Noise and Fano-factor Control in AC-Driven Aharonov-Casher Ring

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The spin dependent current and Fano factor of Aharonov-Casher semiconducting ring is investigated under the effect of microwave, infrared, ultraviolet radiation and magnetic field. Both the average current and the transport noise (Fano factor) characteristics are expressed in terms of the tunneling probability for the respective scattering channels. For spin transport induced by microwave and infrared radiation, a random oscillatory behavior of the Fano factor is observed. These oscillations are due to constructive and destructive spin interference effects. While for the case of ultraviolet radiation, the Fano factor becomes constant. This is due to that the oscillations has been washed out by phase averaging (i.e. ensemble dephasing) over the spin transport channels. The present investigation is very important for quantum computing and information processing.

1 Introduction

The field of spintronics is devoted to create, store, manipulate at a given location, and transport coherent electron spin states through dilute magnetic semiconductors and conventional semiconductor heterostructure [1]. The two principle challenges for new generation of spintronics devices are efficient injection of spins into various semiconductor nanostructures and coherent control of spin. In particular, preserving spin coherence, which enables coherent superpositions of states $a|\uparrow\rangle + b|\downarrow\rangle$ and corresponding quantum-interference effects, is essential for both quantum computing with spin-based qubits [2, 3]. The electrical control of spin via Rashba spin-orbit coupling [4], which arises due to inversion asymmetry of the confining electric potential for tow-dimensional electron gas (2DEG), is very important physical parameter when dealing with semiconductor spintronics. The pursuit of fundamental spin interference effects, as well as spin transistors with unpolarized charge currents [3, 5–10] has generated considerable interest to demonstrate the Aharonov-Casher effect via transport experiments in spin-orbit coupled semiconductor nanostructures [7, 11].

The ballistic spin-resolved shot noise and consequently Fano factor in Aharonov-Casher semiconducting ring is investigated in the present paper. The effects of both electromagnetic field of wide range of frequencies and magnetic field are taken into consideration.

2 Theoretical Formulation

It is well known that shot noise and consequently Fano factor is a powerful quantity to give information about controlling decoherence of spin dependent phenomena [12, 13]. So we shall deduce an expression for both shot noise and Fano factor for spintronic device considered in the paper [10]. This device is modeled as follows: Aharonov-Casher interferometer ring in which a semiconductor quantum dot is embedded

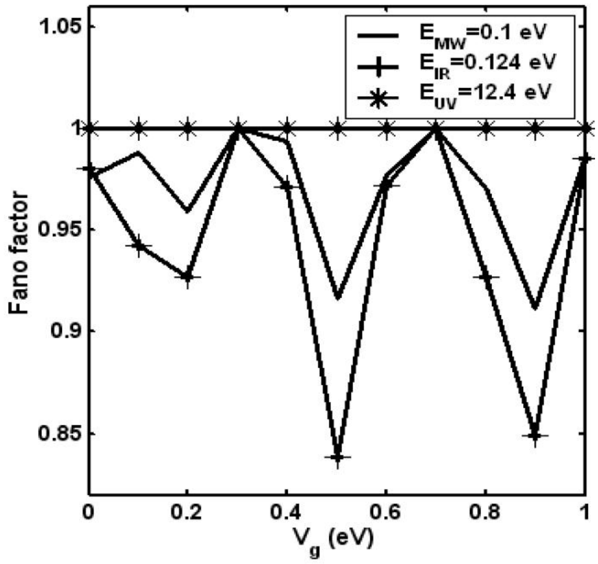

Fig. 1: The variation of Fano factor with gate voltage at different photon energies.

in one arm of the ring. The form of the confining potential is modulated by an external gate electrode allowing for direct control of the electron spin-orbit coupling. The effect of electromagnetic field of wide range of frequencies (microwave, infrared, ultraviolet) is taken into consideration.

The spin dependent shot noise $S_{\alpha\beta}^{\sigma\sigma'}(t-t')$ is expressed in terms of the spin resolved currents $I(\uparrow)$, and $I(\downarrow)$ due to the flow of spin-up $\uparrow$ and spin-down $\downarrow$ electrons through the terminals of the present device [14] as

$$S_{\alpha\beta}^{\sigma\sigma'}(t-t') = \frac{1}{2}\left\langle \delta\hat{I}_{\alpha}^{\sigma}(t)\,\delta\hat{I}_{\beta}^{\sigma'}(t') + \delta\hat{I}_{\beta}^{\sigma'}(t')\,\delta\hat{I}_{\alpha}^{\sigma}(t)\right\rangle \quad (1)$$

where $\hat{I}_{\alpha}^{\sigma}(t)$ is the quantum mechanical operator of the spin resolved ($\sigma \Rightarrow \uparrow, \downarrow$) current in left lead α, $\hat{I}_{\beta}^{\sigma'}(t')$ is the same

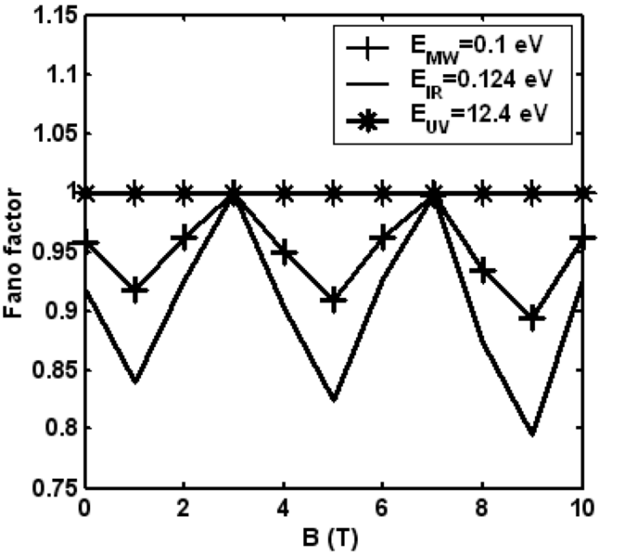

Fig. 2: The variation of Fano factor with magnetic field at different photon energies.

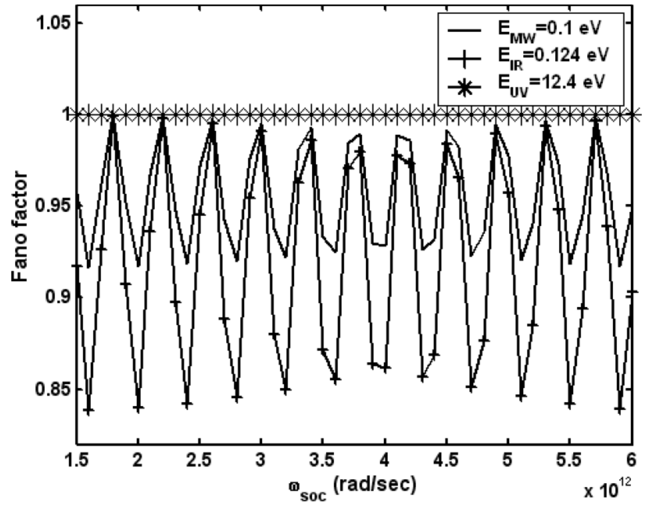

Fig. 3: The variation of Fano factor with frequency ω_{Soc} at different photon energies.

definition of $\hat{I}_{\alpha}^{\sigma}(t)$, but for the right lead β. In Eq. (1), the parameter $\delta\hat{I}_{\alpha}^{\sigma}(t)$ represents the current fluctuation operator at time t in the left lead α with spin state σ (up or down) and is given by

$$\delta\hat{I}_{\alpha}^{\sigma}(t) = \hat{I}_{\alpha}^{\sigma}(t) - \left\langle \hat{I}_{\alpha}^{\sigma}(t) \right\rangle \tag{2}$$

where $\langle -- \rangle$ denotes an ensemble average. The Fourier transform of Eq.(1), which represents the spin resolved noise power between the left and right terminals of the device, is given by

$$S_{\alpha\beta}^{\sigma\sigma'}(\omega) = 2\int d(t-t')\, e^{-i\omega(t-t')} S_{\alpha\beta}^{\sigma\sigma'}(t-t'). \tag{3}$$

Since the total spin dependent current is given by

$$I_{\alpha} = I_{\alpha}^{\uparrow} + I_{\alpha}^{\downarrow}, \tag{4}$$

the corresponding noise power is expressed as

$$S_{\alpha\beta}(\omega) = S_{\alpha\beta}^{\uparrow\uparrow}(\omega) + S_{\alpha\beta}^{\downarrow\downarrow}(\omega) + S_{\alpha\beta}^{\uparrow\downarrow}(\omega) + S_{\alpha\beta}^{\downarrow\uparrow}(\omega). \tag{5}$$

Now, expressing the spin-resolved current $\hat{I}_{\alpha}^{\sigma}(t)$ in terms of the creation and annihilation operators of the incoming electrons $\hat{a}_{\alpha}^{\sigma+}(E)$, $\hat{a}_{\alpha}^{\sigma}(E')$ and for the outgoing electrons $\hat{b}_{\alpha}^{\sigma+}(E+n\hbar\omega)$, $\hat{b}_{\alpha}^{\sigma}(E'+n\hbar\omega)$ [15], as follows:

$$\hat{I}_{\alpha}^{\sigma}(t) = \frac{e}{h}\sum_{n}\int\int dE\,dE'\, e^{i(E-E')t/\hbar} \times$$
$$\left[\hat{a}_{\alpha}^{\sigma+}(E)\,\hat{a}_{\alpha}^{\sigma}(E') - \hat{b}_{\alpha}^{\sigma+}(E+n\hbar\omega)\,\hat{b}_{\alpha}^{\sigma}(E'+n\hbar\omega)\right]. \tag{6}$$

Now, in order to evaluate the shot noise spectrum $S_{\alpha\beta}(\omega)$ this can be achieved by substituting Eq.(6) into Eq.(1), and using the transmission eigenfunctions [10] through the present spintronic device, we can determine the expectation value [15, 16]. We get an expression for the shot noise spectrum $S_{\alpha\beta}(\omega)$ as follows:

$$S_{\alpha\beta}(\omega) = \frac{2eP_0}{h}\sum_{\sigma}\int_{0}^{\infty} dE \left|\Gamma_{\mu\ with\ photon}(E)\right|^2 \times$$
$$f_{\alpha FD}(E) \times \left[1 - f_{\beta FD}(E+n\hbar\omega)\right] \tag{7}$$

where $\left|\Gamma_{\mu\ with\ photon}(E)\right|^2$ is the tunneling probability induced by the external photons, and $f_{\alpha FD}(E)$, $f_{\beta FD}(E+n\hbar\omega)$ are the Fermi distribution functions, and P_0 is the Poissonian shot noise spectrum [15].

The tunneling probability $\left|\Gamma_{\mu\ with\ photon}(E)\right|^2$ has been determined previously by the authors [10]

The Fano factor, F, of such mesoscopic device is given by [17]:

$$F = \frac{S_{\alpha\beta}(\omega)}{2eI}. \tag{8}$$

The explicit expression for the Fano factor, F, can be written as, after some algebraic computation of Eqs.(7, 8), [18, 19]:

$$F = \frac{\left[\sum_{n}\sum_{\mu}\left|\Gamma_{\mu\ with\ photon}(E)\right|^2\left(1 - \left|\Gamma_{\mu\ with\ photon}(E)\right|^2\right)\right]}{\sum_{n}\sum_{\mu}\left|\Gamma_{\mu\ with\ photon}(E)\right|^2}. \tag{9}$$

3 Results and Discussion

The Fano factor F Eq.(9) has been computed numerically as a function of the gate voltage V_g magnetic field B and function of the frequency ω_{Soc} due to spin-orbit coupling. These calculations are performed over a wide range of frequencies of the induced electromagnetic field (microwave, MW, infrared, IR, and ultraviolet, UV). We use the semiconductor heterostructures as *InGaAs/InAlAs* as in the paper [10]. The main features of the present obtained results are:

(1) Fig.1, shows the dependence of Fano factor on the gate voltage V_g at photon energies for microwave, infrared, and ultraviolet. As shown from the figure that, the Fano factor fluctuates between maximum and minimum values for the two cases microwave and infrared irradiation. While for the case of ultraviolet irradiation, the Fano factor is constant and approximately equals ∼1.

(2) Fig.2, shows the dependence of Fano factor on the magnetic field B at photon energies for microwave, infrared, and ultraviolet. The trend of this dependence is similar in a quite fair to the trend and behavior of Fig.1.

(3) Fig.3, shows the dependence of Fano factor on the frequency ω_{Soc} associated with the spin-orbit coupling at photon energies for microwave, infrared, and ultraviolet. An oscillatory behavior for this dependence for the two cases microwave and infrared are shown. While for the case of ultraviolet, the Fano factor is constant and approximately equals ∼1 as in Figs. 1, 2.

These results might be explained as follows: Computations show that the average current suppression is accompanied by a noise maxima and remarkably low minima (Fano factor). These cases are achieved when the electron spin transport is influenced by both microwave and infrared photons. Such results have been observed previously by the authors [20–22]. The random oscillatory behavior of the Fano factor can be understood as the strength of the spin-orbit coupling is modified by the gate electrode covering the Aharonov-Casher ring to tune constructive and destructive spin interference effect [10]. For the case of the induced ultraviolet radiation, the results show that the Fano factor becomes approximately constant. These results have been observed previously by the authors [23,24]. The constancy of Fano factor might be due to washing out of the oscillations by phase averaging (i.e. ensemble dephasing) over the spin transport channels [23, 24].

We conclude that these phenomena can be used to devise novel spintronic devices with a priori controllable noise levels. The present investigation is very important for quantum computing and quantum information processing.

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