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J. F. Song, Y. Ochiai, and J. P. Bird

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J. F. Song
Center for Frontier Electronics and Photonics, Chiba University, 1-33 Yayoi, Inage, Chiba 236-8522, Japanand College of Electronic Science and Engineering, State Key Laboratory on Integrated Optoelectronics, Jilin University, Changchun, 130023 People's Republic of China

Y. Ochiai
Department of Materials Technology, Chiba University, 1-33 Yayoi, Inage, Chiba 236-8522, Japan and Center for Frontier Electronics and Photonics, Chiba University, 1-33 Yayoi, Inage, Chiba 236-8522, Japan

J. P. Bird[a)]
Nanostructures Research Group, Department of Electrical Engineering, Arizona State University, Tempe, Arizona 85287-5706 and Center for Frontier Electronics and Photonics, Chiba University, 1-33 Yayoi, Inage, Chiba 236-8522, Japan

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We describe how a spin filter may be realized in open quantum-dot systems, by exploiting the Fano resonances that occur in their transmission characteristics. In quantum dots in which the spin degeneracy of carriers is lifted, we show that the Fano resonances may be used as an effective means to generate spin polarization of transmitted carriers, and that electrical detection of the resulting polarization should also be possible.
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Recently, there has been much interest in understanding the manner in which the unique properties of semiconductor *nanostructures* may be exploited in *spintronic* devices, which utilize the spin degree of freedom of the electron as the basis of their operation.[1–7] There are a number of features of nanostructures that make them well suited to such applications. The form of their confining potential is easily modulated by an external gate, allowing for direct control of the spin–orbit interaction.[2,6] Nanostructures typically exhibit strong quantization of their density of states, so that large conductance modulations may result from spin-dependent operations. A natural feature of these devices is the direct connection between their conductance and their quantum-mechanical transmission properties, which may allow their use as an *all-electrical* means for *generating* and *detecting* spin-polarized distributions of carriers. Finally, nanostructures are well suited to *integration* into larger electrical circuits, allowing complicated logic operations to be built up from much simpler basic functions.

One important spintronic device is a spin filter,[4–7] which may be used to generate spin polarization of carriers, using only electrical means. In this letter, we describe how such a filter may be realized in *open quantum-dot* systems, by exploiting the Fano resonances[8] that occur in their transmission characteristics.[9] Such quantum dots offer great potential as spintronic components, since transport within them is coherent, which makes them suitable for application to quantum computing. In quantum dots in which the spin degeneracy of carriers is lifted, we show that the Fano resonances may be used as an effective means to generate the spin polarization of transmitted carriers, and that electrical detection of the resulting polarization should also be possible.

The quantum-dot geometry considered here is shown in Fig. 1 and consists of a central cavity that is connected to semi-infinite, one-dimensional, waveguide leads. The dot dimensions considered here are chosen to correspond to those of typical structures studied in experiment,[10] although we emphasize that the generality of our conclusions does not depend upon the specific choice of these values. To study the transmission properties of this system, we utilize the scattering-matrix theory[11] to solve the single-particle Schrödinger equation for the open system, subject to Dirichlet boundary conditions. In this formalism, the quantum dot is

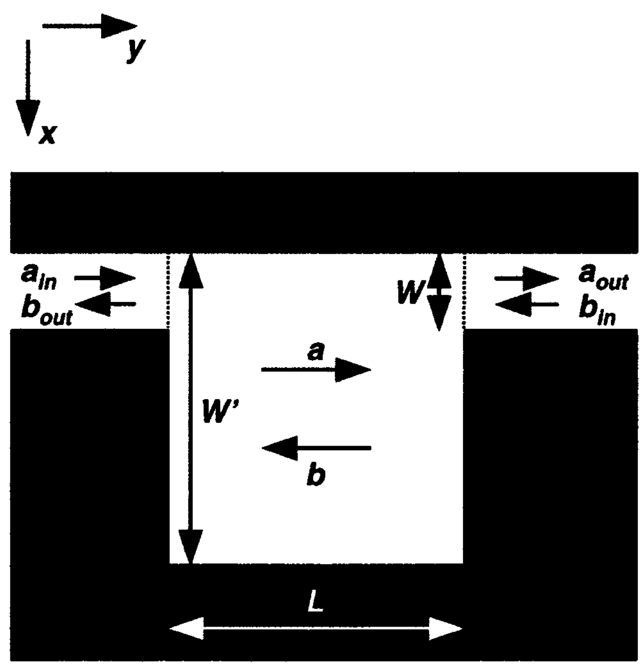

FIG. 1. Schematic illustration of the quantum-dot geometry that we model here. The system is assumed to be formed from hard walls. In the calculations here, we will assume $L=250$ nm, $W'=250$ nm, and $W=50$ nm.

[a)]Electronic mail: bird@asu.edu

treated as a two-port system, in which waves incident on one port (lead) are transmitted through the dot to the other port. According to this theory, the wave function coefficients a_{in} and b_{in} are related to a_{out} and b_{out} (see Fig. 1 for definitions) according to:

$$\begin{pmatrix} S_{1,1} & S_{1,2} \\ S_{2,1} & S_{2,2} \end{pmatrix}\begin{pmatrix} a_{\mathrm{in}} \\ b_{\mathrm{in}} \end{pmatrix}=\begin{pmatrix} b_{\mathrm{out}} \\ a_{\mathrm{out}} \end{pmatrix}, \tag{1}$$

where the matrices S_{ij} are terms of the scattering matrix. Using the coordinate system indicated in Fig. 1, the wave function in the left-hand side lead, the central cavity, and the right-hand side lead may be written, respectively, as

$$\psi_{\mathrm{left}}(x,y)=\sum_n f_n(x)[a_n^{\mathrm{in}}e^{ik_ny}+b_n^{\mathrm{out}}e^{-ik_ny}], \tag{2}$$

$$\psi_{\mathrm{cavity}}(x,y)=\sum_n f_n'(x)[a_ne^{ik_n'y}+b_ne^{-ik_n'y}], \tag{3}$$

$$\psi_{\mathrm{right}}(x,y)=\sum_n f_n(x)[a_n^{\mathrm{out}}e^{ik_ny}+b_n^{\mathrm{in}}e^{-ik_ny}]. \tag{4}$$

The summation in Eqs. (2)–(4) runs over the number of modes transverse to the direction of propagation, and the distinct wave numbers in the separate regions of the device are defined according to

$$k_n=\sqrt{\frac{2m^*E}{\hbar^2}-\frac{\pi^2}{W^2}n^2}, \tag{5}$$

$$k_n'=\sqrt{\frac{2m^*E}{\hbar^2}-\frac{\pi^2}{W'^2}n^2}, \tag{6}$$

where m^* is the electron effective mass and E is the electron energy. The x components of the wave functions in Eqs. (2)–(4) are defined according to

$$f_n(x)=\sqrt{\frac{2}{W}}\sin(n\pi x/W), \tag{7}$$

$$f_n'(x)=\sqrt{\frac{2}{W'}}\sin(n\pi x/W'). \tag{8}$$

In the case where we impose electrons from the left-hand side port ($b_{\mathrm{in}}=0$), the transmitted and incident currents may be expressed, respectively, as

$$I_{\mathrm{in}}=\frac{e\hbar}{m^*}\sum_n \mathrm{Re}(k_n)|a_n^{\mathrm{in}}|^2, \tag{9}$$

$$I_{\mathrm{out}}=\frac{e\hbar}{m^*}\sum_n \mathrm{Re}(k_n)|a_n^{\mathrm{out}}|^2. \tag{10}$$

Finally, we obtain the transmission of the system as

$$T=\frac{I_{\mathrm{out}}}{I_{\mathrm{in}}}. \tag{11}$$

In Fig. 2, we show the calculated variation of the transmission over a narrow range of energy. The GaAs effective mass ($m^*=0.067m_0$) has been assumed, in this and all subsequent calculations, although this is not crucial to the obtained results. The calculations shown here are obtained for the case where just *one* mode contributes to transmission in

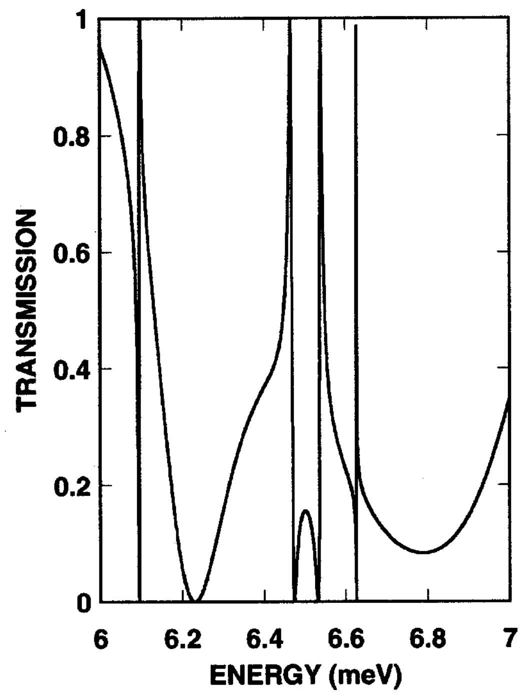

FIG. 2. Calculated variation of transmission with energy for the quantum dot of Fig. 1.

the waveguide leads, and this point *will* be important for our discussion of the spin-filter action. Superimposed on the slowly varying background in Fig. 2 are a series of sharp resonances, which, as we illustrate in Fig. 3, have the characteristic form of Fano resonances.[8,12] Such resonances have recently been observed in studies of tunnel coupled quantum dots,[13] and are also known to be important for transport in open dots.[9,10]

The concept of exploiting the Fano resonances as the basis of a spin filter is illustrated in Fig. 4. The contour plots in Fig. 4 show the computed variation of the transmission of the single-mode dot, as a function of energy (on the horizontal axis) and spin splitting (which we represent as an effective energy on the vertical axis). To construct these contours, we assume a spin-dependent form to the electron energy:

$$E_\uparrow=E_\downarrow+\Delta E, \tag{12}$$

and then use these distinct energies to compute the spin-dependent transmission probabilities $T_\uparrow$ and $T_\downarrow$. In the different panels of Fig. 4, we show the variation of the weighted spin polarizations:

$$P_{\uparrow/\downarrow}=\left|\frac{T_\uparrow-T_\downarrow}{T_\uparrow+T_\downarrow}\right|T_{\uparrow/\downarrow}. \tag{13}$$

While the first term on the right-hand side of Eq. (13) is the spin polarization, it is important to realize that this quantity may be of order unity, even in the limit where $T_\uparrow$ and $T_\downarrow$ are *both* small. Effective spin polarization requires the transmission of the filtered spin component to be *high*, however, and it is for this reason that we introduce the weighted polarizations defined by Eq. (13). The various panels of Fig. 4 show the weighted polarizations computed for the two different Fano resonances shown in Fig. 3. Since the line shape of these resonances is different, their spin-filter characteristics also differ, as can be clearly seen in Fig. 4. Both resonances

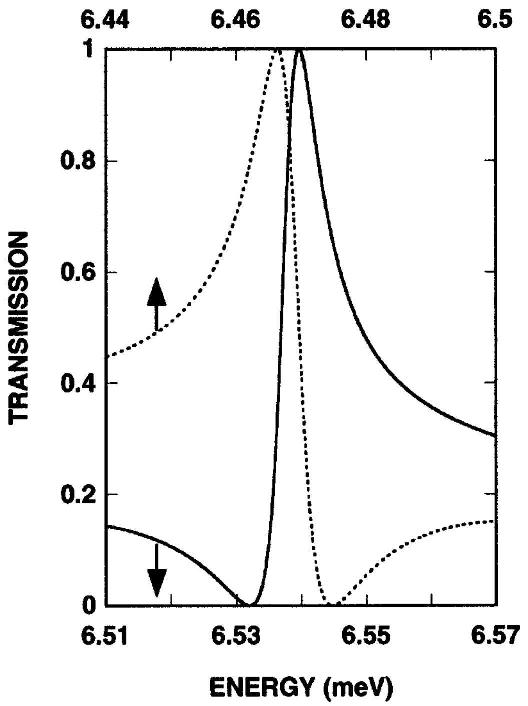

FIG. 3. Expanded view of the energy-dependent transmission over two different ranges of energy, showing the two Fano resonances whose spin-filter action we consider here.

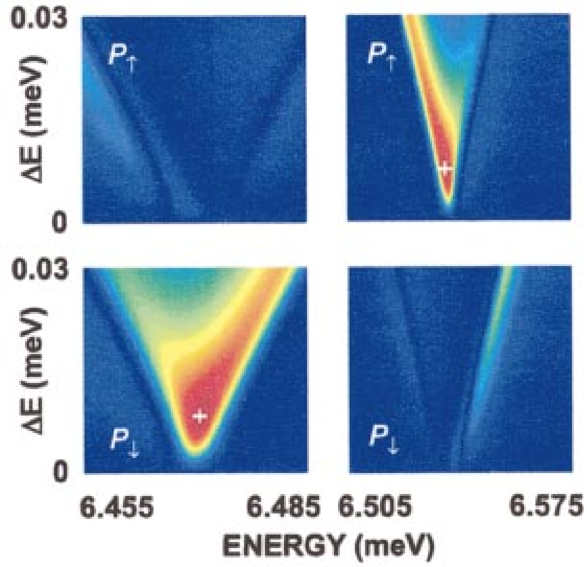

FIG. 4. (Color) The various color panels show the weighted polarizations for spin-up and spin-down electrons, for the two different Fano resonances shown in Fig. 3 (note the energy scales in Figs. 3 and 4). A color variation from blue to red corresponds to a change of polarization from 0 to 1, respectively. The symbols marked "+" denote the range of parameters for which maximum spin-filter action is achieved.

yield a region of parameter space for which the transmission of one spin species is close to unity (we have marked these regions with the "+" symbols in Fig. 4), while that of the other is close to zero. Due to the different line shape of the resonances, however, they actually favor full polarization of *opposite* spin species. This suggests that controlled tuning of the energy to align with specific resonances may be used as a means to achieve efficient filtering of *either* spin.

A few further comments should be made at this point. Thus far, we have assumed that the spin degeneracy of the carriers is lifted by an energy amount ΔE. In practice, the simplest way to achieve this is by the application of an external magnetic field. More desirable, however, is to use the Rashba effect to lift the spin degeneracy of the carriers at *zero*-magnetic field.[2,14,15] This can be achieved quite controllably in narrow-band-gap semiconductors, such as InGaAs,[15] and, since only a small energy splitting is required to generate the spin-filter action (see Fig. 4), gate-voltage induced control of this effect should be possible. This should be contrasted with the recent demonstration of an open dot as a spin filter, in which an externally applied magnetic field was used to induce the spin splitting.[16] Another important feature to note is that the Landauer formalism ensures that the achievement of full spin polarization should be directly measurable via the conductance of the system. With one spin fully transmitted (as indicated by the "+" symbols in Fig. 4) and the other completely reflected, the conductance of the dot will be exactly e^2/h. While the mechanism that we have proposed here will typically be limited to low-temperature applications, one can easily imagine the extension of the spin filter to allow logic operations, by coupling two such structures to each other and exploiting the details of their resonant levels.

In conclusion, we have described how a spin filter may be realized in open quantum-dot systems, by exploiting the Fano resonances that occur in their transmission characteristics. In quantum dots in which the spin degeneracy of carriers is lifted, we have shown that the Fano resonances may be used as an effective means to generate spin polarization of transmitted carriers, and that electrical detection of the resulting polarization should also be possible.

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