Plasma-Induced Phase Transformation of SnS$_2$ to SnS

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Layered van der Waals materials have recently attracted attention owing to their exceptional electrical and optical properties in thin layer form. One way to extend their utility is to form a heterostructure which combines various properties of layered materials to reveal intriguing behavior. Conventional heterostructure synthesis methods are difficult to develop and the heterostructure formed can be limited to a small area. Here, we investigate the phase transformation of SnS$_2$ to SnS by removing sulfur atoms at the top surface using Ar plasma. By varying the plasma power and exposure time, we observed that SnS is subsequently formed on top of the mogul-like structure of SnS$_2$. Since SnS is a $p$-type semiconductor and SnS$_2$ is an $n$-type semiconductor, we naturally formed a vertical $p$-$n$ junction.

By using graphene at the top and bottom as transparent electrodes, a vertical $p$-$n$ diode device is constructed. The device demonstrates good rectifying behavior and large photocurrent generation under white light. This method can be applied to large-area heterostructure synthesis using plasma via phase transformation of various metal dichalcogenides to metal monochalcogenides.

Motivated by graphene with extremely high electrical mobility but poor on/off current ratio, which is a serious drawback for switching device applications, other types of two-dimensional (2D) layered materials such as layered metal dichalcogenides and h-BN have emerged recently as promising candidates for devices with both high mobility and high on/off current ratio. Numerous research studies have focused on their physical, chemical, thermal, mechanical, and optical properties$^{1-4}$. The most common sample preparation method is mechanical exfoliation. Since the size is limited to a few micrometers, this is an obstacle for some measurements and for industrial-scale manufacture, several methods of synthesizing large area samples have been developed. One typical simple method is chemical vapor deposition (CVD), which is a reasonable approach for wafer-scale fabrication with fairly good sample quality achievable$^{5-10}$.

While layered metal dichalcogenides themselves reveal various intriguing properties, many interesting properties emerge in heterostructures, the construction of which using CVD approaches is still an exploratory area$^{11-15}$. Although there are a few reports of CVD-grown vertical heterostructures, most researchers aim for lateral heterostructures. Lateral heterostructures composed of transition metals (Mo and W) and chalcogens (S and Se), such as MoS$_2$-WS$_2$, MoS$_2$-WSe$_2$, WS$_2$-WSe$_2$, and MoS$_2$-MoSe$_2$ have been grown using a CVD method$^{16-19}$. Although the size is still limited to several micrometers, these monolayer lateral heterostructures demonstrate two well-defined regions which show typical diode behavior due to work function difference$^{20-22}$. An atomically sharp interface is, however, difficult to control while avoiding overlapped regions. In addition, the junction area is too narrow and hence, large optical gain cannot be expected. To overcome this obstacle, CVD-grown vertical heterostructures could be an ideal platform for practical optoelectronics. When two different materials are grown vertically, the entire overlapped region can be considered as a heterojunction. The effective area for carrier transport and light detection is larger than that of a lateral heterostructure$^{21,22}$. Furthermore, in situ CVD-grown vertical heterostructures may ensure a clean interface. The interface can significantly alter carrier transport and optoelectronic properties depending on the quality of interface$^{23,24}$. Nevertheless, the realization of CVD-grown vertical heterostructures over large areas has been sparse and remains elusive.

Another approach to form heterostructures is to take advantage of structural phase transformation$^{25,26}$. Phase transition from semiconducting to metallic phase has been provoked via laser irradiation$^{27,28}$ or Li-intercalation$^{29}$.

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to reduce contact resistance in field-effect transistors. Up to now, these methods have been restricted to the modification of phases in the lateral direction. Another interesting method to achieve vertical heterostructures is to use electron beam or laser irradiation on a SnS2 (tin disulfide) thin film and to convert the top layers into SnS (tin monosulfide) to form a SnS2-SnS heterostructure. While this method yields an in situ vertical heterostructure at the irradiated area, which is advantageous for micro-patternning, phase conversion of the whole area is still not easily achievable.

In this work, we used Ar ion bombardment to induce the phase transformation of a SnS thin film and constructed a semiconductor heterostructure of the converted top SnS and the remaining bottom SnS2. Sulfur atoms are partially kicked out from SnS2 to form a stable orthorhombic SnS phase. The constructed vertical heterostructure of n-SnS/p-SnS2 forms a type II p-n band alignment, which clearly demonstrates the diode characteristics.

**Methods**

**Sample preparation.** Commercially available SnS2 single crystal was purchased (2D semiconductors). The SnS2 crystal was then transferred onto a 300 nm SiO2 (300 nm)/Si substrate by mechanical cleavage. Ar plasma treatment was conducted by a reactive ion etch (RIE) system (AFS-R4T, All For System). The system is equipped with CCP (capacitively-coupled plasma) source type bottom plasma source with a 13.56 MHz bottom RF generator. Prior to plasma exposure, the vacuum chamber was filled with Ar gas of 50 sccm for 10 minutes to remove any residual gas such as N2 or O2. The as-prepared sample was put into the RIE vacuum chamber and pumped out to reach a basal pressure below 20 mtorr. Ar gas flow was fixed to 20 sccm for all experiments. The power of Ar plasma was controlled from 40 W to 140 W depending on the experimental conditions. Exposure time was also varied from 20 s to 120 s. An optical microscope (BX51RF, Olympus) was used to observe color and morphology change before and after plasma treatment. All procedures mentioned above were conducted in a clean room of a class of 1000.

**Characterization.** Thickness and morphology were checked using atomic force microscopy (AFM) (E-sweep, Seiko). Micro-Raman spectroscopy (RM1000-Invia, Renishaw, 532 nm) were performed before and
after the plasma treatment for material property analysis. For transmission electron microscopy (TEM) measurements (JEM ARM200F, JEOL), two types of samples were prepared. For top-view measurement, a SiO\textsubscript{2}/Si substrate with plasma-treated flakes was immersed in a buffered oxide etchant (1178-03, J.T. Baker) for detachment. The resulting flakes were transferred onto a TEM grid. To obtain cross-sectional TEM images, the samples were prepared with a focused ion beam (JIB-4601F, JEOL). For elemental analysis, Energy-dispersive X-ray spectroscopy (EDS) in TEM was employed.

**Device fabrication and electrical measurement.** Graphene was mechanically exfoliated on a pre-patterned SiO\textsubscript{2} (300 nm)/Si substrate. The plasma-treated flake was then transferred with alignment onto graphene flake. Another piece of graphene flake was again transferred on the pre-stacked heterostructure for the top electrode. E-beam lithography was conducted to pattern electrical pads that connect from the top and bottom graphene, followed by e-beam deposition of Cr/Au (5/50 nm). Electrical characterization and photocurrent measurements were conducted with a laboratory-built probe station equipped with Agilent B2902A precision source/measure unit.

**Results and Discussions**

A schematic illustration of SnS\textsubscript{2} to SnS phase transformation is shown in Fig. 1(a). Bulk SnS\textsubscript{2} was mechanically exfoliated on a Si substrate with a 300 nm thermally oxidized SiO\textsubscript{2} layer. The sample was subsequently put into a reactive ion etch (RIE) chamber for plasma treatment (See Methods section). Ar plasma generated by RF plasma was accelerated to collide onto SnS\textsubscript{2} flakes. After Ar\textsuperscript{+} radicals strike the surface of SnS\textsubscript{2}, they transfer their kinetic energy to the SnS\textsubscript{2} flake. The transferred kinetic energy can break the Sn-S bonding. As a consequence, both S and Sn atoms can be kicked out from the SnS\textsubscript{2} surface\textsuperscript{30}. S atoms are more likely to escape from SnS\textsubscript{2} than Sn atoms due to their lighter mass, which could induce a SnS phase on the top of SnS\textsubscript{2}. Plasma treatment will first remove SnS\textsubscript{2} layers which results in thinning of the flake. Figure 1(b,c) are optical images and atomic force microscopy (AFM) images of the pristine and Ar plasma-treated SnS\textsubscript{2} flake. It clearly shows that the thickness decreases from 68 nm to 13 nm after plasma treatment.

Figure 2. (a) AFM scanning of plasma treated surface of SnS\textsubscript{2} flake. All images were exposed for 20 seconds. Scale bar insist 500 nm. (b) Grain size and root-mean-square (RMS) value variation under different plasma power. Grain size and RMS value increase significantly as plasma power increases. (c) SnS peak evolution measured by Raman spectroscopy with varied time and plasma power. The graph is mapped according to SnS A\textsubscript{1g} peak (97 cm\textsuperscript{-1}).
probe force microscopy (KFM) scanning. For this sample, we deposited Au metal to partially passivate the surface of the SnS₂ flake via patterning by electron beam lithography. We then exposed the sample to plasma irradiation. The Au layer was etched away later by Au etchant (TFA, Transene). The left image is a topography scanning image which shows two distinct regions with different contrast. The upper region is the plasma-treated region while the lower region is a pristine region. Interestingly, the KFM shows a distinct contrast, with a chemical potential difference of ~70 mV (right in Fig. 1(e)), which is attributed to the emerging phase of SnS at the exposed area.

To observe the evolution of phase and morphology change, we conducted AFM measurements. Figure 2(a) shows the AFM topography of the plasma-treated SnS₂ flake. The plasma power was varied from 60 W to 140 W, while fixing Ar gas flow at 20 sccm and exposure time to 20 s. We clearly observe granular structures on the sample surface. Unlike ideal isotropic etching, the surface of the flake has mogul-like shapes after plasma treatment. As the power increases, the hemispheres of the moguls grow larger in diameter and the root-mean-square (RMS) value also increases (Fig. 2(b)).

We investigated the evolution of phase change from SnS₂ to SnS as a function of the power and time for plasma. The plasma power was varied from 60 W to 140 W in intervals of 20 W, while the exposure time was chosen to be 10, 20, 30, 60, and 120 s. Ar gas flow was fixed at 20 sccm. Figure 2(c) shows the intensity changes of the SnS A₁ peak near 97 cm⁻¹, a typical Raman peak that implies phase transformation from SnS₂ to SnS. The peak intensity is at a maximum at around 120 W for 20 s. At low plasma power, no SnS peak was detected, even at a longer exposure time of 120 s. The SnS₂ surface was etched away, resulting in thinning of SnS₂ with minimal SnS formation. Excessive plasma treatment with high power and long exposure time decreases the SnS peak, presenting degradation of the SnS lattice. We conclude that an intensive exposure at high power and short time would maximize the amount of SnS on the SnS₂ surface.

To analyze its atomic structure, cross-sectional transmission electron microscopy (TEM) was used. The flake was exposed to 120 W Ar plasma for 180 s and subsequently cut with a focused ion beam (FIB) for cross-section imaging. Figure 3(a) shows a cross-section image which reveals pillar-like structures formed on the upper part of the flake. Although the exact mechanism is not clear, it is possible that plasma preferentially attacks defects under optimum plasma conditions, resulting in a different etching rate in the perpendicular direction, thus creating a pillar-like structure. Meanwhile, plasma removes sulfur atoms from the remaining SnS₂. This leads to SnS formation throughout the surface of the pillar structure, increasing the SnS portion, as evidenced by the Raman signals. Energy-dispersive X-ray spectroscopy (EDS) mapping of the same area indicates that while Sn atoms exist in the overall region (Fig. 3(b)), the S ratio was dramatically reduced at the top of the pillar structure (Fig. 3(c)). Figure 3(d) is a cross-sectional high-resolution transmission electron microscopy (HR-TEM) image.
of the pillar-like region. The configuration depicts vertical heterostructure overall but reveals a mixed orientation of SnS on single-crystal SnS$_2$. As shown in Fig. 3(d), two distinct regions can be observed with a significant difference in the interlayer distance. The pristine SnS$_2$ region has an interlayer distance of 0.6 nm, while the SnS region has an interlayer distance of 0.295 nm$^{33-38}$. Despite the fact that the SnS$_2$ region has a single-crystalline structure, the plasma etching results in the formation of poly-crystalline SnS. The crystal orientation of the SnS is randomly formed above SnS$_2$. Fast Fourier transform (FFT)-diffraction analysis observed in each region is shown in Fig. 3(e). The interlayer distance of two materials can be precisely measured from this image. Furthermore, it is difficult to obtain structural information from top-view HR-TEM but the FFT-diffraction image obtained from the red-boxed region shows coexistence of the two materials (Fig. 3(f)). Both hexagonal SnS$_2$ and orthorhombic SnS can be observed from FFT-diffraction$^{38}$.

We further demonstrated a vertical transistor using the SnS-SnS$_2$ heterostructure. Figure 4(a) shows a schematic illustration and optical image of a SnS-SnS$_2$ heterostructure vertical device. After plasma treatment, the SnS-SnS$_2$ heterostructure (white dotted area) was align-transferred on the bottom graphene electrode (blue dashed area) and top graphene electrode (green dotted area). Active device region (yellow colored area) is the overlapped region. Scale bar is 10$\mu$m. (b) Rectifying behavior of the diode. Ideality factor (n) is calculated to be 3.20 (inset). (c) Photocurrent measurement under white light exposure. Under white light illumination, rapid increase of photocurrent is observed. (d) A schematic drawing of band alignment and photocurrent generation of graphene-SnS-SnS$_2$-graphene vertical device.

Figure 4. (a) A schematic illustration (left) and optical image (right) of SnS-SnS$_2$ heterostructure $p$-$n$ diode. The scheme illustrates graphene-SnS-SnS$_2$-graphene stacked layers. Optical image shows the top-view of the device. Plasma treated SnS$_2$ flake (SnS-SnS$_2$ heterostructure; white dotted line) is sandwiched between bottom graphene electrode (blue dotted line) and top graphene electrode (green dotted line). Active device region (yellow colored area) is the overlapped region. Scale bar is 10$\mu$m. (b) Rectifying behavior of the diode. Ideality factor (n) is calculated to be 3.20 (inset). (c) Photocurrent measurement under white light exposure. Under white light illumination, rapid increase of photocurrent is observed. (d) A schematic drawing of band alignment and photocurrent generation of graphene-SnS-SnS$_2$-graphene vertical device.
SnS$_2$ (n-type) form a p-n junction and show typical rectifying diode behavior (Fig. 4(b)). The diode performance shown in Fig. 4(b) (inset) can be estimated using the Shockley diode equation, which is expressed as:

$$I = I_0 \left( \exp \frac{qV}{nkT} - 1 \right)$$

where $I$ is diode current, $I_0$ is reverse bias saturation current, $V$ is the voltage across the diode, $n$ is ideality factor and $T$ is temperature. $q$ and $k$ are constants which are elementary charge and Boltzmann constant, respectively. Ideality factor ($n$) usually relates to junction quality and varies from 1 to 2 in a conventional diode. From the Shockley diode equation, our device shows an ideality factor of $n = 3.20$. This high $n$ value is attributed to defects and trap sites at the junction area developed during plasma treatment which promote the carrier recombination process. Previous reports from the literature have shown that in two-dimensional layered structures, an ideality factor of $>2$ is frequently observed since the defect sites play a more significant role, while defect healing methods can improve such issues. A possible photocurrent generation mechanism was depicted in Fig. 4(d). SnS$_2$ is an n-type semiconductor with ~2.2 eV bandgap. SnS, on the other hand, is a p-type semiconductor with ~1.2 eV bandgap. SnS$_2$ and SnS form staggered band alignment with type II heterojunctions, resulting in typical rectifying diode behavior as shown in Fig. 4(b). Typical photovoltaic photocurrent generation from p-n junction should reveal the open-circuit voltage ($V_{oc}$) and short-circuit current ($I_{sc}$). However, these parameters do not appear clearly in this measurement, which is attributed to carrier recombination from large trap density caused by plasma damage. Therefore, we explain our photoresponse results with the photoconductivity effect. Under light illumination, carriers are photo-excited in both materials creating electrons and holes. Due to band bending, electrons that are created in SnS move to lower energy region (SnS$_2$ conduction band) while hole that are created in SnS$_2$ move to SnS valence band. These carriers reach top and bottom graphene contacts under applied bias.

**Conclusion**

We have investigated the phase transformation of SnS$_2$ to Sn by Ar plasma treatment. By removing S atoms on the surface of SnS$_2$, we successfully synthesized a SnS-SnS$_2$ heterostructure. Anisotropic etching is observed which forms pillar-like structure on the surface which is covered with SnS. SnS is well formed when exposed to high power for a short duration. Since SnS is a p-type and SnS$_2$ is an n-type, we made a vertical diode using graphene for transparent electrodes and measured IV characteristics. Electric field formation between the two materials led to photocurrent generation under white light illumination.

**References**

1. Duong, D. L., Yun, S. J. & Lee, Y. H. Van der Waals Layered Materials: Opportunities and Challenges. ACS Nano 11, 11803–11830 (2017).
2. Chhowalla, M. et al. The Chemistry of Two-dimensional layered transition metal dichalcogenide nanosheets. Nat. Chem. 5, 263–275 (2013).
3. Choi, W. et al. Recent development of two-dimensional transition metal dichalcogenides and their applications. Mater. Today 20, 116–130 (2017).
4. Tan, C. et al. Recent Advances in Ultrathin Two-Dimensional Nanomaterials. Chem. Rev. 117, 6225–6331 (2017).
5. Yun, S. I. et al. Synthesis of Centimeter-Scale Monolayer Tungsten Disulfide Film on Gold Foils. ACS Nano 9, 5510–5519 (2015).
6. Yun, S. I., Kim, S. M., Kim, K. K. & Lee, Y. H. A systematic study of the synthesis of monolayer tungsten diselenide films on gold foils. Curr. Appl. Phys. 16, 1216–1222 (2016).
7. Park, J. C. et al. Phase-Engineered Synthesis of Centimeter-Scale 1T’- and 2H-Molybdenum Ditelluride Thin Films. ACS Nano 9, 6548–6554 (2015).
8. Kim, H. et al. Role of alkali metal promoter in enhancing lateral growth of monolayer transition metal dichalcogenides. Nanotechnology 28, 36LT01 (2017).
9. Han, G. H. et al. Absorption dichroism of monolayer 1T’-MoTe2 in visible range. 2D Mater. 3, 031010 (2016).
10. Park, J. H. et al. Large-Area Monolayer Hexagonal Boron Nitride on Pt Foil. ACS Nano 8, 8520–8528 (2014).
11. Doan, M.-H. et al. Charge Transport in MoS2/WSe2 van der Waals Heterostructure with Tunable Inversion Layer. ACS Nano 11, 3832–3840 (2017).
12. Lee, C.-H. et al. Atomically thin p-n junctions with van der waals heterointerfaces. Nat. Nanotechnol. 9, 676–681 (2014).
13. Furchi, M. M., Pospischil, A., Libisch, F., Burgdorfer, J. I. & Mueller, T. Photovoltaic Effect in an Electrically Tunable van der Waals Heterojunction. Nano Lett. 14, 4785–4791 (2014).
14. Cheng, L. et al. Electroluminescence and Photocurrent Generation from Atomically Sharp WSe2/MoS2 Heterojunction p-n Diodes. Nano Lett. 14, 5590–97 (2014).
15. Jin, Y. et al. A Van Der Waals Homojunction: Ideal p-n Diode Behavior in MoS2. Adv. Mater. 27, 5534–5540 (2015).
16. Huang, C. et al. Lateral heterojunctions within monolayer MoS2/WSe2 semiconductors. Nat. Mater. 13, 1096–1101 (2014).
17. Gong, Y. et al. Two-Step Growth of Two-Dimensional WSe2/MoS2 Heterostructures. Nano Lett. 15, 6135–6141 (2015).
18. Zhang, X.-Q., Lin, C.-H., Tseng, Y.-W., Huang, K.-H. & Lee, Y.-H. Synthesis of Lateral Heterostructures of Semiconducting Atomic Layers. Nano Lett. 15, 410–415 (2015).
19. Chiu, M.-H. et al. Determination of band alignment in the single-layer MoS2/WSe2 heterojunction. Nat. Commun. 6, 7666, https://doi.org/10.1038/ncomms8666 (2015).
20. Ling, X. et al. Parallel Stitching of 2D Materials. Adv. Mater. 28, 2322–2329 (2016).
21. Duan, X. et al. Lateral epitaxial growth of two-dimensional layered semiconductor heterojunctions. Nat. Nanotechnol. 9, 1024–1030 (2016).
22. Gong, Y. et al. Vertical and in-plane heterostructures from WS2/MoS2 monolayers. Nat. Mater. 13, 1135–1142 (2014).
23. Luong, D. H. et al. Tunneling Photocurrent Assisted by Interlayer Excitons in Staggered van der Waals Hetero-Bilayers. Adv. Mater. 29, 1–8 (2017).
Amani, M.

Wang, F.

Pospischil, A., Furchi, M. M. & Mueller, T. Solar-energy conversion and light emission in an atomic monolayer p-n diode.

Y e, L., Li, H., Chen, Z. & Xu, J. Near-Infrared Photodetector Based on MoS2/Black Phosphorus Heterojunction.

Liu, Y.

Yue, G. H., Wang, L. S., Wang, X., Chen, Y. Z. & Peng, D. L. Characterization and Optical Properties of the Single Crystalline SnS Nanowire Arrays. 

Chao, D. et al. Array of nanosheets render ultrafast and high-capacity Na-ion storage by tunable pseudocapacitance. Nat. Commun., 7, 12122, https://doi.org/10.1038/ncomms12122 (2016).

Dean, C. R. et al. Boron nitride substrates for high-quality graphene electronics. Nat. Nanotechnol. 5, 722–726 (2010).

Cui, X. et al. Multi-terminal transport measurements of MoS2 using a van der Waals heterostructure device platform. Nat. Nanotechnol. 10, 534–540 (2015).

Liu, Y. et al. Toward Barrier Free Contact to Molybdenum Disulfide Using Graphene Electrodes. Nano Lett. 15, 3030–3034 (2015).

Neudeck, G. W. & Pierret, R. F. The PN Junction Diode. In Modular Series on Solid State Devices Addison Wesley Publishing Vol. 2 (1989).

Pospischil, A., Furchi, M. M. & Mueller, T. Solar-energy conversion and light emission in an atomic monolayer p-n diode. Nat. Nanotechnol., 9, 257–261 (2014).

Ye, L., Li, H., Chen, Z. & Xu, J. Near-Infrared Photodetector Based on MoS2/Black Phosphorus Heterojunction. ACS Photonics 3, 692–699 (2016).

Wang, F. et al. Tunable GaTe-MoS2 van der Waals p-n junctions with Novel Optoelectronic Performance. Nano Lett. 15, 7558–7566 (2015).

Amani, M. et al. Near-unity photoluminescence quantum yield in MoS2. Science 350, 1065–1068 (2015).

Campbell, P. & Green, M. A. Light trapping properties of pyramidally textured surfaces. J. Appl. Phys. 62, 243 (1987).

Burton, L. A. et al. Synthesis, Characterization, and Electronic Structure of Single-Crystal SnS, SnS2, and SnS3. Chem. Mater. 25, 4908–4916 (2013).

Chia, X., Lazar, P., Sofer, Z., Luxa, J. & Pumera, M. Layered SnS versus SnS2: Valence and Structural Implications on Electrochemistry and Clean Energy Electrocatalysis. J. Phys. Chem. C 120, 24098–24111 (2016).

Burton, L. A. et al. Electronic and optical properties of single crystal SnS2: an earth-abundant disulfide photocatalyst. J. Mat. Chem. A, 4, 1312 (2016).

Devika, M., Koteeswara Reddy, N., Patolsky, F. & Gunasekhar, K. R. Ohmic contacts to SnS films: Selection and estimation of thermal stability. J. Appl. Phys. 104, 124503 (2008).

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Author Contributions
J.H.K. and S.J.Y. designed the experiment system. J.H.K. conducted plasma treatment, Raman spectroscopy, AFM, device fabrication and device measurement. S.J.Y. performed Raman spectroscopy and TEM analysis. H.S.L. contributed to data analysis and manuscript preparation. J.Z. conducted TEM measurement. H.B. contributed to data analysis. Finally, Y.H.L. contributed to experiment planning and manuscript preparation.

Additional Information
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