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Dependences of spin polarization on the control parameters in the spin-polarized injection through the magnetic p-n junction*

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Effective spin-polarized injection from magnetic semiconductor (MS) to nonmagnetic semiconductor (NMS) has been highlighted in recent years. In this paper we study theoretically the dependence of nonequilibrium spin polarization (NESP) in NMS during spin-polarized injection through the magnetic p-n junction. Based on the theory in semiconductor physics, a model is established and the boundary conditions are determined in the case of no external spin-polarized injection and low bias. The control parameters that may influence the NESP in NMS are indicated by calculating the distribution of spin polarization. They are the doping concentrations, the equilibrium spin polarization in MS and the bias. The effective spin-polarized injection can be realized more easily by optimizing the above parameters.

Keywords: spin polarization, spin-polarized injection, magnetic semiconductor, p-n junction
PACC: 7340L, 7550P

1. Introduction

Compared with traditional microelectronic devices, semiconductor spintronic devices have broader applications for the use of additional degree of freedom, i.e. spin, rather than the charge. Effective spin-polarized injection is the crucial puzzle in the applications. Since it was proposed,[1] effective spin-polarized injection from magnetic materials to nonmagnetic semiconductor (NMS) has been highlighted recent years. The most popular schemes use a ferromagnetic metal or magnetic semiconductor (MS) as the spin-polarized injection source. The spin-polarized injection rate from a ferromagnetic metal directly into NMS is quite low [2,3] due to the conductance mismatch,[4] though this scheme can be performed at room temperature. The scheme using MS, however, can obtain exciting results for its avoidance of conductance mismatch between the spin-polarized injection source and NMS.[5−7] Moreover, several kinds of MSs were reported with the Curie temperature (T_C) higher than room temperature.[8−14] And the efforts to find more MSs with high T_C by the first principle calculations have obtained many instructive conclusions.[15,16]

On the other hand, theoretical models for spin-polarized injection from magnetic materials into NMS were developed simultaneously.[4,17−26] However, there has been no generally accepted theory concerning the spin-polarized injection and transport through the MS/NMS junction up to now.[24−26] Fabian *et al*[24] proposed an explanation by using the semiconductor drift-diffusion theory, but they ignored the quasi-chemical potential (QCP) spin-split in NMS arising from the magnetic impurity in MS. Furthermore, the dependences of spin polarization on the control parameters in the spin-polarized injection from MS into NMS are not clear yet.

This paper investigates the spin-polarized injection through the n-MS/p-NMS junction. A model is established based on the theory in semiconductor physics and the boundary conditions are determined with the QCP relations between different spins. The simulation is accomplished in the case of low bias and no external spin-polarized injection (ESPI). The dependences of spin polarization on the control parameters are demonstrated by calculating the distribution

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of spin polarization.

2. Theory and model

Without ESPI, the energy band structure of the n-MS/p-NMS junction can be described as in Fig.1. The semiconductor homojunction is doped with magnetic impurity in the n region. There is a spin-split (2ξ) between the subband edges of spin-up and spin-down carriers in MS due to the spontaneous magnetization. The subband edge spin-split is small in most cases. Therefore, the magnetic impurity doping has no effects on the basic energy band structure of semiconductor materials, i.e. the effective band gaps of NMS and MS are equal.

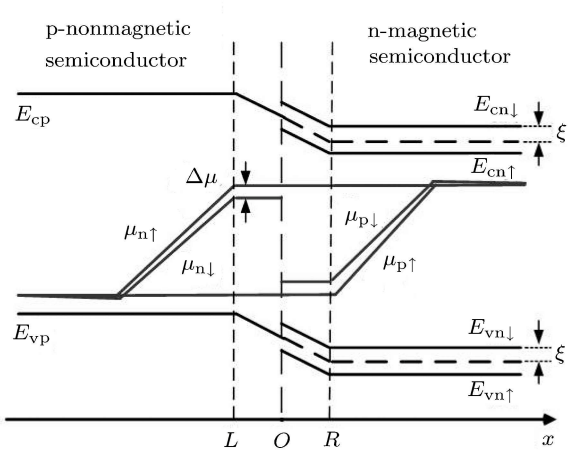


Fig.1. The energy band structure of n-MS/p-NMS p-n junction with low bias and no ESPI. x is the position, and the areas $x < 0$ and $x > 0$ are the p and n regions respectively. Spin-up is supposed to be the major electron spin. E_c (E_v) is the conduction (valence) band edge and μ is the QCP. The subscripts $\uparrow$ and $\downarrow$ represent spin-up and spin-down respectively. $\Delta\mu$ is the QCP spin-split of the electron.

The model supposes that the bias is lower than the build-in voltage, and the semiconductor is nondegenerate in the temperature range interested, which is below the Curie temperature of MS. No ESPI is introduced in the boundaries. Spin-flip in the depletion region is neglectable, because the spin diffusion length is much longer than the width of the depletion region. Furthermore, the spin-up and spin-down carriers can be considered as independent and can be calculated separately within the spin diffusion length. Therefore, the n-MS/p-NMS junction can be denoted as two parallel NMS heterojunctions, corresponding to the carriers with two different spins.

In the measurements to determine the nonequilibrium spin polarization (NESP) by luminescence,[5−7] only one-type of carriers contributes to the final results. Therefore, this paper is focused only on the electron, and the 'spin' mentioned next denotes the spin of the electron. Actually the behaviour of the hole can be obtained in the same way.

Our model is based on the theory in semiconductor physics. The distribution of nonequilibrium electron (spin) density in p-NMS neutral region can be solved from semiconductor drift–diffusion theory and current continuity equation:[24]

$$\delta n = \delta n_{\rm L}\cosh(\eta_{\rm np}) + F_{\rm np}\sinh(\eta_{\rm np}), \tag{1}$$

$$\delta s = \delta \tilde{s}_{\rm L}\cosh(\eta_{\rm sp}) + F_{\rm sp}\sinh(\eta_{\rm sp}), \tag{2}$$

where $\eta_{\rm np} \equiv (x + d_{\rm p})/L_{\rm np}$, $\eta_{\rm sp} \equiv (x + d_{\rm p})/L_{\rm sp}$. $L_{\rm np}(L_{\rm sp})$ is the electron (spin) diffusion length in the p region, $d_{\rm p}(d_{\rm n})$ is the width of the p (n) depletion region, $\delta\hat{s} = s - \alpha_0 n$ is the effective nonequilibrium spin density, and α_0 is the equilibrium spin polarization (ESP). $F_{\rm np}(F_{\rm sp})$ is the flux parameter of electron (spin) in the p region. The subscript L (R) represents the boundary of the p (n) depletion region (see Fig.1).

The boundary conditions can be determined according to the QCP relations. Spin-up is supposed to be the major spin, as shown in Fig.1. At low bias, the transport of spin-down electron through the junction includes both diffusion mechanism and hot electron emitting mechanism due to the band edge peak in spin-down conduction subband resulting from the subband edge spin-split in MS. The QCP of spin-down electron is discontinuous at the junction interface according to current continuity equation, however the QCP of spin-up electron is continuous. Therefore, the QCP gap of spin-down electron ($\Delta\mu$) is also the QCP spin-split in NMS, as written in the boundary conditions:

$$\begin{cases} \mu_{+R} = \mu_{+L} + \dfrac{\Delta\mu}{2}, \\ \mu_{-L} = \dfrac{\Delta\mu}{2}, \end{cases} \tag{3}$$

where $\mu_+ = (\mu_\uparrow + \mu_\downarrow)/2$ and $\mu_- = (\mu_\uparrow - \mu_\downarrow)/2$; $\mu_\uparrow(\mu_\downarrow)$ is the QCP of spin-up (spin-down) electron, $\delta n_{\rm L}$ and $\delta\hat{s}_{\rm L}$ are obtained from the boundary conditions.

$$\delta n_{\rm L} = n_{0\rm L}(\mathrm{e}^{V-\Delta\mu/2} - 1), \tag{4}$$

$$\delta\tilde{s}_{\rm L} = n_{0\rm L}\mathrm{e}^{V-\Delta\mu/2}\tanh(\Delta\mu/2). \tag{5}$$

Then the distributions of the electron (spin) density and spin polarization can be obtained from Eqs.(1), (2), (4) and (5). It is demonstrated that

NESP in NMS is determined by $\Delta\mu$, i.e., spin-polarized electrons in NMS can be produced just by magnetic impurity in MS even without ESPI.

Furthermore, $\Delta\mu$ can be solved by the method similar to the treatment of semiconductor heterojunctions.[27] In low bias the hot electron emitting current at the p-n junction interface is given by

$$j_{\rm e} \approx q\frac{v_{\rm n}}{4}n_{\downarrow 0{\rm n}}{\rm e}^{V_{\rm n}-V_{\rm bn}}(1-{\rm e}^{-\Delta\mu}), \tag{6}$$

where $v_{\rm n} = (8k_{\rm B}T/\pi m_{\rm n})^{1/2}$ is the electron average velocity, $m_{\rm n}$ is the electron effective mass. $V_{\rm bp}$ ($V_{\rm bn}$) and $V_{\rm p}$ ($V_{\rm n}$) are the built-in potential and the bias in the p (n) region respectively. In this paper, the units of potential and energy are $k_{\rm B}T/q$ and $k_{\rm B}T$ respectively.

Ignoring the recombination of the carriers in depletion regions, the hot electron emitting current should be equal to the minor carrier (electron) diffusion current at the boundary of p depletion region, described as follows:

$$j_{\rm Dn} = q\frac{D_{\rm np}}{L_{\rm np}}n_{\downarrow 0{\rm n}}{\rm e}^{\xi-V_{\rm b}}[{\rm e}^{V-\Delta\mu}-1], \tag{7}$$

where $D_{\rm np}$ is the electron diffusion coefficient. Then $\Delta\mu$ can be given by

$$\Delta\mu = \ln\left(\frac{\dfrac{4D_{\rm np}}{v_{\rm n}L_{\rm np}}{\rm e}^{\xi-V_{\rm bp}+V_{\rm p}}+1}{\dfrac{4D_{\rm np}}{v_{\rm n}L_{\rm np}}{\rm e}^{\xi-V_{\rm bp}-V_{\rm n}}+1}\right). \tag{8}$$

From the expression of the distribution of spin polarization, the control parameters that may influence NESP in p-NMS include the doping concentrations, the bias and the ESP in MS. The details will be described in the next section.

3. Simulations and discussions

Spin-polarized injection from MS to NMS is simulated based on the model proposed in this paper. The material parameters used in computation are taken from those of GaAs. The simulation bias is smaller than 1V for the low bias limitation, and the ESPI is not introduced. The dependences of NESP in NMS on the doping concentration, the ESP in MS and the bias are obtained by calculating the distributions of spin polarization in magnetic p-n junction.

Dependences of NESP in NMS on the doping concentrations are achieved via build-in voltage and vary in a complicated way as shown in Fig.2. The NESP in NMS is near to zero when the acceptor concentration in NMS is smaller than the donor concentration in MS. And the NESP in NMS increases up to over 40% with the increase of the ratio of acceptor to donor concentration ($N_{\rm a}/N_{\rm d}$) up to 10^2. NESP increases slightly when the concentration ratio exceeds 10^2. When the concentration ratio is fixed, the NESP in NMS decreases with the increase of doping concentration.

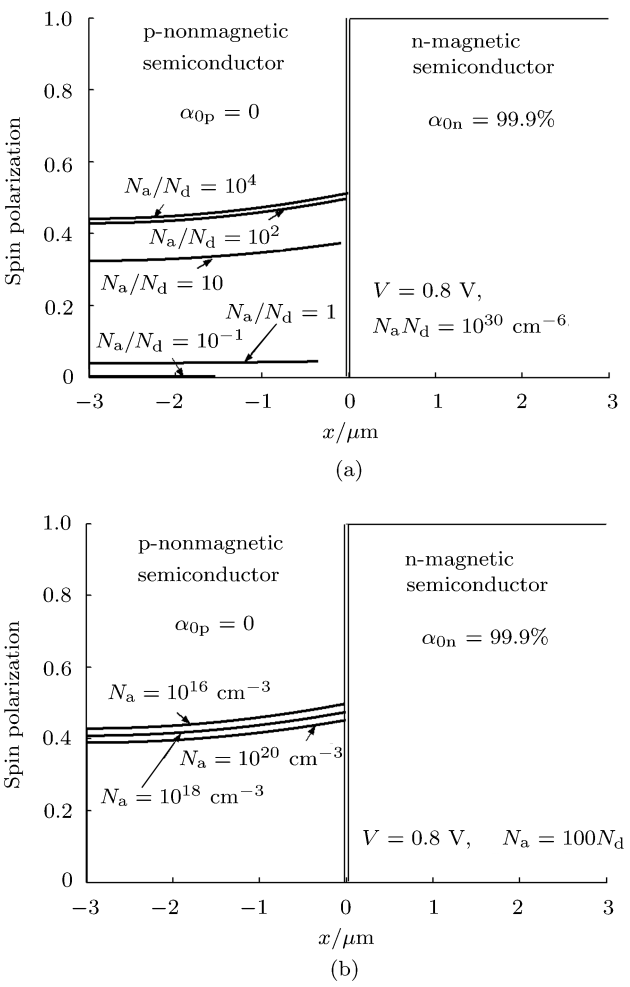


Fig.2. Dependences of the NESP in NMS on the ratio ($N_{\rm a}/N_{\rm d}$) (a) and the product ($N_{\rm a}N_{\rm d}$) (b) of the acceptor concentration in NMS and donor concentration in MS for $\alpha_{0\rm n} = 99.9\%$, $v = 0.8$ V, and (a) $N_{\rm a}N_{\rm d} = 1\times 10^{30}$ cm^{-6}, (b) $N_{\rm a} = 100N_{\rm d}$.

From Eq.(8), the concentration ratio ($N_{\rm a}/N_{\rm d}$) affects the distribution of the build-in voltage and the bias in the p and n regions, and then the QCP spin-split in NMS ($\Delta\mu$). In a certain range, $\Delta\mu$ and then the NESP in NMS increase with the increase of the concentration ratio. On the other hand, the concentration product ($N_{\rm a}N_{\rm d}$) will influence the build-in voltage and then $\Delta\mu$ which increases with the decrease of the concentration product. Therefore, it is helpful to the improvement of the NESP in NMS by the re-

duction of the doping concentration and the increase of the concentration ratio.

Dependence of the NESP in NMS on the bias is demonstrated in Fig.3. In low bias, the NESP in NMS increases about 5% with the increase of the bias from 0.3 to 0.9V, because more spin-polarized electrons can be injected into n region when driven by the electric field. However, the influence of the bias on NESP in NMS is not so remarkable.

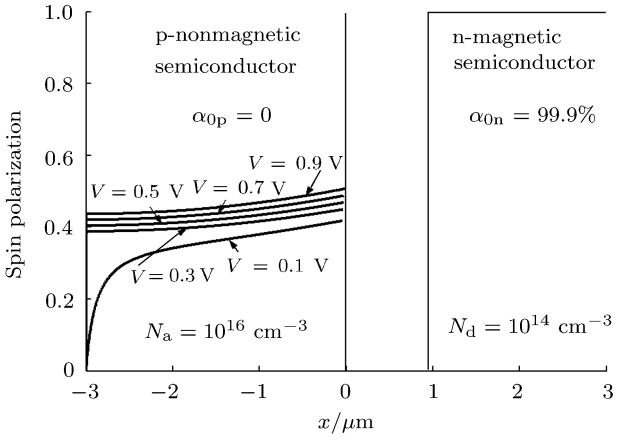


Fig.3. Dependence of the NESP in NMS on the bias for $\alpha_{0n} = 99.9\%$, $N_d = 1 \times 10^{14}$ cm^{-3}, $N_a = 1 \times 10^{16}$ cm^{-3}.

The ESP in MS corresponds to the subband spin-split in MS (i.e. 2ξ), and the NESP in NMS increases with the increase of ESP in MS (α_{0n}) as shown in Fig 4. The value of the NESP is above 65% when α_{0n} is 99.99%. However, the NESP in NMS decreases sharply when α_{0n} is not high enough, it is equal to only 7% when $\alpha_{0n} = 90\%$, and even 2% when $\alpha_{0n} = 10\%$. Therefore, the improvement of the ESP in MS is crucial for obtaining higher NESP in NMS, which can be achieved by selecting a magnetic impurity with higher spontaneous magnetization or increasing the magnetic doping concentration.

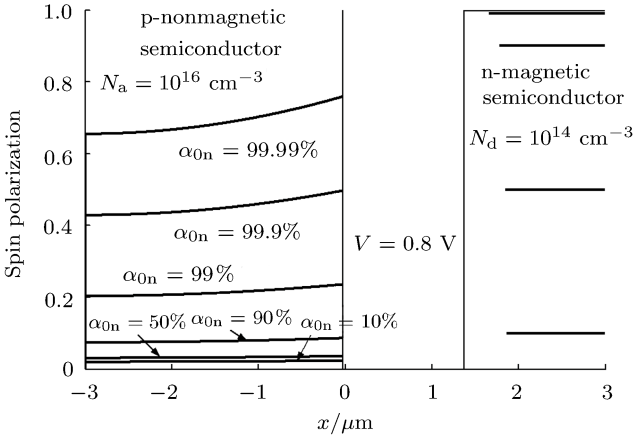


Fig.4. Dependence of the NESP in NMS on the ESP in MS for $V = 0.8$ V, $N_a = 1 \times 10^{16}$ cm^{-3}, $N_d = 1 \times 10^{14}$ cm^{-3}.

4. Conclusions

Based on the drift-diffusion theory and continuity equation, we have established a model to study the dependences of the NESP in NMS on the control parameters in the spin-polarized injection from MS into NMS. Boundary conditions are determined by analysing the QCP relations at the junction interface. The simulation has been performed for the case of low bias and no ESPI. The control parameters that may affect the NESP in NMS include the doping concentration, the bias and the ESP in MS. To improve the NESP in NMS, the doping concentration product should be decreased; however, the ESP in MS, the bias and the doping concentration ratio should be increased also.

References

[1] Aronov A G and Pikus G E 1976 *Sov. Phys. Semicond.* **10** 698

[2] Hammar P R, Bennett B R, Yang M J and Johnson M 1999 *Phys. Rev. Lett.* **83** 203

[3] Zhu H J, Ramsteiner M, Kostial H, Wassermeier M, Schönherr H P and Ploog K H 2001 *Phys. Rev. Lett.* **87** 016601

[4] Schmidt G, Ferrand D, Molenkamp L W, Filip A T and van Wees B J 2000 *Phys. Rev.* B **62** 4790

[5] Fiederling R, Kleim M, Reuscher G, Ossau W, Schmidt G, Waag A and Molenkamp L W 1999 *Nature* **402** 787

[6] Ohno Y, Young D K, Beschoten B, Matsukura F, Ohno H and Awschalom D D 1999 *Nature* **402** 790

[7] Jonker B T, Park Y D, Bennett B R, Cheong H D, Kioseoglou G and Petrou A 2000 *Phys. Rev.* B **62** 8180

[8] Ueda K, Tabata H and Kawai T 2001 *Appl. Phys. Lett.* **79** 988

[9] Han S J, Song J W, Yang C H, Park S H, Park J H, Jeong Y H and Rhie K W 2002 *Appl. Phys. Lett.* **81** 4212

[10] Ogale S B, Choudhary R J, Buban J P, Lofland S E, Shinde S R, Kale S N, Kulkarni V N, Higgins J, Lanci C, Simpson J R, Browning N D, Sarma S Das, Drew H D, Greene R L and Venkatesan T 2003 *Phys. Rev. Lett.* **91** 077205

[11] Coey J M D, Douvalis A P, Fitzgerald C B and Venkatesan M 2004 *Appl. Phys. Lett.* **84** 1332

[12] Song H Q, Chen Y X, Ren M J and Ji G 2005 *Acta Phys. Sin.* **54** 369 (in Chinese)

[13] Kuang A L, Liu X C, Lu Z L, Ren S K, Iiu C Y, Zhang F M and Du Y W 2005 *Acta Phys. Sin.* **54** 2934 (in Chinese)
[14] Wang Y, Sun L, Han D D, Liu L F, Kang J F, Liu X Y, Zhang X and Han R Q 2006 *Acta Phys. Sin.* **55** 6651 (in Chinese)
[15] Sato K, Dederics P H and Katayama-Yoshida H 2003 *Europhys. Lett.* **61** 403
[16] Lin Q B, Li R Q, Zeng Y Z and Zhu Z Z 2006 *Acta Phys. Sin.* **55** 873 (in Chinese)
[17] Rashba E I 2000 *Phys. Rev.* B **62** 16267
[18] Fert A and Jaffres H 2001 *Phys. Rev.* B **64** 184420
[19] Smith D L and Silver R N 2001 *Phys. Rev.* B **64** 045323
[20] Yu Z G and Flatte M E 2002 *Phys. Rev.* B **66** 235302
[21] Albrecht J D and Smith D L 2003 *Phys. Rev.* B **68** 035340
[22] Saikin S, Shen M, Cheng M C and Privman V 2003 *J. Appl. Phys.* **94** 1769
[23] Agrawal S, Jalil M B A, Tan S G, Teo K L and Liew T 2005 *Phys. Rev.* B **72** 075352
[24] Fabian J, Zutic I and Sarma S Das 2002 *Phys. Rev.* B **66** 165301
[25] Khaetskii A, Egues J C, Loss D, Gould C, Schmidt G and Molenkamp L W 2005 *Phys. Rev.* B **71** 235327
[26] Zutic I, Fabian J and Erwin S C 2006 *Phys. Rev. Lett.* **97** 026602
[27] Ye L X 1984 *Semiconductor Physics* (Beijing: Higher Education Press) p471 (in Chinese)