SYSTEMS ENGINEERING RESEARCH CENTER

2D Materials for Spintronics and Quantum Sensing

WRT-1046

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STEVENS INSTITUTE OF TECHNOLOGY

ANNUAL RESEARCH REVIEW 2022

Gyroscopes – Needs and Challenges

- The need for *alternatives to GPS* is evident as the GPS signal sees real threats due to local jammers denying access in the region.
- *Optical gyroscopes* are widely used for inertial navigation, stabilization and positioning control systems. However, the substantial increase in cSWaP is not conducive to the existing volume constraints.
- *MEMS gyroscopes* - vendors' specifications are listed only after standard testing, and do not include the shift-after-shock bias, scale factor or misalignment after the shock event.

Sagnac Interferometers

- 1913, Sagnac proposed the idea of using a ring interferometer as a rotation rate sensor in order to detect “the effect of the relative motion of the ether.”

Optical gyroscopes

- no moving parts
- 0.01 degree/hr bias stability
- HRG costs > $1M
- 50 cm^3, 19 lb, 30W

Atom Gyroscopes

- sensitivity ($Mc^2 / \hbar\omega \sim 10^{10}$): 60 μdegree/hr bias stability
- operation at ~100nK, high vacuum, high magnetic fields
- Very heavy: several hundred kilograms

Electron interferometers:

- $Mc^2 / \hbar\omega \sim \mathbf{10^6}$
- Solid-state device: low fabrication costs, light weight, and direct ntegration with solid state electrical circuits

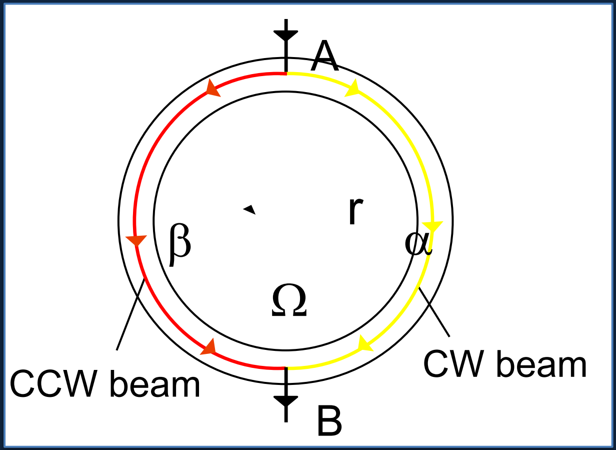
Surprisingly no discussion on gyroscopes; only experiments were done with electron beams in vacuum.

Matter Wave Interferometers

- 1913, Sagnac proposed the idea of using a ring interferometer as a rotation rate sensor in order to detect "the effect of the relative motion of the ether."
- In 1924 de Broglie proposed that ordinary "particles" such as **electrons**, protons, or bowling balls could also exhibit wave characteristics in certain circumstances.
- For de Broglie matter waves, the phase difference is where is the enclosed area of the interferometer, the rotation rate, the particle mass, and is Planck's constant.

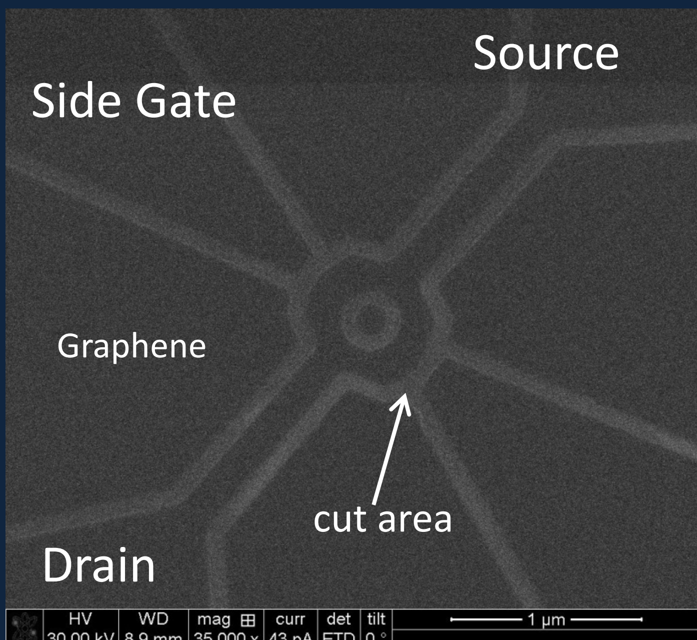
$$\boxed{\delta\varphi_{\alpha\beta} = \frac{2Am}{\hbar}\Omega}$$ for matter waves

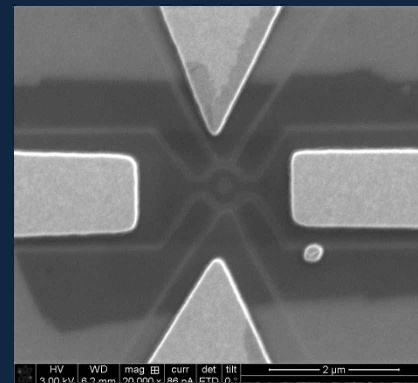
The measured signal would be larger than an optical interferometer, which is the ratio of the energy of massive particle to that of a photon.

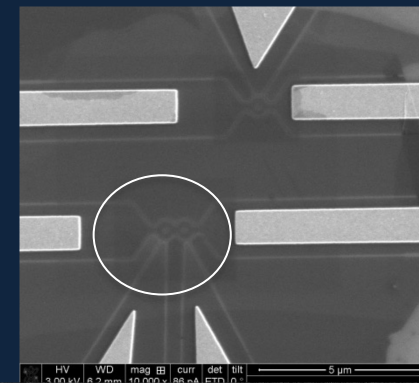


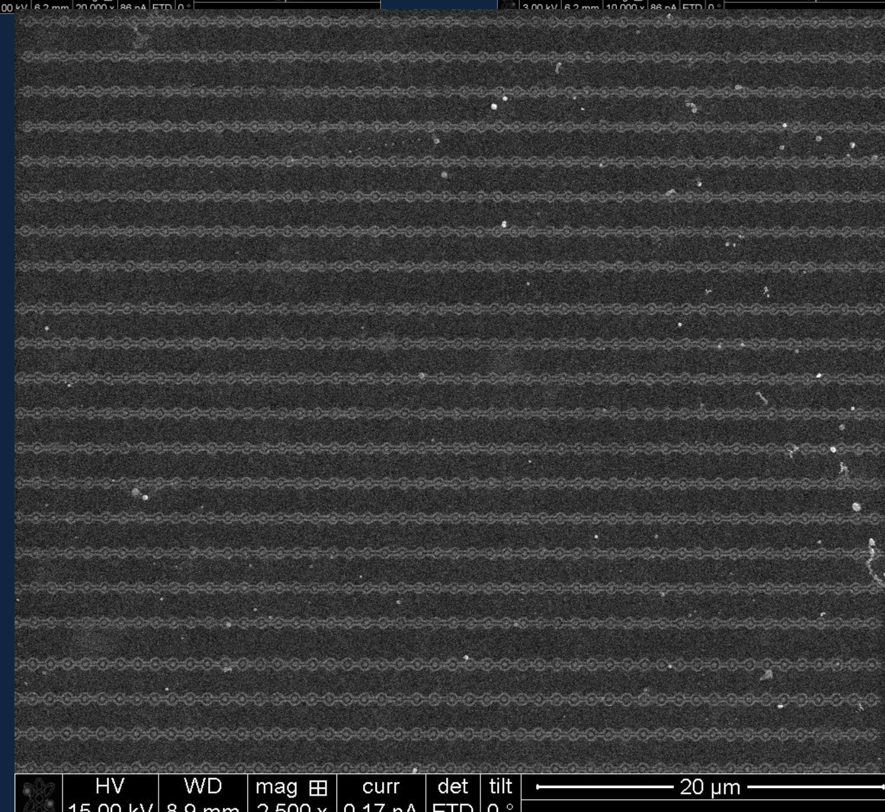
Graphene Patterning toward Solid-State Interferometers

Single Ring Device



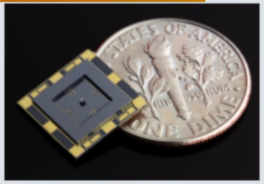




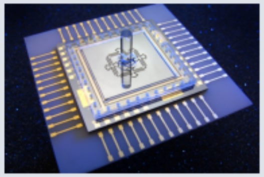


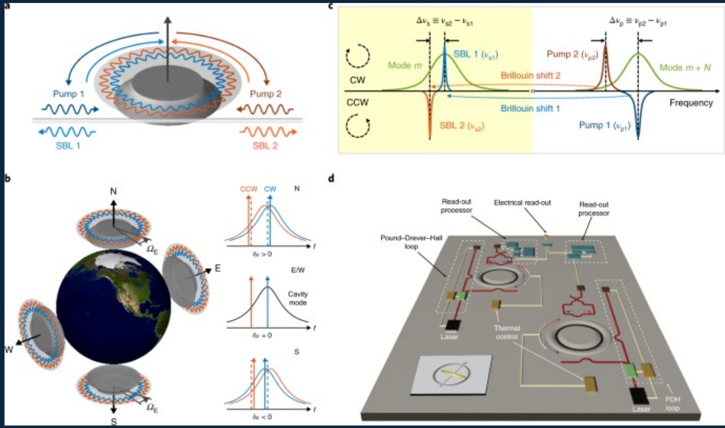
How to test Sagnac effect in graphene ring structures under development?

(Tang, 1998) All silicon, closed loop cloverleaf micro gyro (1.0 deg/hr)

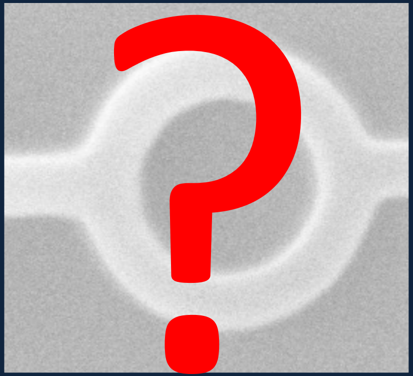


(Wiberg, 2002) Meso-scale, post resonator gyro (0.1 deg/hr)





Nat. Photonics **14**, 345–349 (2020)



Aharonov-Bohm (AB) Interferometer

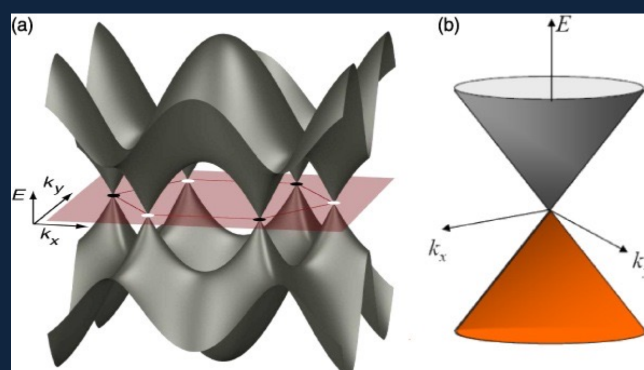
- Aharonov-Bohm effect: the oscillations in the resistance of a conducting ring as a function of an external magnetic flux piercing the ring.
- The Aharonov-Bohm phase shift φ_{AB}, is
- $$G = G_Q \frac{(1-\cos\chi)(1+\cos^2\varphi_{AB})}{\sin^2\chi+[\cos\chi-(\cos\varphi_{AB})/2]^2}$$

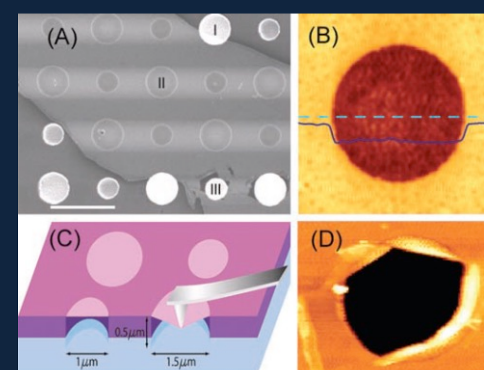
where G_Q is the conductance quantum, c is the electron phase shift when traveling between scatters, and φ_{AB} is the gauge-invariant combination of the phases.

- Magnetoconductance measurements show fringes as a function of the applied magnetic field, characterized by fringe contrast and used to sense magnetic fields.
- An interferometer based on AB oscillations is in principle equivalent to a rotation sensor.

What materials we should use for solid-state electron interferometers?

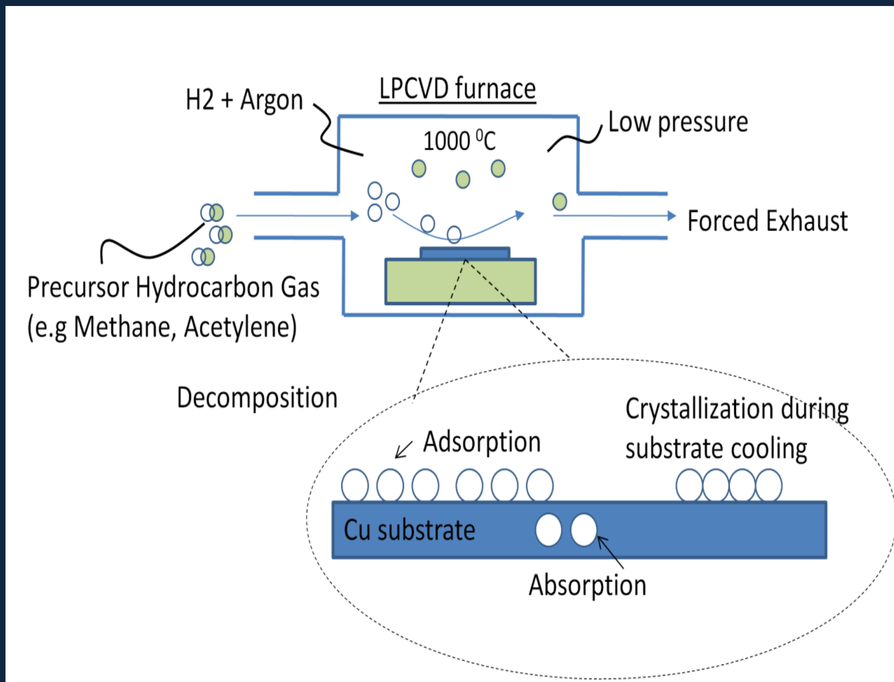
- Although scientists knew graphene existed, no-one had worked out how to extract it from graphite, until it was isolated in 2004 by Geim and Novoselov who received Nobel Prize (2010).
- Graphene has become a valuable nanomaterial due to its exceptionally high tensile strength, electrical conductivity, and transparency.
- Graphene acts as a 2D ballistic, phase coherent electron system with long phase coherence length that exceeds **5μm**. (Science, 317(5844), 1530 (2007))





Science 321, 385 (2008)

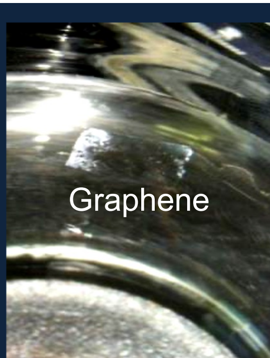
CVD Graphene Growth



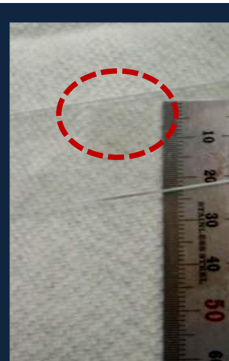
Cu Substrate

Ar+H_2+CH_4 flow

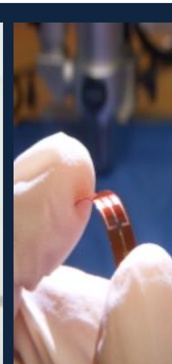
Computerized
Precise heating and
cooling cycles



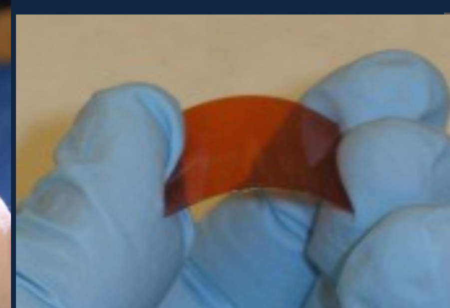
Graphene on water

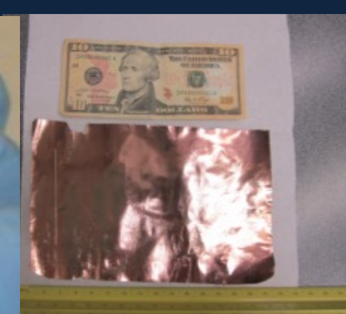


Transferred graphene on glass

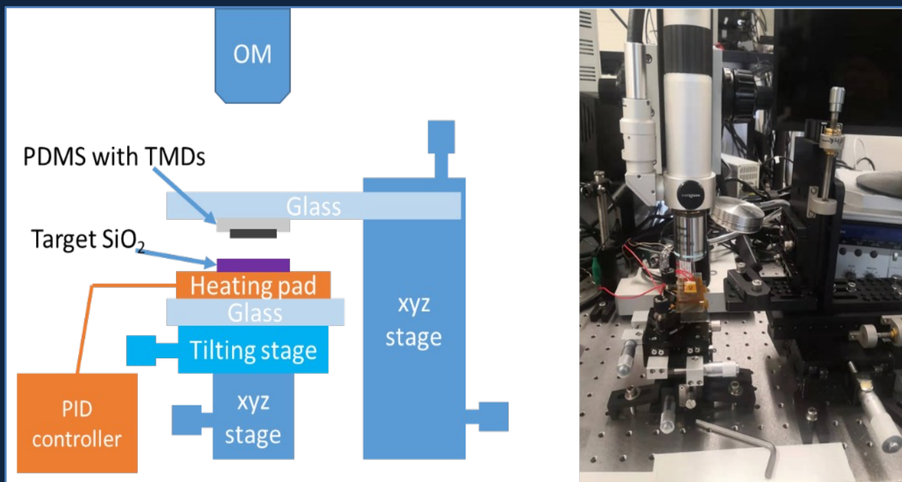


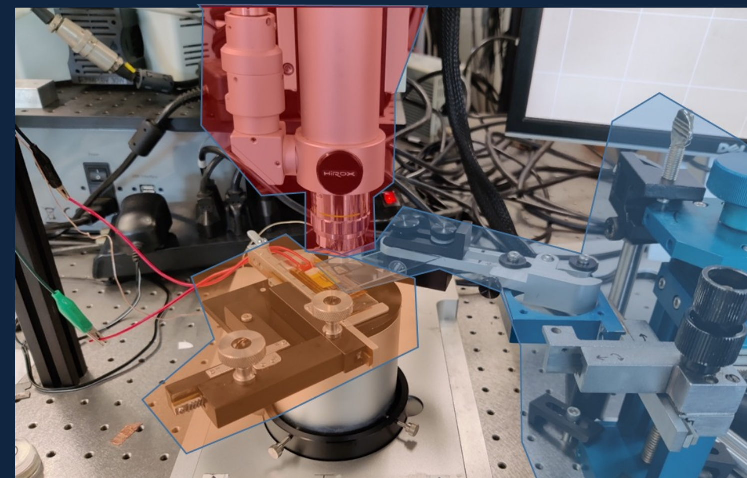
Transferred graphene on flexible substrate

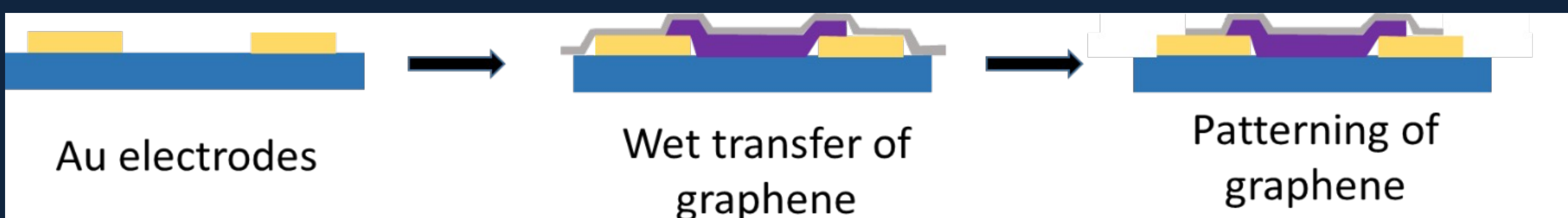




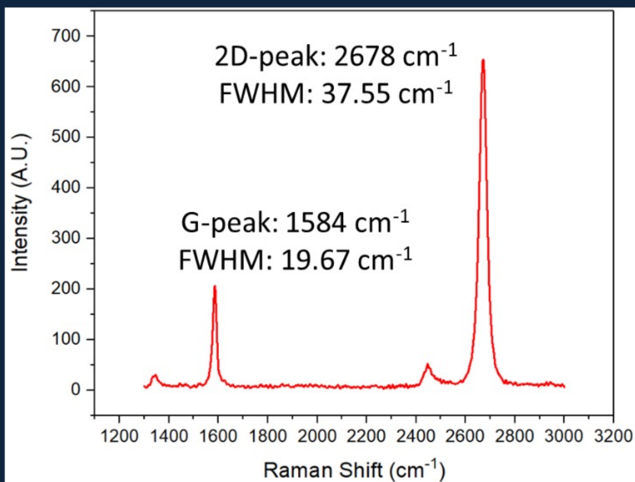
Graphene Device Fabrication



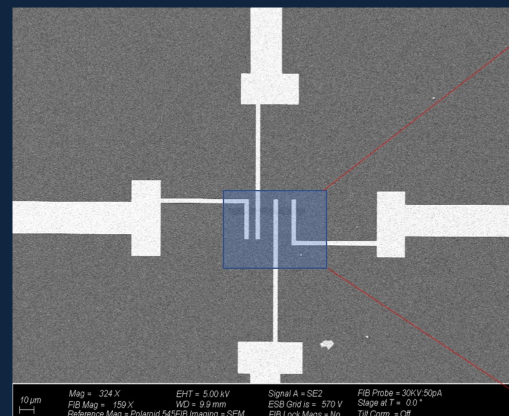


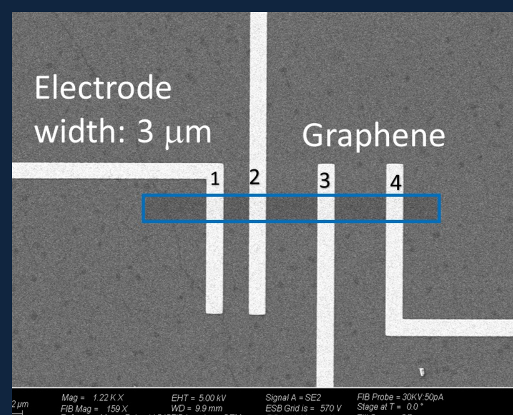


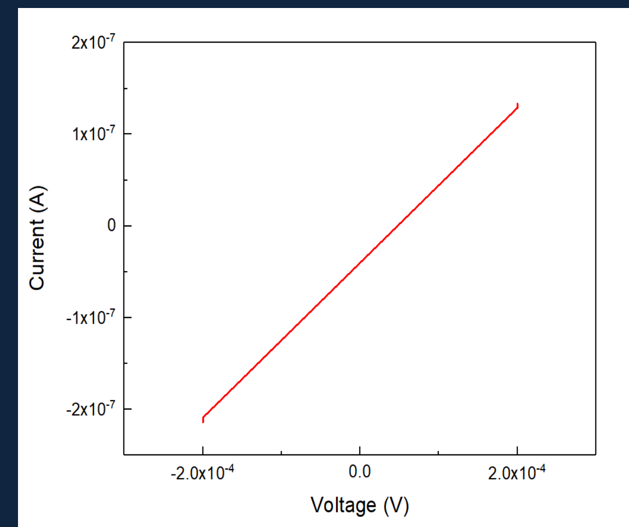
Characterization of Material Qualities



Raman spectra from a graphene ring

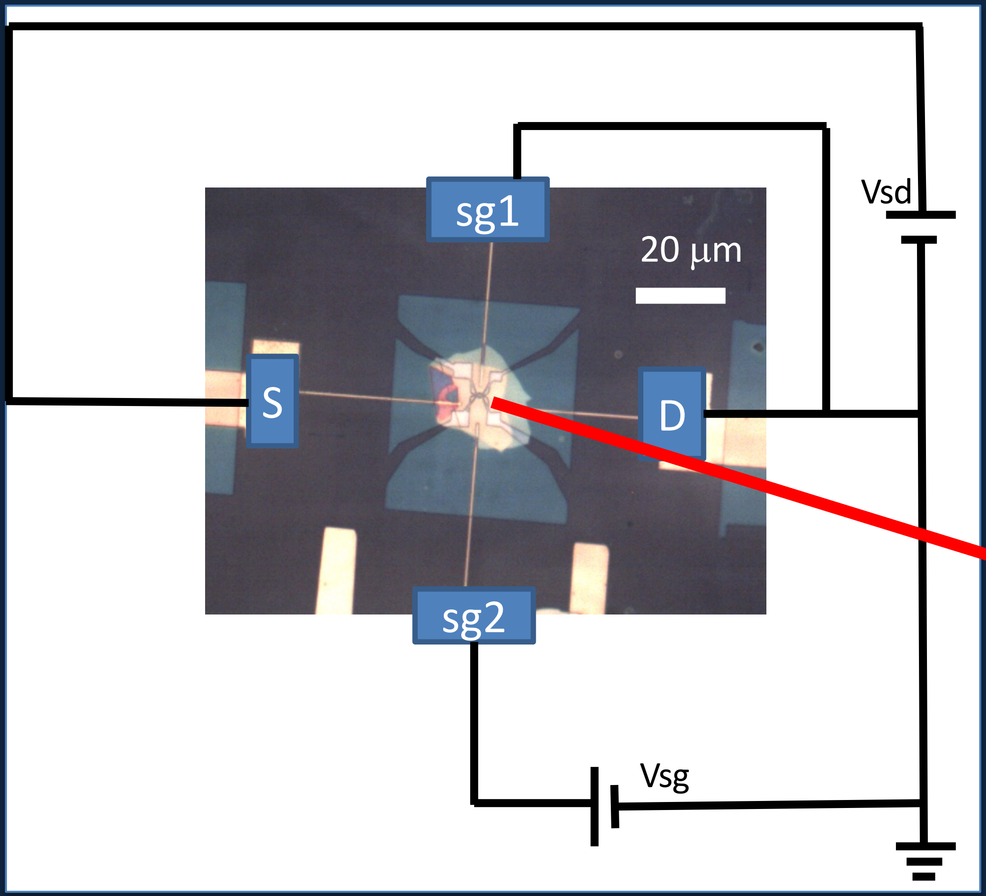


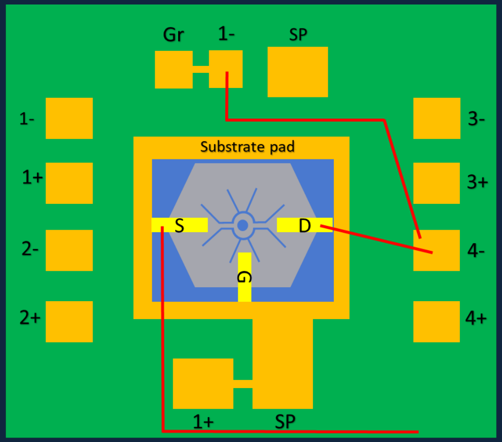


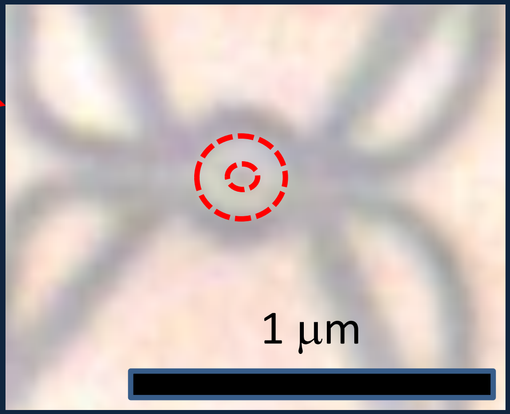


IV curve from channel 1-2
Channel Length: 4.74 μm
Resistance: ~ 1kOhm

Graphene Ring Fabrication







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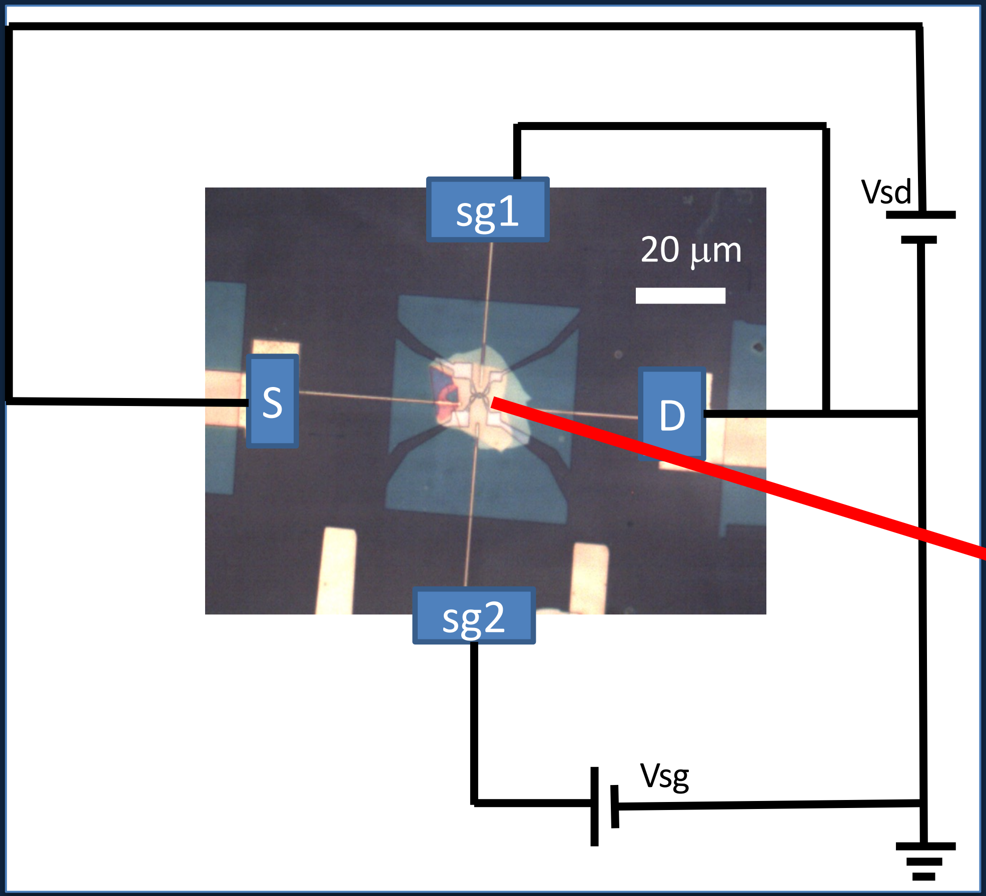
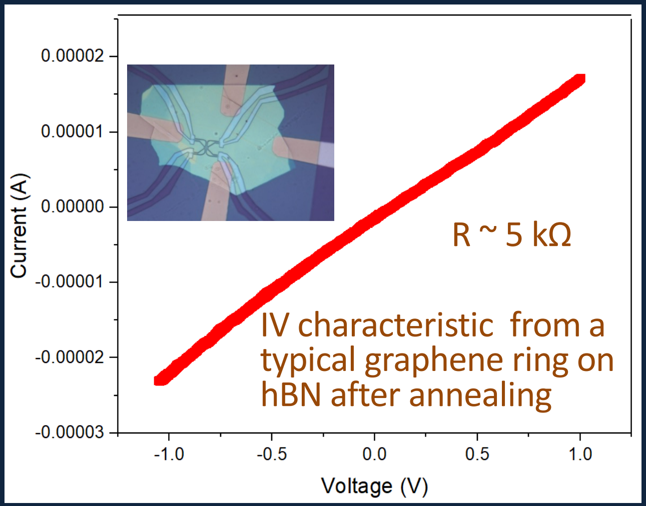
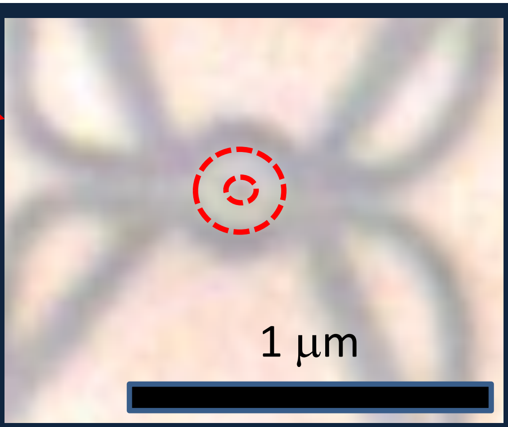
Graphene Ring Fabrication







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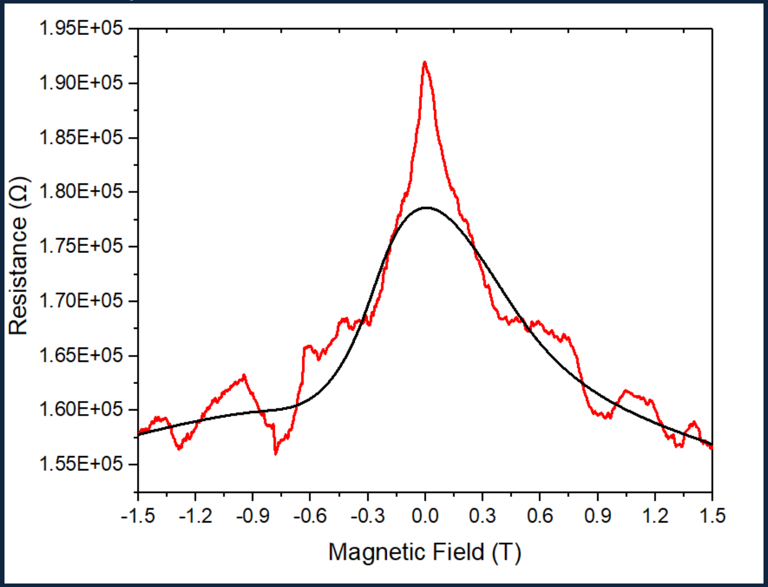
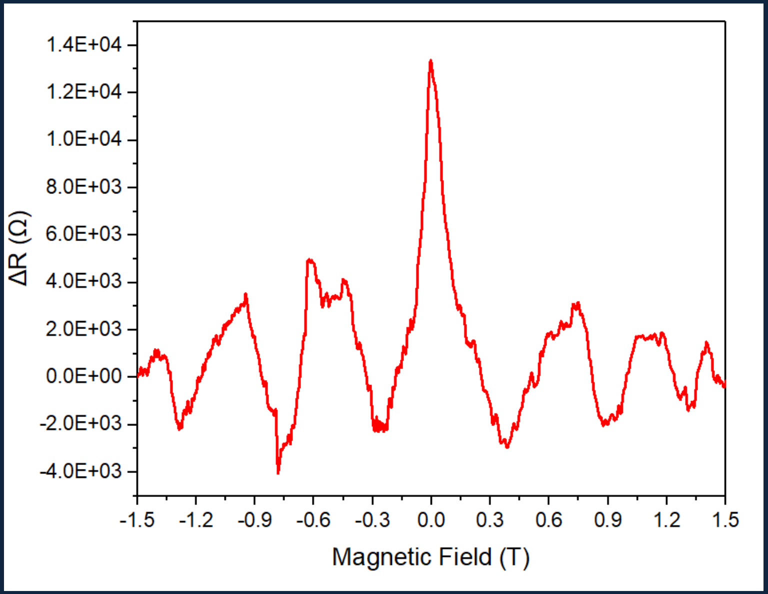
Conductance Oscillations under Magnetic Fields

Magnetic fields: -1.5 to 1.5 T.
Source-Drain voltage (Vsd): 4 mV.
Side gate voltage (Vsg): 99 mV
Temperature: 4 K

Landau level quantization effect



Low frequency background resistance (black) & magnetoresistance (red)



Oscillations obtained after baseline subtraction

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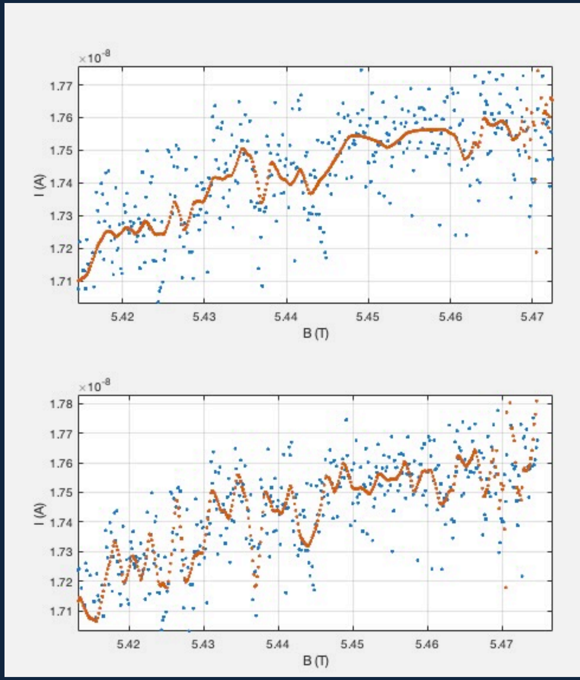
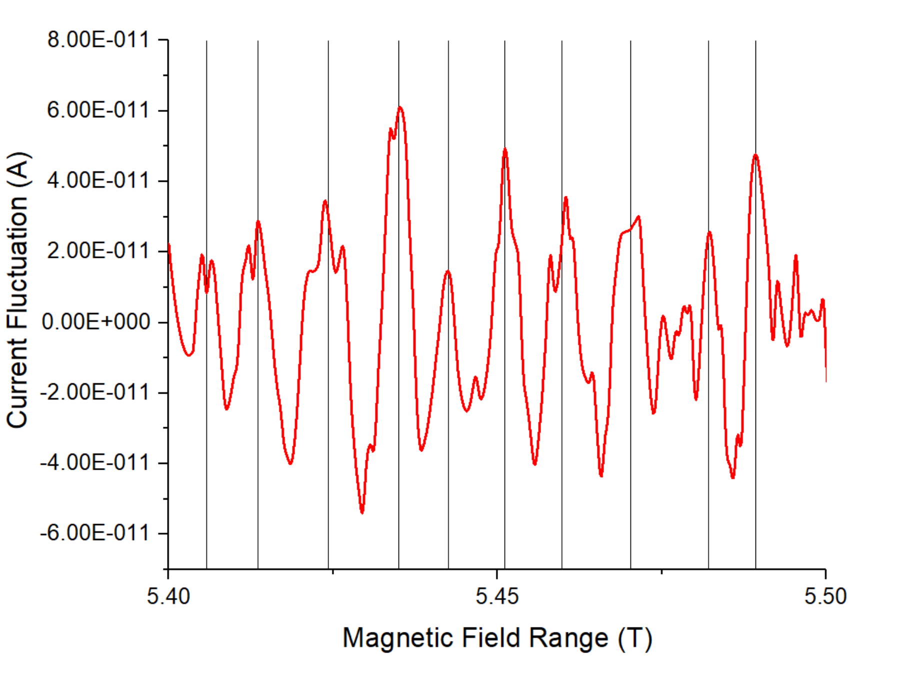
Baseline Subtraction





Levels denoising (red curves) and magnetoresistance data.

After baseline subtraction: peak spacing ~ 0.82 mT.

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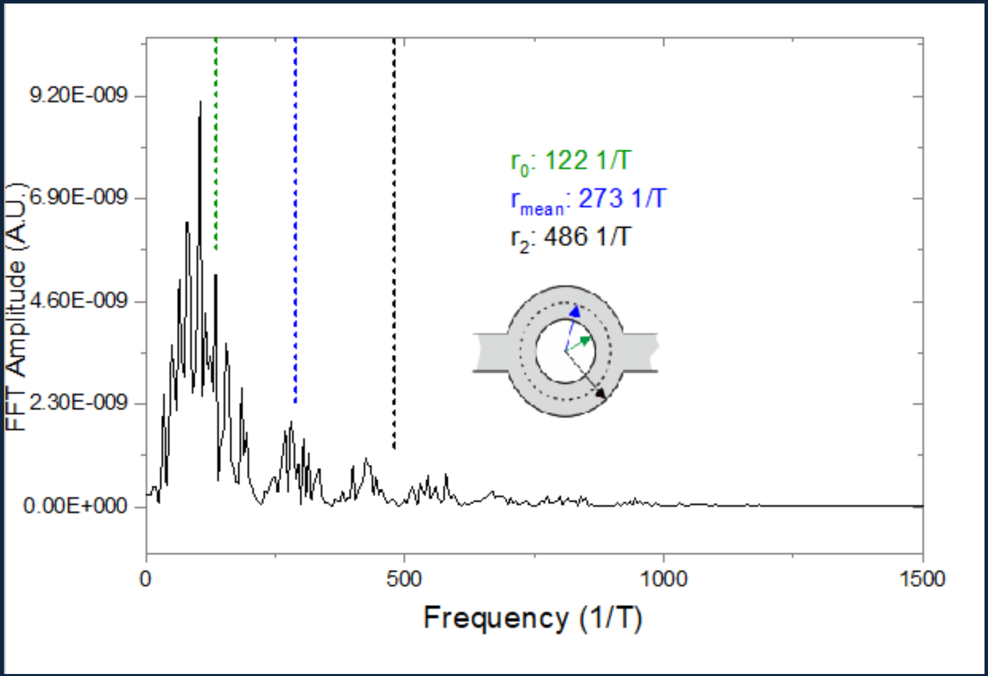
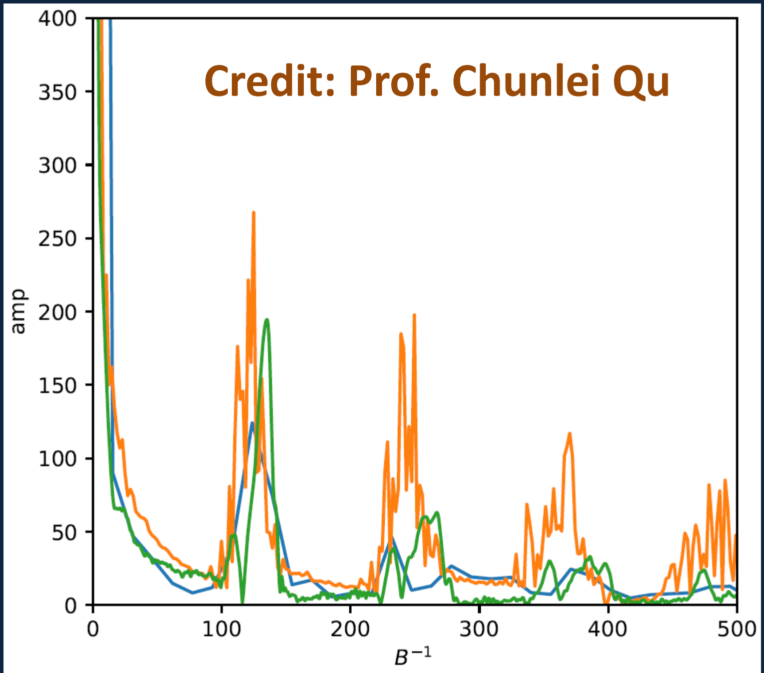
Aharonov-Bohm (AB) Oscillations





h/e oscillation frequencies corresponding to the different ring radii

Calculations not included defects, edge states, spin-orbit-coupling, top and side gate potentials, temperature effects, etc.

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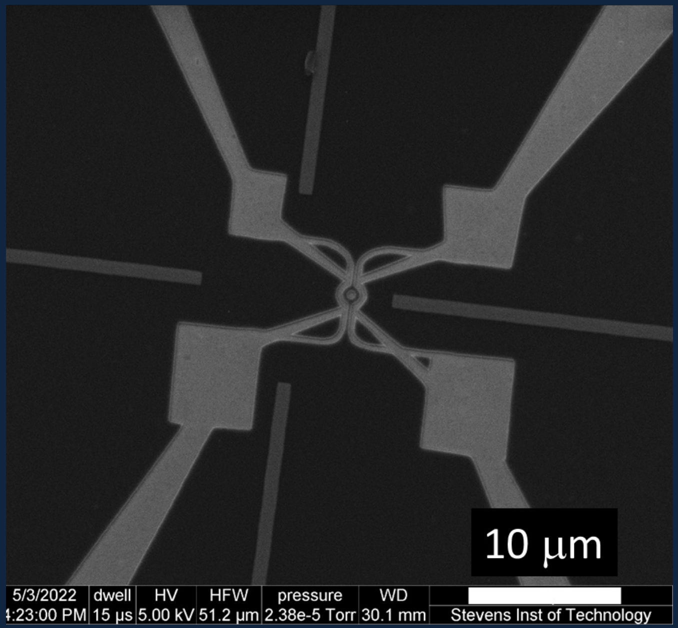
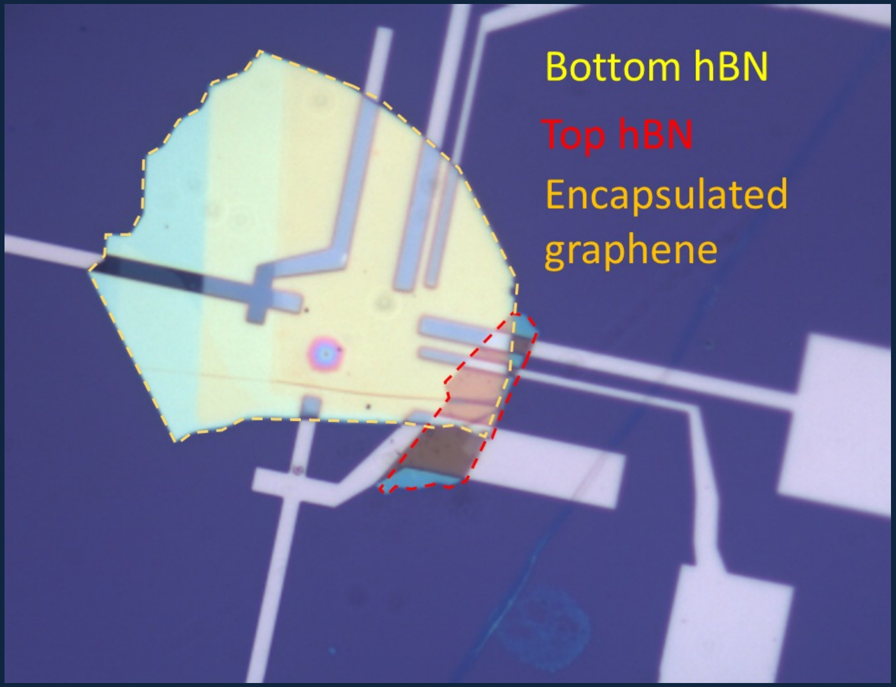
Enhanced Design, Fabrication & Gate-Tuning





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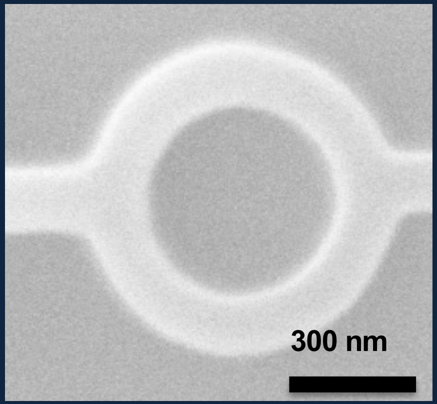
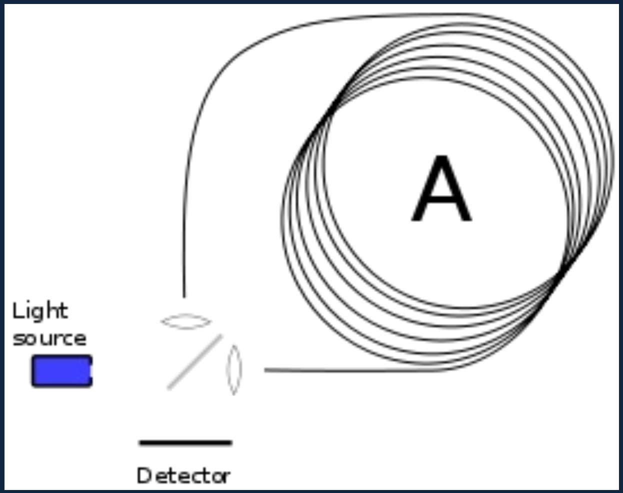
Limitations

- **Sagnac effect:** a phase coherent effect where rotations of the ring result in a shift in the interference pattern proportional to the rotation rate.

$mc^2 / \hbar\omega \sim \mathbf{10^5}$ $\boxed{\Delta\phi = 2mA\Omega / \hbar}$ $\boxed{G = I / V = (e^2 / h)\cos^2(\Delta\phi + \theta)}$ Credit: Prof. Chris Search

- *But, in graphene nanorings, Sagnac effect is not enough to create a measurable conductance change (limited phase coherent length).*
- The phase change must be enhanced to the detectable levels.

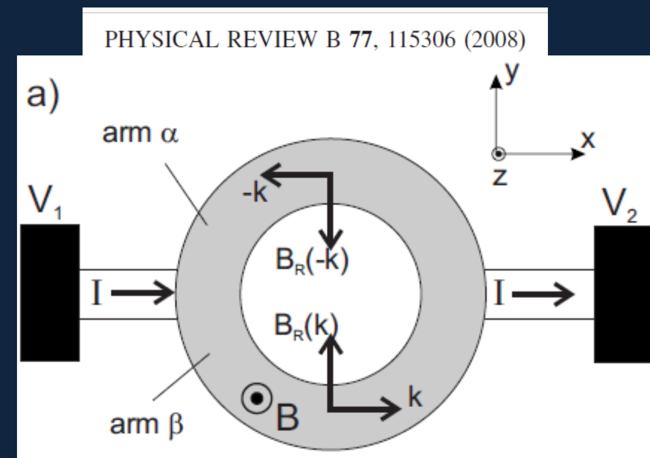


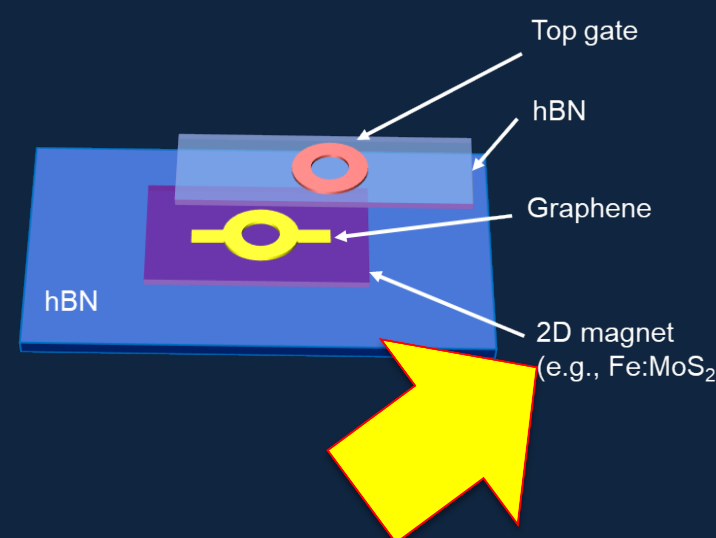


https://en.wikipedia.org/wiki/Sagnac_effect

Possible Solutions

- Required Conditions:
  - A quasi-one-dimensional ring of radius r_o
  - Arms behave as a ballistic conductor
  - Ring coupled to a bias voltage V_1-V_2
  - *Perpendicular to the plane of the ring a magnetic field **B** and electric field **E** are applied*
- Consider the following effects:
  - Zeeman splitting (due to the applied magnetic field)
  - Rashba spin-orbit interaction (due to the applied electric field and the geometry of the ring)

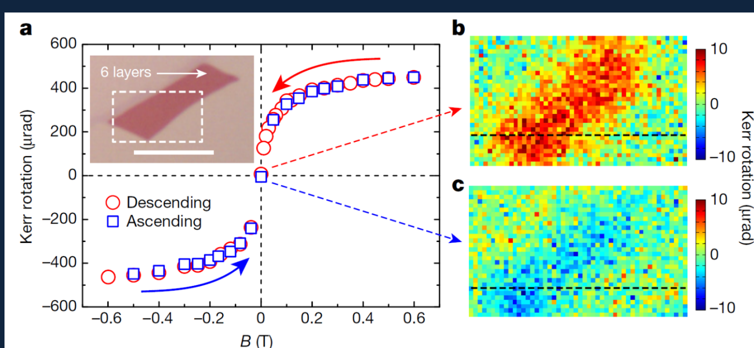




2D Ferromagnetic Crystals

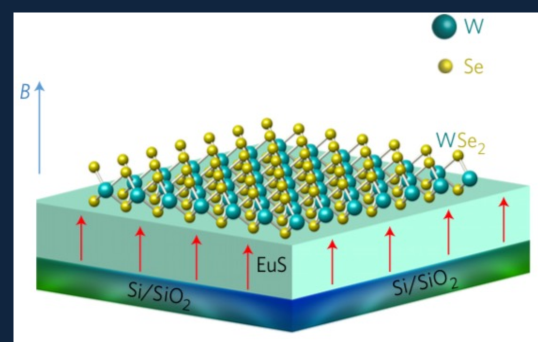
- In early 2017, the first observations of ferromagnetism at cryogenic temps were reported.
- CrI_3 on EuS, WSe_2 monolayers on EuS, WSe_2 monolayers on 10 nm CrI_3.

exfoliated, insulator or conductor, unstable in air



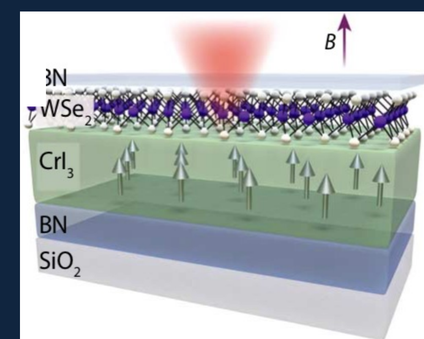
CrI_3 on EuS ➔ T_c ~ 45K

Gong, *et al., Nature* **546**, 265 (2017)



WSe_2 on EuS ➔ T_c ~ 16.5K

Zhao *et al.*, *Nat. Nano.*, **12**, 757 (2017)



WSe_2/CrI_3 ➔ T_c ~ 61K

Zhong *et al.*, *Sci. Adv.*, **3**, 6586 (2017)

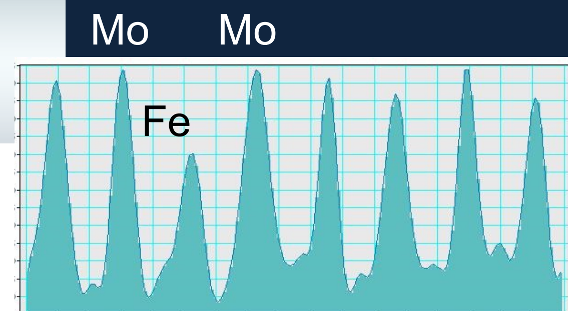
CVD-grown Fe:MoS_2 Monolayers

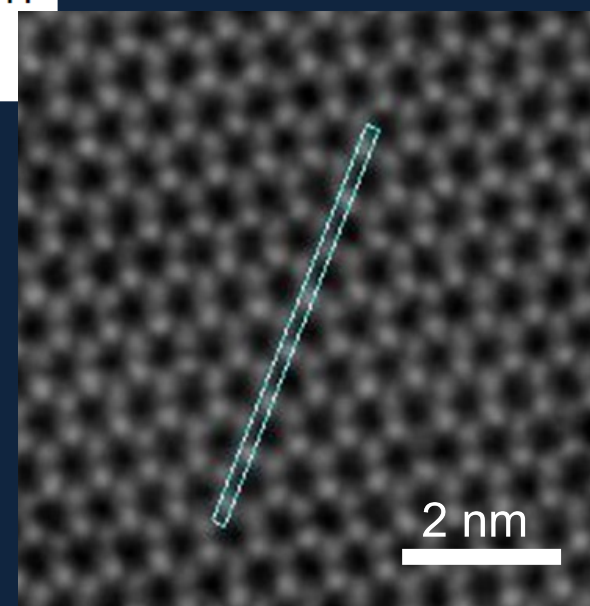
nature COMMUNICATIONS

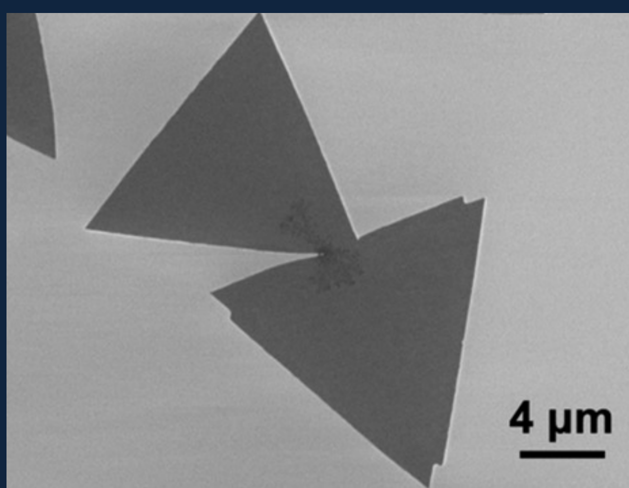
ARTICLE

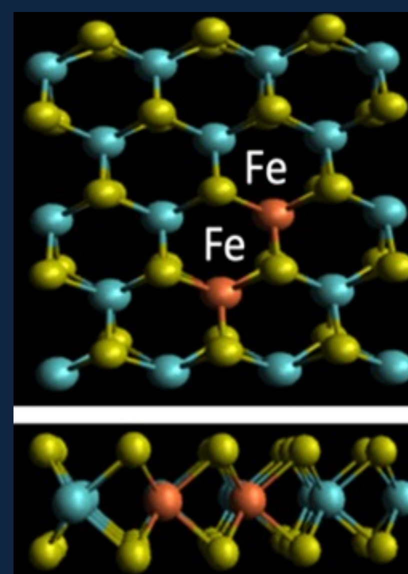
https://doi.org/10.1038/s41467-020-15877-7 OPEN

Enabling room temperature ferromagnetism in monolayer MoS_2 via in situ iron-doping



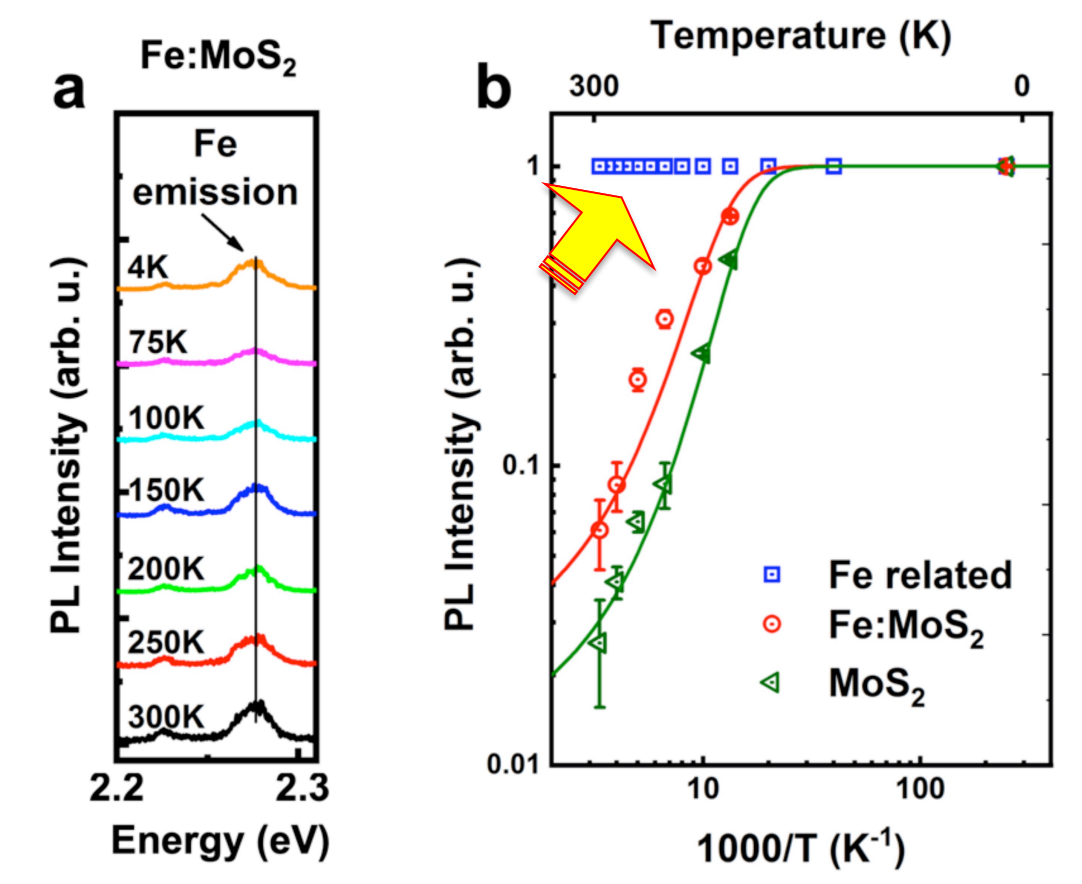






Terrones group (Penn State)

Fe-related PL Emission

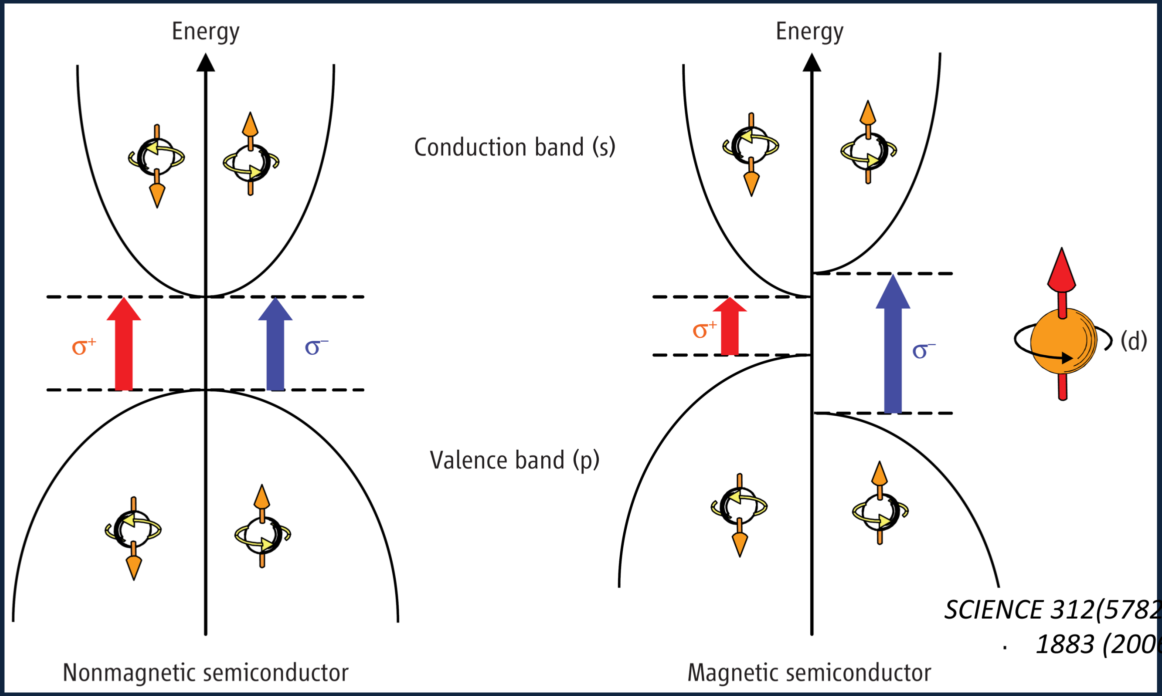


Measured at Strauf Lab (Stevens)

- Integrated PL for the bandgap emission in MoS_2 (green triangle), Fe:MoS_2 (red circle) and for the Fe-related emission (blue square).
- Solid red and green lines - standard Arrhenius fits for the exciton emission

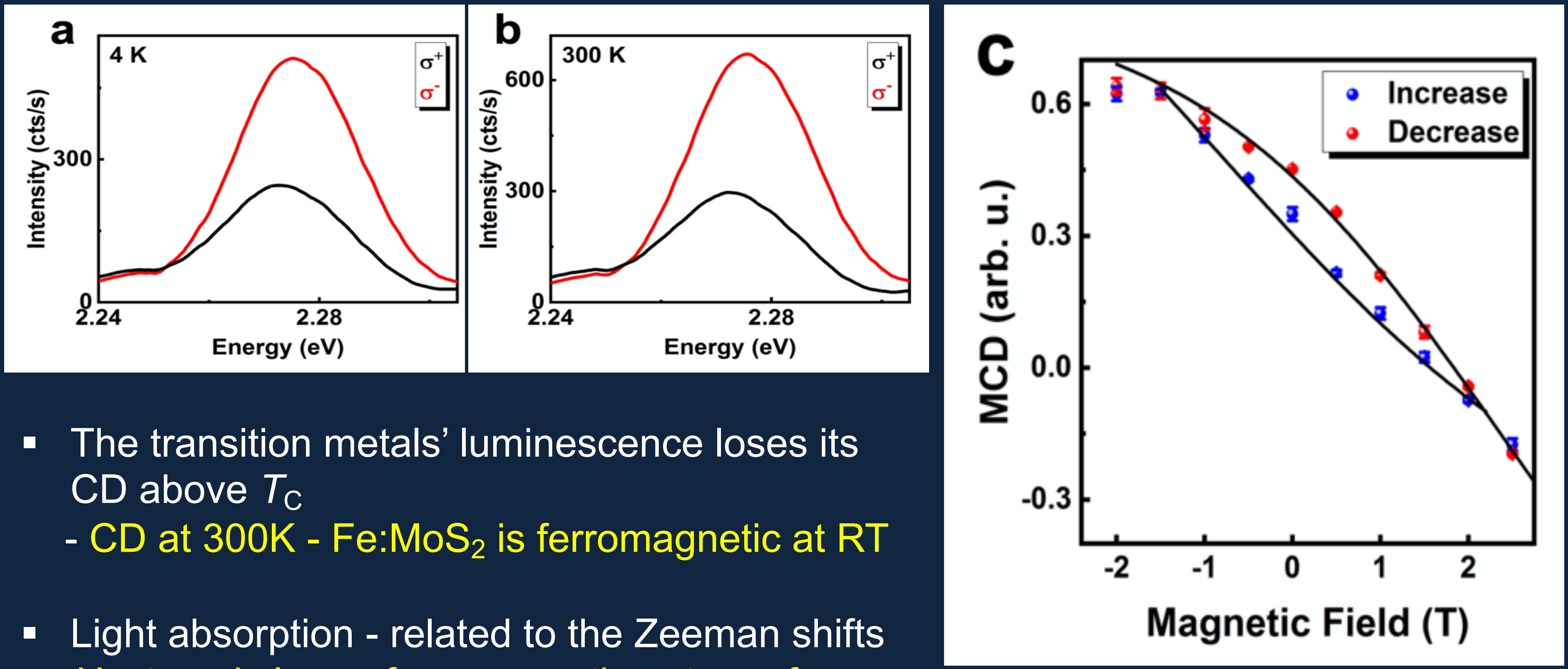
Fu, *et al., Nature Communications*, 11, 2034 (2020)

Zeeman Splitting and Magnetic Circular Dichroism (MCD) Effects



- (Left) Nonmagnetic semiconductors
- (Right) In magnetic semiconductors: the conduction band and valence band are split depending on the spin direction (Zeeman splitting).
- This spin-polarized semiconductor band structure alters the absorption of clockwise and counterclockwise-polarized light (MCD effect).

Magneto-PL (Fe-related)



Measured at Strauf Lab (Stevens)

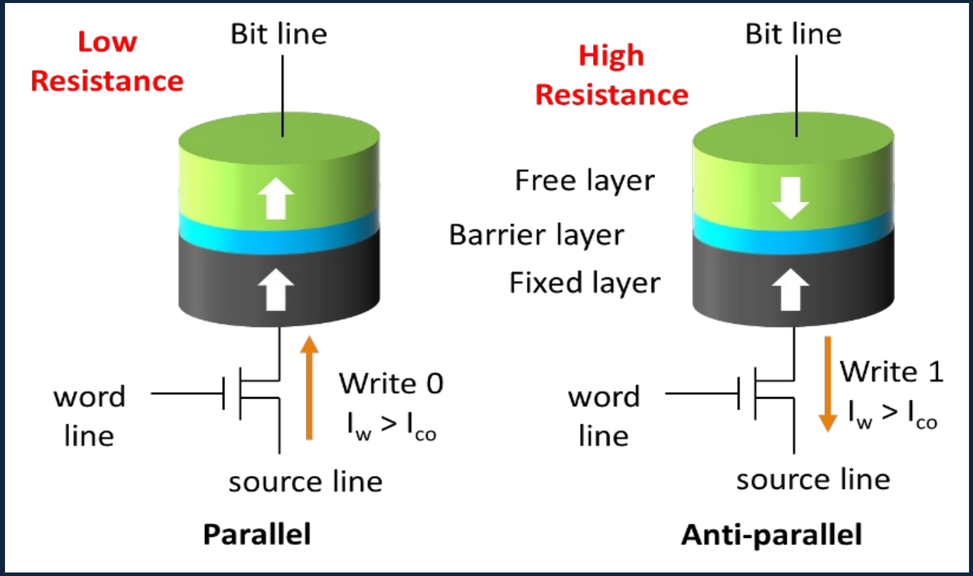
- The transition metals' luminescence loses its CD above T_C
  - CD at 300K - Fe:MoS_2 is ferromagnetic at RT
- Light absorption - related to the Zeeman shifts
  Hysteresis loop - ferromagnetic nature of emission.

Fu, *et al., Nature Communications*, 11, 2034 (2020)

Magnetic Tunnel Junction (MTJ)

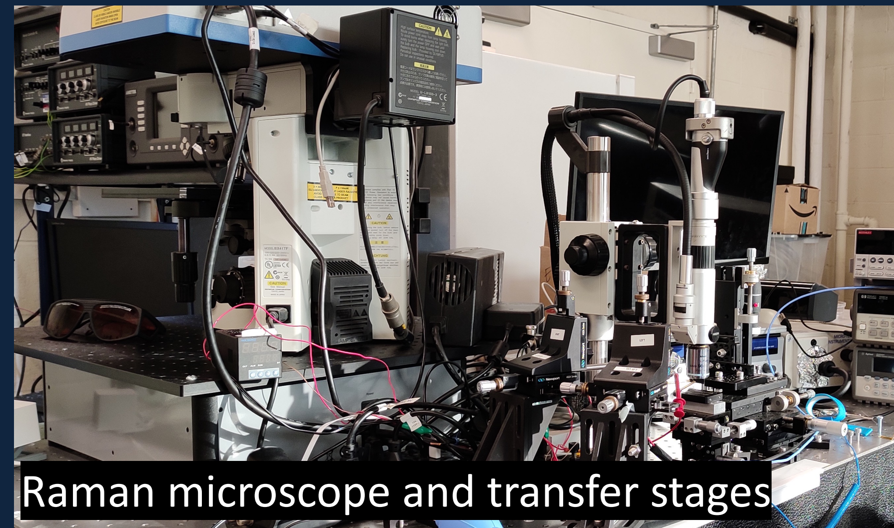
- Electrons flow through the MTJ to transfer spin angular momentum between the magnetic layers.

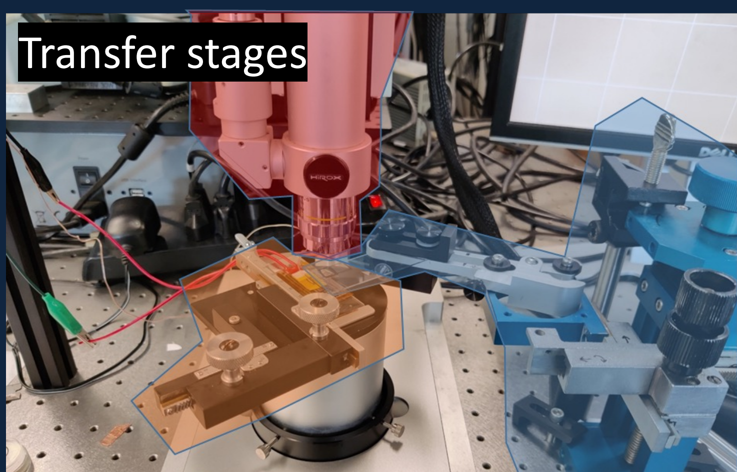
→ Changing the magnetic state of the free layer, and thus writing information.

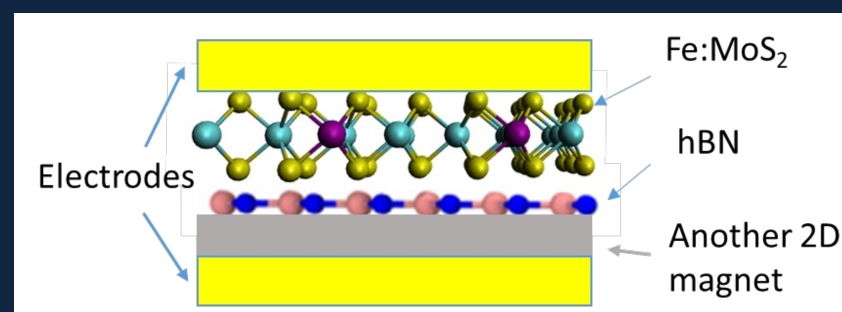


The **free layer** stores information, and the **fixed layer** provides a reference frame required for reading and writing.

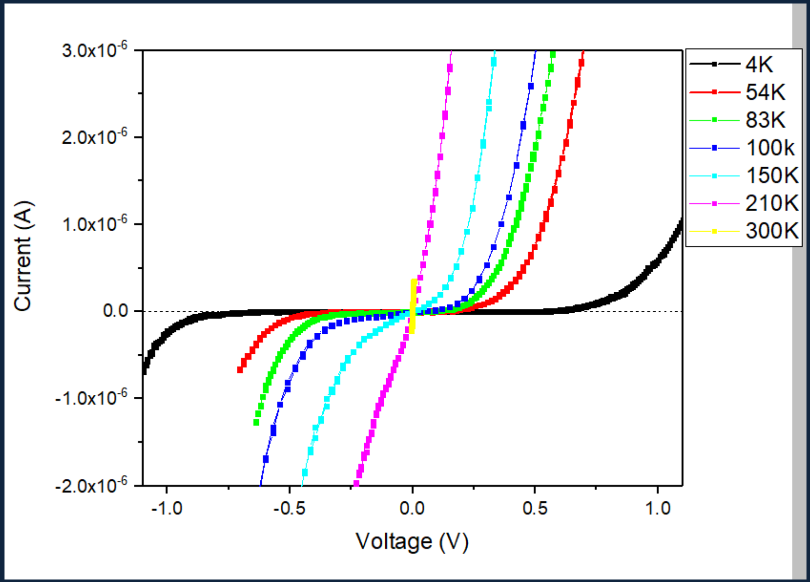
Magnetic Tunnel Junction in 2D

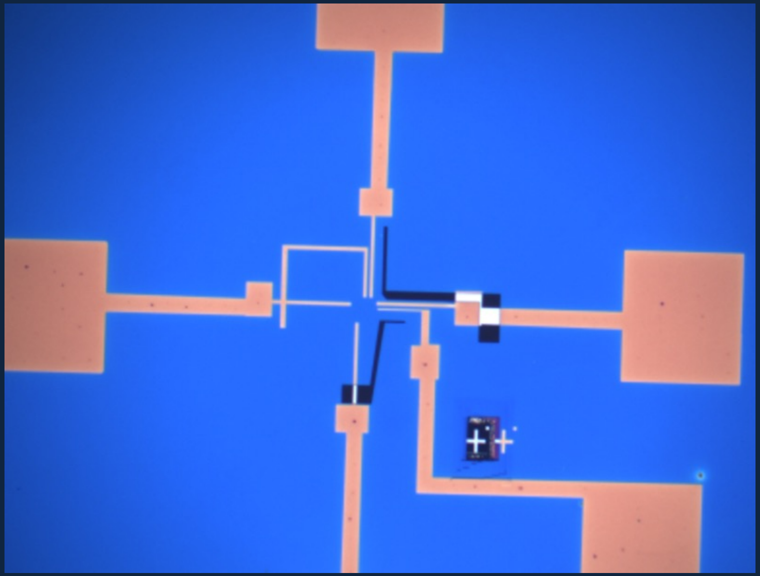






Tunneling Characteristics of Fe:MoS_2-based MTJ

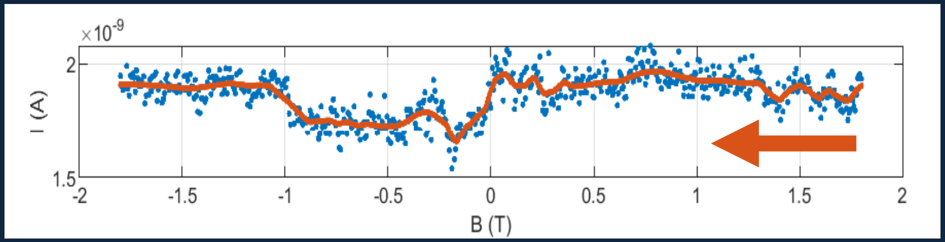


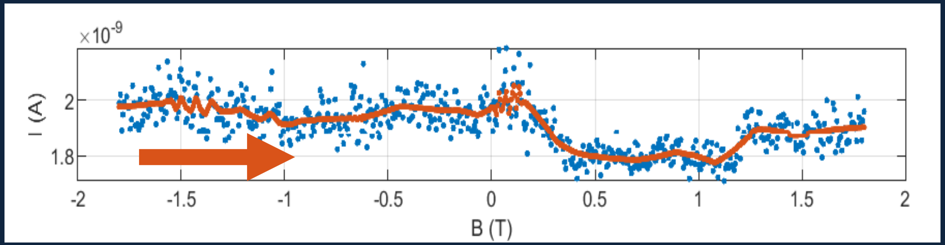


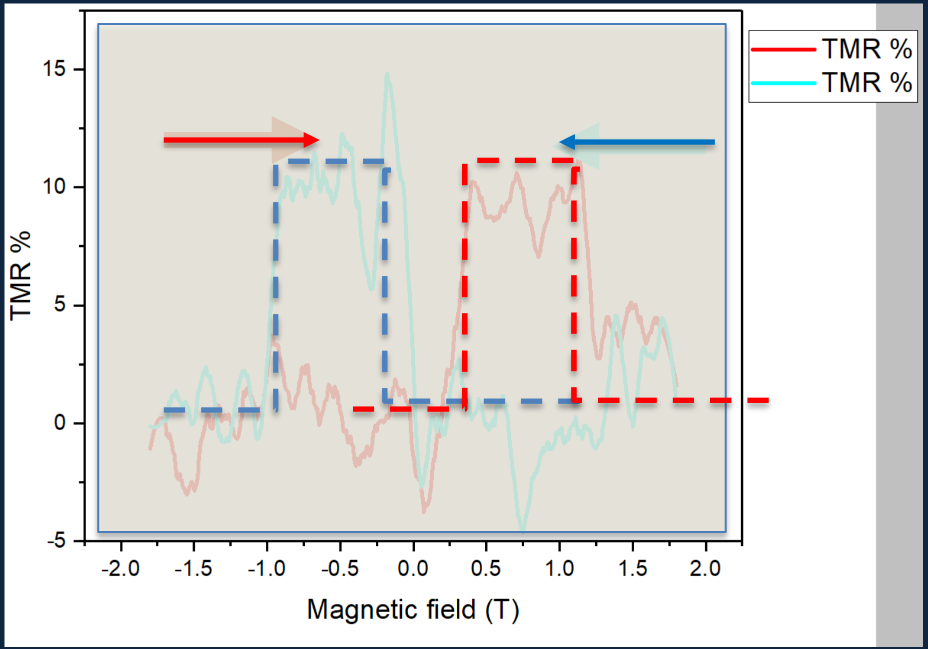
Tunneling through 2D layers - below 150K charge carriers in semiconductor start freezing; the resistance increases.

unpublished

Change of Magnetic States



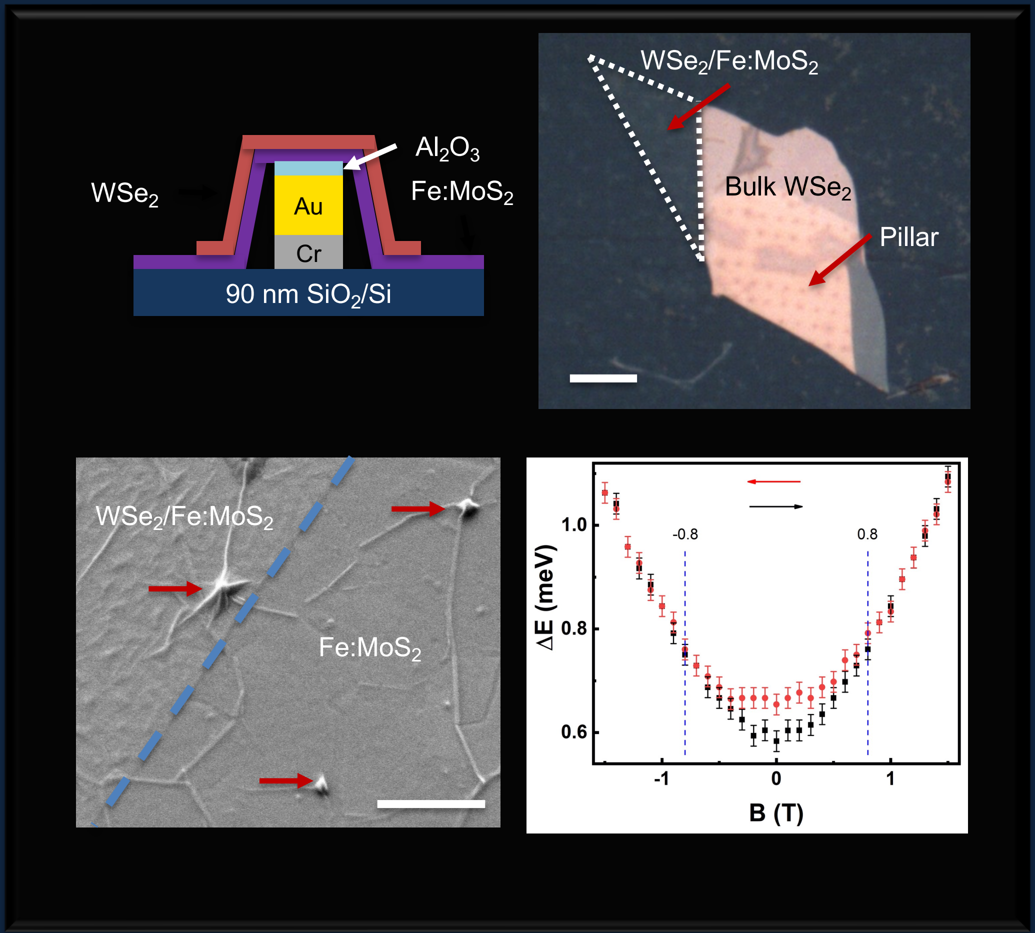




Demonstrating the control of magnetoresistance

unpublished

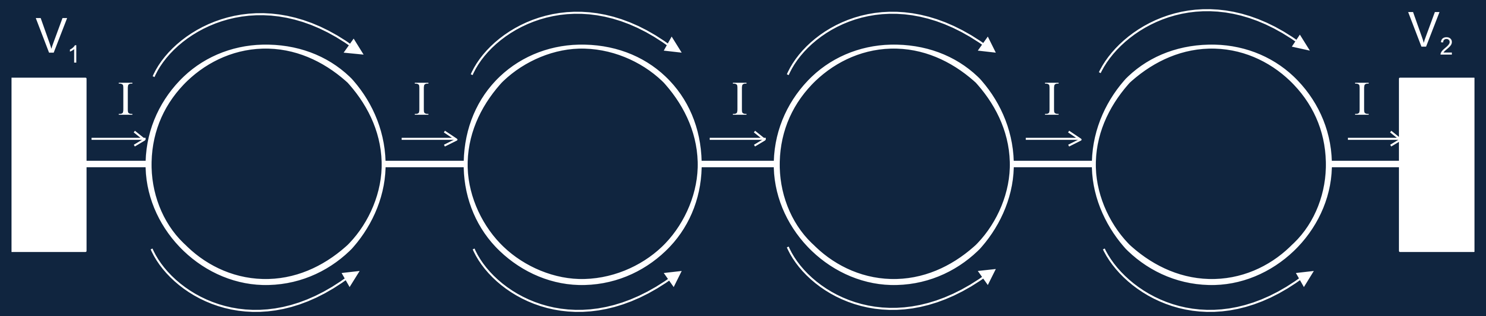
Magnetic Proximity Coupling



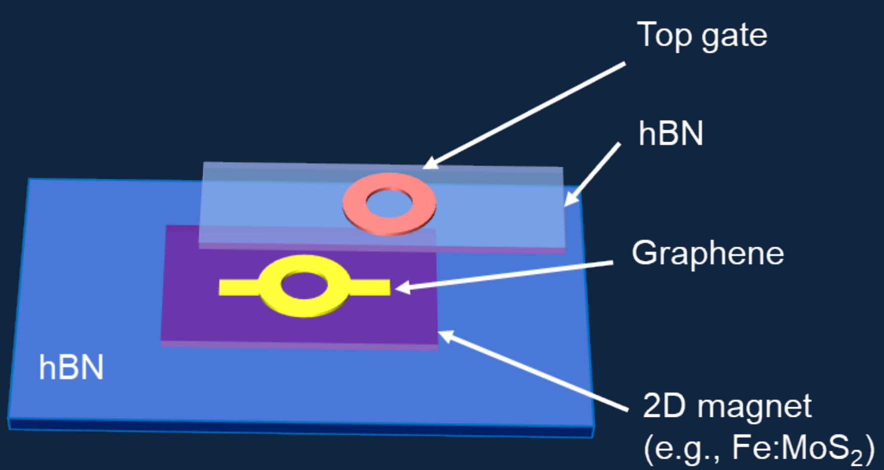
Strauf and Yang

unpublished

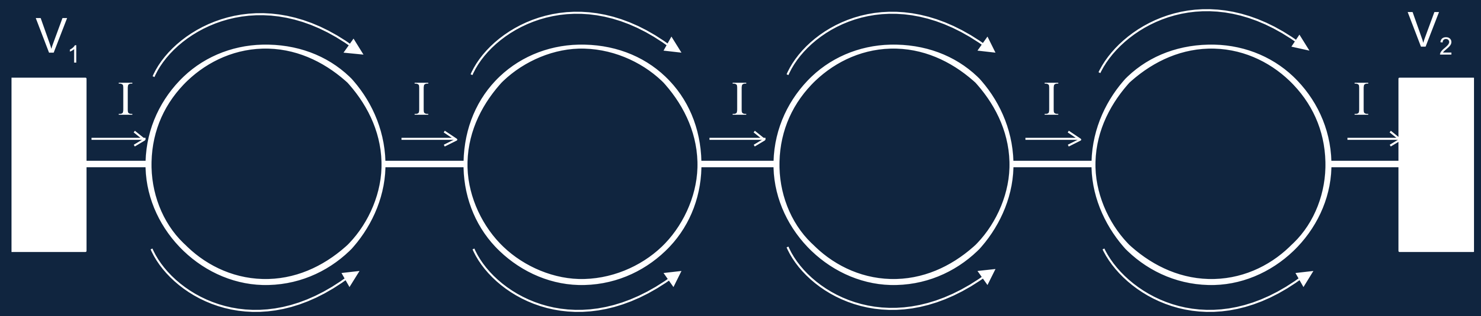
Enhancing Phase Change



- The phase change may be enhanced by incorporating **2D magnets** and **the gate-potential control** → Realizing on-chip electron interferometers.



Linear Array of Graphene Rings



$$G^{-1} \propto N\left(\Delta\Phi_S / 2\right)^2$$

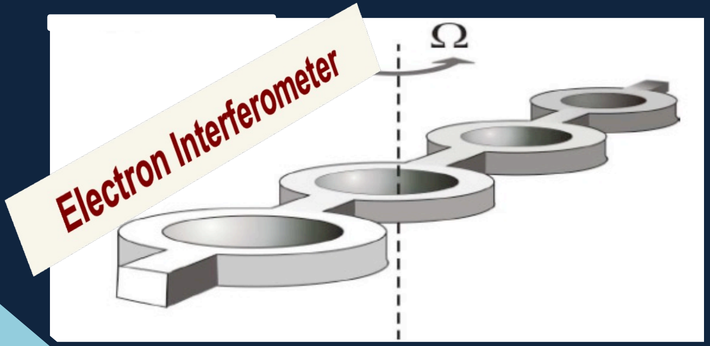
Sagnac phase shift is independent of the center of rotation

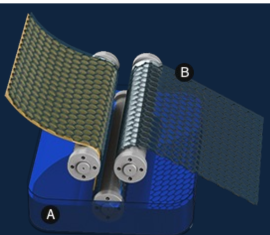
- If we fabricate 3×10^6 rings (1 μm ring radius), *assuming there is complete dephasing of electrons in the branches between adjacent rings*, this could yield an effective phase shift 0.1 radians at 1 Hz of rotation (*<u>further verification is required</u>*).

Credit: Prof. Chris Search

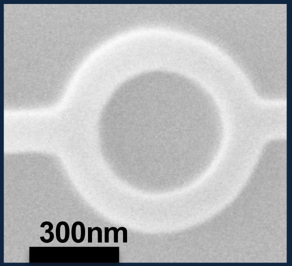
Existing Inertial Rate Sensing Technologies

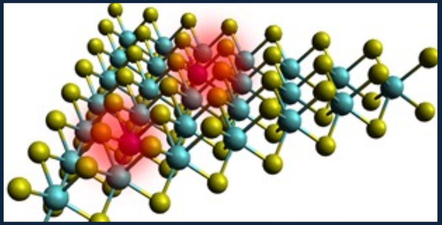
Future: High-g Survivable, Chip-Scale Technologies



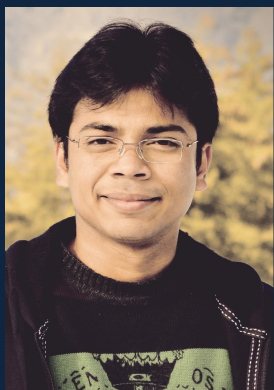


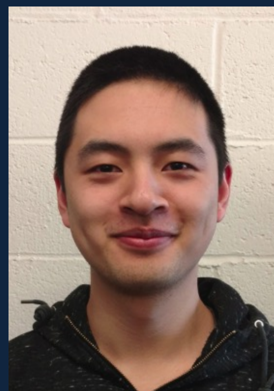
http://www.graphenesq.com/whatis/mass.asp

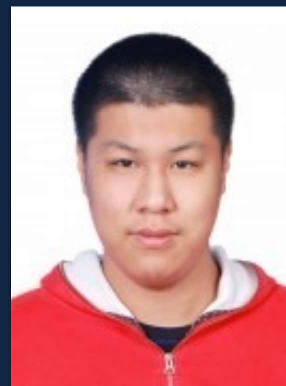




Acknowledgements


Abdus Sarkar


Siwei Chen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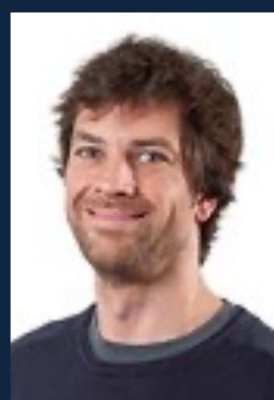
Chunlei Qu


Aron Cummings


Greg Hader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THANK YOU

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