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Measuring Thickness-dependent Electronic Properties & the 2D-3D Transition

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ABSTRACT

A recent Australian collaboration locates the key transition point from 3D properties to 2D properties in van der Waals material tungsten ditelluride (WTe_2).

Constraining the movement of charge carriers to two dimensions (relative to the scale of their wavelength) unlocks unusual quantum properties, resulting in useful electronic properties.

INTRODUCTION

An Australian study published recently in *Physical Review B* [1] quantifies the 2D-3D transition point in the promising van der Waals materials material tungsten ditelluride (WTe_2).

The layers within van der Waals materials are referred to as ‘2D’ (two dimensional) when the restriction of a particle’s movement perpendicular to the plane of the material is on a scale that is proportional to the de Broglie wavelength of the particle.

In essence, this means the range from a few hundred nanometres down to a few nanometres.

Much can be learned by observing precisely at what thickness such new effects emerge. Ie, the transition point from 3D to 2D behavior.

The Study

This study began at the University of Wollongong (UOW) under Professor Xiaolin Wang, with Dr Feixiang Xiang (see Fig. 1) first studying the special electronic structure of bulk WTe_2 samples that leads to the material’s very large magnetoresistance (previously published [2]).

Fig.1: Left: Ashwin Srinivasan (UNSW). Right: Feixiang Xiang (Credit: FLEET/UNSW).

Thin films of different thickness were cleaved from a single crystal using micro-exfoliation onto a substrate.

After study of WTe_2 thin films at UOW, Dr Xiang used University of New South Wales (UNSW) laboratories to fabricate the devices from thin-film samples and perform transport measurements using ultralow temperature and high magnetic field measurement facilities.

Alignment markers, electrodes, and bonding pads were fabricated by E-beam lithography (see Fig. 2).

Angle-dependent quantum oscillation measurements were performed in very high magnetic fields at Professor Alex Hamilton's lab at UNSW, revealing how the material's band structure changed with decreasing thickness, with a 3D–2D crossover when the sample thickness was reduced below 26 nm.

This pins down two critical length scales of the thickness-dependent electronic structure in WTe_2 thin films.

Analysis indicated that the area of Fermi pockets decreases in thinner samples, suggesting the overlap between the conduction band and valence band becoming smaller. This not only explains the measured decrease of carrier density in a thinner sample, it suggests it is possible to open a band gap and realize the 2D topological insulator in even thinner samples, as has been predicted by theory [3], and observed in related compounds (MoS_2 and $MoTe_2$) [4].

Tungsten ditelluride (WTe_2) is a layered, transition metal dichalcogenide with several promising properties:

- extremely large magnetoresistance, with potential for use in magnetic sensors.
- bulk WTe_2 predicted to be a type-II Weyl semimetal [5]
- monolayer WTe_2 is a high temperature topological insulator [6], a superconductor, and a ferroelectric.
- Transition metal dichalcogenides (TMDs) are a class of van der Waals materials, comprising many atomically-thin atomic layers bound by weak intermolecular forces.

We refer to TMDs as 'two dimensional' because of this layered crystal structure.

Constraining the movement of charge carriers to two dimensions results in very different electronic properties compared to 3D 'bulk' materials, which also suggests that more, different physical properties could happen at the monolayer limit – the transition point from 3D to 2D.

The study *Thickness dependent electronic structure in WTe_2 thin films* was published in July 2018 [1].

Measurements found:

- WTe_2 thin films cross from 3D to 2D electronic systems at thickness of ~ 20 nm
- overlap between conduction and valence bands decrease at thickness below ~12 nm, implying that even thinner samples might achieve a bandgap.

The study was conducted at the UNSW, Sydney and the UOW's Australian Institute for Innovative Materials (AIIM) with funding from the Australian Research Council Centre of Excellence in Future Low-Energy Electronic Technologies (FLEET).

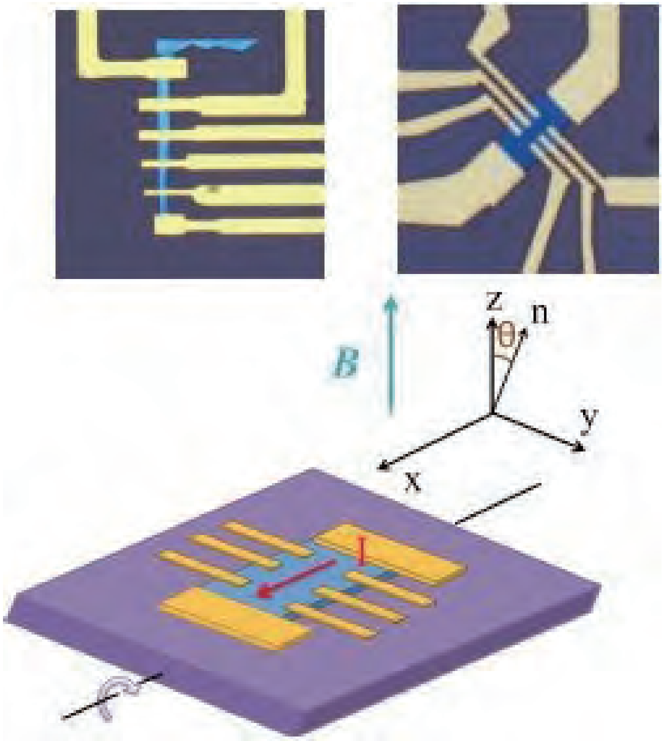

Fig.2: 2D WTe_2 samples (upper) and experimental schematic (lower) diagram of angle-dependent measurement configuration.

STUDY OF NOVEL MATERIALS AND TOPOLOGICAL INSULATORS AT FLEET

The electronic properties of WTe_2 and other TMDs are studied at FLEET, which brings together over a hundred Australian and international experts, with the shared mission to develop a new generation of ultra-low energy electronics.

The impetus behind such work is the increasing challenge of energy used in computation, which uses 5–8% of global electricity [8] and is doubling every decade [9].

FLEET takes advantage of established research links with some of the leading researchers in their fields across the Asia-Pacific region, including at partner organisations:

- Tsinghua University (China)
- National University of Singapore

- Nanyang Technical University (Singapore)
- Beijing Computational Science Research Center (China)
- Australian Nuclear Science & Technology Organisation (ANSTO)
- The Australian Synchrotron.

Topological insulators

Study co-author Professor Alex Hamilton (UNSW) heads FLEET's study of topological materials, which aims to produce an ultra-low energy topological transistor.

This approach to achieving electrical current flow with near-zero resistance is based on a paradigm shift in the understanding of condensed-matter physics and materials science: the advent of topological insulators [9].

Unlike conventional insulators, which do not conduct electricity at all, topological insulators conduct electricity, but only along their edges.

Along those edge paths, they conduct electrons strictly in one direction, without the back-scattering of electrons that dissipates energy in conventional electronics.

FLEET's challenge is to create topological materials that will operate as insulators in their interior, and have switchable conduction paths along their edges, operating at or near to room temperature.

Topological transistors would switch, just as a traditional transistor does: Applying a controlling voltage would switch the edge paths of the topological material between being a topological insulator ('on') and a conventional insulator ('off').

Approaches used are:
- Magnetic topological insulators and the quantum anomalous Hall effect (QAHE).
- Topological Dirac semimetals
- Artificial topological systems.

Novel materials

Study co-author Professor Xiaolin Wang (UOW and AIIM) leads FLEET's atomically thin and novel materials technology research.

Each of FLEET's three research themes is heavily enabled by the science of novel, atomically-thin, 2D materials. To provide these materials, FLEET draws on extensive expertise in materials synthesis in Australia and internationally, from bulk crystals to thin films to atomically-thin layers.

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More information is available at www.FLEET.org.au or @FLEETCentre.

References

[1] F. Xiang et al Phys. Rev. B 98, 035115 (2018)].
[2] F. Xiang et al Europhys. Lett. 112, 37009 (2015).
[3] X. Qian et al Science 346, 1344 (2014).
[4] K. F. Mak et al, Phys. Rev. Lett. 105, 136805 (2010), D.H. Keum et al, Nat. Physics 11, 482 (2015).
[5] A.A. Soluyanov et al Nature 527, 495 (2015).
[6] X. Qian et al Science 346, 1344 (2014).
[7] *FLEET Annual Report* (FLEET.org.au/annual-report).
[8] A.S.G. Andrae, *A Total Consumer Power Consumption Forecast* Nordic *Digital Business* Summit, Helsinki (2017).
[9] W. Van Heddeghem *Trends in worldwide ICT electricity consumption from 2007 to 2012* (2014).
[10] J.E. Moore, Nature 464, 194 (2010).

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