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PHOTON-INDUCED FERMI LEVEL SHIFTS AND ENERGETIC MODULATION OF RESONANT STATES IN DOUBLE-BARRIER RESONANT TUNNELING NANOSTRUCTURES

Shokhjakhon O. Mamadaliev[1], Mukhammadjon G. Dadamirzaev[1], Munirakhon K. Uktamova[1], Sobirjon R. Boidedaev[1], Kudiratulla B. Umarov[1], Yusuf Usmanov[2]
[1]Namangan State Technical University, Namangan, Uzbekistan
[2]Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, National Research University, Tashkent, Uzbekistan
**Corresponding author e-mail: shoxjaxonmamadaliyev371@gmail.com*
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This paper presents a theoretical analysis of quantum tunneling mechanisms under photon energy excitation within the framework of the Landauer–Büttiker formalism. The study considers the effects of photon absorption during resonant tunneling, leading to modifications of the Fermi–Dirac distribution and shifts in the chemical potentials. It is shown that photogeneration processes induced by optical excitation enhance the tunneling probability, cause an energy broadening of the transmission function, and result in a shift of the resonant peak in the current–voltage (I–V) characteristics. Based on the proposed model, a nonlinear dependence of quantum conductance on photon energy is established, and it is theoretically demonstrated that an increase in photon energy leads to enhanced tunneling conductance. The developed approach provides a deeper insight into optically excited quantum transport phenomena and establishes a new theoretical basis for the design of light-controlled transport systems in nanoelectronic devices.
Keywords: *Landauer–Büttiker formalism; Quantum tunneling; Photon energy; Fermi–Dirac distribution; Transmission function; Chemical potential shift; Nonlinear conductance*

INTRODUCTION

Resonant tunneling diodes (RTDs) are semiconductor nanostructures based on quantum-mechanical transport phenomena and play a crucial role in the development of high-speed electronic and optoelectronic devices [1, 2]. These structures operate on the principle of a double-barrier quantum well (DBQW) and are characterized by a distinctive N-shaped current–voltage (I–V) characteristic associated with the presence of negative differential resistance (NDR) [3]. In RTD structures, resonant tunneling of electrons through potential barriers significantly enhances the transmission probability, leading to the formation of the NDR region [1, 3, 5]. Experimental studies performed by Romeira and co-authors (2013) on resonant tunneling diode photodetectors (RTD-PDs) revealed pronounced modifications of the I–V characteristics under optical illumination [5]. In particular, an increase in light intensity resulted in a shift of the resonance peak and a substantial enhancement of the photocurrent. These findings experimentally demonstrate the high sensitivity of RTD-PD devices to optical signals and the efficient modulation of quantum electron transport under optical excitation [4]. However, the theoretical mechanisms underlying these effects, including the shift of Fermi levels, the modification of the transmission function, and the generation of photocurrent under illumination, have not yet been fully explained within the framework of the Landauer–Büttiker formalism [6, 7]. In recent years, RTDs and RTD-based nanostructured devices have attracted growing attention as key components of high-speed electronic and optoelectronic systems. In particular, RTDs have been widely explored for applications in terahertz (THz) frequency generators, high-speed signal modulators, and light-sensitive quantum devices. Scientific studies published between 2018 and 2026 have focused on advancing the materials platforms, understanding quantum transport mechanisms, and investigating optical effects in RTD technologies. Improving RTD performance is primarily associated with enhancing the quality of the resonance peak and the NDR region. For instance, graphene-based RTDs have demonstrated high peak-to-valley current ratios, highlighting the potential of two-dimensional materials for significantly improving RTD efficiency [8]. Strong NDR and stable resonant tunneling regimes have also been reported in WSe_2/h-BN/WSe_2 heterostructures and related low-dimensional systems [9]. One of the major factors limiting RTD performance in practical devices is interface roughness and structural imperfections. Recent theoretical and numerical studies have shown that correlated interface roughness strongly affects resonant energy levels and tunneling current characteristics, emphasizing the need for nanometer-scale technological control in RTD fabrication [10]. Significant progress has also been achieved in high-frequency RTD applications, particularly in the development of THz oscillators based on optically coupled RTD arrays, demonstrating improved output power and stability [11]. From a theoretical perspective, the Landauer–Büttiker formalism remains one of the most powerful approaches for describing quantum transport in RTD systems. This framework has been successfully applied to model optical transport in graphene-based devices and resonant tunneling structures [12]. Moreover, external influences such as bias voltage, mechanical strain, and electromagnetic fields have been shown to effectively control the tunneling transmission function, as demonstrated in piezotronic resonant tunneling junctions [13].

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Resonant tunneling of electrons and holes in complex heterostructures, including AlGaAs/GaAsBi/AlGaAs systems, further confirms the possibility of engineering resonant energy levels through material and structural design [14-17]. Additionally, symmetric doping-free resonant tunneling phenomena in polar heterostructures have recently been investigated both experimentally and theoretically [18-21]. Recent review studies on quantum transport under external perturbations, including time-dependent electromagnetic fields, highlight the crucial role of photon–matter interactions in RTDs and related nanostructures [22, 23]. Nevertheless, in most existing works, the light-induced shift of I–V characteristics, redistribution of Fermi levels, and photocurrent generation in RTD-PD devices are often interpreted using optical or simplified approaches. Therefore, a consistent theoretical model that provides an integral description of optically excited quantum transport in RTD-PD structures within the Landauer–Büttiker formalism is still lacking. This work aims to fill this gap by providing a comprehensive theoretical analysis of photon-induced quantum transport mechanisms in RTD-PD devices based on the Landauer–Büttiker approach, relying on recent scientific results published between 2018 and 2026.

METHODS

A resonant tunneling diode (RTD) is a semiconductor device based on quantum-mechanical phenomena, whose primary operating principle relies on the resonant tunneling of electrons through a potential barrier [1, 2]. In this work, the following parameters of the resonant tunneling diode are theoretically investigated: the dark current I_{dark}, the total current under illumination I_{light}, the photocurrent defined as the difference between illuminated and dark currents, the current–voltage (I–V) characteristics, the photon energy in the heterostructures $-\text{h}\nu$, the transmission function $\mathrm{T}(\mathrm{E}, \mathrm{h}\nu)$ and the Fermi–Dirac distribution functions at the contacts, $f_p(E)$ and $f_n(E)$. The calculations are performed using current expressions derived from the Landauer–Büttiker formalism, and numerical computations are carried out using the Maple software package. To describe the current flow in the RTD, the Landauer–Büttiker theoretical approach is employed [6, 7]. Within this framework, the electric current arises from the quantum-mechanical tunneling of electrons through the potential barrier, where electrons exhibit wave-like behavior during transmission. The general expression for the current is given by

$$J(V) = \frac{2q}{h}\int_{-\infty}^{\infty} T(E)[f_p(E) - f_n(E)]dE \tag{1}$$

Here, $-T(E)$ denotes the transmission function of the structure, while $f_p(E)$ and $f_n(E)$ are the Fermi–Dirac distribution functions of the p- and n-type electrodes, respectively. This expression serves as the basis for determining the dark current in RTD devices. The electron tunneling process through the double-barrier potential structure described by Eq. (1) is illustrated schematically in Figure 1.

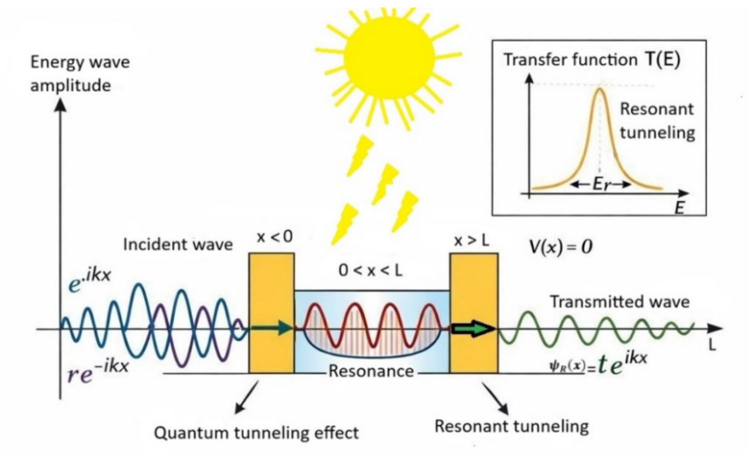

Figure 1. The electron tunneling process through a quantum structure consisting of two potential barriers is illustrated

As a result of quantum tunneling, electrons exhibit a high transmission probability at specific resonance energies, leading to the observation of the resonant tunneling effect. Using the Schrödinger equation,

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{d(x)^2} + V(x)\psi(x) = E\psi(x). \tag{2}$$

The electron transport through a double-barrier quantum well (DBQW) structure is analyzed. For the left $(x < 0)$ and right $(x > L)$ contact regions, the potential is taken as $V(x) = 0$, corresponding to free electrons. The transmission coefficient $T(E)$is obtained from the corresponding wave functions. In the left contact region, the wave function is expressed as $\psi_L(x) = e^{ikx} + re^{-ikx}$ representing the incident and reflected electron waves, where (r) is the reflection amplitude. In the right contact region, the transmitted wave function takes the form $\psi_R(x) = te^{ikx}$ where (t) denotes the transmission amplitude. Inside the quantum well region $(0 < x < L)$, the electron wave function in the resonant state is written as $\psi_w(x) = A\phi(x)$, with (A) being the amplitude inside the well. The continuity conditions for the wave function and its derivative at the interfaces,$\psi_L(0) = \psi w(0)$; $\psi'_L(0) = \psi'_w(0)$; $\psi_w(L) = \psi_R(L)$; $\psi'_w(L) = \psi'_R(L)$ lead to a linear system of equations for the coefficients (r), (t), and (A) [28, 29].

For an open quantum system, the discrete energy level in the quantum well becomes a metastable resonant state due to coupling with the left and right contacts. As a result, the resonant energy acquires a complex form,

$$\widetilde{E_r} = E_r - i\frac{\Gamma}{2}, \ \Gamma = \Gamma_p + \Gamma_n \tag{3}$$

$\widetilde{E_r}$–is the resonance energy, that is, the energy at which an electron forms a temporarily bound state within the quantum well which physically corresponds to an electron being temporarily confined in the well before tunneling out through the barriers. The transmission probability can be conveniently expressed using the Green's function formalism. The retarded Green's function is given by

$$G^r(E) = \frac{1}{E - E_r + i\frac{\Gamma}{2}} \tag{4}$$

The energy-dependent transmission function then takes the Lorentzian form

$$T(E) = \frac{\Gamma_p \, \Gamma_n}{(E - E_r)^2 + \left(\frac{\Gamma_p + \Gamma_n}{2}\right)^2} \tag{5}$$

The Lorentzian transmission function arises naturally from the retarded Green's function description of a single resonant state coupled to two contacts. In the resonant tunneling regime, the finite coupling between the quantum well state and the contacts leads to an energy broadening characterized by Γ_p and Γ_n. Consequently, the transmission probability exhibits a Lorentzian line shape centered at the resonant energy Er. This result is well established in resonant tunneling theory and quantum transport calculations [1, 29].
Here, Γ_p and Γ_n represent the coupling (broadening) strengths associated with the *p* and *n* type contacts, respectively, and E_r denotes the resonant energy level.

For InGaAs/AlAs nanostructures, the lowest resonant energy typically lies in the range $E_r \sim 0.1 - 0.3\, eV$. The resonance peak is centered at the resonant energy E_r=0.2 eV, illustrating the transmission characteristics of the InGaAs/AlAs double-barrier structure. The corresponding Lorentzian transmission probability calculated from Eq. (5) is plotted in Figure 2.

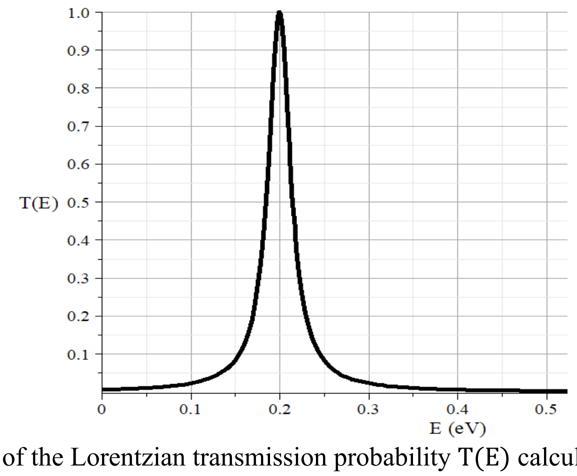

Figure 2. Energy dependence of the Lorentzian transmission probability T(E) calculated using Eq. (5) for an ideal resonant tunneling diode

RESULTS

At finite temperatures, electrons can occupy not only energy states below the chemical potential μ but also states with energies higher than μ. This occurs because thermal excitation allows electrons to transition from lower-energy states to higher-energy states. Under these conditions, the probability that an electron occupies an energy state at the Fermi level is equal to ½, while the probability of occupying states above the Fermi level is nonzero. Since the function $f(E)$ represents the probability that an electron occupies a given energy state, the complementary probability that this energy state is unoccupied by electrons is given by

$$f'(\varepsilon) = 1 - f(\varepsilon) \tag{6}$$

This expression therefore describes the probability that a given energy state is empty of electrons. For an energy level with degeneracy g_i, of which n_i states are occupied by electrons, the Fermi–Dirac distribution function can be written as

$$f(E) = \frac{n_i}{g_i} = \frac{1}{e^{\frac{\varepsilon-\mu}{kT}}+1} \tag{7}$$

Accordingly, the probability of hole occupation, corresponding to an unoccupied electronic state with energy (E), is expressed as

$$f(E) = \frac{n_i}{g_i} = \frac{1}{e^{\frac{\mu-\varepsilon}{kT}}+1} \tag{8}$$

This function represents the probability that an energy state with energy E is occupied by a hole. In semiconductors, mobile holes obey this distribution function. The resulting band diagram, showing the conduction and valence bands, the Fermi level, and electron and hole occupations, is presented in Figure 3.

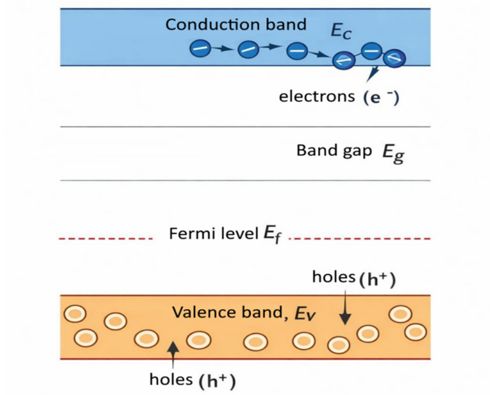

Figure 3. Schematic energy-band diagram illustrating the conduction band, valence band, Fermi level, and electron–hole occupation in a semiconductor

$$f'_p(E) = \frac{1}{e^{-\frac{\mu-\varepsilon}{kT}}+1} \tag{9}$$

Here, -$\mu_p$enotes the Fermi level of the *p-contact,* -k, is the Boltzmann constant, and -T, is the absolute temperature. This expression is particularly relevant for regions with a high concentration of acceptor impurities, where hole transport dominates:

In the n-contact, where donor impurities dominate, and electrons are the majority charge carriers, the Fermi–Dirac distribution function describing the energy-dependent occupation probability of electrons is used. In this case, the distribution function is given by [8, 9]:

$$f_n(E) = \frac{1}{1+e^{\left(\frac{E-\mu n}{kT}\right)}} \tag{10}$$

Here,−μ_n denotes the Fermi level of the n-contact. This distribution function describes the probability that an electronic state with energy (E) is occupied by an electron in the n-type semiconductor region:

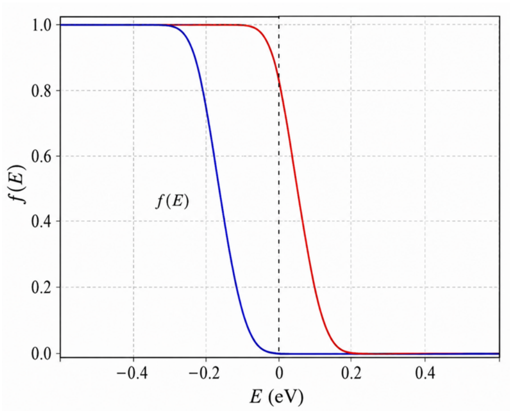

Figure 4. Illustration of the overlap between the Fermi–Dirac distributions of the p- and n-contacts, indicating the energy region where resonant tunneling is expected to occur

By combining the Fermi–Dirac distribution functions of the p- and n-contacts, an energy window can be identified in which resonant electron tunneling occurs [10, 11]. This overlap region defines the range of energies for which charge carriers can effectively tunnel through the double-barrier structure and contribute to the resonant transport process. This overlap of the Fermi-Dirac distributions of the p- and n-contacts is shown in Figure 4.

Using the generalized current expression given in Eq. (1), the current–voltage (I–V) characteristics of the resonant tunneling diode can be obtained [12–14]. In particular, the dark current (J_{dark}) is calculated by integrating the transmission function over the energy range defined by the Fermi–Dirac distributions of the contacts.

The dark current of the resonant tunneling diode is expressed as:

$$J_{dark}(V) = \frac{2q}{h} \int_{\mu_p}^{\mu_n+qV} \frac{\Gamma_p \Gamma_n}{(E-E_r)+\left(\frac{\Gamma_p+\Gamma_n}{2}\right)^2} \cdot \left[\frac{1}{1+e^{\left(\frac{E-\mu_p}{kT}\right)}} - \frac{1}{1+e^{\left(\frac{E-\mu_n+qV}{kT}\right)}}\right] dE \tag{11}$$

This expression describes the current–voltage (I–V) characteristics associated with resonant electron tunneling through the double-barrier structure and is valid for the ideal equilibrium (dark) condition.

When optical illumination is applied, the quasi-Fermi levels of electrons and holes shift due to nonequilibrium carrier generation. This effect can be expressed as

$$\mu_p, \mu_n \rightarrow \mu_p + \Delta\mu_p, \mu_n + \Delta\mu_n \tag{12}$$

Under illumination, electron–hole pairs are generated in the material, disturbing the equilibrium and leading to shifts in the quasi-Fermi levels [18]. The resulting Fermi-level shift can be approximated by:

$$\Delta\mu \approx kT \ \ln\left(1 + \frac{G\,\tau}{n_0}\right) \tag{13}$$

Where, $G -$ is the photogeneration rate, τ- is the carrier lifetime, and, $n_0$is the equilibrium sheet carrier density. For InGaAs/AlAs RTD-PD structures, typical values lie in the range $n_0 \sim 1 \cdot 10^{11} - 1 \cdot 10^{12} cm^{-2}$ .The magnitude of Δμdepends on the illumination intensity and material parameters and directly reflects the increase in current under optical excitation.

The photogeneration rate is defined as

$$G = \int_{E_g}^{\infty} \phi(E)[1 - \omega\alpha(E)]\, dE \tag{14}$$

Here, (G) is the photogeneration rate. It represents the number of electron–hole pairs generated per unit volume (or per unit area) per second. This formula incorporates the following processes: photons incident over the spectral distribution $-\phi(h\nu)$,their absorption probability $-(\alpha(E)\omega)$,as well as the forbidden bandgap energy of the InGaAs material, which is approximately $E_g \sim 0.75\ eV$. Here, ω denotes the effective optical path length (or effective absorption thickness) of the active region in the RTD structure. For InGaAs/AlAs resonant tunneling nanostructures, $\omega -$ is taken to be on the order of 1-2 nm. In the present calculations, a representative value of $\omega = 2\ 10^{-9} m$ is used [22-24, 27].
The absorption coefficient is given by

$$\alpha(E) = \begin{cases} \left(\alpha_0 + \beta_0 \frac{h\nu}{E_g}\right) \cdot \sqrt{\frac{h\nu}{E_g} - 1} & h\nu \geq E_g; \\ 0 & h\nu \leq E_g \end{cases} \tag{15}$$

The absorption coefficient $-\alpha(h\nu)$ is an optical parameter that characterizes the intensity of photon absorption in a semiconductor material [25, 26]. For InGaAs/AlAs nanostructures, this parameter corresponds to barrier layers with thicknesses of, 1–2 nm. The values are taken as $\alpha_0 = 1 \cdot 10^9\ m^{-1}, \beta_0 = 1 \cdot 10^9 m^{-1}$.
The photon flux is defined as

$$\phi(h\nu) = \begin{cases} \left(\phi_0 e^{[-\eta(h\nu - E_g)]}\right) & h\nu \geq E_g \\ 0 & h\nu < E_g \end{cases} \tag{16}$$

Here,$-\phi(h\nu)$ denotes the photon flux density, that is, the number of photons with energy $-(h\nu)$ incident on a unit area per unit time. The parameter $-\eta$ is the decay coefficient, which determines how rapidly the photon flux decreases as the photon energy increases. In theoretical models of photon-assisted tunneling, $\eta \sim 0.01\ (10^{-2})$. Under strong illumination conditions, $\eta \sim 0.05$,The parameter ϕ_0 represents the initial photon flux and corresponds to its maximum value. If $h\nu < E_g$ i.e., when the photon energy is smaller than the forbidden bandgap energy, no electron–hole pairs are generated. When $h\nu \geq E_g$ this condition is satisfied and electron–hole pair generation occurs [28]. Illustrating the formation of electron–hole pairs and the competition between photogeneration and recombination processes. In this case, by combining Eqs. 13, 14, 15, 16, the shift of the chemical potentials under illumination can be written as

$$\Delta\mu \approx kT \ \ln\left(1 + \frac{\tau}{n_0} \int_{E_g}^{\infty} \phi_0 e^{[-\eta(h\nu - E_g)]} \left[1 - e^{\left(-\omega\left(\alpha_0 + \beta_0 \frac{h\nu}{E_g}\right) \cdot \sqrt{\frac{h\nu}{E_g} - 1}\right)}\right] dE\right) \tag{17}$$

The resulting dependence of the quasi-Fermi level shift on photon frequency, obtained from Eq. (17), is shown in Figure 5.

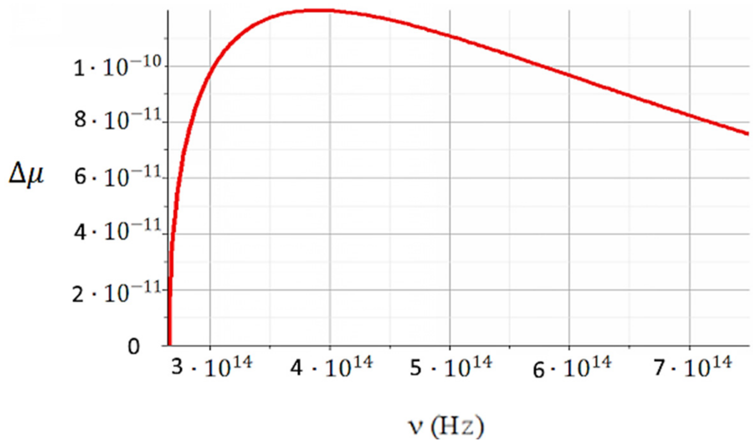

Figure 5. Dependence of the quasi-Fermi level shift ($\Delta\mu$) on the photon frequency under optical illumination

Next, we analyze the influence of optical absorption on the transport characteristics. According to expression (5), the coupling parameters Γ_p and Γ_n which describe the interaction between the contacts and the resonant state, are affected by photon absorption processes. Under optical excitation, photon absorption and emission enhance the contact–resonance coupling, leading to an increase in the total broadening parameter -Γ. As a result, the resonance width becomes larger. For convenience, the photon energy is expressed as $E=\hbar\omega$ and the parameter -Γ, is commonly modeled as a function of the photon energy. The light-induced broadening of the resonant level can be written as,

$$\Gamma_{L,R} = \eta_{L,R} I_{ph} \delta(E_0 \pm \hbar\omega - E) \tag{18}$$

or, in a simplified form,

$$\Gamma_{L,R} = \Gamma_{L,R}{}^{(0)} \left[1 + \eta_{L,R} \frac{I_{ph}}{(\hbar\omega)^2}\right] \tag{19}$$

Here, $-\hbar\omega$ is the photon energy, $-I_{ph}$ denotes the light intensity, and, $-\eta_{L,R}$ is the electron–photon interaction coefficient. The parameter $(-\eta_{L,R}\ is\ taken\ to\ be\ approximately\ 0.01)$. Thus, in order to account for the effect of optical excitation on the resonance energy broadening, the transmission function can be written in the following form:

$$T(E) = \frac{\Gamma_L(\hbar\omega)\Gamma_R(\hbar\omega)}{(E-E_0)^2 + \left[\frac{\Gamma_L(\hbar\omega)+\Gamma_R(\hbar\omega)}{2}\right]^2} \tag{20}$$

In this case, the electron tunnels not only at the resonant energy $-E_0$ but also at energies shifted by $E_0 \pm (\hbar\omega)$.

In the absence of light (dark condition), the transmission spectrum exhibits a Lorentzian resonance profile, whereas under optical illumination the resonance evolves into an asymmetric Fano line shape.

Under illumination, the carrier lifetime changes due to electron–photon interactions. Therefore, both illuminated and non-illuminated cases are considered. The carrier lifetime is given by

$$\tau = \frac{\hbar}{\Gamma_p + \Gamma_n} \tag{21}$$

In the absence of external influence, the Lorentzian resonance appears as shown in Figure 6(a), whereas the Fano resonance emerges under illumination, as illustrated in Figure 6(b).

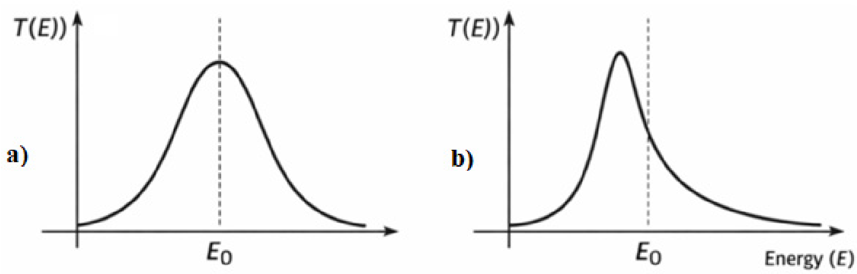

Figure 6. Panels (a) and (b) illustrate the transmission spectra in the absence and presence of optical illumination, respectively

When light is incident on the structure, charge carriers can absorb or emit photons, which modifies their lifetime. In this case, the electron acquires additional energy,

$$E_{ph} = \hbar\omega \tag{22}$$

allowing it to overcome the potential barrier more easily. Accordingly, the partial broadening parameters are expressed as

$$\Gamma_p = \Gamma_p^{(0)} + \Gamma_p^{(ph)} \tag{23}$$

$$\Gamma_n = \Gamma_n^{(0)} + \Gamma_n^{(ph)} \tag{24}$$

Here, $\Gamma^{(ph)}$ denotes the light-induced contribution to the resonance broadening. According to Eq. (21), under optical illumination the lifetime of charge carriers takes the following form:

$$\tau = \frac{\hbar}{\left(\Gamma_p^{(0)} + \Gamma_p^{(ph)}(\hbar\omega)\right) + \left(\Gamma_n^{(0)} + \Gamma_n^{(ph)}(\hbar\omega)\right)} \tag{25}$$

In this expression, the total (effective) lifetime of the charge carriers is obtained by taking into account both the intrinsic and light-induced broadening contributions. As a result, an additional quasi-potential emerges, which allows us to understand how the transmission probability (T(E)) is modified under illumination. Consequently, we obtain an additional impurity potential, which allows us to understand how the transmission probability changes. In the absence of light: a) In the figure, there is no change in the impurity potential, and the transparency also remains unchanged. In the presence of light: b) In the figure, due to illumination, electron-hole pairs are generated, which modifies the tunneling process. As a result, the transmission profile changes toward a Fano resonance, as illustrated in Fig. 7. Schematically illustrates that, due to the generation of additional charge carriers and the resulting shift , extra tunneling channels appear. These additional channels give rise to interference effects, causing the transparency to evolve from a Lorentzian profile to a Fano resonance under optical excitation.

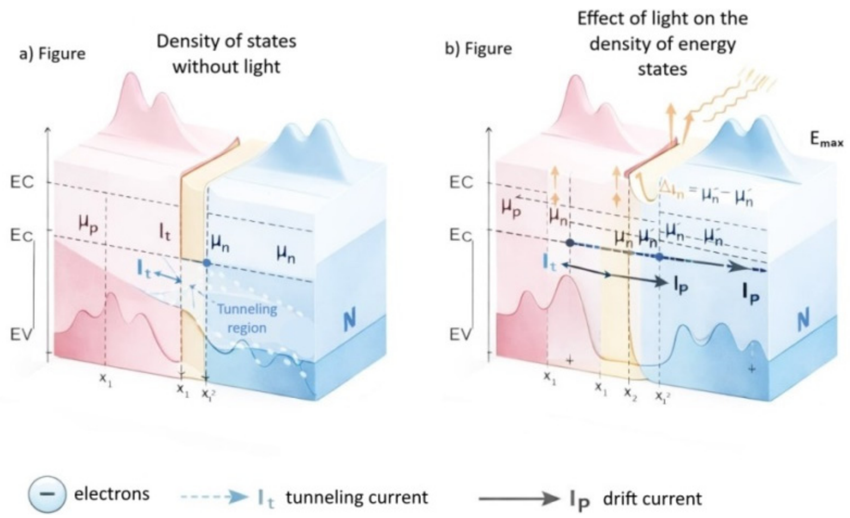

Figure 7. Schematic representation of the density of localized states and charge-carrier transport mechanisms: (a) in the dark, showing tunneling current, and (b) under illumination, showing photoinduced changes in the density of states and drift current

In the absence of illumination, the Fermi levels are taken as, μ_p=0.2 eV and μ_n=0.1 eV. Under optical illumination, the shifts, $\Delta\mu_p$=0.3 eV and $\Delta\mu_n$=0.2 eV occur. These shifts arise due to the photogeneration of charge carriers and lead to a modification of the Fermi energy. The photocurrent under illumination is given by the following expression:

$$J_{light}(V) = \frac{2q}{h}\int_{\mu_p+\Delta\mu_p}^{\mu_n+\Delta\mu_n+qV} \frac{\Gamma_p\,\Gamma_n}{(E-E_r)+\left(\frac{\Gamma_p+\Gamma_n}{2}\right)^2}\left[\frac{1}{1+e^{\left(\frac{E-\mu_p+\Delta\mu_p}{kT}\right)}} - \frac{1}{1+e^{\left(\frac{E-\mu_n+\Delta\mu_n+qV}{kT}\right)}}\right]dE \tag{26}$$

From Eq. (26), only the current generated under optical illumination can be obtained. If the total (net) current is required, it can be written as $J_{net}(V) = J_{light}(V) - J_{dark}(V)$ where the resulting net current represents exclusively the contribution induced by illumination [18, 30-32]. By combining Eq. (26) with Eq. (11) and analyzing the results separately, the illuminated and non-illuminated cases can be directly compared. The corresponding behaviors are illustrated in the graphs presented below. When light is incident on the device, photogeneration leads to a shift of the quasi-Fermi levels, which increases the tunneling probability and results in a higher total current J_{light} compared to the dark current J_{dark}. The difference between these two currents represents the pure photocurrent.

The calculated current–voltage (J–V) characteristics of the resonant tunneling structure under dark and illuminated conditions are shown in Figure 8.

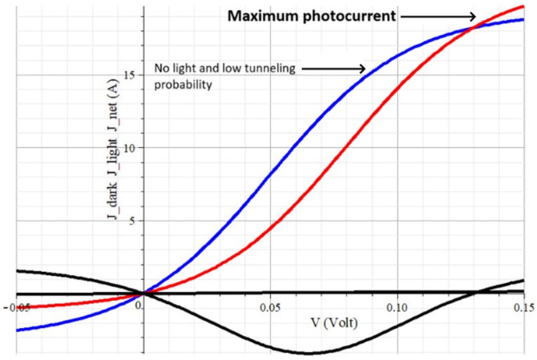

Figure 8. Current–voltage (J–V) characteristics of the resonant tunneling structure under dark and illuminated conditions.

The red curve $-J_{light}(V)$, represents the total current under illumination. When light is incident on the semiconductor, photogeneration occurs in the active region, leading to the formation of additional electron–hole pairs. As a result, the quasi-Fermi levels (μ_p, μ_n) shift, the tunneling probability increases, and consequently the total current is enhanced. This explains why the red curve is located at the highest level.

The blue curve corresponds to the dark current $-J_{dark}$ which represents the current prior to illumination. In the absence of photogeneration, the Fermi energy levels do not shift, the tunneling probability remains low, and therefore the current is smaller. As a result, the blue curve lies below the red one.

The black curve denotes the net current $-J_{net}(V)$defined as the difference $J_{net}(V) = J_{light}(V) - J_{dark}(V)$ which corresponds to the additional current generated exclusively by illumination, commonly referred to as the photocurrent. This curve is not shown as a current flowing “below” the others; instead, it is presented as a differential quantity, representing the amplitude of the photocurrent. From a physical point of view, this indicates that electron transport and photogeneration occur simultaneously, while the plotted net current reflects only the contribution induced by optical excitation.

A pronounced modification of the I–V characteristics under illumination is observed. When light is absorbed, electron–hole pairs are generated, which induces a shift of the chemical potentials (Fermi levels) at the heterojunctions. As a consequence of this Fermi level shift, the energy range favorable for electron tunneling is broadened, and the resonant current peak is shifted toward higher values (Fig. 8). As a result, the photocurrent in the RTD structure increases under illumination, providing clear evidence of light-controlled resonant tunneling. Furthermore, in comparison with the dark condition, a broadening of the N-shaped resonant peak is observed in the current–voltage characteristics. This behavior can be consistently explained by the photogeneration rate described by Eq. (14) and the chemical potential shift given by Eq. (13).

Therefore, the obtained results indicate the following:

1. Resonant tunneling is significantly enhanced under illumination.
2. The shift of the chemical potentials ($\Delta\mu$) directly leads to an increase in the tunneling current.
3. RTD structures can be utilized as highly sensitive nano-photodetectors or photomodulators for optoelectronic applications.

Thus, the investigated model enables a detailed analysis of the resonant tunneling mechanism under illumination and provides a theoretical basis for predicting photoinduced currents in semiconductor tunnel diodes.

For comparison with the theoretical results, the experimentally observed photocurrent characteristics reported by Romeira et al. are shown in Figure 9.

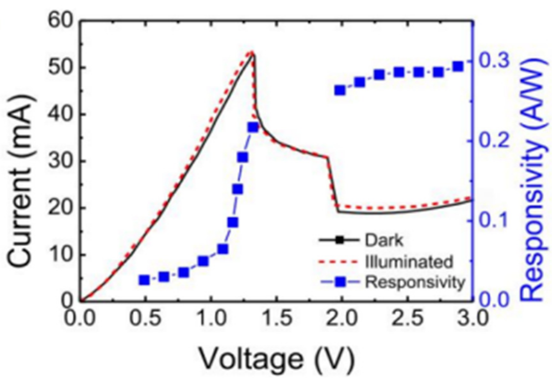

Figure 9. Experimentally observed variation of the photocurrent reported by Romeira et al. (2013).

According to the experimental results presented by Romeira et al. [5], a resonant tunneling diode photodetector (RTD-PD) based on an InGaAs/AlAs heterostructure was systematically investigated. In their study, when optical radiation with a wavelength of 1.55 μm was incident on the RTD-PD structure, pronounced modifications were observed in the current–voltage (I–V) characteristics. These experimental observations are illustrated in Fig. 9.

In particular, with increasing light intensity, the resonant peak voltage was found to shift by approximately $\Delta V_{peak} \approx 0.3$ V accompanied by a significant increase in the photocurrent. These results clearly demonstrate the light-sensitive transport behavior of the RTD-PD device. The theoretical model developed in this work provides a consistent explanation of this phenomenon through the following relation:

$$V_P = \frac{\Delta\mu_p - \Delta\mu_n}{q} \tag{27}$$

Where $\mu_p$and μ_n, denote the light-induced shifts of the chemical potentials at the *p* and *n* contacts, respectively, and q is the elementary charge.

As a result of photogeneration, electron–hole pairs are created, leading to a modification of the potential profile near the contacts. Consequently, the resonant energy level involved in the tunneling process is shifted. This shift of the resonant level results in an increase of the peak voltage toward higher values, which is in excellent agreement with the experimentally observed shift of approximately 0.3 V reported in Ref. [5]. The close correspondence between the theoretical predictions and experimental data confirms the validity of the proposed photogeneration-assisted resonant tunneling model. Thus, under illumination, the transmission function T(E) broadens as a result of the light-induced shift of the Fermi levels, leading to an increase in the current ($I_{light} > I_{dark}$) and an upward shift of the resonant energy state. In this way, the proposed theoretical model provides a consistent physical explanation for the experimentally observed I-V peak shift and photocurrent enhancement reported by Bruno Romeira et al. [5].

1. The transport processes in the RTD structure were comprehensively analyzed within the framework of the Landauer–Büttiker formalism. While previous studies mainly applied this approach to purely electrical transport, in this work it is implemented in an integral form to describe resonant tunneling processes modified by optical excitation.
2. In the theoretical model of the RTD device, the photogeneration process, the light-induced shift of the Fermi levels, and the photon-energy dependence of the transmission function are integrated into a unified analytical formulation. Although these components have been treated separately in earlier studies, their combined analysis within a single generalized framework is demonstrated here for the first time.
3. A new analytical expression is proposed to describe the variation of the resonant tunneling probability and the shift of the resonant peak in the current–voltage (I–V) characteristics with increasing photon energy. Using this expression, the nonlinear dependence of the light-controlled photocurrent on illumination intensity is theoretically established.
4. The proposed model identifies the mechanism of light-induced chemical potential shifts in RTD structures and enables a combined analysis of resonant tunneling and photogeneration processes.

CONCLUSIONS

In this study, quantum transport processes occurring under illumination in a resonant tunneling diode (RTD) device were theoretically analyzed using the Landauer–Büttiker formalism. The results show that electron–hole pairs generated due to photon absorption lead to shifts in the Fermi levels, which enhance the tunneling probability and cause an upward shift of the resonant peak in the current–voltage (I–V) characteristics.

Using the proposed theoretical model, the Fermi–Dirac distribution, photogeneration rate, and transmission function were analyzed in an integral and self-consistent manner, and the nonlinear dependence of the photocurrent on light intensity was theoretically demonstrated.

The theoretical predictions are in good qualitative agreement with the experimental observations reported by Romeira et al. (2013). In particular, both studies demonstrate resonant tunneling behavior, nonlinear current-voltage characteristics, and enhanced photocurrent under optical illumination. The remaining differences can be attributed to real-device effects, such as contact heating, structural imperfections, series resistance, and other non-ideal parameters that are not included in the present theoretical model. Overall, the proposed model enables the analysis of light-controlled chemical potential shifts in RTD structures and establishes a new theoretical basis for the design of nano-photodetectors and optoelectronic sensors.

ORCID

M.G. Dadamirzaev, https://orcid.org/0000-0001-8258-4617; **M.K. Uktamova,** https://orcid.org/0009-0005-7562-2677
Y. Usmanov, https://orcid.org/0000-0002-0509-999X

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ФОТОІНДУКОВАНІ ЗСУВИ РІВНЯ ФЕРМІ ТА ЕНЕРГЕТИЧНА МОДУЛЯЦІЯ РЕЗОНАНСНИХ СТАНІВ У ДВОБАР'ЄРНИХ РЕЗОНАНСНО-ТУНЕЛЬНИХ НАНОСТРУКТУРАХ

Шохжахон О. Мамадалієв[1], Мухаммаджон Г. Дадамірзаєв[1], Мунірахон К. Уктамова[1], Собіржон Р. Бойдедаєв[1], Кудіратулла Б. Умаров[1], Юсуф Усманов[2]
[1]Наманганський державний технічний університет, Наманган, Узбекистан
[2]Ташкентський інститут інженерів іригації та механізації сільського господарства, Національний дослідницький університет, Ташкент, Узбекистан

У цій роботі представлено теоретичний аналіз механізмів квантового тунелювання під впливом збудження енергією фотонів у межах формалізму Ландауера–Бюттікера. Дослідження розглядає ефекти поглинання фотонів під час резонансного тунелювання, що призводять до модифікації розподілу Фермі–Дірака та зсувів хімічних потенціалів. Показано, що процеси фотогенерації, індуковані оптичним збудженням, підвищують ймовірність тунелювання, спричиняють енергетичне розширення функції проходження та призводять до зсуву резонансного піка на вольт-амперних характеристиках (ВАХ). На основі запропонованої моделі встановлено нелінійну залежність квантової провідності від енергії фотонів, а також теоретично доведено, що підвищення енергії фотонів призводить до посилення тунельної провідності. Розроблений підхід забезпечує глибше розуміння явищ квантового транспорту під впливом оптичного збудження та створює нове теоретичне підґрунтя для проєктування систем транспорту з оптичним керуванням у пристроях наноелектроніки.

Ключові слова: *формалізм Ландауера–Бюттікера; квантове тунелювання; енергія фотонів; розподіл Фермі–Дірака; функція проходження; зсув хімічного потенціалу; нелінійна провідність*