for which better I-V characteristics could be obtained from RTDs of flat interfaces. Obviously, interface roughness plays an important role on peak current density and valley current density. Growth interruptions of only 15s at AlAs barrier interfaces even had no negative differential resistance in I-V characteristics due to inferior interfaces quality as can be seen in Fig.3(a) as well as RHEED patterns. For Fig.3(b) a PVR of 17 was obtained with growth interruptions of 40 s. And we found that I–V characteristics would be degraded when growth interruptions exceeded 90s. Concerning long growth interruptions at AlAs barrier interfaces resulting in degraded I–V characteristics, one has the opinion that incorporation of impurity results in the accumulation of deep levels in the growth chamber as detected by Deep Level Transient Spectroscopy. So growth interruptions at barrier interfaces were fatal to I–V characteristics of RTDs. So we conclude that growth interruptions in excess of 30s and less than 90s at AlAs barrier interfaces are necessary.

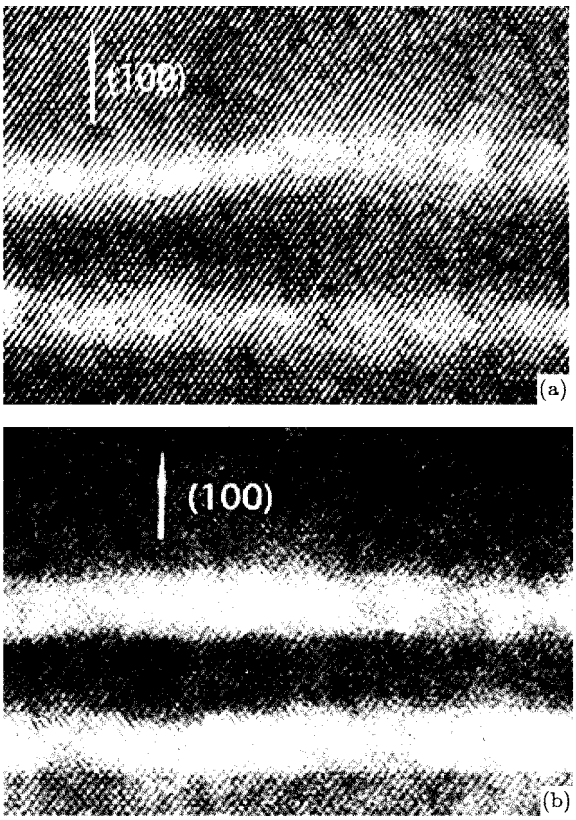


Fig.3. (a) HRTEM cross sectional micrograph across $AlAs/In_{0.53}Ga_{0.47}As$ interfaces for growth interruptions of 15 s. (b) HRTEM cross sectional micrograph across $AlAs/In_{0.53}Ga_{0.47}As$ interfaces for growth interruptions of 40 s

4. Conclusion

In summary, RTD structures with sub-well InAs and AlAs barriers based InP substrates have been fabricated, which show improved PVR than that based GaAs substrates. An important advantage of using InAs in the well is that it permits a thinner well while still maintaining a low resonance energy level with respect to the emitter conduction band and gives an additional degree of freedom in designing RTDs. HRTEM cross sectional micrographs show essential growth interruptions at AlAs barrier interfaces are absolutely necessary.

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