Correlation of magnetoresistance and lateral photovoltage in Co$_3$Mn$_2$O/SiO$_2$/Si metal–oxide–semiconductor structure

H Wang$^{1,4}$, S Q Xiao$^1$, C Q Yu$^1$, Y X Xia$^1$, Q Y Jin$^2$ and Z H Wang$^3$

$^1$Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China
$^2$State Key Lab for Advanced Photonic Materials and Devices, Fudan University, Shanghai 200433, People’s Republic of China
$^3$Department of Physics, Nanjing University, Nanjing 210093, People's Republic of China
E-mail: huiwang@sjtu.edu.cn

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Abstract. Though separate studies on the individual properties of photovoltage and magnetoresistance (MR) have made much progress, work integrating the two phenomena into one kind of structure has not been reported so far. This study combines MR and lateral photovoltage (LPV) in a magnetic oxidized film Co$_3$Mn$_2$O deposited on a n-type Si substrate with a native ultrathin SiO$_2$ surface by sputtering. The effective resistance shows a marked transition for temperature around 240 K. Both negative MR $\{MR = [R(H) − R(0)]/R(0) \times 100\%\}$ of $-11\%$ at 4.2 K and a large positive MR of 70% at 300 K at a magnetic field of 6 T were observed. This phenomenon can be explained by the conducting channel switching from the upper film to the Si inversion layer. Under the nonuniform illumination of a laser beam, the LPV shows a high sensitivity to the spot position on the Co$_3$Mn$_2$O film plane. The current–voltage ($I$–$V$) characteristic of the Co$_3$Mn$_2$O/SiO$_2$/Si metal–oxide–semiconductor (MOS) structure exhibits rectifying $I$–$V$ behavior, which suggests that the lateral photoeffect (LPE) can be interpreted in terms of the metal–semiconductor (MS) junction that exists between the magnetic film and silicon substrate. When an external magnetic

$^4$Author to whom any correspondence should be addressed.
field is applied perpendicular to the film, the LPV shows a monotonic increase with increasing magnetic field. The variation of LPV reaches 93.2% at 2 T. This intriguing effect may be due to the Lorentz force acting on the photo-generated carriers.

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1. Introduction

Metal–oxide–semiconductor (MOS) structures with a native thin insulating layer less than 25 Å have been extensively studied as solar cell materials (transverse photovoltage) for many decades [1]–[6]. It has been well established that the mechanism of such MOS solar cells is similar to that of metal–semiconductor (MS) solar cells [1, 3], which is featured by the MS junction (Schottky barrier) formed between the metal and the semiconductor. Apart from the transverse photoeffect, MOS structures can exhibit another photoeffect: the lateral photoeffect (LPE) [7]–[9]. In our previous work, we have also observed the LPE in Co–SiO$_2$–Si MOS structures [10]. The key mechanism behind LPE can also be attributed to the MS junction. The relevant lateral photovoltage (LPV) on MS junctions can present a good output linearity versus excitation position [7]–[17] and can be utilized in a variety of optical transducers and sensors [18]–[21]. Usually, MS junctions present some problems: if the metal is a fast diffuser into the semiconductor at room temperature, the Schottky barrier will degrade in time. However, this problem can be avoided in MOS structures because the semiconductor surface is passivated with a thin oxide layer between the metal and the semiconductor [22].

Since the insulator is thin enough, tunneling through the insulator is the main transport mechanism [3, 23, 24]. According to the tunnel MOS theory [25, 26], the conductivity type of the semiconductor surface underneath the interfacial layer is easily inverted. A pseudo p–n junction is formed and the conversion of radiation to charge carriers occurs in the bulk of the base semiconductor [26]. Consequently, the semiconductor from the interface to bulk in such MOS structures can be divided into three regions: the inversion layer, depletion region and neutral region. The inversion layer of such an MOS structure, where a two-dimensional electron (or hole) gas forms at the surface of the semiconductor, can be a controllable conducting channel. As a result, the inversion layers show interesting effects such as metal–insulator transition at low temperature [27, 28] and magnetoresistance (MR) [29]–[34]. The most general application of this structure is the so-called MOS field-effect transistors (MOSFETs). Since both the LPV and the MR of inversion layers can be measured on the metal film side, it is possible to
integrate both effects into one kind of MOS structure using the same dimension configuration, and this makes the modulation between LPV and MR feasible.

Furthermore, in our previous work [10], we have proved that the LPV of such MOS structures is strongly influenced by the resistivity of the inversion layer, which can be affected by the external magnetic field (the MR effect of the inversion layer), so one can predict that it is possible to realize the magnetic field modulation of LPE. In this paper, we provide an unambiguous experimental study for the combination of MR with LPV that simultaneously occurred in an MOS structure of Co$_3$Mn$_2$O/SiO$_2$/Si deposited on an Si substrate. Also, the preliminary modulation of LPV by magnetic field in this structure is investigated.

2. Experimental details

The Co$_3$Mn$_2$O (21 Å) films were grown either on n-type Si(111) or on glass substrates by dc magnetron reactive sputtering. Experimental details are similar to [35]. Although our previous paper [35] did not mention the native oxide layer, we further confirm that Si substrates are covered with a thin native SiO$_2$ layer of about 1.2 nm as per transmission electron microscope (TEM) and x-ray photoelectron spectra (XPS) measurements.

Both these samples were scanned spatially with an He–Ne laser (3 mW and 632 nm) focused on a roughly 50 µm-diameter spot at the surface and without any spurious illumination (e.g. background light) reaching the samples. This beam was chopped and the resulting photovoltage was measured using standard lock-in techniques. All the contacts (less than 1 mm in diameter) to the films were formed by alloying indium and showed no measurable rectifying behavior.

The magnetization curves were measured by the vibrating sample magnetometer (VSM) option of the physical property measurement system (PPMS; Quantum Design). The magnetic field was applied perpendicular to the film plane. The resistivity ($\rho$) and MR of Co$_3$Mn$_2$O/SiO$_2$/Si were determined using current in the film plane (CIP) geometry four-terminal method on the film plane by PPMS. The topography of the Co$_3$Mn$_2$O film and the MOS structure were characterized by TEM. The composition of the oxidized film was analyzed by XPS.

3. MOS structure

In order to perform TEM measurements, we deposited a thick calibration film of about 30 nm on the same Si substrate (the studied sample is too thin to perform TEM measurements). A TEM cross section micrograph of the calibration MOS structure of Co$_3$Mn$_2$O (30 nm)/SiO$_2$/Si and a TEM planar-view image of the calibration Co$_3$Mn$_2$O film (30 nm) are shown in figure 1. The cross section micrograph gives a clear view of the three layers of the MOS structure. The native SiO$_2$ layer is estimated to be about 1.2 nm. The planar-view image shows that the films have a granular structure with particles less than 10 nm in diameter. Most of the particles are well separated, and a few of them touch each other.

The Co 2p, Mn 2p, O 1s and Si 2p spectra of Co$_3$Mn$_2$O/SiO$_2$/Si are shown in figure 2. As illustrated in figures 2(a) and (b), the binding energy of the Co 2p$_{3/2}$ and Mn 2p$_{3/2}$ peaks is located at 780.3 and 640.2 eV, respectively, which suggests that Co and Mn ions in the oxidized film are mainly in Co$^{2+}$ and Mn$^{2+}$ states. The Co 2p$_{3/2}$ and Mn 2p$_{3/2}$ main peaks have the satellite structure on the higher-binding-energy side separated by ~7 and ~6 eV, respectively, and this
is consistent with other reports [36]–[38]. In the Si 2p3/2 spectrum, the peak located at 99.5 eV comes from the bonds between Si and Si, while the peak at 103.5 eV comes from the bonds between Si and O, indicating that the Si surface is oxidized and the Co3Mn2O film and SiO2 layer are so thin that XPS can explore the Si signal from the substrate.

4. Magnetic properties

Figure 3(a) shows magnetization curves for Co3Mn2O/SiO2/Si and Si substrates at various temperatures. As seen both the magnetization curves at 300 and 4.2 K for Co3Mn2O/SiO2/Si exhibit a slope at high magnetic fields and another magnetic component at low fields. The high field slope is mainly due to a diamagnetic contribution from the Si substrate, as illustrated by the open symbols representing measurements on Si substrate without deposition. The $M$–$H$ curves (see figure 3(b)) of Co3Mn2O/SiO2 (glass) measured at both 4.2 and 300 K show a hysteresis loop with the coercive field ($H_c$) of 74 and 105 Oe, respectively. This clear hysteresis loop indicates that there is obvious ferromagnetic behavior for Co3Mn2O/SiO2. As we know, the Neel temperatures of MnO and CoO are 122 and 291 K, respectively [39]. At temperatures above 291 K, both MnO and CoO exhibit paramagnetism. Therefore the origin of the room-temperature ferromagnetism must be from unoxidized magnetic metal granules including Co and Mn. When the diamagnetic signal from the Si substrate is subtracted, the magnetization curves of Co3Mn2O/SiO2/Si are in excellent agreement with those of Co3Mn2O/SiO2.

The electrical transport properties of Co3Mn2O/SiO2/Si were measured from 4.2 to 300 K using PPMS. As shown in figure 4, the resistance shows an abrupt drop at about 240–280 K.
A similar transport behavior has been reported in other MOS structures [31]–[34]. This phenomenon can be explained by the conducting channel switching between the upper film and the Si inversion layer formed at the Si interface, characteristic of the MOS structures. At room temperature, the native Si oxide layer is transparent to electrons; the electrons in the magnetic film can be emitted into the Si inversion layer by thermal excitation [40]. Since the inversion layer is expected to have a much lower resistivity, it should dominate almost the entire current. When the temperature is decreased, the thermal excitation, and thus the number of electrons emitted to the Si inversion layer, decreases exponentially. The current will be mainly carried by the granular film, which has a higher resistance.

According to the above discussion, it is reasonable to infer that the temperature dependence of the resistivity between 4.2 and 240 K is mostly due to the Co$_3$Mn$_2$O film. Below 10 K, $\rho$ increases greatly and $\ln \rho$ is nearly proportional to $T^{-1/2}$ (the inset of figure 4), which is characteristic of tunneling conductance in granular systems [41, 42]. A similar relation of $\ln \rho$ versus $T^{-1/2}$ at low temperatures has also been observed in another granular system of CoAlO [43].

Figure 5 shows the MR (MR = $[R(H) - R(0)]/R(0) \times 100\%$) of Co$_3$Mn$_2$O/SiO$_2$/Si with the magnetic field applied perpendicular to the film at various temperatures. At 300 K,
Figure 3. Magnetization curves for (a) Co$_3$Mn$_2$O/SiO$_2$/Si and Si substrates and (b) Co$_3$Mn$_2$O/SiO$_2$ (glass) at various temperatures.

our sample shows a large positive MR of 70% at a field of about 6 T. As the temperature decreases, the MR reduces rapidly. At 250 K, the maximum of this positive MR reduces to about 4%. Eventually, the MR becomes negligible within the accessible range of $0 < H < 6$ T at a temperature from 240 to 50 K. At temperatures below 50 K, however, both positive and negative MRs can be observed. At 4.2 K, the MR is positive in a relatively weak field and a maximum of about 0.4% is observed around 4500 Oe. Then, with increasing magnetic field, the MR changes swiftly to negative and reaches $-11\%$ at a field of 6 T. At a temperature from 4.2 to 40 K, the magnetic field dependence of MR behaves qualitatively similar to that of the MR at 4.2 K, and furthermore, the positive MR is almost the same but the negative MR
Figure 4. Temperature dependence of resistivity ($\rho$) for Co$_3$Mn$_2$O/SiO$_2$/Si. The inset shows $\ln \rho$ as a function of $T^{-1/2}$ at low temperatures.

decreases significantly with increasing temperature. When the magnetic field $H$ is applied parallel to the plane of the Co$_3$Mn$_2$O film, however, the insignificant positive MR disappears, as shown in the inset of figure 5.

Now we turn to analyze the temperature-dependent MR. The large positive MR around room temperature has been reported in many MOS-like structures [31]–[34]. Dai et al [33] have systematically studied the metal/SiO$_2$/Si structure and obtained the largest MR of about 18% at 9 T. However, when the metal layer was replaced by the magnetic compound Fe$_3$C, an MR as large as 45% at 7 T can be achieved [34]. In our case, the magnetic granular film Co$_3$Mn$_2$O used as the metal layer has realized an excellent switching effect and quite a large MR value. Therefore, the positive MR can be attributed to the high-mobility holes in the Si inversion layer [30, 44] and originates from the Lorentz force acting on the holes. According to the channel switching effect, the Co$_3$Mn$_2$O film will play a more and more important role in the effective conductivity of the sample when the temperature decreases. This positive MR effect should therefore become less pronounced for relatively lower temperatures, as observed. This positive MR disappears at 240 K, which is in good agreement with the transition temperature.

Below 240 K the current flows predominantly in the Co$_3$Mn$_2$O film, which hints that both the negative MR and the insignificant positive MR are due to the magnetic granular film. The low-temperature negative MR has always been observed in granular systems, such as CoAlO systems [43], CoO-coated Co cluster assemblies [45], Fe–MgF$_2$ films [46] and so on. Usually, the negative MR should be proportional to the square of magnetization, i.e. $\Delta \rho/\rho_0 \propto (M/M_s)^2$ [47, 48], where $M$ and $M_s$ are the magnetization varied as a function of $H$ and the saturation magnetization, respectively. According to this relation, the negative MR should saturate as the field reaches a certain value. But the negative MR in figure 5(b) increases
Figure 5. MR measurements at (a) high temperatures and (b) low temperatures with the magnetic field applied perpendicular to the film for Co$_3$Mn$_2$O$_4$/SiO$_2$/Si. The inset shows the MR at low temperatures with the magnetic field applied parallel to the film plane.
Figure 6. $I-V$ curve of the Co$_3$Mn$_2$O/SiO$_2$/Si MOS structure at room temperature. The dashed curve represents the function: $I = 0.1 \times \{\exp(eV/kT) - 1\}$. The inset shows the schematic circuit of the sample measurement.

greatly and exhibits a very hard saturation trend with increasing field until 6 T. As mentioned above, the transport mechanism is tunneling, so the MR is most probably correlated with the alignment of the spins at the surfaces/interfaces of the particles. Because of the pinning effect of surface defects and the large surface anisotropy, the moments at the surface of the magnetic nanoparticles are hard to align to the applied field direction. Therefore, the negative MR increases with the field to 6 T with a difficult saturation trend.

Since the small positive MR vanishes when $H$ is applied parallel to the film plane, the low-temperature negligible positive MR at a relatively weak magnetic field in figure 5(b) is most probably caused by the rotation of spins from its original in-plane direction to the perpendicular direction. The maximum of the MR may correspond to the ‘knee’ of magnetization.

5. LPE

The $I-V$ characteristic of the Co$_3$Mn$_2$O/SiO$_2$/Si MOS structure was measured with a pulse-modulated current source at room temperature. According to the thermionic emission theory [49], the current $I$ for an applied voltage $V$ of an ideal MS junction is given by

$$I = I_0 \{\exp(eV/kT) - 1\},$$

where $e$ is the electron charge, $k$ the Boltzmann constant and $T$ the absolute temperature. We show the $I-V$ characteristic of our experimental result compared with the theoretical function $I = 0.1 \times \{\exp(eV/kT) - 1\}$ in figure 6. The $I-V$ behavior of our sample exhibits
Figure 7. (a) A three-dimensional schematic illustration of the LPV measurement using fixed electrodes and a variable light spot position; (b) a three-dimensional plot of the LPV as a function of the laser spot in the $\text{Co}_3\text{Mn}_2\text{O}$ film plane for $\text{Co}_3\text{Mn}_2\text{O}/\text{SiO}_2/\text{Si}$. A and B in (b) correspond to the positions illustrated in (a).

good nonlinearity and rectifying $I$–$V$ behavior, which is the main feature of most MS junctions. However, the current of the experimental result grows far more slowly than the theoretical value as the forward (positive) applied voltage increases, indicating that the forward characteristic increases more slowly than $\exp(eV/kT)$. This is consistent with Crowell and Sze [50] and Smith’s [51] theoretical prediction, where they ascribed it to the effect of the insulating interfacial layer between the metal and the semiconductor.

A three-dimensional schematic illustration of the LPV measurement geometry is shown in figure 7(a). Figure 7(b) shows the three-dimensional exterior view of the LPV as a function of the laser position in the $\text{Co}_3\text{Mn}_2\text{O}$ film plane. The LPV shows an approximately linear dependence as the spot is scanned along the lines $y = $ constant in the $\text{Co}_3\text{Mn}_2\text{O}$ film plane, becoming null at the midline $x = 0$. The photovoltage sign reverses when the laser spot is moved across the center line between the two contacts. The signal is roughly plane symmetric on a plane normal to the $y$-axis at $y = 0$. Usually, only the LPV as a function of the laser spot scanned along the line between two ohmic contacts is often discussed. This is because the LPV obtained in this way can achieve the highest position sensitivity and an excellent linearity. The dependence of the LPV on the position of light scanned along the line $y = 0$ is shown in [35]. The largest open-circuit position sensitivity, which means the variation of the output voltage for one unit displacement of the laser spot, is about 34.3 mV mm$^{-1}$. In other studies, the reported highest position sensitivity is about 1.5 mV $\mu$m$^{-1}$ in Ti/Si amorphous superlattices prepared by molecular beam epitaxy [14]. However, in layered structures, such as MS devices, the position sensitivity can only reach a maximum of about 20 mV mm$^{-1}$ [16]. For the other sample deposited on glass, however, there is no obvious LPV observed.
In general, the LPV in such MOS structures can be ascribed to the MS junction. Since the Si surface is inverted in such MOS structures, a pseudo p–n junction is formed between the inversion layer and the neutral region. In other words, the key mechanism behind this LPV can be attributed to the pseudo p–n junction, which results in the formation of a depletion region in the semiconductor region. As illustrated in figure 8, when the light impinges at one point on the surface, the radiation absorbed in the substrate generates hole–electron pairs. The minority holes in the neutral region are swept into the inversion layer, and the minority electrons in the inversion layer move to the neutral region. Because the structure is only partially illuminated by a laser pulse, the presence of the injected carriers will give rise to a nonequilibrium distribution, generating a gradient between the illuminated and the nonilluminated zones. So the excess holes in the inversion layer and the excess electrons in the neutral region move laterally away from the illuminated spot. If the lateral distance of the laser spot from each electrode is different, then the quantity of the collected carriers at the two contacts will be different. A lateral field is therefore set up, in addition to the LPV.

6. Modulation of LPV by magnetic field

According to the above discussions about the magnetic properties and the LPE, we can conclude that both MR and LPV have a strong relationship with the inversion layer. On the one hand, the carriers in the inversion layer can be strongly affected by an external magnetic field applied perpendicular to the film due to the Lorentz force (the MR effect of the inversion layer). On the other hand, the diffusion of photo-generated carriers that results in the LPV partially occurs in the inversion layer. Therefore, it may be possible to modulate LPV by using an external magnetic field and we focus on this in this section.
Figure 9. MR (with the magnetic field perpendicular to the film) and LPV as functions of magnetic field ($H$) for Co$_3$Mn$_2$O/SiO$_2$/Si at room temperature. The inset of (b) shows the schematic measurement of LPV with the magnetic field perpendicular to the film and an He–Ne laser continuously incident on one electrode.

A representative sketch of LPV and effective resistivity as functions of magnetic field for Co$_3$Mn$_2$O/SiO$_2$/Si at room temperature is shown in figure 9. Because of the experimental condition confinement, the power of the laser applied to this configuration is limited to only 0.5 mW and the external magnetic field can only reach a maximum of 2 T. Consequently, the LPV is relatively smaller than that shown in figure 7 by using a 3 mW He–Ne laser. As seen, the LPV shows quite a similar dependence on magnetic field to the effective resistivity. However, the relative variation of LPV [defined as $(\text{LPV}(H) - \text{LPV}(0))/\text{LPV}(0) \times 100\%$] at 2 T is about 93.2%, which is almost one order of magnitude larger than the MR value of 13.3% (the relative variation of resistivity). This fantastic phenomenon can be explained as follows: as discussed in
the LPE part, the LPV is partially due to the diffusion of the injected holes in the inversion layer. When an external magnetic field is applied perpendicular to the inversion layer, the injected holes will undergo a spiral movement due to the Lorentz force during the diffusion course from A to B. Then, less holes will arrive at contact B and the difference of the quantity of the collected carriers at the two contacts becomes larger accordingly. Therefore, the LPV increases monotonically with the applied magnetic field. The similar dependence of LPV and MR on magnetic field further supports our interpretation. However, the rate of variation of LPV with magnetic field is much larger than that of MR, and the detailed reason remains unclear and needs further investigation.

7. Conclusions

In summary, both a large positive MR of more than 70% at 300 K and a negative MR of −11% at 4.2 K were found at a magnetic field of 6 T for an MOS structure of Co$_3$Mn$_2$O/SiO$_2$/Si grown by reactive sputtering. The conducting channel-switching mechanism was introduced to interpret the transport and magnetotransport properties. Interestingly, besides the MR, a large LPV that depends in a linear way on the incident light spot position in the film plane was observed. The largest open-circuit position sensitivity was about 34.3 mV mm$^{-1}$. Furthermore, when an external magnetic field is applied perpendicular to the film, the LPV shows a monotonic increase with increasing magnetic field. The variation of LPV reaches 93.2% at 2 T. The variation rate of LPV with magnetic field is quite remarkable and may open the prospect of wide applications such as novel sensors. We believe that this work can inspire further work and promises much opportunity for future applications of MR incorporating photovoltage, such as double-control devices that are sensitive to both magnetic field and light.

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References

[1] Card H C and Rhoderick E H 1971 J. Phys. D: Appl. Phys. 4 1589
[2] Charlson E J and Lien J C 1975 J. Appl. Phys. 46 3982
[3] Lillington D R and Townsend W G 1976 Appl. Phys. Lett. 28 97
[4] Godfrey R B and Green M A 1979 Appl. Phys. Lett. 34 790
[5] Srivastava A K, Guha S and Arora B W 1982 Appl. Phys. Lett. 40 43
[6] Kumar A, Rosenblum M D, Gilmore D L, Tufts B J, Rosenbluth M L and Lewis N S 1990 Appl. Phys. Lett. 56 1919
[7] Aguas H, Pereira L, Costa D, Fortunato E and Martins R 2005 Opt. Mater. 27 1088
[8] Aguas H, Pereira L, Costa D, Fortunato E and Martins R 2005 J. Mater. Sci. 40 1377
[9] Aguas H, Pereira S, Costa D, Barquinha P, Pereira L, Fortunato E and Martins R 2007 Thin Solid Films 515 7530
[10] Xiao S Q, Wang H, Yu C Q, Xia Y X, Lu J J, Jin Q Y and Wang Z H 2008 New J. Phys. 10 033018
[11] Willens R H 1986 Appl. Phys. Lett. 49 663
[12] Levine B F, Willens R H, Bethea C G and Brasen D 1986 Appl. Phys. Lett. 49 1537
[13] Levine B F, Willens R H, Bethea C G and Brasen D 1986 Appl. Phys. Lett. 49 1608
[14] Willens R H, Levine B F, Bethea C G and Brasen D 1986 Appl. Phys. Lett. 49 1647
[15] Henry J and Livingstone J 2001 J. Mater. Sci.: Mater. Electron. 12 387
[16] Henry J and Livingstone J 2004 Appl. Phys. Lett. 39 2584
[17] Henry J and Livingstone J 2001 Adv. Mater. 13 167
[18] Kaufmann K J 1997 Photon. Spectra 31 167
[19] Buhler D W, Oxland T R and Nolte L P 1997 Med. Eng. Phys. 19 187
[20] Kim J, Kim M, Bae J H, Kwon J H, Lee H and Jeong S 2000 Appl. Opt. 39 2584
[21] Park W S and Cho H S 2002 Opt. Eng. 41 860
[22] Ague H, Pereira L, Ferreira I, Ramos A R, Viana A S, Andreu J, Vilarinho P, Fortunato E and Martins R 2004 J. Non-Cryst. Solids 338–340 810
[23] Card H C and Yang E S 1976 Appl. Phys. Lett. 29 51
[24] Shewchun J, Singh R and Green M A 1977 J. Appl. Phys. 48 765
[25] Pufley D L 1978 IEEE Trans. Electron Devices 25 1308
[26] Shewchun J, Burk D and Spitzer M B 1980 IEEE Trans. Electron Devices 27 705
[27] Popovic D, Fowler A B and Washburn S 1997 Phys. Rev. Lett. 79 1543
[28] Kravchenko S V, Kravchenko G V and Fureneaux J E 1994 Phys. Rev. B 50 8039
[29] Bagwell P F, Park S L, Yen A, Antoniades D A, Smith H I, Orlando T P and Kastner M A 1992 Phys. Rev. B 45 9214
[30] Overend N, Nogaret A, Gallagher B L, Main P C, Henini M, Marrows C H, Howson M A and Beaumont S P 1998 Appl. Phys. Lett. 72 1724
[31] Pakhomov A B, Denardin J C, de Lima O F, Knobel M and Missell F P 2001 J. Magn. Magn. Mater. 226–230 1631
[32] Carvalho H B, Brasil M J S P, Denardin J C and Knobel M 2004 Phys. Status Solidi a 201 2361
[33] Dai J, Sinhu L, Wang K, Malkinski L and Tang J 2000 J. Phys. D: Appl. Phys. 33 L65
[34] Tang J, Dai J, Wang K, Zhou W, Ruzycki N and Diebold U 2002 J. Appl. Phys. 91 8411
[35] Xiao Q, Wang H, Zhao Z C and Xia Y X 2007 J. Phys. D: Appl. Phys. 40 5580
[36] Mizokawa T, Nambu T, Fujimori A, Fukumura T and Kawasaki M 2002 Phys. Rev. B 65 085209
[37] Lee G and Oh S-J 1991 Phys. Rev. B 43 14674
[38] Okabayashi J, Ono K, Mizuguchi M, Oshima M, Gupta S S, Sarma D D, Mizokawa T and Fujimori A 2004 J. Appl. Phys. 95 1373
[39] Morrish A H 1965 The Physical Principles of Magnetism (New York: Wiley)
[40] Markiewicz R S and Harris L A 1981 Phys. Rev. Lett. 46 1149
[41] Abeles B, Sheng P, Coputts M D and Arie Y 1975 Adv. Phys. 24 407
[42] Sheng P, Abeles B and Arie Y 1973 Phys. Rev. Lett. 31 44
[43] Mitani S, Fujimori H and Ohnuma S 1997 J. Magn. Magn. Mater. 165 141
[44] Dobrovolsky V and Krolevets A 1999 J. Appl. Phys. 85 1956
[45] Peng D L, Sumiyama K, Yamamuro S, Hihara T and Konno T J 1999 Appl. Phys. Lett. 74 76
[46] Furubayashi T and Nakatani I 1996 J. Appl. Phys. 79 6258
[47] Chein C L, Xiao J Q and Jiang S 1993 J. Appl. Phys. 73 5309
[48] Mitani S, Takahashii S, Takanashi K, Yakushiji K, Maekawa S and Fujimori H 1998 Phys. Rev. Lett. 81 2799
[49] Henisch H K 1957 Rectifying Semiconductor Contacts (Oxford: Clarendon)
[50] Crowell C R and Sze S M 1966 Solid-State Electron. 9 1035
[51] Smith B L 1969 PhD Thesis University of Manchester

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