

Electronic and Plasmonic Phenomena at Graphene Grain Boundaries



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Symposium on New Developments in Defects Mechanics 

Brief Introduction



Scanning Plasmon Interferometry



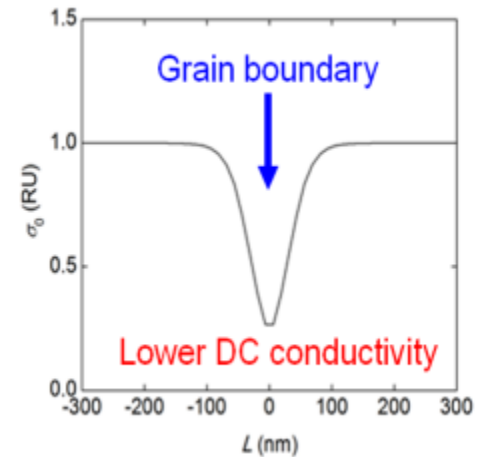
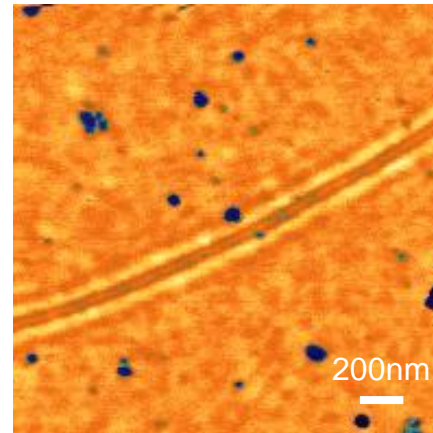
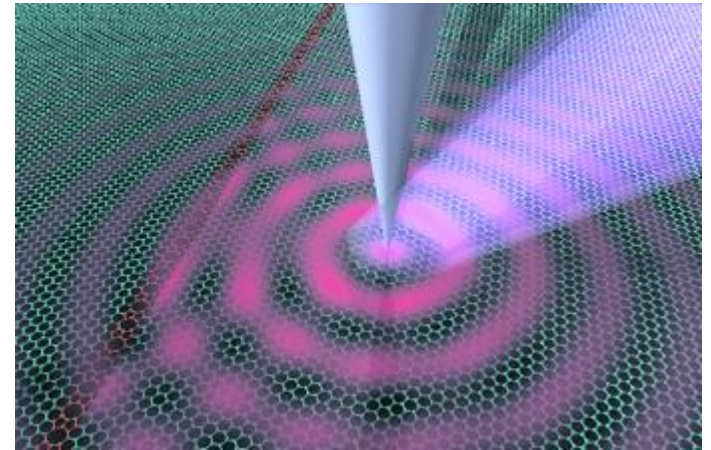
Imaging Grain Boundaries



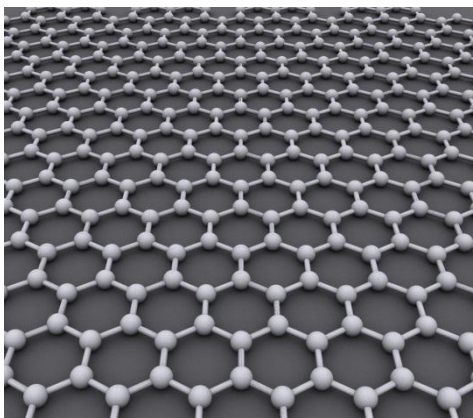
Modeling and Analysis



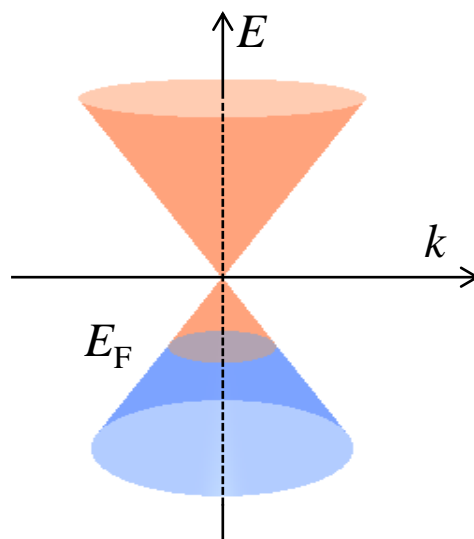
Summary



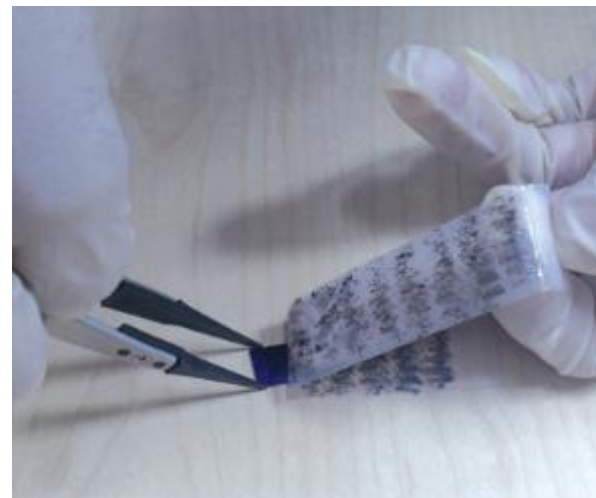
Graphene, one atomic layer of carbon atoms arranged on a honeycomb structure.



Graphene

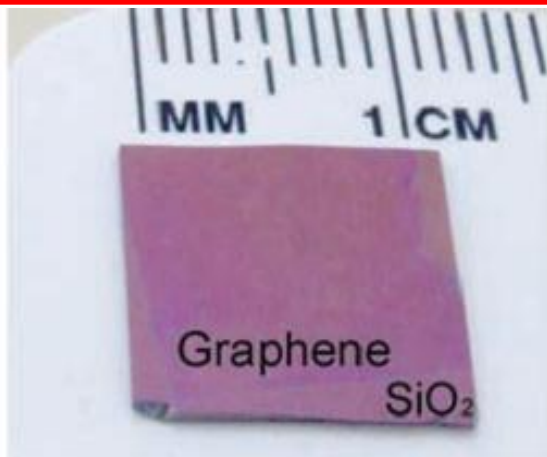


Dispersion

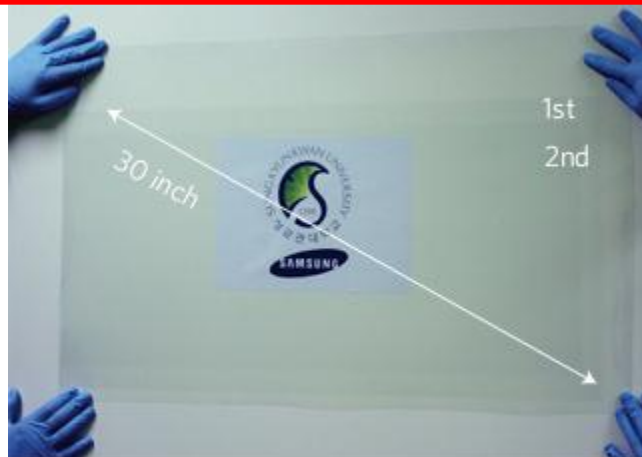


Scotch Tape

- ✓ Extraordinary **Mechanical**, **Electrical**, **Thermal**, **Optical**, and **Plasmonic** Properties.
- ✓ Wide applications in **Electronics**, **Photonics**, **Mechanical** and **Energy Engineering**.



Li et al. Science (2009)

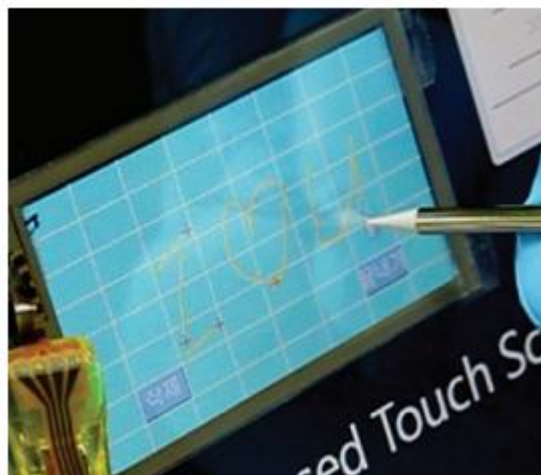


Bae et al. Nature Nano (2010)

CVD graphene grown on Cu

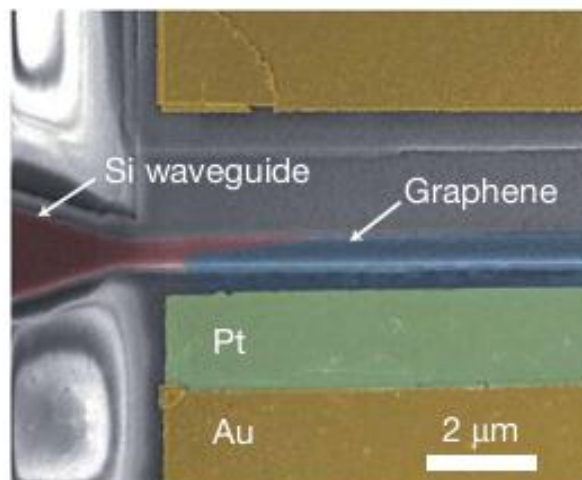
- ✓ Reliable
- ✓ Scalable
- ✓ Cheap
- ✓ Easy to transfer

Suitable for technological applications!



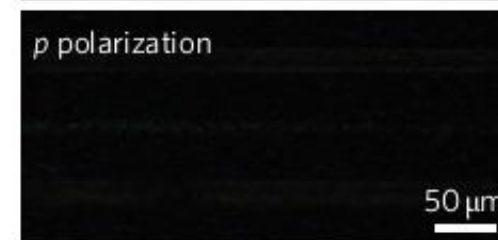
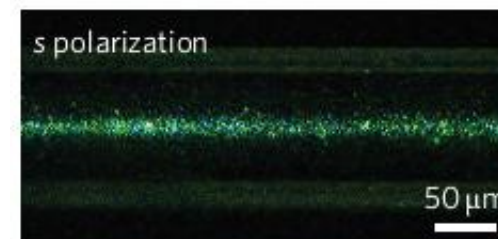
Touch screen

Bae et al. Nature Nano (2010)



Ultrafast optical modulator

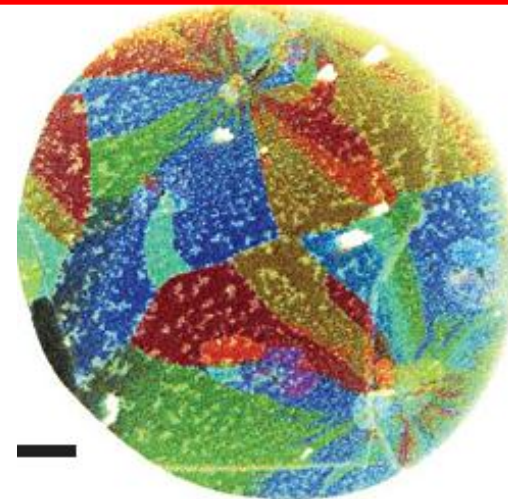
Liu et al. Nature (2011)



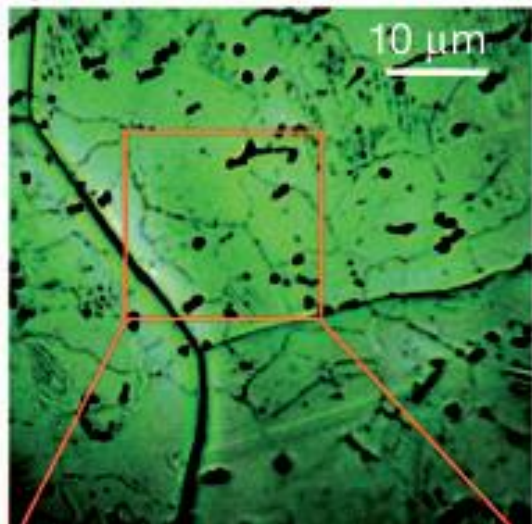
Optical polarizer

Bao et al. Nature Photon. (2011)

- ✓ Large-area CVD graphene is always **polycrystalline**
- ✓ Grain boundaries are popular line defects
- ✓ Mapping
 - + Efficient, Non-destructive, convenient
- ✓ Characterization

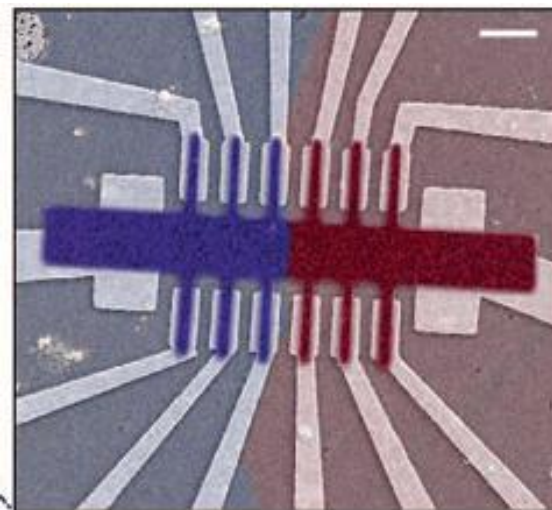


Huang et al. Nature (2011) Dark-field TEM



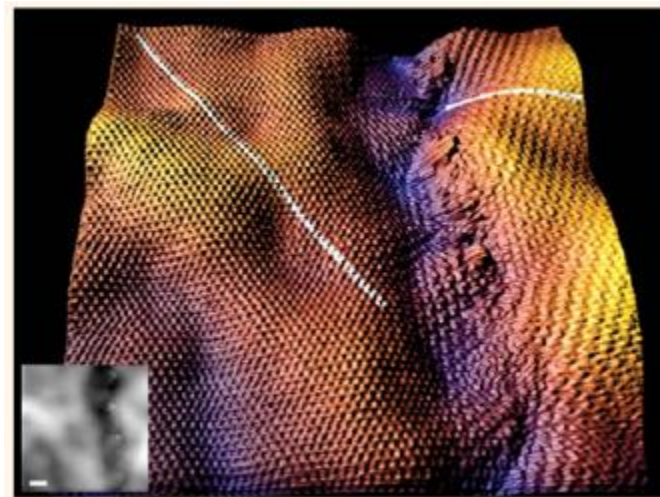
Optical microscopy

Duong et al. Nature (2012)
Kim et al. Nature Nano (2011)



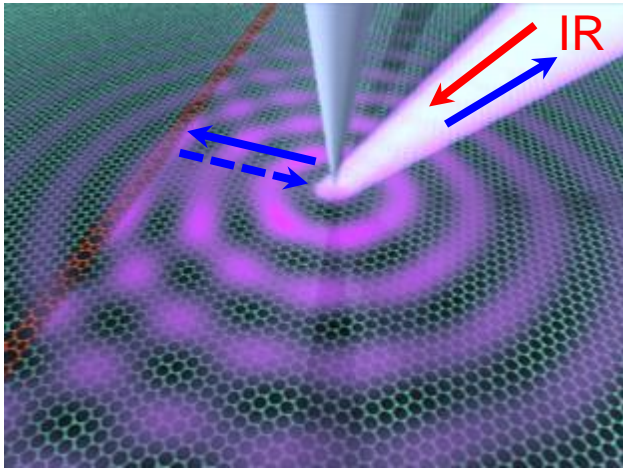
Transport

Tsen et al. Science (2012)
Kim et al. ACS Nano (2011)

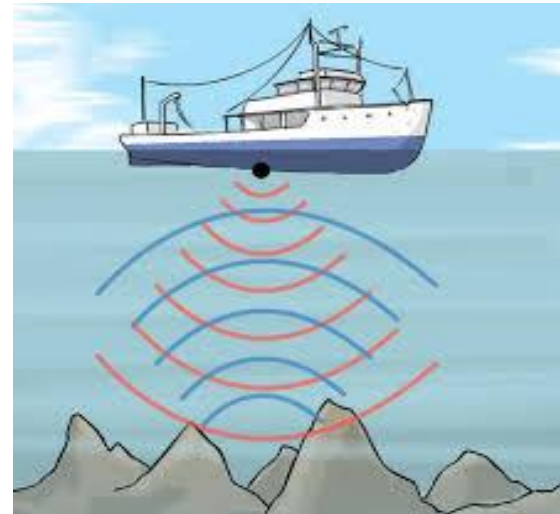


STM

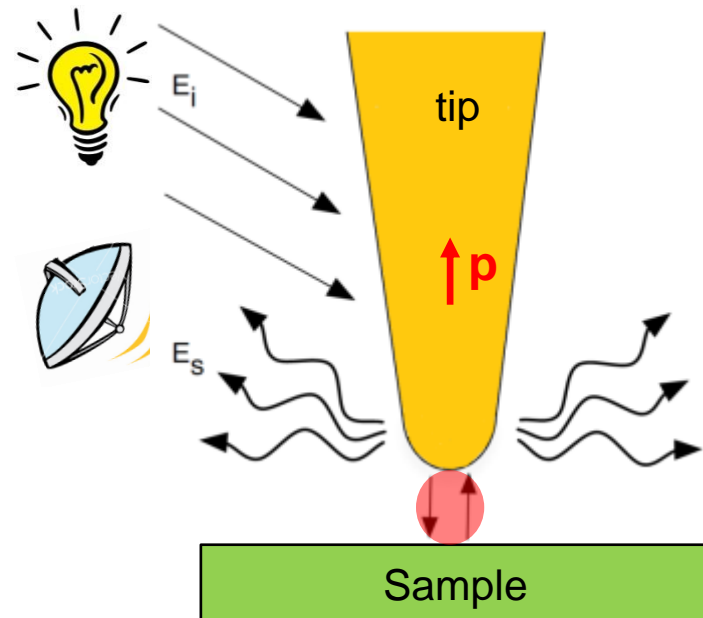
Koepke et al. ACS Nano (2012)
Tapaszto et al. APL (2012)

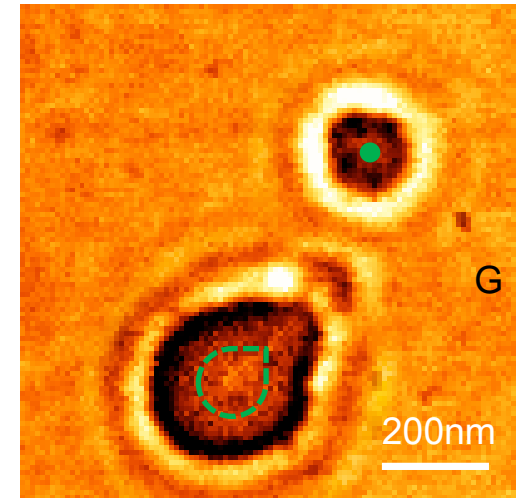
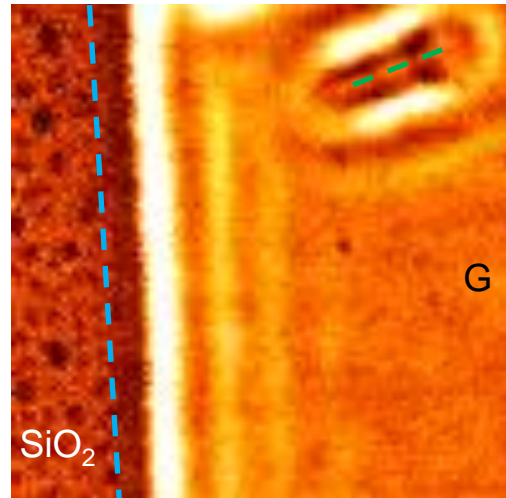
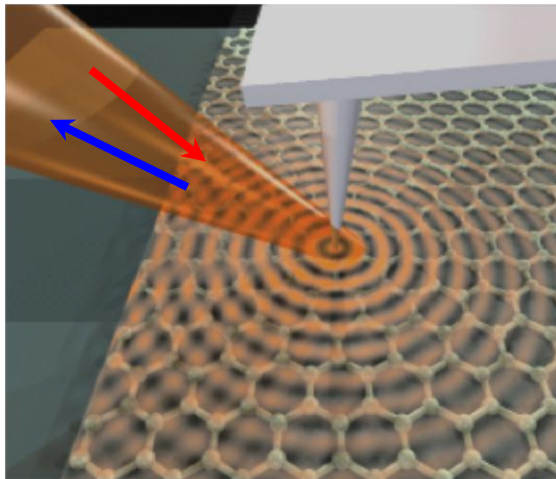


Scanning Plasmon Interferometry



- ✓ Tip launches Plasmons
- ✓ Plasmon 'Sonar'
- ✓ Tip probes sample & Field



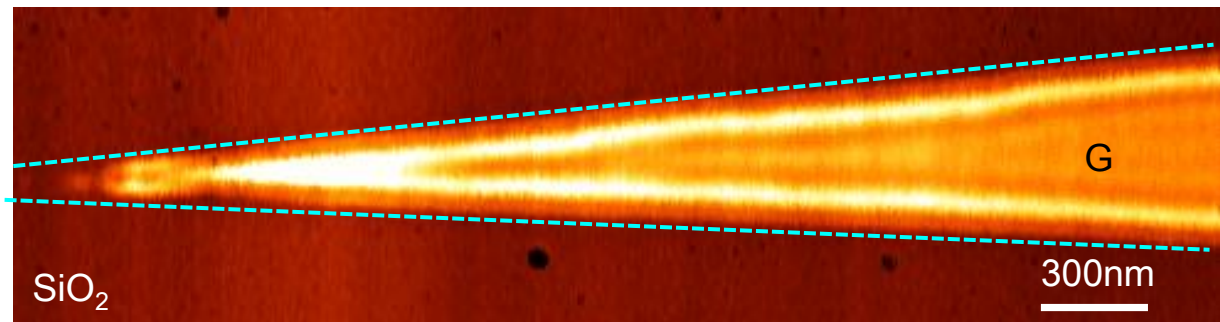


Bright Fringes!

$\lambda_0 = 11.2 \mu\text{m}$

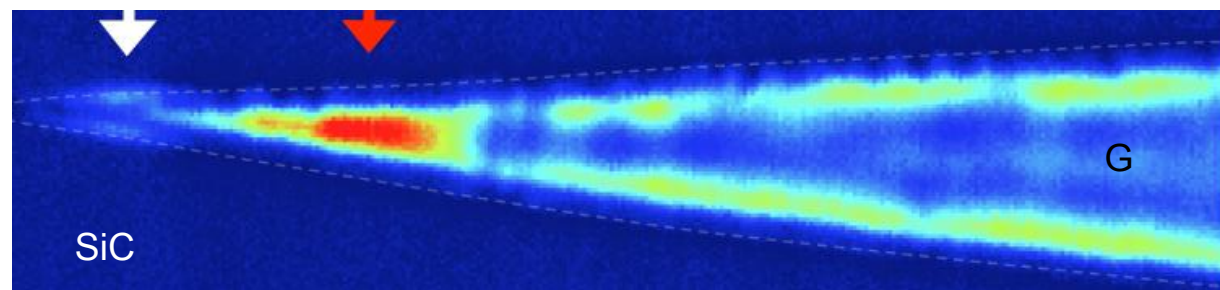
IR amplitude

Min  Max



Fei et al. Nature 2012

Chen et al. Nature 2012

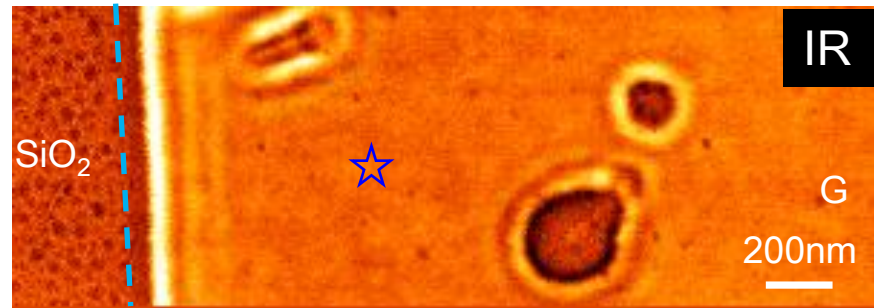


Min  Max

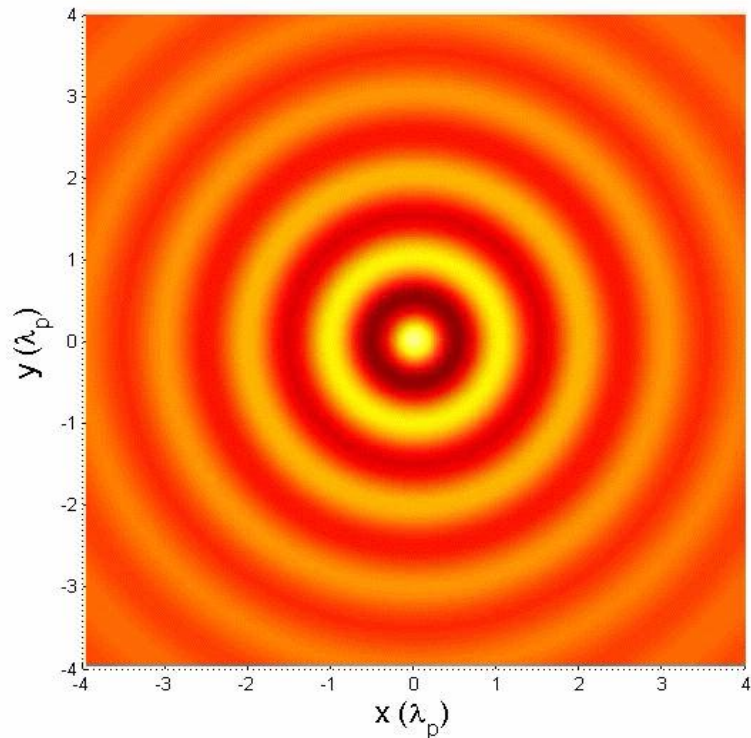
Fringes formation

Far away from edge

☆ AFM tip



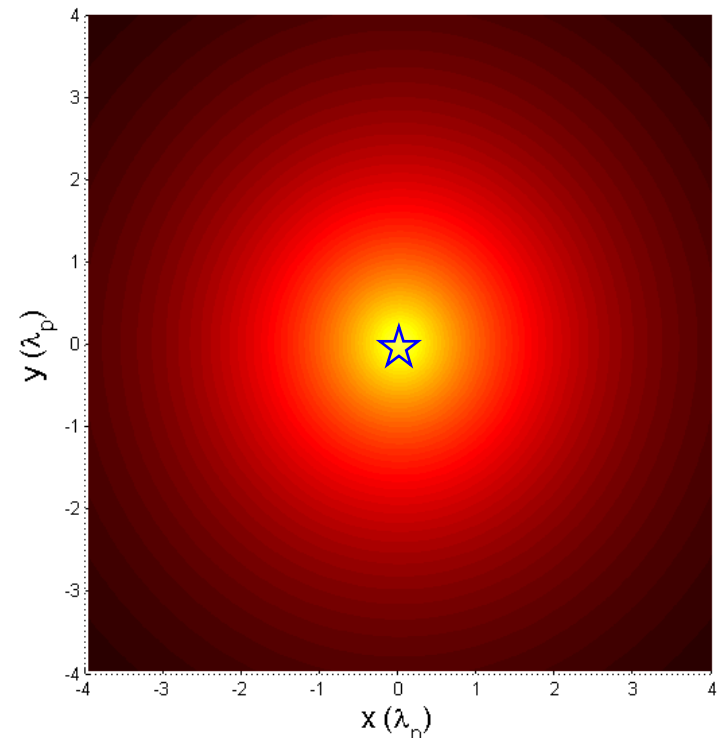
Graphene



Re(E_z)

Graphene

Tip @ (0,0)

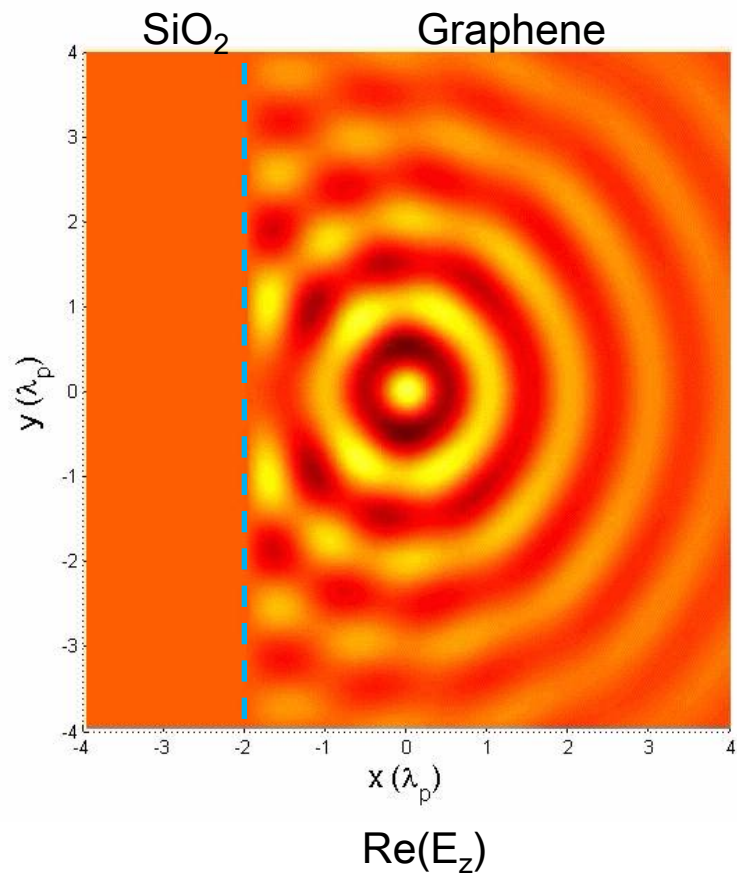
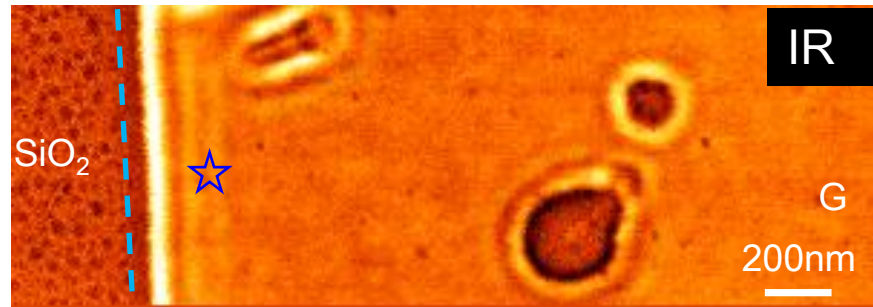


Amplitude $|E_z|$

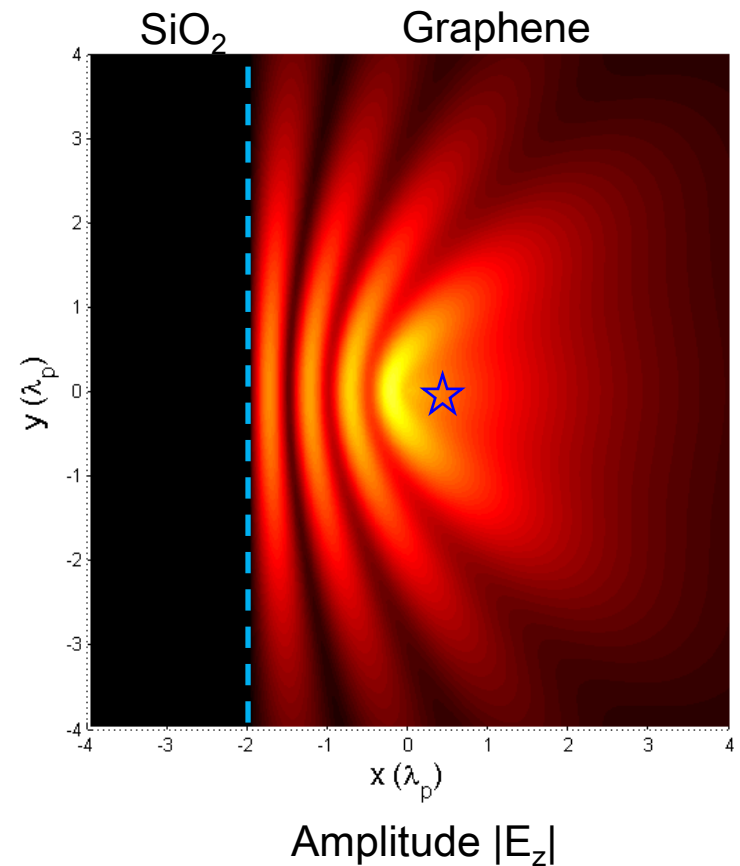
Fringes formation

$2\lambda_p$ away from edge

☆ AFM tip

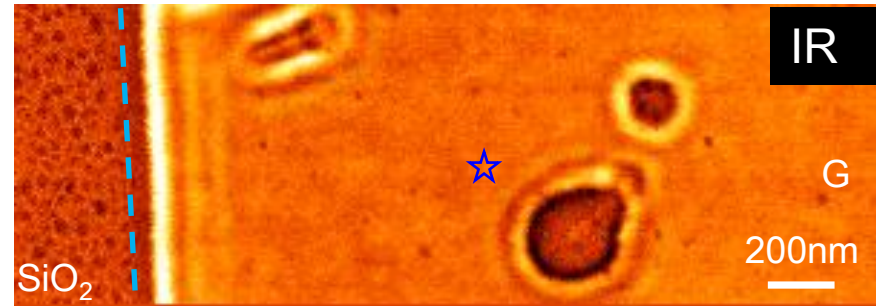
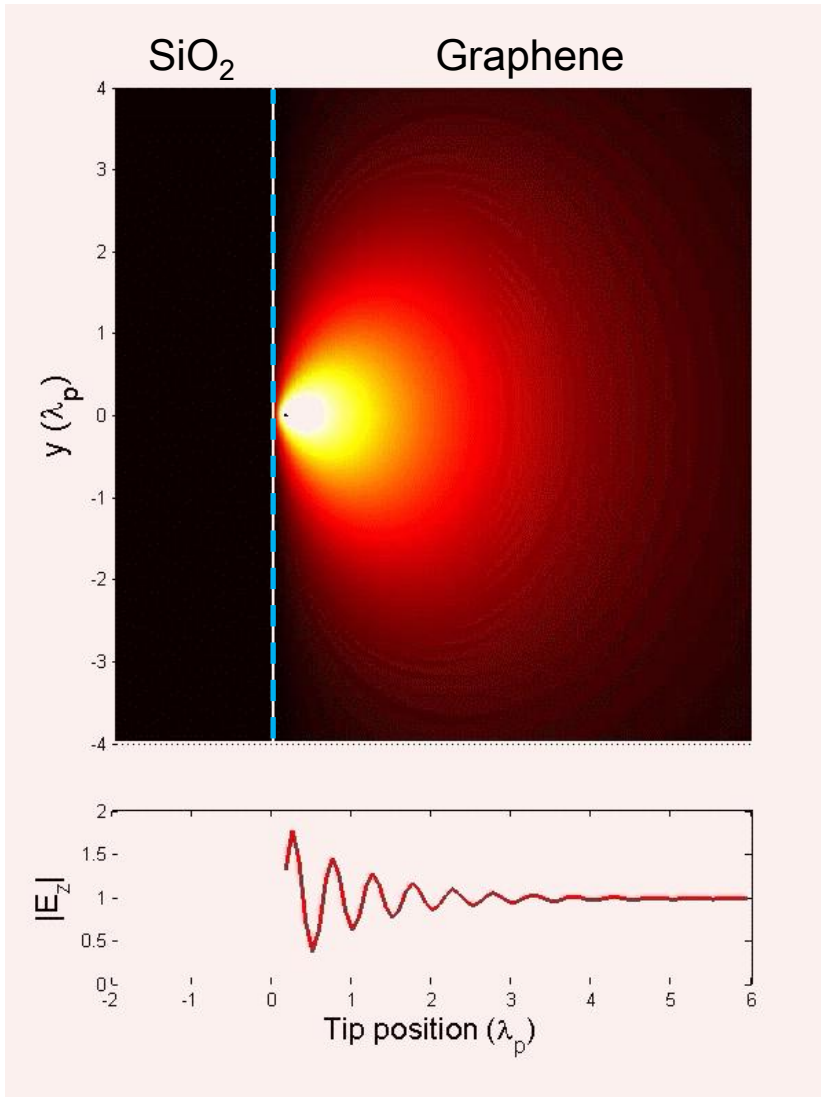


Tip @ (0,0)



Fringes formation

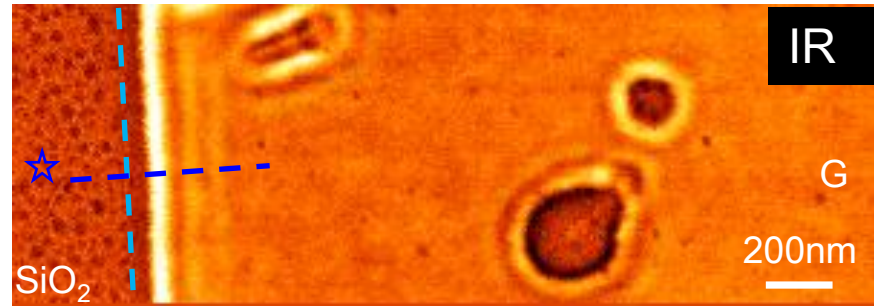
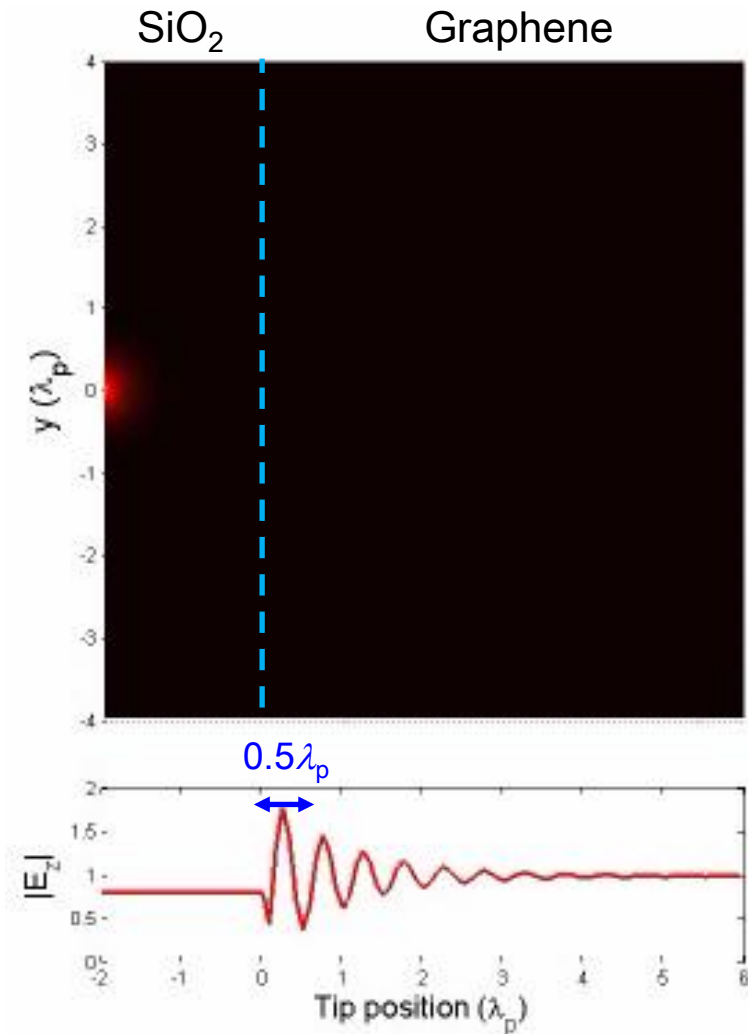
Scanning the tip from interior towards the edge of graphene



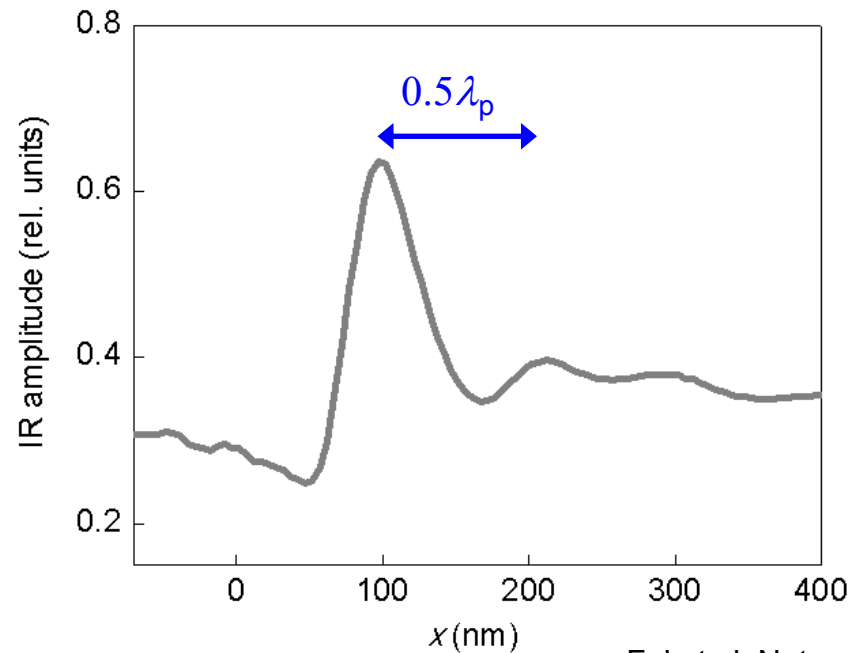
✓ Scanning across plasmon standing waves

Fringes formation

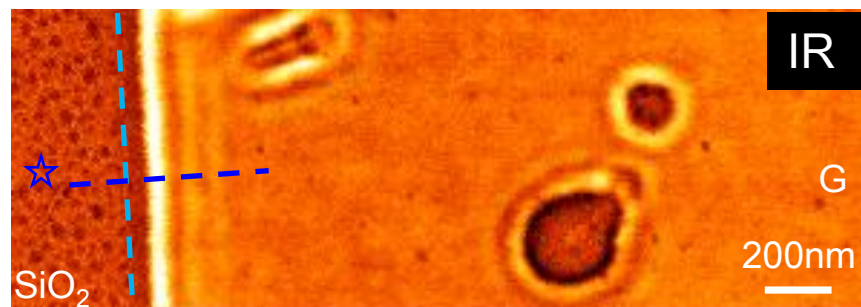
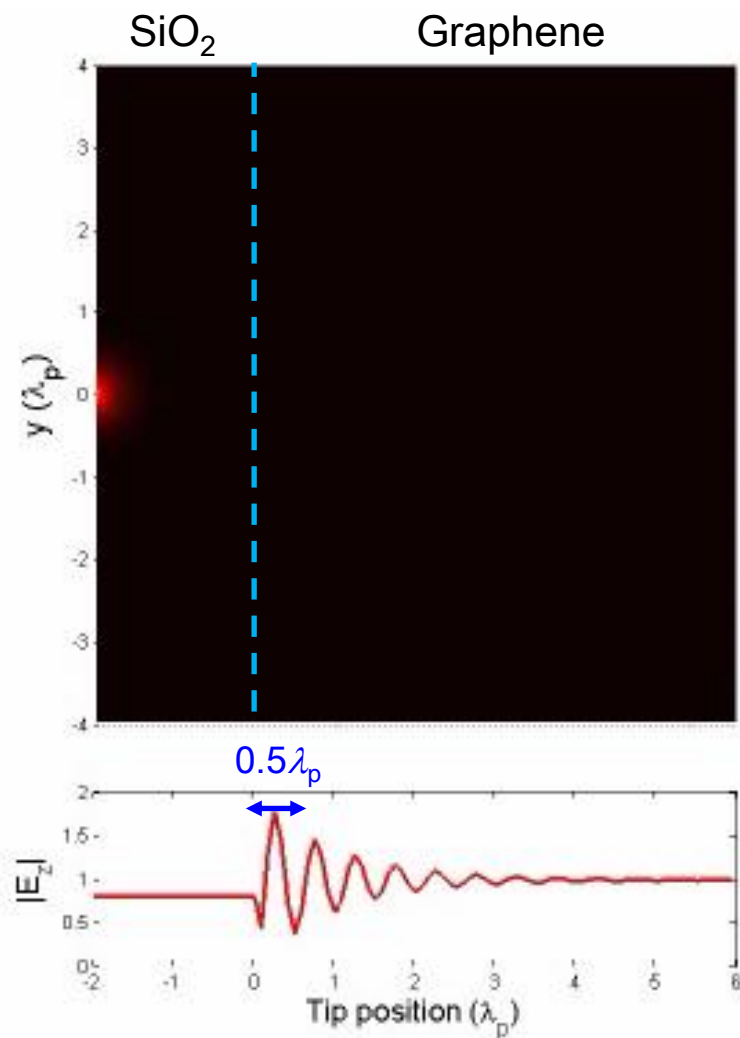
Scanning the tip from interior towards the edge of graphene



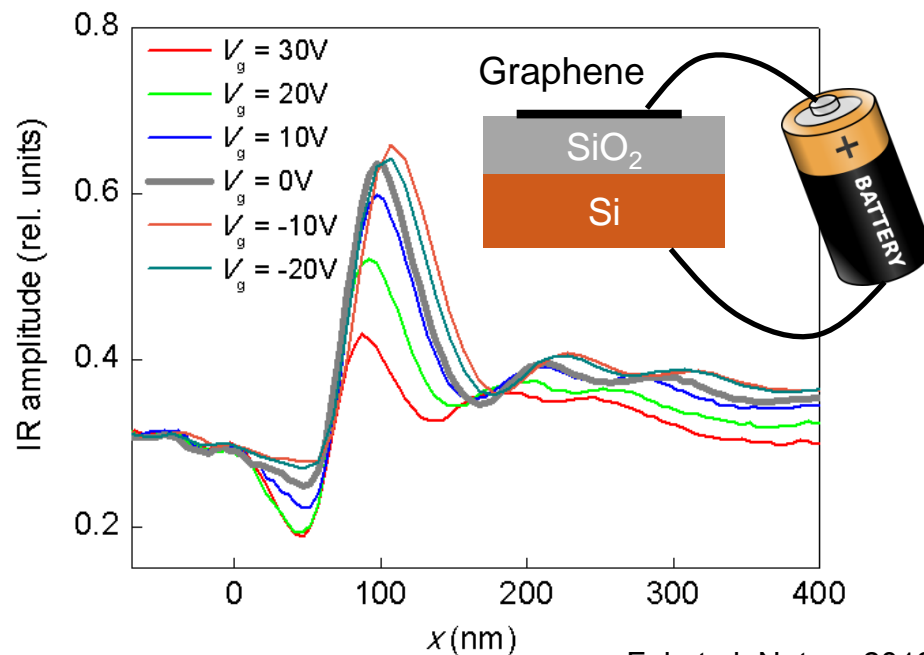
✓ Scanning across plasmon standing waves



Scanning the tip from interior towards the edge of graphene

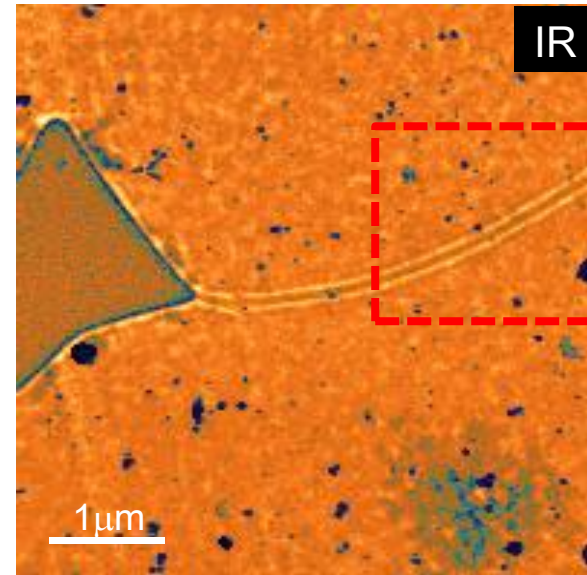
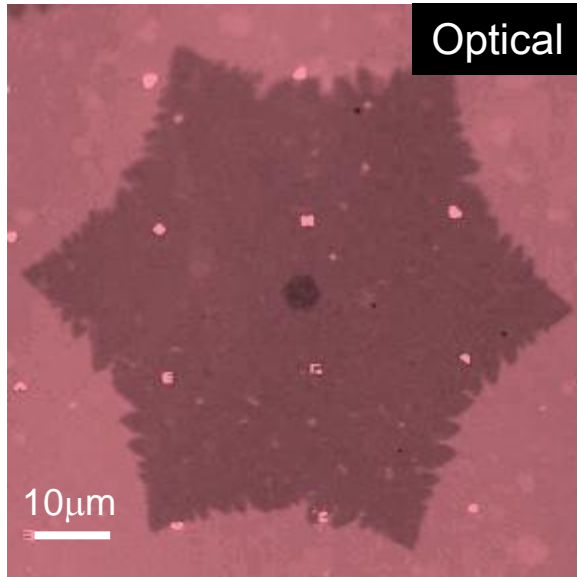


✓ Scanning across plasmon standing waves

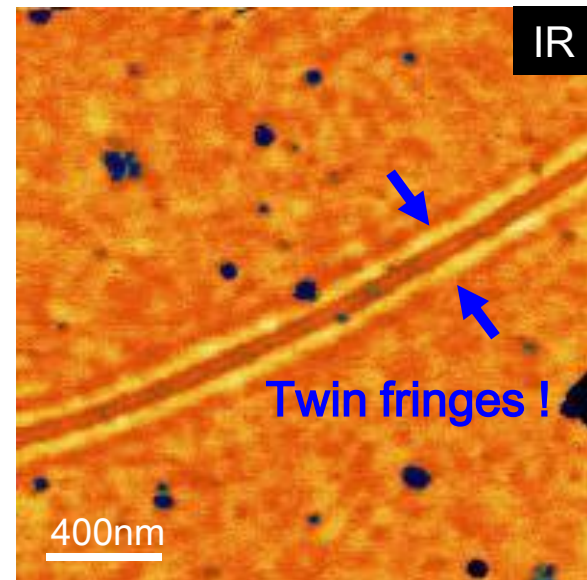
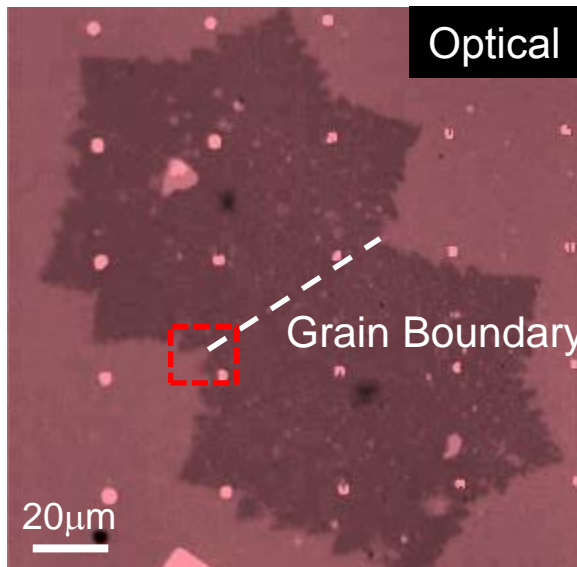


Grain Boundary

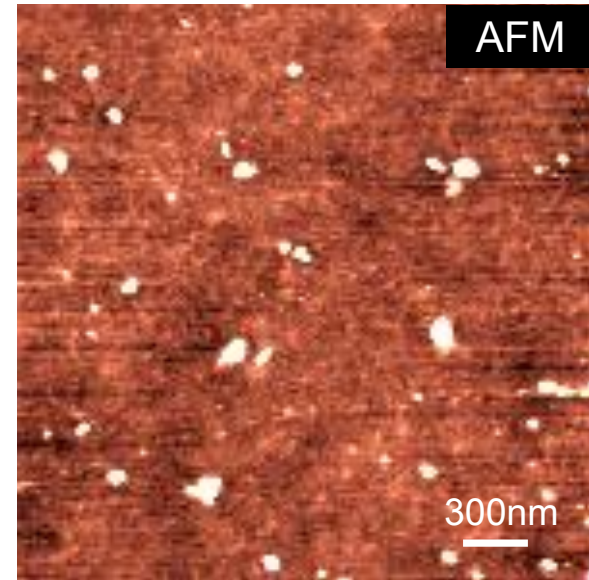
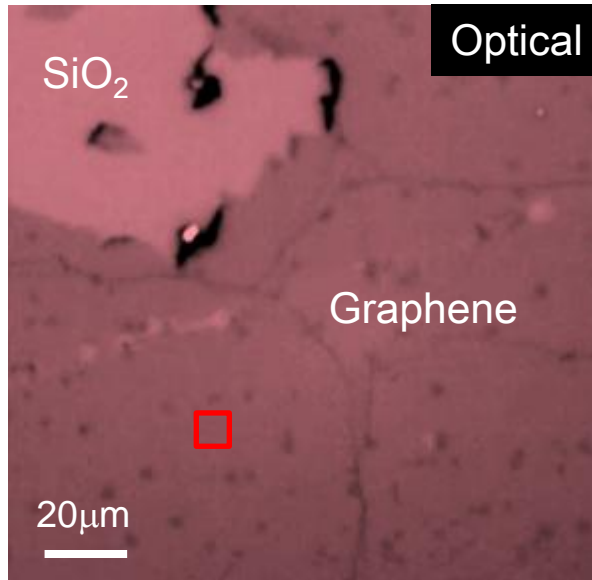
Single Domain



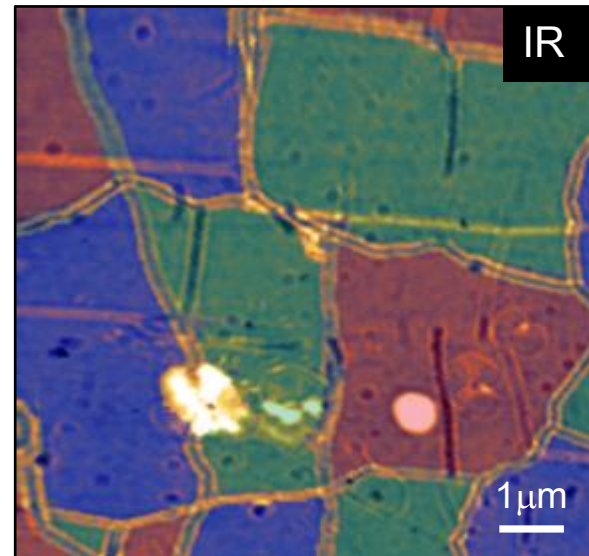
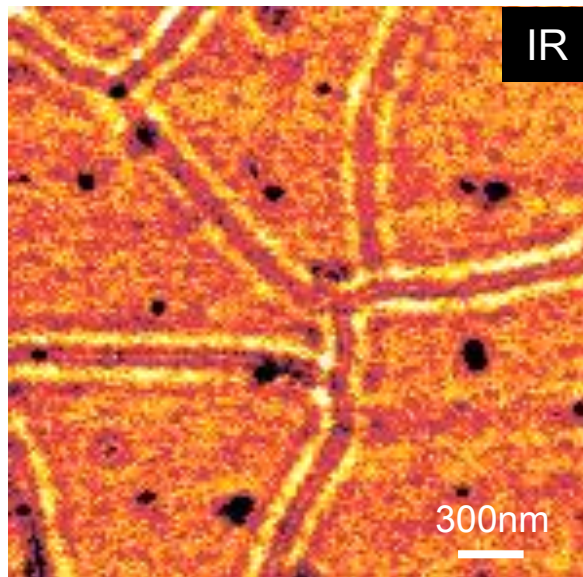
Connected Domains

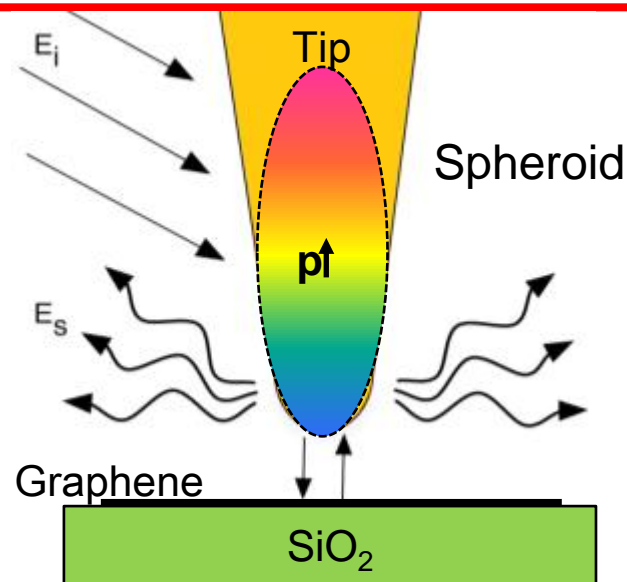
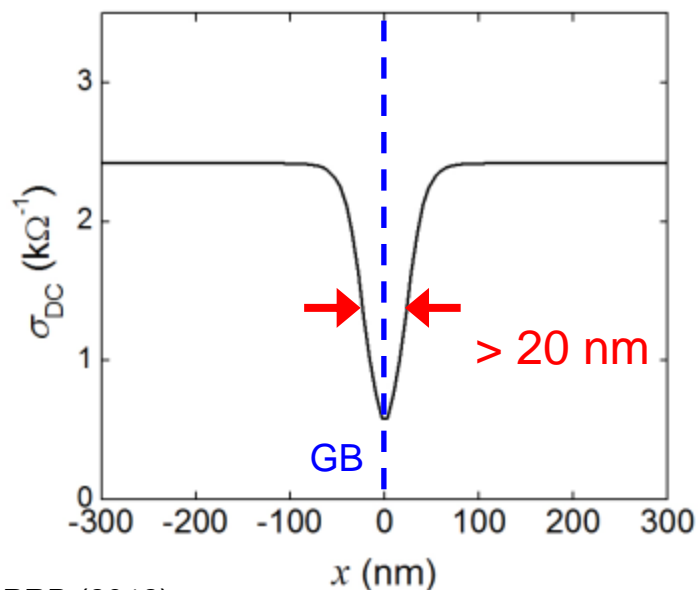
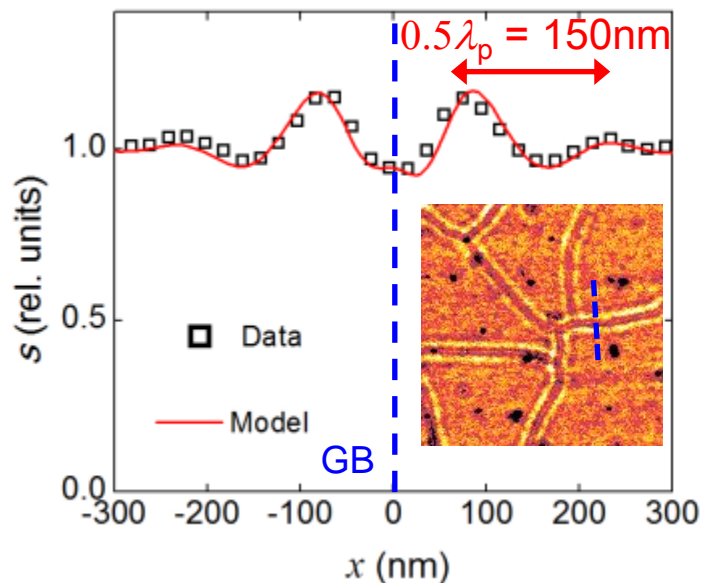


Continuous
Film

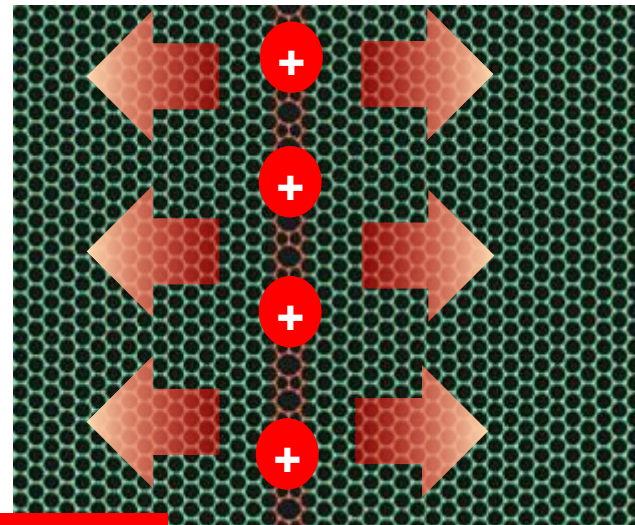
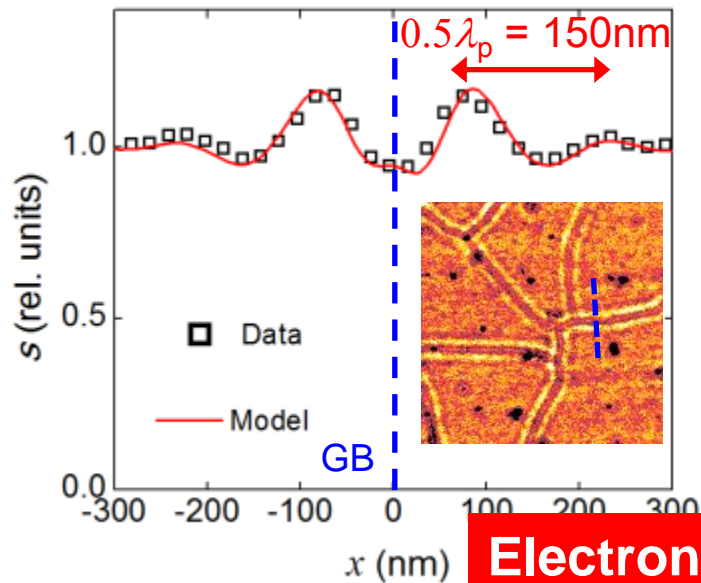


Grain boundary
Network



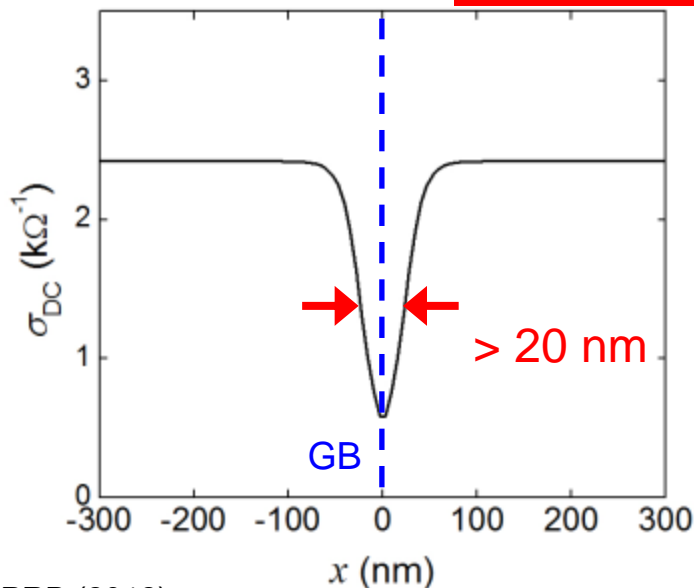


✓ Suppress local conductivity



Electronic Boundary!

$\rightarrow \leftarrow < 1\text{ nm}$



- ✓ Suppress local conductivity
- ✓ Wide 'effective' width
- ✓ Intrinsic Electronic Properties
- ✓ Coulomb Interaction and Screening

✓ Plasmon Interferometry

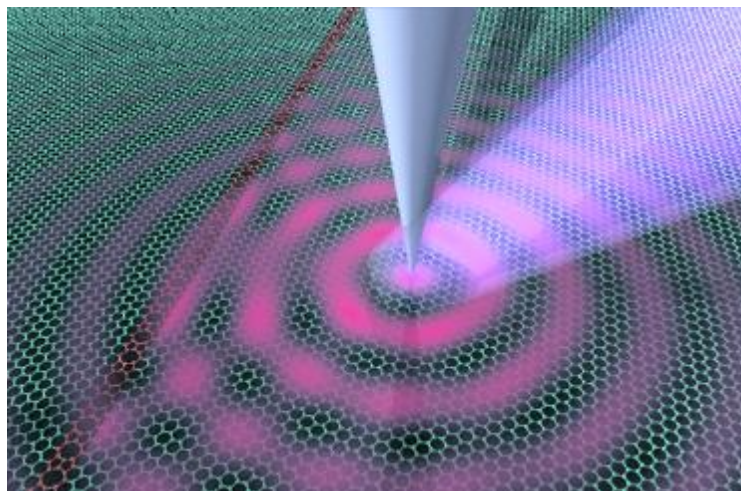
Plasmon 'Sonar'

✓ Imaging Grain Boundaries

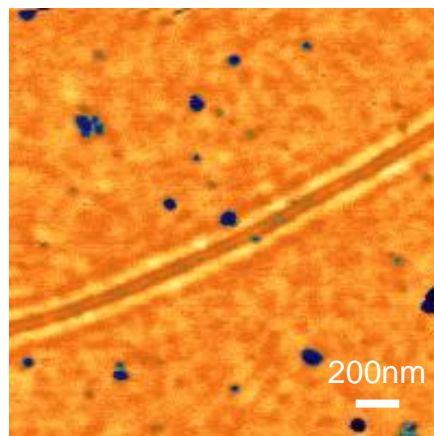
Twin Plasmon Fringes

✓ Modeling and Analysis

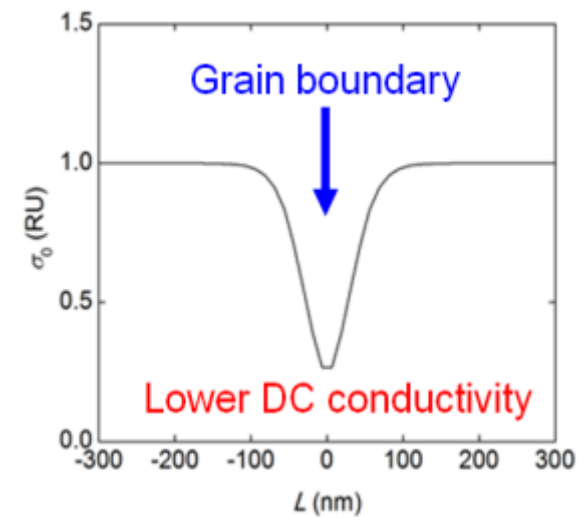
Electronic Boundary



Scanning Plasmon Interferometry



Twin Fringes



Acknowledgement



D. N. Basov
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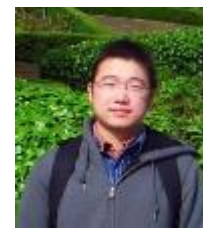
A. S. McLeod
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M. Wagner
UCSD



S. Dai
UCSD



M. K. Liu
UCSD



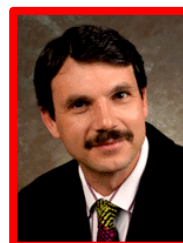
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W. Bao
UMD



Z. Zhao
UCR



A. Zettle
UCB



W. Gannett
UCB



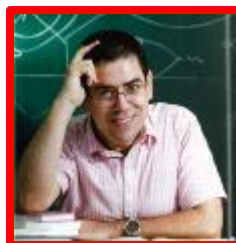
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M. M. Fogler
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NUS



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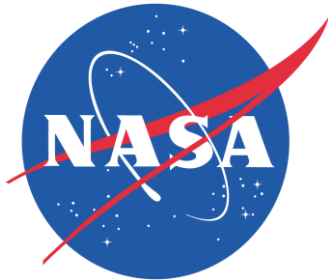


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MPI

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Thank you!