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Generation of spin polarization in a multibarrier structure

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Abstract

The possibility to induce polarized transmission is investigated in a system of multibarrier magnetic junction. In the undeformed system, the transmission is shown to depend on the incident energy but almost independent of inhomogeneity of potential barrier. A proper selection of incident energy is found sufficient to control both direction and strength of spin polarization. When deformation of momentum wave-vector is introduced, the spin polarization does not only change its dependence on energy but also its intensity. This provides evidence that besides energy, deformation of momentum wave vector could also influence and be used to drive spin of the transmitted current; gaining further control on both direction and intensity. A short survey on the role of local magnetic splitting, ordering of local magnetic field on the spin polarization is also given.

Keywords: Magnetic, spin polarization, deformation, multibarrier

INTRODUCTION

One of the most challenging goals in the semiconductor-based electronics is the practical implementation of the spin manipulation of charge carrier which could serve as a basis for quantum information and quantum processing devices. Due to its importance, the last decade has seen a growing effort to realize such aim and a number of proposals for spin-based semiconductor have been reported both theoretically and experimentally in various low-dimensional quantum structures consisting of quantum dots, heterostructures and related lateral structures [1] [2].

There are usually two major approaches to generate spin in the low dimensional system. The first is to employ a magnetic material on the lateral structures or equivalently to generate magnetic islands which are responsible to induce spin imbalance either locally or spatially. This approach has been realized in a number of experiments and it seems to be applicable in a wide range of materials [3] [4]. Its main drawback is the difficulty to control rapid loss of polarization which could appear as a consequence of imperfection induced by various structural defects [5] [6] [7].

Other route involves spin manipulation via spin-orbit coupling without the use of any magnetic materials. In this scheme, polarization of spin comes intrinsically within the structure of the crystal such that its manipulation might be controlled via electric field without additional external magnetic field. Due to the absence of magnetic material and or external field, this approach does not suffer too much from additional structural disturbances and it has been considered to be rather superior than that the previous approach. It is interesting however to remember that albeit having certain advantages, this approach has its own difficulty that is related to requirement of structural symmetry which is certainly essential for the emergence of the spin orbit coupling [8] [9].

Over the past two decades, there have been a lot of experimental and theoretical activities in exploring both approaches using various

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materials and structural setups. In the magnetic material based approach, realization of spin polarization usually involves semiconductor such as GaAs, which is combined with magnetic material, usually from the member of transition metals or its compound such as EuS, or by using diluted magnetic semiconductor which is doped with Mn. In the spin-orbit coupling based approach, experimental realization has been shown in the $\mathrm{In_{1-x}Al_xAs}$, AlGaAs which might appear in various dimension [9] [10].

Despite such high activities which makes a rapid progress in the field, there are several interesting aspects which have been overlooked since their contributions are considered to be less important and hence their signature has been presumed not to be traceable in the spin transmission or current. Among them, it can be argued that influence of potential inhomogeneity which appears together with mechanical deformation has not been fully explored. Another aspect is perhaps the role of gap which could appear as a result of momentum deformation or the use of certain type of barrier. It is important to mention that potential inhomogeneity might arise during experimental patterning of gate while a band gap and mechanical deformation may appear as a result of structural imperfection due to merging of two different systems. In order to clarify this aspect, we investigate in the present contribution the magnitude of spin polarization of two-dimensional electron gas which is confined to form a waveguide of one dimensional structure. We consider a multibarrier structure which is expected to provide various means in generating polarized transmission. In order to induce spin polarized carrier, we shall follow the first scheme outlined above by employing the magnetic material attached as a barrier and will induce a splitting of spin. Below, we start by describing the system of consideration which is followed by presentation of the results. We close the discussion by remarks and conclusion.

MULTIBARRIER MAGNETIC JUNCTION

In order to describe propagation of electron along one dimensional axis we consider a Hamiltonian of the form

$$H = \frac{p^2}{2m^*} + V(x), \qquad (1)$$

consisting of kinetic term with momentum p and effective mass m^* which defines electronic dispersion of free moving particles. The second term on the other hand describes a constant potential $V(r) = V$ which is induced by either magnetic or non-magnetic barrier. In order to specify the potential structure with the possibility of carrying a local magnetic field, we consider a function as follows

$$V(x) = \begin{cases} 0 & x \le L_1, \\ V_1 + \sigma M_1, & L_1 \le x \le L_2, \\ 0, & L_3 \le x \le L_4, \\ V_2 + \sigma M_2, & L_5 \le x \le L_6, \\ 0, & L_7 \le x \le L_8, \\ V_3 + \sigma M_3\,, & \le x \le L_{10}, \\ 0 & x \le L_{10}, \end{cases} \qquad (2)$$

where V_1, V_2, V_3 refer to potential height consisting of different width L, $\sigma = \pm 1$ denotes spin orientation and M_1, M_2, M_3 describes induced magnetic field arises from ferromagnetic material. As we shall be further discussed below, in the absence of $M_2$and M_3, electron shall repeatedly tunnel through non-magnetic and magnetic barrier. On the other hand when $M_1 = M_2 = M_3 \neq 0$, it shows a tunneling of electron through a constant magnetic field of barrier. We shall examine below, how much such variation influences transmission.

As discussed above, the combination of two different system does not only create a potential structure but may also add perturbation in terms of momentum wave-vector deformation. In order to incorporate such possibility, we shall need to modify the Hamiltonian of Eq.(1). The approach followed in the present work will be on the phenomenological level which equals to modify momentum and it is accompanied by a new potential energy. This rather simple scheme could be defended by looking that the deformation will not distort the original dependence of dispersion but only on its position. Specifically, the presence of deformation will be represented by strain along x direction ϵ_{xx} with potential energy c_x. By incorporating the above consideration, in Eq.(1), we may rewrite a new Hamiltonian in the form of $H_d = \frac{(p-k_0)^2}{2m} + V(x) + c_x \epsilon_{xx}$, in which k_0 describes momentum-related deformation. It is clear from the above expression that the inclusion of mechanical deformation tends to move dispersion while keeping the overall quadratic dependence. In addition, at certain parameter values, a gap could also appear.

We can now derive the final form of polarization of carrier by first solving the wavefunction of Hamiltonian Eq.(1) together with potential V of Eq.(2). Our approach below shall be based on the one dimensional scattering theory which is valid for potential as mentioned above. By combining V together with Eq.(1), we shall be arriving at the general expression of the spin-dependent wavefunction as $\psi_\sigma(x) = A_\sigma e^{-ik_\sigma x} + B_\sigma e^{ik_\sigma x}$, where k_σ denotes the spin-dependent wave-vectors for each region assigned in Eq.(2). Its exact expression could be easily obtained from H or H_d and it is characterized by the absence or presence of potential V, magnetic field M, strain parameter or momentum k_0. An important part of the solution is then to derive an expression of A_σ, B_σ which correspond to undetermined coefficients with a value that shall be determined upon solving the boundary conditions. After performing the above steps for each boundary and for each spin direction, we will arrive at the expression of the transmittance or equivalently the transmission following the usual relation $T = tt^*$, where t transmission coefficient which could be related to one of wavefunction coefficients A_σ or B_σ. Finally, having obtained the transmission coefficients, we may evaluate the total polarization according to

$$P = \frac{T_\uparrow - T_\downarrow}{T_\uparrow + T_\downarrow}, \qquad (3)$$

where $T_\uparrow$ correspond to transmission of spin up while $T_\downarrow$ for spin down carrier.

In our discussion below we keep the effective mass of typical semiconductor system at the order of 0.06 m_e with m_e is the mass of electron, a unit of energy $\epsilon_0 = 1\, eV$. Other parameters will be further explained below while discussing the results.

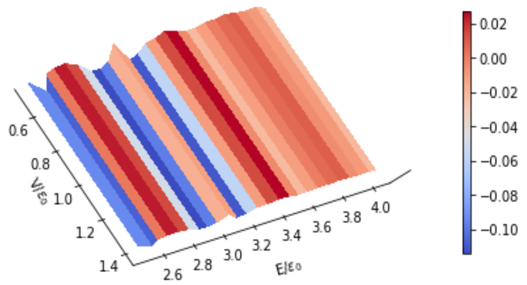

Fig. 1 Spin polarization according to Eq(3), $M_1 = M_3 = 0, M_2 \neq 0$.

RESULTS AND DISCUSSION

Let us discuss the first scenario consisting of undeformed tunnel junction with a ferromagnetic material deposited between non-magnetic barrier. We have chosen the width and the distance between the barrier to be uniform at 70 nm and keep the local magnetic field around 0.1 eV. The spin polarization evaluated according to Eq (3) is shown in Fig. 1 which is derived upon varying energy and potential height.

As expected, the presence of local magnetic field in only one of the barrier is sufficient to induce spin splitting and thus results in the polarized transmission. We directly see in Fig.1 that polarization depends on the incident energy but much less on the strength of the potential barrier. The role of the latter is clearly to move the emergence of non-zero transmission while a rapid change of polarization from positive to negative values along with energy follows the typical character of transmission as a function of energy. It is interesting to recall that in the absence of magnetic material, the transmission of one or multiple barrier system surely shows an oscillatory dependence on energy similar to what is seen in Fig. 1 and it arises from the wave-vector k appears in the wave function. In the present context, however, oscillatory character which fluctuates from negative to positive and with maxima around -0.1 to 0.02 reveals a new insight. It tells us that polarization could be switched from positive to negative and

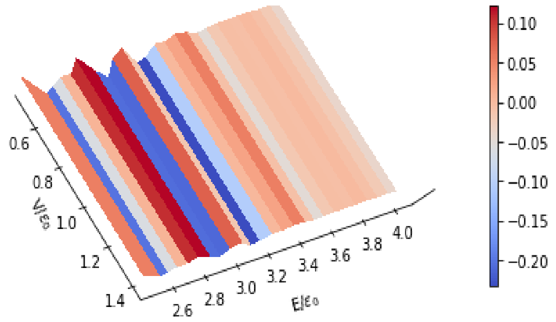

Fig. 4. P with $M_1 = M_2 = M_3 = 0.1\ eV$.

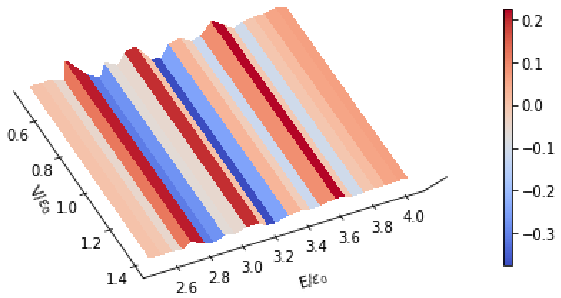

Fig. 3. Polarized transmission with non-zero deformation in the middle barrier and $M_2 \neq 0, M_1 = M_3 = 0$.

it is achieved by varying the incident energy alone. A rather similar behavior is also seen when all barrier consists of ferromagnetic strip with local fields are kept at $M_1 = M_2 = M_3 =$ 0.1 eV. As shown in Fig. 2, positive to negative switching could also be induced by varying energy like the previous case. The most important feature is, however, the improvement of P, indicated by an increase up to around 10 or 20% as compared to the previous case. The reason for this might follow from the presence of local field on all barriers whose role is to maintain spin direction. This is in contrast to the that in Fig. 1 derived from only one ferromagnetic strip in which a direction of polarization might be distorted upon entering non-magnetic barriers.

When the middle barrier is deformed, we obtain the polarized transmission plotted in Fig. 3. In the calculation, we have used $c_x\epsilon_{xx}$= 0.4 eV and $|k_0| = 4|p|$, with the absolute denotes a numerical value of the wave-vector. Other parameters follow those used in Fig. 1. By looking at the energy dependence, we easily realize that it is generally not too much different from what is seen in Fig. 1; it also consists of an oscillatory dependence as a function of energy and could be interpreted similar to what has been mentioned above. In Fig.3 we observe again, an increase of intensity of P of almost around 10%. The enchancement of polarization is further notable when all barriers are affected by the same amount of deformation as shown in Fig. 4. Apart from the oscillation as a function of energy, we could see a significant increase of polarization up to almost 40 to 60 percent, much

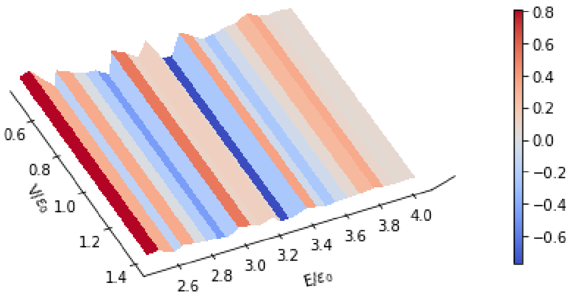

Fig. 2 Polarized transmission for $M_1 = M_2 = M_3 = 0.1\ eV$, *with non-zero deformation.*

larger than what is seen in the undeformed system. This result is the most interesting one and essential in our presentation. First it gives a clear proof of possibility to generate an almost fully polarized carrier in the multibarrier junction. In addition it also provides a new look on the way to control spin polarization. From Figs. 3 and 4, we thus learn that besides incident energy, variation of momentum arises from mechanical deformation could also be used as a tool to control the amount of both intensity and direction of the spin polarization. The latter could be easily realized by comparing Fig. 3 and Fig. 4 within the same energy. From our observation, it is important also to realize that similar to energy, further increasing the momentum k_0 does not necessarily leads to positive effect on polarization. Our calculation also indicated a possibility of a decrease of polarization when strain parameters are set up to two times larger than the above mentioned value.

In spite of this, the presented result remains interesting since combination of incident energy and deformation of momentum could be used interchangeably to achieve the desired amount of polarization.

Before summarizing our presentation, it is perhaps also important to mention that an increase of polarization may also be controlled by setting a larger magnetic field of barrier which clearly requires a material with larger magnetization. Calculation shows that setting magnetic fields three times larger than what is used above might yield an increase of polarization up to 20%. In opposite case, our calculation also indicated that having different magnetization direction among barriers will result in a reduction of polarization.

CONCLUSION

In this contribution, it has been shown that polarization of spin in the multibarrier structure could be realized with various configuration. The spin polarization clearly depends on the incident energy more than potential height inhomogeneity. In this way, a selection of the polarization direction as well as its magnitude could be achieved by carefully choosing the energy. Our model also suggests that a deformation in the momentum wave-vector might be seen as an alternative way to control spin direction and its magnitude. This is not only change the direction of polarization but at certain parameter could also improve the intensity. Analysis indicates that the latter could also help to reach an almost fully polarized transmission.

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