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THz-field-induced electronic transmission step-structure for a quantum wire*

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We study theoretically the low-temperature electronic transport property of a straight quantum wire under the irradiation of a finite-range transversely polarized external terahertz (THz) electromagnetic (EM) field. Using the free-electron model and the scattering matrix approach, we show an unusual behaviour of the electronic transmission of this system. A sharp step-structure appears in the electronic transmission probability as the EM field strength increases to a threshold value when a coherent EM field is applied. We demonstrate that this effect physically comes from the inelastic scattering of electrons with lateral photons through intersubband transitions.

Keywords: quantum wires, THz electromagnetic field, electronic transmission, scattering matrix
PACC: 7320D, 7335C, 7865H

1. Introduction

Structures of a mesoscopic size, created in a two-dimensional electron gas (2DEG) of a $GaAs/Al_xGa_{1-x}As$ semiconductor heterojunction using a split gate technique,[1] have been a subject of intensive investigations during the last decade.[2,3] In the ballistic regime and at low temperatures quantum coherent effects will dominate the electronic transport properties of a mesoscopic system. The most important feature is that the conductance of a quantum wire (quantum point contact, or narrow channel) shows an histogram structure when its lateral size varies, and each step has a height of $2e^2/h$ or integer times of it.[4]

The electronic transport properties of quantum wires can be affected by many factors. The presence of disorders in a quantum wire results in a suppression of the conductance plateaus below the integer values,[4,5] and the interaction of electrons induces transport anomalies.[6] The coupling among wire and reservoirs (leads) has also been studied.[7] Geometrically, the variation of the lateral shape of the wire yields a mixture of different electron modes. However, if this variation is slow enough to satisfy the adiabatic approximation, the histogram structure of conductance is still preserved, but it is totally determined by the narrowest neck part of the whole wire.[8]

Recently, there has been growing interest in the time-dependent transport for quantum wire systems, such as the presence of a time-modulated potential[9] and quantum pumping.[10] Moreover, when a quantum wire is irradiated under a coherent external EM field,[11–19] many new features arise due to the inelastic scattering of electrons by photons. The typical values of the lateral energy level separation and the Fermi energy are of the order of $1-100$meV for semiconductor quantum wires. This corresponds to frequencies of the order of $0.25-25$THz, which are available in experiments with the development of the ultrafast laser technology.[20] When the Fermi level is below the lowest lateral level in the neck part of a wire, electrons cannot go through without the assistance of external field. However, under the external field irradiation, electrons in the wire can absorb photons and go through this geometric barrier.[11–14] Therefore, in the region of barrier the electron reflection is induced by the combination of the external EM field

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effect and the lateral shape variation.[11−17] However, the pure external EM field effect (subtracting the effect of geometric barrier) on the electronic transport for a straight uniform quantum wire has attracted less attention. This effect may be important for the understanding of basic physics feature and for the future nanoscale circuit applications. Up to now, to our knowledge, the influence of a transversely polarized EM field on a straight quantum wire has only been studied with a delta-profile range of the field irradiation.[20]

In this paper, we study the quantum transport property of a straight long quantum wire irradiated under a finite-range transversely polarized THz EM field. We have studied the same system with a Hamiltonian in terms of canonical momentum and vector potential gauge, and reported a step-structure on the transmission as a function of the total electron energy.[21] In this paper we use an alternative Hamiltonian in terms of the electric field gauge with more detailed analytical calculations, and show that the transmission step-structure also exists as the field strength increases to a threshold value.

In Section 2 we present the formulation for solving the time-dependent Schrödinger equation of the system. In Section 3 we study the electronic transmission property of the system by means of the scattering matrix and present a numerical example. We summarize the paper in Section 4.

2. Model and formalism

The system under study is an ideal straight quantum wire which smoothly connects the two electron reservoirs (leads) at the ends.[21] The x-axis is longitudinally along the wire, and the y-axis describes the transversal direction. The quantum wire part of the system is irradiated under a transversely polarized THz EM field within a finite-range of $0 < x < L$ in an unspecified way. Because the transversal size of the quantum wire is much less than the wavelength of the illuminating wave, the field vector potential can be written as $\boldsymbol{A}(t) = (\varepsilon/\omega)\cos(\omega t)\hat{j}$, where ε and ω are the strength and angular frequency of the EM field respectively, $\hat{j}$ is the unit vector of the y coordinate. Thus the time-dependent electric field is

$$\boldsymbol{E}(t) = \varepsilon \sin(\omega t)\hat{j}. \tag{1}$$

At low temperatures and in ballistic regime we can use the free electron model to describe the electronic dynamics. Therefore, the appropriate time-dependent Schrödinger equation for an electron in the range of $0 < x < L$ is

$$\begin{aligned} &\mathrm{i}\hbar\frac{\partial}{\partial t}\psi(x,y,t) \\ &=\left[\frac{\hat{p}^2}{2m^*} + U(y) + e\varepsilon y\sin(\omega t)\right]\psi(x,y,t), \end{aligned} \tag{2}$$

where $\hat{p} = -\mathrm{i}\hbar\nabla$ is the momentum operator, m^* and e are the effective mass and charge of the electron, respectively. $U(y)$ is in the form of either hard-wall potential or parabolic one which confines the electrons in the wire and in the leads.

We assume that the electronic wavefunction in Eq.(2) has a form of separation variables

$$\psi(x,y,t) = \sum_k \mathrm{e}^{\mathrm{i}kx}\sum_n a_n(t)\phi_n(y), \tag{3}$$

where k is the longitudinal wavevector of the electron, $a_n(t)$ is the time-dependent amplitude, and $\phi_n(y)$ are the transversal eigenfunctions which satisfy the steady-state Schrödinger equation

$$\left[\frac{\hat{p_y}^2}{2m^*} + U(y)\right]\phi_n(y) = \epsilon_n\phi_n(y), \tag{4}$$

where ϵ_n are transversal energy levels. For simplicity, we only consider the transition between the two lowest transversal (lateral) energy levels with the Fermi level between them and ignore other higher levels. Inserting Eq.(3) into Eq.(2), multiplying ϕ_1^*, ϕ_2^* respectively on both sides and integrating in transversal dimension, we obtain the matrix form of Schrödinger equation

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\begin{bmatrix} a_1(t) \\ a_2(t) \end{bmatrix} = H\begin{bmatrix} a_1(t) \\ a_2(t) \end{bmatrix}, \tag{5}$$

where the two-level Hamiltonian

$$H = \begin{bmatrix} \epsilon_1 + \dfrac{\hbar^2k^2}{2m^*} & -e\varepsilon l\sin(\omega t) \\ -e\varepsilon l\sin(\omega t) & \epsilon_2 + \dfrac{\hbar^2k^2}{2m^*} \end{bmatrix}, \tag{6}$$

and $l = -\int \phi_1^* y\phi_2 \mathrm{d}y = -\int \phi_2^* y\phi_1 \mathrm{d}y = 0.18d$ (d is the width of the wire) is a two-level interaction constant.

A time-dependent unitary transformation is used for the treatment of a two-level atom interaction with single-mode light in quantum optics[22]

$$U = \begin{bmatrix} \mathrm{e}^{-\mathrm{i}(\epsilon_1 + \frac{\hbar^2k^2}{2m^*} - \frac{\delta}{2})t} & 0 \\ 0 & \mathrm{e}^{-\mathrm{i}(\epsilon_2 + \frac{\hbar^2k^2}{2m^*} + \frac{\delta}{2})t} \end{bmatrix}, \tag{7}$$

where $\delta = \hbar\omega - (\epsilon_2 - \epsilon_1)$ is the detuning; then Eq.(5) is transformed into

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\begin{bmatrix} a_1' \\ a_2' \end{bmatrix} = \left(U^{\dagger}HU - \mathrm{i}U^{\dagger}\frac{\partial U}{\partial t}\right)\begin{bmatrix} a_1' \\ a_2' \end{bmatrix}, \quad (8)$$

where $(a_1', a_2')^T = U^{+}[a_1(t), a_2(t)]^T$ is a new row vector. Thus, using the rotating wave approximation the time-dependent Schrödinger equation (5) is finally reduced to time-independence under the transformation

$$\frac{1}{2}\begin{bmatrix} \delta & \mathrm{i}e\varepsilon l \\ -\mathrm{i}e\varepsilon l & -\delta \end{bmatrix}\begin{bmatrix} a_1' \\ a_2' \end{bmatrix} = \lambda\begin{bmatrix} a_1' \\ a_2' \end{bmatrix}. \quad (9)$$

The two eigenvectors of Eq.(9) are

$$\begin{bmatrix} a_1' \\ a_2' \end{bmatrix} = \begin{bmatrix} 1 \\ A_{\pm} \end{bmatrix},$$

$$A_{\pm} = \mathrm{i}\left[\frac{-\delta \pm \sqrt{\delta^2 + (e\varepsilon l)^2}}{e\varepsilon l}\right], \quad (10)$$

and the two corresponding eigenvalues are $\lambda_{\pm} = \pm\frac{1}{2}\sqrt{\delta^2 + (e\varepsilon l)^2}$. Through an inverse transformation we finally obtain the electronic wavefunction in the EM field irradiated region

$$\psi(x, y, t) = \sum_k [c_{k,+}|+> \mathrm{e}^{-\mathrm{i}\lambda_+ t} + c_{k,-}|-> \mathrm{e}^{-\mathrm{i}\lambda_- t}]\mathrm{e}^{\mathrm{i}kx}, \quad (11)$$

where $c_{k,\pm}$ are two arbitrary constants, $|\pm>$ are two row vectors

$$|\pm> = \begin{bmatrix} \mathrm{e}^{-\mathrm{i}(\epsilon_1 + \frac{\hbar^2k^2}{2m^*} - \frac{\delta}{2})t} \\ A_{\pm}\mathrm{e}^{-\mathrm{i}(\epsilon_2 + \frac{\hbar^2k^2}{2m^*} + \frac{\delta}{2})t} \end{bmatrix}. \quad (12)$$

3. Electronic transmission

Firstly, we consider the electronic transmission through the left interface (boundary) between regions with and without field irradiation. The transmission property of the right interface can be obtained symmetrically.[23] When an electron with energy E emits from the left reservoir to the interface at $x = 0$, transmission and reflection will take place simultaneously. Because the electron has a certain probability of absorbing a photon after penetrating the interface, transition from lower mode to upper mode happens. So there are two energy components of E and $E + \hbar\omega$ in the reflection wave in the region of $x < 0$,

$$\psi(x < 0) = [\mathrm{e}^{\mathrm{i}(k_1 x - Et/\hbar)} + c_1\mathrm{e}^{-\mathrm{i}(k_1 x + Et/\hbar)}]\phi_1(y) + c_2\mathrm{e}^{-\mathrm{i}[k_2 x + (\omega + E/\hbar)t]}\phi_2(y), \quad (13)$$

where c_1, c_2 are reflection coefficients of the two modes, and $k_1 = \sqrt{2m^*(E - \epsilon_1)}/\hbar$ and $k_2 = \sqrt{2m^*(E - \epsilon_2 + \hbar\omega)}/\hbar$ are the two wavevectors. Similarly, from Eq.(11) we can obtain the electronic wavefunction in the region of $x > 0$,

$$\psi(x > 0) = [c_+\mathrm{e}^{\mathrm{i}(k_+ x - Et/\hbar)} + c_-\mathrm{e}^{\mathrm{i}(k_- x - Et/\hbar)}]\phi_1(y) + [A_+c_+\mathrm{e}^{\mathrm{i}[k_+ x - (E/\hbar + \omega)t]} + A_-c_-\mathrm{e}^{\mathrm{i}[k_- x - (E/\hbar + \omega)t]}]\phi_2(y), \quad (14)$$

where c_+, c_- are the transmission coefficients of the two modes, and

$$k_{\pm} = \sqrt{2m^*(E - \epsilon_1 + \delta/2 - \lambda_{\pm})}/\hbar \quad (15)$$

are the two field-split electron wavevectors (momentums). Now we can match these two wavefunctions at the interface of $x = 0$ (i.e. letting the two wavefunctions and their differentials be continuous) to determine the four constants c_+, c_-, c_1 and c_2 and to calculate the transmission probability of the single interface case.

In our numerical example, the quantum wire is taken to be in a 2DEG of high-mobility $GaAs/Al_xGa_{1-x}As$ with a typical electron density $n \sim 2.5 \times 10^{11}/\mathrm{cm}^2$ and $m^* = 0.067m_e$. We use the hard-well confining potential of $U(y)$ and choose the width of the wire d=50nm for the system. Correspondingly, the two lowest levels are $\epsilon_1 = 2.25$meV and $\epsilon_2 = 9$meV with a total electron energy $E = 2.5$meV. Figure 1 shows the calculated electronic transmission probability T through one interface as a function of ω and ε. In the absence of the EM field the transmission of the system would be a constant of unity. In the case of EM field irradiation, however, there is a strong variation of the transmission probability between 0.5 (black area) and 1 (white area) in the $\omega - \varepsilon$ plane, in which the resonant absorption around EM field frequency $\omega \sim 10$THz is indicated.

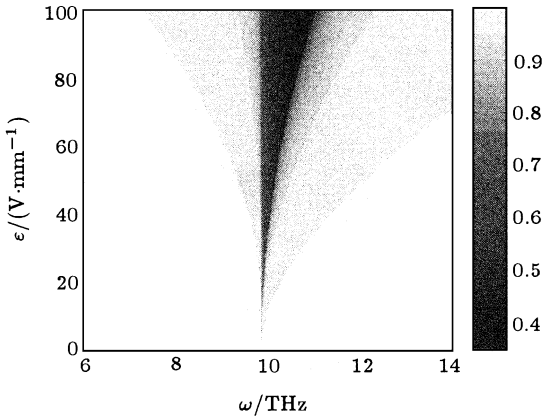


Fig.1. Transmission probability T as a function of ε and ω of the EM field for one interface. The parameters are $\epsilon_1 = 2.25$meV, $\epsilon_2 = 9$meV, $d = 50$nm and $E = 2.5$meV.

Since the main point of physics may appear in the vicinity of the resonant frequency so we only give the results for the resonant case ($\delta = 0$, $\lambda_\pm = \pm e\varepsilon l/2$) in the following arguments. In this case the unnormalized transmission and reflection matrices are

$$t' = \begin{bmatrix} k_1/(k_1+k_+) & 0 \\ k_1/(k_1+k_-) & 0 \end{bmatrix}, \tag{16}$$

$$r = \begin{bmatrix} (k_1^2 - k_+k_-/[(k_1+k_+)(k_1+k_-)] & 0 \\ -\mathrm{i}k_1(k_- - k_+)/[(k_1+k_+)(k_1+k_-)] & 0 \end{bmatrix}, \tag{17}$$

from which we can obtain the electronic transmission probability through the left interface

$$T = 2\left|\frac{\sqrt{k_1k_+}}{k_1+k_+}\right|^2\theta(k_+^2) + 2\left|\frac{\sqrt{k_1k_-}}{k_1+k_-}\right|^2\theta(k_-^2), \tag{18}$$

where $\theta(\cdots)$ is the step function and the two split wavevectors in Eq.(15) are simply reduced to

$$k_\pm = \sqrt{2m^*(E-\epsilon_1 \pm e\varepsilon l/2)}/\hbar. \tag{19}$$

The solid line in Fig.2 shows the resonant transmission probability versus the field strength according to Eq.(18) with the same parameters as those in Fig.1. One can clearly see a step-dropping of the transmission as the field strength increases to $\varepsilon = 2(E-\epsilon_1)/el = 55.6$V/mm. This pure external EM field effect does not exist for a straight quantum irradiated under a longitudinally polarized EM field[19] and for the neck-shape wires[11−16] even under a transversely polarized EM field irradiation. In our case of a straight quantum wire, when an electron penetrates through the interface into the irradiated region of the wire, the transverse levels of the electron are dressed and one electron mode is split into two time-dependent modes $|+\rangle \mathrm{e}^{-\mathrm{i}(e\varepsilon l/2+k_+^2)t}$ and $|-\rangle \mathrm{e}^{-\mathrm{i}(-e\varepsilon l/2+k_-^2)t}$ with the longitudinal momenta k_+ and k_- respectively. From Eq.(19) we know that k_+ is always real. However, k_- is imaginary when $\varepsilon > 55.6$V/mm; in this case the mode $|-\rangle \mathrm{e}^{-\mathrm{i}(-e\varepsilon l/2+k_-^2)t}$ corresponds to an evanescent (nonpropagating) mode which contributes nothing to the transmission, so that the total transmission probability is suppressed to near 0.5. When $\varepsilon < 55.6$V/mm, the two modes become propagating and thus both can contribute to the transmission. Furthermore, when $\varepsilon << 55.6$V/mm, the field is too weak to affect the system, and thus the transmission probability is close to 1 like that without field. This effect of splitting wavevectors originally comes from the intersubband transition.

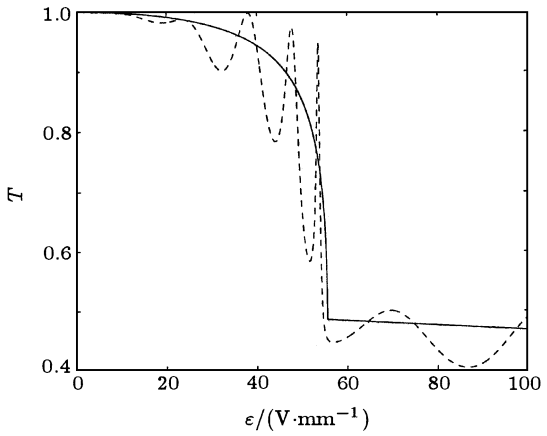


Fig.2. Resonant transmission probability T versus field strength ε with the same parameters as those in Fig.1. The dashed curve for the case of one interface and the solid curve for the case of two interfaces with a field irradiation length of $L = 800$nm.

Next, we consider the electronic transmission of the whole system. In this case the system contains two interfaces between regions with and without field irradiation. To obtain the total transmission through the two interfaces with a length of field irradiation range L, we use the approach recently developed by Torres and Saénz.[23] This approach needs to derive the total scattering matrix which is expressed in terms of the transmission matrix and reflection matrix on each interface. The total transmission matrix is just the anti-diagonal submatrix of the total scattering matrix in the case of symmetrical system. Detailed knowledge about this aspect can be found in Ref.[23] and is not presented here.

Because of the similarity of the two interfaces, one does not have to match the wavefunctions at the right

interface, but one needs to know the transmission and reflection matrices from right to left for the first interface. The electronic wavefunction in the EM field irradiated region is

$$\begin{aligned}\psi(0<x<l) =&[c_+^{\rm e}{\rm e}^{-{\rm i}k_+x}+c_-^{\rm e}{\rm e}^{-{\rm i}k_-x}\\&+c_+^{\rm r}{\rm e}^{{\rm i}k_+x}+c_-^{\rm r}{\rm e}^{{\rm i}k_-x}]{\rm e}^{-{\rm i}Et/\hbar}\phi_1\\&+[A_+c_+^{\rm e}{\rm e}^{-{\rm i}k_+x}+A_-c_+^{\rm e}{\rm e}^{-{\rm i}k_-x}\\&+A_+c_+^{r}{\rm e}^{{\rm i}k_+x}+A_-c_-^{r}{\rm e}^{{\rm i}k_-x}]\\&\times{\rm e}^{-{\rm i}(E/\hbar+\omega)t}\phi_2,\end{aligned}\tag{20}$$

where $c_\pm^{\rm e}$ are coefficients of electrons emitting from right to left, and $c_\pm^{\rm r}$ are associated reflection coefficients. Correspondingly, the electronic wavefunction in the region of $x<0$ is

$$\begin{aligned}\psi(x<0) =&c_1^t{\rm e}^{-{\rm i}(k_1x+Et/\hbar)}\phi_1\\&+c_2^t{\rm e}^{-{\rm i}[k_2x+(E/\hbar+\omega)t]}\phi_2,\end{aligned}\tag{21}$$

where c_1^t and c_2^t are the transmission coefficients. These two wavefunctions also satisfy the continuous condition at $x=0$, from which we can obtain the transmission and reflection matrices from right to left for the interface,

$$r'=\begin{bmatrix}(k_+-k_1)/(k_1+k_+) & 0\\ 0 & (k_--k_1)/(k_1+k_-)\end{bmatrix},\tag{22}$$

$$t=\begin{bmatrix}2k_+/(k_1+k_+) & 2k_-(k_1+k_+)\\ (2k_+)/(k_1+k_+) & -2k_-/(k_1+k_+)\end{bmatrix}.\tag{23}$$

The transfer matrix between the two interfaces is

$$X=\begin{bmatrix}{\rm e}^{{\rm i}k_+L} & 0\\ 0 & {\rm e}^{{\rm i}k_-L}\end{bmatrix}.\tag{24}$$

Because of the symmetry of the system, the total transmission matrix is $t_{\rm tot}=S_{12}=t(1-Xr'Xr')^{-1}Xt'$.[21] Thus the total electronic transmission probability through the two interfaces is

$$T={\rm Tr}[t_{\rm tot}^+t_{\rm tot}]=P_1+P_2,\tag{25}$$

where

$$\begin{aligned}P_1=&\left|\frac{2k_1k_+}{{\rm e}^{-{\rm i}k_+L}(k_1+k_+)^2+{\rm e}^{{\rm i}k_+L}(k_1-k_+)^2}\right.\\&\left.+\frac{2k_1k_-}{{\rm e}^{-{\rm i}k_-L}(k_1+k_+)^2-{\rm e}^{{\rm i}k_-L}(k_1-k_-)^2}\right|^2,\end{aligned}\tag{26}$$

$$\begin{aligned}P_2=&\left|\frac{2k_1k_+}{{\rm e}^{-{\rm i}k_+L}(k_1-k_+)^2+{\rm e}^{{\rm i}k_+L}(k_1-k_+)^2}\right.\\&\left.-\frac{2k_1k_-}{{\rm e}^{-{\rm i}k_-L}(k_1+k_+)^2-{\rm e}^{{\rm i}k_-L}(k_1-k_-)^2}\right|^2,\end{aligned}\tag{27}$$

are the populations of electrons occupying the lower and the higher modes, respectively.

The dashed curve in Fig.2 shows the calculated total transmission probability as a function of ε, with L=800nm (other parameters are the same as those of the corresponding dashed curve) according to Eqs.(25)–(27). One can see that for the same reason the dashed curve also has a step-structure at the point ε=55.6V/mm. However, it apparently shows an interference pattern. As the length of the field irradiation range L is an integer time of π/k_-, the peaks appear. One can find that the dashed curve is just the solid one superimposed with some interference pattern due to the interference between the forward-going and backward-going waves in the EM field irradiated region of the wire.

From the above demonstration, we know that the electronic transmission through a straight quantum wire irradiated by a finite-range transversely polarized EM field has a sensitive response to both external field strength and frequency. This result of theoretical analysis may arouse some experimental interest.

4. Summary

In this paper we have taken a semiconductor quantum wire of 2DEG as a numerical example, but the analytical calculation is a general scheme for any straight quantum wire which is suited for the free-electron model. For a three-dimensional metallic nanowires[24] the transverse level separation is large and the resonant field frequency will be high up to the near-infrared range. Moreover, the calculation is independent of the specific type of the confining potential. The different confining potential (either a hard-wall potential or a parabolic potential) results in different transverse eigenfunctions ϕ_n, whereas it only affects the two-level interaction parameter l, and the behaviour of the transmission will be qualitatively the same.

In summary, using the method of time-dependent mode matching and the scattering matrix, we have studied the electronic transport in a quantum wire (electron waveguide) irradiated under a finite-range transversely polarized external THz EM field. We demonstrate that, when the field frequency is in resonance with the lateral level separation, the electronic transmission probability shows an apparently

asymmetric absorption peak at any field strength. The transmission probability in the resonant case always shows an interesting step-structure as the field strength ε increases to a threshold value, and shows an interference pattern in the case of two interfaces. More detailed studies of these systems are worth continuing to gain the knowledge of THz wave interaction with matter.[2,3,24]

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