A RESONANT TUNNELLING STRUCTURE OF GaAs ALLOYS

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Abstract

The resonant tunneling concept in multiple quantum well structures is exhibited through transmission and current-voltage characteristics. The triangular quantum well is chosen in the device, because its response to an external electric field is at ease in comparison with that of rectangular-shaped wells. Also, a laser field is theoretically applied to the structure to show that it improves the control of the performance of the device

Keywords: Resonant tunneling, dwell time, current-voltage characteristics

INTRODUCTION

Resonant tunneling phenomena form the way of the design of quantum diodes [1] and quantum transistors [2]. The observation of the current-voltage (I-V) characteristic of a resonance tunneling diode (RTD) is actually the use of the device. It is useful the calculate the I-V properties beforehand. The formation of resonant states depending on the structural parameters such as the widths of wells and barriers, the depths of wells, and the heights of barriers formed by their semiconducting composition and their responses to the external probing fields is the mainstream of the calculations [3-5].

An external magnetic field application is employed to provide a control mechanism for the device [6]. A high-frequency laser field can also be applied to influence the transition coefficients. This is called resonance tuning and provides optical control of the current-voltage characteristics [7-9]. The geometric parameters of an RTD may not be ideal for tunneling in practice. A laser field has a restorative effect on this problem [10].

It has been found that the tunneling time is shortened and the resonance transition becomes more effective if a potential well is placed just after the emitter. This quantum well is thus named as "accelerating well" [11,12].

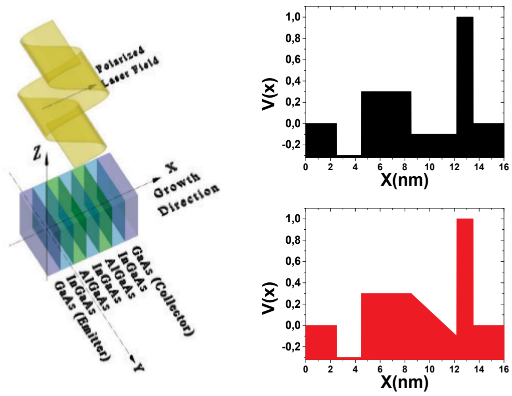

Fig. 1. Potential profiles of the resonance tunneling diodes.

The resonance tunneling structure in question includes a triangular potential well between the two barriers after the accelerating well, the absence of which is also taken into account in the I-V characteristic of the diode. Also, the laser field effect on that RTD is discussed by its appearance on the current-voltage characteristics.

THEORY

Resonance tunneling diodes can be designed as combinations of quantum wells and barriers. The two diodes shown in Fig. 1 both consist of two potential wells separated by a potential barrier, and their structures end with a sharp potential barrier before the exit to the collector. The only difference between the diodes is the shape of the well between the two barriers. The first one with a square-shaped has been studied earlier [13].

In the high-frequency limit [14], the Hamiltonian in part j for the structure is divided into N part, for an electron under an intense laser field polarized along the crystal growth direction-x

$$\left[-\frac{\hbar^2}{2m_j^*}\nabla^2 + V_j(x,\alpha_0)\right]\Phi_j(x) = E\Phi_j(x) \ , \quad 1$$

where $V_j(x,\alpha_0)$ is the laser-dressed potential given by

$$V_j(x,\alpha_0) = \frac{w}{2\pi}\int_0^{2\pi/w} V(x+\alpha(t))dt \ . \quad 2$$

In Eqs. 1 and 2, $j = 1,2,\ldots,N$ and $\alpha(t)$ in Eq.2 is the laser dressing parameter describing the effect of the laser field. It is given by $\alpha(t) = \alpha_0 \cos \omega t$ with an amplitude $\alpha_0 = \frac{eA_0}{m_1^* \omega}$. It is noted that the number N has to be extended up to ten thousand for an acceptable precision when the laser field is considered.

The electronic wave function $\Phi_j(x)$ is given by

$$\Phi_j(x) = A_j \exp(k_j x) + B_j \exp(-k_j x) \quad , \quad 3$$

where k_j is the wave number expressed as

$$k_j = \begin{cases} i\dfrac{\sqrt{2m_j^*(E-V_j)}}{\hbar}, & (E > V_j) \\ \dfrac{\sqrt{2m_j^*(V_j-E)}}{\hbar}, & (E < V_j) \end{cases} \quad . \ 4$$

Using the standard boundary conditions and the transfer matrix method given elsewhere in more detail [15], the transmission coefficient $T(E)$ and the dwell time τ are given by

$$T(E) = \frac{|A_N|^2 \hbar k_N / m_N^*}{|A_1|^2 \hbar k_1 / m_1^*} \quad 5$$

and

$$\tau = \frac{m_1^*}{\hbar k_1}\int_{x_1}^{x_N} |\psi(x)|^2 dx \quad 6$$

where $\hbar k_1 / m_1^*$ is probability density flow [16].

Finally, the current density J as a function of the applied voltage V is

$$J = A\int_0^\infty T \ln\left(\frac{1+\exp\left\{\frac{(E_F - E)}{k_B T_K}\right\}}{1+\exp\left\{\frac{(E_F - E - eV)}{k_B T_K}\right\}}\right) dE \quad ,7$$

where $A = \frac{e m_1^* k_B T_K}{2\pi^2 \hbar^3}$ and the Fermi energy was taken to be $E_F \approx 0.004\ eV$ [17].

The method described above was tested on the earlier experimental resonant tunneling diode study [18]. In the latter study, the current/current peak unity value is measured for 0.2 V and the same result is obtained by our calculations.

RESULTS AND DISCUSSIONS

An RTD requires a system consisting of two quantum wells separated by a quantum barrier, or vice versa. They can be grown to desired electronic characteristics.

In Fig.2 the transmissions of electrons from the RTD with and without potential V_2 are given as functions of electron energies. The resonance transmissions occur at the same energy found as $E_{rez} = 0{,}222\ eV$ for both structures. However, the transmission intensity and the dwell times exhibit differences between them. The first resonance transmission intensity and dwell time without V_2 structure are $T = 0{,}99$ and $t_d = 282\ fs$ against those quantities $T = 0{,}76$ and $t_d = 216\ fs$ for the structure with V_2 structure. The dwell time shortens by 23% if V_2 exists in the RTD in comparison with that of V_2 does not exist case. For this reason, the V_2 potential can be called “accelerating well”. Also, the second and third resonances with the accelerating well are sharper than the structure without it.

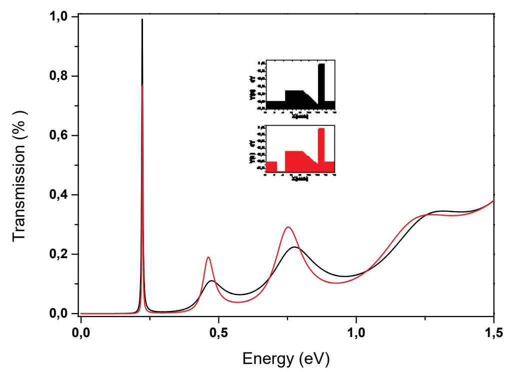

Fig. 2. *Transmission without (black lines) and with accelerating well (red lines). Inset shows the potential profiles of the considered TRTDs.*

The resonance transmission calculations are in the means of varying electron energy and calculate the transmission probability for constant local potentials as obtained $T = 0{,}76$ for the RTD with the accelerating well. As not concerned here, one must point out that the transmission can be set to unity minimizing the local potentials which are to vary indium or aluminum concentrations in the barriers and wells.

The transmission coefficients of the two RTDs with the triangular-shaped V_4 potential (TRTD) and the square V_4 potential (SRTD) without electric field application and under $0.5\ V$ forward bias are shown in Fig.3. The transmission properties of the SRTD have been previously presented [13]. The two RTDs present different transmission characteristics. When there is no electric field application, the first transmission peaks are sharp having the shape of Dirac-delta functions for both RTDs. The first (or resonance) transmission occurs at quite low energies at $\sim 0.05\ eV$ for the SRTD. This energy for the TRTD is $\sim 0.20\ eV$ which is fourfold higher than that of the SRTD. For the no electric field case in both structures, the intensities of both resonances are almost the same at $\sim 75\%$. The second and third transmissions are broad and at close energies with each other.

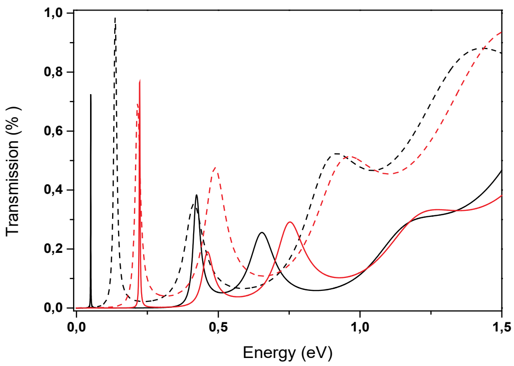

Fig. 3. Comparison of the transmission coefficients of the RTDs with the triangular shaped V_4 potential (red lines) with that of previously studied RTD with square V_4 potential (black lines) under zero (solid lines) and $0.5\ V$ forward bias (dashed lines). Inset shows both potential profiles as $0.5\ V$ external fields applied.

When $0.5\ V$ forward bias is on, the resonance transmission energy of the SRTD is $\sim 0.15\ eV$ shifted from $\sim 0.05\ eV$ in a no-bias case. Meantime, the transmission probability is raised to almost unity by the field application. For TRTD, the first resonance appeared at the same resonance energy as before the electric field, but the line shapes are slightly different. Most interestingly, the transmission probability also remains the same whether the field is applied or not.

As I-V characteristics are the most constitutive properties for device applications, the current densities of TRTDs with and without an accelerating well are calculated as functions of the external electric field strength. They are shown in Fig. 4. As the reverse bias gives no current for both TRTDs, the characteristic differences between these two are remarkable in the $0 - 2\ V$ range. In the absence of the accelerator well, the second resonance transition disappears with a very broad peak and the third resonance transition is also broadened carrying a very large current.

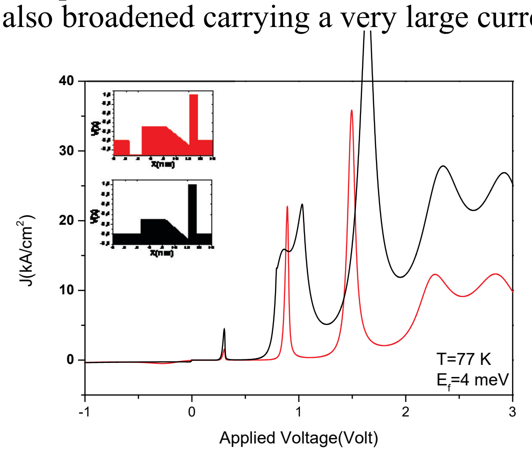

Fig. 4. Forward and reverse bias current density-voltage characteristics of the RTD involving the triangular quantum well with (red lines) and without (black lines) the accelerating well. Inset shows the two potential profiles.

On the other hand, the TRTD with the accelerating well, as seen in Fig.4 as well, has three sharp signal-like currents which might become very useful diode properties.

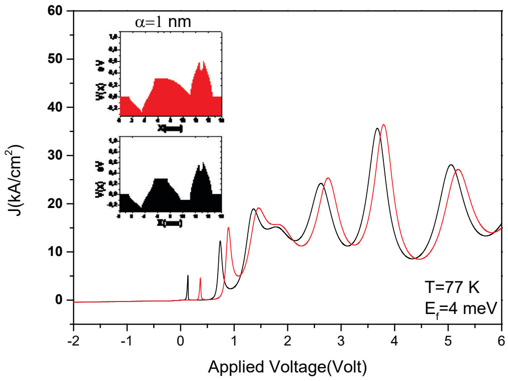

Fig. 5. Laser field effect on forward and reverse bias current-voltage characteristics of the RTDs with the accelerating wells with the triangular (red lines) and the square (black lines) V4 potentials. Inset shows the potential energy profiles tailored by laser field application on the potential profiles of the two structures as no voltage is applied.

Applying a laser field to a working RTD can change its properties positively. In Fig.5, the changes in current-voltage characteristics as a result of applying a laser field to a TRTD and an SRTD are shown. Both diodes are considered to have an accelerator well. Apparently, the laser field changes the potential shapes of the structures as seen in the insets of Fig.5. Also, the current-voltage relations are quite diversified in both samples compared with those given in the absence of the field. With the TRTD, the intensity of the first resonant current is $\sim 2\ kA/cm^2$ when the laser field is not applied (Fig.4). It is increased to $\sim 5\ kA/cm^2$ without any shift in its position at $\sim 0{,}4\ V$. Against that, the intensity of the first resonance current intensity shows no change whether a laser field is applied or not with SRTD (Fig.4 and Fig.5). However, the transition localized at $\sim 0.4\ V$ in the absence of the laser field shifts backward to $\sim 0.2\ V$ if the laser field is applied.

CONCLUSION

The two resonance tunneling diodes, so-called TRTD and STRD were investigated in terms of whether they have accelerating quantum wells or not. Their abbreviated names come from their triangular and square-shaped potential wells beyond the accelerating well in their structure. It is once more established that the existence of the accelerating well shortens the dwell times leading to the realization of the "fast electronic" concept.

The widths of the well and barriers and the depth of the wells and the height of the barriers were taken to be constant in the TRTD and STRD to be able to compare the effects of two geometrically different wells on the transmission and the current-voltage characteristics. The transmission probabilities of the resonances, their energies, and the current density-voltage characteristics can be differed owing to having different well shapes in the TRTD and STRD structures.

Once an RTD was grown, its member wells and barriers cannot be changed geometrically and energetically. However, a laser field application manages these by modifying the overall potential profile, as shown on the suggested TRTD. Thus, the laser field effect on the current-voltage characteristics is assessable in the applications.

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