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Fabrication of high performance solar cells with few-layered WSe_2

○Yoshiki Yamaguchi, Wakana Okita, Toshiki Akama, Chao Li, Toshiro Kaneko, and Toshiaki Kato

Department of Electronic Engineering, Tohoku University, Sendai, 980-8579, Japan
Tel: +81-22-795-7046, E-mail: yoshiki.yamaguchi.t5@ecei.tohoku.ac.jp

Abstract

Mono- or few-layered transition metal dichalcogenides (TMDs) are known as true two-dimensional materials. They have excellent semiconducting properties with strong light-matter interaction. Thus, TMD is an attractive material for semitransparent and flexible solar cells. In spite of the recent progress of solar cells with TMD, the development of a scalable method to fabricate semitransparent and flexible solar cells with mono- or few-layered TMD still remains a crucial challenge. Here, we show an easy and scalable fabrication of a few-layered TMD solar cell using a Schottky-type configuration to obtain a power conversion efficiency (PCE) of approximately 0.01%. Because high solar cell performance along with excellent scalability can be achieved through the proposed process, our finding can contribute to accelerating the industrial use of TMD as the semitransparent and flexible solar cell.

1. Introduction

Atomic scale 2D sheets attract intense attention due to their superior electrical, mechanical, and optical features. Layered transition metal dichalcogenide (TMD) is known as a true 2D material with excellent semiconducting properties (Fig. 1(a)) [1]. TMD is one of the most attractive materials for future high performance transparent and flexible solar cells due to their atomically thin structure, band gap in visible light range, and high optical transparency. Although the solar cell of TMD has been widely investigated by many groups, those are based on the pn junction type solar cell. Since complicated structures are required to form pn junction structures in TMD such as dual gate electrodes or position selective doping, the device size of pn junction solar cell with TMD is limited within very small region (few μm). The Schottky type solar cell is known as another type of solar cell and it is possible to scale up the device up to the practical size because of the simple device structures. However, the detailed study of Schottky type solar cell with TMD has not been reported.

Because the Schottky barrier is formed at the contact region between electrode and TMD, it is important to select appropriate electrode pairs for end of electrodes. In this study, we have investigated the combination of end electrodes and the distance of each electrode to obtain the better performance. Through the adjustment of these factors we have succeeded in the fabrication of the high performance Schottky type solar cells with few-layer WSe_2.

2. Experimental

Device fabrications were carried out by following process. First, few-layered TMD was prepared by mechanical exfoliation from a bulk crystal (2D semiconductor) with blue tape (HAKUTO) and transferred to a SiO_2 (300 nm)/Si substrate. Then, conventional photolithography, electron beam lithography, vacuum evaporation of metal, and lift off were used to fabricate the symmetric and asymmetric devices. For the suspended device fabrication, TMD was position-selectively transferred to the electrode pattern by a homemade transfer system with a micro positioner and microscope.

Device performance was measured with a vacuum probe station with a semiconductor parameter analyzer (HP 4155C) at room temperature.

3. Results and discussion

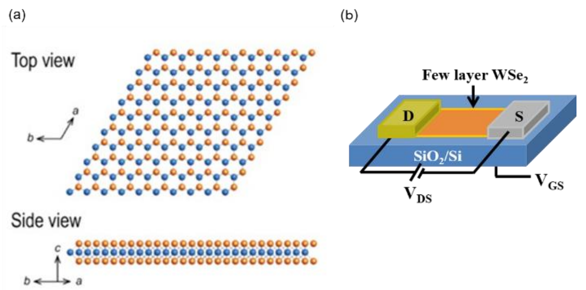

Fig. 1. (a) Schematic illustration of the monolayer WSe_2 structure. The yellow and blue spheres represent Se and W atoms, respectively. (b) Typical image of FET device with few-layer WSe_2.

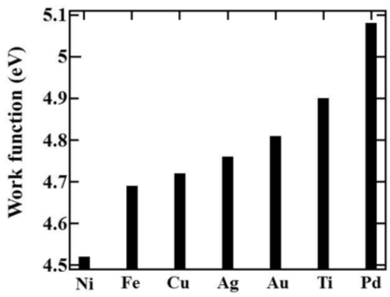

Fig. 2. Work function of various metals measured by photoelectron yield spectroscopy (PYS).

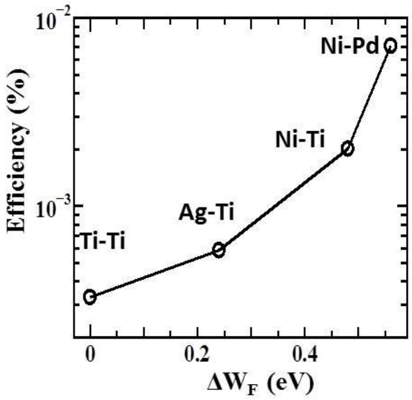

Fig. 3. Plot of PCE vs. ΔW_F for various electrode pairs used in solar cell device. (The distance between the electrodes is 10 μm.)

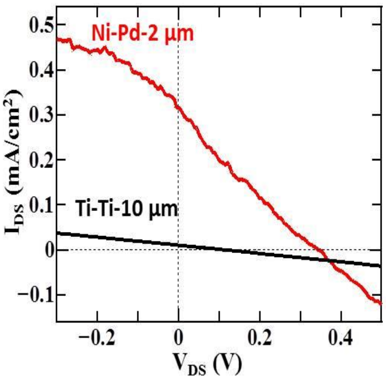

Fig. 4. Typical I_{DS}-V_{DS} characteristics of few-layer WSe_2 Schottky solar cells with light illumination.

In this study, we used tungsten diselenide (WSe_2) as a TMD material. A Schottky-type solar cell was fabricated via mechanical exfoliation from bulk WSe_2 crystal. First, the photovoltaic features were measured with symmetric Ti electrodes (Ti electrode was covered by 30 nm Au to protect Ti surface from oxidation) (Fig. 1(b)). The structures of WSe_2 were characterized by atomic force microscopy (AFM), optical microscopy (OM), Raman scattering, and photoluminescence (PL) spectroscopy. The source-drain current (I_{DS}) vs. source-drain voltage (V_{DS}) curve with light illumination was measured for the symmetric source and drain electrode (T_i). A clear short circuit current (I_{sc}) and open circuit voltage (V_{oc}) were observed. Based on the photocurrent mapping measurements, we confirmed that power generation occurred only at the contact region between the electrode and WSe_2, indicating that Schottky-type power generation occurred in this device. Since the photogenerated carriers travel in the opposite direction at both ends of the electrode, the photocurrent generated at the left and right sides of the electrode should, in principle, cancel out, resulting in zero power generation. Therefore, the power generation obtained must be caused by inhomogeneous contact between the left and right electrodes. By following this model, an ideal structure can be realized, where only one of the electrodes generates carriers with the Schottky barrier and the other electrode effectively collects the carriers with Ohmic-like contact. Then, we attempted to find a suitable electrode pair for Schottky-type solar cells with WSe_2. Since the contact structure between the electrode and WSe_2 is basically governed by the work function difference of each material, we systematically measured the work function (WF) of various metals used as electrodes by photoelectron yield spectroscopy. Figure 2 shows the obtained WF for various metals. Since "as exfoliated few-layered WSe_2" is naturally p-doped by some impurities, the Fermi energy of our WSe_2 can be assumed to be around 5 eV. Thus, Ti (WF = 4.9 eV) or Pd (WF = 5.08 eV) can work as an Ohmic contact for few-layered WSe_2, whereas Ni (WF = 4.52 eV), which has the lowest work function in this measurement, can form a large Schottky barrier at the contact region with WSe_2. A Schottky-type solar cell with an asymmetric electrode pair was fabricated with various electrodes. A clear difference in I_{ds}-V_{ds} could be observed depending on the electrode pair under light illumination with a solar simulator. The normalized PCE was plotted as a function of the WF difference between the left and right sides of the electrode (ΔW_F) (Fig. 3). The efficiency clearly depended on ΔW_F, and a higher efficiency could be obtained with higher ΔW_F (Pd-Ni), which is consistent with our concept, where Ni and Pd can form large and small Schottky barriers to operate as power-generation and carrier-collect regions, respectively.

The electrode distance is also important factor to decide the dynamics of optically-generated carriers. Then the distance of both electrode was systematically adjusted between 0.5 to 14 μm. It is found that the highest efficiency can be given with 2.2 μm distance. The photocurrent mapping measurements revealed that the suitable distance should be decided by the balance of exciton diffusion length and momentum transfer distance of separated carriers. Based on these optimizations of electrodes and distance, the power conversion efficiency can be reached up to 0.01 %, which is 40 times higher than that before the optimization (symmetric electrodes with long distance) (Fig. 4). This power conversion efficiency is comparative or slightly higher than that of pn junction type solar cell with similar TMD thickness.

4. Conclusions

We developed a high-performance Schottky type solar cell with few-layered WSe_2. The Pd-Ni electrode showed the highest PCE because of the asymmetric contact of Pd-WSe_2 and Ni-WSe_2 as Ohmic-like and Schottky-type contacts, respectively. Based on the systematic investigation of the electrode type and distance adjustment, PCE can be improved up to 0.01%, which is the relatively high value among solar cells with similar TMD thicknesses. Since our established Schottky type solar cell with asymmetric electrodes can be easily scale up, our findings can contribute to the practical application of TMD-based flexible and transparent solar cells.

References

[1] T. Kato and T. Kaneko, ACS Nano **8**, 12777 (2014).