Theoretical analysis of AlGaN/GaN resonant tunnelling diodes with step heterojunctions spacer and sub-quantum well

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Abstract. In this paper, we proposed to use step heterojunctions emitter spacer (SHES) and InGaN sub-quantum well in AlGaN/GaN/AlGaN double barrier resonant tunnelling diodes (RTDs). Theoretical analysis of RTD with SHES and InGaN sub-quantum well was presented, which indicated that the negative differential resistance (NDR) characteristic was improved. And the simulation results, peak current density \( J_P = 82.67 \, mA/\mu m^2 \), the peak-to-valley current ratio \( P/V = 3.38 \), and intrinsic negative differential resistance \( R_N = -0.147 \Omega \) at room temperature, verified the improvement of NDR characteristic brought about by SHES and InGaN sub-quantum well. Both the theoretical analysis and simulation results showed that the device performance, especially the average oscillator output power presented great improvement and reached \( 2.77 \, mW/\mu m^2 \) magnitude. And the resistive cut-off frequency would benefit a lot from the relatively small \( R_N \) as well. Our works provide an important alternative to the current approaches in designing new structure GaN based RTD for practical high frequency and high power applications.

1. Introduction

Resonant tunneling diodes (RTDs) characterized by negative differential resistance (NDR) have attracted researchers’ attention because of its potential wide range application prospects, among which terahertz oscillator is an important branch and has been studied in many papers [1-4]. The lower junction capacitance of RTD comparing with other NDR devices, such as Esaki tunnel and transferred electron devices [5], makes it an excellent candidate in the generation and detection of terahertz waves. And enormous amounts of previous researches focused on AlAs/InGaAs/AlAs quantum well structural RTDs. However, it showed a tremendous challenge to design a stable and reliable terahertz oscillator when it comes to high frequency and high power. Apparently, the output power and temperature stability have become the bottleneck for conventional RTDs (such as GaAs based RTD). Naturally, gallium nitride (GaN) based RTDs gained researchers’ attention gradually these years due to its large electron effective mass [5] and longitudinal optical phonon energy [6] enable it very high speed devices, especially the advantage of wide bandgap (~3.43eV), large conduction band discontinuity, high carrier mobility, and the thermal stability [8] comparing with second generation semiconductors paved the way toward higher frequency, higher power applications at room temperature for GaN based RTDs.

Despite of the great promises for GaN based RTDs, the measurements of devices, theoretical analysis, and simulations all have indicated that there are still plenty of works, for example, decreasing device series resistance \( (R_S) \), realizing reproducible NDR characteristic and higher output power etc., need to do before practical applications. The typical figures of merit in NDR devices are the intrinsic
negative differential resistance $R_N$ ($R_N = \Delta V \times \Delta f^{-1}$), peak-to-valley current ratio PVCR ($PVCR = I_p \times I_v^{-1}$), and average oscillator output power $P_{MAX}$ ($P_{MAX} = 3\Delta f \times \Delta V \times 10^6$ [9]). The $R_N$ is particularly important for increasing the resistive cutoff frequency $f_R$ ($f_R \propto (R_N C)^{-1}$) for RTD. In recent researches, GaN/AlGaN (GaN/AlN) and GaN/InAlN (GaN/InN) are the hotspots, and many groups have spent a lot of attention on them these years [5, 8, 10-12]. The works of Bayram, C. et al. verified that the reproducibility of NDR benefit a lot from the low Al content AlGaN barrier [5, 8, 10]. Subhra C. et al. combined RTD and HEMT together [13]. Yang et al. have simulated the RTD oscillator instantaneous characteristics [14]. And for AlGaN/GaN/AlGaN double barrier RTDs, its peak current density ($J_P$) and PVCR reached around 1.23–11.2mA/μm² and 1.03–9.03 [6, 15], respectively. However, papers reported about GaN based RTDs rarely focus on $f_R$ and $P_{MAX}$ at present, which means the problems about increasing peak current ($J_P$) and PVCR and decreasing valley current ($I_V$), $R_N$ and $R_S$ are still great challenges. So for the sake of promoting RTD device performance, in this paper, we proposed to use SHES and InGaN sub-well for AlGaN/GaN/AlGaN double barrier RTDs to increase $J_P$, and decrease $R_N$. Meanwhile, $P_{MAX}$ was promoted a lot as well.

2. Device structure and energy band analysis

The device structure of GaN based RTD with SHES and sub-quantum well is shown in figure 1 (a). First, the double barrier (DB) region consists of $Al_{0.2}Ga_{0.8}N$ (1.5nm), $Al_{0.2}Ga_{0.2}N$ (1.5nm), and $Al_{0.2}Ga_{0.2}N$ (1.5nm), thus, an inherent lattice mismatch between materials is inevitable [10]. However, the critical thickness above which dislocations are generated is inversely proportional to Al content for GaN homo-epitaxial growth [10]. And in our simulations, the NDR phenomenon weakened with the increasing of the DB region thickness, and when the thickness was greater than 1.8nm, the NDR phenomenon disappeared nearly. This NDR degradation verified the critical thickness (~1.8nm for $Al_{0.2}Ga_{0.8}N$) and the negative effect of the dislocations on the NDR phenomenon. So in our works, low aluminum content (20%) and thin barrier (1.5nm) was employed to form DB region which could minimize active layer related dislocations [10]. Next, AlGaN (5nm) layer with its Al content reducing in ladder type is the emitter spacer, namely the step heterojunctions emitter spacer (SHES) region in figure 1 (a). Then $In_{0.6}Ga_{0.4}N$ (2nm) layer was inserted between DB region and SHES region, which formed a sub-quantum well before the DB region. The collector spacer consists of 5nm GaN layer. Finally, emitter region and collector region is composed of heavily doped, 1x10²¹cm⁻³ $Al_{0.2}Ga_{0.8}N$ layer on the top and GaN layer on the bottom, respectively. The heavily doped emitter and collector region are aimed to ensure the Ohmic contact between the device and electrodes.

![Device structure and energy band diagram](image)

**Figure 1.** (a) The device structure and (b) energy band diagram and electron density before resonant of GaN based RTD with SHES and sub-quantum well.

The energy band diagram of GaN based RTD with SHES and sub-quantum well is shown in figure 1 (b). As you can see, the $In_{0.6}Ga_{0.4}N$ sub-quantum well turned the tunneling mode for electrons from 3D-2D-3D mechanism to 2D-2D mechanism which means higher tunneling efficiency and consequently
higher peak current. Then, the SHES formed continuous heterojunctions, which means continuous electron triangular quantum wells are formed, thus 2-dimensional electron gas (2DEG) was produced in these triangular quantum wells. The 2DEG accumulated before DB region which you can see from the electron density curve in figure 1 (b), with much higher mobility than common electron carriers accelerated electrons tunneling process from emitter region to the DB region, which could boost the peak current immensely. It is indicated that the SHES and InGaN sub-well promoted the emitter region’s electron carrier mobility, and transmission coefficient which could reduce the carrier’s transportation time in the device, consequently enabling RTD higher frequency. The heavily doped Al_{0.4}Ga_{0.6}N layer acts as the emitter region offering the electron source for the tunneling process.

3. Simulation
In our simulation, the mesa was set to be 30μm². Figure 2 (a) shows the IV characteristic comparison of different structure RTDs. Apparently, the IV characteristic of RTD with SHES and InGaN sub-well is the best, having the I_p=2.48A, R_N=0.147Ω and P_{MAX}=83mW. And the device performance was elevated a lot by the SHES and sub-well comparing with previous works [6, 15]. As you can see, the peak current increase from 0.282A to 2.48A and P_{MAX} increased from 13.03mW to 83mW, both of the two typical figures of merit presented around one order of magnitude promotion while the PVCR maintained at 3.38. It is also found that the peak voltage (V_p) increased with the appearing of SHES. V_p is related with series resistance (R_S) and the difference between the bound state energies (ΔE_{(n+1,n)}) in the quantum well. And we calculated R_S using equation (1). Because the second positive resistance region of the IV curves in figure 2 (a) are approximately parallel but I_p increased a little with the SHES appearing, R_S of RTD with SHES and sub-quantum well is a little greater than RTD without them, which contributed to the increasing of V_p partly.

\[ R_S = \frac{dV}{dI} - \left( \frac{kT}{q} \right) \frac{1}{I_D} \]  \hspace{1cm} (1)

Then, V_p is also proportional to ΔE_{(n+1,n)}, but equation (2) indicates that the ΔE_{(n+1,n)} should be the same because of the same DB active regions of different structure RTDs. So the increasing of V_p may be due to the increasing of the difference between the tunnelling energy levels. And the SHES and sub-quantum well do have lowered the energy level before the DB active region which you can see from the energy band diagram in figure 1 (b).

\[ ΔE_{(n+1,n)} = E_{n+1} - E_n = \frac{\hbar^2}{2mL_w} \left( \frac{\pi}{L_w} \right)^2 [(n+1)^2 - n^2] \]  \hspace{1cm} (2)

After calculating the R_N, it was found that the absolute value of R_N decreased from 1.023 to 0.147, so for the resistive cut-off frequency f_R, it could be increased about one order of magnitude. Terahertz oscillator application of RTD will benefit a lot from the relatively small R_N. And after doing more optimizing works to decrease R_S, the maximum oscillating frequency (f_{MAX}) is expected to reach 2.07THz when the R_S=1/2R_N.
Figure 2. (a) IV characteristic comparison of different structure RTD (b) I-V characteristic of DB RTD with different In content In$_2$Ga$_{1-x}$N sub-quantum well.

Then, we studied the In content of In$_2$Ga$_{1-x}$N sub-quantum well (y range from 0.01 to 0.03), its influence on the performance of RTD is shown in figure 2 (b). Both the $I_P$ and $I_V$ are increasing with the increasing of the In content from 0.01 to 0.03, consequently, the $P_{\text{MAX}}$ increased from 51.54 to 99.4 mW. However the PVCR decreased from 4.61 to 2.68 and absolute value of $R_N$ increased from 0.098 to 0.181 which is not good for increasing the resistive cut-off frequency. However, after applying equation (1) to the IV curve of figure 3 (b), it was found that $R_S$ was decreasing with the increasing of the In content. This phenomenon may indicate a feasible method for decreasing $R_S$, thus realizing $R_S=1/2R_N$, even if sacrificing some of frequency characteristic. In our previous works, to make a trade-off between the frequency and output power characteristic, we chose the 0.02 In content for In$_2$Ga$_{1-x}$N sub-quantum well.

4. Conclusion
In this paper, we presented a comparative analysis of the electrical characteristics of GaN based RTDs with and without step heterojunctions emitter spacer (SHES) and sub-quantum well. Through theoretical analysing on the energy band and simulating the electrical characteristics at room temperature, it was verified that the SHES and sub-quantum well could elevate the RTD performance greatly. In our works, the $J_P$ and $P_{\text{MAX}}$ reached 82.67mA/μm² and 2.77mW/μm², respectively, and the PVCR maintains at 3.38. The results indicated that most of the typical figures of merits in RTD realized great magnitude promotion; especially our peak current density and output power are superior to the papers reported to date. And due to the pretty small intrinsic negative differential resistance $R_N$, while the series resistance $R_S$ meets the equation of $R_S=1/2R_N$, the maximum oscillating frequency is expected to be 2.07THz magnitude. Meanwhile, we found a feasible method to decreasing the series resistance which is favourable for realizing maximum oscillating frequency. The results of GaN based RTD with SHES and sun-quantum well in our works make RTD more applicable for high frequency and high power applications. The works we did also activate further researches toward deceasing valley current $I_V$ for increasing PVCR and decreasing $R_S$ for realizing the expected maximum oscillating frequency.

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