Momentum-Resolved View of Highly Tunable Many-Body Effects in a Graphene/hBN Field-Effect Device

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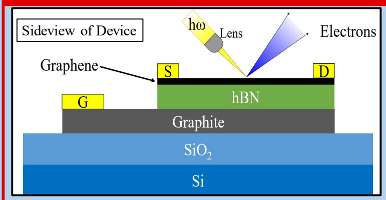
Abstract

Graphene on hexagonal boron nitride (hBN) is of the most well-studied heterostructures studied in two-dimensional (2D) materials research. One of the first measurements of this system showed resistivity tuning of graphene through electrostatic gating. Today, the carrier tunability, controlled by electrostatic gating, is used in a variety of experiments but its modulation of the electronic band structure is not understood in detail. In this work, we use micro-focused angle-resolved photoemission spectroscopy (microARPES) to uncover the detailed many-body interactions in back-gated graphene on hBN. We observe interactions varying greatly as we finely and reversibly tune the carrier concentrations in our device.

Heterostructure and Device Fabrication



- Graphene, hBN and graphite were exfoliated on to separate 300nm SiO2 substrates.
- Flakes were successively transferred using a PDMS/PC stamp on a custom-built transfer tool.
- Au(110nm)/Cr(5nm) thick electrodes (source, drain, and gate) were defined with electron-beam lithography and deposition.

Methods of *in-Operando* ARPES

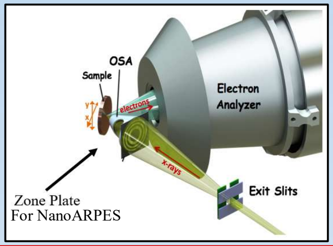
- Measures kinetic energy and ejection angle of photoemitted electron
- Reconstructs the solid's momentum resolved occupied band structure

Standard Technique for Fermi-level Shifting:

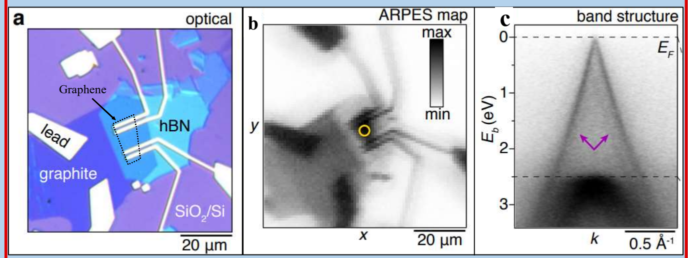
- Standard techniques for boosting the fermi-level and changing the system's charge carrier density is through alkaline metal deposition[1]
- Alkaline metal deposition is difficult to control, irreversible, and it can disrupt many-body interactions

In-Operando Fermi-level Tuning:

- We built our device as a capacitor
- Applying a voltage between the plates charge accumulates on graphene
- Its carrier concentration and fermi-level is then finely and reversibly tuned to the desired strength



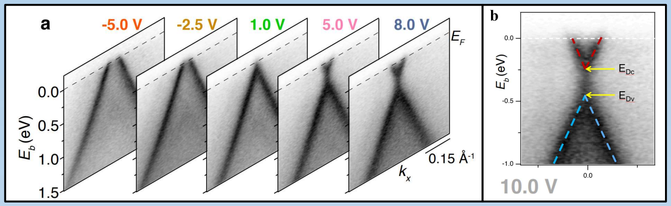
Spatially Resolved ARPES Map of the Device



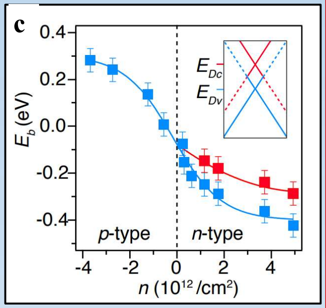
a) An optical image of the device
b) An ARPES map where the dark regions show maximum photoemission
c) Spectrum taken at the yellow circle in (b)

- The ARPES map is made by taking spectra while scanning around the sample, creating an electron dispersion at every spatial point

Reconstruction of the Dirac Point



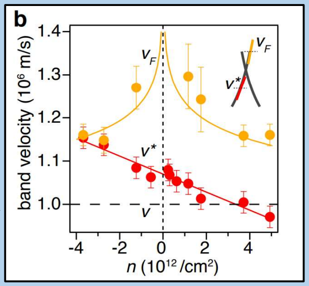
- Ignoring many-body interactions, the Dirac cones in graphene touch at a single point in momentum space labeled "K"
- At high voltages, the Dirac point becomes stretched, an indication of electron-plasmon interactions[2]
- E_{DC} and E_{DV} are the conduction and valence band Dirac point respectively
- C results show the separation between the cones increases as a function of carrier concentration
- This agrees with previous findings in potassium deposition[2]



Controlling the Dirac Cone Curvature

To lowest order, the electronic band structure of graphene is linear

- V, represents linear bands (constant at all doping)
- V*: slope of the band 300meV below the Dirac point
- V_F: slope of the band at the fermi-level
- V_F and V* differ greatly which shows the differential curvature of the bands
- The sharpening of V_F near charge neutrality is consistent with electron-electron interactions[3]



Conclusion and Future Plans

- This is the first *in-operando* microARPES from a functional device where the high data quality makes it possible to reliably analyze many-body interactions.
- We observe renormalization of the Dirac point due to electron-plasmon coupling
- Electron-electron coupling results in differential curvature of the bands
- We move forward towards more complex device configurations to unveil novel many-body physics in 2D systems

References

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[4] M. Calandra, F. Mauri, Phys. Rev. B 76, 205411 (2007).
[5]Muzzio *et al.* (2020) **arXiv:2001.03355** Paper containing data presented here

Acknowledgements

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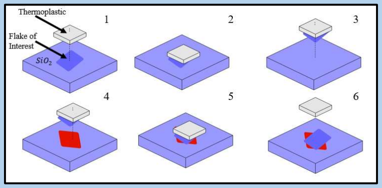
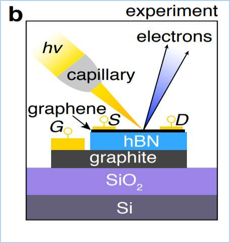
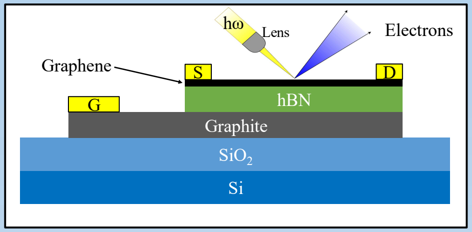
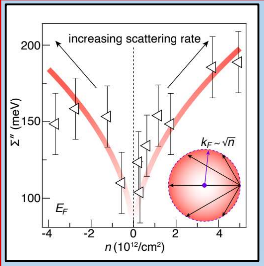






Controlling the Dirac Cone Curvature



- Σ'', the imaginary self-energy, is proportional to the scattering rate
- The data is fitted to a $\sqrt{n}$ dependence plus a constant
- This agrees with theory for short-range electron-defect scattering and electron-phonon interactions[4]
- These scattering events reduce the carrier mobility in our device