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Relationship between the electric performance and the photoluminescence spectra of resonant tunnelling diodes

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Resonant tunnelling diodes with different structures were grown. Their photoluminescence spectra were investigated. By contrast, the luminescence in the quantum well is separated from that of other epilayers. The result is obtained that the exciton of the luminescence in the quantum well is partly come from the cap layer in the experiment. So the photoluminescence spectrum is closely related to the electron transport in the resonant tunnelling diode structure. This offers a method by which the important performance of resonant tunnelling diode could be forecast by analysing the integrated photoluminescence intensities.

Keywords: resonant tunnelling diode, photoluminescence, negative differential resistance, integrated luminescence intensity

PACC: 7855E, 7360L

1. Introduction

Since the pioneering work of Chang, Tsu and Esaki on the resonant tunnelling diode (RTD),[1] RTD has attracted much attention for its potential excellent application in high-frequency devices. In recent years, most works have been directed to practical application such as RTD fabrication, high-frequency devices and the integration of RTD with other high-frequency devices.[2−5] As the unique electric characteristic of RTD, the negative differential resistance (NDR) in the current–voltage (I–V) curve is the precondition for these RTD applications.

Photoluminescence (PL) measurement as a usual method has been used much on RTD. But the measurements were mainly focused on the exciton transition and the fine energy band structure.[6−7] The aim of this paper is to find the relation between the PL spectra and the RTD electric performance. Because the structure parameter is the key element affecting the RTD electric performance, the RTDs with different structure sizes were grown and PL measurements were made. By comparing these results, we found a way to predict before making a device whether an RTD could show the NDR in its I–V characteristic or not. This paper firstly investigates the PL spectra and I–V characteristics of RTD with different structures. Then we distinguish the luminescence in the quantum well from that in other layers. An explanation about the electronic source of luminescence in the quantum well is given. The luminescence integral intensities in the quantum well and the cap layers of RTDs with different barrier widths are shown. It was observed that a key point was the size of quantum barrier of the RTD structure. It is the RTD of just the same size as the barrier width that shows the NDR phenomenon.

2. Device structure and fabrication process

All samples used in the present work have the traditional double-barrier structure. The epitaxial layer was grown on the semi-insulating GaAs (001) substrate. All GaAs epilayers were grown at 580°C, the

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AlAs epilayers at 620°C and the InGaAs epilayers at 520°C. In the structure of sample A, B and C, there were two n^+-GaAs layers ($1\times10^{18}/cm^3$) on the top and bottom of the epitaxial layer.

Their thickness was 300nm and 500nm, respectively. Two 10nm GaAs spacer layers were located outside the double-barrier structure. The double-barrier structure consists of two quantum barriers and a 6nm quantum well. Three samples with different quantum barrier widths were grown. Their widths were 9nm, 6nm and 2.5nm, respectively. In sample D the top and bottom layers were not doped and this sample was not made into a device. In sample E, the width of the InGaAs layer was 8nm. The structure details are shown in Tables 1 and 2.

Table 1. Basic structure of samples.

Name of layer	Ingredient	Si doping density/cm^{-3}
Top cap layer	GaAs	1.5×10^{18}
Top spacer layer	GaAs	undoped
Top barrier layer	AlAs	Undoped
Well layer	$In_{0.16}Ga_{0.84}As$	Undoped
Bottom barrier layer	AlAs	Undoped
Bottom spacer layer	GaAs	Undoped
Bottom cap layer	GaAs	1.5×10^{18}
Substrate	SI-GaAs	

Table 2. Structure details of all samples.

	Top cap layer thickness/nm	Spacer layer thickness/nm	Barrier thickness/nm	Well thickness/nm	Bottom cap layer thickness/nm
Sample A	300	10	9	6	500
Sample B	300	10	6	6	500
Sample C	300	10	2.5	6	500
Sample D	30 (undoped)	10	2.5	6	500 (undoped)
Sample E	300	10	2.5	8	500

PL measurements of Samples A, B, C, D, E were made. The basic conditions used for PL measurements were:

(i) Ar-ion laser was used as exciting source, with wavelength set at 514.5nm. The excitation power density was 300 mW/cm^2.

(ii) The detectors were InSb-detector and Si-diode detector.

(iii) The PL measurement temperature was set at 77K.

The devices were fabricated using contact photolithography and wet chemical etching. Au/Ge/Ni was used to make the ohmic contact to two Si-doped GaAs layers. The time and temperature of ohmic metallization were 30s and 430°C, respectively. The mesa area of devices was $12\times12\mu m^2$.

3. Experimental results and discussion

Figure 1 shows the PL spectra of samples A, B and C. The two high energy luminescence peaks of samples A and B are located at 1.52eV and 1.48eV. The higher peak obviously comes from GaAs luminescence, because it agrees with the GaAs band gap. The heavy doping in cap layers gives the 1.48eV luminescence peak. Because the structures of these three samples are similar and the locations of the luminescence peaks are close to each other, the luminescence mechanism of the three samples should be the same. Figure 1 also shows that, compared with the PL of sample C, the low energy luminescence peak of sample B is shifted to a higher energy and the position of high energy luminescence peaks does not change when the width of barriers (W_b) increases. According to the quantum mechanics, the change of W_b could only bring about the shift of the energy level in the quantum well. At the same time the low energy peak in sample B is located at 1.3917eV. This agrees with the calculated result of 1.3995eV,[8] obtained by the model-solid theory[9] and effective mass approach.[10] Moreover, the results of Ref.[11] prove that the width of barriers hardly changes the location of the level in the well, when the width of barriers exceeds 4nm. So, in Fig.1, the location of the low energy luminescence peak of sample A is almost the same as of that of Sample B. Figure 2 shows the PL spectra of samples C and E. Their structures were the same except for the well width. In their spectra, the low energy peak obviously has shifted and there is almost no change in other features. The above two phenomena prove that the low energy luminescence peak comes from the electron transition in the well.

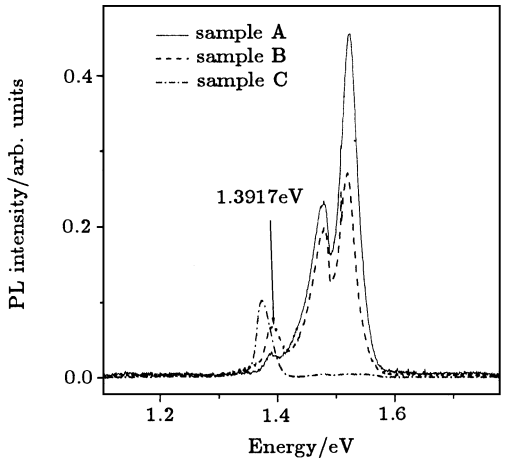


Fig.1. PL of samples A, B and C.

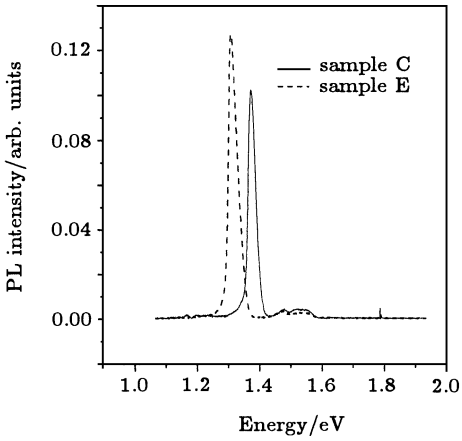


Fig.2. PL of samples C and E.

In our PL measurement, the material of the barrier was AlAs, which is an indirect-gap semiconductor. Therefore, its luminescence was very weak and our detector hardly detected the luminescence in AlAs layers. Figure 3 shows the PL spectra of samples C and D. There were the 300nm GaAs doping layers on the top and bottom of sample C, while there were no doping layer on the top and the bottom of sample D. This was the only difference between sample C and D in structure. In the PL spectra of sample D, the high energy luminescence peak reduces to one small peak located at 1.506 eV. This value agrees with the GaAs band gap. At the same time, the low energy luminescence peaks are almost unchanged. In any event, the high energy luminescence peaks come from the cap layers and spacer layers.

The excitons in the low energy luminescence peak should consist of two parts. The first part comes from the direct excitation in the well by the laser. The second part should come from the carrier activated

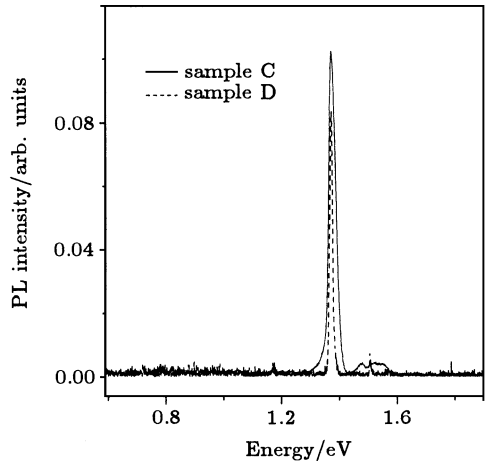


Fig.3. PL of samples C and D.

in the doping cap layer and tunnelled through the barrier into the quantum well. From Fig.1, when the width of the quantum barriers is bigger, the PL intensity of low energy luminescence band notably weakens and the high energy luminescence band notably increases. This is because the increase of the barrier decreases the probability of electron tunnelling through the barrier and thus more activated electron are stopped outside the well. Figure 4 shows the integrated PL intensities of samples A, B and C. It shows that the PL integrated intensities of the low energy luminescence (luminescence in well) gradually increases as the width of quantum barriers is reduced. This is also because the reduction of quantum barrier width has increased the probability of tunnelling and more electrons participate in the luminescence in the well. All the results prove that the electrons in the luminescence of the well partly come from those that have been activated in the cap layer and then tunnelled through the barriers.

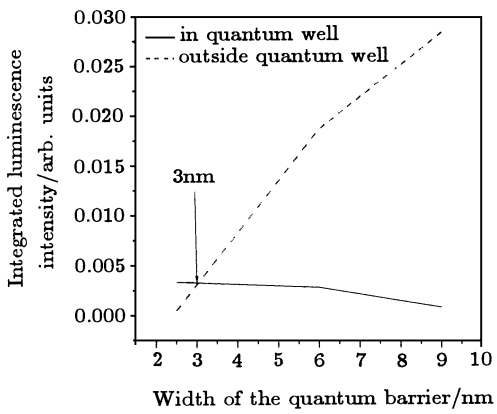


Fig.4. Integrated PL intensities of samples A, B and C in and outside the quantum well.

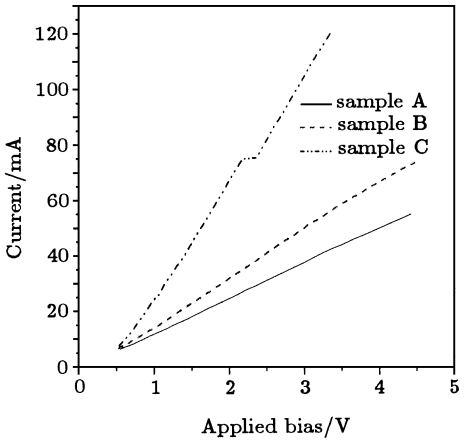


Fig.5. I–V characteristics of samples A, B and C.

Since the intensities of the high energy luminescence peaks and the low energy one are closely related to the number of electrons tunnelling through the quantum barriers and that of electrons not tunnelling through the quantum barriers, respectively, we reasonably believe that a critical thickness of barrier could be found by comparing the two parts of integrated luminescence intensities. When the width of quantum barriers is shorter than that critical point, the tunnelling process becomes the main mechanism of the electron transport in RTD. Because the tunnelling process is the key element affecting the emergence of NDR and performance of RTD, they could be forecast by the PL spectra of RTD. In our experiment, we found that the intersection of two integrated luminescence intensities in Fig.4 may be regarded as that point. In Fig.5, the I–V curves of samples A, B and C also proved that. The barrier width of samples A and B was below the intersection and the I–V curves of them did not show the NDR. At the same time, the I–V curves of sample C showed the NDR, as its width was higher than that point.

4. Conclusion

In conclusion, we have grown the RTD with different barrier widths and performed PL measurement with them. By comparing RTDs of different structures, the different luminescence peaks were separated, and we found that the excitons in the quantum well luminescence partly come from those that were activated in the cap layer and have transported into the well by tunnelling effect. The tunnelling effect is the important mechanism for RTD's practical application. Therefore, we connect the RTD performance with its PL spectra to derive a method by which whether NDR of RTD emerges or not could be forecast by analysing the integrated PL intensities in the PL spectra. This could enable us to fix on the right structure parameter of RTD more easily.

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