Organic spin valves: effect of magnetic impurities on the spin transport properties of polymer spacers

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Abstract. We report the effect of magnetic impurities in the spacer layer of polymeric spin valves (PSV) with the sandwich configuration of La\textsubscript{0.67}Sr\textsubscript{0.33}MnO\textsubscript{3} (LSMO)/π-conjugated polymer regio-random poly(3-hexyl thiophene)/cobalt (Co), showing giant magnetoresistance (GMR) response. Different deposition rates of Co at the top electrode resulted in two types of devices: one with lower device resistance and linear current–voltage (\textit{I–V}) characteristics and the other with very low inclusion of Co and exhibiting higher device resistance and nonlinear \textit{I–V} characteristics. We observed an asymmetric dc bias dependence of magnetoresistance (MR) in devices with more Co inclusion, while for the other type of device, bias dependence was more symmetric. At higher bias, \%MR of both types of device showed no significant difference (5–10%), but at low dc bias it ranged between 50 and 160\% MR. This can be attributed to the higher tunneling probability of spin-polarized carriers from one ferromagnetic electrode to the other. Magnetic tunnel junction-like features are observed in the devices with greater Co inclusions. Anomalous MR peaks were also observed in these devices and their origin was explained in terms of presence of additional scattering centers around the included metal ions and increased spin relaxation due to high magnetic anisotropy in the system. Both types of PSVs showed a monotonic decrease in MR with temperature at high bias currents.

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1. Introduction

Spin electronic (‘spintronic’) devices [1], based on the utilization of the spin of electrons, in addition to their charge, open up an entirely new era of electronics. Spins can be manipulated faster and with lower energy than charges [2]. The discoveries of giant magnetoresistance (GMR) [3] and tunneling magnetoresistance (TMR) [4] in metallic spin valves (SVs) and magnetic tunnel junctions (MTJ) have already found widespread applications in magnetic recording and memory. An SV is a layered structure of two ferromagnetic (FM) electrodes with different coercive fields ($H_C$) separated by a nonmagnetic spacer [5]. The spacer decouples the two FM electrodes and allows spin polarized (SP) carriers to travel through it without much relaxation. Traditionally, metals and inorganic semiconductors are used as the spacer material in SVs. However, a few factors like the spin scattering due to large atomic radii of the spacer materials (e.g. Ga, As and In) and scattering from the FM/spacer interface, limit the efficiency of such SVs to a certain level. One solution to the first problem could be the introduction of spacer materials made from lighter elements, e.g. carbon, that will also have spin-transporting capabilities. Following the success of $\pi$-conjugated polymers and organic materials for commercial electronic applications, they were considered a promising alternative for spin transport [6]. The weak spin–orbit and hyperfine interactions of organic semiconductor (OS) small molecules and conjugated polymers lead to the possibility of preserving spin–coherence over times and distances much longer than the conventional metals or semiconductors [7]. Furthermore, polymers are very attractive spacer materials due to their easy processibility and subsequent usage in large scale applications. The first experimental verification of room-temperature SP transport in vacuum-evaporated OS was done by Dediu et al [8] when they observed SP transport in a planar La$_{0.67}$Sr$_{0.33}$MnO$_3$ (LSMO)/sexithienyl ($T_6$)/LSMO device. Later, Xiong et al [9] found 40% GMR at a low temperature (11 K) in SVs made using a vacuum evaporated OS, 8-hydroxyquinoline aluminum (Alq$_3$), as the spacer and Petta et al [10] found 16% MR at 4.2 K in MTJs made using a self-assembled monolayer of a molecular barrier between nickel electrodes (Ni–octanethiol–Ni).

In our device structure we chose LSMO as the spin-injecting electrode because FM metals like Ni and Co give disordered and unstable structure in the polymer/FM interface [11] and have weak polarization of 30–40% [12]. LSMO is a half-metallic ferromagnet with nearly 100% spin polarization [13]. It is also a very stable oxide and forms a well-defined interface with the spacers. Both these facts led to very efficient spin injection from LSMO into the spacer. Moreover, the conductivity mismatch problem of FM metal and OS can be satisfactorily removed by the use of a half-metal. However, it was experimentally verified [14] that although the bulk spin polarization of LSMO is maintained above room temperature, the surface SP of LSMO starts decreasing at much lower temperature ($\sim 220$ K) and at room temperature the
amount of injected SP carriers from the LSMO electrode will be considerably lower. Earlier, we have also shown that with better spin injecting LSMO, the spin response of the polymeric SV (PSV) device improves only marginally as the LSMO-polymer interface loses most of the spin polarization at higher temperature. In this article, we investigate the role of inclusion of FM nanoparticles/clusters in the organic spacer layer. Due to the soft texture of the polymers, the top electrode metal (Co, Fe or Ni) penetrates deep inside the organic spacers during the device fabrication procedure and gives rise to an ill-defined spacer layer with magnetic impurities. Additionally, they could give rise to complicated features in the device spin response. A study of the literature shows that for the same LSMO/Alq3/LSMO device architecture, different SV responses were obtained by different groups [9, 16]. We believe that this discrepancy arises due to different device fabrication techniques leading to different spacer characteristics (with more or less top electrode penetration). In this article, we have investigated the effect of these magnetic impurities, i.e. Co pinholes, in the polymeric spacer layer by studying the MR switching response, and the bias and temperature dependence of the SV devices with varying amount of Co inclusions. We have fabricated PSVs with different evaporation rates of the Co counter-electrode, leading to two different kinds of device—one having much lower device resistance and linear I–Vs (set 1) and the other having much higher device resistance and nonlinear I–Vs (set 2). While both the device sets show appreciable MR response, switching is more defined and sharp in devices with fewer Co inclusions. The bias and temperature dependence of the PSV are thoroughly investigated, and the spin transport through the polymer spacers with and without magnetic impurities at different operating conditions of the devices is explained.

2. Experimental

The device structure is shown in the inset of figure 1(a). The LSMO films were made using the pulsed laser deposition technique as reported earlier [15]. After cleaning the LSMO films with acetone, we spin-coated the regio-random poly(3-hexyl thiophene) (RRaP3HT) films from a 10 mg ml\(^{-1}\) chloroform solution and annealed them at 80 °C for 10 h in a nitrogen-filled glove box. Finally, Co was vacuum-evaporated on top of the RRaP3HT films with two different rates of evaporation and an Al layer was evaporated on top of Co without breaking the vacuum and using the same mask to prevent oxidation of the Co film. The RRaP3HT film thicknesses of both sets of devices before the Co deposition, measured with AFM, were \(\sim 100\) nm. The effective thicknesses of the spacer were smaller due to penetration of Co into the film during evaporation. The Co was evaporated at 1.5–2 Å s\(^{-1}\) for the set 1 devices and at 0.2–0.5 Å s\(^{-1}\) for the set 2 devices. In both cases, the target was \(\sim 25\) cm away from the boat with the Co source. The effective thickness of the set 2 devices is found to be 70–80 nm from charge extraction by linearly increasing voltage (CELIV) measurements [17] while that of the set 1 devices did not give any accurate measure of the thickness using CELIV, indicating the absence of a clear polymer spacer between the two metal electrodes. The MR of the PSVs was measured using four probes, one pair of current and voltage leads connected to the LSMO, while the other pair were connected to the Al, varying the in-plane B between +300 and −300 mT and the temperature (T) between 5 and 300 K. AC conductivity of the set 2 samples was measured using the same geometry with a wave generator (Wavetek 114) and lock-in amplifier (SR 830).
3. Results and discussion

The $I–V$ curves for all the set 1 devices show a completely linear behavior (figure 1(a)), while those of the set 2 devices show a non-linear behavior maintaining symmetry for both forward (when positive bias is applied to LSMO) and reverse bias (figure 1(b)) for $T = 5–300$ K.

Earlier, we identified this linearity as due to the similarity of work functions [18], but later on it was found that although LSMO, Co and RRaP3HT have almost similar work functions and highest occupied molecular orbital (HOMO) level (5.1 eV), a small Schottky barrier exists in the FM/organic interface giving rise to nonlinearity in the $I–V$s. This is clearly observed in the set 2 devices where instead of metal inclusions a clean polymer layer still exists. We believe that the set 1 devices had Co penetration in the whole polymer layer during deposition and the ballistic transport through these embedded metal clusters inside the polymer acts as magnetic nanocontacts between the two FM electrodes. This plays an important role in the spin transport, especially at low temperature. This is also identified from the device resistance and the temperature dependence of it. The total device resistance per unit area ($R_S$) ($\sim 5 \times 10^5 \Omega \text{ cm}^{-2}$) for the set 1 devices and that for the set 2 devices ($\sim 4 \times 10^8 \Omega \text{ cm}^{-2}$) are a few orders of magnitude higher than the in-plane resistance per unit area of the LSMO bottom electrode ($\sim 4.17 \times 10^3 \Omega \text{ cm}^{-2}$). For 16 measured samples of set 1 and 6 of set 2, the $R_S$ varied within the range of $\pm 5\%$. Therefore, in the set 1 devices, the relative contributions from the two conduction channels should be considered—drift/diffusion through the polymeric spacer and ballistic SP transport through the pinhole nanocontacts [19] that connect the two FM electrodes. On the contrary, in the set 2 devices, the transport is mainly governed by drift/diffusion through RRaP3HT due to decreased Co penetration in the bulk. It has been shown earlier [20] that
Figure 2. Cross-sectional schematic diagram of the set 1 and set 2 devices showing different conduction channels for SP carriers in these two device sets. Curved arrows indicate hopping conduction through the clean polymer layer, while straight arrows indicate channels shorted by Co inclusions (set 1).

des these ballistic channels are magnetoresistive, and if the domain wall width at the nanocontact is sufficiently thin so that the spin does not have time to flip, then the ballistic spin-dependent transport becomes quite similar to the spin conserved tunneling in MTJs and can contribute sufficiently to the total MR response of the devices.

When $T$ is lowered to 5 K, $R_{SV}$ shows either a metallic behavior or semiconductor–metal transition (SMT) for different set 1 devices (figure 1(b), inset), while $R_{SV}$ increases by a few orders of magnitude for the set 2 devices. The SMT, observed in 80% of the set 1 devices, leads to an understanding that although all the set 1 devices are shorted, the transport does not always strictly follow the ohmic transport through the metal nanocontacts and there is still a considerable contribution from the parallel conduction channel through RRaP3HT, as shown in figure 2.

For set 2 devices, $R_{SV}$ increases with decreasing temperature until 84 K, indicating semiconductor-like behavior. At lower temperatures, this changes to metal-like behavior exhibiting decreasing $R_{SV}$ with decreasing temperature. Although the bottom LSMO electrode has a metal-like temperature dependence in the above-mentioned temperature range, the observed temperature dependence of the device resistance can be indicative of the fact that at very low temperatures tunneling transport sets in through the metal inclusions, thus decreasing the effective device resistance. However, as the $R_{SV}$ for set 2 devices is 5 orders of magnitude higher than the in-plane resistance of the bottom LSMO electrode, we can justifiably predict that in spite of Co inclusions, there exists an undoped polymeric layer in which the transport is dominated by carrier drift/diffusion.

The $H_C$ values of the LSMO and Co films measured at 5 K for their respective same film thicknesses were 26 and 10 mT, respectively [21]. So, the two electrodes become anti-parallel (AP) to each other between ±10 and ±26 mT and $R_{SV}$ shows a maximum in this region. The %MR is defined as $\frac{R_{SV_{\text{max}}}-R_{SV_{\text{min}}}}{R_{SV_{\text{min}}}} \times 100\%$, i.e. the maximum relative change in $R_{SV}$ within the SV hysteresis. However, the observed MR hysteresis loop is much broader than the difference in the coercive fields. The lower switching field matches well with the $H_C$ of Co but the higher switching field is much higher than the $H_C$ of LSMO. Yet another observation is that the switching is not very sharp in both set 1 and set 2 devices, as was observed earlier for regio-regular poly(3-hexyl thiophene) (RRP3HT) devices [21]. The additional magnetic anisotropy caused by the Co nanoclusters, which are randomly distributed inside the polymer matrix, plays an important role in this broadening. A similar type of enhanced upper switching field has previously
been observed in highly resistive inorganic MTJs. Qiang et al [22] have reported the SP electronic structure calculations of Co nanoclusters embedded in a Cu matrix and found that the magnetization of the Co clusters is lower than that of bulk Co. They ascribed this effect to the suppression of Co moments at the interface between the atoms in the matrix and clusters, which is often magnetically dead. So, while considering the switching phenomenon in our devices, we have to consider the anisotropy effect arising from the nanoclusters and, hence, the modified coupling between the top and bottom FM electrodes. The matching of the lower switching field in the MR indicates that the magnetic switching occurs when one of the electrodes switches its magnetization direction. The enhancement of the upper switching field indicates that some magnetic structures have much enhanced effective coercivity, which can be related to either the different switching fields of the Co clusters embedded in the polymer (as discussed above) or the charge trapping and scattering in the disordered polymeric spacer. The MR versus $B$ for set 1 and set 2 devices (figures 3(a) and (b), respectively) at 5 K show similar MR response for high
bias measurements. For both sets of devices, the MR increases rapidly with decreasing current. With low bias current, \( \sim 50\% \) MR was observed in most of the set 1 devices at 5 K, while some showed even \( \sim 160\% \) MR at 150 nA. The observed MR for set 2 devices was \( \sim 60\% \) at 5 K for low bias current. Widely varying MR in set 1 devices definitely indicates that without well-controlled top electrode evaporation it is impossible to make reproducible devices. The junction resistance of all the set 1 devices was \( \sim 10^5 \, \Omega \, \text{cm}^{-2} \) for all the measured currents, eliminating the possibility of observing experimental artifacts.

All the PSVs show a normal MR effect (\( (R_{SV})_{AP} > (R_{SV})_P \)) (see figure 3) for all temperature and bias currents, whereas an inverse MR effect was observed in our comparative measurements for LSMO/Alq3/Co devices, in agreement with the results reported by Xiong et al [9]. LSMO is always positively SP but Co can give positive or negative polarization depending on the modification of the end bonds at the spacer/Co interface [23]. At \( E_F \), the Co d-band is strongly negative-polarized, i.e. the density of states (DOS) of the ↑ spin sub-band is less than the ↓ spin sub-band DOS. So, the negative polarization of Co arises from the selection of d-band electrons, whereas the positive one is due to the selection of the s-band electrons. Additionally, figures 3(a) and (b) show that \( R_{SV} \) does not saturate in our devices even after the two electrodes are in the P configuration due to the negative high field MR effect of LSMO as also observed earlier in LSMO/OS SVs and diodes [24].

The efficiency of an SV depends mainly on spin injection and transport. Spin injection is strongly influenced by the FM LSMO/polymer interface and the defect sites created there. Ruden et al [25] predicted that a spin-selective tunnel barrier at the FM/organic interface could enhance spin injection. In our earlier study with RRP3HT PSVs [21], we showed that the chemical bonding between LSMO and RRaP3HT enhances spin injection in the device, thus showing almost 80% MR at 5 K for those devices.

For set 1 devices, we have observed additional bias-dependent features in the MR hysteresis loops. With decreasing bias, the MR increases. Devices having 6% MR for 1 mA at 5 K (figure 3(a)) increase to 160% MR for 150 nA at 5 K (figure 3(c)). Below a certain critical current (\( I_{C1} \)), two additional peaks appear at \( B = 0 \) for both increasing and decreasing \( B \). This type of complicated structure in the MR loop has previously been observed in low-resistance LSMO-based MTJs [26], but the authors could not provide any satisfactory explanation for the phenomenon. For our PSVs, the two additional peaks increase in height with decreasing \( I \) and eventually merge so that no hysteresis is visible below another critical current, \( I_{C2} \) (\( I_{C2} < I_{C1} \)). We note that this is a consistent behavior for all the set 1 RRaP3HT PSVs and cannot be negated as noise. Although the physical origin of this behavior is still not very well understood, our hypothesis is that this complicated switching originates from the increased spin relaxation near the magnetic impurities in the RRaP3HT spacer. Several mechanisms can be responsible for spin relaxation of conduction electrons [27] within the polymer spacer. Spins can relax via momentum scattering as suggested by the Elliot–Yafet mechanism when facing more scattering centers inside the spacers. In set 1 devices, higher amounts of included metal particles produce more FM metallic clusters inside the polymer compared with the set 2 devices. These metallic clusters produce energetic disorder in the system and cause trapping or scattering sites for the SP carriers. Once a carrier is trapped in such a site, these trapped polarized spins produce some local magnetic moments inside a magnetic field, increasing the inhomogeneity and disorder in the system. Bobbert et al [28] described spin diffusion in an OS as a combination of carrier hopping in a Gaussian DOS and spin precession around a local magnetic field. At each hopping site, the effective field is \( B_{eff} = B_{hf} + B \), where \( B_{hf} \) is the random hyperfine field at this site and \( B \) is the
Figure 4. The %MR versus measured current ($I$) for typical set 1 and set 2 devices at 5 K showing similar bias dependence of both types of device and higher MR response around zero bias. The inset shows the normalized differential conductance of one of the typical set 2 devices at 5 and 300 K, showing the absence of any discontinuity around zero bias.

applied magnetic field. Now, in the presence of the included metal ions and inhomogeneous distribution of magnetic clusters as in the set 1 devices, the effective magnetic field at each site is higher than the externally applied field. This leads to a gradual relaxation of SP carriers away from their initial spin direction and modification of the spin diffusion length inside the OS. So, in the PSV devices with more metal inclusions, spins can either relax via momentum scattering or due to spin precession around the phase-separated magnetic domains with high anisotropy. These relaxation effects can give additional higher resistance states in the set 1 devices. When measured with the smaller bias current, the SP electrons in set 1 devices travel with much lower drift velocity, and hence their probability of getting trapped or scattered at the defect sites increases while the parallel conduction channel through the nanocontacts remains unaffected. No additional peaks in the set 2 devices indicate much simpler charge/spin transport only by rift or diffusion.

Figure 4 shows the logarithmic change in MR in the PSVs with bias current. The bias dependence shows that MR is maximum close to zero current for both sets of PSVs. A small change in the bias current near zero changes the MR response drastically. The bias dependence of MR in previously reported LSMO/SrTiO$_3$/Co devices [29] shows a change in DOS at $E_F$ of the FM electrodes with applied bias, thus changing the magnitude and direction of spin polarization. A small change in the current cannot cause a similar change in the DOS at $E_F$ of the FM electrodes in our devices. It is more likely that at higher bias ‘hot electron’ transport through the polymer layer increases spin scattering and reduces the MR. For the set 1 devices, electrons travel ballistically through the pinhole shorts at low temperatures and bias. However, at higher bias, ‘hot electron’ transport through the pinholes results in heat dissipation within the nanocontact region just outside the ballistic channel [30] and thus increases the resistance. The
dissipated heat causes larger phonon DOS at the nanocontact, reducing the transmittivity even further. So, in the set 1 devices, the possibility of spin scattering at higher bias is even higher than that in set 2 devices. There is also an asymmetric bias dependence of MR in both types of PSVs (figure 4). The MR decays more slowly with positive current than negative current. However, the asymmetry is more in set 1 devices than set 2 devices. This asymmetric bias dependence was earlier observed for MTJs with LSMO and Co or CoFe electrodes [29, 31]. While both the reports agreed that the DOS at Fermi level for the two electrodes for an applied bias causes this asymmetric bias dependence, Hayakawa et al [31] suggested that the bias-voltage dependence of the TMR effect strongly depends also on the fabricating condition of the spacer. From our previous results [15, 21] and the present experimental observations, it can be concluded that the spacer layer and the spacer/FM interface are responsible for most of the spin loss in the device and different device behaviors can be observed depending on the fabrication conditions.

To verify that the observed phenomenon at low bias is not due to the dc offset effect, we measured the dynamic conductance ($dI/dV$) as a function of the bias voltage ($V_{dc}$) of the devices at 5 and 300 K (inset of figure 4). The devices were excited with both dc and ac voltages. A small ac voltage of 8 mV was used to sense the variation of the polarization as a function of $V_{dc}$. The conductivity minimum at low bias voltage is very smooth without any sharp peaks, which could be due to Co inclusions at the interface. Metallic clusters at the interface show a Coulomb gap in its low bias conductance [9] and the conductance minima relate to the effective capacitance of the inclusion cluster, which is roughly proportional to the cluster size. A distribution of such Coulomb gaps could smear out the sharp low bias cusp, producing a smooth minimum.

For both sets of devices, it is observed that MR decreases with $T$ when measured at high bias current (figure 5). Due to increased scattering at high temperatures with low currents, experimental accuracy was restricted by the high noise level. The monotonic decrease of MR response with increasing temperature in both sets of devices indicates that spin transport through the bulk of the polymer is similar for high bias measurements. In the absence of $T$ dependence of

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{The %MR as a function of temperature ($T$) for a certain measured current ($I$) for typical set 1 and set 2 devices showing similar decrease of MR response with increasing temperature.}
\end{figure}
MR data at low bias, we cannot see the effect of ballistic spin transport channels and additional higher resistance states at high temperatures in the set 1 devices. More experiments are needed to fully elucidate the temperature dependence of spin transport in the set 2 PSVs at low bias currents.

In conclusion, we have observed the GMR in both shorted and good RRaP3HT-based PSVs. Bias-current dependence of the PSVs is more asymmetric in nature in those devices with more Co inclusions. Below a critical bias current, a complicated $R-H$ loop was observed in Co contaminated PSVs, while no complicated lineshape was found with low bias currents for the good devices. In high bias current measurements, the MR switching response and the $T$ dependence of MR are unaffected by the spacer quality. At low bias, the metallic cluster-embedded polymer spacer leads to a very complicated spin transport phenomenon and should be avoided as much as possible in order to have better spin response and reproducibility. Finally, the present paper discusses an important practical difficulty in device fabrication (metal inclusion and shorted devices), compares the possible spin transport mechanism in both kinds of devices and conclusively proves that different fabricating conditions of the device can lead to completely different spin responses in PSV devices.

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**References**

[1] Prinz G A 1998 *Science* **282** 1660
[2] Sharma P 2005 *Science* **307** 531
[3] Baibich M, Broto J M, Fert A, Nguyen Van Dau F, Petroff F, Eitenne P, Creuzet G, Friederich A and Chazelas J 1988 *Phys. Rev. Lett.* **61** 2472
[4] Moodera J S, Kinder L R, Wong T M and Meservey R 1995 *Phys. Rev. Lett.* **74** 3273
[5] Tang C, Fontana R, Lin T, Heim D E, Speriosu V S, Gurney B A and Williams M L 1994 *IEEE Trans. Magn.* **30** 3801
[6] Davis A H and Busmen K 2003 *J. Appl. Phys.* **93** 7358
[7] Vardeny Z V, Heeger A J and Dodabalapur A 2005 *Synth. Met.* **148** 1
[8] Rocha A R, Garcia-suarez V M, Bailey S W, Lambert C J, Ferrer J and Sanvito S 2005 *Nat. Mater.* **4** 335
[9] Dediu V, Murgia M, Matacotta F C, Taliani C and Barbanera S 2002 *Solid State Commun.* **122** 181
[10] Xiong Z H, Wu D, Vardeny Z V and Shi J 2004 *Nature* **427** 821
[11] Petta J R, Slater S K and Ralph D C 2004 *Phys. Rev. Lett.* **93** 136601
[12] Tibb M V, Kurnosikov O, Flipse C F J, Koopmans B, Swagten H J M, Kohlhepp J T and de Jonge W J M 2002 *Surf. Sci.* **498** 161
[13] Ranno L, Llobet A, Hunt M B and Pierre J 1999 *Appl. Surf. Sci.* **138–139** 228
[14] Park J-H, Vescovo E, Kim H-J, Kwon C, Ramesh R and Venkatesan T 1998 *Nature* **392** 794
[15] Garcia V, Bubes M, Barthelemy A, Bowen M, Jacquet E, Contour J-P and Fert A 2004 *Phys. Rev. B* **69** 052403
[16] Majumdar S, Huhtinen H, Majumdar H S, Laiho R and Österbacka R 2008 *J. Appl. Phys.* **104** 033910
[17] Vinzelberg H, Schumann J, Elefant D, Gangineni R B, Thomas J and Büchner B 2008 *J. Appl. Phys.* **103** 093720
[18] Juška G, Arlauskas K, Viliūnas M and Kočka 2000 *Phys. Rev. Lett.* **84** 4946

*New Journal of Physics* **11** (2009) 013022 (http://www.njp.org/)
[18] Majumdar S, Majumdar H S, Laiho R and Österbacka R 2006 J. Alloys Compd. 423 169
[19] Mukhopadhyay S and Das I 2006 Phys. Rev. Lett. 96 026601
[20] Price E P, Smith D J, Dynes R C and Berkowitz A E 2002 Appl. Phys. Lett. 80 285
[21] Majumdar S, Majumdar H S, Laukkanen P, Väyrynen J, Laiho R and Österbacka R 2006 Appl. Phys. Lett. 89 122114
[22] Qiang Y, Sabirianov R, Jaswal S S, Liu Y, Haberland H and Sellmyer D J 1977 Phys. Rev. B 66 064404
[23] Teresa J M D, Barthélémy A, Fert A, Contour J P, Montaigne F and Seneor P 1999 Science 286 507
[24] Wu D, Xiong Z H, Li X G, Vardeny Z V and Shi J 2005 Phys. Rev. Lett. 95 016802
[25] Ruden P P and Smith D L 2004 J. Appl. Phys. 95 4898
[26] Sun J Z and Gupta A 1998 Annu. Rev. Mater. Sci. 28 45
[27] Žutić I, Fabian J and Das Sharma S 2004 Rev. Mod. Phys. 76 323
[28] Bobbert P A, van Oost F W A and Wohlgenannt M 2008 unpublished work
[29] Teresa J M D, Barthélémy A, Fert A, Contour J P, Lyonnet R, Montaigne F, Seneor P and Vaurés A 1999 Phys. Rev. Lett. A 82 4288
[30] Gurevich V L 1997 Phys. Rev. B 55 4522
[31] Hayakawa J, Ito K, Kokado S, Ichimura M, Sakuma A, Sugiyama M, Asano H and Matsui M 2002 J. Appl. Phys. 91 8792