Spin-Dependent Transport through Aharonov-Casher Ring Irradiated by an Electromagnetic Field

Walid A. Zein*, Nabil A. Ibrahim†, and Adel H. Phillips*

*Faculty of Engineering, Ain-Shams University, Cairo, Egypt
†Higher Technological Institute, Ramadan Tenth City, Egypt
E-mail: adel_phillips@yahoo.com

The spin dependent conductance of mesoscopic device is investigated under the effect of infrared and ultraviolet radiation and magnetic field. This device is modeled as Aharonov-Casher semiconducting ring and a quantum dot is embedded in one arm of the ring. An expression for the conductance is deduced. The results show oscillatory behavior of the conductance. These oscillations might be due to Coulomb blockade effect and the interplay of Rashba spin orbit coupling strength with the induced photons of the electromagnetic field. The present device could find applications in quantum information processing (qubit).

1 Introduction

Advances in nanotechnology opened the way for the synthesis of artificial nanostructures with sizes smaller than the phase coherence length of the carriers [1]. The electronic properties of these systems are dominated by quantum effects and interferences [2]. One of the goals of semiconductor spintronics [3,4] is to realize quantum information processing based on electron spin. In the last decades, much attention is attracted by many scientists to study the spin-dependent transport in diverse mesoscopic systems, e.g., junctions with ferromagnetic layers, magnetic semiconductors, and low-dimensional semiconducting nanostructures [5, 6]. Coherent oscillations of spin state driven by a microwave field have been studied extensively [7–11].

Many authors investigated the spin transport through quantum rings [12–18]. These rings are fabricated out of two dimensional electron gas formed between heterojunction of III–V and II–VI semiconductors. Spin-orbit interaction (SOI) is crucial in these materials. The purpose of the present paper is to investigate the quantum spin transport in ring made of semiconductor heterostructure under the effect of infrared and ultraviolet radiations.

2 Theoretical treatment

In order to study the quantum spin characteristics of a mesoscopic device under the effect of both infrared (IR) and ultraviolet (UV) radiation, we propose the following model:

A semiconductor quantum dot is embedded in one arm of the Aharonov-Casher ring with radius comparable with the Fermi-wavelength of semiconductor heterostructure. This ring is connected to two conducting leads. The form of the confining potential is modulated by an external gate electrode allowing for direct control of the electron spin-orbit interaction. By introducing an external magnetic field, we also calculate the combined Aharonov-Casher, and Aharonov-Bohm conductance modulations. The conductance G for the present investigated device will be calculated using Landauer formula [17–19] as:

$$G = \frac{2e^2}{h} \sin\phi \sum_{\mu=1,2} dE \left(-\frac{\partial j_{FD}}{\partial E}\right) \left|\Gamma_{\mu,with\ photon}(E)\right|^2 , \qquad (1)$$

where f_{FD} is the Fermi-Dirac distribution function, e is the electron charge, h is Planck's constant, ϕ is the electron phase difference propagating through the upper and lower arms of the ring, and $\left|\Gamma_{\mu,with\ photon}(E)\right|^2$ is the tunneling probability induced by the external photons.

Now, we can find an expression for the tunneling probability $\left|\Gamma_{\mu,with\ photon}(E)\right|^2$ by solving the following Schrodinger equation and finding the eigenfunctions for this system as follows:

$$\left(\frac{P^2}{2m^*} + V_d + eV_g + E_F + eV_{ac}\cos(\omega t) + \right.$$
$$\left. + \frac{\hbar e B}{2m^*} + \widehat{H}_{Soc} + eV_{Sd}\right)\psi = E\psi , \qquad (2)$$

where V_d is the barrier height, V_g is the gate voltage, m^* is the effective mass of electrons, E_F is the Fermi-energy, B is the applied magnetic field, and V_{ac} is the amplitude of the applied infrared, and ultraviolet electromagnetic field with frequency ω. In (2) $\widehat{H}_{Soc}$ is the Hamiltonian due to the spin-orbit coupling which is expressed as:

$$\widehat{H}_{Soc} = \frac{\hbar^2}{2m^* a^2}\left(-i\frac{\partial}{\partial\phi} - \frac{\Phi_{AB}}{2\pi} - \frac{\omega_{Soc} m^* a^2}{\hbar}\,\sigma_r\right), \qquad (3)$$

where $\omega_{Soc} = \alpha/(\hbar a)$ and it is called the frequency associated with the spin-orbit coupling,α is the strength of the spin-orbit coupling, a is the radius of the Aharonov-Casher ring, and σ_r is the radial part of the Pauli matrices which expressed in the components of Pauli matrices σ_x, σ_y as:

$$\begin{aligned} \sigma_r &= \sigma_x\cos\phi + \sigma_y\sin\phi, \\ \sigma_\phi &= \sigma_y\cos\phi - \sigma_x\sin\phi . \end{aligned} \qquad (4)$$

Due to the application of magnetic field B, normal to the plane of the device, the Aharonov-Bohm phase will be picked up by an electron which encircling the following magnetic flux Φ_{AB}, see Eq. (3), as:

$$\Phi_{AB} = \frac{\pi e B a^2}{\hbar}. \quad (5)$$

Now, the solution of Eq. (2) will consist of four eigenfunctions [17, 18, 20], where $\psi_L(x)$ is the eigenfunction for transmission through the left lead, $\psi_R(x)$ for the right lead, $\psi_{up}(\theta)$ for the upper arm of the ring, and $\psi_{low}(\theta)$ for the lower arm of the ring. Their expressions are:

$$\psi_L(x,t) = \sum_\sigma \sum_{n=-\infty}^{\infty} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\left[Ae^{ikx}+Be^{-ikx}\right]\chi^\sigma(\pi)\,e^{-in\omega t}, \quad (6)$$

$\chi \in [-\infty, 0]$

$$\psi_R(x,t) = \sum_\sigma \sum_{n=-\infty}^{\infty} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\left[Ce^{ik'x}+De^{-ik'x}\right]\chi^\sigma(0)\,e^{-in\omega t}, \quad (7)$$

$\chi \in [0, \infty]$,

$$\psi_{up}(\theta,t) = \sum_{\sigma,\mu} \sum_{n=-\infty}^{\infty} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)F_\mu e^{in'^\sigma_\mu \phi}e^{-in\omega t}\chi^\sigma(\phi), \quad (8)$$

$\phi \in [0, \pi]$,

$$\psi_{low}(\theta,t) = \sum_{\sigma,\mu} \sum_{n=-\infty}^{\infty} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)G_\mu e^{in^\sigma_\mu \phi}e^{-in\omega t}\chi^\sigma(\phi), \quad (9)$$

$\phi \in [\pi, 2\pi]$

were $J_n(eV_{ac}/(\hbar\omega))$, Eqs. (6–9), is the n^{th} order Bessel function. The solutions, Eqs. (6–9), must be generated by the presence of the different side-bands n, which come with phase factor $\exp(-in\omega t)$. The parameter $\chi^\sigma(\phi)$ is expressed as:

$$\chi^1_n(\phi) = \begin{pmatrix} \cos(\theta/2) \\ e^{i\phi}\sin(\theta/2) \end{pmatrix} \quad (10)$$

and

$$\chi^2_n(\phi) = \begin{pmatrix} \sin(\theta/2) \\ -e^{i\phi}\cos(\theta/2) \end{pmatrix} \quad (11)$$

where the angle θ [17, 18, 21] is given by

$$\theta = 2\tan^{-1}\left(\frac{\Omega - \sqrt{\Omega^2 + \omega^2_{Soc}}}{\omega_{Soc}}\right) \quad (12)$$

in which Ω is given by

$$\Omega = \frac{\hbar}{2m^* a^2}. \quad (13)$$

Also, the parameters n'^σ_μ and n^σ_μ expressed respectively as:

$$n'^\sigma_\mu = \mu k' a - \phi + \frac{\Phi_{AB}}{2\pi} + \frac{\Phi^\sigma_{AC}}{2\pi}, \quad (14)$$

$$n^\sigma_\mu = \mu k a - \phi + \frac{\Phi_{AB}}{2\pi} + \frac{\Phi^\mu_{AC}}{2\pi}, \quad (15)$$

in which $\mu = \pm 1$ corresponding to the spin-up, and spin-down of the transmitted phase, expressed as [17, 18, 20]:

$$\Phi^\mu_{AC} = \pi\left[1 + \frac{(-1)^\mu\left(\omega^2_{Soc} + \Omega^2\right)^{1/2}}{\Omega}\right]. \quad (16)$$

The wave numbers k' and k are given respectively by

$$k' = \sqrt{\frac{2m^*(E + n\hbar\omega)}{\hbar^2}}, \quad (17)$$

and

$$k = \sqrt{\frac{2m^*}{\hbar^2}\left(V_d + eV_g + \frac{N^2e^2}{2C} + E_F + n\hbar\omega - E\right)}, \quad (18)$$

where V_d is the barrier height, V_g is the gate voltage, N is the number of electrons entering the quantum dot, C is the total capacitance of the quantum dot, e is the electron charge, E_F is the Fermi energy, m^* is the effective mass of electrons with energy E, and $\hbar\omega$ is the photon energy of both infrared and ultraviolet electromagnetic field.

Now, the tunneling probability $\left|\Gamma_{\mu,with\ photon}(E)\right|^2$ could be obtained by applying the Griffith boundary condition [15, 17, 18, 20, 21] to Eqs. (6–9). The Griffith boundary condition states that the eigenfunctions, Eqs. (6–9), are continuous and their current density is conserved at each intersection. Accordingly therefore, the expression for the tunneling probability is given by:

$$\left|\Gamma_{\mu\ with\ photons}(E)\right|^2 = \quad (19)$$

$$= \sum_n J^2_n \left[\frac{8i\cos\left(\frac{\Phi_{AB}+\Phi^\mu_{AC}}{2}\right)\sin(\pi k a)}{4\cos(2\pi k' a) + 4\cos\left(\Phi_{AB} + \Phi^\mu_{AC}\right) + 4\sin(2\pi k' a)}\right]^2.$$

Now, substituting $\left|\Gamma_{\mu\ with\ photons}(E)\right|^2$, into Eq. (1), we get a full expression for the conductance G, which will be solved numerically as will be seen in the next section.

3 Result and discussion

Numerical calculations are performed for the conductance G as function of the gate voltage V_g, magnetic field B, and function of ω_{Soc} frequency due to spin-orbit coupling at specific values of photon energies, e.g., energies of infrared and ultraviolet radiations. The values of the following parameters

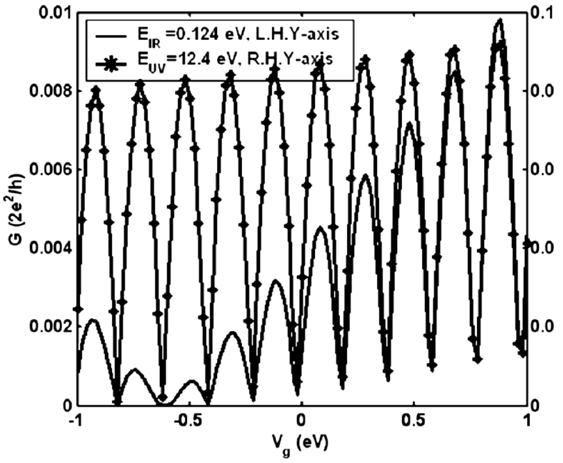

Fig. 1: The variation of the conductance G with the gate voltage V_g at different photon energy E_{IR} and E_{UV}.

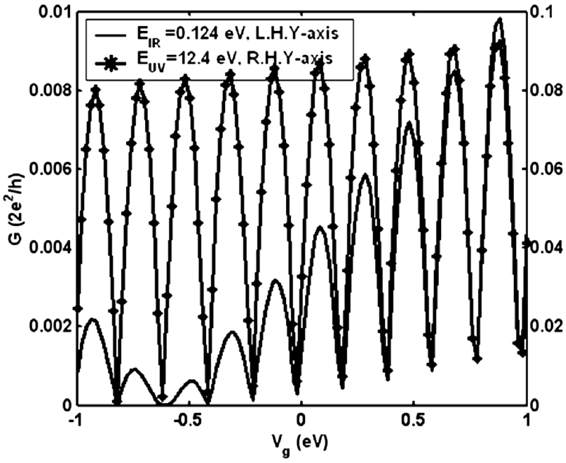

Fig. 3: The variation of the conductance G with the frequency ω_{Soc} at different photon energy E_{IR} and E_{UV}.

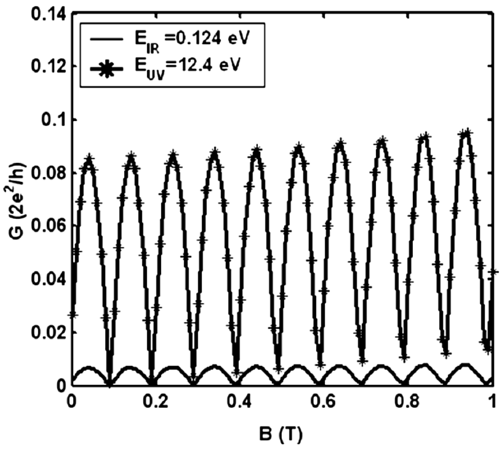

Fig. 2: The variation of the conductance G with the magnetic field B at different photon energy E_{IR} and E_{UV}.

have been found previous by the authors [22–24]. The values of $C \sim 10^{-16}$ F and $V_d \sim 0.47$ eV. The value of the number of electrons entering the quantum dot was varied as random number.

We use the semiconductor heterostructures as In Ga As/ In Al As. The main features of our obtained results are:

1. Fig. (1), shows the dependence of the conductance G, on the gate voltage V_g, at both photon energy of infrared (IR), and ultraviolet (UV) radiations. Oscillatory behavior is shown. For the case of infrared radiation, the peak height strongly increases as gate voltage increases from –0.5 to 1. But for the case ultraviolet, this increase in peak height is so small.
2. Fig. (2), shows the dependence of the conductance G, on the applied magnetic field B, at both the photon energies considered (IR and UV). A periodic oscillation is shown for the two cases, the periodicity equals $\tilde{t}$he quantum flux h/e.
3. The dependence of the conductance G, on the frequency associated with the spin-orbit coupling, ω_{Soc}. at different values of the investigated applied photon energies is shown in Fig. 3.

The obtained results might be explained as follows: The oscillatory behavior of the conductance is due to spin-sensitive quantum interference effects caused by the difference in the Aharonov-Casher phase accumulated by the opposite spin states. The Aharonov-Casher phase arises from the propagation of the electron in the spin-orbit coupling. The quantum interference effect appears due to photon spin-up, and spin-down subbands coupling. Our results are found concordant with these in the literature [15, 16, 25].

4 Conclusion

The Aharonov-Casher, and Aharonov-Bohm effects are studied, taking into consideration the influence of both infrared (IR), and ultraviolet (UV) electromagnetic field. This could be realized by proposing a semiconducting quantum dot embedded in one arm of semiconducting ring. Spin filtering, and spin pumping due to the effect of photons are studied by deducing the spin transport conductance. The present results are valuable for the application in the field of quantum information processing (qubit) quantum bit read out, and writing.

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