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High mobility Ni-doped topological Dirac semimetal Cd_3As_2 films

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Abstract

The magnetic and transport properties of Ni-doped topological Dirac semimetal Cd_3As_2 films have been investigated. A ferromagnetic transition temperature of ~45 K is observed in a 2% Ni-doped sample, while its electron mobility as high as ~1000 cm^2/Vs at 3 K is obtained and manifested by the Shubnikov-de Haas oscillation and the quantum Hall effect. A small band gap in the range of 50-100 meV is deduced by the semiconducting-like temperature dependence of the longitudinal resistance, which is ascribed to the strain exerted by the GaAs substrate.

1. Introduction

As a representative material of topological Dirac semimetal, Cd_3As_2 has been intensively studied both theoretically and experimentally in recent years [1-9]. Many novel physical properties have been identified in this material, among which the electronic Weyl orbits enable the observation of quantum Hall effect in bulk material, providing a new scheme for the exploration of three dimensional quantum Hall physics [7-9]. Nevertheless, the studies on Cd_3As_2 films with magnetic doping are rare.

In this work, single crystal Cd_3As_2 films have been synthesized by molecular-beam epitaxy, based on which successful Ni doping is then accomplished. High electron mobility of ~1000 cm^2/Vs is maintained at 3 K for a ~2% Ni-doped sample, for which a ferromagnetic order is observed below a transition temperature of ~45 K.

2. Experiments and Results

Cd_3As_2 films were directly grown on semi-insulating GaAs (111)B substrate by molecular-beam epitaxy, during which the beam fluxes of Cd and As were independently controlled. The growth temperature window is relatively narrow, in the range of 180 °C to 220 °C. Both *in situ* reflection high energy electron diffraction (RHEED) and *ex situ* XRD measurements indicate the good single crystal quality of Cd_3As_2 films. We then successfully doped Ni with various concentrations into Cd_3As_2 films with thickness of ~20 nm, and the typical streaky RHEED pattern and XRD results are presented in Fig. 1. In addition to the three sharp XRD peaks corresponding to the GaAs {111} planes, five diffraction peaks induced by the Cd_3As_2 {112} planes can be observed. Notice that Cd_3As_2 (112) is a quasi-close-packed plane, and is hence naturally parallel with the GaAs (111) plane.

The Ni-doped Cd_3As_2 films were then fabricated into Hall bar devices by standard optical lithography and ion beam etching. The 20 μm wide Hall bar channel was parallel with the GaAs [11-2] direction, while the distance between the nearest electrodes along the channel was 60 μm.

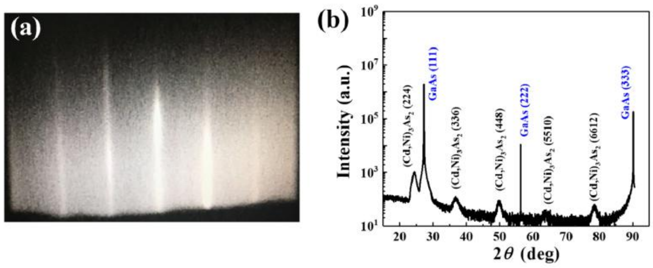

Fig. 1 (a) RHEED pattern and (b) XRD curves of Cd_3As_2 film epitaxied on GaAs (111)B substrate.

Figure 2(a) shows the longitudinal resistance (R_{xx}) vs. temperature curve of a Cd_3As_2 sample doped with ~2% Ni, in which a clear metal to insulator transition was observed at ~150 K. The insulting transport behavior could be explained by the existence of small bandgap (in the range from 30-100 meV for different samples), which was attributed to the large strain exerted by the substrate. Magnetic field dependence of R_{xx} curve up to 9 T at 300 K is roughly parabolic, which can be ascribed to the dominance of the ordinary magnetoresistance, as shown by the blue line in Fig. 2(b). When decreasing the temperature to 3 K, an obvious Shubnikov-de Haas (SdH) oscillation was observed even at magnetic field as low as 3 T (black line in Fig. 2(b)), implying a high carrier mobility of our sample. The sheet carrier density determined by the SdH oscillation was ~8×10^{11} cm^{-2}, similar with the typical value of ~6×10^{11} cm^{-2} at 3 K for undoped Cd_3As_2 films.

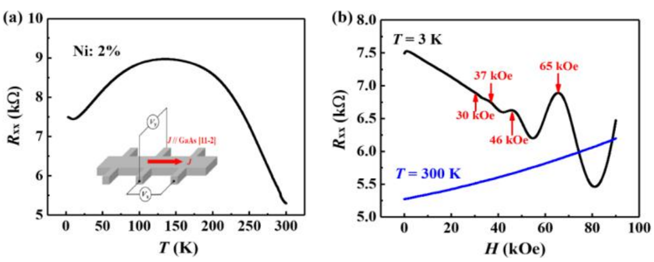

Fig. 2 (a) Temperature and (b) magnetic field dependence of a Cd_3As_2 films doped with ~2% Ni.

We also carried out the Hall measurements at different temperatures simultaneously to quantitatively extract out the information of the carrier mobility and density. A linear magnetic field dependence of the Hall resistance was observed at 300 K (blue line in Fig. 3(a)), from which the carrier density was determined to be ~3.5×10^{12} cm^{-2}, higher than the one obtained by SdH oscillation at 3 K. This higher carrier density could be intuitively explained by considering the small band gap of our strained Cd_3As_2 films, which allows thermal activation of significant electrons from the valence band to the conduction band at room temperature. The electron mobility was ~300 cm^2/Vs, much lower than the value obtained in bulk materials. Interestingly, when the temperature was lower to 3 K, several plateaus as the signature of quantum Hall effect appeared. Quantitative analyses indicated that these plateaus were indeed corresponding to the quantized Hall resistance characterized by fundamental physical constants (h/e^2~25.812 kΩ). Combining the linear curve in the low magnetic field range with the longitudinal resistance shown in Fig. 2, the electron mobility of our sample is then calculated to be ~1000 cm^2/Vs, which usually does not support the emergence of quantum Hall plateau at such low magnetic filed of ~5 T. This might correlates with the Weyl orbits, but the detailed reason is still unclear, which calls for further theoretical explanations.

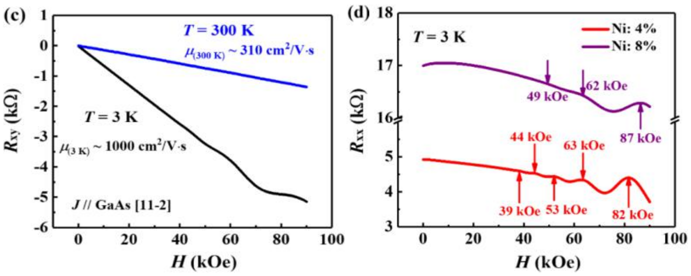

Fig. 3 Hall measurement results for Ni-doped Cd_3As_2 films with nominal concentration of (a) 2% and (b) 4% and 8%.

The magnetoresistance of Cd_3As_2 films doped with nominally 4% and 8% Ni were measured as well, as shown in Fig. 3(d). For these samples, obvious SdH oscillation could also be seen at 3 K, but the magnetic filed corresponding to the first peak became larger as the Ni concentration increased. Moreover, the quantum Hall plateaus gradually disappeared as the Ni concentration was enhanced (not shown). Similarly, the sheet electron density can be determined both by the SdH oscillation of longitudinal resistance and the Hall coefficients obtained by the transverse resistance, which were consistent with each other. The electron density increased to the order of 1×10^{12} cm^{-2} at 3 K, however, these values were not simply proportional to the Ni concentration, which was understandable since the many defects might contribute to the mobile charge carriers in such complex and narrow gap compounds.

Finally, the magnetic properties of Ni-doped Cd_3As_2 films were characterized by superconducting quantum interference device (SQUID) magnetometer. As can be seen by the temperature dependent magnetization shown in Fig. 4(a), a clear ferromagnetic order was identified at temperature lower than ~45 K. No signatures of any second ferromagnetic phase were observed, implying the intrinsic ferromagnetism of these samples. Magnetic field dependence of the normalized magnetization curves measured along different directions are shown in Fig. 4(b), the three curves almost overlapped with each other, indicating a weak magnetic anisotropy for these Ni-doped Cd_3As_2 films.

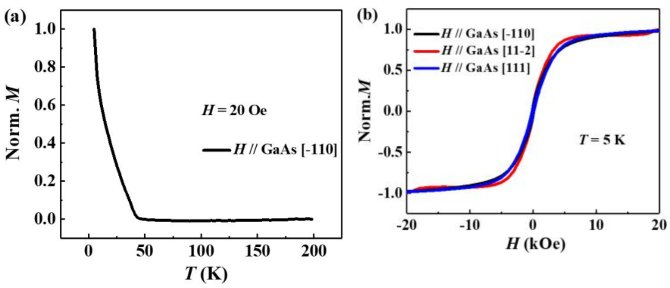

Fig. 4 (a) Temperature and (b) magnetic field dependence of the normalized magnetization for 2% Ni-doped Cd_3As_2 films.

3. Conclusions

In conclusion, epitaxial Ni-doped Cd_3As_2 films on GaAs (111)B substrates were successfully grown by low temperature molecular-beam epitaxy. A small bandgap of several tens of meV was implied by the semiconducting transport behavior, and its electron density was in the order of 1×10^{12} cm^{-2}. Moreover, ferromagnetic order with Curie temperature of ~45 K was achieved while the electron mobility was as high as ~1000 cm^2/Vs. Our work provides a new pathway for the realization of high mobility magnetic semiconductor, in spite of the relatively narrow bandgap of our samples.

Acknowledgements

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