Giant gate-controlled odd-parity magnetoresistance effect in InAs/(Ga,Fe)Sb

Ryota Fukuzawa and Koseku Takiguchi

Authors

- Ryota Fukuzawa:
  - Field: Development of new techniques in atomic force microscopy based on local electrostatic force detection for electrical device investigation
  - Contribution: Investigation of the potential distribution in InAs by atomic force microscopy
- Kosuke Takiguchi:
  - Field: New phenomena in magnetoresistance
  - Contribution: Sample preparation and resistance measurements

Abstract

Electrical resistance behaves evenly with respect to the magnetic field $\boldsymbol{B}$. However, some systems have been reported to contain an odd functional component to the magnetic field $\boldsymbol{B}$ (odd-parity magnetoresistance effect: OMR). There are two possible origins of the OMR: 1. an edge state due to the topological of the band, and 2. an edge state due to a triangular potential derived from Fermi-level pinning. In this study, the authors confirmed that OMR is observed in InAs/(Ga,Fe)Sb heterojunctions at room temperature and investigated the in-plane distribution of the work function using atomic force microscopy, and clarified that the origin of OMR is due to the triangular potential caused by Fermi-level pinning.

1 Intoduction

From Onsager's contradiction, it is generally known that the electrical resistance of a material behaves as an even-ordered with magnetic field $\boldsymbol{B}$. Recently, however, there have been reports of the appearance of odd-order components for magnetic fields (OMR)[1, 2, 3, 4]. Such OMRs appear in

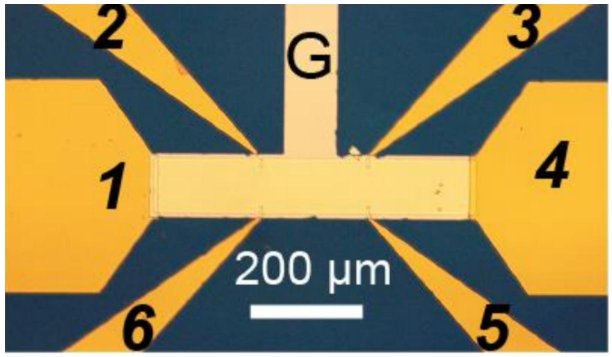

Fig. 1: Optical microscopic image of the Hall bar device with the gate electrode G.

systems where the spatial and time reversal symmetries are severely broken. However, the essential understanding of OMR has not been achieved. Previous studies by the authors have theoretically shown that electrical conduction at the sample edge (edge conduction) is responsible for the appearance of OMR. As the origin of this edge conduction, [5], which originates from the topological nature of the bands, and [6], which originates from the triangular potential due to surface Fermi-level pinning, have been proposed.

In the present study, we have undertaken a self-directed joint research to clarify the origin of the OMR observed in InAs/(Ga,Fe)Sb heterojunctions.

2 Experimental

2.1 Sample preparation

The samples were prepared using molecular beam epitaxy method. The sample structure consists of InAs (15 nm)/($Ga_{1-x}Fe_x$) (15 nm, $x = 0.2$) / AlSb (200 nm)/AlAs (10 nm)/GaAs (100 nm) crystals grown on GaAs(001) (semi-insulating) substrate in order from the surface.

2.2 Resistivity measurements

On the prepared InAs/(Ga,Fe)Sb, electrodes as shown in Fig. 1 are connected, and the electrical resistance is measured between several terminals of the hole bar. The electrical resistance in a magnetic field acts as tensor. Here, we define the resistance as $R_{ij} := V_{ij}/I_{14}$ using the voltage V_{ij} between terminals i, j when a current, I_{14}, flows in the direction of electrodes 1 to 4.

2.3 Surface potential measurements

To verify the formation of a triangular potential at the edge of InAs, we used frequency modulated Kelvin probe force microscopy (FM-KFM). Frequency modulation atomic force microscopy (FM-AFM) is a technique to detect the interaction force between the tip and a sample surface from the change in the vibration state of the cantilever, and FM-KFM is one of the applications of FM-AFM. The equation of motion when the interaction force $F(z) \approx F(z_0) + (\partial F(z_0)/\partial z)\Delta z$ (z: distance between the tip and the sample) acts on the tip is as follows.

$$\begin{aligned} m\ddot{z} &= -k\Delta z - \gamma\dot{z} + F(z_0) + (\partial F(z_0)/\partial z)\Delta z + O(\Delta z) \\ &= F(z_0) - \left(k - \frac{\partial F(z_0)}{\partial z}\right)\Delta z - \gamma\dot{z} + O(\Delta z) \end{aligned} \tag{1}$$

Here, k is the spring constant, γ is the damping coefficient, and m is the effective mass of the cantilever. From Eq.(1), the force gradient $(\partial F(z_0)/\partial z)$ of the interaction changes the spring constant, which in turn changes the resonant frequency.

The electrostatic force F_{ef} induced when an AC voltage $V_{\mathrm{AC}} \sin \omega t$ and a DC bias V_{DC} are applied between the tip and sample, the total electrostatic energy, U, can be written as

$$\begin{aligned} U(C,V) &= \frac{1}{2}CV^2 + (Q_{\mathrm{total}} - Q)V \\ &= -\frac{1}{2}CV^2 + Q_{\mathrm{total}}V, \end{aligned}$$

under the parallel plate approximation (C: capacitance, V: voltage between that tip and sample, Q_{total}: total held charge in the system which consists of the source and the capacitor). Therefore, the electrostatic force is expressed as

$$\begin{aligned} F_{\mathrm{ef}} &= \frac{1}{2}\frac{dC}{dz}\left(\underbrace{V_{\mathrm{DC}} - \frac{\Delta\phi}{e}}_{:=V_0} + V_{\mathrm{AC}} \sin \omega t\right)^2 \\ &= \frac{1}{2}\frac{dC}{dz}\left(V_0\right)^2 + \frac{1}{4}V_{\mathrm{AC}}^2 \\ &\quad + \frac{dC}{dz}\left(V_{\mathrm{DC}} - \frac{\Delta\phi}{e}\right)V_{\mathrm{AC}} \sin \omega t \ (=: F_{1\omega}) \\ &\quad - \frac{1}{4}\frac{dC}{dz}\cos 2\omega t, \end{aligned}$$

where $\Delta\phi, e, z$ is the work function difference between the tip and sample, elementary charge ($-e$ for the electron charge) and the distance between the tip and sample, respectively. In FM-KFM, the frequency ω component $\Delta f_{1\omega}(\propto F_{1\omega})$ of the shift in the mechanical resonance frequency of the cantilever due to the force gradient of electrostatic interaction (Δf) is detected by lock-in, and the work function difference $\Delta\phi$ can be obtained by V_{DC} value so that $\Delta f_{1\omega}$ is canceled using V_{DC} feedback control. By measuring $\Delta\phi$ over the sample surface, the surface potential distribution can be measured.

Electrostatic force is a long-range interaction, which acts not only on the tip but also on the cantilever, and the spatial resolution is reduced. However, the distance between the cantilever part and the sample surface is about four orders of magnitude larger than the distance between the tip and the sample surface, and the gradient of the electrostatic force is also sufficiently small compared to the tip, so this cantilever contribution can be reduced if the force gradient is detected. In this study, we used FM-KFM, which detects the force gradient instead of the force, to significantly reduce the contribution of the cantilever part and achieve high resolution.

In FM-KFM, the potential resolution is governed by the detection limit of the frequency shift. Therefore, the higher the Q value of the cantilever, the higher the accuracy and sensitivity can be expected. In addition, the presence of surface-adsorbed water can change the surface potential. In this study, the measurements were performed in a vacuum environment ($\sim 10^{-5}$Pa) to increase the Q value and remove adsorbed water.

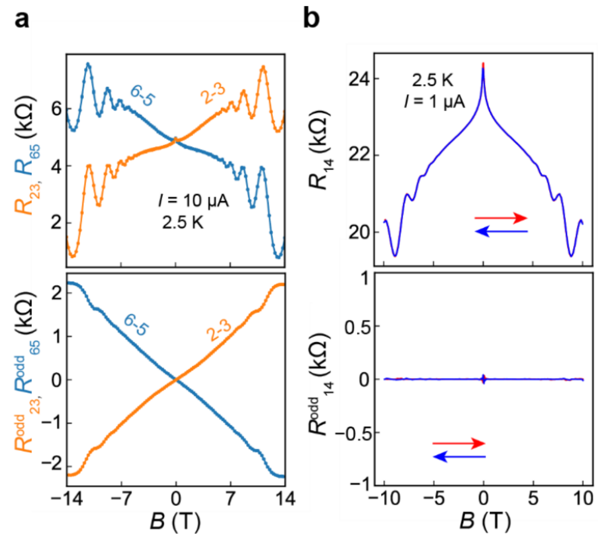

Fig. 2: a, Comparison of the B dependences of R23 and R_{65} (upper panel) and their odd-function components (lower panel) measured with a fixed current of 10 μA at 2.5 K. b, MRs of R_{14} (upper panel) and its odd component (lower panel) measured with a fixed current of 1 μA at 2.5 K

3 Results and discussions

The results of the magnetic field dependence measurement of resistance are shown in Fig. 2. The odd function component R_{ij}^{odd} is extracted from the upper part of the figure and plotted in the lower part. It can be confirmed that R_{23}^{odd} and R_{65}^{odd} vary almost linearly with the magnetic field. On the other hand, R_{14}^{odd} is zero regardless of the magnetic field. This may be due to the involvement of edge conduction in R_{ij}^{odd}. In R_{14}^{odd}, the contribution from edge conduction on the terminal 1 side and the contribution from edge conduction on the terminal 4 side cancel each other out due to symmetry, so that R_{14}^{odd} due to edge conduction does not appear. The temperature dependence of R_{24}^{odd} is then shown in Fig. 3. In the present system, the OMR was confirmed even at room temperature. The gap as a topological material is roughly 4 meV, and the OMR at room temperature cannot be explained by topological properties alone.

The results of the surface potential measurement of InAs by FM-KFM are shown in Fig. 4, where the surface potential measurement along the InAs edge shows that the band is bent by approximately 20 meV towards the edge.

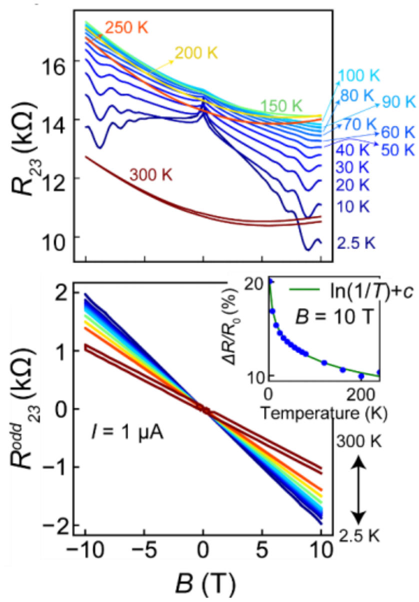

Fig. 3: Temperature dependences of R_{23} and $R_{23}^{\rm odd}$ at $2.5-300$K under 1μA

However, the transition region is on the order of μm, which is wider than the expected potential. This is because the triangular potential exists from the surface to the depth due to the surface level at the near surface of the sample, and it is expected to be wider than the band bending toward the edge in the bulk. It has been reported that the surface potential difference is less than half of the bulk theoretical value and that the transition region is wider than the theoretical value in general pn junction potential measurements [7, 8]. We interpret that such effects are also manifested in the present experiment, but we believe that the qualitative behavior of the potential distribution is identical. Therefore, the KFM results suggest the existence of a triangular potential at the InAs edge.

From the above results of the temperature dependence and the surface potential measurement, the edge conduction originated from the Fermi level pinning is considered to be dominant in the origin of the OMR observed in InAs/(Ga,Fe)Sb.

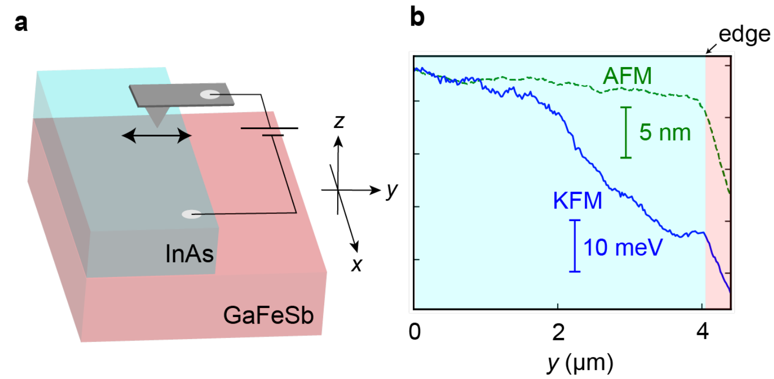

Fig. 4: Surface potential distribution on InAs by FM-KFM. a, schematic diagram of the KFM measurements. b, height and potential distributions around edge of InAs.

4 Conclusions

In this study, we performed temperature-dependent and surface potential measurements to elucidate the odd-order magnetoresistance (OMR) effect observed in InAs/(Ga,Fe)Sb. The observation of OMR at room temperature and the existence of a triangular potential at the InAs edge were confirmed, suggesting that the OMR in InAs/(Ga,Fe)Sb is due to the edge conduction due to the Fermi level pinning, which contributes to the OMR.

Acknowledgements

The authors sincerely thank our supervisors, Professors Takuji Takahashi and Masaaki Tanaka, and our sub-supervisors, Professors Toshiro Hiramoto and Kyoko Ishizaka, for their support and cooperation in this research. We also thank MERIT for the opportunity to conduct this research.

References

[1] Moubah, R. *et al. J. of Appl. Phys.* **115**, 053911 (2014).

[2] Wang, Y *et al. Nat. Commun.* **11**, 216 (2020).

[3] Fujita, T C *et al. Sci. Rep.* **5**, 9711 (2019).

[4] Albarakati, S *et al. Sci. Adv.* **5**, eaaw0409 (2019).

[5] J. A. Peters *et al. Phys. Rev. B* **82**, 205207 (2010).

[6] Suzuki, K *et al. Phys. Rev. B* **87**, 235311 (2013).

[7] S. Saraf, *Surf. Sci.* **574**, L35 (2005).

[8] T. Uruma, *et al. Jpn. J. Appl. Phys.* **55**, 08NB10 (2016).