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Spin-orbit Interaction Investigated by Weak Anti-Localization Analysis in III-VI Layered Semiconductor GaSe Thin Film

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Abstract

Magneto-conductance (MC) at low temperature is measured to investigate spin related transport in GaSe thin film. MC shows weak anti-localization, and its analysis reveals that the dominant spin relaxation is governed by the D'yanokov- Perel' mechanism with the Rashba spin-orbit interaction. The estimated Rashba SOI strength is as large as InGaAs quantum wells (QWs) and one order larger than that in GaAs QWs.

1. Introduction

After the discovery of graphene, much attention is focused on transition-metal dichalcogenides (TMDs) for next generation electronic materials. Recently, III-VI compound semiconductors have emerged as new type layered materials. The unusual distortion of valence-band maximum is predicted to create an indirect band-gap and singularity of density-of-states, which causes tunable ferro-magnetism in *p*-type monolayer GaSe [1]. The topological insulator transition in layered GaSe and GaS is predicted by introducing tensile strain [2]. Transistors operation in GaS and GaSe single layers were demonstrated [3]. High performance of photo detectors due to the direct band gap was made by using atomic layered GaSe [4], [5]. Quantum Hall effect and anomalous optical response were observed in atomically thin InSe with high electron mobility [6]. Although III-VI compound layer semiconductors have been extensively investigated, experimental studies on spin related transport is very limited. The purpose of this study is to clarify the spin-orbit interaction (SOI) in III-VI GaSe thin films.

2. Sample Preparation

GaSe thin films were exfoliated by mechanical cleavage method from bulk GaSe sample grown by Bridgman method. These films were attached on cleaned *p*-doped Si/SiO_2 (300 nm, thermal oxidation) substrates. This SiO2 oxide layer was used as a gate dielectric layer for a back-gate electrode (p-doped Si). An optical microscope was used to locate GaSe thin films and optical images were captured. To identify GaSe thin films, 15 nm Cr/ 150 nm Au markers were patterned on substrates before a GaSe attachment.

Layer thickness of GaSe thin films were determined by color contrast for optical images of GaSe layers. The relationship between color contrast and GaSe thickness was obtained by atomic force microscope and Raman spectra. The Raman spectra showed that the present samples used in the experiment are ε-GaSe layer structure. For electrical measurement, GaSe samples were processed to form Hall bar structure. Ag electrode patterns of devices were defined by electron beam lithography.

3. Magneto-Conductance and Analysis

A quantum interference effect such as weak localization (WL) is sensitive to phase coherence as well as spin relaxation, and WL becomes weak anti-localization (WAL) when spin relaxation length ℓ_{SO} is shorter than phase coherence length ℓ_{ϕ}. In III-V compound QWs, WAL analysis has been utilized to estimate the strength of SOI [7]. Magneto-conductance (MC) was measured with a conventional lock-in method at low temperature T as shown in Fig. 1. MC data show a strong temperature dependence and conductance peak around zero magnetic field with amplitude order of e^2/h. These features are originated from WAL properties. The experimentally observed WAL cannot be explained if only the Dresselhaus SOI exists since the Dresselhaus effective SOI field is out-of-plane and uni-directional orientation with three rotational symmetry [8]. This Dresselhaus SOI induced by spin splitting in GaSe at Γ-point resembles the case of III-V GaAs [110] quantum wells (QWs) [9].

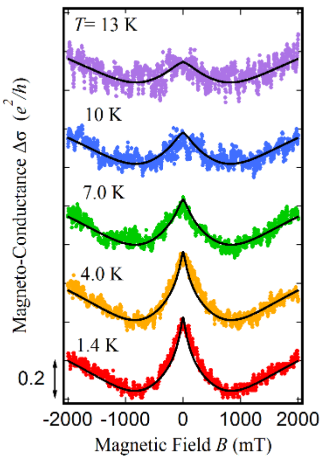

Fig. 1 Magneto-conductance (MC) data observed at low temperature. The MC data are well reproduced by WAL theory. Solid curves are theoretical fittings with the ILP theory.

There are two possible reasons for the WAL, namely, the Elliot-Yafet (EY) and D'yakonov-Perel' (DP) spin relaxation mechanisms [10]. The EY spin relaxation mechanism is associated with admixture of spin up and down states where spin and momentum are entangled by SOI, so the momentum scattering events cause the spin flip process. The DP spin relaxation mechanism is essentially due to a motion-narrowing effect of spin precession induced by an effective magnetic field, which appears in spin splitting of a band with the lack of spatial inversion symmetry.

The experimentally measured WAL data are well reproduced by Iordanskii, Lyanda-Geller and Pikus (ILP) theory [11] based on the DP mechanism. In Fig. 1, the black solid curves are obtained from analysis using the ILP theory. The ILP analysis including only the Rashba term was utilized as described in Ref. [7]. The Hikami, Larkin and Nagaoka (HLN) theory [12] with an assumption of the EY mechanism failed to reproduce the WAL data. This result indicates that the DP spin relaxation mechanism is dominant in the present GaSe samples. Therefore, it is suggested that the Rashba SOI causes WAL and is attributed to the origin of the DP spin relaxation mechanism. The Rashba SOI is originated from structural inversion asymmetry, therefore, the above results indicate that the surface or the interface between GaSe and substrate plays an important role.

The temperature dependence of ℓ_ϕ and ℓ_{SO} extracted from the ILP analysis is plotted in Fig. 2, showing that ℓ_ϕ is almost inversely proportional to temperature T while ℓ_{SO} is independent of T. The strong T dependence of ℓ_ϕ is due to electron-electron scattering and has been reported in dirty 2D metals. The T independent properties of ℓ_{SO} suggest constant Rashba SOI strength as is discussed below.

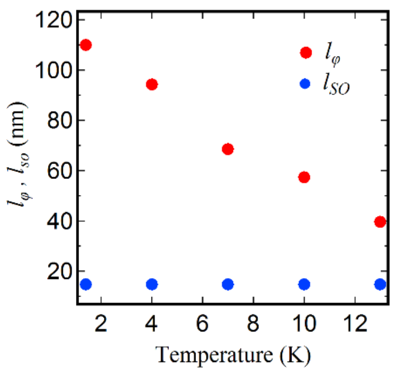

Fig. 2 Temperature dependence of phase coherence length ℓ_ϕ and spin relaxation length ℓ_{SO} extracted from the ILP analysis.

The relation between Rashba SOI strength α and spin relaxation length is given by the following equation [25].

$$\alpha = \frac{\hbar^2}{2\sqrt{2}\ell_{SO} m^*} \qquad (1)$$

To extract the Rashba SOI strength α , we need to know the value of effective mass m^* of GaSe layers. Recently, the effective mass of InSe thin film was found to be $m^*= 0.14$ - 0.17 from temperature dependence of Shubnikov-de Haas oscillation amplitude [6]. However, the data of effective mass in GaSe is very limited, so we assume $m^*= 0.25$ for GaSe film by taking the ratio of energy gap between InSe and GaSe into account [13]. By using the above assumption, the estimated α is about 7.2x 10^{-12} eVm, which is the same order of InGaAs QWs [14], and one order higher than that of GaAs QWs [15].

We measured the back gate voltage and in-plane magnetic field direction dependences of WAL. These results also suggest that the Rashba SOI is dominant over the Dresselhaus SOI. These results shed light on the spin transport and SOI induced intriguing phenomena in III-VI compound semiconductors thin films

4. Conclusions

Well-established WAL analysis used in III-V compound semiconductors were applied to III-VI compound GaSe layered film. The WAL, which is not expected only from the Dresselhaus SOI in GaSe, was observed at low temperatures. The WAL analysis reveals that the dominant spin relaxation mechanism is attributed to the DP mechanism with the Rashba SOI. The estimated Rashba SOI strength in the present GaSe film is as large as InGaAs QWs and one order larger than that in GaAs QWs.

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