Large nonlinear Hall effect in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions

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The large nonlinear Hall effect was found in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions formed by sputtering amorphous p -type $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ magnetic semiconductor films on near intrinsic n -type Ge substrate. It is very interesting that the mechanisms of the large nonlinear Hall effect in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions are different at different temperature ranges. Below 10 K, the Hall resistance of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions is almost the same as the anomalous Hall effect of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ ferromagnetic films. While the temperature increased from 10 to 60 K, the nonlinear Hall resistance, longitudinal conductance, and magnetoresistance all increased quickly and reached the maximum at $T = 60$ K. In this case, thermally excited conducting carriers can tunnel through the interfacial potential barrier in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions. Thus, in the range of 10–60 K, the enhanced nonlinear Hall resistance can be attributed to the anomalous Hall effect which was further enhanced by interfacial Rashba spin–orbit coupling effect. When the temperature further increased from 60 to 250 K, the interfacial potential barrier weakened gradually, and the Hall resistance and magnetoresistance decreased due to the shunting of the Ge substrate. In this case, the nonlinear Hall effect of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions can be explained very well by the two-band model of nonlinear Hall effect.

Keywords: Nonlinear Hall effect; Rashba spin–orbit coupling; two-band model; $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions.

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1. Introduction

Hall effect consistently plays an important role in condensed matter physics for their applications in the fundamental physics and engineering technologies. Usually, ordinary Hall effect (OHE) dominates in *n*-type or *p*-type semiconductors and Hall resistance is proportional to external magnetic fields, while anomalous Hall effect (AHE) occurs in ferromagnetic materials related to the exchange interaction between isolated magnetic sites and itinerant carriers, which displays a nonlinear relationship between Hall resistance and external magnetic fields.^{1–3} But the nonlinearity of Hall resistance versus external magnetic fields has been found and studied in some nonmagnetic films,^{4–8} especially in some heterojunctions.^{9–15}

There are two kinds of sights about nonlinear Hall effect in heterojunctions. The first viewpoint attributed the nonlinear Hall effect to the OHE, which held two types of carriers with different densities and/or mobility participated in the magnetotransport, such as in GeMn/Ge and Bi₂Se₃/YIG heterojunctions.^{10–12} However, this model overlooked the influence of interfacial potential barrier on the magnetotransport in heterojunctions. The second viewpoint attributed the nonlinearity to the AHE originated from the interfacial Rashba spin–orbit coupling due to the structure inversion asymmetry in the heterojunctions, such as in Mn_{*x*}Si_{1–*x*}/Si heterojunctions,¹³ which ignored the electrical transport affects of double conductance layers. Moreover, Alegria *et al.*¹⁴ tried to use AHE and two-band model to investigate the high field nonlinear Hall effect in their Bi₂Te₃/Cr₂Ge₂Te₆ heterojunctions, respectively, and found both models resulted in nearly identical predictions for $R_{xy}(B)$. Until now, it is unknown whether the two-band model, or Rashba spin–orbit coupling of interface, or the above two mechanisms contributes together. So it is important to investigate the mechanisms of the nonlinear Hall effect in heterostructures.

In this paper, we report the large nonlinear Hall effect of (FeCo)_{0.67}Ge_{0.33}/Ge heterojunctions, which were fabricated by sputtering *p*-type (FeCo)_{0.67}Ge_{0.33} amorphous magnetic semiconductor films on near intrinsic *n*-type Ge substrates. It is very interesting that the mechanisms of the large nonlinear Hall effect in (FeCo)_{0.67}Ge_{0.33}/Ge heterojunctions are different at different temperature ranges. Below 10 K, the Hall resistance of (FeCo)_{0.67}Ge_{0.33}/Ge heterojunctions is almost the same as the AHE of (FeCo)_{0.67}Ge_{0.33} ferromagnetic films. In the temperature from 10 to 60 K, the enhanced nonlinear Hall resistance can be attributed to AHE which was further enhanced by interfacial Rashba spin–orbit coupling effect. When the temperature further increased from 60 to 250 K, the Hall resistance decreased due to the shunting of the Ge substrate, which can be explained very well by the two-band model of nonlinear Hall effect.

2. Methods

2.1. Sample preparation

The samples with the nominal composition of (FeCo)_{0.67}Ge_{0.33} film were prepared by using the magnetron sputtering machine through co-sputtering high purity FeCo

Table 1. Samples identification (ID).

ID	Fabricated samples
Sample A	$(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ with 13 nm-thickness $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ film
Sample B	$(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{glass}$ with 13 nm-thickness $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ film
Sample C	$(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ with 20 nm-thickness $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ film

(99.99%) alloy target and Ge (99.999%) target on near intrinsic n -type Ge substrate. And the resistivity of near intrinsic n -type Ge substrate is about $50 \Omega \cdot \text{cm}$ at room temperature. The base pressure before co-sputtering was about 1.0×10^{-5} Pa. During co-sputtering, the Ar pressure was kept at 1.4 Pa, and the Ge substrate was rotated and kept at $T = 293$ K by water cooling for obtaining homogeneous $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films. The growth rates of FeCo and Ge was fixed at 0.24 and $0.17 \text{ \AA} \cdot \text{s}^{-1}$, respectively. Before preparing the studied samples, the thicker $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films from 100 to 200 nm were deposited. The thickness was confirmed by the surface profiler, which was agreed with that from weighing method. Then, the 13 and 20 nm thickness $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films were prepared on Ge substrates under the same conditions by controlling co-sputtering time, respectively. And a 2 nm Ge layer was sputtered on the top surface to protect $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films. For comparison, the $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films were prepared on insulating glass substrates under the same conditions and a 2 nm Ge layer was also sputtered on the top surface. For convenience, the samples were labeled as shown in Table 1.

2.2. Physical characterization

The structural properties of samples were detected by X-ray diffraction with Cu K_α radiation. No any diffraction peak except Ge substrates was detected, indicating that $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films have an amorphous structure. The Hall effect, longitudinal conductance, and magnetoresistance (MR) were characterized by four-probe method using a Quantum Design instrument with a Keithley2400 source meter and a Keithley2182 nanovoltmeter. The device temperature range is from 2 to 400 K, and the magnetic field intensity is up to 70 kOe. The little electrodes are on the surface of the top layer. The contact resistance is negligible as compared with the junction resistance.

3. Results and Discussions

Figures 1(a)–1(d) show the dependence of Hall resistance on magnetic fields (R_{xy} – H curves) for samples A, B, C and the Ge substrate measured at different temperatures with a magnetic field applied perpendicular to the film plane, respectively.

From Fig. 1(a), it is found that the R_{xy} – H curves of sample A were the remarkable resemblance to the anomalous Hall curves of sample B shown in Fig. 1(b) at 5 and 10 K, which were hysteretic at low fields and nearly saturated at high fields. However, as temperature increased, Hall resistance of sample A became very

Fig. 1. (Color online) The dependence of Hall resistance on magnetic fields R_{xy} - H curves measured at different temperatures for sample A (a), sample B (b), sample C (c) and Ge substrate (d).

different from that of sample B. For sample B, the R_{xy} - H curves measured above 10 K still kept the same tendency as ones measured at 5 and 10 K. And the saturated Hall resistance decreased slowly from $R_H = 5.663 \Omega$ at $T = 5 \text{ K}$ to $R_H = 4.292 \Omega$ at $T = 300 \text{ K}$, which originated from $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ magnetic semiconductors films.¹⁶ While, the Hall resistance of sample A increased nonlinearly and abruptly reached the peak value of 206.44Ω at $T = 60 \text{ K}$, $H = 8 \text{ kOe}$, which is about 41 times larger than that of sample B. Moreover, the Hall resistance of sample A changed from positive into negative at $T = 300 \text{ K}$. The Hall resistance of Ge substrate shown in Fig. 1(d) increased linearly with external magnetic field, which is a typical semiconductor behavior. In addition, it shows a p -type conduction below room temperature and a n -type conduction at about room temperature.¹⁰

Obviously, the Hall resistance of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions is neither similar to that of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films nor similar to that of Ge substrate. Therefore, we infer preliminarily that the interfacial potential barrier should exist in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions. Below 10 K, no conductive carriers went through the strong potential barrier, so sample A exhibited the same anomalous

Hall curves as sample B. While, in the temperature range of 10 to 60 K, the dramatically enhanced nonlinear Hall resistance may be from the interfacial Rashba spin-orbit coupling, which occurred when conducting carriers went through the emerging built-in electrical field at the interface of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions, similar to the results reported by Yang *et al.*¹³

In order to verify the effect of interfacial potential barrier in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions, the samples with thicker $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films on Ge substrate named sample C were fabricated. The $R_{xy}-H$ curves of sample C were shown in Fig. 1(c). It can be seen that the shape of the Hall resistance $R_{xy}-H$ curves is the same as that of samples A and/or B at 5 and 10 K. Furthermore, the Hall resistivity is equal to that of samples A and/or B. In other words, below 10 K, Hall effect of sample C derived from $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films, and above 10 K, the Hall resistance $R_{xy}-H$ curves of sample C exhibited the same tendency as sample A. However, the peak value R_{xy} is only 80 Ω at $T = 60$ K, $H = 8$ kOe, which is much less than that of sample A. Therefore, by comparing the similarities and differences between the samples A and C, it can be concluded that the effect of interfacial potential barrier on Hall resistance of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions is related to the thickness of the $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films, the thinner the $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films, the stronger the Hall resistance.

In order to further understand the nonlinear Hall effect of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions, the dependences of the longitudinal conductance on temperatures ($G_{xx}-T$ curves) were measured for samples A, B and Ge substrate, respectively. The results were shown in Fig. 2. The parallel conduction of sample B and Ge substrate was obtained by adding the conduction values of sample B and Ge substrate together.

Fig. 2. (Color online) The dependence of the longitudinal conductance on temperatures ($G_{xx}-T$ curves) for sample A (black), sample B (red), Ge substrate (blue) and sample B + Ge substrate (green).

Clearly, the G_{xx} - T curve of sample A is different from that of sample B or Ge substrate. The G_{xx} - T curve of sample B increased slowly from $G = 0.00133 \Omega^{-1}$ at 5 K to $G = 0.00140 \Omega^{-1}$ at 300 K, which is a typical conducting behavior of the weakly localized carriers on the metallic side of the metal-insulator transition.^{17,18} The conductance value of Ge substrate is about $0.0105 \Omega^{-1}$ at $T = 30$ K, which is higher than that of samples A or B. As temperature increased, the conductance of Ge substrate decreased dramatically in the range of 30–100 K, and nearly equaled to the conductance of sample A at 60 K, and equaled to the conductance of sample B at 98 K, respectively. When the temperature increased from 100 to 250 K, the conductance of Ge substrate kept decreasing smoothly and then increased slowly from 250 to 300 K. It is worth noting that the conductance values of sample A can be distributed into several regions. Below 45 K, it was approximately equal to that of sample B within the measurement error range, which indicated that the conductance of sample A mainly derived from $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films. However, from 45 to 60 K, the G_{xx} - T curve of sample A went up abruptly and reached the peak value $G = 0.00346 \Omega^{-1}$ at $T = 60$ K, about 2.6 times larger than that of sample B. With temperature increasing, the G_{xx} - T curve declined smoothly until $T = 250$ K. When the temperature was above 250 K, the G_{xx} - T curve of sample A began to increase slowly, which was similar to that of Ge substrate.

About the parallel conduction of sample B and Ge substrate, clearly, it was larger than that of sample A in the whole temperature range, especially below 60 K. This is due to the interfacial potential barrier which weakens the conductance of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions. However, from 60 to 300 K, the parallel conductance curve displayed similar tendency to that of sample A. When the potential barrier lowered down gradually with increasing temperature, the conducting carriers went across the interface, and then Ge substrate took part in parallel conduction with the $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ film together.

The dependence of the MR on magnetic fields (MR- H curves) was exhibited for the samples A, B and Ge substrate in Fig. 3. The MR is defined as $\text{MR} = \frac{R_H - R_0}{R_0} \times 100\%$, where R_H and R_0 are the resistance measured with and without magnetic fields, respectively. Figure 3(a) shows the MR- H curves of sample A. It can be seen that the MR- H curves are negative below 10 K and as small as that of sample B shown in Fig. 3(b). As temperature increased, the MR- H curves of sample A changed into positive ones and reached to the largest value about 250% at $T = 60$ K, $H = 60$ kOe. However, it can be seen from Fig. 3(b) that the MR- H curves of sample B kept negative and small from 5 to 300 K, which originated from the contribution of magnetic $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films due to a spin-dependent hopping behavior. The MR- H curves of Ge substrate are shown in Fig. 3(c), which are positive in the whole temperature range. Comparing Figs. 3(a)–3(c), the results of MR- H curves illustrate that the strong interfacial potential barrier existed in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions and the negative MR is mainly contributed by $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ layer below 10 K. Above 10 K, the interfacial potential

Fig. 3. (Color online) The dependence of the MR on magnetic fields applied perpendicular to the film plane for sample A (a), sample B (b) and Ge substrate (c) measured at different temperatures.

barrier between $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ and Ge weakened gradually, and the positive MR of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ is not solely originated from $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ layer.

From Figs. 1(a), 2 and 3(a), it can be seen that the Hall resistance, longitudinal conductance and MR of sample A reached the maximum value at the same temperature of 60 K. Below 10 K, the strong interfacial potential barrier of the $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions completely blocked Ge substrate shunting effect.¹⁰ While from 10 to 60 K, the decreased interfacial potential barrier has the potent effect on the Hall effect, longitudinal conductance and MR. Above 60 K, the barrier height and depletion layer of the $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions continued to recede, Ge substrate became shunting. An alternative model, i.e., the two-band model was used to investigate nonlinear Hall effect.^{5–7,20,21} The presence of parallel conduction channels with differing mobility but comparable overall

Fig. 4. (Color online) Two-band model fitting the Hall resistance of sample A measured from 60 to 250 K (a). The symbols and the solid lines represent the experimental data and the fitting curves, respectively. The fitting carrier densities and mobility at different temperatures (b), the solid and the hollow symbols indicate the carrier densities and the mobility, respectively.

conductance would produce a similar nonlinearity, as observed in many heterojunctions.^{12,14} In the two-band model, the Hall resistance depending on the magnetic field can be described as following^{6,9,19}:

$$R_{xy} = \frac{B}{e} \cdot \frac{(n_1 \mu_1^2 + n_2 \mu_2^2) + (n_1 + n_2) B^2 \mu_1^2 \mu_2^2}{(n_1 \mu_1 + n_2 \mu_2)^2 + (n_1 + n_2)^2 B^2 \mu_1^2 \mu_2^2}. \quad (1)$$

Here, B is the external magnetic fields, n_1 and n_2 are the surface carrier densities of the $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ layer and Ge substrate, μ_1 and μ_2 are the carrier mobility, which are supposed to be dependent on temperature only, independent of fields, and e is the carrier charge and equals to the value 1.6×10^{-19} C.

Figure 4(a) shows the experimental and corresponding fitting R_{xy} - H curves for sample A. It can be seen that the R_{xy} - H curves fitted by the two-band model in the range of 60–250 K agreed with that of experimental curves generally. However, the R_{xy} - H curves below 60 K cannot be fitted well (not shown here). The corresponding fitting parameters at different temperatures are shown in Fig. 4(b). As can be seen that carrier densities n_1 , n_2 are all positive, indicating the conduction is p -type in sample A. The carrier density n_1 was $1.370 \times 10^{18} \text{ m}^{-2}$ at 60 K and increased smoothly with temperature. Another carrier density n_2 was $3.257 \times 10^{15} \text{ m}^{-2}$ at 60 K and decreased slowly with temperature. Obviously, n_1 is larger than n_2 by three orders of magnitude in the whole measured temperature. Moreover, the carrier mobilities μ_1 and μ_2 at 60 K are 6.21×10^{-3} and $3.68 \text{ m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$, respectively. Evidently, μ_1 was less than μ_2 by three orders of magnitude. That is to say, the conductance of the two-type carriers is in the same order of magnitude.

By the formula $G = ne\mu$, we calculated the conductance value of the two-type carriers using the fitting parameters shown in Fig. 4(b). The conductance values at 60 K are 1.36×10^{-3} and $1.92 \times 10^{-3} \Omega^{-1}$ for the two kinds of carrier densities, respectively. Adding the above values together, the total value is $3.28 \times 10^{-3} \Omega^{-1}$,

Fig. 5. (Color online) The MR- H curves for sample A measured at various temperatures. The solid lines with symbols indicate the experimental data and the solid lines represent the fitting curves using the formula (2).

approximately equaled to the value $3.47 \times 10^{-3} \Omega^{-1}$ of sample A showed in Fig. 2. It is worth noting that the surface carrier density n_2 is in the same order of magnitude as that of Ge substrate from 20 to 250 K, shown in Fig. 1(d), which is in the range of 2.40×10^{15} – $3.18 \times 10^{15} \text{ m}^{-2}$.

From the two-band model, the formula of the dependence of MR on the magnetic field is shown in the following⁷:

$$R_{xx} = \frac{1}{e} \cdot \frac{(n_1\mu_1 + n_2\mu_2) + (n_1\mu_2 + n_2\mu_1)B^2\mu_1\mu_2}{(n_1\mu_1 + n_2\mu_2)^2 + (n_1 + n_2)^2B^2\mu_1^2\mu_2^2}. \quad (2)$$

We substituted the fitting parameters (n_1, μ_1, n_2, μ_2) obtained by formula (1) into the formula (2), and the corresponding fitting MR- H curves are shown in Fig. 5 (solid lines). Although the fitting MR- H curves deviated from the experimental MR- H curves, the disagreement became increasingly thinner as the temperature increased. Mentioned above, the Hall effect and longitudinal conductance can be consistently described by parallel conductance, although the MR was not sufficiently explained by the same model. This result is consisted with that reported by Simons *et al.*¹¹

It is well known that nonlinear Hall effect, derived from two-type carriers, should be attributed to OHE in nature and different from AHE. It can be seen from Fig. 1(b) that anomalous Hall resistance of sample B is in the range of 5.663–4.292 Ω from 5 to 300 K, which was very small and negligible as compared with the nonlinear Hall resistance of sample A shown in Fig. 1(a) in the whole temperature range. Therefore, it is reasonable that the nonlinear Hall effect of sample A from 60 to 250 K should be fitted generally by the two-band model, under the circumstance of ignoring the AHE derived from $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films.

By comparing the data of Hall effect, the longitudinal conductance, and MR, it is worth mentioning the following features: (i) Below 10 K, the strong interfacial potential barrier certainly occurred in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions, and prevented conducting carriers from entering into Ge substrate. Consequently, Hall effect, longitudinal conductance and MR for $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}_{0.33}$ heterojunctions agreed with those of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ films. (ii) As we known, thermally excited conducting carriers can tunnel through the interfacial potential barrier in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions. Thus, in the range of 10–60 K, the enhanced nonlinear Hall resistance can be attributed to AHE which was further enhanced by interfacial Rashba spin–orbit coupling effect.²² In fact, it is hard to detect how the Hall voltage was controlled by external electrical fields, because our sample A with high carrier density is liable to breakdown. Nevertheless, according to the results reported by Yang *et al.*,¹³ Rashba spin–orbit coupling had enhanced AHE in $\text{Mn}_x\text{Si}_{1-x}/\text{SiO}_2/\text{Si}$ p–i–n junctions. Therefore, it is reasonable to believe that AHE dominated large nonlinear Hall resistance in the temperature range of 10–60 K. (iii) As temperature further increased, the interfacial potential barrier became thinner, and the conducting carriers penetrated into Ge substrates. At this temperature range, Ge substrates participated in electrical transport of the $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ samples, the nonlinear Hall effect can be explained by the two-band model.

4. Conclusions

In summary, the large nonlinear Hall effect of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions has been studied. It is very interesting that the mechanisms of the large nonlinear Hall effect in $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions are different at different temperature ranges. Below 10 K, the Hall resistance of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions is almost the same as the AHE of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}$ ferromagnetic films. While the temperature increased from 10 to 60 K, the nonlinear Hall resistance, longitudinal conductance, and MR all increased quickly and reached the maximum at $T = 60$ K. In this temperature range, the enhanced nonlinear Hall resistance can be attributed to AHE which was further enhanced by interfacial Rashba spin–orbit coupling effect. When the temperature further increased from 60 to 250 K, the experimentally observed nonlinear Hall effect of $(\text{FeCo})_{0.67}\text{Ge}_{0.33}/\text{Ge}$ heterojunctions can be explained very well by the two-band model of nonlinear Hall effect.

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References

1. N. Nagaosa *et al.*, *Rev. Mod. Phys.* **82**, 1539 (2010).

2. S. H. Chun *et al.*, *Phys. Rev. Lett.* **98**, 026601 (2007).
3. D. Yue and X. Jin, *J. Phys. Soc. Jpn.* **86**, 011006 (2017).
4. R. Chambers, *Proc. Phys. Soc. London A* **65**, 903 (1952).
5. G. Pettinari *et al.*, *Appl. Phys. Lett.* **101**, 222103 (2012).
6. Y. Kumar *et al.*, *Appl. Phys. Lett.* **107**, 022403 (2015).
7. Y. Q. Xu *et al.*, *Appl. Phys. Lett.* **98**, 112109 (2011).
8. S. Agan *et al.*, *Phys. Rev. B* **63**, 075402 (2001).
9. J. S. Kim *et al.*, *Phys. Rev. B* **82**, 201407 (2010).
10. N. Sircar *et al.*, *Phys. Rev. B* **83**, 125306 (2011).
11. A. Simons *et al.*, *J. Appl. Phys.* **115**, 093703 (2014).
12. Z. Jiang *et al.*, *Appl. Phys. Lett.* **104**, 222409 (2014).
13. A. C. Yang *et al.*, *RSC Adv.* **6**, 55930 (2016).
14. L. D. Alegria *et al.*, *Appl. Phys. Lett.* **105**, 053512 (2014).
15. A. Matos-Abiague and J. Fabian, *Phys. Rev. Lett.* **115**, 056602 (2015).
16. J. Pei *et al.*, *J. Alloys Compd.* **658**, 98 (2016).
17. F. Hellman *et al.*, *Phys. Rev. Lett.* **77**, 4652 (1996).
18. Y. F. Qin *et al.*, *J. Appl. Phys.* **109**, 083906 (2011).
19. N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Harcourt College Publishers, 1976).
20. S. M. Watts, S. Wirth and S. V. Molnar, *Phys. Rev. B* **61**, 9621 (2000).
21. S. Zhou *et al.*, *Appl. Phys. Lett.* **95**, 172103 (2009).
22. A. Manchon *et al.*, *Nature Mater.* **14**, 871 (2015).