Giant bipolar unidirectional photomagnetoresistance

Yucheng Jiang[1]

[1]School of Physical Science and Technology, Suzhou University of Science and Technology, Suzhou 215009, China
jyc@usts.edu.cn

Positive magnetoresistance (PMR) and negative magnetoresistance (NMR) describe two opposite responses of resistance induced by a magnetic field. Materials with giant PMR are usually distinct from those with giant NMR due to different physical natures. Here, we report the unusual photomagnetoresistance in the van der Waals heterojunctions of WSe_2/quasi-two-dimensional electron gas, showing the coexistence of giant PMR and giant NMR. The PMR and NMR reach 1,007.5% at –9 T and –93.5% at 2.2 T in a single device, respectively. The magnetoresistance spans over two orders of magnitude on inversion of field direction, implying a giant unidirectional magnetoresistance (UMR). By adjusting the thickness of the WSe_2 layer, we achieve the maxima of PMR and NMR, which are 4,900,000% and –99.8%, respectively. The unique magnetooptical transport shows the unity of giant UMR, PMR, and NMR, referred to as giant bipolar unidirectional photomagnetoresistance. These features originate from strong out-of-plane spin splitting, magnetic field–enhanced recombination of photocarriers, and the Zeeman effect through our experimental and theoretical investigations. This work offers directions for high-performance light-tunable spintronic devices.NMR)

Index Terms*: *Photomagnetoresistance, Spin polarization, Two-dimensional electron gas, Van der Waals heterojunction, WSe_2

I. Introduction

Ordinary magnetoresistance (MR) is commonly found in conductive materials [1]. Most materials show the positive magnetoresistance (PMR) effect originating from the Lorentz force [2]-[3], which describes a magnetic field–induced increase of resistance. In contrast, the negative magnetoresistance (NMR) usually results from the spin-dependent scattering in the magnetic materials [4]-[5]. Large MR effects have attracted much interest for their valuable applications as spintronic sensors and memory devices [6]-[8]. Distinct in their physical mechanisms, PMR and NMR effects often counteract each other, inevitably rendering one dominant over the other in a single large-MR material. To the best of our knowledge, there has been no report of the systems with both giant PMR and giant NMR.

In this work, we fabricated lateral van der Waals (vdW) heterojunctions between WSe_2 and quasi-two-dimensional electron gas (WSe_2/Q2DEG) on $SrTiO_3$ (STO) substrates. Since the vdW heterojunctions are electrically insulating at low temperatures, we focus on the magnetic transport behavior of photocarriers : that is, photomagnetoresistance. In this system, we observe the giant bipolar unidirectional photomagnetoresistance (GBU-PhMR). With the definition of MR = $[R(B) / R(0) - 1] \times 100\%$, $R(B)$ and $R(0)$ represent the resistances under the magnetic field and the zero field respectively. the single device shows PMR of 1,007.5% at –9 T and NMR of -93.5% at 2.2 T, indicating the coexistence of giant PMR and giant NMR. The MR changes over two orders of magnitude upon reversing the magnetic field, displaying a giant unidirectional magnetoresistance (UMR) effect. By adjusting the thickness of the WSe_2 layer, we achieve the maxima of PMR and NMR that are 4,900,000% and –99.8%, comparable with the highest values reported so far [e.g., about 15,000,000% for PMR at 1.8 K in gray arsenic [9] and about –99% for NMR at 2 K in CrI_3 [10]]. Through theoretical and experimental studies, the GBU-PhMR can be attributed to the combined effect of strong out-of-plane spin splitting, magnetic field–enhanced recombination of photocarriers, and the Zeeman effect. This work explores the unique magnetic transport of photocarriers in a WSe_2/Q2DEG heterojunction and its potential applications in high-sensitivity spintronic devices.

II. Results

Fig. 1a shows a schematic of WSe_2/Q2DEG heterostructure. Based on our recent work, the Ar^+ ion bombardment assistant (AIBA) method is used to fabricate the device [11]. We used the WSe_2 crystals with a 2H phase and the (100) STO substrates with a perovskite structure. After the AIBA fabrication, a vdW contact can be achieved at the edges of WSe_2 and Q2DEG in Fig. 1b. Due to the intrinsic p-type conduction of WSe_2, a p–n junction is formed at the interface of WSe_2 and Q2DEG.

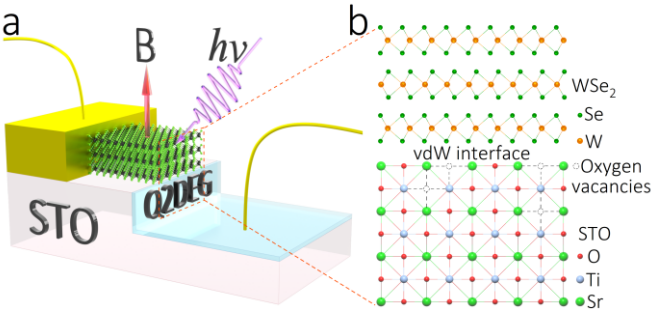

Fig. 1. Structure of the device. (a) Structural schematic of the WSe_2/Q2DEG heterostructure, showing the electric measurement under the magnetic field and light illumination. (b) Schematic diagram showing the vdW contact between WSe_2 and the oxygen-deficient STO surface.

Fig. 2a shows the MR as a function of the magnetic field, along the negative direction, the MR increases monotonously with the field, displaying giant PMR about 1,007.5%. However, the MR decreases greatly first and then, increases with the increase of the positive field. The largest NMR reaches –93.5% at 2.2 T). the device shows a coexistence of giant PMR and giant NMR accompanied by significant MR anisotropy depending on the sign of magnetic field, regarded as a GBU-PhMR effect. As is well known, the conventional MR materials usually exhibit the parity-symmetric field dependence of resistance. Distinctively, the GBU-PhMR device shows the

unidirectional dependence of MR on the magnetic field. The MR spans over two orders of magnitude on inversion of field direction, implying a giant UMR. We plotted the UMR vs. field curve in Fig. 2a, *Inset* with the definition of UMR = $[R(B) - R(-B)]/[R(B) + R(-B)] \times 100\%$. It is observed that the maximum UMR is over 95%, much higher than the other UMR materials reported recently.

Fig. 2b shows the *Resistance*$_j$ (R_j)–B curves with different thicknesses of WSe_2. Among them, the 11.3-nm device exhibits the largest PMR value and the approximate parity symmetry with respect to B = 0 T. The magnetic field induces an increase of R_j over four orders of magnitude, where MR = 4,900,000%. In the 40.3-nm sample, the NMR value reaches its maximum at 3.9 T, where MR = − 99.8%.

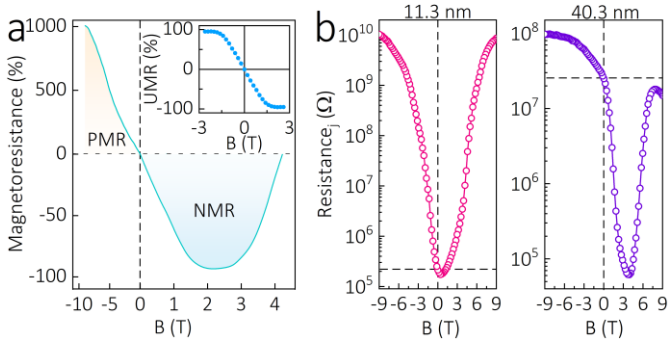

Fig. 2. GBU-PhMR. (a) Magnetic field dependence of magnetoresistance at continuous 405-nm optical illumination, where the different scales for positive and negative coordinates are used for a detailed description of giant PMR and NMR. (a, Inset) UMR vs. field. (b) *Resistance*$_j$–B curves at different WSe_2 thickness.

The definition of MR is usually used for measuring the large PMR effect. However, for large NMR, it is difficult to implement a detailed description of the resistance decrease induced by magnetic field if the resistance drops over two orders of magnitude. Thus, such a definition is not appropriate for the GBU-PhMR effect with both giant PMR and NMR. Here, we use MR_{GBU} defined as $MR_{GBU} = R(B)/R(0)$, to describe the giant PMR and NMR together. It is PMR if $MR_{GBU} > 1$ or NMR if $MR_{GBU} < 1$. In general, both PMR and NMR shown in the GBU-PhMR device are quite impressive, compared with other well-known materials with large PMR and NMR, it is in the most excellent category, as shown in Fig. 3.

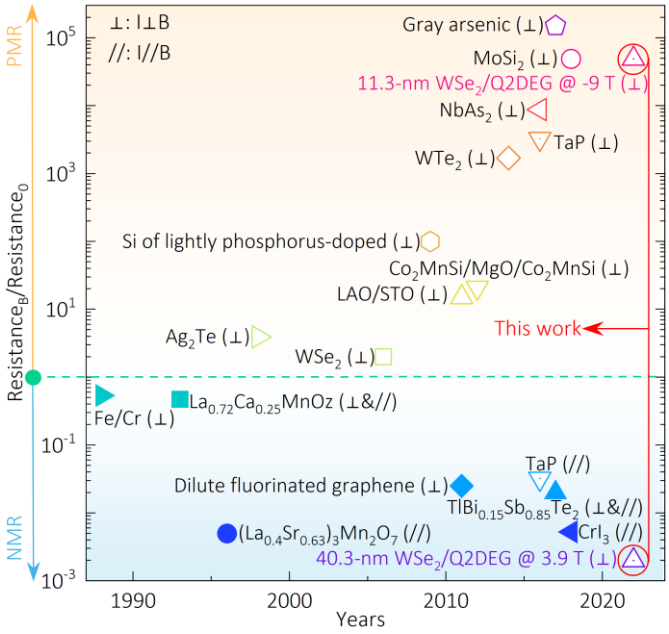

Fig. 3. A comparison of PMR and NMR of some well-known spintronic materials over four decades; 11.3- and 40.3-nm WSe_2/Q2DEG heterojunctions exhibit the giant PMR and NMR, respectively, comparable with those classic PMR and NMR materials. The symbols ⊥ and // show the current perpendicular and parallel to the magnetic fields, respectively.

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