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Citation: Chin. Phys. B . 2018, 27(2): 028103. **doi:** 10.1088/1674-1056/27/2/028103

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Observation of oscillations in the transport for atomic layer MoS_2*

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(Received 7 July 2017; revised manuscript received 9 November 2017; published online 5 January 2018)

In our experiment, an atomic layer MoS_2 structure grown on SiO_2/Si substrates is used in transport test. The voltage $U_{14,23}$ oscillates and the corresponding period varies with applied current. The largest period appears at 45 μA. The oscillation periods are different when samples are under laser radiation or in darkness. We discover that under the laser irradiation, the oscillation period occurs at lower current than in the darkness case. Meanwhile, the drift velocity is estimated at $\sim 10^7$ cm/s. Besides, by studying the envelope of $U_{14,23}$ versus applied current, we see a beating phenomenon at a certain current value. The beating period in darkness is larger than under laser irradiation. The difference between beating periods reveals the energy difference of electrons. Similar results are obtained by using different laser power densities and different light sources. The possible mechanism behind the oscillation period is discussed.

Keywords: atomic-layer MoS_2, oscillations in the transport, circular polarized light, photo-excited carriers

PACS: 81.07.–b, 73.23.–b, 68.65.–k **DOI:** 10.1088/1674-1056/27/2/028103

1. Introduction

Two-dimensional molybdenum disulfide (2D-MoS_2) with honeycomb structure is one of the most attractive members of transition metal dichalcogenides (TMDs).[1] Unlike graphene, inversion symmetry is broken in 2D-TMD (2D-MoS_2), resulting in spin splitting in the valence bands. Broken spin degeneracy, together with time-reversal symmetry, leads to inherent coupling between valley and spin on the valence bands.[2] The valley-selective circular dichroism is tightly cooperated with 2D-TMD, including 2D-MoS_2.[3–6]

Valley Hall effect with the feature of electrons acquiring transverse velocities was observed.[7] Photo-induced current of layered MoS_2-based transistor was studied.[8] Experimentally a spin-coupled valley photocurrent was demonstrated,[9] whose direction and magnitude depend on the degree of circular polarization of the incident radiation and can be further modulated by an external electric field. The room-temperature generation and electrically-controlled valley and spin photocurrent pave the way for investigating the electrons in such systems. Therefore, it enables an additional degree of freedom in quantum-confined spintronic device. All the measurements on the spin photocurrent generation were performed at room temperature. Based on such intriguing features, atomically thin 2D-TMD (2D-MoS_2) shows great promise in electrical and optical devices.[10,11]

The physics of layered TMD is abundant and the phase diagrams are very rich. For example, the metallic edge state of single layer MoS_2 was observed.[12] During transport, electrons induced by the electrostatic field effect are populated in the edge states before occupying the bulk.[12] Atomic layer crystals of MoS_2 are also regarded as a class of material that shows strong light–matter interaction,[13,14] which can result in the formation of exciton polariton at high temperature. The coupling between the 2D excitons and the "cavity photons" has been experimentally observed.[13] In this sense, 2D-MoS_2 can provide delocalized (Wannier–Mott) excitons with a valley degree of freedom.[14]

In the meantime, imperfections are inevitable during fabrication and experiments,[15,16] so that in-gap bound states are introduced. The electrical and optical properties of 2D-MoS_2 are significantly affected by impurities and the dielectric environment.[10] The scattering and disorder originate from lattice defects, charged impurities in the substrates or surface adsorbates.[10,17] In samples synthesized by different conditions there appear various features. For example, in atomic layer MoS_2, the chemical ratio of S/Mo was reported to be in a range rather than 2 in the stoichiometric formula.[18,19]

Methodologically, the valley-polarized 2D-MoS_2 multi-terminal as well as the physics for manipulating the valley degrees of freedom in 2D-MoS_2 has been extensively heavily studied.[10] Using a galvanostatic measurement method, we measure the voltage dependence on temporal resolution. Our study focuses on an oscillation phenomenon. The results pave the way for future working on dephasing four-terminal two-

*Project supported by the Zhejiang Provincial Natural Science Foundation, China (Grant Nos. LY16F040003 and LY16A040007) and the National Natural Science Foundation of China (Grant Nos. 51401069 and 11204058).

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dimensional electron gas (2DEG) devices, which provides a guideline for future improvement of the device performance.

2. Experiment

In our experiments, atomic layer MoS_2 ultra-thin films grown on SiO_2/Si substrates are synthesized via a chemical vapor deposition method on the basis of sulfurization of molybdenum trioxide (MoO_3). Our results of the ultra-thin films MoS_2 synthesis have been reported elsewhere.[20,21] A mesoscopic 2D-MoS_2 structure in micrometer-size (the thickness is about 2 nm, and the width is about 300 μm) with four-terminals was prepared by a mask as shown in Fig. 1. Voltage ($U_{14,23}$) was collected using galvanostatic measurement. We applied a current to contacts 1 to 4 and measured the voltage between contacts 2 and 3. A microcomputer control system (CorrTest 350) is used to test transport properties at room temperature. The galvanostatic measurements were applied under light irradiation (laser and/or sodium lamp) and no irradiation (dark), respectively. Two kinds of light sources were used in our measurements. One was an He–Ne laser at 633-nm wavelength with a laser power of about 500 μW. After a linear polarizer and a quarter-wave modulation, the light is circularly polarized. Another light source was a sodium lamp with a wavelength of 589 nm. Under our experimental conditions, the light spots are both large enough to cover the whole device.

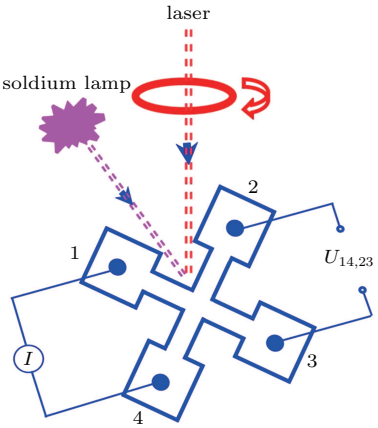


Fig. 1. (color online) Schematic diagram of the experimental setup with a mesoscopic 2D-MoS_2 structure at a micrometer-scale of four terminals.

3. Results and discussion

Small currents are used in the galvanostatic measurements. Figure 2(a) shows the plots of voltage $U_{14,23}$ versus time for applied currents of 30 μA–45 μA in darkness and under laser irradiation separately. We find that the oscillations are not clearly periodic as shown in the upper blue line in Fig. 2(a). In contrast, the oscillations are visible at 45 μA. Under an applied current of 35 μA, we notice that the oscillations are visible under laser irradiation but invisible in darkness as shown with a red line in the middle of Fig. 2(a). The periods of the oscillations in darkness/laser irradiation are nil/2.38 s for 35 μA, and 5.35 s/7.87 s for 45 μA, respectively. From these cases, the periods in darkness are smaller than under laser irradiation. The effect of laser irradiation on the oscillations is clear.

However, as the applied current increases, the oscillations disappear as indicated in Fig. 2(b). Figure 2(b) shows the typical voltage $U_{14,23}$ oscillations under 50 μA, 52 μA, 58 μA currents in darkness and under laser irradiation, respectively. The oscillations are not so clearly periodic as those in Fig. 2(a).

Figure 2(c) shows the voltage $U_{14,23}$ oscillations at a current of 62 μA in darkness and under laser irradiation, respectively. Notably, the envelope of voltage $U_{14,23}$ shows a typical beating shape. The beating period in darkness is about 8.3 s, which is larger than in the presence of laser (3.6 s). Physically, the different beating periods indicate the frequency difference between two encountered waves. The difference in beating period reveals the difference in energy between electrons. Specifically, our results show that the frequency difference in darkness is smaller than under laser irradiation.

Figure 2(d) shows the voltage $U_{14,23}$ oscillations in a range of 68 μA–95 μA. By comparing results in Fig. 2(a) with those in Fig. 2(d), we find that the effect of laser on oscillation is smaller in Fig. 2(d). The period of the oscillations in darkness is comparable to that under laser irradiation.

In Fig. 2(e), we plot the oscillation periods versus applied current. For the dark case and laser-irradiated case, the largest periods appear around 45 μA, which matches previous description. As a whole, the laser-irradiated curve (red curve) shifts towards lower applied current direction compared with the darkness curve (blue curve). The influence from laser is larger when applied current is small. We consider that the laser irradiation supplies the additional change in the photoexcited carriers and creates smaller 'required supplied current'. Quantitatively, the current difference between dark and laser is $\Delta I < 4$ μA. We set the current difference to be 4 μA, i.e., $\Delta I = 4$ μA. Note that current density $J = nq\upsilon_d$, $\Delta J = \Delta nq\upsilon_d$, and $J = J_0 + \Delta J = (n_0 + \Delta n)q\upsilon_d$, hence we obtain $I/\Delta I = J/\Delta J = (n_0 + \Delta n)/\Delta n$ which implies that $\Delta n = n_0/(I/I_0 - 1)$. If $n_0 \sim 10^{14}$ cm^{-2}, we have $\Delta n \sim 10^{13}$ cm^{-2}. From $J = nq\upsilon_d$ it follows that $\upsilon_d = \Delta J/\Delta nq = 2 \times 10^7$ cm/s. The drift velocity is estimated at about 10^7 cm/s. This analysis is valid when the specimen has a higher carrier density and higher carrier mobility, which is the condition of our experiment. By high resolution characterization methods, our 2D-MoS_2 material sample is found to be rich in sulfur.[18] Large amount of sulfur provides the interfacial S atoms, which are responsible for the change in band structure and the shift of the valence band edge.

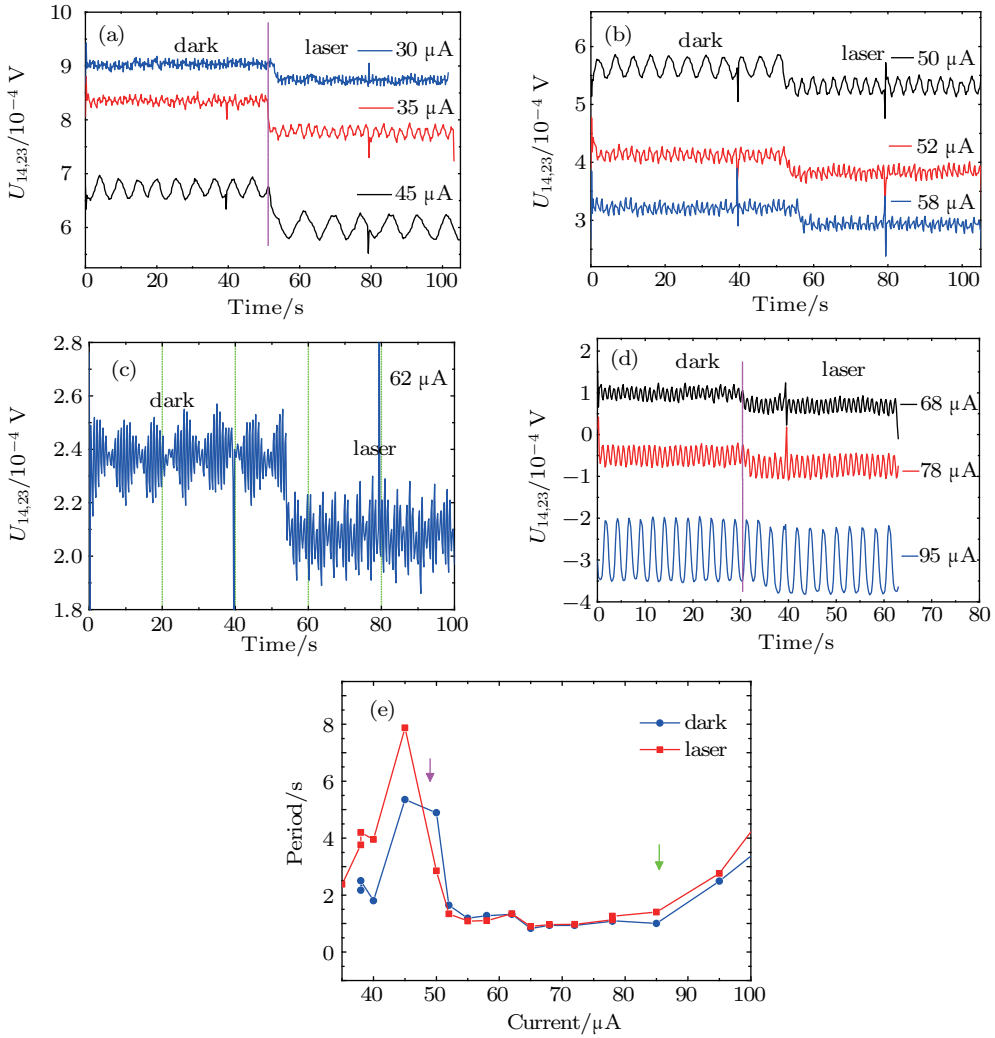


Fig. 2. (color online) Time evolutions of the voltage $U_{14,23}$ with the laser light irradiation on and off at different applied currents: (a) 30 μA–45 μA; (b) 50 μA–58 μA; (c) 62 μA; (d) 68 μA–95 μA; (e) evaluated corresponding oscillation period dependence on the current under the condition of darkness (in blue) and laser irradiation (in red).

To investigate the effect of circular polarization on the oscillation, the laser power density is changed in a duration of 30s during the galvanostatic measurements. Figure 3(a) shows the results of the voltage $U_{14,23}$ oscillations at different laser densities under the applied current of 50 μA. We reduce the laser power density in the sequence shown in Fig. 3. Qualitatively, as we expected, the period of the oscillation changes following the laser power density. Quantitatively, the evaluated values of period versus laser power density are plotted (red curve) in Fig. 3(c). The period of the oscillation decreases with laser power density. This result coincides with Fig. 2(b) and further verifies the effect of circularly polarized laser on oscillation. The same experiment is also done at 90 μA applied current. Results are plotted in Fig. 3(b). The period of the oscillation increases with laser power density increasing, which also coincides with the feature of curve at 90 μA in Fig. 2(e).

Interestingly, the oscillation period difference relates to the circularly polarized light. To investigate the physical mechanism behind these oscillations, we test the oscillations under different irradiation conditions: dark (no irradiation), sodium lamp (non-polarized light with a wavelength of 589 nm) and laser (circularly polarized light with a wavelength of 633 nm). The light sources are changed every 30 seconds. Specifically, we switch on our light sources in the sequence as shown in Fig. 4, i.e., 1 dark→2 sodium lamp→3 sodium lamp and laser→4 sodium lamp→5 sodium lamp and laser→6 sodium lamp→7 dark→8 sodium lamp→9 sodium lamp and laser→10 sodium lamp→11 sodium lamp and laser. The voltage $U_{14,23}$ values are drawn under 50 μA current. When the light source is switched between dark and sodium lamp, the variance of the $U_{14,23}$ oscillation is not evident as shown in the circled line in magenta. In contrast, when the laser is switched on and off, the voltage $U_{14,23}$ curve sharply jumps up and down as shown by the squares in magenta. In physics, the carrier density will increase under the light of sodium lamp with a wavelength of 589 nm, so that the voltage $U_{14,23}$ should change slightly. However, due to the limit to observation reso-

lution, the slight change is unable to be observed. The periods under different light irradiations are shown by the lower line in Fig. 4. Like voltage $U_{14,23}$, the oscillation period falls down to the lower step when the laser is on. The results under different light irradiations indicate that the oscillation period is a response to circularly polarized light.

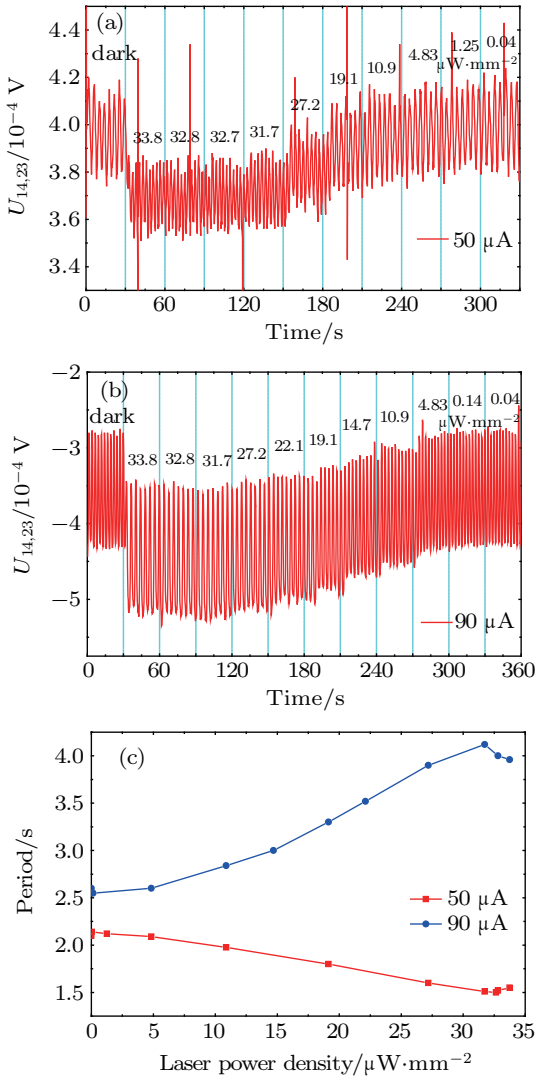


Fig. 3. (color online) Time evolutions of the voltage $U_{14,23}$ under laser light irradiation and in darkness with the laser power density in time steps of 30 s at different applied currents: (a) 50 μA; (b) 90 μA. (c) Variations of corresponding evaluated period of the oscillation with laser power density at applied currents of 50 μA and 90 μA, respectively.

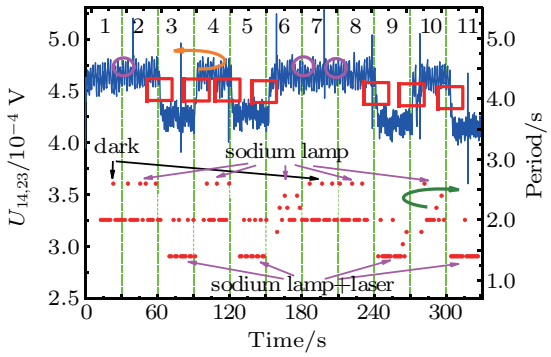


Fig. 4. (color online) Voltage $U_{14,23}$ oscillation (blue line) and the corresponding period response to light irradiation (red dots).

Oscillations reveal the existence of some phase coherences in our measurements. Currently, we cannot address the specific origin of these behaviors. One possible explanation is the beating effects from the photoexcited electrons with energy differences due to the feature of valleys based on the coherence mechanism. Under our experimental conditions, the configuration of our sample can be considered as two junctions connected by a single bend structure. In the presence of such a complex in-plane electric field and circularly polarized light, the valley polarized photoexcited current can be generated and accumulated electrons can be detected by $U_{14,23}$ based on the intriguing features of 2D-MoS_2. Monolayer MoS_2 has a direct bandgap of nearly 1.8 eV with the splitting feature of two valleys (K and K'). At corresponding optical frequencies, monolayer MoS_2 has a strong excitonic resonance.[3,4,22] The valley-selective circular dichroism is tightly cooperated with 2D-MoS_2. Atomic layer crystals of MoS_2 are regarded as a type of material that shows strong light–matter interaction.[13,14] They can provide delocalized excitons with a valley degree of freedom.[14] Hence, under the condition of circular polarized light irradiation with a wavelength of 633 nm, energy oscillations exhibit the feature of valley designation during the 2D exciton–photon coupling based on the coherence mechanism.[14] Therefore, the circularly polarized light can build up the relationship between the differences in energy between the electrons and the valleys. Furthermore, it can lead to the variation of the period based on the coherence mechanism. In contrast, the light of sodium lamp is unable to achieve that, which is consistent with Fig. 4.

Another possible reason for the energy differences is the presence of defect states of atomic layer MoS_2.[16,23] As is well known, defects are experimentally inevitable in the real synthesis process,[15,16] which may change the topology of the system and induce in-gap bound states. Our previous characterization results show that there are some defects in our material.[18,20] This feature can be considered as being equivalent to a defect state. And the light irradiation can tune the surface potential of monolayer MoS_2.[17] During measurements, electrons moving to the 2D- MoS_2 may experience a spatially nonuniform Coulomb interaction,[12] and the fluctuation of disorder potential, which may lead to the small energy difference. Our studies provide a guideline for the future improvement of the device performance.

4. Conclusions

On atomic layer MoS_2 film grown on SiO_2/Si substrate, a mesoscopic structure with four-terminals is used to test the voltage $U_{14,23}$ by using a galvanostatic measurement under the conditions with or without light irradiation. It is found that the

voltage $U_{14,23}$ oscillates and the corresponding period varies with applied current. The largest period appears around at 45 μA. The oscillation periods are also different under dark conditions and under laser irradiation. Based on the relationship of the oscillation period and the applied current, the laser-irradiated curve is obtained and it shifts towards low applied current direction compared with the darkness curve. From this shift, the drift velocity is estimated at 10^7 cm/s. Besides oscillations, the envelope of voltage $U_{14,23}$ shows a typical beating shape, revealing typical beating wave profiles. As it relates to beating behaviors, the different beating periods indicate the difference in frequency between two encountered waves. The difference between beating periods reveals the difference in energy between electrons. Specifically, our results show that the frequency difference in darkness is smaller than under laser irradiation. The voltage $U_{14,23}$ oscillations at different laser power densities are also measured. It is observed that the period of the oscillations decreases with laser power density increasing at 50 μA, but increases at 90 μA. This result is in accordance with the above relationship between oscillation period and current. When we use a sodium lamp light, rather than laser, the variation of the period induced by the $U_{14,23}$ oscillation is not evident. In contrast, when the laser is periodically switched on and off, the voltage $U_{14,23}$ curve and the corresponding period curve jump up and down. The experimental results suggest that the change of the period is related to the circularly polarized light. In fact, currently, the specific mechanisms behind the oscillations have not been thoroughly and clearly proven. One possible explanation is the beating effect from the photoexcited electrons with energy differences due to the feature of valleys based on the coherence mechanism.

Acknowledgment

The authors would like to thank Yu Zhou, Chen Wang, and Shikuan Wang for meaningful discussion, and also thank Xingmei Xu, Suping You, Fang Ge, for their encouragement in the work.

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