UNITECH 2023 GABROVO

INTERNATIONAL SCIENTIFIC CONFERENCE
17-18 November 2023, GABROVO

THE PRE-WELL POTENTIAL AND CENTRAL WELL WİDTH EFFECTS ON A RESONANT TUNNELLING DIODE UNDER LASER FIELD

Hulya KES

Department of Physics, Faculty of Science, Trakya University, 22030 Edirne, Turkey

Abstract

A resonant tunneling diode, GaAs/$In_xGa_{1-x}As/Al_yGa_{1-y}As$/GaAs/$Al_{0.3}Ga_{0.7}As$/GaAs was studied under laser field. The effect of the pre-well potential $In_xGa_{1-x}As$ on the current voltage characteristics was examined depending on the indium concentration. It has been observed that the current-voltage characteristic exhibits a critical value if the depth of the pre-well increased by increasing indium concentration. The electrons are accelerated for shallow pre-wells before that critical value and decelerated for deeper pre-wells than that of the critical value potential. In addition, the current is decreased increasing the width of the GaAs central well. The performance of the devices can be changed by applying a laser field when the geometric parameters are adjusted in resonant tunneling diodes.

Keywords: Resonant tunneling, laser field, current-voltage characteristics.

INTRODUCTION

Resonant tunneling diodes (RTDs) and resonant tunneling hot electron transistors have a place in production of electronic devices. Therefore, the designing RTDs continues to be an important research field, at present [1-9].

An RTD can be described as a quantum well and quantum barrier combination. By applying a voltage bias on them the phenomenon of resonant tunneling occurs, and the electron transmission coefficient peaked to hundred percent sharply at particular and low energy values.

In a previous study, intense laser field effects on the resonance tunnel diode have been investigated using numerical methods. The potential profiles of symmetrical and asymmetrical rectangular double-barrier structures were considered to be produced from $(Ga, Al)As/GaAs$ and the transmission coefficient in these structures were investigated under intense laser field. The results showed that the laser field changes the potential profile and therefore the transmission coefficient can be controlled by the laser field [10]. In another study, it was calculated how the conduction coefficient, the dwell time and resonance energy were affected as a result of changing the potential profile of formation by an intense laser field. The laser fields provide complete control over the performance of the RTD, as its geometric constraints in tunneling conditions are overcome. In addition, it becomes possible to select the resonance energy value depending on the field strength [11]. Also, various RTDs were modeled for a constant resonance energy and the electronic properties of the diodes were investigated. The laser field have been shown to be enriching the functionality of these devices [12]. Bati examined the transmission properties of an electron in a symmetrical triple inverted parabolic barrier structure separated by a pair of wells under an intense laser field. It has been demonstrated that laser fields have effects on tunneling. By changing the structure parameter and intensity of the laser field, an accommodation to a blue or red shifts in the electronic spectrum. These results prove that lasers can be used to tune the electronic and optical properties of RTDs. In addition, the well and barrier widths are effective in determining the resonance energy. Increasing the well width causes the incoming electron waves to become localized. As a result, the transmission decreases and the resonance peak becomes smaller or disappears. It has been stated that it is possible to design a resonance tunneling device with the desired properties by changing the structure parameter and intensity of the laser field [13]. Sadi et al. investigated the performance of double and triple barrier heterostructured armchair graphene nanoribbon diodes, AGNR-RTD. The results showed that its production was quite worthwhile [14].

One of RTD kinds studied here and sketched in Fig.1 is described as an undoped $GaAs$ quantum well sandwiched between two $Al_yGa_{1-y}As$ barrier potentials. Before the structure is ended with two doped $GaAs$ probes, namely emitter and collector, the existence of an $In_xGa_{1-x}As$, so-called pre-well in the title after the emitter side is considered. By applying a voltage bias on the collector, and maintaining the emitter grounded, the subband and fermi levels are modified to give a resonant tunneling. The pre-well is actually known as the accelerating well, because it realizes a shortening effect on the dwell time [15]. The aim is to investigate if the positive effect of the pre-well is always valid or this can be otherwise if its depth varied under laser fields.

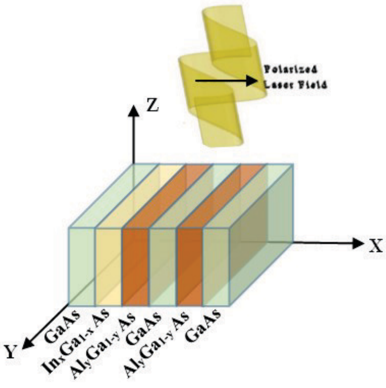

Fig. 1. Schematic presentation of the RTD

THEORY

The Hamilton function of an RTD electron under the influence of an externally applied electric field and a polarized high-frequency laser field along the magnification direction x can be expressed as

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

where $V_j(x,\alpha,V_a)$ represents the jth (j=1,2….6) individual potential in the structure. The potential variables x, α, and V_a determine the geometry of the potential profile, laser field intensity, and bias voltage, respectively. Solutions were obtained by the transfer matrix method [10]. The wavenumbers k_j of the electron are given by

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

The transmission coefficient $T(E)$ is defined by

$$T(E) = \frac{|A_6|^2\hbar k_6/m_6^*}{|A_1|^2\hbar k_1/m_1^*} \quad , \quad (3)$$

where $\hbar k_j/m_j^*$ is probability density flow [16].

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

$$J = A\int_0^\infty T\,\ln\left[\frac{1+e^{\frac{(E_F-E)}{k_BT_K}}}{1+e^{\frac{(E_F-E-eV_a)}{k_BT_K}}}\right]dE \ , \quad (4)$$

where $A = \frac{em_1^*k_BT_K}{2\pi^2\hbar^3}$ [17] and the Fermi energy was taken to be $E_F \approx 0.15\ eV$ at $T = 77\ K$. The method described above have been tested on a previous experimental resonant tunneling diode study [18].

RESULTS

The RTD structure designed in the composition given in Fig.1 was employed in determination of the current voltage characteristics under the laser field by using different indium concentrations in the pre-well potential and the different widths of the center well. First, the variations in the potential profile of this RTD for four different case which depend on the externally applied $\boldsymbol{V_a}$ voltage and laser field intensity α are given in Fig.2. As seen the laser field dresses the total potential profile interestingly.

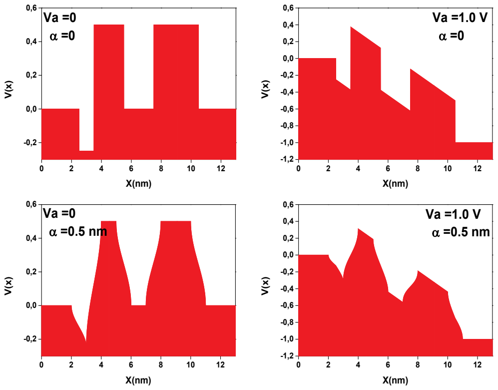

Fig. 2. *Potential profiles of the resonance tunneling diodes.*

Table 1. *Input parameters used in calculations. Subscripts aw, lb, cw, and rb stand for accelerating well, left barrier, center well, and right barrier, respectively.*

Material	*Label*	*Width/nm*	$V_j(x,0,0)/eV$
$GaAs$	*collector*	2.5	0
$In_xGa_{1-x}As$	L_{aw}	0, 1, *and* 2	0, -0.25, and -0.5
$Al_yGa_{1-y}As$	L_{lb}	2.5	0.5
$GaAs$	L_{cw}	2, *and* 5	0
$Al_yGa_{1-y}As$	L_{rb}	3	0.5
$GaAs$	*emitter*	2.5	0

Fig. 3 shows the dependence of the transmission in the RTDs described in Table 1, in the absence of a laser field and the application of an $\alpha = 0.5\,nm$ laser field, combined with no voltage and the application of two different voltage values $V_a = 0.5\,V$, and $1\,V$.

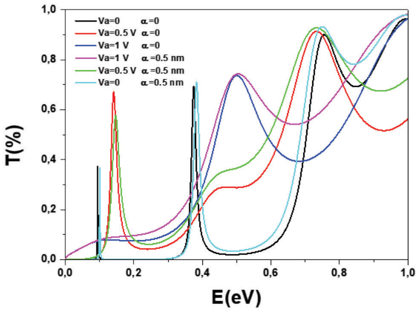

Fig. 3. *Electron energy dependence of transmission coefficient of the RTD for various field applications.*

As seen in Fig. 3, the resonance peaks occurred in the electron energy range of $0.1\,eV$ to $0.4\,eV$. It is seen that when the externally applied Va voltage increases to $0.5\,V$, the resonance peaks shift to the smaller values in comparison with no-field case, and disappear as the voltage value increases further. There are small changes in the peak values for the laser intensity $\alpha = 0.5\,nm$ in comparison with the $\alpha = 0$ case.

When the indium concentration in the front well is taken to zero, the diode structure consists of two barriers and one well sandwiched between them. The current-voltage characteristics of this diode is given in Fig. 4. It is seen that the current voltage characteristics changed when we increased the width of the center well. When the center well width is small, the current peak value is higher. For $L_{cw} = 2\,nm$, while the externally applied laser field slightly reduced the intensity of the current density peak, it shifted the voltage value to the higher values. For $L_{cw} = 5\,nm$, almost no effect of the laser field was observed.

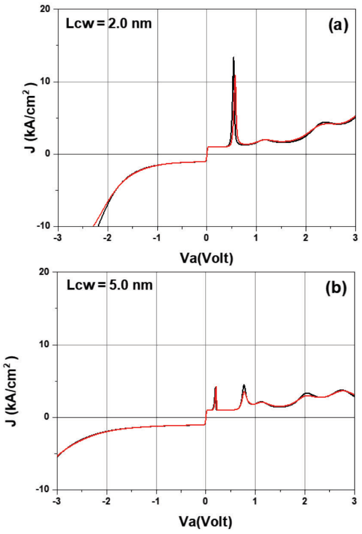

Fig. 4. *Current voltage changes when there is no laser field (black lines) and when there is a field (red lines) for the center well widths of RTD;* ***(a)*** $L_{cw} = 2$ *nm and* ***(b)*** $L_{cw} = 2$ *nm.*

The current-voltage characteristics for $L_{cw} = 5\,nm$ and the pre-well potentials -0.25 eV and $-0.50\,eV$ simultaneously considering without and with laser field effect are shown in Fig. 5. By increasing the center well width from 2 nm (not given for the sake of brevity) to 5 nm, the first resonance current density peak shifted from 0.5 V to 0.2 V. Also, the intensity of the current density decreased significantly. The results show that the second resonance current density peak has become more prominent than the first peak. While the effect of the laser field is low on the first peaks, its effect is greater on the second peaks.

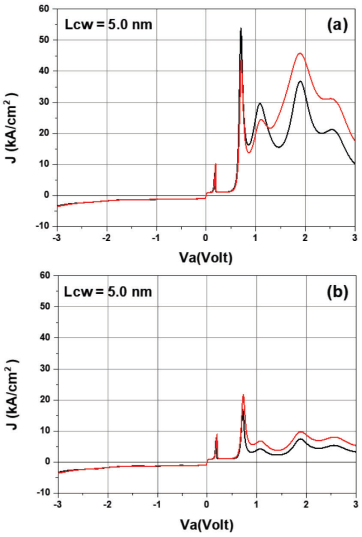

Fig. 5**. Current-voltage characteristics with* $L_{cw} = 5\ nm$ ***(a) $V_{aw} = -0.25\ eV$, and ***(b)*** $V_{aw} = -0.50\ eV$, *in the absence of laser field (black lines) and in the presence of field (red lines).*

When the attractive potential was $-0.25\ eV$, the laser field reduced the value of the second peak from 54 kA/cm^2 to 44 kA/cm^2. When the attractive potential was $-0.5\ eV$, the laser field increased the value of the second peak from 17 kA/cm^2 to 22 kA/cm^2.

CONCLUSION

Six different resonance tunneling diodes were studied theoretically. It was observed how important geometric parameters are in the design of resonance tunneling diodes. In addition, it has been shown that the function of RTDs can be temporarily changed in the desired direction with an externally applied laser field. This feature may find a place in technological applications.

REFERENCES

[1] Tsu R., Esaki L. Tunneling in a Finite Superlattice. Appl. Phys. Lett. 1973; 22(11): 562.

[2] Yokoyama N., Imamura K., Muto S., Hiyamizu S., Nishi H. A New Functional, Resonant-Tunneling Hot Electron Transistor (RHET). Jpn. J. Appl. Phys. 1985; 24(11): L853.

[3] Nakagawa T., Imamoto H., Kojima T., Ohta K. Observation of resonant tunneling in AlGaAs/GaAs triple barrier diodes. Appl. Phys. Lett. 1986; 49: 73.

[4] Wolak E., Ozbay E., Park B.G., Diamond, S.K. Bloom D.M., Harris J.S. The design of GaAs/AIAs resonant tunneling diodes with peak current densities over 2 x 10^5 A cm^{-2}. J. Appl. Phys. 1991; 69(5): 3345.

[5] Boykin T.B., van der Wagt J.P.A., Harris J.S. Tight-binding model for GaAs/AlAs resonant-tunneling diodes. Phys. Rev. B. 1991;43(6): 4777.

[6] Yang C.H., Wilson R.A. Realization of a novel resonant-tunneling hot-electron transistor: Competition of ultrafast resonant-tunneling and energy relaxation Solid-State Electron. 1994; 37: 805.

[7] Ohki S., Funato H., Suhara M., Okumura T., Wernersson L.E., Seifert W., Appl. Surf. Sci., 190, 2002, p. 288.

[8] Çelik H., Cankurtaran M., Altunoz S. Vertical transport in GaAs/$Ga_{1-y}Al_yAs$ barrier structures containing quantum wells: Current–temperature characteristics. Superlattice Microst. 2008; 44: 237.

[9] Almansour S.A., Hassen D. Theoretical Study of Electronic Transmission in Resonant Tunneling Diodes Based on GaAs/AlGaAs Double Barriers under Bias Voltage. Opt. Photonics Jou. 2014; 4: 39.

[10] Aktas S., Bilekkaya A., Boz F.K., Okan S.E. Electron transmission in symmetric and asymmetric double-barrier structures controlled by laser fields. Superlattice. Microst. 2015; 85: 266.

[11] Aktas S., Kes H., Boz F.K., Okan S.E. Control of a resonant tunneling structure by intense laser fields. Superlattice. Microst. 2016; 98: 220.

[12] Okan S.E., Boz F.K., Aktas S. Theoretical suggestions of resonant tunneling diodes and laser field effects on their current-voltage characteristics. Superlattice. Microst. 2019; 133: 106207.

[13] Bati M. The effects of the intense laser field on the resonant tunneling properties of the symmetric triple inverse parabolic barrier double well structure. Physica B: Physics of Condensed Matter. 2020; 594: 412314.

[14] Sadi A.E. Performance Comparison of Different AGNR RTD. In: Munna M.R., Alam M., 12th International Conference on Electrical and Computer Engineering (ICECE), 2022, p. 40-43.

[15] Abe M., Hamaguchi H., Yamamoto H, Yamada N. Dwell Time in Asymmetrical Double-Barrier Structures under DC Bias Voltage. Electronics and Communications in Japan, Part 2 2005; 88: 720.

[16] Takura H., Yamamoto H. Theoretical analysis of tunneling phenomenon in asymmetrical triple-barrier structures with outer wells. Electron. Comm. Jpn. 2007; 90: 113.

[17] Arakawa N., Otaka Y., Shiiki K. Evaluation of barrier height and thickness in tunneling junctions by numerical calculation on tunnel probability. Thin Solid Films 2006; 505: 67.

[18] Jackiv R., Trebicky T., Voves J., Vyborny Z., Cukr M., Jurka V. Experimental and theoretical study of the I-V bistabilities of resonant tunneling diodes. In: IEEE 24th MIEL Proceedings 1, 2004, p. 359-362.