

# SPIN-POLARIZED ELECTRON TRANSPORT THROUGH NANOSCALE DEVICES

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## Introduction

Classical electronics exploits the electron charge to designate binary information, whereas spintronics is an emerging field in which the *spin* of the electron is used for switching purposes and to communicate information [1]. Spin-dependent effects arise from interactions of the electron with an external magnetic field or with magnetic properties of the conduction material. The investigation of electron-spin transport in semiconductor nanostructures and nanoscale electronic devices has attracted recent attention [2, 3]. Quantum dots (QD's) offer unique possibilities for manipulating and utilizing the spin of electrons in individual quantum states. The spin relaxation rate in quantum dots is expected to be very low because of forbidden transitions. By this we mean that the spin of the electron can only couple to the environment indirectly through the spin-orbit coupling, which renders the spin fairly stable against random charge fluctuations. Experimental demonstration of spin filtering controlled by gate voltages in a semiconductor QD has been observed [4], or by applying a large magnetic field ( $=12T$ ) parallel to the plane of the structure [6]. In order to obtain good spin-polarization in experimental devices, it is also necessary for the Zeeman energy to be larger than the thermal energy ( $k_B T$ ), which is accomplished by performing the measurements in a dilution refrigerator at a low base temperature of 20-70 mK [4, 5].

Theoretical works have suggested that QD's can provide spin-filtering in conjunction with Zeeman-split energy levels due to an external magnetic field, or by means of voltage-induced energy level splitting [6]. With QD's embedded in the arms of a nanoscale ring, or Aharonov-Bohm (AB) interferometer, a combination of AB-and Zeeman effects introduce novel transmission resonances which facilitate spin-filtering. Our goal is to investigate spin-quantum states by studying the interference effects in the transmission resulting from double QD's in an AB ring. Our recently investigated results on sharpened AB oscillations for parallel double QD's in resonance [7] suggests a feasible mechanism for spin polarization or filtering of spin states. When the transmission resonance is a sharp function of energy or magnetic field, different electron spin states should be transmitted with a high degree of polarization.

## Theoretical Model and Calculations

A schematic of the model used in this work is shown in Fig. 1, which illustrates the spin-split QD's in each arm of an AB-ring. The ring is coupled to semi-infinite leads which are assumed to be spin-neutral, which can be accomplished, for example, by using materials for which the g-factor of the leads is much lower than for the QD's. The incident and reflected electron wave functions are shown on the left, and the transmitted wave function is shown on the right of the ring.

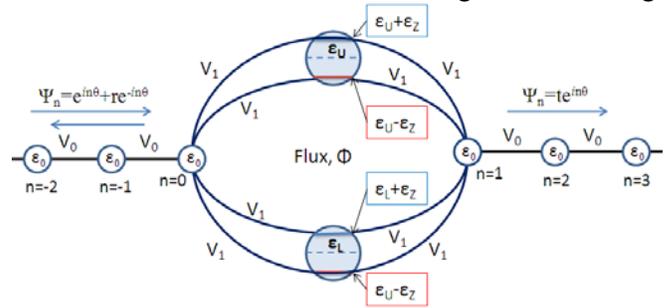


Fig. 1 Model of AB-ring with embedded quantum dots, showing the spin-split energy levels,  $\epsilon_U \pm \epsilon_Z$  (upper QD) and  $\epsilon_L \pm \epsilon_Z$  (lower QD). The coupling parameter,  $V_0=1$ , is used as a unit of energy in our results. The QD-lead coupling,  $V_1$ , is specified for each case.

The solution of the Schrödinger equation for this nanodevice, using the exactly solvable tight-binding model, gives analytical expressions for the transmission,  $T$ , in terms of the incident electron energy and the magnetic flux through the ring.

## Results and Discussion

The exact analytical expression for the ring is used in calculating the transmission plots, but it is not presented here due to its complicated form. In Fig. 2, a perpendicular field is used, which produces both Zeeman splitting in the QD's and an AB-phase shift. The QD energy values are anti-symmetric and set to  $\epsilon_U = -\epsilon_L$  and  $\epsilon_Z = 0$ . For QD-lead coupling of  $V_1=0.2$ , Fig. 2 shows a series of transmission plots as a function of electron energy. A contour plot of the transmission and

perpendicular flux (normalized to the flux quantum,  $\Phi_0 \equiv h/e$ ) is shown in Fig. 2a. An increasing flux magnitude splits the QD energy levels into spin-up (lower energy,) and spin-down (higher energy) resonance peaks. The spin-down state goes to higher energy due to the negative gyromagnetic ratio,  $g = -$ , for GaAs. The electron spin orientation (with respect to the external field) is indicated by the up or down arrows on the graphs. For  $\Phi/\Phi_0=0$  (Fig. 2b), no Zeeman splitting occurs, and only two resonance peaks appear, one for each QD energy value. As the magnetic flux increases, these two peaks separate into four spin-split resonance peaks, shown in Fig. 2c. The central transmission minimum does not reach zero due to AB interference effects. In Fig. 2d, at  $\Phi/\Phi_0=1.12$ , the two inner peaks have nearly overlapped, producing a spin-mixed state. In Fig. 2e, the flux value is set at  $\Phi/\Phi_0=1.19$  which makes the Zeeman energy exactly equal to one-half the difference of the QD energy levels. This unique value produces the sharp resonance zero shown at  $E = 0$  in Fig. 2e. In Fig. 2f, an even higher flux value causes the two inner peaks to cross over each other, reversing the order of the polarization sequence of the inner resonance peaks (compare Fig. 2c to Fig. 2f). Since the Zeeman-split QD energy states are occupied by electrons of opposite spins, the distinct transmission peaks in Fig. 2 are effectively spin-polarized.

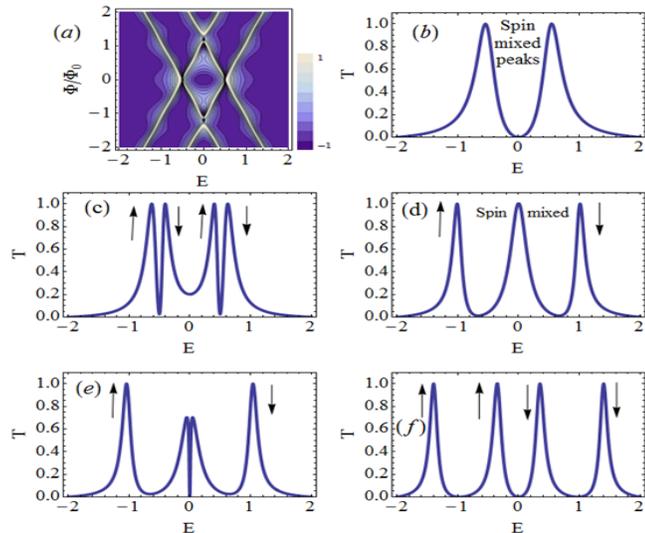


Fig. 2 Combined Zeeman and AB-effects on transmission resonances; spin-polarization is indicated by the arrows, for increasing perpendicular flux.

To effectively identify the degree of spin-polarization in the transmission, we calculate a weighted polarization function for each spin state, and their difference:

$$Pol_{up,down} = T_{up,down} \frac{|T_{up} - T_{down}|}{T_{up} + T_{down}}, \quad \Delta Pol = Pol_{up} - Pol_{down}$$

The  $\Delta Pol$  function is  $\pm 1$  depending upon whether the transmission is completely polarized spin-up or spin-down. Figure 3 presents a contour plot of  $\Delta Pol$  as a function of electron energy and magnetic flux, showing separated spin-polarized transmission states. The central region of the plot shows narrowly separated regions of opposite spin-polarized states, which result from the narrowly-defined resonance sharpening of the AB effect in this region of parameter space.

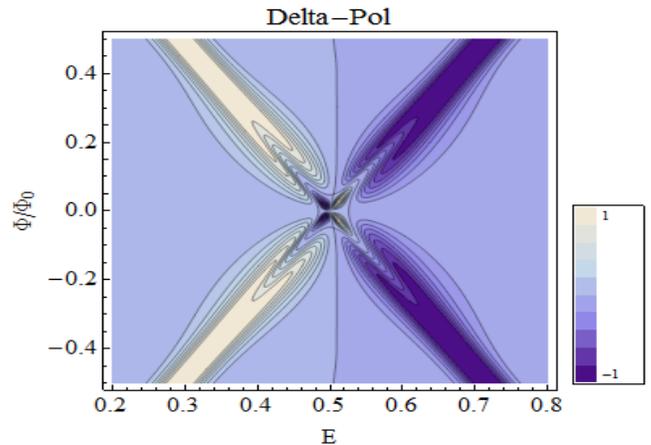


Fig. 3  $\Delta Pol$  as a function of flux and energy.

## Conclusion

By calculating the transmission through an AB-ring with embedded QD's, we have demonstrated the unique resonance features with combined Zeeman and AB-effects, and have shown that such a device has the potential to be utilized as an effective spin-polarizer.

## References

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