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Large magnetoresistance effect in nitrogen-doped silicon

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In this work, we reported a large magnetoresistance effect in silicon by ion implantation of nitrogen atoms. At room temperature, the magnetoresistance of silicon reaches 125 % under magnetic field 1.7 T and voltage bias -80 V. By applying an alternating magnetic field with a frequency (f) of 0.008 Hz, we find that the magnetoresistance of silicon is divided into f and $2f$ two signal components, which represent the linear and quadratic magnetoresistance effects, respectively. The analysis based on tuning the magnetic field and the voltage bias reveals that electric-field-induced space-charge effect plays an important role to enhance both the linear and quadratic magnetoresistance effects. Observation as well as a comprehensive explanation of large MR in silicon, especially based on semiconductor CMOS implantation technology, will be an important progress towards magneto-electronic applications. © *2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [http://dx.doi.org/10.1063/1.4972795]

Recently the large magnetoresistance (MR) effects in non-magnetic semiconductor materials, such as $Ag_{2+\delta}Se$,[1] GaAs,[2] Ge[3–5] and Si,[6–10] *etc*. are widely reported. In contrast with the conventional semiconductor MR theory, the MR effects in these non-magnetic semiconductor materials are large, linear and unsaturated. These advantages make these non-magnetic materials be considered as ideal candidates for future magnetotronics, however a fully compatible with the current CMOS technology method to achieve the large MR effects in nonmagnetic materials is still lacking,[11] which limits the further application of these non-magnetic materials.

Here we implanted nitrogen atoms into the intrinsic silicon to develop silicon based magnetoelectronics and observed a large MR effect at room temperature. We systematically studied the MR in doped silicon by applying an alternating magnetic field with a frequency of 0.008 Hz. In all devices obvious linear and quadratic MR effects were observed. By analyzing the f and $2f$ MR signals with voltage bias from −80 V to 80 V and magnetic field range from −1.7 T to + 1.7 T, the linear MR was considered as an uncompensated Hall field due to the inhomogeneous distribution of implantation ion, and the quadratic MR was explained by the second-order magnetic deflection effect. The experimental data showed that the space-charge effect significantly enhanced these two MR effects at high electric field. Because the large MR in silicon was realized by strictly controlling the doping nitrogen atoms into the intrinsic silicon, our work provided a simple and universal method to fabricate silicon-based MR devices.[12–16]

We chose the (110)-oriented silicon substrate with resistivity 250 $M\Omega \cdot m$ to implanted nitrogen atoms. The experimental work was carried out at the 320 kV platform for multi-discipline research with highly charged ions at the Institute of Modern Physics, Chinese Academy of Sciences. The implantation energy was fixed at 40 kV and the depth of ion implantation was about 200 nm. The doped concentration was controlled by the implantation time. After implantation, four electrodes

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of Ta were sputtered on the corners of implanted surface of silicon with high vacuum 3×10^{-5} Pa. The electrical resistivities of our samples without magnetic field were measured in clover-leaf van der Pauw geometry. The magnetic field was applied in-plane and perpendicular to the current. Electrical resistances with alternating magnetic field were measured with a two-terminal arrangement on samples of Pt electrode/sample/Pt electrode. Keithly 6221 and keithly 2182 were used as current source and voltage meter in our experiment. Here we use the devices with the nitrogen concentration 2×10^{15} atom/cm^3 to demonstrate MR behavior of implanted silicon with resistivity about 1 k$\Omega \cdot m$. The size of the devices are 3 mm $\times$ 3 mm $\times$ 0.5 mm.

Figure 1 presented the waveform of the magnetic field we applied, which was fitted well with sinusoidal function with the amplitude 0.3 T and the frequency 0.008 Hz. The corresponding response to the sample resistance at voltage 80 V and −80 V are shown in Fig. 1b and 1c, respectively. It is clear to see that the time dependence of resistance is divided into f and $2f$ two signal components, which are fitted very well as following equation:

$$R = R_0 + R_{lin} \cdot H + R_{quad} \cdot H^2, \tag{1}$$

where the first, the second and the third terms represent the resistance without the magnetic field, the linear MR and quadratic MR, respectively. The corresponding MR ratio is defined as $[R(H)/R(0) - 1] \times 100\%$, where $R(H)$ and $R(0)$ are the resistance with and without the magnetic field, respectively. It should be interesting and necessary to compare MR effect in our sample with large MR reported in the previous works.[17–20] As shown in Fig. 1, the linear MR at bias voltage 80 V is 0.5 %, while the linear term of MR at bias voltage −80 V is −4.1 %. One can easily find that R_{lin} in our experiments occurs at low magnetic field and changes the sign at the ±80 V. As a typical characteristic of nonmagnetic materials with large MR, the linear MR effect is usually caused by two mechanisms. The one is the quantum theory of MR effect,[20] which is that the individual quantum levels associated with the electron orbits are distinct. For silicon, this effect can be ruled out. The other is the model of inhomogeneity conductors,[17,18] in which such inhomogeneities could produce large spatial fluctuation in the conductivity tensor and large MR effect. However, in contrast with the R_{lin} in our experiments, the linear MR effect due to inhomogeneity conductors usually occurs at the large magnetic field and

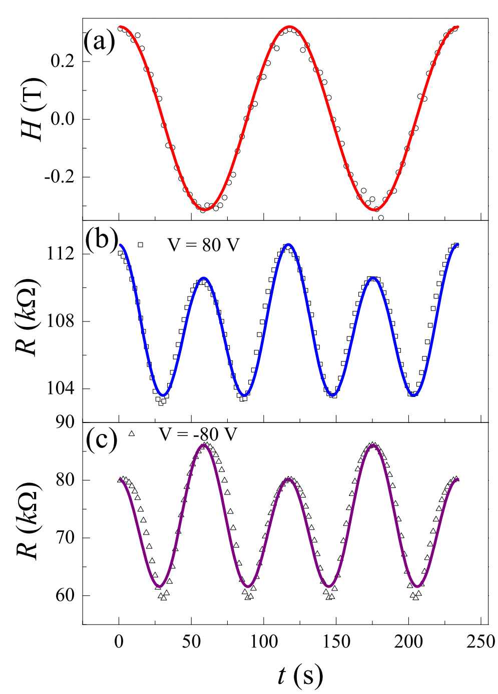

FIG. 1. (a) Waveform of the magnetic field we applied with the amplitude 0.3 T and the frequency 0.008 Hz. (b) and (c) are the corresponding response of the sample resistance at driven voltage 80 V and −80 V, respectively. All curves are fitted by Eq(1).

should be symmetry with respect to the sign of the voltage bias. Due to the sign changed of R_{lin} at ±80 V in our experiment, the direct Hall effect should be involved to R_{lin}. According to the Eq. 1, at +80 V and −80 V the Hall coefficient are $3{\times}10^2$ cm^3/C and $2.7{\times}10^3$ cm^3/C, respectively. This is in reasonable agreement with the Hall coefficient ($2.94{\times}10^3$ cm^3/C) measured by Hall experiment. However, the absolute values of the Hall coefficient for ±80 V are not equal. This result indicates that the linear MR effects based on inhomogeneity conductors might contribute to R_{lin}. The quadratic terms of MR at bias voltage 80 V and −80 V are 4.8 % and 9.5 %, respectively. The quadratic MR effect is usually considered as ordinary MR, the value of MR could be calculated by the equation[7,21] $MR = (\mu H)^{\,2} = (R_{quad}/R_0)^{\,1/2}$. Considering the carrier mobility $\mu = 321$ $cm^2/(\text{V}\cdot\text{s})$ measured by the Hall experiment, the quadratic MR should be 0.01% which is two orders of magnitude less than the experimental result 1.6% at 1 V and 0.3 T. The extremely large quadratic MR in our experiments suggests a new mechanism, which may be related with the ion implantation method.

To further explore the origin of the large MR effect of implanted silicon, we compared the measured MR curves to the calculated results according to Eq. 1, where the fitted parameters we used are same with that in Fig. 1(c). The large MR effect strongly depends on the voltage we applied. For bias voltage -80 V, the MR curves do not obey with the Eq. 1. With further increasing magnetic field beyond 0.5 T, the MR becomes gradually saturated($\mu H > 1$). This result seems consistent with the ordinary magnetoresistance (OMR).[22] While, the MR curve at the voltage bias 1 V still obeys well with the Eq. 1 even at magnetic field 1.1 T ($\mu H < 1$), as shown in Fig. 2(b). We explain the MR with respect to the voltage as space charge effect occurred at the higher voltage. Interestingly, the space change effect was usually reported to enhance the linear MR in previous uniform doping silicon,[9] here we noticed that the space-charge effect also significantly enhanced the quadratic ordinary MR. This might stem from the doping inhomogeneity with ion implantation.

Figure 3 shows MR curves at a wide bias voltage range from −80 V to +80 V. The color represents the values of resistance. This color map shows three features. Firstly,the resistance at zero magnetic field decreases with the increasing voltage. The detailed values of R_0 as a function of the voltage were shown in Fig. 4(a), by fitting the curves in Fig. 3. One can find that the R_0 is not the constant in the whole voltage range, which is caused by the contact barrier. Secondly, there is an asymmetric distribution of resistance with magnetic field. This is consistent with the existence of the hall effect (R_{lin}) as we

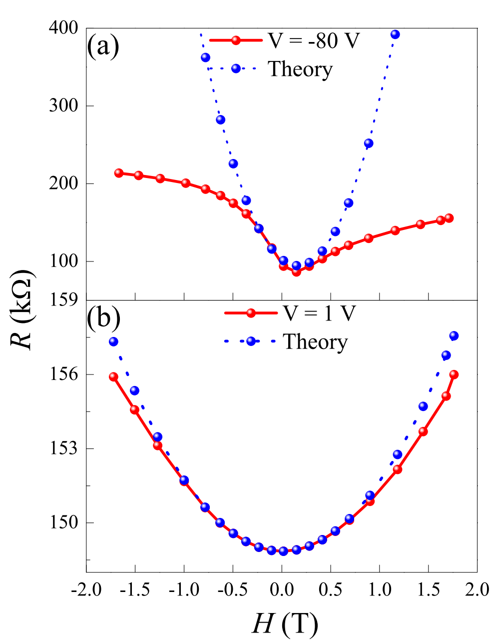

FIG. 2. The MR curves of nitrogen-doped silicon at 300 K under voltage bias −80 V (a) and 1 V (b). The experiment and calculation results are shown as the red dots lines and blue solid lines, respectively.

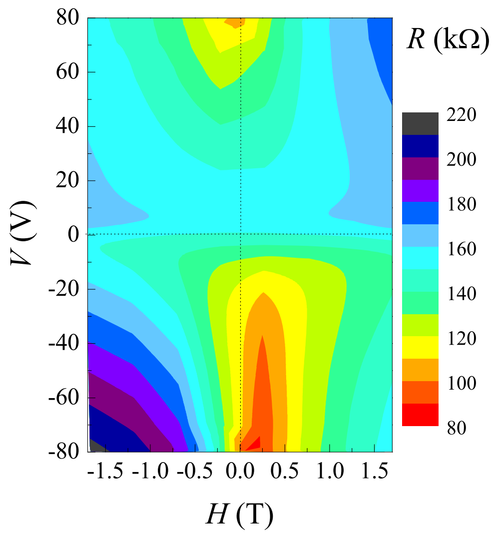

FIG. 3. The resistance R as a function of both bias voltage V and magnetic field H. R is indicated by a color bar on the right and ranges between 85 $k\Omega$ and 220 $k\Omega$. The measurement geometry was in in-plane vertical magnetic field.

discussed before. Fig. 4(b) shows an asymmetric distribution of R_{lin} when voltage changed. Finally, the gradient distribution of resistance shows that the MR is saturated at large field. The saturated MR is the characteristic of OMR which we believe the quadratic MR in our experiment be. The quadratic MR is shown in Figure 4(c). Because R_{quad} increased with the bias voltage, the result indicates that the electric-field-induced space-charge effect enhanced not only the linear MR but also the quadratic MR. This may be associated with the inhomogeneous distribution of impurity ions in nitrogen-doped silicon.

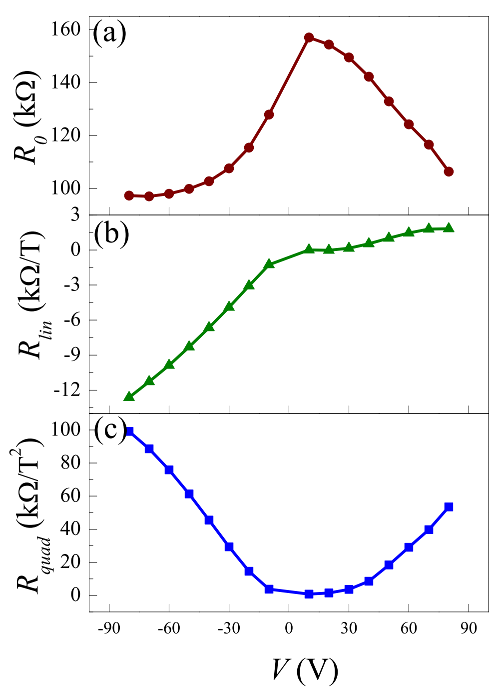

FIG. 4. Voltage dependence of the intrinsic resistance(a), the linear resistance(b) and the quadratic resistance(c). The asymmetric curves are derived from the the preparation of the contact.

In summary, we provide a simple and universal method to fabricate silicon-based MR devices. The MR behavior in these devices under various voltages and magnetic fields can be divided well into linear and quadratic MR. The analysis based on the fitted parameters reveals that the quadratic MR effect stems from the electric-field-induced space-charge effect and the linear MR is explained by the Hall effect due to the inhomogeneous distribution of implantation ion. This method to fabricate silicon-based MR devices could help understand the mechanism of the MR effect in non-magnetic semiconductor materials at room temperature.

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