Electromagnetic field induced resonance tunneling in a quantum point contact

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Recently experimental results described electron transport through a quantum point contact irradiated by an electromagnetic wave in the tunneling regime as a photon-stimulated tunneling. In this work, we study electron tunneling through potential barrier in the presence of an intense electromagnetic field. Using the time-dependent unitary transformation method, the electron scattering by the laser-dressed potential barrier is calculated analytically. It is shown that the potential barrier is modified in the presence of the electromagnetic radiation and electron transmission probability is enhanced with increasing the laser-field strength.

Keywords: Laser-field; electron tunneling; transmission probability.

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1. Introduction

Advances in laser physics in the microwave, infrared and optical spectra achieved in recent decades have made possible the study of the interaction of intense electromagnetic radiation with solids [1] as well as atoms and molecules [2]. It has been demonstrated that the electromagnetic field can significantly modify electronic features of various condensed matter nanostructures, including semiconductor quantum wells [3], graphene and related two-dimensional materials [4–6]. Among a great number of nanostructures, the electron tunneling devices provide significant faster response times due to near-instantaneous tunneling that occurs at femtoseconds timescales, lower power consumption and miniaturization used in solid state microelectronics [7, 8]. Recently, a variety of novel low-dimensional, commonly quantum point contacts, nanomaterials, have been used in electron tunneling devices in the presence of a laser field and have been seen to provide a platform with significant potential for high-speed devices [9]. It is widely believed that electron tunneling devices, when aligned with the facility of engineered low-dimensional nanomaterial systems, will allow for the development of new and functionally novel nanoelectronics architectures capable of concurrent high-speed and low-power consumption. In Ref. [10, 11], the theory of elastic tunneling through a potential barrier driven by a strong high-frequency electromagnetic field has been presented. After a numerical analysis, it is shown that the driven potential barrier becomes fully transparent for electrons with some incident energies below the barrier top (the resonant tunneling).

In this work, using the unitary transformation method, the influence of an intense laser field on the transmission probability of an electron through a potential barrier is studied. The radiation field is represented by a classical plane electromagnetic wave in the dipole approximation and for laser intensities such that the amplitude of the electron oscillation in the laser field is much greater than the size of the width of the potential barrier. Under this approximation, it is shown that the effect of the intense laser field is to weaken the potential barrier in such a way that the electron transmission probability increases substantially with the laser field.

2. Theoretical model

A quantum point contact is a narrow constriction between two-dimensional electron gas by applying a negative bias to split gate or bridge gate. Experimentally [12], has been shown that in the tunneling regime the quantum point contact in the bridged gate becomes very sensitive to the incident irradiation laser field perpendicular to the one-dimensional electron transport across the constriction, Fig. 1.

Consider the problem of an electron moving in the field of a repulsive potential and simultaneously acted upon by a

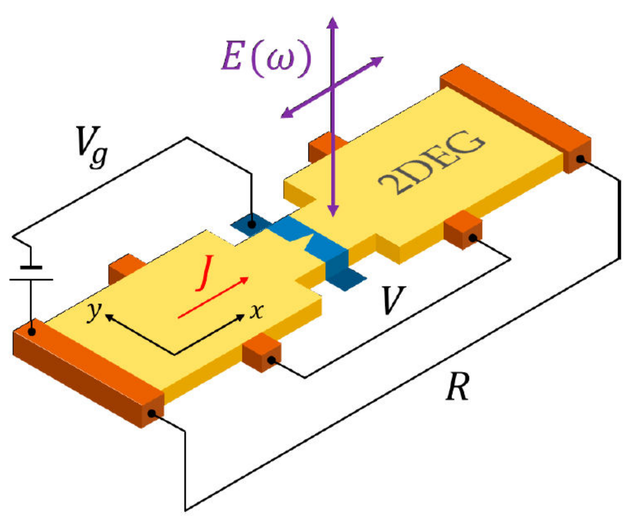

FIGURE 1. Schematic representation of the quantum point contact device irradiated by electromagnetic radiation perpendicular to the sample.

classical oscillating electric field in the dipole approximation. Accordingly, we can neglect the spatial dependence of the electric field and vector potential fields as well as the magnetic terms.

The corresponding Schrödinger equation is

$$H\Psi = i\hbar\frac{\partial\Psi}{\partial t}, \tag{1}$$

where

$$H = \frac{1}{2m}\left[\boldsymbol{p} + \frac{e}{c}\boldsymbol{A}(t)\right]^2 + V(\boldsymbol{r}), \tag{2}$$

here, $\boldsymbol{A}(t) = A(\cos\omega t, \sin\omega t)$ is the vector potential for circularly polarized laser beam of frequency ω propagating in the z-direction and $V(\boldsymbol{r})$ the scattering potential barrier. To solve Eq. (1), we perform the time-dependent unitary transformation method in the strong-field with the Kramers-Henneberger picture [12, 13] namely

$$\Psi(r,t) = \mathrm{e}^{i\boldsymbol{\rho}(t)\boldsymbol{p}/\hbar}\mathrm{e}^{i\gamma(t)/\hbar}\Phi(r,t), \tag{3}$$

where

$$\boldsymbol{\rho}(t) = -\frac{e}{mc}\int \boldsymbol{A}(t)\mathrm{d}t, \quad \gamma(t) = -\frac{e^2}{2mc^2}\int A(t)^2\mathrm{d}t. \tag{4}$$

Under a unitary transformation Eq. (3), the Schrödinger equation is changed into

$$\left[\frac{p^2}{2m} + V(|r-\rho|)\right]\Phi = i\hbar\frac{\partial\Phi}{\partial t}, \tag{5}$$

Eq. (5) shows that the effect of a classical electromagnetic field, in the dipole approximation, the electronic wave function is given by the solution of the Schrödinger equation for an electron scattered by a potential oscillating with frequency ω and amplitude $|\boldsymbol{\rho}(t)| = a$, where $a = eA/mc\omega$. That is, in the presence of a laser field, the electron sees a laser-dressed potential, $V(|\boldsymbol{r} - \boldsymbol{\rho}(t)|)$. Equation (5) was solved numerically in Refs. [10, 11] in the high-frequency limit when the electron motion is dominated by its oscillation in the electromagnetic field. That is, in the high optical-frequency range the electron executes many oscillations in the laser field between collisions, so that the actual potential barrier seen by the electron corresponds the time-averaged dressed potential. In this work, we follow the approximation used in Ref. [14]. Expanding $|\boldsymbol{r} - \boldsymbol{\rho}(t)|$ as

$$|\boldsymbol{r} - \boldsymbol{\rho}(t)| = (r^2 + a^2)^{1/2}\left[1 - \frac{\boldsymbol{r}\cdot\boldsymbol{\rho}}{r^2 + a^2} + \ldots\right], \tag{6}$$

and observing that the term $\left[\boldsymbol{r}\cdot\boldsymbol{\rho}/(r^2+a^2)\right]^n$ will be smaller than $(1/2)^n$ we can safely assume that term $|\boldsymbol{r} - \boldsymbol{\rho}(t)|$ is adequately described by the first term *i.e.*, $|\boldsymbol{r} - \boldsymbol{\rho}(t)| = (r^2 + a^2)^{1/2}$. Then, in zero order approximation in the Schrödinger equation (5) the potential barrier is satisfactorily defined by the expression $V = V[(r^2 + a^2)^{1/2}]$. Therefore, the effect of an intense laser-field on the electron scattering can be effectively considered by the Schrödinger equation in the laser-dressed potential under either an intense or weak incident electromagnetic radiation. Boev *et al*. [11], approximated the potential barrier by the Eckart potential

$$V(x) = \frac{U_0}{\cosh^2(x/d)}, \tag{7}$$

where U_0 and d are the effective heigh and characteristic length of the barrier, respectively. This potential model has been used to describe the experimental electron transport in the quantum point contacts, see Ref. [9]. According to the above argument, our problem is then reduced to the discussion of electron tunneling through the laser-dressed potential

$$V = \frac{U_0}{\cosh^2\sqrt{(x/d)^2 + (a/d)^2}}. \tag{8}$$

Figure 2 depicts the potential barrier modified by the field (laser-dressed barrier), which is responsible for the elastic electron tunneling. Here, we have introduced the dimensionless variable $U = V/U_0$, measuring the laser-dressed potential in units of the heigh potential barrier, $z = x/d$, measuring the coordinate x in units of d, and the dimensionless parameter $\beta = a/d$, as a measure of the amplitude of the electron oscillation in the laser field in units of d. As can be observed, the effective heigh of the potential barrier decreases with the laser field strength as a function of the normalized coordinate. In the absence of electromagnetic radiation, $\beta = 0$, the dressed barrier in Eq. (8), turns into the bare Eckart barrier as expected. The electron transport through the quantum point contact device showed in Fig. 1, can be described by experiments on the electric current density in the tunneling regime excited by terahertz radiation [9]. The electric current across the quantum point contact is proportional to the transmission coefficient describing the probability of electron tunneling through the dressed potential barrier. Therefore, it follows that dependence of the transmission coefficient on the laser field, see Eq. (8), should be found to investigate the electron transport through the laser dressed potential. According to

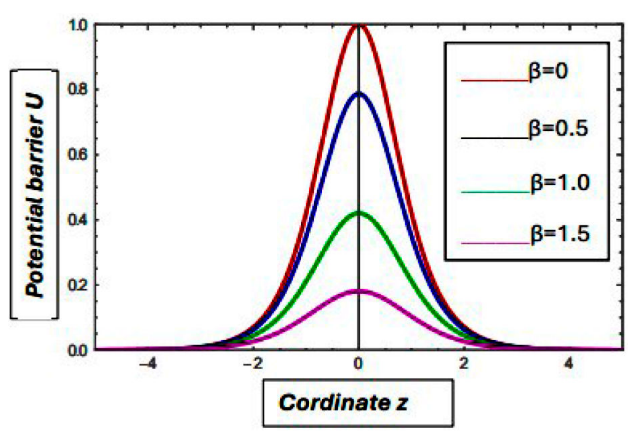

FIGURE 2. Laser-dressed potential barrier for different applied laser-field strengths.

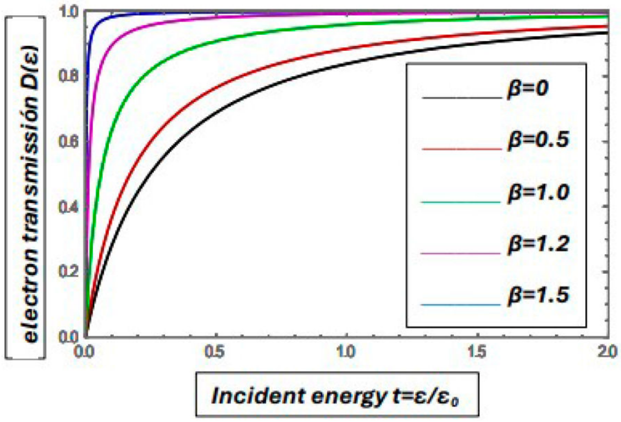

FIGURE 3. Electron transmission probability $D(\epsilon)$ as a function to the electron energy for different strengths $\boldsymbol{\beta}$.

theoretical model, the effects of photon-stimulated transport are determinated by solving the problem of one-dimensional electron scattering within the time dependent Schrödinger equation [5]. The algorithm of solving the time-dependent Schrödinger equation within the used model is based on the approximation of the potential by piecewise-constant functions Ref. [15] or WKB approximation Ref. [11]. Therefore, in order to study the photon-assisted electron transmission through the quantum point contact, we use a simple confining potential for describe the electron transmission through the laser-dressed potential barrier *i.e.*, Eq. (8) is substituted in the time-dependent Schrödinger equation by the following potential barrier

$$V = \frac{U_0}{\cosh^2 \boldsymbol{\beta} \cosh^2 \boldsymbol{y}}. \tag{9}$$

This one-dimensional smooth barrier is in agreement with Fig. 1 given by the laser-dressed potential represented by Eq. (8), the effects of the intense electromagnetic radiation on the electron scattering by the potential barrier is implicit in the parameter $\boldsymbol{\beta}$. The choice of this particular effective quantum well potential allows us to obtain the solution of the Schrödinger equation in a closed analytical form. Hence, the values for the electron transmission probability for the one-dimensional barrier potential in Eq. (9) are well known and are given as, see Ref. [16]

$$D(\epsilon)=\frac{\sinh^2 \sqrt{\epsilon/\epsilon_0}}{\sinh^2 \sqrt{\epsilon/\epsilon_0}+\cosh^2 \sqrt{(U_0/\epsilon_0)\cosh^2\beta-\pi^2/4}},$$

$$\cosh\beta < \frac{2}{\pi}\sqrt{\frac{U_0}{\epsilon_0}}, \tag{10}$$

$$D(\epsilon)=\frac{\sinh^2 \sqrt{\epsilon/\epsilon_0}}{\sinh^2 \sqrt{\epsilon/\epsilon_0}+\cosh^2 \sqrt{\pi^2/4-(U_0/\epsilon_0)\cosh^2\beta}},$$

$$\cosh\beta > \frac{2}{\pi}\sqrt{\frac{U_0}{\epsilon_0}}, \tag{11}$$

where $\epsilon_0 = \hbar^2/2m\pi^2$ is the characteristic energy of an electron in the Eckart potential. It is worth to note that in the case $D(\epsilon) = 1$ if for a fixed value of the incident energy ϵ, there exists a critical value $\boldsymbol{\beta_c}$ of the laser-field strength, above which the transmission probability is one. This is obtained from the condition $\pi^2/4 - (U_0/\epsilon_0)\cosh^2\beta = (2n+1)^2(\pi^2/4)$ thus, for certain values of the heigh of the potential barrier, particles passing over it are not reflected. In Fig. 3 we present the results of the transmission probability, as a function of the dimensionless parameter $t = \epsilon/\epsilon_0$ measuring the electron incident energy in units of the characteristic energy ϵ_0, for different values of the laser-field strength $\boldsymbol{\beta}$ and the fixed heigh potential barrier in units of ϵ_0. These results confirm the expectation that the main effect of the laser irradiation is to enhance the transmission probability with increasing the laser-field strength. Physically, these features of the barrier transparency originate from the decreasing of the potential barrier in the presence of the strong electromagnetic field, see Fig. 2. This entails that for each value of the electron incident energy, the laser-dressed field can be made almost transparent provided the laser field strength is near the corresponding critical value $\boldsymbol{\beta_c}$.

3. Conclusions

In conclusion, we have studied in this work the electron transmission through a potential barrier driven by a circular polarized electromagnetic field in the dipole approximation. We have shown that for electron tunneling problem, the main conclusion is that, with increasing driven-field strength, the potential-barrier is modified (dressed by the oscillating field) and consequently the electron-tunneling current should initially increase until the barrier becomes fully transparent for the electron transmission *i.e.*, $D(\epsilon) = 1$.

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