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Observation of the current–voltage plateau-like structure of resonant tunnelling diode with prewells under different magnetic fields

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We have grown resonant tunnelling diodes (RTDs) with different sized emitter prewells and without a prewell. The current–voltage (I–V) characteristics of them in different magnetic fields were investigated. Two important phenomena were observed. First, a high magnetic field can destroy the plateau-like structure in the I–V curves of the RTD. This phenomenon is ascribed to the fact that the high magnetic field will demolish the coupling between the energy level in the main quantum well and that in the emitter quantum well or in the prewell. Secondly, the existence and size of the prewell are also important factors influencing the plateau-like structure.

Keywords: resonant tunnelling diode, plateau-like structure, magnetic field
PACC: 7360L, 7280E

1. Introduction

Since the first observation two decades ago of resonant tunnelling from a double-barrier made of GaAs–GaAlAs grown by molecular beam epitaxy (MBE),[1] as one candidate of high frequency devices, the resonant tunnelling diode (RTD) has been studied extensively.[2−8] The effect of magnetic field on the electronic transport in the resonant tunnelling structure (RTS) has also attracted attention for some time. In 1986, Mendez *et al*[3] reported the magnetotunnelling phenomena in RTD in the presence of a magnetic field perpendicular to the heterostructure interface. When the magnetic field is applied parallel to the electric field, the electron motion becomes quasi-one-dimensional and the electron states in the plane perpendicular to the barriers direction are quantized in discrete Landau levels. This dimensional reduction of electron motion has a great effect on the I–V characteristic of the RTD.

In 1987, Goldman *et al*[9] first observed the plateau-like structure in the current–voltage (I–V) curve of the RTD. Because the phenomenon might reflect the electron motion in nanometre-sized devices, a great amount of research on it has been performed.[8−11] Despite this, the explanation of the origin of the plateau-like structure remained controversial for a long time. Goldman *et al* thought that intrinsic charge bistability caused it. Sollner[10] attributed it to external circuit-induced high-frequency oscillations of current in the negative differential resistance (NDR) region of devices. More recently, Zhao *et al*[8] ascribed it to the coupling between the energy level in the emitter quantum well (EQW) and that in the main quantum well. The EQW is formed by the energy band bending while the bias is applied to devices.

Although much research on the RTD and the effect of the magnetic field has been performed, the effect of magnetic field on the RTS with a quantum well in front of the main well (named as prewell) is still unknown. In order to explore deeply the effect of transverse magnetic field on the plateau-like structure, we grew several samples with different sized prewells and without a prewell. After making the RTD, a magnetic field perpendicular to the heterostructure interface was

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applied to the devices. We demonstrated the I–V characteristics of different-width prewells in different magnetic field intensity and found that the plateau-like structure in the I–V curves would disappear in higher magnetic field intensity. Additionally, the effect of prewell size on the plateau-like structure was experimentally proved.

2. Experiment and results

Our samples were grown on semi-insulated GaAs substrates by MBE. The difference of these samples was in the existence and width of the prewell. Sample A was the traditional double-barrier structure. There were 4 and 6 nm prewells in sample B and sample C respectively. The quantum well material in all the samples was $In_{0.16}Ga_{0.84}As$ and the barrier material was AlAs for a better peak–valley ratio. The density of Si-doping in the top contact region and in the bottom contact region was $1\times10^{18}/cm^3$. The other layers were undoped. The structure details of these samples are shown in Tables 1–3. $In_{0.16}Ga_{0.84}As$ layers were grown at 640°C. AlAs and GaAs layers were grown at 700°C. The devices were fabricated using contact photolithography and wet chemical etching. Au/Ge/Ni was used to make the ohmic contact to the two Si-doped GaAs layers. The time and temperature of ohmic metallization were 30 s and 430°C, respectively. Mesa area was $12\times12\,\mu m^2$. The I–V curves of the samples were measured at 1.5 K. A 66.7 pF capacitor was connected parallel with the devices to eliminate the external circuit oscillation. A magnetic field perpendicular to the heterostructure interface with its intensity ranging from 0 to 10 T was applied in measurements. All I–V characteristics were recorded with a Keithley 2300 source measure unit.

Table 1. The structure details of sample A.

Ingredient	Thickness/nm	Doping density (Si doping)/cm^{-3}
GaAs	300	1.5×10^{18}
GaAs	10	undoped
AlAs	2.5	undoped
$In_{0.16}Ga_{0.84}As$	4	undoped
AlAs	2.5	undoped
GaAs	10	undoped
GaAs	600	1.5×10^{18}
Semi-insulated GaAs substrate		

Table 2. The structure details of sample B.

Ingredient	Thickness/nm	Doping density (Si doping)/cm^{-3}
GaAs	300	1.5×10^{18}
GaAs	10	undoped
$In_{0.16}Ga_{0.84}As$	4	undoped
AlAs	2.5	undoped
$In_{0.16}Ga_{0.84}As$	4	undoped
AlAs	2.5	undoped
GaAs	10	undoped
GaAs	600	1.5×10^{18}
Semi-insulated GaAs substrate		

Table 3. The structure details of sample C.

Ingredient	Thickness/nm	Doping density (Si doping)/cm^{-3}
GaAs	300	1.5×10^{18}
GaAs	10	undoped
$In_{0.16}Ga_{0.84}As$	6	undoped
AlAs	2.5	undoped
$In_{0.16}Ga_{0.84}As$	4	undoped
AlAs	2.5	undoped
GaAs	10	undoped
GaAs	600	1.5×10^{18}
Semi-insulated GaAs substrate		

Figures 1–3 show the I–V curves of samples A, B and C in different magnetic fields respectively. Because sample A was a symmetric structure and the effect of EQW was the focus of research, only the data in the range of $V > 0$ were adopted. For comparison with sample A, the data of the other two samples were also acquired under similar conditions. From these figures, we can observe the shift of peak voltage with the increase of magnetic field intensity. The shift of peak voltage in I–V characteristic of samples is greater than that of valley voltage. In zero magnetic field, the plateau-like structure of samples B and C is distinct, and that of sample A is barely observed. With the increase of magnetic field, the plateau-like structure of sample A disappears rapidly, while that of sample C also disappears when the magnetic field intensity is equal to 10 T; but that of sample B does not disappear during the variation of the magnetic field intensity from 0 to 10 T.

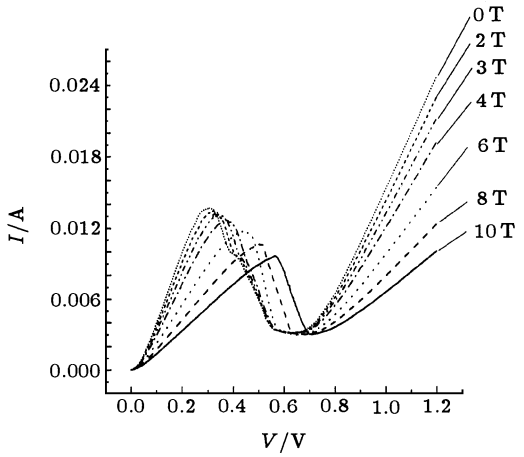


Fig.1. The I–V characteristic of sample A in different magnetic fields.

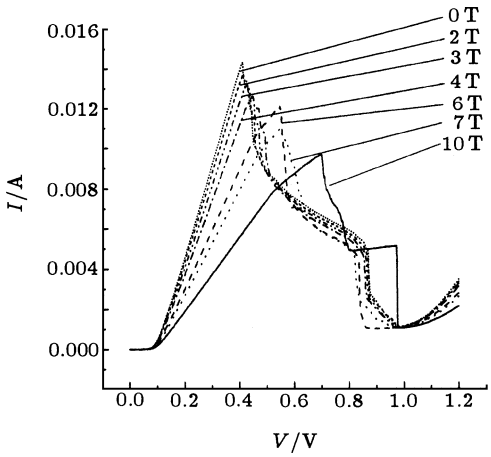


Fig.2. The I–V characteristic of sample B in different magnetic fields.

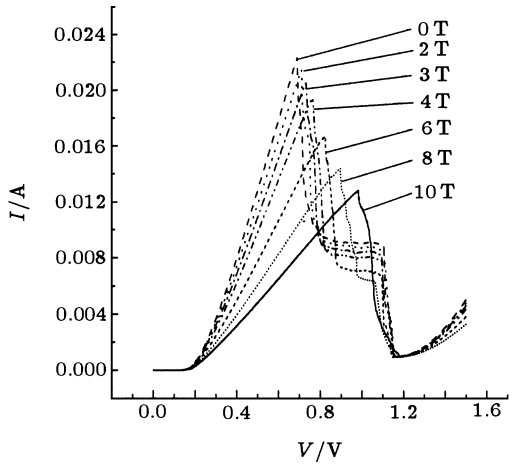


Fig.3. The I–V characteristic of sample C in different magnetic fields.

3. Discussion

Two important phenomena were noticed. Firstly, the magnetic field parallel to the electric field could destroy the plateau-like structure in the usual I–V characteristics. Secondly, the existence of prewell could change the form of the plateau-like structure and the plateau-like structure of the RTD with different-sized prewells disappears under the magnetic field of different intensities.

During the formation of the plateau-like region, the coupling between the energy level in the main quantum well (QW) and that in the EQW is a key factor.[8] When the bias is applied to sample A, the emitter depletion leads to the formation of the EQW. So a quasi-bound state may begin to couple with the energy level in the QW. Initially, the quasi-bound state is below the energy level in the QW and the coupling tends to push the energy level in the QW upward. At the same time, the bias applied to sample A tends to depress the energy level in the QW downward. When the bias continues to increase to a critical value, the energy level in the QW will be just below that in the EQW. From then on, the coupling and the bias will together push down the energy level in the QW. At this time, the current shows a rapid decrease and the plateau-like region results. When an additional magnetic field is applied parallel to the electric field, the electron energy is quantized into Landau levels in the electric field direction. This would demolish the coupling between the energy levels in the main QW and in the EQW. So the change of magnetic field intensity must have a strong effect on the plateau-like structure. Thus, when the magnetic field intensity increases to a certain value, the plateau-like structure will disappear.

In samples B and C, the effect of prewells is similar to that of the EQW in sample A. A higher magnetic field tends to destroy the plateau-like structure of samples B and C. However, in the I–V characteristics of samples B and C, the effect of magnetic field on the plateau-like structure is different from that in the I–V characteristics of sample A. The difference between electron energy states in the prewells of samples B and C and that in the EQW of sample A should be responsible for the above phenomenon. In the EQW, the electron energy state is the quasi-bound state, whereas that in the prewell of samples B and C is the bound state similar to that in a standard QW. Thus, the coupling between the energy levels in QW and in the prewell is stronger, and to wipe out the plateau-like structure also requires a higher magnetic field. Moreover, because the width of the prewell can influence

the electron energy state in prewells, it can also have an effect on the plateau-like structure in the I–V characteristic of the RTD. In a narrower prewell of sample C, the electron energy state is closer to the quasi-bound state in EQW. Thus, the plateau-like structure of sample C can disappear in a 10 T magnetic field and that of sample B does not disappear during the variation of the magnetic field intensity from 0 to 10 T.

4. Conclusion

The coupling between the energy levels in QW and in EQW or in prewell is the key factor during the formation or quenching of the plateau-like structure in the I–V curves of RTD. Moreover, a high magnetic field can demolish the coupling. Sequentially, the high magnetic field can destroy the plateau-like structure in the I–V curves of RTD.

We have observed that the RTDs with different-sized prewell and without the prewell showed different plateau-like structures in zero and magnetic fields. The energy states in prewells and EQW are different from each other. Therefore, the coupling mentioned above is also influenced by these structure parameters of RTD. So the existence and size of prewells are also important factors influencing the plateau-like structure.

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