Magnetic heterostructures with tunable spin-dependent transport properties

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ABSTRACT

The scattering of an unpolarized electron wave is considered on a film, consisting of N periodic ferromagnetic nanolayers separated by nonmagnetic layers. The layer materials are chosen such that the potential relief of the structure consists of N identical magnetized barriers separated by nonmagnetic quantum wells. The entire system is splitted by two "magnetic domains" of length n and $N-(n+1)$ with parallel magnetizations, separated by an $(n+1)$-th barrier with noncoplanar magnetization ("noncoplanar defect"). The polarization degree of the transmitted wave is investigated on the dependence of the noncoplanar degrees of freedom, *i.e.*, the coordinates of the "defect" and the incident wave momentum.

Keywords: spin transport, resonant tunneling, valve effect, spin polarization, magnetic nanostructure, "noncoplanar defect", transfer-matrix, transmission amplitudes

1 INTRODUCTION

The transport properties in various structures containing magnetic nanolayers changes in the presence of preferred noncollinear or noncoplanar directions, for example, due to the differences in the direction of the magnetization in varies nanolayers. This circustance leads to two-channel scattering processes of the electron wave - without and with spin flip. The amplitudes of the forward and backward scattering, and, therefore, the transport characteristics can strongly depend on certain quantities that determine the mutual orientation of these distinct (preferred) directions (noncollinear or noncoplanar degrees of freedom). A spin-valve, GMR and TM are examples of such characteristic effects of simiar nature [1-3]. Another example of noncollinearity effect was considered in Ref. [4]. The noncollinearity effects [5] because of the spin-transport scattering of a polarized wave on an isolated magnetized barrier was investigated in [6,7]. The transmission coefficient and the degree of spin polarization of the transmitted incident nonpolarized (wave) electron through a the system consisting of two identical barriers with noncollinear magnetizations was studied. The transport characteristics of a two-barrier noncoplanar system were also calculated [8].

2 SYSTEM WITH NONCOMPLANAR "DEFECT"

Below we consider the scattering of a nonpolarized electron wave on a system of N identical magnetic barriers spaced equidistant from each other and separated by nonmagnetic quantum wells. Each of the barriers is characterized by the induction vector of the internal magnetic field having the following configuration: the first $n-1$ and the last $N-n$ barriers are magnetized so that their internal magnetic field vectors are parallel, and the internal field of the n-th barrier is oriented noncoplanar towards the internal fields of the $N-1$ barriers. We assume that the distance between adjacant quantum wells is large enough that the exchange interaction between wells can be ignored. Thus, the whole system is divided into two "ferromagnetic domains", of length $n-1$ and $N-n$, which are separated by a "noncoplanar defect". This kind of "defect" can be formed during the ferromagnetic nanolayer deposition, however, one can create such defects also artificially. How much changes can produce such artificial defect, will be seen from the results of calculations of the properties and the degree of polarization of the transmitted wave, which is a function of noncoplanar degrees of freedom, as well as the coordinates of the "defect" (the number of the corresponding barrier).
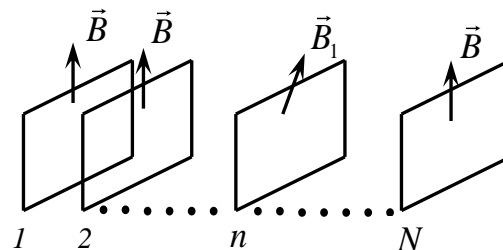

Fig.1 The schematic heterostructure containing N magnetic nanolayers: the internal magnetic fields of $N-1$ layers and the internal field of the n-th layer is noncoplanar (out of plane).
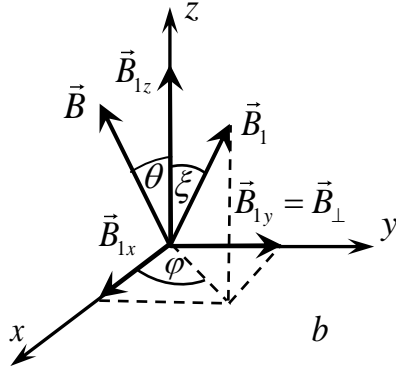
Fig.2 The configuration of the internal field in the $n-\text{th}$ layer. It is further assumed that the magnitudes of fields, $|B|=|B_1|$, are equal,
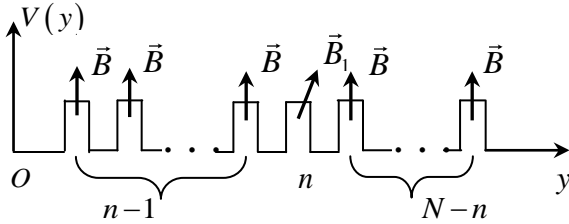

Fig.3 Potential relief of the discussed system having N identical magnetic barriers spaced equidistant from each other and separated by nonmagnetic quantum wells. $\vec{B}_1$ and $\vec{B}$ are noncoplanar.

3 TRANSFER-MATRIX OF THE SCATTERING PROBLEM

To solve the scattering problem, we used the transfer-matrix method for spin-dependent scattering [1]. In our case, it can be represented as follows:

$$S = S_0^{n-1}\left(US_0U^+\right)S_0^{N-n}A^{-N} ,$$

where S_0 - is the transfer-matrix describing the scattering on a single isolated barrier:

$$S_0 = \begin{pmatrix} \alpha & \beta^* \\ \beta & \alpha^* \end{pmatrix}, \quad \alpha = \begin{pmatrix} 1/t_1 & 0 \\ 0 & 1/t_2 \end{pmatrix}, \quad \beta = \begin{pmatrix} r_1/t_1 & 0 \\ 0 & r_2/t_2 \end{pmatrix},$$

$r_\ell = r\left(V_0 \mp \gamma B, E\right),\ t_\ell = t\left(V_0 \mp \gamma B, E\right),\ \left(\ell=1,2\right)$ - are the amplitudes of reflection and transmission, taking into account (with considering) the Zeeman splitting of the "peak" (vertex) of the barrier, U - is the unitary matrix that diagonalizes the spin part of the Hamiltonian $\vec{\sigma}\vec{B}_1$

$$U = \begin{pmatrix} e^{-i\varphi/2}\cos\xi/2, & -e^{-i\varphi/2}\sin\xi/2 \\ e^{i\varphi/2}\sin\xi/2, & e^{i\varphi/2}\cos\xi/2 \end{pmatrix},$$

Where φ and ξ - are spherical angles defining the spatial orientation of the internal field of the defect, and A - is the translation of 4×4 matrix on inter-barrier distance. Then S_0^{n-1} and S_0^{N-n} describe scattering on two collinear domains, and US_0U^+ - on the defect. The matrices S_0^{n-1} and S_0^{N-n} are block-diagonal matrices whose elements are expressed in terms of transmission and reflection amplitudes for the corresponding domains [7,8]. Thus, the transfer matrix allows one to construct the transmission and reflection amplitudes.

3 RESULTS

To construct the plots of the degree of polarization dependences on various variables, we use the following approximating model Hamiltonian:

$$H_{\text{int}} = \left(\omega-\gamma B\sigma_z\right)\sum_{\ell=1}^{N}{}'\delta\left(y-\ell\right)+\left(\omega-\gamma\vec{B}_1\vec{\sigma}\right)\delta\left(y-n\right) ,$$

given in dimensionless quantities: $\omega=\Omega/E_0a$, Ω - is the "amplitude" of the δ - potential, $\gamma=\mu/2E_0$, μ - is the electron magnetic momentum, $E_0=\hbar^2/2ma^2$, a - is a constant of the order of atomic dimensions, the prime on the sum sign denotes the absence of the term with $\ell=n$; this term is presented separately; it describes the interaction of the electron spin with a "noncoplanar defect", y - is a dimensionless coordinate variable.

Below are the calculated graphs for $N=7$, i.e., a system containing seven magnetized barriers. The degree of polarization of the transmitted wave depends on three variables: the degree of noncollinearity - the angle θ between the z axis, the component of the vector $\vec{B}_1$ on the plane of the nanolayer and the ratio $\eta=B_\perp/B_{1z}$ of the two components of the "defect" internal field, and the momentum of the electron wave k. Two variables are fixed and the dependence of the polarization on the third variable is constructed.

For simplicity, we consider the degree of polarization in scattering on a system of 7-barriers, when the internal fields of all the barriers are directed in the same way (a single-domain system). This is necessary for comparison with the corresponding plot of our problem.
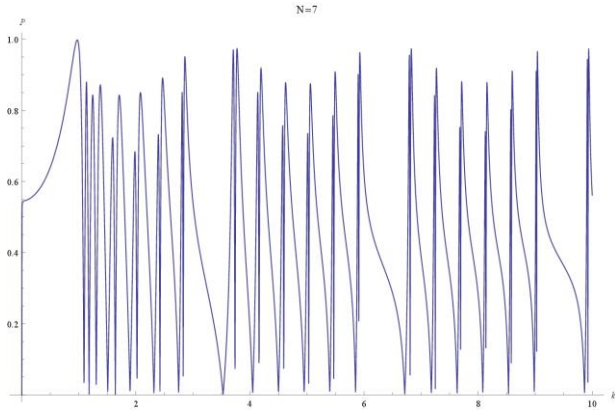
Fig.4 The dependence of polarization degree in transmitted wave on the momentum k of the system with parallel internal fields $\left(\eta=0;\;\theta=0\right)$.

In this case, the dependence $P=P(k)$ is a sequence of peaks, some of which reach a maximum.
In this case, the scattering channel with spin flip is closed $\left(T_{\uparrow\downarrow}=T_{\downarrow\uparrow}=0\right)$, and the degree of polarization is equal to

$$P(k)=\left|P_z(k)\right|=\frac{\left|T_{\uparrow\uparrow}\right|^2-\left|T_{\downarrow\downarrow}\right|^2}{\left|T_{\uparrow\uparrow}\right|^2+\left|T_{\downarrow\downarrow}\right|^2},$$

where $T_{\uparrow\uparrow}$, $T_{\downarrow\downarrow}$ - are the amplitudes of transmission without a spin flip. At the partial resonance of transmission, for example, $\left|T_{\uparrow\uparrow}\right|=1$, $\left|T_{\downarrow\downarrow}\right|\ll1$, and then $P(k)=1$ up to small terms. Thus, the maximum spin polarization is achieved only at partial resonance of transmission. Furthermore $P(k)$, as well as the envelope of local maxima are periodical functions (Fig.4).
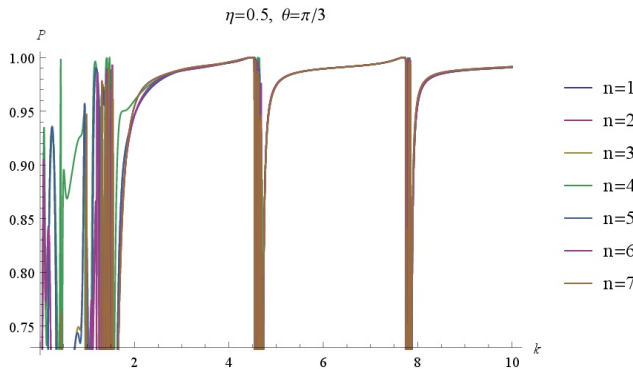

Fig.5 The dependence of $P(k)$ in case of "noncoplanar defect".

In the case when there exists a "noncoplanar defect" in the system, the picture changes significantly. In the region of small k, peaks are again present on the plot, however, in the region of large k, there arise peculiar "windows of polarization" - the range of values k, where $P(k)$ change quite slowly, and besides its numerical value is close to unity. These ranges of values k are separated by narrow regions, in which $P(k)$ is practically zero. Because of the presence of a second scattering channel-with a spin flip, the squares of the transmission amplitude are rapidly oscillating functions of k, the period of which is $\pi/2N$, hence $\pi/14$ - in our case; as a result, the curve in Fig.4. is the envelope of the maxima of these oscillations. Wherein $P(k)$ varies very slowly with the values η and θ. $P(k)$ weakly depends on the "defect" coordinate. From Fig.5. it is clear that for large k this dependence simply disappears.
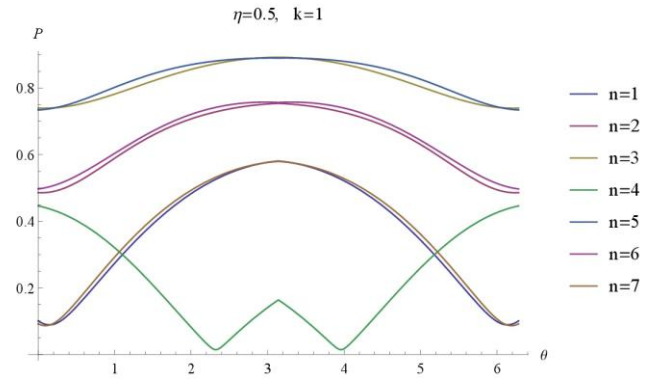

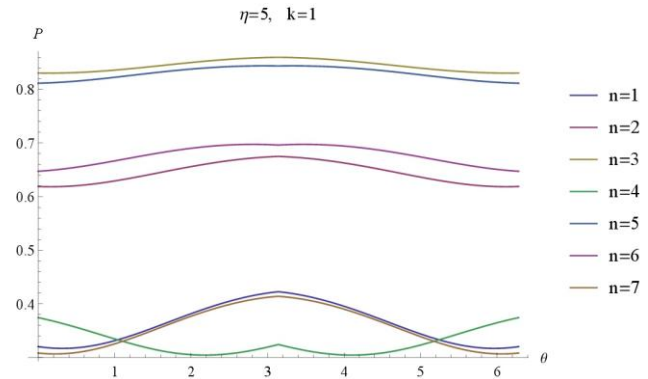Fig.6 The dependence of $P(\theta)$ at $k=1,\;\eta=0,5$.

Fig.7 The dependence of $P(\theta)$ at $k=1,\;\eta=5$.

The degree of polarization is a 2π-periodic function of θ. With increasing η, the amplitude decreases, i.e. suppression of 2π-oscillations occurs. In addition, as can be seen from Fig.6 and Fig.7, $P(\theta)$ essentially depends on the coordinate of the "defect".
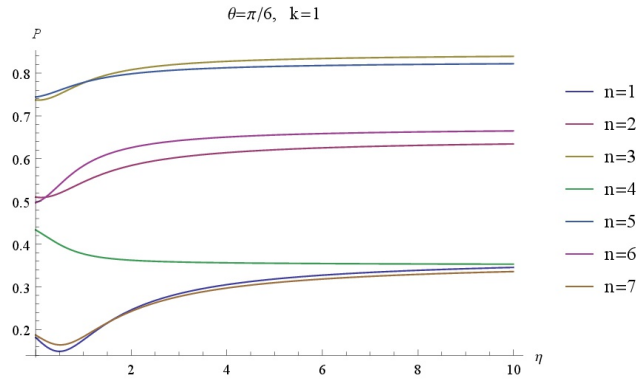

Fig.8 The dependence of $P(\eta)$ at $\theta = \pi/6$, $k = 1$.

Can be seen from Fig. 8 that the degree of polarization is a slowly varying function of η, and at large η it reaches the plateau; except this, there is a significant dependence on the coordinate of the "defect".

4 CONCLUSION

We studied nanostructures consisting of realistic magnetic barriers with "defect" produced by the deposition of ferromagnetic strips on heterostructures. From the results presented, it can be seen that the proposed system has a strong spin-polarizing properties. In the region of sufficiently large k there exist "spin-polarization windows" in which the degree of polarization depends weakly on the momentum k, and is close to unity. Two "neighboring windows" are separated by narrow ranges of values k, in which the degree of polarization is zero. The degree of polarization is a 2π-periodic function of the angle θ. The growth of the parameter η leads to the suppression of 2π-oscillations. The degree of polarization $P(\theta)$ essentially depends on the coordinate of the "defect". $P(\eta)$ is a slowly varying function of the parameter η; for large η, $P(\eta)$ goes to the plateau, and, in addition, it essentially depends on the coordinate of the "defect". These effects can be employed in the efficient control of spin polarization via the application of weak, moderate and strong fields.

Finally, the transfer matrix method used here is a generalization of the well-known method constructed for the scalar scattering problem [9,10]. It is a useful tool for studying the transport properties of the noncoplanarity-containing magnetic systems described herein.

5 ACKNOWLEDGEMENT

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