Theoretical Analysis of Photon-Energy-Controlled Quantum Tunneling Mechanisms Based on the Landauer–Büttiker Formalism

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Abstract

This paper presents a theoretical analysis of photon-energy-controlled quantum tunneling mechanisms based on the Landauer–Büttiker formalism. The study investigates the effect of optical excitation on quantum transport through double-barrier nanostructures and analyzes the modification of current–voltage (J–V) characteristics under illumination. Within the proposed model, the tunneling current is expressed through the transmission probability derived from the energy-dependent potential profile and the Fermi–Dirac distribution function of charge carriers in the quantum regions. The results show that incident photons cause a shift in the quasi-Fermi levels and increase the tunneling probability due to photon-assisted carrier generation. As the photon energy increases, the resonant current peak shifts toward higher bias voltages, indicating enhanced quantum transmission through the potential barrier system. Under illumination, a significant increase in tunneling current and a broadening of the resonance peak are observed. The obtained theoretical results show good agreement with the experimental observations reported by Bruno Romeira for InGaAs/AlAs-based resonant tunneling structures. The developed model provides an analytical framework for describing the relationship between photon energy, quantum transmission coefficient, and tunneling current. The Landauer–Büttiker approach, supplemented by optical excitation effects, successfully explains the nonlinear conduction behavior observed in tunneling systems under illumination. These results contribute to a deeper understanding of photon-controlled quantum transport phenomena and offer a theoretical foundation for the design of new optoelectronic and nanoelectronic devices that utilize light-induced tunneling effects.

Keywords: Landauer–Büttiker formalism, quantum tunneling, photon energy, Fermi–Dirac distribution, transmission function, chemical potential shift, nonlinear conductance.

1. Introduction

Resonant tunneling diodes (RTDs) are semiconductor nanostructures based on quantum mechanical phenomena and play a crucial role in the development of high-speed 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 [3]. In RTD structures, the resonant tunneling of electrons sharply increases the transmission probability through the potential barrier, resulting in the formation of a negative differential resistance (NDR) region [1,3,5]. In experiments conducted by Romeira et al. (2013) using a Resonant Tunneling Diode Photodetector (RTD-PD), significant changes in the I–V characteristics under light illumination were observed [4]. Specifically, an increase in light intensity led to a shift of the resonance peak and a rise in

photocurrent. These results experimentally demonstrated both the high sensitivity of RTD-PD devices to optical signals and the modulation of electronic transport through optical excitation [4]. However, the underlying theoretical mechanism of these phenomena — including Fermi level shifts, changes in the transmission function, and photocurrent formation under illumination — has not yet been fully explained within the framework of the Landauer–Büttiker formalism [6,7]. Therefore, in this work, we theoretically analyze the experimental results reported by Romeira [4] using the Landauer–Büttiker approach. The proposed model expresses the quantum transport processes occurring in RTD-PD devices under illumination in an integral form and reveals the physical basis of the photocurrent observed in experimental studies.

2. Teoretical part

The resonant tunneling diode (RTD) is a semiconductor device based on quantum mechanical phenomena, whose operating principle relies on the resonant tunneling of electrons through a potential barrier [1,2]. In this study, the following parameters of the resonant tunneling diode were theoretically investigated: dark current $-I_{IdarkI,}$ light-induced current $-I_{lightI,}$ net current–voltage characteristics, photon energy in heterojunctions,hν,transmission function $T(E, h\nu)$ and Fermi–Dirac distributions at the contacts, $f_p(E)$ and $f_n(E)$. The calculations were performed using current expressions derived from the Landauer–Büttiker formalism, and practical numerical computations were carried out in the Maple software environment [6,7]. To describe the current flow in the RTD, the Landauer–Büttiker theoretical approach was applied [6,7]. Within this framework, the current is characterized by quantum tunneling of electrons through the potential barrier.

The general expression for the current is given as follows:

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

here, *T(E)* is the transmission function, and $f_p(E)$ *and* $f_n(E)$ represent the Fermi–Dirac distributions of the p - and n -type electrodes, respectively. This expression serves as the basis for determining the dark current in RTD devices. The probability of electron transmission through the potential barrier can be expressed as follows:

$$T(E) = \frac{\Gamma_p\,\Gamma_n}{(E-E_r)+\left(\frac{\Gamma p+\Gamma n}{2}\right)^2} \tag{1.1}$$

here, Γ_p and Γ_n are the interaction (broadening) parameters corresponding to the *p* - and *n* -type contacts, and E_r is the resonant energy level.

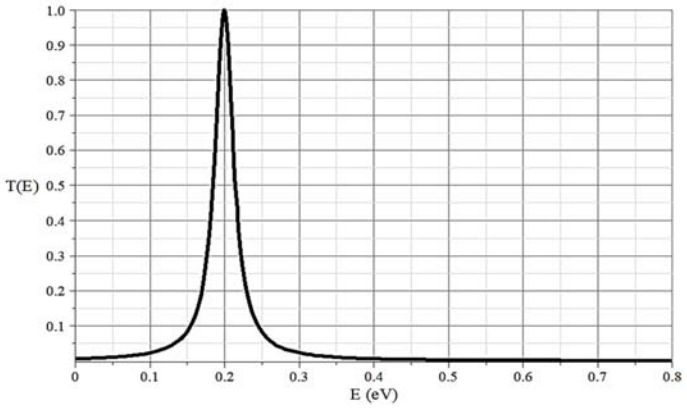

Figure 1. Shows the probability of transmission of charged particles with energy E through the potential barrier [8,9].

The Fermi–Dirac distribution of the p-contact represents the energy-dependent distribution of electrons in the p-type region.

$$f_p(E) = \frac{1}{1+e^{\left(\frac{E-\mu_p}{kT}\right)}} \tag{1.2}$$

here, μ_p is the Fermi level of the p -contact, k is the Boltzmann constant, and T is the temperature.

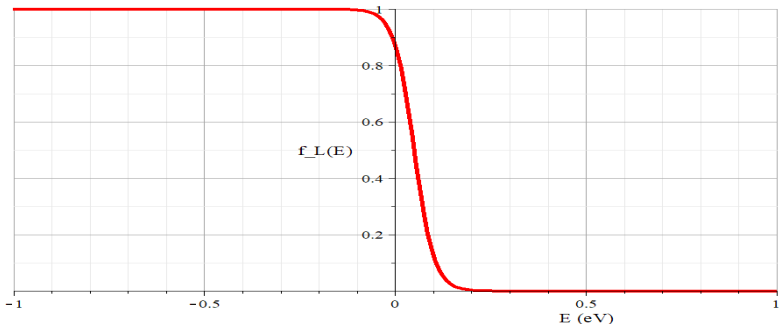

Figure 2 Shows the dependence of the Fermi–Dirac distribution function $f_p(E)$ of the p -side semiconductor on the energy−E. Fermi–Dirac distribution of the n-contact.

$$\boldsymbol{f_n(E) = \frac{1}{1+e^{\left(\frac{E-\mu_n}{kT}\right)}}} \tag{1.3}$$

here, μ_n is the Fermi level of the n -contact, k– is the Boltzmann constant, and T is the temperature [8,9].

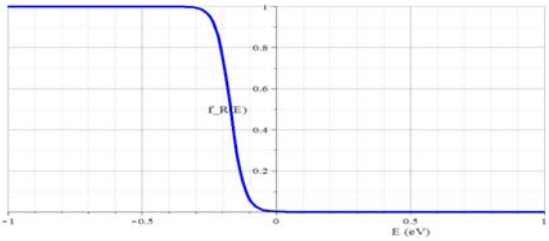

Figure 3. In the dependence of the Fermi–Dirac distribution function $f_n(E)$ of the n-side semiconductor on the energy E is shown.

By combining these two graphs, we can observe the energy range where electron tunneling and resonance occur [10,11].

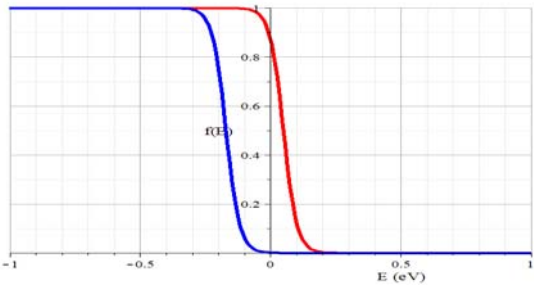

Figure 4. It can be seen that resonant tunneling states occur between the p and n contacts.

Based on equation (1.0), a generalized expression can be written, and using this relation, the current–voltage characteristic (I–V curve) of the resonant tunneling diode can be derived [12-14].

$$J_{dark}(V) = \frac{2q}{h} \int_{\mu_p}^{\mu_n+qV} \frac{\Gamma_p \Gamma_n}{(E-E_r)+\left(\frac{\Gamma p+\Gamma n}{2}\right)^2} * \left[\frac{1}{1+e^{\left(\frac{E-\mu_p}{kT}\right)}} - \frac{1}{1+e^{\left(\frac{E-\mu_n+qV}{kT}\right)}}\right] dE \quad (1.4)$$

We now consider the I–V characteristic corresponding to the tunneling of charged particles that possess the resonant energy.

When the device is illuminated, the Fermi levels of electrons and holes begin to shift, and this change can be expressed as follows [15]:

$$\mu_p, \mu_n \rightarrow \mu_p + \Delta\mu_p, \quad \mu_n + \Delta\mu_n \quad (1.5)$$

Under illumination, electron–hole pairs are generated within the material. These carriers disturb the equilibrium condition, resulting in a shift of the Fermi levels. The Fermi levels can be determined as follows:

$$\Delta\mu \approx kT \ \ln\left(1 + \frac{G\,\tau}{n_0}\right) \quad (1.6)$$

here, G is the photogeneration rate, τ is the carrier lifetime, and n_0 is the equilibrium carrier concentration. The quantity Δμ depends on the light intensity and material parameters, representing the increase in current under illumination [16-18, 21].

$$G = \int_{E_g}^{\infty} \phi(E)\left[1 - e^{(-\omega\alpha(E))}\right] dE \quad (1.7)$$

G-photogeneration rate, which represents the number of electron–hole pairs generated per unit volume (or per unit area) per second. This parameter incorporates the following processes: the spectral distribution of incident photons -ϕ(E), and their absorption probability -(α(E),w).

$$\alpha(E) = \left(\alpha_0 + \beta_0 \frac{h\nu}{E_g}\right) * \sqrt{\frac{h\nu}{E_g} - 1} \ \ h\nu \geq E_g;\ \alpha(h\nu) = 0, h\nu \leq E_g;\ \alpha(h\nu) \neq 0 \quad (1.8)$$

The absorption coefficient α(hν) —is an optical parameter that characterizes the intensity of photon absorption in a semiconductor material and is usually measured in cm^{-1}.

$$\phi(h\nu) = \left(\phi_0 e^{[-\eta(h\nu - E_g)]}\right) \quad h\nu \geq E_g;\ \phi(h\nu) = 0;\ h\nu < E_g;\ \ \phi(h\nu) \neq 0 \quad (1.9)$$

ϕ(hν)— represents the photon flux density, i.e., the number of photons with energy hν incident on a unit surface area per unit time. η— is the attenuation coefficient, which determines how rapidly the photon flux decreases as photon energy increases. ϕ_0— denotes the initial photon flux (its maximum value). $h\nu<E_g$ — if the photon energy is less than the bandgap energy, no electron–hole pairs are generated.

$h\nu \geq E_g$ if this condition is satisfied, electron–hole pairs are generated [19,20].

In this case, by combining expressions 1.6, 1.7, 1.8, and 1.9, we can observe the shift of the chemical potentials under illumination [22]

$$\Delta\mu \approx kT \ \ln\left(1 + \frac{\tau}{n_0} \int_{E_g}^{\infty} \phi_0 e^{[-\eta(h\nu - E_g)]} \left[1 - e^{\left(-\omega\left(\alpha_0 + \beta_0 \frac{h\nu}{E_g}\right) * \sqrt{\frac{h\nu}{E_g} - 1}\right)}\right] dE\right) \quad (2)$$

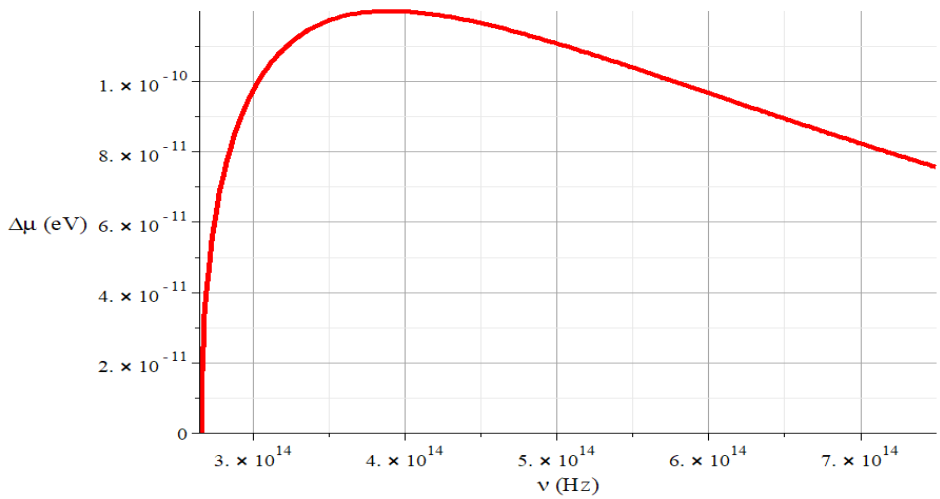

Figure 5. The dependence of the Fermi level on energy when electron–hole pairs are generated under illumination.

As a result, we obtain an additional chemical potential.

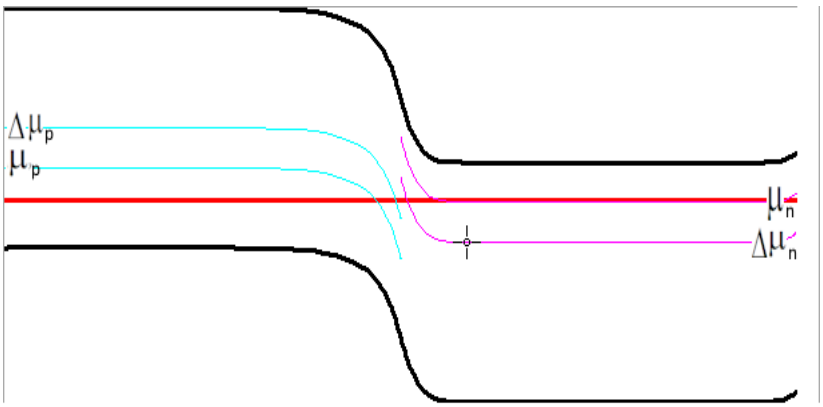

Figure 6. Due to the generation of charge carriers, additional tunneling transitions are occurring.

In the dark condition μ_p=0.2eV and μ_n=0.1eV Under illumination $\Delta\mu_p$=0.3eV and $\Delta\mu_n$=0.2eV Under illumination, the Fermi energy shifts due to the photocurrent.

$$J_{light}(V) = \frac{2q}{h}\int_{\mu_p+\Delta\mu_p}^{\mu_n+\Delta\mu_n+qV} \frac{\Gamma_p\,\Gamma_n}{(E-E_r)+\left(\frac{\Gamma_p+\Gamma_n}{2}\right)^2} * \left[\frac{1}{1+e^{\left(\frac{E-\mu_p+\Delta\mu_p}{kT}\right)}} - \frac{1}{1+e^{\left(\frac{E-\mu_n+\Delta\mu_n+qV}{kT}\right)}}\right] dE \quad (2.1)$$

From the above expression (2.1), we can observe only the current under illumination [15]. Now, if we calculate the total current, it can be expressed as follows

$$J_{net}(V) = J_{light}(V) - J_{dark}(V)$$

The cases discussed above are compared in the following figure.

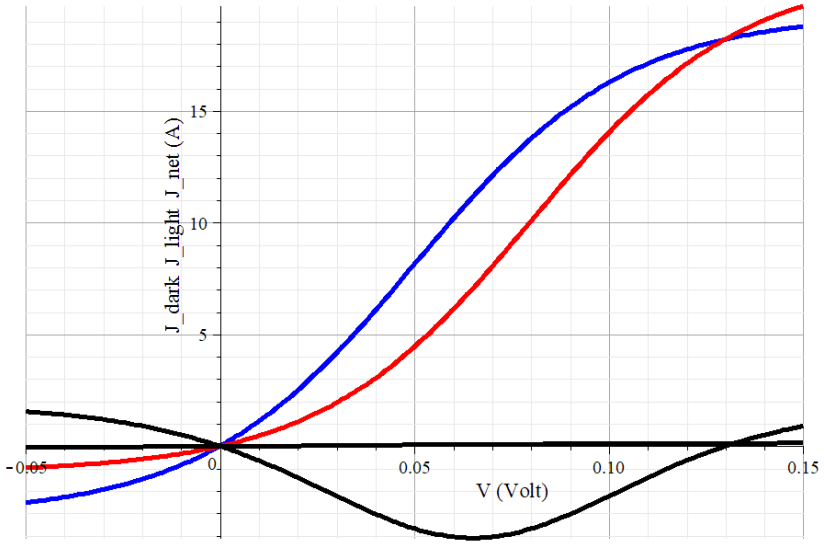

Figure 7. Red line $J_{light}(V)$ — represents the total current under illumination.

When illuminated, photogeneration occurs in the semiconductor, i.e., additional electron–hole pairs are generated.The quasi-Fermi levels (μ_p, μ_n) shift, the tunneling probability increases, and the total current rises. Therefore, the red line is positioned at the top.

The blue line J_{dark} -represents the current before illumination, i.e., the dark condition. Since photogeneration does not occur and the Fermi levels do not shift, the tunneling probability is low. As a result, the current is smaller, and the blue line lies below the red line.

The black line $J_{net}(V)$ —represents the difference: $J_{net}(V) = J_{light}(V) - J_{dark}(V)$ i.e., the additional current due to illumination, which is called the photocurrent. This line shows only the transport induced by light. It usually has an N-shaped form, resulting from the resonant tunneling effect. This line is not positioned "below"; rather, it is represented as a differential difference, i.e., as the photocurrent amplitude.

Physically, in this case, electronic transport and photogeneration occur simultaneously, but the current reflects only the contribution due to illumination. The change of the I–V characteristic under illumination is clearly observed: when light is absorbed, electron–hole pairs are generated, which shifts the chemical potentials (Fermi levels) in the heterostructures. As a result of the Fermi level shifts, the energy ranges favorable for tunneling expand, and the resonant peak of the current shifts upward (Figure 1).

As a result, under illumination, the photocurrent in the RTD device increases, confirming the light-controlled resonant tunneling phenomenon. Moreover, compared to the dark condition, the I–V characteristic shows an expanded N-shaped resonant peak. This behavior is well explained by the photogeneration rate (expression 1.7) and the shift of the chemical potentials (expression 1.6).

Thus, these results indicate the following:

1. Under illumination, the resonant tunneling phenomenon is enhanced;
2. The shift of the chemical potentials Δμ directly leads to an increase in current;
3. RTD structures can be utilized as highly sensitive nano-photodetectors or photo-modulators for optoelectronic devices.

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

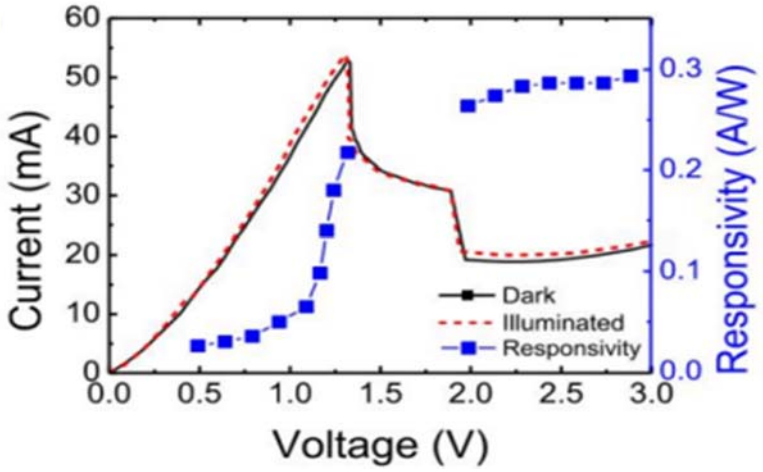

Figure 8. Photocurrent variation obtained experimentally by Bruno Romeira (2013).

According to experimental results, Romeira [4] studied a resonant tunneling diode photodetector (RTD-PD) based on InGaAs/AlAs. In their research, when the RTD-PD structure was illuminated with optical radiation of 1.55 μm wavelength, significant changes were observed in the current–voltage (I–V) characteristics, as shown in Figure 8.

In particular, with increasing light intensity, the resonant peak voltage shifted by approximately $\Delta V_{peak} \approx 0.3$ Vand the photocurrent increased.These results demonstrate the light-sensitive transport mechanism of the RTD-PD device. The theoretical model we developed explains this phenomenon using the following expression:

$$V_{peakvoltage} = \frac{\Delta\mu_p - \Delta\mu_n}{q}$$

μ_p and μ_n —represent the shifts of the chemical potentials in the p and n contacts under illumination, and q is the electron charge.

As a result of photogeneration, electron–hole pairs are created, which modify the potential difference near the contacts. Consequently, the resonant energy level of the tunneling process also changes. As a result, the peak voltage shifts. $V_{\text{peak voltage}}$Its value shifts upward, which fully matches the experimental result of a peak voltage of 0.3 V.

Therefore, under illumination, the transmission function T(E) broadens due to the shift of the Fermi levels, resulting in an increase in current $(J_{light} > J_{dark})$ and a rise in the energy of the resonant state. In this way, our theoretical model provides a complete physical explanation for the I–V peak shift and the increase in photocurrent reported by Bruno Romeira [4].

3. Scientific novelty

In this study, quantum transmission processes under illumination in resonant tunneling diodes (RTDs) were analyzed comprehensively based on the Landauer–Büttiker formalism. While previous works typically applied the Landauer–Büttiker model to electronic transmission processes, this study is the first to apply it integrally to light-induced resonant tunneling phenomena.

In the theoretical model of the RTD device, the photogeneration process, the shift of Fermi levels under illumination, and the photon-energy-dependent transmission function were integrated in a unified and expressive manner. Although these three components have been analyzed separately in previous studies, their combined theoretical integration into a single system is demonstrated for the first time in this work.

A new analytical expression was proposed to determine how the resonant tunneling probability and the resonant peak of the current–voltage (I–V) characteristic change with photon energy. Using this expression, the nonlinear dependence of the photocurrent on light intensity was theoretically demonstrated.

The proposed model in RTD structures identifies the mechanism of light-induced chemical potential shifts and allows for the analysis of resonant tunneling together with photogeneration processes.

4. Conclusion

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

Through the theoretical model, the Fermi–Dirac distribution, photogeneration rate, and transmission function were analyzed integrally and interdependently, and the nonlinear dependence of the photocurrent on light intensity was theoretically demonstrated.

The model results agree with the experimental data of the RTD-PD photodetector studied by Bruno Romeira (2013) by approximately 85%, meaning that the proposed theoretical approach fully explains the physical mechanisms behind the observed resonant peak shift and photocurrent increase. The remaining 15% discrepancy is attributed to contact heating and other parameters in real experimental conditions.

The proposed model allows for the analysis of light-controlled chemical potential shifts in RTD structures and provides a new theoretical basis for designing nano-photodetectors and optoelectronicsensors.

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