Hong Kong Forum of Physics 2022:

Frontiers of Quantum Materials Research

December 12 – 15, 2022

Lecture Theatre T4 - 5, 1/F, Meng Wah Complex and Online

Organized by
Area of Excellence on 2D Materials Research
HKU-UCAS Joint Institute of Theoretical and Computational Physics

Organizing Committee

Dongkeun Ki (The University of Hong Kong) (Chair)
Wang Yao (The University of Hong Kong) (Co-chair)
Maohai Xie (The University of Hong Kong)
Xiaodong Cui (The University of Hong Kong)
Ning Wang (Hong Kong University of Science and Technology)
Sen Yang (Hong Kong University of Science and Technology)

Sponsored by
Croucher Foundation
Area of Excellence on "2D Materials Research: Fundamentals Towards Emerging Technologies"
HKU-UCAS Joint Institute of Theoretical and Computational Physics,
HK Institute of Quantum Science & Technology

Monday, December 12, 2022 (Day 1) 09:10 – 09:40

Dipole Ladders with Giant Hubbard U in a Moiré Exciton Lattice

Prof. Xiaodong Xu
University of Washington

Two-dimensional semiconductor moiré superlattices have emerged as a powerful platform for engineering correlated electronic phenomena. On the other hand, optical excitation creates charge neutral interlayer excitons with an out-of-plane electric dipole. Strong onsite dipole-dipole interaction promises the formation of correlated bosonic states, akin to the Mott states of electrons, but its observation remains elusive. In this talk, we report a giant exciton Hubbard *U* and consequent dipole ladders with spin- and electron-filling dependence in WSe_2/WS_2 moiré superlattices. By measuring interlayer exciton photoluminescence as a function of excitation intensity, we identify successive new peaks emerge with an energy separation of ~34 meV above the ground state. This corresponds to the sequential injection of excitons into a single site with an energy cost to overcome the remarkably large exciton Hubbard *U*, forming a dipole ladder. Based on findings of local magnetic moments at two holes per moiré cell, we show that excitons can also fill a second moiré orbital, establishing the two-orbital nature of the moiré potential landscape. An electrostatic gating study further unravels the interplay of exciton dipoles with the correlated charge orders and magnetic interactions. Our results pave the way for investigating the Bose-Hubbard model with possible exciton crystal phases in interacting opto-moiré quantum matter.

Monday, December 12, 2022 (Day 1) 09:40 – 10:10

Moiré Luttinger Liquids in Two Dimensions

Prof. Sanfeng Wu
Princeton University

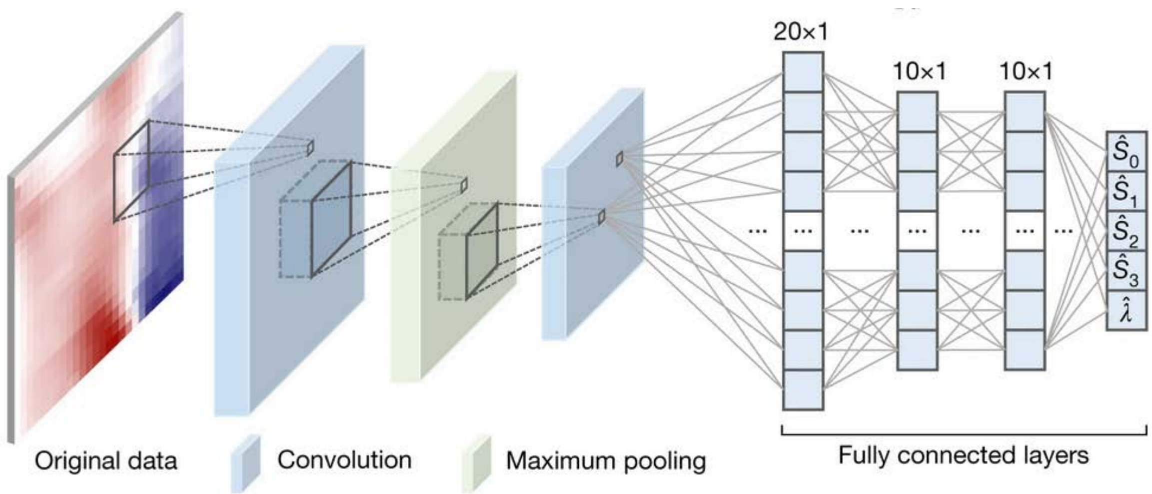
Interacting electrons in metals are typically described by the established Fermi liquid theory, which is qualitatively similar to the theory of a non-interacting Fermi gas. One known exception is the interacting one-dimensional (1D) conductors, in which electrons only move along one spatial direction and are generally described by the Luttinger liquid model at low temperatures. The 1D Luttinger liquids host interesting phenomena due to strong correlations, including the power law suppression of the density of states at Fermi energy and the spin-charge separation. Can the novel Luttinger liquid phenomena, expected in a 1D system, emerge in a two-dimensional (2D) system at low temperatures? In this talk, I aim to address this long-standing question based on our recent experiments on twisted bilayer WTe_2 ($tWTe_2$). I will argue that this new moiré material provides an excellent platform for studying emergent Luttinger liquids in an anisotropic 2D system and may be related to various coupled-wire models for investigating strongly correlated physics.

Monday, December 12, 2022 (Day 1) 10:10 – 10:40

Intelligent sensing enabled by tunable moiré quantum geometry

Prof. Fengnian Xia
Yale University

It is widely accepted in optics community that different kinds of photonic devices are needed to sense the rich physical properties of light. Power meter is used to measure the light intensity; spectrometer is utilized to determine the wavelength information of light; polarimeter can be leveraged to measure the light polarization state. In this talk, I will discuss how we challenge this conventional notion using graphene moiré material. I will first report the observation of tunable mid-infrared bulk photovoltaic effect at 5 μm and 7.7 μm in twisted double bilayer graphene (TDBG), arising from the moiré-induced strong symmetry breaking and quantum geometric contribution. The photoresponse depends substantially on the polarization state of the excitation light and is highly tunable by external electric fields. This wide tunability in quantum geometric properties enables us to use a trained convolutional neural network (CNN) to achieve full-Stokes polarimetry together with wavelength detection simultaneously, using only one single TDBG device with a subwavelength footprint of merely 3×3 μm^2. Our work not only reveals the unique role of moiré engineered quantum geometry in tunable nonlinear light–matter interactions but also identifies a pathway for future intelligent sensing technologies in an extremely compact, on-chip manner.



The figure above illustrates the concept of intelligent sensing. The two-dimensional photoresponse data (left) have been interpreted using a trained CNN, providing the intensity, polarization and wavelength information (right).

*This presentation is based on our recent publication by Ma et al, "Intelligent infrared sensing enabled by tunable moiré quantum geometry," *Nature* **604**, 266–272 (2022). https://doi.org/10.1038/s41586-022-04548-w

Monday, December 12, 2022 (Day 1) 11:00 – 11:30

Atomic Lego for future computing

Prof. Feng Miao
Nanjing University

Van der Waals (vdW) heterostructures ("Atomic Lego") are formed by stacking layers of different 2D materials and offer possibilities to design new atomic structures with rich functions. In this talk, I will show how these heterostructures provide unprecedented opportunities to realize device applications in the field of future computing, including quantum simulation and neuromorphic computing.

I will first present our observation of tunable quantum criticalities in an experimental simulator of the extended Hubbard model with spin–valley isospins arising in chiral-stacked twisted double bilayer graphene [1]. The results demonstrate a highly tunable solid-state simulator with intricate interplay of multiple degrees of freedom for exploring exotic quantum critical states and behaviours.

vdW vertical heterostructures can also be exploited to realize neuromorphic computing devices. I will show that highly robust memristors can be created from a vdW heterostructure composed of graphene/$MoS_{2-x}O_x$/graphene [2]. Our recent results on a prototype reconfigurable neural network vision sensor based on a WSe_2/BN heterostructure [3], and in-sensor broadband convolutional processing using a band-alignment-tuneable $PdSe_2$/$MoTe_2$ heterostructure [4] will also be presented.

References:

[1] Qiao Li, Feng Miao, et. al., Nature 609, 479–484 (2022).
[2] Miao Wang, Feng Miao, et. al., Nature Electronics 1, 130 (2018).
[3] Chen-Yu Wang, Feng Miao, et. al., Science Advances 6, eaba6173 (2020).
[4] Lejing Pi, Feng Miao, Tianyou Zhai, et al., Nature Electronics 5, 248–254 (2022)

Monday, December 12, 2022 (Day 1) 11:30 – 12:00

Low-voltage transistors and diodes; Extending the road beyond CMOS

Prof. Sungjae Cho
KAIST

The continuous transistor down-scaling has been the key to the successful development of the current information technology. However, with Moore's law reaching its limits the development of alternative transistor architectures is urgently needed. Transistors require at least 60 mV switching voltage for each 10-fold current increase, i.e. subthreshold swing (SS) 60 mV/dec. Alternative tunnel field-effect transistors (TFETs) are widely studied to achieve a sub-thermionic SS and high I_{60} (current where SS becomes 60 mV/dec). Heterojunction (HJ) TFETs bear promise to deliver high I_{60}, but experimental results do not meet theoretical expectations due to interface problems in the HJs constructed from different materials. Here, we report a natural HJ-TFET with spatially varying layer thickness in black phosphorus (BP) without interface problems. We achieved record-low average SS over 4 decades of current, $SS_{ave\_4dec} \approx 22.9$ mV/dec with record-high I_{60} (= 19.5 μA/μm), paving the way for the application in low power switches. Low-power transistors, such as tunnel field-effect transistors (TFETs), negative-capacitance field-effect transistors (NC-FETs), and Dirac-source field-effect transistors (DS-FETs), have been realised to break the thermionic limit of the subthreshold swing (SS). However, a low power diode rectifier, which breaks the thermionic limit of an ideality factor (η) of 1 at room temperature, has not been proposed yet. In this study, we have realized a DS diode, which exhibits a steep slope characteristic curve, by utilising the linear density of states (DOSs) of graphene. For the developed DS diode, $\eta < 1$ for more than two decades of drain current with a minimum value of 0.76, and the rectifying ratio is large (> 10^5). The realisation of a DS diode paves the way for the development of low-power electronic circuits.

References:

[1] *Dirac-Source Diode with Sub-unity Ideality Factor*
Gyuho Myeong†, Wongil Shin†, Kyunghwan Sung† (equal contribution), Seungho Kim, Hongsik Lim, Boram Kim, Taehyeok Jin, Taehun Lee, Jihoon Park, Machael S. Fuhrer, Kenji Watanabe, Takashi Tanigichi, Fei Liu****, Sungjae Cho*** , **Nature Communications** (2022)

[2] *Monolayer Hexagonal Boron Nitride Tunnel Barrier Contact for High Performance Heterojunction Tunnel Field-Effect Transistors*
Seungho Kim, Gyuho Myeong, Jihoon Park, Kenji Watanabe, Takashi Taniguchi, **Sungjae Cho***
Nano Letters 5, 3963 (2020)

[3] *Thickness-Controlled Black Phosphorus Tunnel Field-Effect Transistor for Low Power Switches*
Seungho Kim, Gyuho Myeong, Wongil Shin, Hongshik Lim, Boram Kim, Taehyuk Jin, Sungjin Chang, Kenji Watanabe, Takashi Taniguchi, **Sungjae Cho***.
Nature Nanotechnology 15, 203 (2020)

Monday, December 12, 2022 (Day 1) 12:00 – 12:30

Piezoelectric response of 2D layered nanosheets and devices

Prof. Jianhua Hao
The Hong Kong Polytechnic University

Piezoelectric response is observed in 2D materials, opening up a new opportunity for investigating fundamentals of piezoelectricity and making novel devices. It is highly desirable to explore diverse 2D layered nanosheets and enhance their piezoelectric response. In this work, we report on synthesizing and processing a variety of piezoelectric 2D nanosheets by mechanical exfoliation, CVD and space-confined method. Structural and physical properties of the synthesized samples are characterized. Through experimental studies and theoretical calculations, enhanced piezoelectric response is observed in the 2D layered heterostructure with a larger interfacial dipole moment resulting from the type II band alignment by interface engineering. We have demonstrated piezoelectric-based human motion sensor and flexible photodetectors using the 2D materials.
This work was supported by the grants from Research Grants Council of Hon
g Kong (GRF No. PolyU 153025/19P, SRFS 2122-5S02, and AoE/P-701/20).

Monday, December 12, 2022 (Day 1) 14:00 – 14:30

Interaction-driven quantum anomalous Hall states and Josephson junctions in moire materials

Prof. Kam Tuen Law
The Hong Kong University of Science and Technology

Coming soon

Monday, December 12, 2022 (Day 1) 14:30 – 15:00

New twists of twisted TMD homo-bilayers: from valley-resolved *moiré* superlattices to quasicrystals

Prof. Chih-Kang Shih
The University of Texas at Austin

The emergence of moire superlattice designed using van der Waals materials (vdW) bilayers (e.g. graphene (Gr), transition metal dichalcogenides (TMD)) has created unprecedented opportunities to engineer 2D electronic materials with novel properties. Thus far, most moire superlattice focus on the "K-valley *moiré*" resulting from the periodic variations in interlayer coupling at the K-valley. Recently, there has been strong interest in exploring the formation of G-valley *moiré* in TMD bilayers with emerging D_6 symmetry in (R-stacking), instead of C_3 symmetry for K-valley *moiré*. Another new twist is the formation of incommensurate *moiré* crystals that have dodecagon rotational symmetry without translational symmetry. These new twists have generated significant excitements in this already supercharged scientific frontier based on artificial *moiré* crystals.

In this talk, I will present these two new aspects based on twisted WSe2 bilayers. First, I will discuss how one can distinguish *moiré* superlattice states at different valleys using a comprehensive mode of scanning tunneling spectroscopy. I will present the distinction of G- and K-valley *moiré* states in the valence bands. We confirm a D6 symmetry for G-valley *moiré* and a C3 symmetry for K-valley *moiré*. Finally, I will show the formation of *moiré* quasicrystals through a 30-degree twist bilayer, exhibiting a rich hierarchical structure in real and reciprocal space, characterized by the dodecagon rotational symmetry without translational symmetry. How quasiperiodicity impacts the electronic structure of the bilayer will be discussed

Monday, December 12, 2022 (Day 1) 15:00 – 15:30

Self-organized quantum dots in marginally twisted bilayers of transition metal dichalcogenides

Prof. Vladimir Fal'ko
National Graphene Institute

Moiré superlattices in twistronic heterostructures, assembled from weakly incommensurate 2D crystals, are a powerful tool for materials engineering. In marginally twisted (small misalignment angle, $\vartheta<1^o$) bilayers of nearly lattice-matched two-dimensional (2D) crystals moiré patterns transform into networks of domains with commensurate stacking of the two layers, separated by a web of domain walls with strain 'hot spots' at the network nodes. Here, we will discuss structural and electronic properties of such reconstructed domain structures in homo- and heterobilayers of transition metal dichalcogenides (TMDs).

In homobilayers with the same orientation of unit cells we find a weak out-of-plane ferroelectric polarization, which can be modified using vertical electrical bias, and develop a string-like theory for the electrical manipulation of domain wall webs in such systems. We also analyze the band edge profiles for electrons and holes across such networks. In homobilayers with reversed orientation of unit cells, we find that piezo-charges around domain network nodes and the interlayer hybridization determine confinement of electrons and holes in different areas of the domain wall network.

For heterobilayers MoX_2/WX_2 of same-chalcogen TMDs (X=S, Se), we predict that nodes of a domain wall web are the hot spots of hydrostatic (biaxial) strain, which sets quantum dots for electrons, holes and optically active interlayer excitons. The electron/hole confinement, which is the strongest for $\vartheta<0.5^o$, leads to a substantial red-shift of their recombination line, broadly tuneable around 1.2eV by the misalignment angle. Such self-organised quantum dots offer new opportunities for creating dense arrays of single-photon emitters, and we also note that the hot spots of strain reduce the intralayer MoX_2 A-exciton energy, enabling selective population of the quantum dot states.

Monday, December 12, 2022 (Day 1) 16:00 – 16:30

Polariton valley Hall effect in monolayer WS_2 on plasmonic metasurface

Prof. Wen-Hao Chang
Academia Sinica

The intertwined valley and spin degrees of freedom (DOF) have manifested many remarkable phenomena in monolayer transition metal dichalcogenides (TMDs) [1]. The interplay of charge with the valley/spin DOF has led to the valley Hall effect [2]. Similarly, the exciton valley Hall effect is due to their interplay with excitons [3]. Polaritons are half-light and half-matter quasiparticles resulting from strong coupling of excitons and electromagnetic field. Such polaritons have optically addressable spin and momentum through the spin-orbit interactions of light. One thus asks: Can valley Hall effect exist for polaritons in ML TMDs? If yes, what will be the experimental signature? By placing monolayer TMDs on the nanostructured plasmonic cavity, we report the observation of polariton valley Hall effect at room temperature through simultaneous observation of valley resolved polaritons in momentum space and a large separation in real space. The valley-contrasting polariton propagation in both real and momentum space is caused by the directional coupling of valley excitons to the surface-plasmon-polariton mode due to the photonic spin-momentum locking. Our results demonstrate a new pathway for transporting and reading out the spin and valley degree of freedoms of valley excitons in 2D semiconductors — a crucial step toward implementing the valleytronic applications.

References:

[1] Xiao, D., Liu, G.-B., Feng, W., Xu, X. & Yao, W. Phys. Rev. Lett. **108**, 196802 (2012).
[2] Xiao, D., Yao, W. & Niu, Q. Phys. Rev. Lett. **99**, 236809 (2007).
[3] Mak, K. F., McGill, K. L., Park, J. & McEuen, P. L. Science **344**, 1489 (2014).
[4] Onga, M., Zhang, Y., Ideue, T. & Iwasa, Y. Nat. Mater. **16**, 1193 (2017).

Monday, December 12, 2022 (Day 1) 16:30 – 17:00

Strong light-matter interaction in 2D materials

Prof. Vinod Menon
City University of New York

Strong exciton-photon interaction results in the formation of half-light half-matter quasiparticles called exciton-polaritons (EPs) that take on the properties of both its constituents. In this talk, I will first introduce polariton formation in 2D semiconductors [1] followed by a discussion of dipolar excitons[2] to realize highly nonlinear interactions to achieve single photon nonlinearity. Finally, we will discuss our recent work on coupling of magnetically correlated excitons in van der Waals magnets with cavity photons[3]. The prospects for modifying magneto-optical response and realizing opto-magnetic devices based on these magneto-polaritons will also be discussed.

References:

[1] Liu, X. *et al*. Strong light–matter coupling in two-dimensional atomic crystals. *Nat Photonics* **9**, 30–34 (2015).
[2] Datta, B. *et al.* Highly nonlinear dipolar exciton-polaritons in bilayer MoS2. *Nature Communications 2022 13:1* **13**, 1–7 (2022).
[3] Dirnberger, F. *et al.* Spin-correlated exciton–polaritons in a van der Waals magnet. *Nature Nanotechnology 2022* 1–5 (2022) doi:10.1038/s41565-022-01204-2.

Monday, December 12, 2022 (Day 1) 17:00 – 17:30

Photoluminescence study on exciton of monolayer TMD

Prof. Xiaodong Cui
The University of Hong Kong

Coming soon

Tuesday, December 13, 2022 (Day 2) 09:00 – 09:30

The Resurrection of Tellurium as an Elemental van der Waals Semiconductor

Prof. Peide Ye
Purdue University

The graphene boom has triggered a widespread search for novel elemental van der Waals materials thanks to their simplicity for theoretical modelling and easy access for material growth. Group VI element tellurium is an unintentionally p-type doped narrow band gap semiconductor featuring a one-dimensional chiral atomic structure which holds great promise for next-generation electronic, optoelectronic, and piezoelectric applications. In this talk, we first review recent progress in synthesizing atomically thin Te two-dimensional (2D) films and one-dimensional (1D) nanowires. Its applications in field-effect transistors and potential for building ultra-scaled Complementary metal–oxide–semiconductor (CMOS) circuits are discussed. We will also overview the recent study on its quantum transport in the 2D limit and progress in exploring its topological features and chiral related physics. We envision that the breakthrough in obtaining high-quality 2D Te films will inspire a revisit of the fundamental properties of this long-forgotten material in the near future.

Tuesday, December 13, 2022 (Day 2) 09:30 – 10:00

Spin waves and magnetic fluctuations in atomically thin MnBi2Te4

Prof. Xiaoqin Li
The University of Texas at Austin

Coming soom

Tuesday, December 13, 2022 (Day 2) 10:00 – 10:30

Bioinspired in-sensor computing with 2D semiconductors

Prof. Yang Chai
The Hong Kong Polytechnic University

Coming soon

Tuesday, December 13, 2022 (Day 2) 11:00 – 11:30

Prof. Xiangfeng Duan
University of California, Los Angeles

Coming soon

Tuesday, December 13, 2022 (Day 2) 11:30 – 12:00

Quantum anomalous Hall effect in MnBi2Te4

Prof. Yuanbo Zhang
Fudan University

Coming soon

Tuesday, December 13, 2022 (Day 2) 12:00 – 12:30

Non-reciprocal charge transport and spin switch in an intrinsic magnetic topological insulator MnBi2Te4

Prof. Wei-Bo Gao
Nanyang Technological University

Symmetries, quantum geometries and electronic correlations are among the most important ingredients of condensed matters, and lead to nontrivial phenomena in experiments, for example, non-reciprocal charge transport. Of particular interest is whether the non-reciprocal transport can be manipulated. Here, we report the controllable large non-reciprocal charge transport in the intrinsic magnetic topological insulator $MnBi_2Te_4$. The current direction relevant resistance is observed at chiral edges, which is magnetically switchable, edge position sensitive and stacking sequence controllable. Applying gate voltage can also effectively manipulate the non-reciprocal response. In addition, we will report the realization of field free spin switch in $MnBi_2Te_4$ with ultra-small current. The observation and manipulation of non-reciprocal charge transport and spin switch reveals the fundamental role of chirality in charge transport of $MnBi_2Te_4$, and pave ways to develop van der Waals spintronic devices by chirality engineering.

Tuesday, December 13, 2022 (Day 2) 14:00 – 14:30

Steady Floquet–Andreev states in graphene Josephson junctions

Prof. Gil-Ho Lee
POSTECH

Engineering quantum states through light-matter interaction has created a new paradigm in condensed matter physics. A representative example is the Floquet-Bloch state, which is generated by time-periodically driving the Bloch wavefunctions in crystals. Previous attempts to realise such states in condensed matter systems have been limited by the transient nature of the Floquet states produced by optical pulses, which masks the universal properties of non-equilibrium physics. I will introduce our recent effort on the generation of steady Floquet Andreev (F-A) states in graphene Josephson junctions by continuous microwave application and direct measurement of their spectra by superconducting tunnelling spectroscopy [1]. We present quantitative analysis of the spectral characteristics of the F-A states while varying the phase difference of superconductors, temperature, microwave frequency and power. We hope that this study can provide a basis for understanding and engineering non-equilibrium quantum states in dissipative condensed matter systems.

Reference:

[1] S. Park et al., Nature 603, 421–426 (2022).

Tuesday, December 13, 2022 (Day 2) 14:30 – 15:00

Bulk-Boundary-Transport Correspondence of Higher-Order Topological Insulators

Prof. Jian Wang
Shenzhen University

Topological phases have corresponding signatures in various spatial domains. For instance, Chern insulator is characterized by Chern number in bulk systems; when it is confined with boundaries, spinless edge states emerges; transport measurements show quantized Hall conductance for open systems. Such a bulk-boundary-transport correspondence is also valid for topological insulators (TI, or quantum spin Hall effect), which is manifested by Z_2 invariance, helical edge states, and quantized spin Hall conductance. For higher-order topological insulators (HOTI), the bulk-boundary correspondence has been well established, but quantized transport signature is still absent. We demonstrate that, for a 2D second-order TI induced by applying an in-plane magnetic field in the Z_2 invariant first-order TI, integer spin quanta are pumped out per cycle when this magnetic field is rotating, giving rise to the quantization of spin transport. Numerical results show that for finite device systems the onset of quantization of spin current corresponds to the formation of topological corner states labeling 2^{nd}-order TI, suggesting that the quantized spin pump can serve as the quantized transport signature for HOTI that evolved from Z_2 invariant first-order TI. The quantized spin current has been tested for different model systems including various versions of BHZ and Kane-Mele models, and it is robust against disorders.

Tuesday, December 13, 2022 (Day 2) 15:00 – 15:30

Symmetry Engineering and Nonlinear Transport in Nanostructures of Transition Metal Dichalcogenides

Prof. Yoshihiro Iwasa
University of Tokyo & RIKEN

Symmetry often plays crucial roles in the properties and functions of materials. In bulk materials, symmetry is basically determined by the space group of single crystals. In sharp contrast, in nanomaterials, symmetry can be controlled as designed. For instance, graphene and bilayer graphene have totally different symmetry, and needless to say, rolling them into tublar structures makes their symmetry reduced to chiral.

In this presentation, we discuss one of the symmetry sensitive properties, bulk photovoltaic effect, in nanotubes [1], van der Waals (vdW) heterostructures [2], and strained [3] transition metal dicalcogenides (TMD). Bulk photovoltaic effect is the photovoltaic effect of uniform materials without p-n junctions, which have been known as a characteristic property of ferroelectric or polar bulk materials. Monolayer TMD has a trigonal structure, which is a noncentrosymmetric but nonpolar structure. Therefore no bulk photovoltaic effect for random light polarization is expected. However, TMD can be changed to polar structures by making tubular structures, vdW heterostructures with twofold rotational symmetry, or strained 3R structure, and thus bulk photovoltaic effect emerges. The light intensity dependence of photocurrent exhibits a crossover from linear to route mean square dependence, in agreement with the quantum mechanical shift current mechanism. Importantly, the observed photocurrent density is rather large comparing to those in bulk polar materials. The present result may indicate a novel route to create new functionalities based on nanostructures through symmetry engineering.

References:
[1] Y. J. Zhang et al., Nature 570, 349 (2019).
[2] T. Akamatsu et al., Science 372, 68 (2021).
[3] Y. Dong et al., Nature Nanotechnology in press

Tuesday, December 13, 2022 (Day 2) 16:00 – 16:30

Probing 2D magnets with transport in nanodevices

Prof. Alberto Morpurgo
University of Geneva

I will present our studies of different 2D magnets based on temperature-dependent transport measurements on tunnel barrier devices and field-effect transistors. We have performed tunneling magnetoconductance in barriers made of a variety of 2D magnets including all Chromium trihalides that in their most common forms are either layered antiferromagnets (CrI_3, $CrCl_3$) or ferromagnets ($CrBr_3$), $MnPS_3$ (which is antiferromagnetic within individual layers), VI_3 (a Mott-Hubbard insulator) and succeeded in all cases to determine their phase diagram and to extract different relevant information about their magnetic properties (magnitude of interlayer exchange, uniaxial anisotropy, etc.). The extremely narrow bands of these materials cause electrons to localize easily, and prevent the realization of good-quality field-effect transistors that operate well at low temperature, making it impossible to investigate field-effect tunable transport in the magnetic state. More recently, we have started to explore much larger bandwidth 2D magnetic semiconductors such as CrSBr and $CrPS_4$, and succeeded to perform systematic field-effect transistor measurements in their magnetic state. In this talk I will present different aspects of this work, focusing on some of the newer results obtained in my group.

Tuesday, December 13, 2022 (Day 2) 16:30 – 17:00

Quantum Transport and Topological Phases in van der Waals Heterostructures

Prof. Jeanie Lau
The Ohio State University

The interplay between quantum confinement, non-trivial band topology, symmetries and electronic interactions gives rise to a rich variety of correlated phenomena and topological phases in van der Waals heterostructures. Here I will present our recent works on this topic, including tunable helical states in few-layer graphene and quasi-1D topological insulators. Also, I will present strong experimental evidence for strong-coupled superconductivity that is enabled by quantum geometry in twisted bilayer graphene.

Tuesday, December 13, 2022 (Day 2) 17:00 – 17:30

Correlated electrons in twisted bilayer graphene: superconductivity to strange metal behavior

Prof. Marc Bockrath
The Ohio State University

Twisted bilayer graphene (tBLG) with interlayer twist angles near the magic angle ~1.08º hosts flat bands and exhibits correlated states including Mott-like insulators, superconductivity and magnetism. We will discuss combined temperature-dependent transport measurements of the longitudinal and Hall resistivities in close to magic-angle tBLG. While the observed longitudinal resistivity follows linear temperature dependence consistent with previous reports, the Hall resistance shows an anomalous temperature dependence with the cotangent of the Hall angle scaling quadratically in temperature. Boltzmann theory for quasiparticle transport predicts that both the resistivity and the Hall angle cotangent should have the same temperature dependence, contradicting the observed behavior. This failure of quasiparticle-based theories is reminiscent of other correlated strange metals such as cuprates. Moreover, we will discuss our recent work in which we study tBLG with an extremely low Fermi velocity, which enables us to find evidence of quantum geometric contribution to the superfluid stiffness, and tune the electrons well into the Bose-Einstein condensate regime.

Wednesday, December 14, 2022 (Day 3) 14:00 – 14:30

New progresses in topological insulator/superconductor hetero-structures

Prof. Jinfeng Jia
SUSTech and Shanghai Jiaotong University

Topological superconductors attract lots of attentions recently, since they are predicted to host Majorana zero mode (MZM), who behaves like Majorana fermion and can be used in fault-tolerant quantum computation relying on their non-Abelian braiding statistics. Currently, most topological superconductors are artificially engineered based on a normal superconductor and the exotic properties of the electronic surface states of a topological insulator. Here, I will show you that the $Bi_2Te_3/NbSe_2$ hetero-structure is an ideal artificial topological superconductor. By using spin-polarized scanning tunneling microscopy/spectroscopy (STM/STS), we observed the spin dependent tunneling effect, which is a direct evidence for the spin selective Andreev reflection from MZMs, and fully supported by theoretical analyses. Recently, the segmented Fermi surface induced by the Cooper pair momentum was observed in a $Bi_2Te_3/NbSe_2$ system. It's found that the shape and size of this Fermi surface can be adjusted by the direction and magnitude of the magnetic field, and can also modulate the topology to build new topological superconductors. This work opens up a new method to manipulate the property of crystals. Finally, the strong proximity effect was found in SnTe-Pb heterostructure. The bulk pairing gap and multiple in-gap states induced by topological surface states can be clearly distinguished. The superconductivity of SnTe is consistent with a new type of topological superconductors under the protection of lattice symmetries. Under lattice-symmetry protection, the superconducting SnTe is predicted to possess multiple MZMs in a single vortex. This system provides a platform to study the coupling of multiple MZMs without the need of real space movement of a vortex.

References:
[1] Mei-Xiao Wang, et al., Science 336, 52-55 (2012)
[2] J.P. Xu, et al., Phys. Rev. Lett. 112, 217001 (2014)
[3] J.P. Xu, et al., Phys. Rev. Lett. 114, 017001 (2015)
[4] H.H. Sun, et al., Phys. Rev. Lett. 116, 257003 (2016)
[5] H.H. Sun, Jin-Feng Jia, NPJ Quan. Mater. 2, 34 (2017)
[6] Z. Zhu, et al., Science 374, 1381 (2021)
[7] H. Yang, et al., Adv. Mater. 31, 1905582 (2019)
[8] H. Yang, et al., Phys. Rev. Lett. 125, 136802 (2020)

Wednesday, December 14, 2022 (Day 3) 14:30 – 15:00

Berry phase and topological properties in superconductors

Prof. Qian Niu
University of Science and Technology of China

We construct a semiclassical theory for the dynamics of the quasiparticles and reveal the Berry curvature distribution in terms of the characteristics of superconductivity. We show that Berry-curvature effects strongly influence the transport and spectroscopic properties of superconductors, such as the local density of states and the anomalous thermal Hall effect. We also construct a semiclassical theory for the topological Josephson junctions starting from a microscopic Hamiltonian that comprehensively includes the interplay among the Majorana qubit, the Josephson phase, and a dissipative environment. We reveal rich dynamical phenomena such as qubit induced charge pumping, effective spin-orbit torque, and Gilbert damping, and demonstrate how they manifest in the transport signatures of the junction, such as the I-V characteristics, Josephson radiation, and Shapiro steps.

References:

[1] Z. Wang, J.J. Feng, Z. Huang, and Q. Niu, arXiv:2204.09923 (2022) (to appear in PRL).
[2] Z. Wang, L. Dong, C. Xiao, and Q. Niu, Phys. Rev. Lett 126 , 187001 (2021).
[3] J.J. Feng, Z. Huang, Z. Wang, and Q. Niu, Phys. Rev. B 101, 180504 (2020).
[4] J.J. Feng, Z. Huang, Z. Wang, and Q. Niu, Phys. Rev. B 98, 134515 (2018).

Wednesday, December 14, 2022 (Day 3) 15:00 – 15:30

Intertwined orders and vortex structures of cuprates

Prof. Ting-Kuo Lee
National Tsing Hua University

We present a comprehensive study of vortex structures in d-wave superconductors from large-scale renormalized mean-field theory of the square-lattice t-t'-J model. which has been shown to provide a quantitative modeling for high-Tc cuprate superconductors. With an efficient implementation of the kernel polynomial method for solving electronic structures, self-consistent calculations involving up to 10^5 variational parameters are performed to investigate the vortex solutions on lattices of up to 10^4 sites. By taking into account the strong correlation of the model, our calculations shed new lights on two puzzling results that have emerged from recent scanning tunneling microscopy (STM) experiments on vortices in cuprates. The first concerns the longstanding puzzle of lack of the zero-biased-conductance peak at the vortex core for most STM experiments [1] on superconducting cuprates. The second issue is the nature of the checkerboard charge density waves and intertwined pair density waves with a period of about 8 unit cells in the vortex halo at optimal doping [2]. We present a coherent interpretation of these experimental results based on systematic studies of the doping and magnetic field effects on vortex solutions with and without a checkerboard structure.

References:
[1] T. Gazdić, I. Maggio-Aprile, G. Gu, and C. Renner, Phys. Rev. X 11, 031040 (2021).
[2] S. D. Edkins, et al., Science 364, 976 (2019).

Other co-authors:
Yi-Hsuan Liu,[1, 2] Wei-Lin Tu,[3] Gia-Wei Chern[2]
[1]Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
[2]Department of Physics, University of Virginia, Charlottesville, VA 22904, USA
[3]Division of Display and Semiconductor Physics, Korea University, Sejong 30019, Korea

Wednesday, December 14, 2022 (Day 3) 16:00 – 16:30

Half-quantized Transport in Axion Insulators

Prof. Xincheng Xie
Peking University

We propose that half-quantized helical hinge currents manifest as the fingerprint of the axion insulator. These helical hinge currents microscopically originate from the lateral Goos-Hänchen (GH) shift of massless side-surface Dirac electrons that are totally reflected from the hinges. The helical current induced by the GH shift is half-quantized. Semiclassical wave packet analysis uncovers that the hinge current has a topological origin and its half-quantization is robust. Lastly, we propose an experimentally feasible six-terminal device to identify the half-quantized hinge channels by measuring the nonreciprocal conductance.

Wednesday, December 14, 2022 (Day 3) 16:30 – 17:00

Excitations, Spin-Charge Separation, and Correlation Function

Prof. Hai-Qing Lin
Zhejiang University

Quasi-particles play important role in condensed matter physics and result in many emergent novel phenomena. In this talk, we discuss collective excitations in one-dimension as exemplified by antiferromagnetic Heisenberg model and δ-function interacting Fermi gas (Yang-Gaudin model). Using the thermodynamic Bethe Ansatz (TBA) formalism, we analytically derive universal properties of the models with arbitrary interaction strength, and present a rigorous understanding of spin-charge separation, a unique feature predicted by the Tomonaga-Luttinger liquid (TLL) theory. Spinon, as an elementary spin excitation, is responsible for the TLL. We show that a dimensionless quantity, the Wilson Ratio (WR), elegantly characterizes quantum liquid phase diagram. For the TLL phase, WR = 4Ks remains almost temperature independent, where Ks is the Luttinger parameter. WR can be used to identify quantum phase transitions for a wide variety of materials. Based on the exact low-lying excitation spectra, we further evaluate the spin and charge dynamical structure factors (DSFs). The peaks of the DSFs exhibit distinguishable propagating velocities of spin and charge as functions of interaction strength, which can be observed by Bragg spectroscopy with ultracold atoms. Combining quantum integrable theory with numerics, we propose a reliable technique to exactly compute the spectral function of 1D many-body models at large scales and demonstrate the technique on the Lieb-Liniger gas. Our results show that a full description of the critical behavior requires system size as large as thousands of particles.

Acknowledgements:
NSAF U1930402 and NSFC 11734002, as well as computational resources from the Beijing Computational Science Research Center

Collaborators:
Guan XW Group: Feng He, Yu-Zhu Jiang, Yi-Cong Yu, Yang-Yang Chen
CSRC & Other Institutes: Song Cheng, Rubem Mondaini, Wen-Li Yang
Rich Univ./US: Randall G. Hulet, Han Pu
Univ. of Warwick/UK: Rudolf A. Romer
Bethe Ansatz Group: X.-G. Yin A. Foerster, M. T. Batchelor, C.-H. Lee

Wednesday, December 14, 2022 (Day 3) 17:00 – 17:30

Half Quantum Hall Effect in Metal

Prof. Shunqing Shen
The University of Hong Kong

The quantum Hall effects refer to a series of peculiar quantum states of matter found in the two-dimensional electron system in a strong magnetic field at very low temperature. Similar phenomena in two-dimensional materials in the absence of magnetic field are named the quantum anomalous Hall effect. So far all the quantum Hall effects occur in insulating phases, and are characterized by an integer or rational fraction. These quantum Hall effects occur when the Fermi level lies in the energy gap of the Landau levels or the band gap, and are characterized by the TKNN number or Chern number for the band structure as a topological invariant. The longitudinal conductivity is zero and either the Hall resistivity or conductivity is quantized. The bulk-edge correspondence illustrates that the number corresponds to the number of the localized edge modes around the system boundary, which carries the dissipationless chiral charge current. Here we report a half-quantized Hall effect in a metal or semimetal. The Hall conductance is half quantized and the longitudinal conductance is nonzero, but the Hall resistivity is not quantized. The half quantization occurs when the Fermi surface is invariant under the parity symmetry while the symmetry is broken in the whole system. A recent experiment reports the observation of the half-quantized Hall conductance in a magnetically-doped topological insulator. We discover that a single gapless Dirac cone exists in the band structure and has the half-quantized conductance when the Fermi level intercepts the gapless surface states in which the parity is invariant for in a finite regime in the Brillouin zone. As there are no chiral edge states in the gapless and metallic system, we also find that the chiral edge current is carried by the gapless surface states. The current density is peaked at the edge and decays in a power law rather than the exponential decay in the quantum anomalous Hall effect. We term the unexpected and nontrivial quantum phase as "parity anomalous semimetal". The work opens the door towards exploring novel topological states of matter with fractional topological charge.

References:

[1] B. Fu, J. Y. Zou, Z. A. Hu, H. W. Wang, and S. Q. Shen, *Quantum anomalous semimetals*, npj Quantum Materials **7**, 94 (2022)

[2] J. Y. Zou, B. Fu, H. W. Wang, Z. A. Hu, and S. Q. Shen, *Half-quantized Hall effect and power law distribution of edge current distribution*, Phys. Rev. B **105**, L201106 (2022)

[3] J. Y. Zou, R. Chen, B. Fu, H. W. Wang, Z. A. Hu, and S. Q. Shen, *Half-quantized Hall effect at the Parity-Invariant Fermi Surface*, arXiv: 2209.03053

Thursday, December 15, 2022 (Day 4) 09:00 – 09:30

Tuning polaritons in 2D semiconductor-photonic crystals

Prof. Hui Deng
University of Michigan

Coming soon

Thursday, December 15, 2022 (Day 4) 09:30 – 10:00

Light-Matter Interaction in Flatland: Excitonic Physics in 2D

Prof. Su-Fei Shi
Rensselaer Polytechnic Institute

The emergence of transition metal dichalcogenides (TMDCs) ushers in a new era of light-matter interaction. In monolayer TMDCs, the reduced screening enhances the Coulomb interaction and gives rise to strongly bound excitons, which possess a new quantum degree of freedom, valley-spin. In this talk, I will discuss our search for valley-contrasting, long-lived quasiparticles through various optical spectroscopy techniques, which advance our understanding of the many-particle excitonic complexes in monolayer WSe_2.

TMDCs also offer unprecedented opportunities in bandstructure engineering and the construction of moiré superlattices, which host flat miniband and lead to high tunable correlated states in 2D. Over the past few years, we have identified various correlated insulating states in the WS_2/WSe_2 heterostructures. The correlated electrons also interact with both the intralayer and interlayer excitons, leading to the opportunities of engineering and exploration of new correlated excitons.

Thursday, December 15, 2022 (Day 4) 10:00 – 10:30

Van der Waals Interface for Highly Efficient Spin Readout as well as Recent Nonlinear Hall effect study on $MoTe_2$

Prof. Kian Ping Loh
The Hong Kong Polytechnic University

The reduced symmetry in strong spin-orbit coupling materials such as transition metal ditellurides (TMDTs) gives rise to non-trivial topology, unique spin texture, and large charge-to-spin conversion efficiencies [1,2]. In the first part if the talk I will discuss the planar Hall effect in 1T'-MoTe2 as well as using this material for spin readout in a van der Waals heterostructure. As an all-electrical scheme to generate, detect and manipulate spin current, the spin Hall effect (SHE) has been heavily investigated as a primary route towards next-generation spintronic devices. SHE-enabled readout of magnetic states (spin states) is central to the operation of energy efficient spin logic device. However, the spin readout signal of nanomagnets based on SHE in heavy metals, which is typically less than 10 mΩ, falls severely short of the operation standards in practical spin logic devices. Herein, by constructing SHE devices using van der Waals (vdW) heterostructures, we achieved nonlocal spin readout signal of 150 mΩ and local spin readout signal of 6.7 Ω, which exceed the state-of-the-art by at least a factor of ~100 and ~20, respectively. The record-high spin readout signal is due collectively to suppressed spin dephasing channels at the vdW interfaces, long spin diffusion and large charge-spin interconversion in semimetal $MoTe_2$.

In the second part of the talk, I will discuss the nonlinear Hall effect (NLHE) in $MoTe_2$ as a function of its symmetry and thickness. NLHE produces a second harmonic Hall voltage that varies quadratically with a perpendicular current under time-reversal symmetric conditions, thus they can be useful as RF rectifier. As-grown bilayer $MoTe_2$ shows out-of-plane ferroelectric polarization, whereas the monolayer and trilayer crystals are non-polar. In addition, we observed large in-plane nonlinear Hall (NLH) effect for the bilayer and trilayer T_d phase $MoTe_2$ under time reversal-symmetric conditions, while these vanish for thicker layers. For a fixed input current, bilayer T_d $MoTe_2$ produces the largest second harmonic output voltage among the thicker crystals tested. Our work therefore highlights the importance of thickness-dependent Berry curvature effects in TMDTs that are underscored by the ability to grow thickness-precise layers. However, the NLHE effect driven by Berry curvature dipole typically vanishes at room temperature or has a very low magnitude in most materials. Thus, there is a need to identify other scattering mechanism that can drive the NLHE up to room temperature and beyond.

References:

[1] Song, P. Kian Ping Loh* *et al.* Coexistence of large conventional and planar spin Hall effect with long spin diffusion length in a low-symmetry semimetal at room temperature. *Nat. Mater.* **19,** 292–298 (2020).
[2] Ma, T., Chen, H., Yananose, K. Kian Ping Loh* *et al.* Growth of bilayer $MoTe_2$ single crystals with strong non-linear Hall effect. *Nat Commun* **13**, 5465 (2022). https://doi.org/10.1038/s41467-022-33201-3

Thursday, December 15, 2022 (Day 4) 11:00 – 11:30

Tunable phonon magnetic moment in bilayer graphene

Prof. Di Xiao
University of Washington

Chiral phonons can induce dynamical multiferroicity from the motions of electrons and nuclei, giving rise to phonon-driven magnetization. Recently, quantum theories of phonon magnetic moment based on the geometric phase of the electronic ground states have been developed. In this talk, I will discuss a first-principles scheme to calculate the phonon magnetic moment. We show in the case of bilayer graphene, the magnetic moments of the two chiral shear phonon modes can reach 0.01 mu_B under a perpendicular electric field E=0.025 V/A. In contrast, the calculated magnetic moments vanish according to the classical theory based on Born effective charge. Our work demonstrates viable routes to control the magnetic moment of phonons, as the moment is largely tunable by the electric field.

Thursday, December 15, 2022 (Day 4) 11:30 – 12:00

Competing mechanisms of high-T_c superconductivity and topological superconductivity in systems of varying dimensionality

Prof. Zhenyu Zhang
University of Science and Technology of China

Identification of the dominant pairing mechanisms in superconducting systems with moderate or high transition temperatures (T_c) has been a perpetual drive of condensed matter physics for decades. The recent marriage of topology and superconductivity in the emerging area of topological superconductivity has further expanded the scope to multiple disciplines with conceptual new challenges and technological incentives. In this talk, I will attempt to give an overview on recent advances in this vibrant area, with some of own stories squeezed in. We start from freestanding or supported superconducting monolayers that exhibit exotic or high-T_c superconductivity [1,2], as well as monolayered systems that display intrinsic *p*-wave superconductivity [3] or coexistence of superconductivity and nontrivial band topology [4-6]. Next we expand to bulk systems that contain stacked superconducting monolayers with weak interlayer coupling [7,8]. On the mechanistic side, we use concrete examples to demonstrate how plasmonic excitations or pronounced correlation effects can effectively enhance the superconductivity of FeSe monolayers supported on STO or bulk FeSe [8,9]. We will also highlight the dominant schemes of achieving topological superconductivity, focusing especially on highly crystalline two-dimensional systems [10].

References:

[1] S. Zhang, T. Wei, J. Guan, Q. Zhu, W. Qin, W. Wang, J. Zhang, E. W. Plummer, X. Zhu, Zhenyu Zhang, and J. Guo, Phys. Rev. Lett. **122**, 066802 (2019).
[2] W. Ding, J. Zeng, W. Qin, P. Cui, and Zhenyu Zhang, Phys. Rev. Lett. **124**, 027002 (2020).
[3] W. Qin, L. Li, and Zhenyu Zhang, Nat. Phys. **15**, 796 (2019).
[4] S. Sun, W. Qin, L. Li, and Zhenyu Zhang, Phys. Rev. B **103**, 235149 (2021).
[5] J. Gao, W. Ding, S. Zhang, Zhenyu Zhang, and P. Cui, Nano Lett. **21**, 7396 (2021).
[6] C. Zhao, L. Li, L. Zhang, J. Qin, H. Chen, B. Xia, B. Yang, H. Zheng, S. Wang, C. Liu, Y. Li, D. Guan, P. Cui, Zhenyu Zhang, and J. Jia, Phys. Rev. Lett. **128**, 206802 (2022).
[7] M. U. Muzaffar, W. Ding, S. Zhang, P. Cui, and Zhenyu Zhang, Phys. Rev. B **102**, 174513 (2020).
[8] W. Ding, Y. Wang, T. Wei, J. Gao, P. Cui, and Zhenyu Zhang, Sci. China-Phys. Mech. Astron. **65**, 267412 (2022).
[9] T. Wei and Zhenyu Zhang, Phys. Rev. B **104**, 184503 (2021).
[10] W. Qin, J. Gao, P. Cui, and Zhenyu Zhang, Sci. China-Phys. Mech. Astron. (invited review) (2022, to appear).

Thursday, December 15, 2022 (Day 4) 12:00 – 12:30

Prof. Nicolas Fang
The University of Hong Kong

Coming soon

Thursday, December 15, 2022 (Day 4) 14:00 – 14:30

Plasmonic nanocavity enhanced interaction of light and low-dimensional materials systems

Prof. Dangyuan Lei
City University of Hong Kong

Coming soon

Thursday, December 15, 2022 (Day 4) 14:30 – 15:00

Engineering Polariton Condensate Lattices and Networks for Quantum Applications

Prof. Qihua Xiong
Tsinghua University

Coming soon

Thursday, December 15, 2022 (Day 4) 15:00 – 15:30

Prof. Jianbin Xu
The Chinese University of Hong Kong

Coming soon

Thursday, December 15, 2022 (Day 4) 16:00 – 16:30

Two-dimensional semiconductor tungsten disulphide: fundamental properties and potential applications

Prof. Ting Yu
Wuhan University

Two-dimensional (2D) materials, such as graphene and monolayer transitional-metal-dichalcogenides (TMDs), have aroused great attention due to the underlying fundamental physics and the promising atomically-thin optoelectronic applications. Among these emerging 2D semiconductors, WS_2 is one of the most promising candidates for advanced light sources including on-chip LED and Lasers. In this talk, I will report our findings on optical characterization and optoelectronic applications of WS_2.

Keywords:
2D semiconductors, WS2, Optoelectronics

Thursday, December 15, 2022 (Day 4) 16:30 – 17:00

Polynomial Sign Problem and Topological Mott Insulator emerging from Twisted Bilayer Graphene

Dr. Zi Yang Meng
The University of Hong Kong

Coming soon

Thursday, December 15, 2022 (Day 4) 17:00 – 17:30

Van der Waals integration of ultrahigh-k dielectrics into 2D transistors

Prof. Lain-Jong (Lance) Li
The University of Hong Kong

Coming soon