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Dependence of current–voltage characteristics of pseudomorphic AlAs/$In_{0.53}Ga_{0.47}As$/InAs resonant tunnelling diodes on quantum well widths

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This paper studies the dependence of $I-V$ characteristics on quantum well widths in AlAs/$In_{0.53}Ga_{0.47}As$ and AlAs/$In_{0.53}Ga_{0.47}As$/InAs resonant tunnelling structures grown on InP substrates. It shows that the peak and the valley current density in the negative differential resistance region are closely related with quantum well width. The measured peak current density, valley current densities and peak-to-valley current ratio of resonant tunnelling diodes are continually decreasing with increasing well width.

Keywords: resonant tunnelling diode, molecular beam epitaxy
PACC: 7360L, 7980

1. Introduction

Resonant transmission of electrons in double-barrier tunnelling structures[1,2] is one of the most interesting quantum-mechanical phenomena in ultrathin heterostructures. Resonant tunnelling diodes (RTDs) exhibit very strong nonlinearity with short time response which makes them attractive in nonlinear applications for millimetre and sub-millimetre wavelengths.[3,4] RTDs have already demonstrated their potential for a variety of high speed applications.[5,6] The terahertz (THz) frequency range is receiving considerable attention recently because of its many possible applications, such as imaging, spectroscopy in chemistry and biotechnology, and high-capacity communications. For these applications, compact and coherent solid-state light sources are important key components. RTDs have been considered as one of the candidates for the THz oscillators at room temperature.[7,8] InP-based resonant tunnelling devices have the potential to be key devices in the near future and have been intensively studied in recent years. In this paper, we investigated the effect of quantum well (QW) width on $I-V$ characteristics of AlAs/$In_{0.53}Ga_{0.47}As$ and AlAs/$In_{0.53}Ga_{0.47}As$/InAs RTDs based InP substrates grown by molecular beam epitaxy (MBE) at room temperature.

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2. Experiments

The RTDs were grown in a Vecoo GENII MBE system. Polished (100) Fe-doped semi-insulating 2-inch InP substrates were used in this work. The two types of epitaxial structures are given in Figs.1(a) and 1(b). All samples had the same thick AlAs barriers and access regions with a stepped doping profile from $2\times10^{17}\,\mathrm{cm}^{-3}$ to $1\times10^{19}\,\mathrm{cm}^{-3}$. They differ mainly owing to the strained InAs layers so that the structure resembles a triple well resonant tunnelling structure. The associated benefits are a reduction of the peak voltage and higher peak-to-valley current ratio (PVR) because the ground state can be lowered. Device areas ranging from $2\times2\,\mu\mathrm{m}^2$ to $5\times5\,\mu\mathrm{m}^2$ were fabricated by using electron beam and conventional UV-line lithography techniques in a microwave-compatible two-step mesa technology. Devices were covered with Si_3N_4 as passivation layer. Ohmic contacts were made by using Ti/Pt/Au for the top and bottom contacts. In that case, the devices were connected to low-loss transmission lines by means of air-bridge interconnection which largely reduced parasitic capacitance. The details of material growth and device fabrication have been described elsewhere.[9–11] A scanning electron microscopy (SEM) of a representative device is shown in Fig.2, which clearly shows that one $2\,\mu$m thick air-bridge interconnects the top mesa and the pad.

100 nm n^+ $In_{0.53}Ga_{0.47}As$ collector contact
100 nm $In_{0.53}Ga_{0.47}As$ collector
1.5 nm $In_{0.53}Ga_{0.47}As$ -Spacer
2.83 nm AlAs
1.2 nm $In_{0.53}Ga_{0.47}As$
variable InAs
1.2 nm $In_{0.53}Ga_{0.47}As$
2.83 nm AlAs
1.5 nm $In_{0.53}Ga_{0.47}As$ -Spacer
100 nm $In_{0.53}Ga_{0.47}As$ emitter
300 nm n^+ $In_{0.53}Ga_{0.47}As$ emitter contact
Semi-insulating InP sbustrate

(a)

100 nm n^+ $In_{0.53}Ga_{0.47}As$ collector contact
100 nm $In_{0.53}Ga_{0.47}As$ collector
1.5 nm $In_{0.53}Ga_{0.47}As$ -Spacer
2.83 nm AlAs
variable $In_{0.53}Ga_{0.47}As$
2.83 nm AlAs
1.5 nm $In_{0.53}Ga_{0.47}As$ -Spacer
100 nm $In_{0.53}Ga_{0.47}As$ emitter
300 nm n^+ $In_{0.53}Ga_{0.47}As$ emitter contact
Semi-insulating InP sbustrate

(b)

Fig.1. (a) Schematic cross section of an AlAs/$In_{0.53}Ga_{0.47}As$/InAs resonant tunnelling diode. (b) Schematic cross section of an AlAs/$In_{0.53}Ga_{0.47}As$ resonant tunnelling diode.

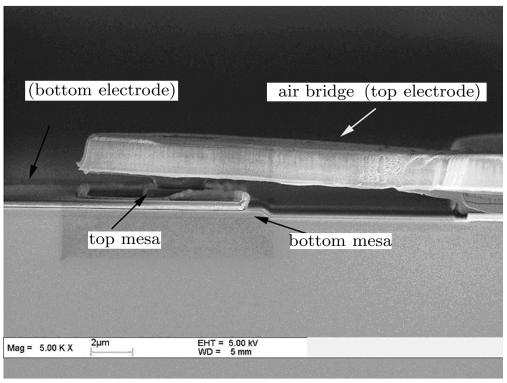


Fig.2. SEM photograph of a fabricated RTD based InP substrate.

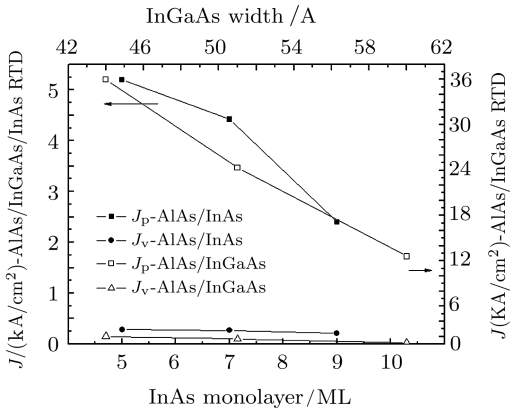


Fig.3. J_p and J_v of AlAs/$In_{0.53}Ga_{0.47}As$/InAs and AlAs/$In_{0.53}Ga_{0.47}As$ RTDs at room temperature as a function of QW width.

3. Results and discussion

The DC current–voltage ($I-V$) characteristics were measured in the negative differential resistance region with a KEITHLEY4200 semiconductor parameter analyser at room temperature. With four monolayer of InAs sub-well in QW a peak current density (J_p) of 5.2 KA/cm^2 and a good PVR of 24 were obtained for this diode at room temperature. The peak (J_p) and valley (J_v) current densities in AlAs/$In_{0.53}Ga_{0.47}As$ and AlAs/$In_{0.53}Ga_{0.47}As$/InAs RTDs are shown in Fig.3 as a function of the QW width (L_{QW}). Both J_p and J_v increase as the well width is reduced in Fig.3. Figure 4 shows the PVR of RTDs measured as a function of L_{QW}. With the increase of the QW width PVR is continuously declining. Increasing the QW width results in higher voltage drop on QW region which shifts to the peak and valley voltage (V_p, V_v) to higher values.

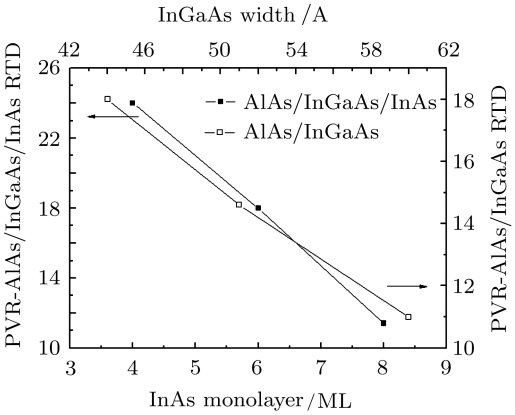


Fig.4. PVR of AlAs/$In_{0.53}Ga_{0.47}As$/InAs and AlAs/$In_{0.53}Ga_{0.47}As$ RTDs at room temperature as a function of QW width.

The J_p can be controlled by the following parameters: (a) barrier height, (b) barrier thickness, (c) well width, (d) impurity concentration in the electrode regions outside the barriers, and (e) spacer thickness. In above factors L_{QW} could affect the shape of the transmission coefficient. When L_{QW} is increased, the reso-

nant current is reduced because of the following reasons. The increase of L_{QW} lowers the first resonance energy, which leads to the increase of the effective barrier height. The increase of the effective barrier height causes the sharpening of the transmission coefficient around the resonance peak, or equivalently, the decrease of the peak transmission coefficient width, which results in the decrease of the resonant tunnelling current. Another possible cause for the smaller J_p is that wider QW implies more impurity accumulated in QW during the material growth, which reduced J_p due to the higher probability of resonant tunnelling electron & impurity scattering in double-barrier structure. The J_v includes inelastic tunnelling current, nonresonant tunnelling current through higher lying quasicontinuum levels, thermionic current and photon assisted electron tunnelling across the double-barrier. When L_{QW} is increased, the increase of the effective barrier height suppressed the thermionic current over the double-barrier structure. This results in the decrease of leak current over the double barrier as L_{QW} is increased. As J_p and J_v are decreased together, the PVR of RTDs is also lowered as L_{QW} is increased. Although PVR is sensitive to the change of J_p and J_v, the change of J_v dominates the magnitude of PVR. For the integration of RTDs with the high electron mobility transistor (HEMT) the match of working current between two devices is necessary. The tune of working current by adjusting QW width of RTDs is easier than by changing the concentration of two-dimensional electron gas in the channel of HEMT. The exact match of working current between RTDs and HEMT is also required to research due to the extreme sensitivity of RTDs to variations in layer thickness and composition.

4. Conclusions

In conclusion, we studied and explained the dependence of QW width on the negative differential resistance of AlAs/$In_{0.53}Ga_{0.47}As$ and AlAs/$In_{0.53}Ga_{0.47}As$/InAs RTDs at room temperature. We have found that J_p, J_v, and PVR can be controlled by changing QW width. By adjusting QW width properly, we obtained a high PVR of 24 at room temperature.

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