

# Magnetic quantum oscillation in a monolayer insulator

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**Citation:** X Lu, Magnetic quantum oscillation in a monolayer insulator[J]. *J. Semicond.*, 2021, 42(6), 060401. <http://doi.org/10.1088/1674-4926/42/6/060401>

The Shubnikov–de Haas (SdH) oscillation, as evidenced by the oscillating resistivity as a function of magnetic field at sufficiently low temperature, is not uncommon in metals, semimetals and narrow gap semiconductors at their conducting state. The origin of SdH oscillation is associated with Landau quantization, at which the cyclotron orbits of electrons are quantized. In other words, electrons can only occupy discrete energy levels, which are called the Landau levels. As the magnetic field increases, the split, quantized Landau levels move across the Fermi level and hence the material's transport properties start to oscillate periodically.

Writing in Nature (<https://doi.org/10.1038/s41586-020-03084-9>), Wang *et al.* shows the oscillatory magnetoresistance in an insulating monolayer<sup>[1]</sup>, which resembles the SdH oscillation in metal. In this work, the Princeton group led by Prof. Sanfeng Wu used single-layer tungsten ditelluride (WTe<sub>2</sub>), a transition metal dichalcogenides, to demonstrate quantum oscillation. Monolayer WTe<sub>2</sub> was predicted to be a two-dimensional topological insulator (behaves as an insulator in the bulk but contains conducting states at the surface) by Qian *et al.* in 2014<sup>[2]</sup>. With the distorted structural phase (1T' phase) which causes the inverted band structure and strong spin-orbit coupling from the heavy metal (tungsten), the crossing points of inverted bands form a two-dimensional topologically insulator. Experimental evidence, including spectroscopic signature and a direct transport measurement, has been reported independently by the Stanford group<sup>[3]</sup> and the Seattle group<sup>[4]</sup> in 2017. Since then, monolayer WTe<sub>2</sub> has been known to show conductance that is localized to the edge up to ~100 K. As a result, WTe<sub>2</sub> single layer allows for the observation of quantum spin hall effect even above the liquid nitrogen temperature<sup>[5]</sup>.

In order to probe the intrinsic resistance (or conductance) from the bulk in the monolayer, the authors have designed a special and creative detection scheme to avoid the conducting edge. As shown in Fig. 1(a), a thin insulating boron nitride (BN) layer is inserted between the monolayer and the palladium electrodes. The metal electrodes are deposited after BN, but they completely avoid touching the edge of the sample and are only in contact with the monolayer at small, selected regions, where BN layer is pre-etched by reactive ion etching. With this device geometry, Wang *et al.* measured the low temperature resistance of 120 MΩ, which strongly indicates that the monolayer WTe<sub>2</sub> is at insulating state and contribution from the edge state is eliminated. By applying an out-of-plane magnetic field, the authors observed

the oscillating magnetoresistance which starts to develop at a small magnetic field (Fig. 1(b)), which mimics the SdH oscillation though the sample is an insulator. The lowest onset magnetic field of quantum oscillation observed by Wang *et al.* is 0.5 T at 500 mK. Such small onset field implies the existence of highly mobile fermions. These fermions cannot be electrons or holes, because the monolayer device is at insulating state with a large resistance. As shown in Fig. 1(b), the measured resistance, from zero to 9 T, is least ~100 MΩ. Quantum oscillation at insulating state is consistently observed in three devices with similar device geometry. Wang *et al.* even observed the quantized regime from another device, where quantum oscillation develops into discrete peaks. The discrete Landau levels are reminiscent of the behavior of high mobility two-dimensional electron gases, where the conductance peak is related to Landau levels at the Fermi level. As monolayer WTe<sub>2</sub> exhibits insulating behavior at all fields, existing theory based on charge carriers could not completely explain the observed phenomena.

It is challenging and non-trivial to demonstrate quantum oscillation in a monolayer WTe<sub>2</sub> device. The low carrier mobility reported in previous reports<sup>[4, 5]</sup> hinders the observation, even in the metallic regime. In this study, the Princeton group has used high quality sample (flux-grown bulk WTe<sub>2</sub>) and adopted the creative design in device geometry as described above. Among the three devices that they have fabricated, device 3 with the highest mobility even exhibits clearly resolved quantum oscillation in the metallic regime (both h-like and e-like) in addition to the insulating regime. While quantum oscillation could not be detected (or weakly resolved) in the other two devices at the metallic state. The authors also noted that mobility of the gate-induced carriers does not affect the quantum oscillation in the insulating regime.

While the existing model and theory could not provide a complete understanding on the observed quantum oscillation in the insulating monolayer, the authors have suggested charge-neutral fermions, which arise from electron fractionalization, as an alternative explanation for this emerging phenomenon. It is important to note that the theory for neutral fermion in monolayer WTe<sub>2</sub> is still under-developed. Yet the experimental demonstration of quantum oscillation in a monolayer insulator is very encouraging, and it will inspire theoretical<sup>[6]</sup> and experimental investigation on fractionalized, neutral Fermi surfaces as well as the unusual insulating ground state of WTe<sub>2</sub>. In particular, the Princeton group further showed experimental evidence of excitonic insulator phase in WTe<sub>2</sub> monolayer<sup>[7]</sup>. The anomalous nature of WTe<sub>2</sub> in its mono- and few-layer forms will continuously render it as an exciting playground for exploring new quantum observation. For in-

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Received 17 JANUARY 2021; Revised 8 MARCH 2021.

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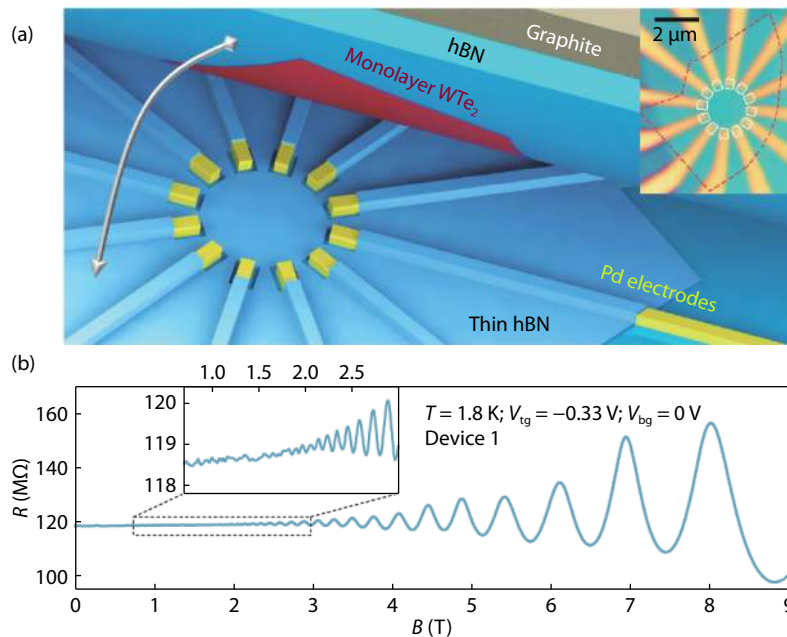


Fig. 1. (Color online) (a) Device schematic showing electrodes in contact with  $\text{WTe}_2$  in small selected areas without touching the edge of the sample. (b) A magnetoresistance curve taken at low temperature. Zoom-in view of data at low field is shown in the inset. Figures are adapted from Ref. [1] with permission.

stance, superconductivity is observed in monolayer with a low electron density and the critical temperature was reported around 1 K<sup>[8, 9]</sup>. In bilayer and trilayer, dramatically increased resistance has been shown, but the mechanism of gap opening has not been completely resolved.

With the rapid development of “twistronics” in twisted homo- and hetero-bilayer system<sup>[10]</sup>, the 2D community has every reason to expect more beyond the  $\text{WTe}_2$  alone. By placing the monolayer  $\text{WTe}_2$  on top of other novel materials (also layered materials or others) with a special twist angle, a promising prospect is to realize more exotic topological phases with 2D topological insulator, as predicted by Fu and Kane<sup>[11, 12]</sup>. The magical twist angle could also play a significant role. As previously demonstrated in graphene<sup>[13, 14]</sup> and the semiconducting 2H-phase  $\text{WSe}_2$  (another transition metal dichalcogenides but without the structural distortion)<sup>[15]</sup>, twist angle is a critical parameter for the observation of tunable zero-resistance state. It is notable that spectroscopic investigation on the emerging twisted layers is bursting as well, in addition to the transport studies. The optical techniques sometimes could overcome the barrier from transport measurements. For instance, the large contact resistance in  $\text{WS}_2$ - $\text{WSe}_2$  heterobilayer makes it almost impossible to directly measure the conductance from sample. However, by taking attractive and repulsive polarons as the optical signature, one can anticipate clear and well-resolved correlated insulating states<sup>[16, 17]</sup> and even signature of Wigner crystal<sup>[18, 19]</sup> from spectroscopy.

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