Available online at www.sciencedirect.com

SCIENCE DIRECT®

Physica E 30 (2005) 74–80

PHYSICA E

www.elsevier.com/locate/physe

Spin-dependent transport of holes in microstructures periodically modulated by diluted magnetic semiconductor sections

Y.O. Ciftci[1], X.F. Wang, P. Vasilopoulos*

Department of Physics, Concordia University, 7141 Sherbrooke Ouest, Montréal, Qué., Canada H4B 1R6

Received 14 June 2005; accepted 4 July 2005
Available online 6 September 2005

Abstract

We study spin transport of holes through microstructures modulated periodically by diluted magnetic semiconductor (DMS) sections, stubless or stubbed. The stubs are symmetric or asymmetric and the magnetizations of consecutive DMS sections are parallel or antiparallel. The transmission coefficients of holes with spin *up* (T^+) or *down* (T^-) are drastically different since the spins feel different potential profiles in the DMS sections. As a result, nearly *square-wave* patterns, or wide plateaus and oscillations, can be obtained for the transmission and the spin polarization as functions of the incident energy or of various parameters of the periodically repeated unit. Results for simple and composite units with and without deviations from perfect periodicity are reported. Some of the structures considered exhibit a strong spin-filtering behavior.

PACS: 73.23−b; 73.40−c; 75.75+a

Keywords: Diluted magnetic semiconductors; Spin-polarized hole transport; Ferromagnets; Magnetization; Spin-filtering; Transmission

1. Introduction

In recent years spin transport has attracted considerable attention as it offers a possibility for new types of devices that would exploit the spin rather than the charge of carriers. One approach to studying it, recently reviewed [1], focuses on the effects of spin–orbit interaction that is expected to lead to devices such as spin transistors [2]. Another approach, with potential applications in quantum computation and quantum logic, concentrates on spin-polarized electronic transport through diluted magnetic semiconductors (DMS) [3] despite the fact that the reported experimental spin polarizations are very low, about 1%, and make the results controversial and attributable to extraneous effects. Experimental work [4] showed that the DMS materials $Ga_{1-x}Mn_xAs$ can be in the metallic ferromagnetic phase with heavy holes as carriers for $0.03 \leqslant x \leqslant 0.05$.

Here we study the spin-dependent transmission of heavy holes through waveguides made of many identical units each of which consists of a nonmagnetic part, A, followed by a DMS one, B, as shown in Fig. 1(b). The aim is to obtain a transistor-like modulation of the spin current carried by holes. Part of the motivation came from previous results on electronic [5] stub tuners as well as from a brief one [6] on spin transport of holes through stubbed waveguides. Further motivation came from spin-filter effects in magnetic heterostructures [7], transmission studies through ferromagnetic-normal-ferromagnetic layered metal structures with antiparallel magnetization alignment [8], and studies of tunneling through double magnetic barriers with parallel or antiparallel magnetizations [9,10] and their influence on the magnetoresistance.

The geometry of the units we consider is shown in Fig. 1(a): they can be simple, for $b_1 = b_2$, or composite with $b_1 \neq b_2$. Stubs can be attached to either part A or part B but it is advantageous to attach them to the DMS part B. We assume that each DMS layer is ferromagnetic and that its

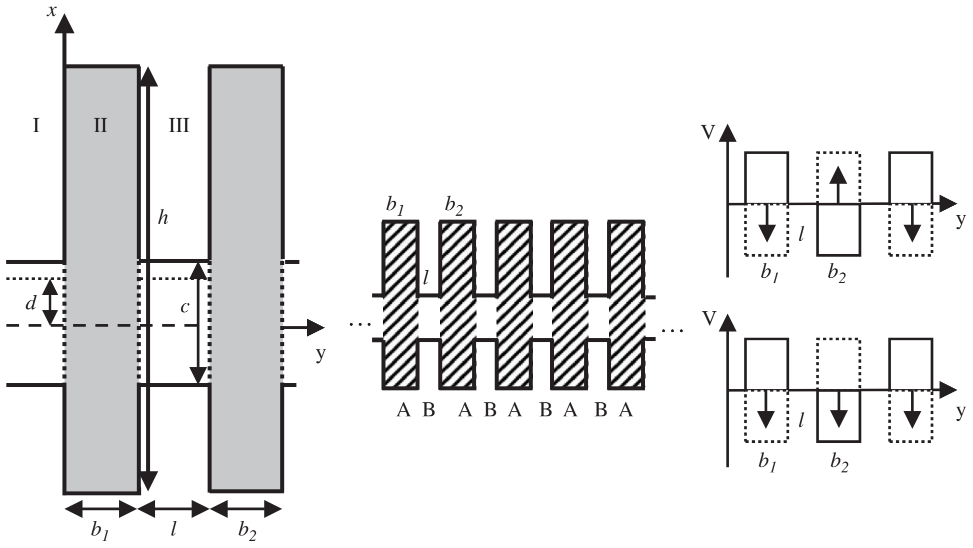
---

*Corresponding author. Tel.: +1 514 848 2424x3290; fax: +1 514 848 2828.

E-mail addresses: yasemin@gazi.edu.tr (Y.O. Ciftci), xuefeng@alcor.concordia.ca (X.F. Wang), takis@alcor.concordia.ca (P. Vasilopoulos).

[1] Permanent address: Physics Department, Gazi University, 06500, Teknikokullar, Ankara, Turkey.

1386-9477/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.physe.2005.07.010



(a) (b) (c)

Fig. 1. (a) A waveguide portion with two stubs (shaded areas). For a simple unit we have $b_1 = b_2$, for a composite one $b_1 \neq b_2$. The midpoints of h and c determine the asymmetry parameter d. (b) A periodically stubbed waveguide (A = GaAs, B = DMS). (c) A possible effective potential V along the growth axis for spin-up (solid curve) and spin-down (dotted curve) holes. The magnetizations of the DMS layers are antiparallel to each other (upper panel) or parallel (lower panel).

magnetization can be controlled and point to the direction of the arrows as shown in panel (c) of Fig. 1 for two particular cases. In addition to the parallel or antiparallel magnetizations shown in Fig. 1, we consider mixed cases as well.

A brief account of results, only for *parallel* magnetizations, was given in Ref. [6]. Here we investigate in detail and contrast the cases of parallel and antiparallel magnetizations. As will become clear below, if the direction of the magnetization is reversed, the potential profile a spin-polarized hole feels is reversed as well, say, if it was a barrier it becomes a well for this hole. Because the transmissions through a barrier and a well are qualitatively different, it is important to study and contrast, as we do, both parallel and antiparallel magnetizations. In doing so, we expect and find new results, especially *square-wave* patterns in both quantities, for *antiparallel* magnetizations of the DMS sections of the composite unit. We also consider more complicated magnetization profiles, e.g., two DMS layers magnetized *up* followed by three DMS layers magnetized *down*. In addition, we present results for the energy dependence of the transmission and polarization and study the effect of deviations from perfect periodicity on the transmission and polarization, that were not studied in Ref. [6]. We present the formalism in Section 2 and a variety of results in Section 3. Concluding remarks follow in Section 4.

2. Formalism

The spin-structure for holes is obtained [11] self-consistently in reciprocal space. The hole interaction with magnetic impurities is described by the potential

$$U_{\text{mag}}(\mathbf{r}) = -I \sum_{i=1}^{\mathrm{N}_i} \mathbf{s}(\mathbf{r}) \cdot \mathbf{S}(\mathbf{R}_i)\delta(\mathbf{r} - \mathbf{R}_i), \tag{1}$$

where I is the $p - d$ exchange coupling constant, $\mathbf{R}_i$ denotes the positions of the N_i impurities Mn, uniformly distributed in the DMS layers, $\mathbf{S}(\mathbf{R}_i)$ is the spin of the impurity, and $\mathbf{s}$ the spin of the hole. We assume that each layer is in its ferromagnetic phase with its magnetization oriented along a single direction. Thus, the spin of the hole is well defined in this direction, being parallel (down) or antiparallel (up) to it. Integrating $U_{\text{mag}}(\mathbf{r})$ over z and x gives the effective potential $V_{\text{mag}}(y)$ in terms of the average magnetization $\langle \mathbf{M} \rangle_j$:

$$V^{\sigma}_{\text{mag}}(y) = V_0 \sigma \sum_j \langle M \rangle_j g_j(y), \tag{2}$$

where $g_j(y) = 1$ if y lies inside the j-layer, and $g_j(y) = 0$ otherwise; $\sigma = \pm 1$ for spin-up and spin-down holes, respectively, and V_0 is a sample-dependent parameter for the strength of the potential. The total potential felt by a hole is $U^{\sigma}_{\text{eff}}(y) = [U_{\text{c}}(y) + V^{\sigma}_{\text{mag}}(y) + U_{\text{h}}(y)]$, where $U_{\text{c}}(y)$ is the confining potential, and $U_{\text{h}}(y)$ the Hatree hole–hole interaction potential. Setting $E_k = h^2k^2/2m^*$ the hole Hamiltonian in the DMS section becomes

$$H = E_k + U^{\sigma}_{\text{eff}}(y) \equiv \begin{bmatrix} E_k + U^{+}_{\text{eff}}(y) & 0 \\ 0 & E_k + U^{-}_{\text{eff}}(y) \end{bmatrix}.$$

The direction of the spin polarization depends on that of $\langle \mathbf{M} \rangle_j$. We assume the latter is along the waveguide (y axis) or along the stub (x axis). Generally, $U^{\sigma}_{\text{eff}}(y)$ is not constant