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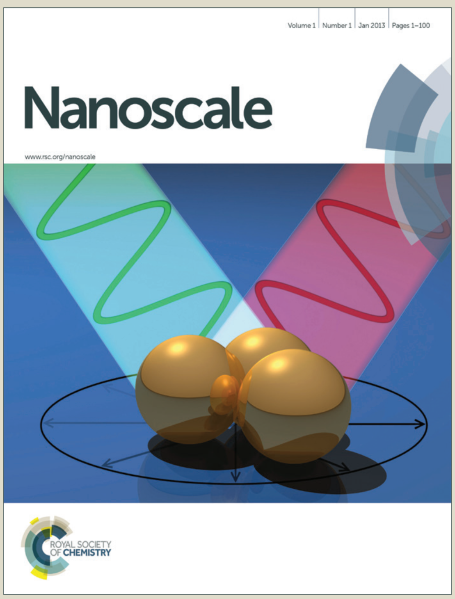

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ARTICLE TYPE

Angular dependence of the magnetoresistance effect in silicon based *p-n* junction device

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We report a pronounced angular dependence of the magnetoresistance (MR) effect in silicon based *p-n* junction device at room temperature by manipulating the space charge region of *p-n* junction under the magnetic field. For the *p-n* junction device with various space-charge region configurations, we find that all the angular dependence of MR effect is proportional to $\sin^2(\theta)$, where the θ is the angle between the magnetic field and driving current. With increasing the magnetic field and driving current, the anisotropic MR effect is obviously improved. At room temperature, under magnetic field 2 T and driving current 20 mA, the MR ratio is about 50%, almost one order of amplitude larger than that in magnetic material Permalloy. Our results furnish an interpretation of the MR effect in the non-magnetic *p-n* junction in terms of the Lorentz force and give a new way for future magnetic sensors with non-magnetic *p-n* junction.

1 Introduction

The control and manipulation of the electron charge and spin by magnetic field in semiconductor electronic devices are central aspect of spintronics.[1] It will have a profound impact on existing and emerging semiconductor industry. Recently such magnetic field-controlled semiconductor electronics has become possible by utilizing the large MR effect in non-magnetic semiconductor material, such as AgAs,[2,3] GaAs,[4] InSb[5] *et al*, which combines the traditional electronic technology with current magnetronic technology naturally.

From the application view of point, silicon can be considered as an ideal magnetic field-controlled semiconductor material, because it is fully compatible with the current CMOS technology and long spin coherence, as well as the low-cost.[6] Despite of the low carrier mobility in silicon, the MR ratio in silicon at room temperature still has been reported much larger than that in magnetic material, by tunneling injection,[7,8] inhomogeneity scattering,[9-10] density fluctuation[12] and current jetting.[12] In contrast with the MR effect in magnetic materials that results from spin-dependent transport of carriers,[13] this large MR effect in silicon derives from the deformation of current paths in inhomogeneous conductors. That causes an uncompensated Hall field to be involved in the transverse MR effect.[14-19]

As an extension of the single doped silicon material with large MR effect, the *p-n* junction device based on silicon is an excellent platform for future magneto-electronics in the semiconductor industry. This is because that the *p-n* junction structure can be considered as a typical electron and hole coexistence system. Due to the opposite sign of the carrier mobility between the electron and the hole, the fluctuation of the carrier mobility in *p-n* junction becomes very large and subsequently enhances the MR effect significantly.[14,15] Although the geometry-enhanced MR might be caused by the incorrect measrument method,[11,20] we also note that a *p–n* boundary could still enhance MR in certain circumstances according to our and others' theoretical calculations and experiments.[19,21] More importantly, an intrinsic space charge region in *p-n* junction can be formed at the interface between the *p* and *n* semiconductors. One possible way to enhance the magnetotransport properties is to design and manipulate the intrinsic space charge region of the *p-n* junction under the magnetic field. In our previous work, we have shown that control the space charge region configurations by magnetic field, instead of external electric field, can efficiently affect the transport properties in *p-n* junction.[21] Owing to the intrinsic space charge region, the large MR effect in *p-n* junction has a small driving voltage only 6 V, while in the doped silicon a large voltage 60 V should be provided to observe an appreciable MR effect. Furthermore, the *p-n* junctions are fundamental elements in modern semiconductor, so the large MR effect in *p-n* junction can be more easily integrated into the modern semiconductor electronics. Very recently, by utilizing the InSb *p-n* junctions with large MR effect, the magnetic-field-controlled reconfigurable semiconductor logic has been proposed and demonstrated, which indicates a new kind of spintronic device based on the non-magnetic semiconductor.[22]

However, until now few experiments have been found to systematically study the angular dependence of these magnetotransport characteristics of non-magnetic semiconductor. The lack of such magnetic field orientation to control MR effects significantly limits the applications of non-magnetic materials. Moreover, the anisotropic magnetotransport properties of non-magnetic semiconductor can help us further understand the mechanism of these unusual MR properties of the *p-n* junction.

In this work, we investigate the angular dependence of the magnetotransport characteristics in silicon based *p-n* junction device with various space charge region configurations. A pronounced anisotropic MR effect in silicon based *p-n* junction device, one or two orders of amplitude larger than that in

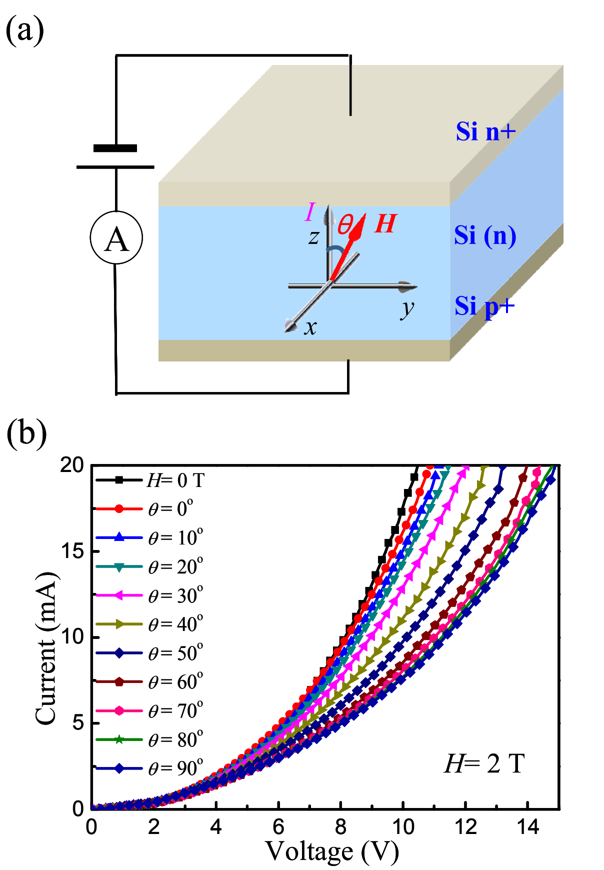

Fig. 1 (a) Schematic illustration of the *p-n* junction device structure and measurement sketch. (b) The *I-V* characteristics under magnetic field H= 2 T at various angel θ from 0° to 90°.

magnetic material, is observed at room temperature. Interestingly, the detailed dependence of the *p-n* junction resistance on the angle θ between the direction of current and the magnetic field can be all fitted well with the $\sin^2(\theta)$. This is also the same angular dependence observed in magnetic material, e.g. Permalloy, despite the mechanisms between them are completely different. These results are promising for the development of the future magnetoelectric devices based on non-magnetic semiconductors.

2 Experiment

The samples were fabricated by the MEMS (Micro Electro Mechanical Systems). The wafers were lightly doped with 10^{12} atom/cm^3 *n*-type dopant to achieve a good surface resistivity higher than 2000 Ω·cm. An oxidation film with a thickness of 6000 Å was grown on the wafers in the oxidation furnace at 1030 □ for 4 hours. After that, the micro-strip patterns were transferred to the wafers by a lithography machine. Then the wafers were further treated with a boron implantation（40 Kev，2×10^{14} atom/cm^3）at top surface and a phosphorus implantation（60 Kev，1×10^{15} atom/cm^3）at back surface by a medium-energy ion implanter. Finally the Cu electrodes at the top and bottom were sputtered separately with the high vacuum 3×10^{-5} Pa.

In order to show how the space-charge region affects the magnetotransport characteristics in *p-n* junction, the voltage between the top and bottom of samples were applied to cause the current I perpendicularly pass though the space-charge region, as shown in Fig. 1a. By rotating the sample holder, the orientation of magnetic field H applied to the device could be controlled to measure the anisotropic MR effect. The MR ratio was defined as $(\rho_H - \rho_0)/\rho_0$, where ρ_H and ρ_0 are the resistivities with and without the magnetic field, respectively. Here we used the Keithley 2400, 220, and 2000 as the voltage source, the current source and the voltage (current) meter, respectively. For the data in Fig.1b, Fig. S1a, Fig. S2a and Fig. S3, we applied the voltage and measured the current under different magnetic field. For the data in Fig.3, Fig. S1b, Fig. S2b and Fig. S4b, we used the current source for a specified current and measured the voltage as a function of the orientation of magnetic field.

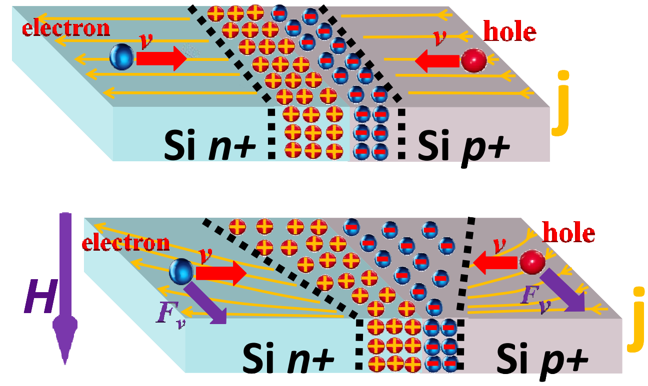

Fig. 2 Schematic illustration of the origin of large MR effect in *p-n* junction due to the spatial distribution of space-charge region induced by the magnetic field. (a) An uniform distribution in space-charge region is formed when the electronic field is applied. (b) A trapezoidal distribution in space-charge region is formed due to the Lorenz force when the magnetic field is applied. The carriers are deflected due to the space-charge region geometry variation.

3 Results and discussion

Fig. 1a shows the schematic illustration of the *p-n* junction device structure and the related measurement diagram. In contrast to the magnetodiode with lateral geometry,[23] the structure Si(*p*+)/Si(*n*)/Si(*n*+) with vertical geometry is chosen to form a wide space-charge region. At room temperature the carrier densities of Si(*p*+), Si(*n*), and Si(*n*+) were 2.0×10^{14} cm^{-3} , 1.0×10^{12} cm^{-3} and 1.0×10^{15} cm^{-3}, respectively. Thus, the width of formed space-charge region in Si(*p*+) and Si(*n*+) are about 100 nm, but the width in Si(*n*) is 22 µm, which critically depends on the intrinsic competition between the diffusion process and the built-in electric field. The thickness of *n* region is about 400 µm.

Fig. 1b shows the typical *I-V* characteristics of the *p-n* junction device for various magnetic field orientations at room temperature. All the *I-V* curves exhibit the obvious rectifying features due to the space-charge region formed in the *p-n* junction. The *I-V* characteristics can be described by the Shockley equation. In contrast, in the reported single doped silicon device the *I-V* characteristics obey the Ohm's law at the low electric field and the Mott-Gurney law at the high electric field.[10] However, when the external magnetic field amplitude and orientation are changed, the transport characteristics in the *p-n* junction is also obviously modulated. In the case of the zero-magnetic field *I-V* curve, the junction current is about 20 mA at V = 10 V. As the external

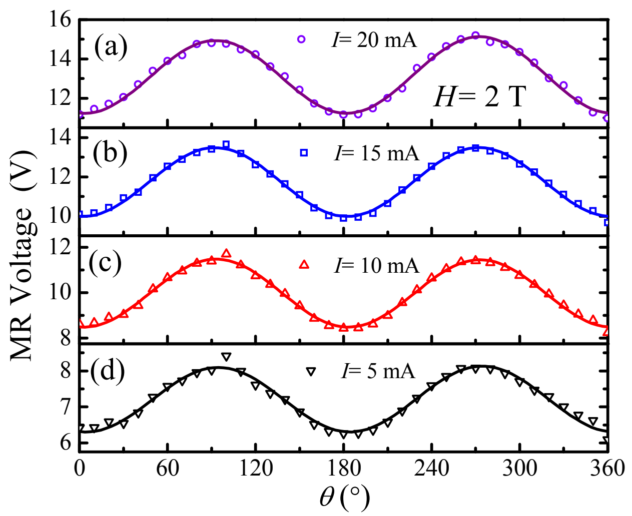

Fig. 3 (a-d) The angular dependence of measured MR voltage at specified current (a) 20 mA, (b) 15 mA, (c) 10mA and (d) 5mA with magnetic field H=2 T. The anisotropy MR curves fitted with the $\sin^2(\theta)$ are shown by the solid lines

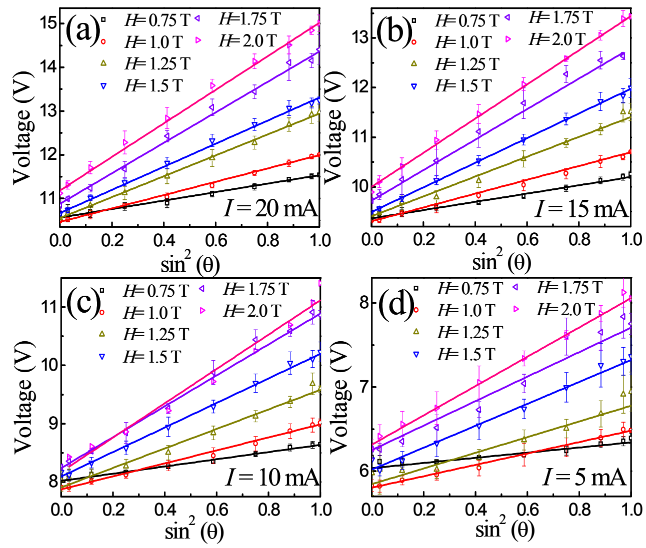

Fig. 4 (a-d) Angular dependence of the measured MR voltage in a wide magnetic field range at a specified current (a) 20 mA, (b) 15 mA , (c) 10 mA, (d) 5 mA. The lines are fitted by equation (1)

magnetic field is applied, a pronounced current suppression effect occurs, and increases with the increase of θ from 0° to 90°. This indicates a large anisotropic MR effect in the *p-n* junction. Remarkably, one can also find that anisotropy MR effect strongly depends on applied current or voltage. The anisotropy MR effect is more significant in the larger current or voltage level. When the applied voltage and the magnetic field are increased to 10 V and 2 T, respectively, the anisotropic MR ratio can reach about 160% at room temperature. We also noted that in the single doped silicon at room temperature the MR ratios were above 1000% at 3T and around 350% at 0.5 T with large voltage bias 70V.[10] Schoonus et al also observed large MR effect in single doped silicon at room temperature, in which the highest MR ratio could be reach above 1000% at 1.26 T with voltage 80 V.[7] Although the MR ratio in our p-n junction is lower than that of single doped silicon at room temperature, the MR effect of p-n junction has a small driving voltage(< 10 V) owing to the intrinsic space charge region, which has an advantage for future application.

Below we will analyze the underlying mechanism in Fig. 1. The MR effect in *p-n* junction in our work is much more complicated than that in the materials worked in the linear transport region.[24] Obviously, the transport characteristics in the *p-n* junction are dominated by the space-charge distribution. When the width of space-charge region is changed by the external electric field, the resistance of *p-n* junction can vary in the range of several orders of amplitude, also known as the rectifying effect. Based on the similar mechanism mediated by the electric field, we further consider how the intrinsic space-charge region of *p-n* junction evolves under the external magnetic field. When the magnetic field is applied, the carriers in *n*-type and *p*-type region are deflected by the Lorentz force and accumulated at the edges of the sample (Fig. 2). As a result, a trapezoidal distribution in space-charge region is formed to balance the Lorentz force. Therefore similar to the rectifying effect under the electric field, the spatial distribution in space-charge region under the external magnetic field can also drastically affect the junction resistance.[21] According to the classical *p-n* junction transport equations, the carrier concentrations in such trapezoidal space charge region have an exponential distribution in order to balance the Lorentz force. In this situation the drift force formed by the carrier concentration gradient compensates the Lorentz force, instead of the Hall voltage in the uniform semiconductor, Although the carrier concentrations are redistributed and shown the exponential distribution under the magnetic field, the total numbers of carriers are the same for the uniform distribution without the magnetic field and the trapezoidal distribution with magnetic field both. In order to keep the total number of carriers conserved, this means the diffusion barrier in some part of the device is lowered while other part is raised. However, considering the exponential distribution of the carrier concentrations, one can easily get that the raised part of space charge region is one or two orders of amplitude larger than the lowered part. As a result, the total resistance of *p-n* junction still increases based on the calculation. This is also consistent with our results.

Obviously, the mechanism in our *p-n* junction device contrasts to that in previous magnetodiode with a similar *p(+)-n-n(+)* structure.[23] The MR effect in previous magnetodiode results from magnetic control of carrier concentration gradient due to the different recombining surfaces and shape ratios. As a result, the correspoinding MR ratio behaves distinct with respect to the sign of applied magnetic field. Here the large MR effect of the *p-n* junction which is due to the space-charge region geometry variation can be ascribed to three possible mechanisms: The first is referred to the *p-n* junction barrier change, where the magnetic field controls the MR effect via changing the tunnel carrier concentrations through the *p-n* junction. The second is that the so-called current trajectory deflected (or current jetting effect) due to the space-charge region geometry variation in *p-n* junction. This mechanism directly involves the Hall voltage into the transverse MR effect. Interestingly, due to such space-charge region geometry, the Hall effect here is uncompensated and could be adjusted with the deformation of space-charge region. The final one is that *p-n* junction can be considered as the electron and

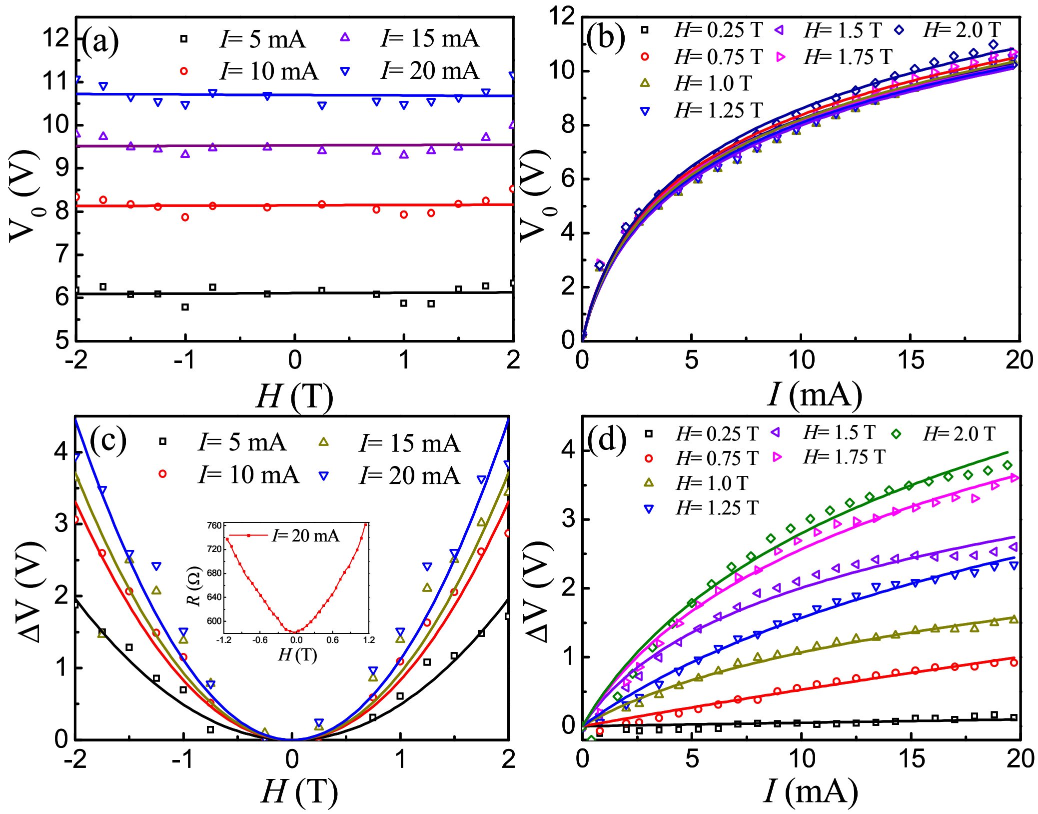

Fig. 5 (a) V_0 as a function of magnetic field *H* at various current from 5 mA to 20 mA. (b) V_0 as a function of current *I* at various *H* from 0.25 T to 2 T. The solid lines were fitted by Shockley equation. (c) ΔV as a function of magnetic field *H* at various current from 5 mA to 20 mA. The solid lines were fitted by parabola. Inset shows the typical MR curve at *I*= 20 mA. (d) ΔV as a function of current *I* at various *H* from 0.25 T to 2 T. The solid lines were fitted by Shockley equation.

hole coexistence model, proposed by Parish and Littlewood, where the MR effect of *p-n* junction critically depends on the carrier mobility fluctuations due to the inverse carrier mobility between the electron and hole carriers.[14,15] Because the current level in *p-n* junction is directly related to the the space charge region, we could measure the anisotropic MR effect via setting the different current levels to represent the various space-charge region configurations in *p-n* junction device.

The corresponding anisotropic MR curves at specified current levels are presented in Fig. 3. The measured MR voltages for various current levels show a strong anisotropy with two-fold symmetry at room temperature. The minimum value is found both at 0^o and 180^o, where the magnetic field is in parallel with the current. While the maximum value is found at 90^o and 270^o, where the magnetic field is perpendicular to the current. Interestingly, for various space charge regions by setting different current levels, the voltage as a function of angle θ can be fitted well by the equation as

$$V=V_0(I,H)+\Delta V(I,H)\times\sin^2(\theta), \quad (1)$$

where the fitted parameters V_0 and ΔV depend on the applied current *I* and the magnetic field *H*. The fitted results are shown as the solid lines in Fig. 3. Again, the anisotropic MR effect is obviously improved with increasing the applied current level, demonstrating that the MR ratio is more sensitive to the magnetic field in the narrower space charge region. We also measured the *I-V* curves at the negative bias. But no obvious MR effect was observed at the negative bias, which is consistent with the conclusion at the positive bias, as shown in Fig. S3. However, we also note that for the single doped silicon the MR properties are symmetric at both positive and negative bias.[7-10,12]

In order to further confirm the anisotropic MR of the *p-n* junction, we measured the angular dependence of MR curves with magnetic field in the range of 0.25 T to 2 T at a specified current level. As shown in Fig. 4, the anisotropic MR effect drastically decreases, as the magnetic amplitude decreases at a fixed current level. However, for different magnetic field amplitudes, all the anisotropic MR curves still fit the equation (1) well, as shown in Fig. 4. This indicates the magnetic field induced anisotropic MR effect in a wide range of current level and magnetic field stems from the unified mechanism. The various space charge region manipulated by current and magnetic field only affects the fitted parameter values in equation (1). We also observed an angular independent MR as noted in Fig.4. The angular independent MR effect might stem from the defects, dislocations or electrical inhomogeneities that scatter the carriers.

Although the anisotropic MR behavior in *p-n* junction has a similar relationship to that usually observed in the ferromagnetic materials, the mechanisms behind them are totally different. The anisotropic MR effect in ferromagnet is due to the intrinsically anisotropic spin-orbit coupling of conduction electrons. However, silicon based *p-n* junction contains no magnetic moments, a spin-mediated mechanism seems unlikely. Furthermore, at room temperature for magnetic field 2 T and current 20 mA, the anisotropic MR ratio of *p-n* junction in our work is about 50%, which is almost one order amplitude larger than that of Permalloy. Obviously, the anisotropic MR effect of *p-n* junction follows the angular dependence of the Lorentz force acting on the carriers. The behavior that MR ratio is proportional to the $H^2\sin^2(\theta)$ here can be usually understood by the second-order magnetic deflection effect, in which the drift current I_z is deflected twice ($I_z \rightarrow I_x \rightarrow I_z$) due to the Lorentz effect by H_y. This is because the energy of the carriers in the semiconductor is dispersive, the Hall electric field can not completely cancel the the deflection of carriers, thus induce a positive MR effect. However, such MR ratio in silicon is usually two orders lower than that reported in silicon based *p-n* junction due to the low carrier mobility of silicon. Here the large anisotropic MR ratio in silicon based *p-n* junction mainly stems from the amplification effect by the change of the space charge region under the magnetic field. This asymmetry distribution of space-charge region which is indicated by the different energy barrier distribution, can significantly enhance the current deflection toward the lower energy barrier. As a result, similar to the geometry MR effect induced by the sample shape ratio, the MR effect in *p-n* junction is directly related to the geometry of space-charge region induced by magnetic field.

It is also very important and necessary to compare our MR devices with the reported dilute magnetic semiconductors.[25-27] Indeed, a large MR effect at room temperature was also observed in p-(In,Mn)As/n-InAs heterojunctions. Although it has a similar *p-n* junction structure, the origin of MR effect differs from that of silicon based on *p-n* junction here. For diluted magnetic semiconductors the large MR effect is still obviously observed even if the magnetic field applied parallel to the flow of current.[25] More importantly, for nonmagnetic InAs *p-n* junction (without the Mn doped), the MR ratios at both 78 and 295 K are less than 0.3%.[26] These results indicate that the large MR effect in the dilute magnetic semiconductors stems from the carrier scattering due to the fluctuations and clustering of the Mn ions at or near the junction. However, for nonmagnetic silicon based on *p-n* junction, a large MR effect with a $\cos^2$ dependence on the angle between the current and magnetic field can be attributed to the Lorentz force.

In addition, in order to check the other possible mechanism of anisotropic MR in *p-n* junction, such as anisotropy of the Fermi surface,[28] anisotropy of orbit,[10] and geometric anisotropy[29] *et al*, we also carefully rotated the magnetic field in the x-z plane and x-y plane to measure the anisotropic MR effect (see the supplementary). For x-z plane, the similar results were observed, while for x-y plane there is no obvious anisotropic MR effect as the magnetic field is always perpendicular to the measured current. This further indicates the anisotropy MR effect in *p-n* junction is mainly related with Lorentz force that depends on the current and magnetic field orientation.

Obviously, the equation (1) was found to be successful to fit all data in a wide range of magnetic field and current level. This allowed us to extract the $V_0(I, H)$ and $\Delta V(I, H)$ for each current and magnetic field. Fig. 5 shows the magnetic field and current dependence of the $V_0(I, H)$ and $\Delta V(I, H)$. As shown in Fig. 5a and 5b, V_0 is almost independent on the magnetic field H, but strongly related to the current. A similar Shockley equation of the idealized *p-n* junction can well describe the data in Fig. 5b, demonstrating that the transport behavior of *p-n* junction is dominated by the space-charge region. The weak magnetic field response for V_0 indicates that the anisotropic MR effect of *p-n* junction is mainly caused by ΔV , which is angular-dependent and strongly depends on both applied current I and magnetic field H. Fig. 5c shows that the ΔV has a parabolic external magnetic field dependence, which is also consistent with the measured MR curves, as shown in the inset of Fig. 5c. Note that the MR behavior in the *p-n* junction that related to H^2 differs from that in the single doped silicon, which has a linear relationship with the H due to the inhomogeneity MR effect.[10] In Fig. 5d, we plot the ΔV as a function of the current for various magnetic field. For a fixed magnetic field, the behavior can also be fitted by the Shockley equation, but as the space-charge region becomes narrower at the higher current level, the ΔV is drastically enhanced, demonstrating the modulation of space charge region by the electric field. In another view, for a specifed current, the ΔV also increases with the increase of the magnetic field H, demonstrating the modulation of space charge region by the magnetic field.

4 Conclusions

We report a novel anisotropic MR effect in non-magnetic *p-n* junction by manipulating the space-charge region with the magnetic field. This anisotropic MR behavior under a wide range of current and magnetic field can be fitted well by the $\sin^2(\theta)$. The analysis based on the fitted parameter reveals that the MR effect stems from the geometry change of space charge region induced by magnetic field. Because this anisotropy MR effect of silicon based *p-n* junction not only has the same behavior with that in magnetic materials, but also the magnetic ratio is one order amplitude larger than that in magnetic materials, this novel anisotropy MR could open a new way for future magnetic sensors with non-magnetic materials based on *p-n* junction.

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Notes

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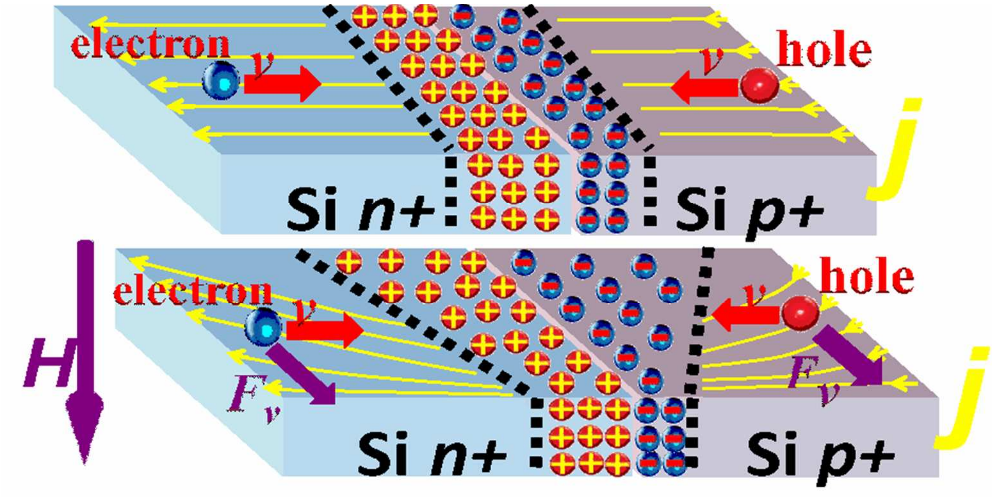
† Electronic Supplementary Information (ESI) available: [**S.** 1(a) shows the *I-V* characteristics of the *p-n* junction device for various magnetic

field orientation in the x-z plane at room temperature. **S.**1(b) shows the corresponding anisotropic MR curves at specified current *I* =20 mA. **S.** 2 shows the *I-V* characteristics of the *p-n* junction device while the magnetic field is applied in the x-y plane. S. 3 shows the *I-V* curves at negative bias with various magnetic field. S. 4(a) shows the *I-V* curves of the sample in various electrodes without magnetic field. The size of the sample is 2.9 mm×2.26 mm. And the thickness is 0.14 mm. S.4(b) shows the hall voltage in sample n region for the current *I* =0.01 mA.].

References

1 H. Ohno, *Science*, 2001, **291**, 840-841.
2 R. Xu, A. Husmann, T. F. Rosenbaum, M. L. Saboungi, J. E. Enderby and P. B. Littlewood, *Nature*, 1997, **390**, 57-60.
3 J. S. Hu, T. F. Rosenbaum and J. B. Betts, *Phys. Rev. Lett.* , 2005, **95**, 186603.
4 Z. G. Sun, M. Mizuguchi, T. Manago and H. Akinaga, *Appl. Phys. Lett.* , 2004, **85**, 5643-5645.
5 S. A. Solin, T. Thio, D. R. Hines and J. J. Heremans, *Science*, 2000, **289**, 1530-1532.
6 R. Jansen, S. P. Dash, S. Sharma, and B. C. Min, *Nat. Mater.* , 2012, **11**, 400-408.
7 J. J. H. M. Schoonus, P. P. J. Haazen, H. J. M. Swagten and B. Koopmans, *J .Phys. D .Appl. Phys*, 2009, **42**, 185011.
8 J. J. H. M. Schoonus, F. L. Bloom, W. Wagemans, H. J. M. Swagten and B. Koopmans, *Phys. Rev. Lett.* , 2008, **100**, 127202.
9 M. P. Delmo, S. Kasai, K. Kobayashi and T. Ono, *Appl. Phys. Lett.* , 2009, **95**, 132106.
10 M. P. Delmo, S. Yamamoto, S. Kasai, T. Ono and K. Kobayashi, *Nature*, 2009, **457**, 1112-1116.
11 C. H. Wan, X. Z. Zhang, X. L. Gao, J. M. Wang and X. Y. Tan, *Nature*, 2011, **477**, 304-308.
12 N. A. Porter and C. H. Marrows, *Scientific Reports*, 2012, **2**, 565
13 S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnar, M. L. Roukes, A. Y. Chtchelkanova and D. M. Treger, *Science*, 2001, **294**, 1488-1495.
14 M. M. Parish and P. B. Littlewood, *Nature*, 2003, **426**, 162-165.
15 M. M. Parish and P. B. Littlewood, *Phys. Rev. B*, 2005, **72**, 094417.
16 J. Hu, M. M. Parish and T. F. Rosenbaum, *Phys. Rev. B*, 2007, **75**, 214203.
17 R. Magier and D. J. Bergman, *Phys. Rev. B*, 2006, **74**, 094423.
18 V. Guttal and D. Stroud, *Phys. Rev. B*, 2005, **71**, 201304.
19 M. P. Delmo, E. Shikoh, T. Shinjo, and M. Shiraish, *Phys. Rev. B* ,2013, **87**, 245301.
20 J. Luo, P. Li, S. Zhang, H. Sun, H. P. Yang and Y. G. Zhao, *Nature,*2013, **501**, E1.
21 D. Z. Yang, F. C. Wang, Y. Ren, Y. L. Zuo, Y. Peng, S. M. Zhou and D. S. Xue, *Adv. Funct. Mater.* , 2013, **23**, 2918-2923.
22 S. Joo, T. Kim, S. H. Shin, J. Y. Lim, J. Hong, J. D. Song, J. Chang, H. W. Lee, K. Rhie, S. H. Han, K. H. Shin and M. Johnson, *Nature*, 2013, **494**, 72-76.
23 T. R. Mcguire and R. I. Potter, *IEEE Trans. Magn.* , 1975, **11**, 1018.
24 D. R. Baker and J. P. Heremans, *Phys. Rev. B* ,1999, **59**, 13927
25 S. J. May and B. W. Wessels, *Appl. Phys. Lett.* , 2006, **88**, 072105.
26 S. J. May and B. W. Wessels, *J. Vac. Sci. Technol. B* , 2005, **23**, 1769 -1772.
27 J. A. Peters, N. D. Parashar, N. Rangaraju, and B. W. Wessels, *Phys. Rev. B* ,2010, **82**, 205207
28 Z. W. Zhu, A. Collaudin, B. Fauqué, W. Kang and K. Behnia, *Nat. Phys.* , 2011, **8**, 89-94.
29 Z. J. Yue, I. Levchenko, S. Kumar, D. H. Seo, X. L. Wang, S. X. Dou and K. K. Ostrikov, *Nanoscale*, 2013, **5**, 9283-9288.



The new MR effect in the non-magnetic p-n junction due to the space-charge region modulated by the external magnetic field.
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