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Design and Realization of Resonant Tunneling Diodes with New Material Structure *

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Abstract: A new material structure with $Al_{0.22}Ga_{0.78}As/In_{0.15}Ga_{0.85}As/GaAs$ emitter spacer layer and $GaAs/In_{0.15}Ga_{0.85}As/GaAs$ well for resonant tunneling diodes is designed and the corresponding device is fabricated. RTDs DC characteristics are measured at room temperature. Peak-to-valley current ratio and the available current density for RTDs at room temperature are computed. Analysis on these results suggests that adjusting material structure and optimizing fabrication processes will be an effective means to improve the quality of RTDs.

Key words: resonant tunneling diodes; quantum effect; DC characterization
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1 Introduction

Resonant tunneling diode (RTD) is one of the most promising devices in the field of nanometer devices. RTD based on resonant tunneling quantum effect has received great attention for their potential applications in digital circuits[1]. Its research will promote the development of nanometer-devices' integrated circuits. Resonant tunneling structure, which gives rise to resonant tunneling quantum effect, is the crucial part of RTD. Recently, some studies[2~6] have been done from conventional GaAs/AlGaAs system to the use of $In_xGa_{1-x}As$ wells and AlAs or AlSb barriers and thereby cut down the non-resonant currents. The incorporation of a low band-gap material like InAs in the well reduces the well width required for a given level with respect to emitter conduction-band edge and improves the peak-to-valley current ratio[7]. The use of the lower band-gap pseudomorphic $In_{0.15}Ga_{0.85}As$ spacer layers gives rise to a significantly enhanced peak-to-valley ratio (PVR) of 3.2 and 14 at 300K and 77K, respectively, as opposed to 2 and 5 obtained with the use of conventional GaAs spacers in identical structure[6]. Riechert *et al*.[8] also reported that the insertion of a "prewell" consisting of

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4nm of undoped $In_{0.15}$-$Ga_{0.85}As$ increased the typical peak-to-valley current ratio of a 4nm-$Al_{0.6}Ga_{0.4}As$/3nm-GaAs double-barrier structure from 4.5 ∶1 (without InGaAs prewell) to 5.7 ∶1 (with prewell). In addition, some results[9] obtained by Wie and Choi demonstrated that a lower band-gap InGaAs layer as an emitter spacer layer greatly improves the peak current density, while as a collector spacer layer it has little effect. In this letter, we propose a new asymmetric material structure for RTD with the lower band-gap $In_{0.15}Ga_{0.85}As$ emitter spacer and well and corresponding RTD devices are fabricated successfully. DC characteristics of RTDs at room temperature are measured and analyzed, which establishes the basis of further development for RTD integrated circuits.

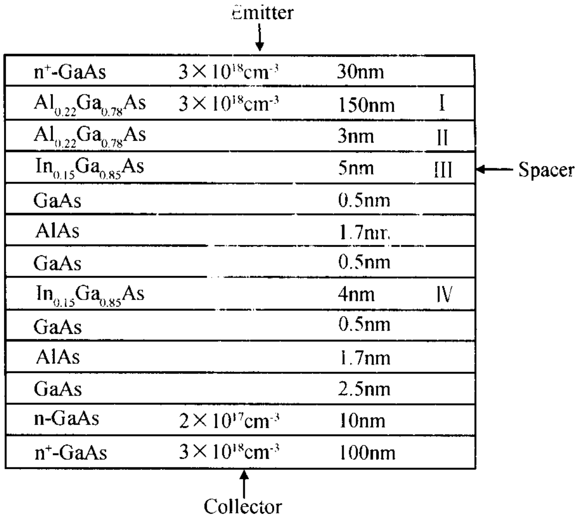
2 Design of RTD new material structure

Under Luryi's sequential tunneling picture[10], the peak current flows when the quasi-stationary resonance level in quantum well is aligned with the bottom (E_0) of the bottom electron energy distribution in the emitter spacer region. Therefore, the peak current density (J_p) is proportional to $E_f - E_0$, where E_f is the Fermi level in the emitter region. Due to experimental valley current density (J_v), the peak current density J_p' can be estimated as follows[9]:

$$J_p' = J_p - J_v = B(E_f - E_0) \qquad (1)$$

where B is a proportional constant. The peak current density can be increased if E_0, the minimum electron energy in the emitter spacer region, can be lowered, and E_f, the Fermi level in the emitter region, can be increased.

According the above analyses, we design and grow the structure for RTDs on PHEMT material structure by molecular beam epitaxy (MBE) shown in Fig. 1. Figure 2 gives the corresponding schematic conduction band diagram. In region Ⅰ of emitter, wide bandgap $Al_{0.22}Ga_{0.78}As$ replaces narrow bandgap GaAs, and dopant concentration increases to $3 \times 10^{18} cm^{-3}$ compared to the conventional value of $2 \times 10^{17} cm^{-3}$. In region Ⅱ of emitter, wide bandgap $Al_{0.22}Ga_{0.78}As$ replaces narrow bandgap GaAs. The above two changes will increase the Fermi level E_f in the emitter region. In region Ⅲ of emitter, conventional GaAs spacer layer is partly replaced by narrow bandgap $In_{0.15}$-$Ga_{0.85}As$. Because the value of ΔE_c for the $In_{0.15}$-$Ga_{0.85}As$/$Al_{0.22}Ga_{0.78}As$ interface is approximately equal to 0.434eV, the use of $In_xGa_{1-x}As$ material in the emitter spacer layer lowers the bottom E_0 of electron energy distribution in the emitter spacer region, increasing the number of resonant tunneling electrons at resonant voltage. In region Ⅳ of resonant tunneling structure, we insert narrow bandgap $In_{0.15}Ga_{0.85}As$ in conventional GaAs quantum well. It will decrease resonant voltage by adding narrow bandgap $In_{0.15}Ga_{0.85}As$.



n^+-GaAs	$3 \times 10^{18} cm^{-3}$	30nm	
$Al_{0.22}Ga_{0.78}As$	$3 \times 10^{18} cm^{-3}$	150nm	I
$Al_{0.22}Ga_{0.78}As$		3nm	II
$In_{0.15}Ga_{0.85}As$		5nm	III
GaAs		0.5nm	
AlAs		1.7nm	
GaAs		0.5nm	
$In_{0.15}Ga_{0.85}As$		4nm	IV
GaAs		0.5nm	
AlAs		1.7nm	
GaAs		2.5nm	
n-GaAs	$2 \times 10^{17} cm^{-3}$	10nm	
n^+-GaAs	$3 \times 10^{18} cm^{-3}$	100nm	

Fig. 1 Schematic material structure for RTD

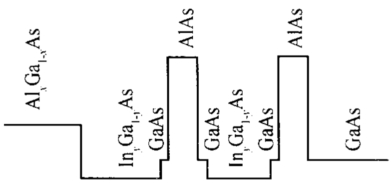


Fig. 2 Schematic conduction band diagram of structure with $x = 0.22$, $y = 0.15$ for RTD in Fig. 1

3 Fabrication processes of RTD

The devices were fabricated using conventional wet etching and lift-off processes. Firstly, RTD layers were etched by $NH_4OH:H_2O_2:H_2O$ (3∶1∶96) down to the collector n^+-GaAs layer using photoresist as a mask. Secondly, a SiO_2 film was deposited with PECVD. Thirdly, the top and bottom electrodes patterns of RTD were formed by developing photoresist, then SiO_2 film on the top of the electrodes was etched with $HF:H_2O$ (10∶1). And Ni/AuGe/Au alloy was splashed and lifted off to make contacts to emitter and collector. Finally these devices were annealed by using rapid heating and cooling procedure in a forming-gas environment so that good ohmic contacts were formed. The schematic structure for RTDs is shown in Fig. 3.

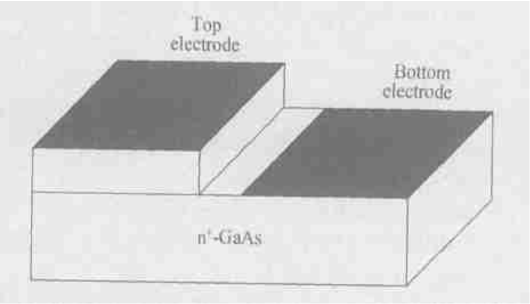


Fig. 3　Schematic structure for RTDs

4　Results and discussion

The RTD devices are fabricated using the mentioned processes. Figures 4 and 5 show the DC current-voltage characteristics of fabricated RTDs measured by Keithley4200 semiconductor characterization system at room temperature. The RTD in Fig. 4 is identified as RTD A and the one in Fig. 5 is identified as RTD B. The annealing temperatures of ohmic contact of RTD A and RTD B are 380 and 370 ℃, respectively.

The quality of a RTD is usually determined by the peak current density J_p and the peak-to-valley current ratio (PVCR $\equiv J_p/J_v$), where J_p and J_v are the peak and valley current densities associated with the NDR (negative differential resistance) region respectively. The completion of RTD circuit logic function requires PVCR as high as possible. Another important parameter is the available current density $\Delta J \equiv J_p - J_v$. High current density is required for fast charging and discharging of RTD. These two parameters are very crucial to the application of RTD on high-speed digital integrated circuits.

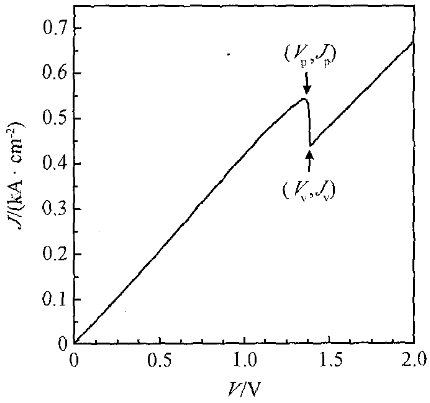


Fig. 4　Current density versus voltage curves for RTD A at room temperature

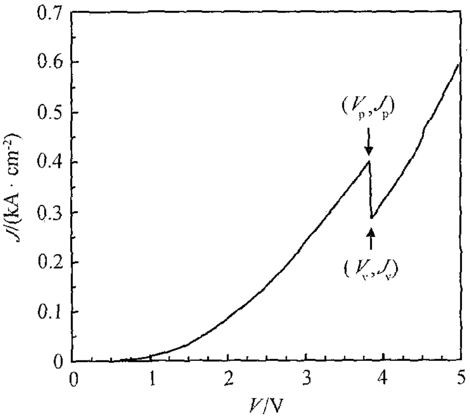


Fig. 5　Current density versus voltage curves for RTD B at room-temperature

For RTD A and RTD B, the peak current density J_p, the valley current density J_v, the peak-valley ratio PVCR, the available current density ΔJ and the peak voltage V_p at room temperature are listed in Table 1, and all show these above characteristics are different for RTD A and RTD B.

Table 1　Electronics characteristics of RTDs at room temperature

RTD	V_p / V	J_p / (kA ·cm^{-2})	J_v / (kA ·cm^{-2})	PVCR	ΔJ / (kA ·cm^{-2})
A	1.36	0.54	0.43	1.26	0.11
B	3.82	0.40	0.28	1.43	0.12

According to Table 1, it is found that the fabrication processes have significant effect on the characteristics of RTDs even if the material structure of RTDs remains the same. The PVCR of RTD A is smaller than that one of RTD B. According to experiment and simulation results[11,12], the spacer thickness has a significant impact on a RTD characteristics. So the PVCR difference between RTD A and RTD B is probably because the deeper diffusion of dopants at 380 ℃ than at 370 ℃ affect the spacer thickness of RTD A and RTD B. It is possible to enhance the PVCR by modifying the emitter width for RTD A. Besides, the peak voltage V_p of RTD A is also smaller than that one of RTD B because of the different characteristics of ohmic contacts for RTD A and RTD B. Therefore, we will be able to increase the peak-to-valley ratio PVCR and the available current ΔJ for RTD by improving material structure and optimizing fabrication processes. This work is expected to promote and speed up the application of RTD on high-speed digital integrated circuits.

5 Conclusion

In this paper, a new material structure with $Al_{0.22}Ga_{0.78}As/In_{0.15}Ga_{0.85}As/GaAs$ emitter spacer layer and $GaAs/In_{0.15}Ga_{0.85}As/GaAs$ well for resonant tunneling diodes is designed and the corresponding devices are fabricated.

The electronic characteristics of RTDs have been measured and analyzed. To the RTD with ohmic contact fabricated at 380 ℃, the peak current density J_p and the valley current density J_v are found to be 0.54 and 0.43kA/cm^2, respectively. The peak-valley ratio PVCR is about 1.26. The peak voltage V_p is about 1.36V and the available current density ΔJ is about 0.11kA/cm^2. To the RTD with ohmic contact fabricated at 370 ℃, the peak current density J_p and the valley current density J_v are found to be 0.40 and 0.28kA/cm^2, respectively. The peak-valley ratio PVCR is about 1.43. The peak voltage V_p is about 3.82V. The valley voltage V_v is about 3.84V and the available current density ΔJ is about 0.12kA/cm^2.

In addition, it is found that the electronics characteristics of RTDs are determined not only by material structure but also by fabrication process. It suggests that adjusting material structure and optimizing fabrication processes will be the effective means to improve the quality of RTDs. This work is very helpful to promote the application of RTD on high-speed digital integrated circuits.

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一种新材料结构的 RTD 器件的设计及实现 *

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摘要: 设计了一种带有 $Al_{0.22}Ga_{0.78}As/In_{0.15}Ga_{0.85}As/GaAs$ 发射极空间层和 $GaAs/In_{0.15}Ga_{0.85}As/GaAs$ 量子阱的共振隧穿二极管(RTD)材料结构,并且成功地制作了相应的 RTD 器件. 在室温下,测试了 RTD 器件的直流特性,计算了 RTD 器件的峰谷电流比和可资电流密度. 在分析器件特性的基础上,指出调整材料结构和优化工艺参数将进一步提高 RTD 器件的性能.

关键词: 共振隧穿二极管; 量子效应; 直流特性

EEACC: 2530C; 2560Z

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