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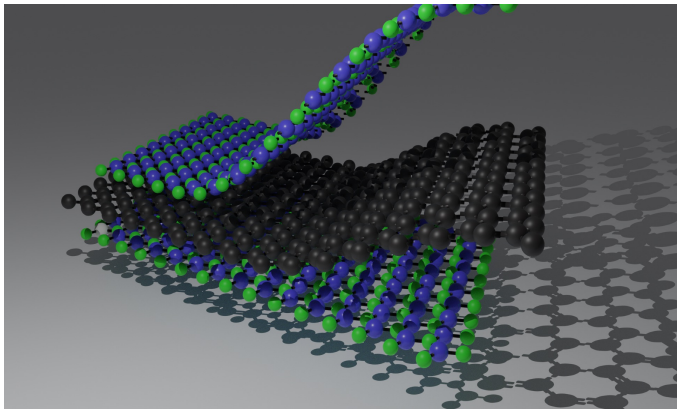
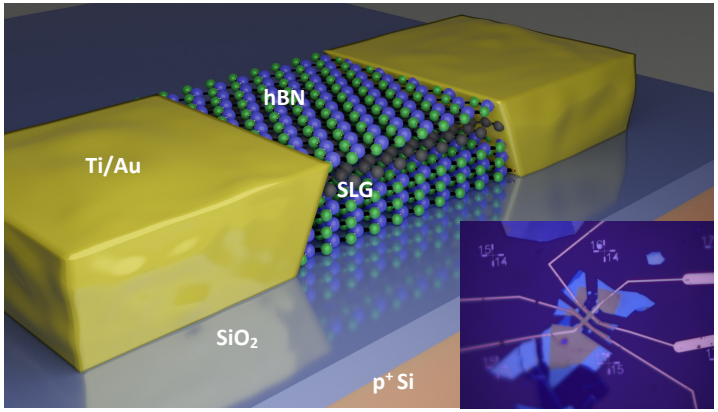
Charge Inhomogeneity mediated Low-Frequency noise in encapsulated graphene field effect transistors

Aroop K. Behera, Charles T. Harris, Douglas V. Pete, Collin J. Delker, Per Erik Vullum, Marta B. Muniz, Ozhan Koybasi, Takashi Taniguchi, Kenji Watanabe, Branson D. Belle, and Suprem R. Das*





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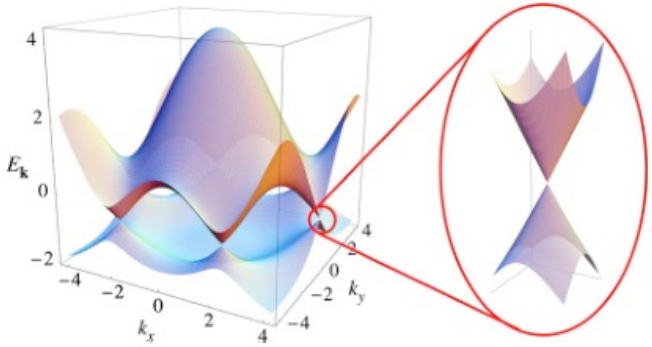
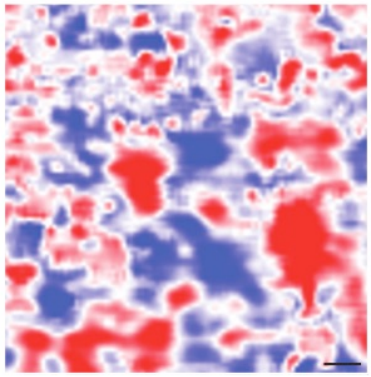
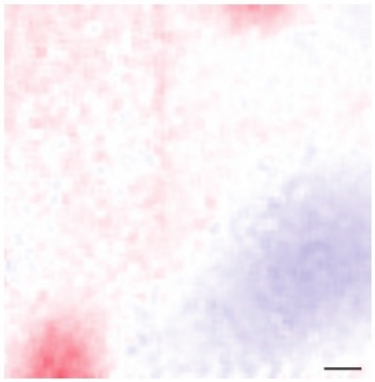
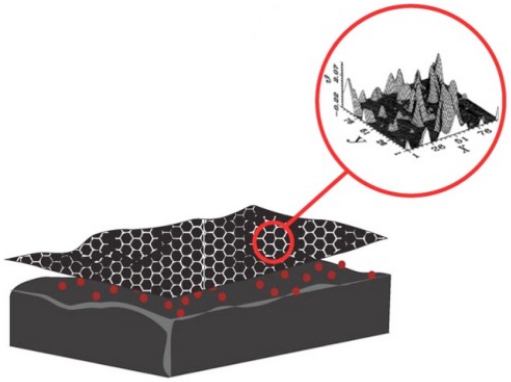
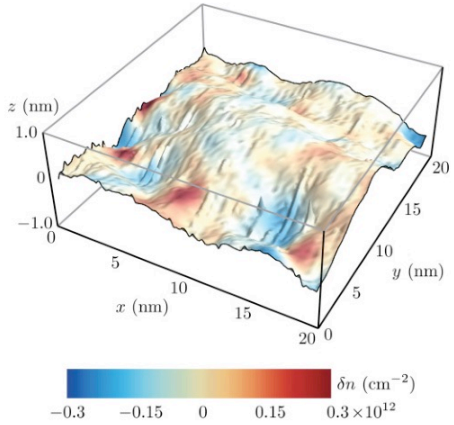
Graphene: A brief review

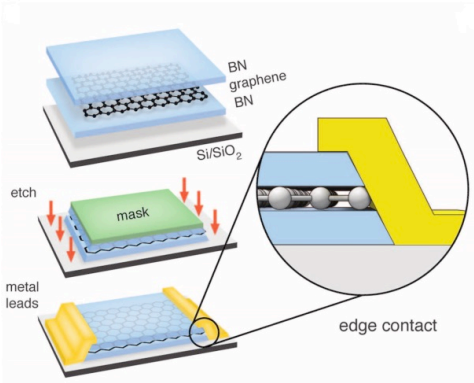












- hBN encapsulation
  - Enhances carrier mobility
  - Lowers contact resistance
  - Low substrate charge impurities

Castro et al., Rev. Mod. Phys. **81**, 109 (2009)
Xue et al., Nat. Mater. **10,** 282 (2011)
Wang et al., Science, **342,** 614 (2013)
Adam et al., PNAS, 104 (47), 18392 (2007)
Gibertini et al., Phys. Rev. B **85**, 201405 (2012)

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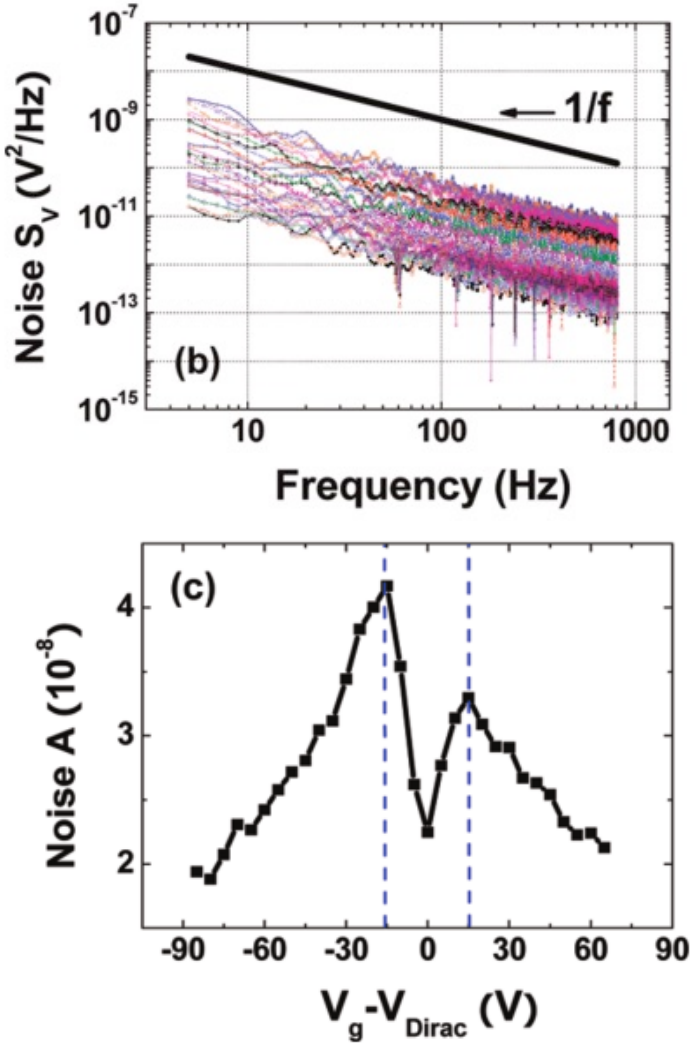
1/f noise: probing carrier properties

- Measured by recording the normalized power spectral density (PSD) of voltage or current across the DUT
- Noise in a semiconducting medium:
  - Mobility fluctuation (Hooge's model)
  - Carrier number fluctuation (McWhorter's model)

$$A = \frac{1}{Z}\sum_{i=1}^{Z} f_i \, S_{Vi}/V^2$$

- Xu et al., used Hooge's model to explain the M type behavior with changing size of puddles.



Xu et al., *Nano Lett.* 2010, 10, 9, 3312–3317

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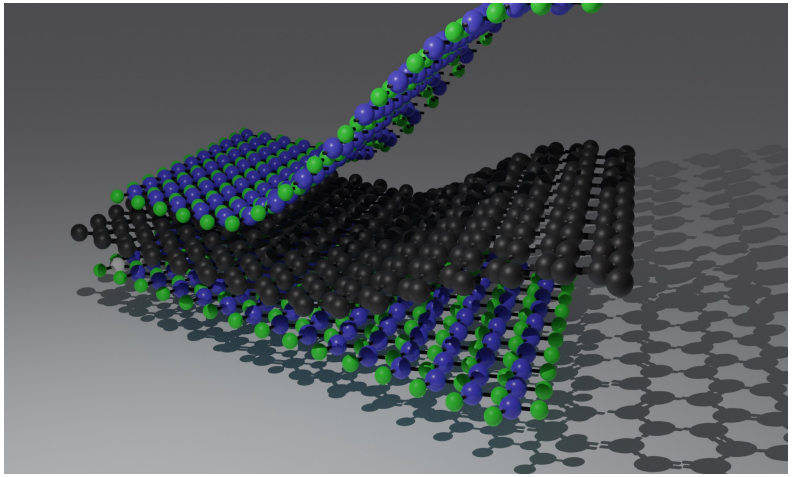
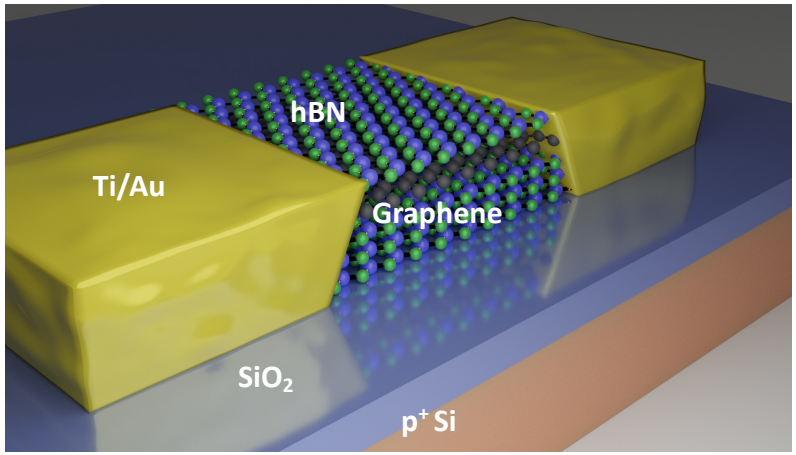
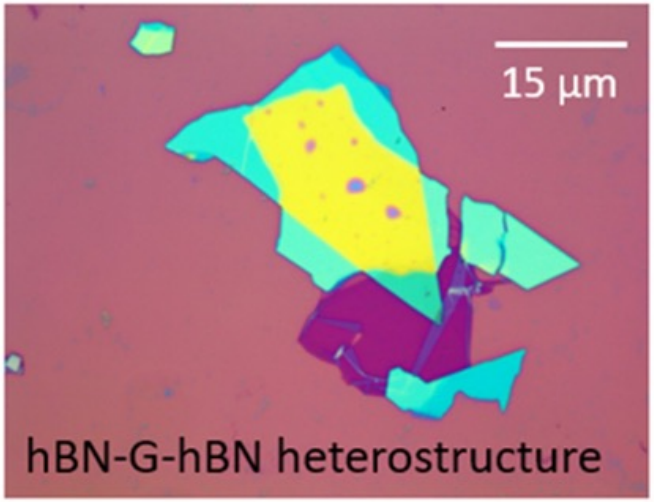
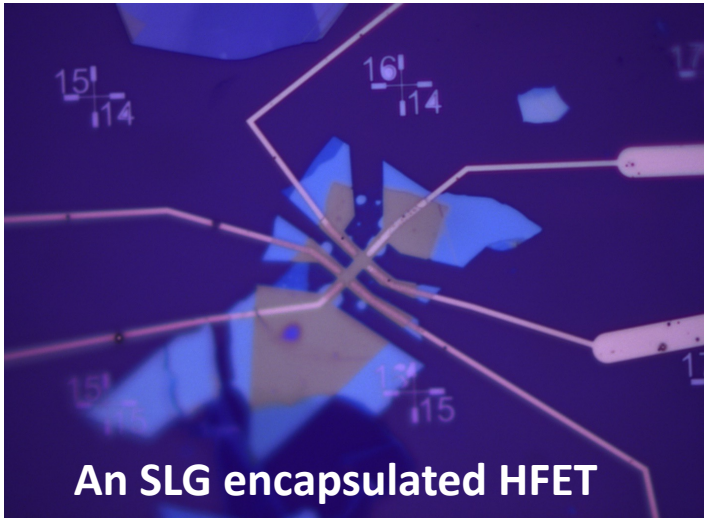
Device fabrication









- Viscoelastic stamping method was used to create the VDW heterostructure.
- RIE and EBL techniques used to fabricate encapsulated-edge contacted graphene devices (HFETs) .

Behera et al., *ACS Appl. Electron. Mater.* 2021, 3, 9, 4126–4134

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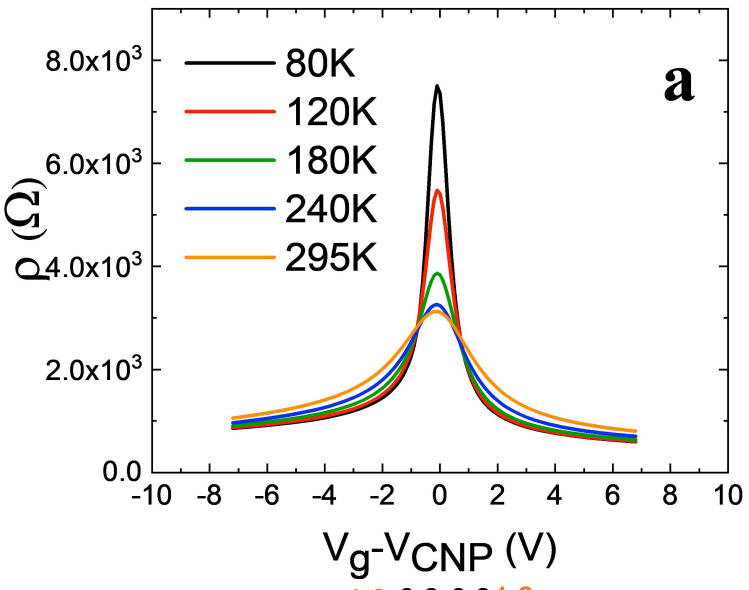
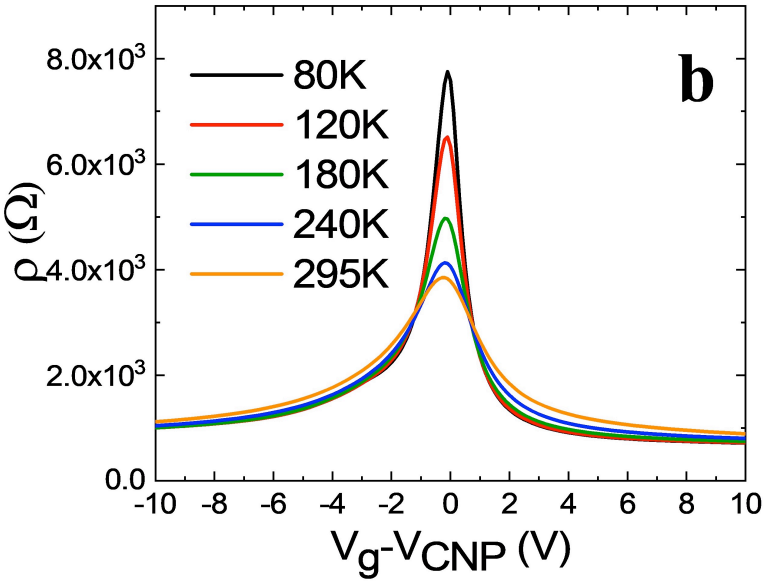
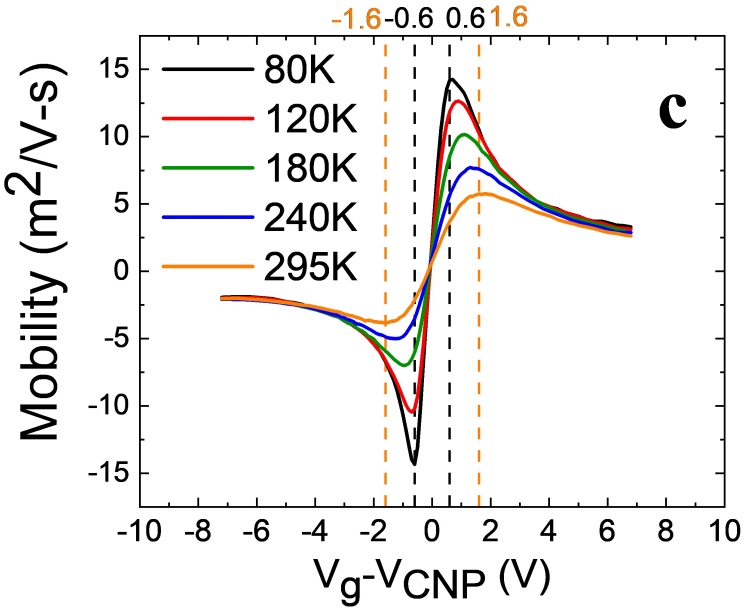
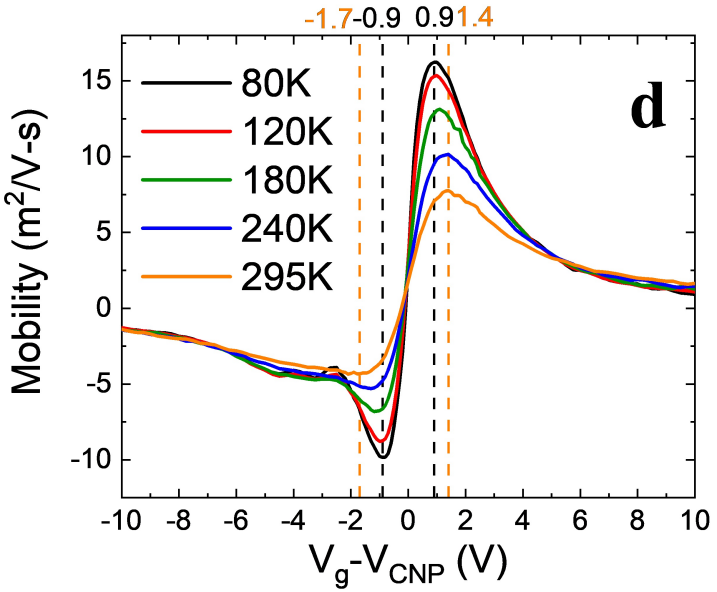
Cryogenic transport measurements



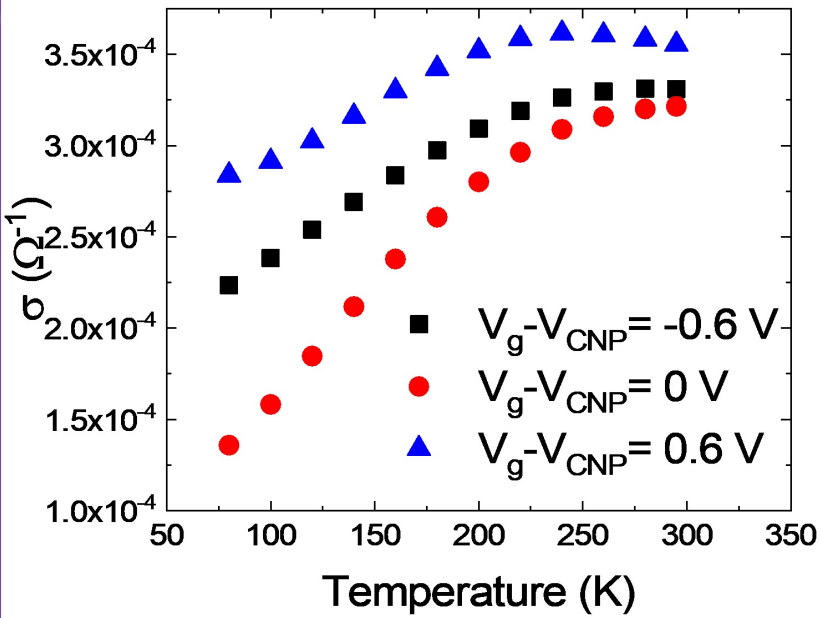


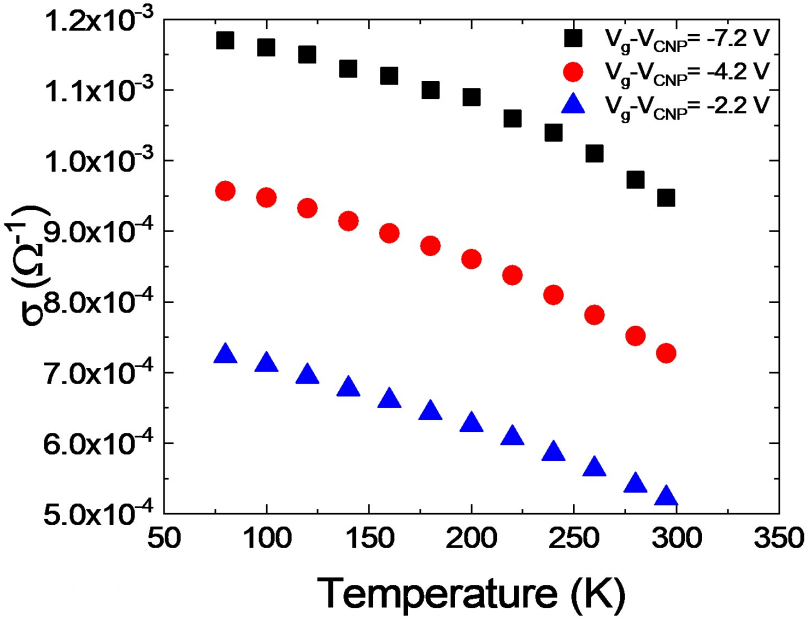




Conductivity

- Conductivity:
  - Residual region: $\sigma(V_g) \approx \left\{C^2 \frac{e^2}{h} \frac{n^*}{n_i}\right\}$
  - Diffusive region: $\sigma(T) \approx \frac{g_s g_v e^2 E_F \tau}{h 2\hbar}$





Similar behavior for BLG sample in the residual region

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McWhorter model for puddles

- Hooge's model: homogenous system, mobility fluctuation
- Presence of electron-hole puddles make the system inhomogenous
- Mcwhorter's model: Carrier number fluctuation

$$\frac{S_I(f)}{I_d^2} = \frac{g_m^2}{I_d^2} S_{V_{fb}}$$

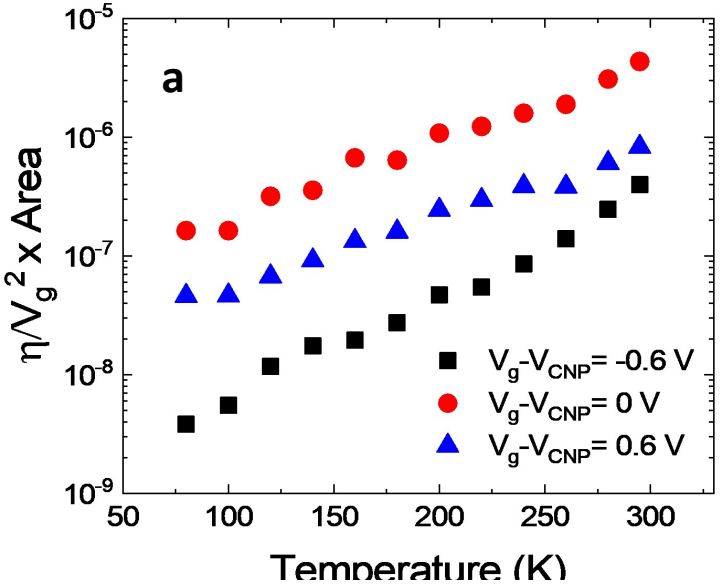
Flat band voltage spectral density

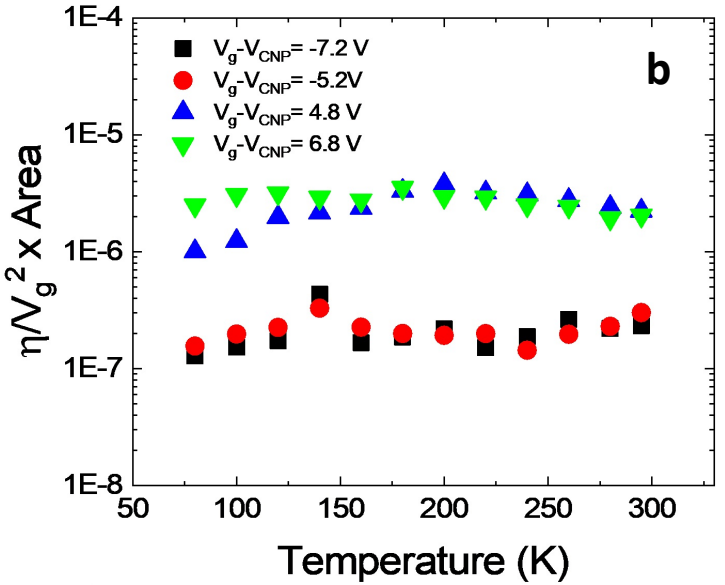
$$\eta = S_{V_{fb}} \times f$$

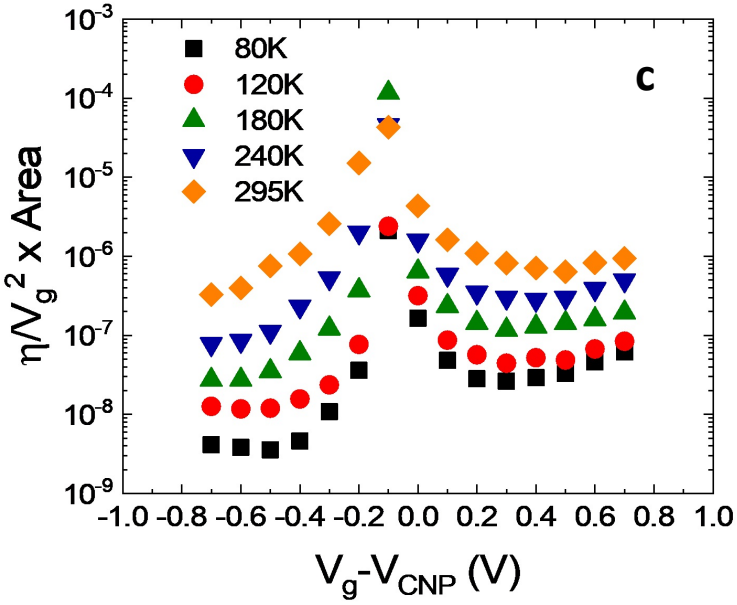
Frequency normalized

- Flat band voltage fluctuation represents the charge fluctuation between the channel and underlying traps in dielectric.

Normalized flat band noise







- High gate voltage: Traps get screened
- Higher temperature: Thermally assisted carrier trapping
- Similar observation in bilayer graphene sample

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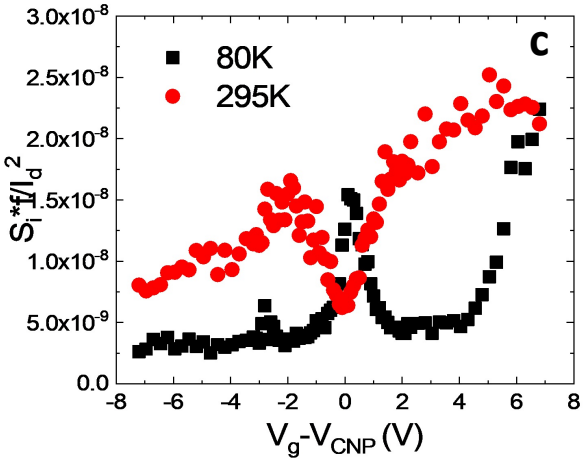
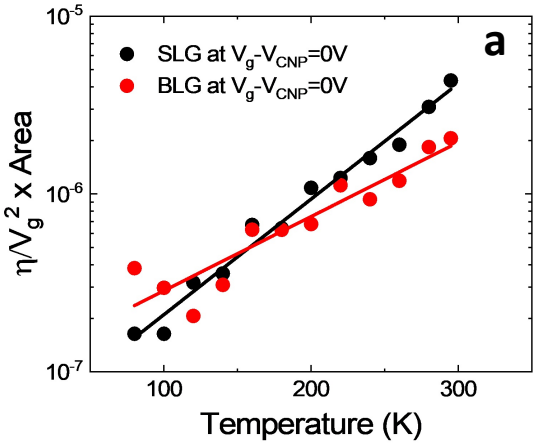
Pinning and depinning of Puddles

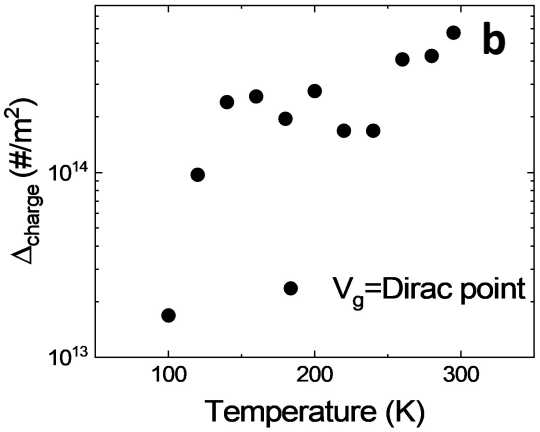
$$\frac{Slope_{BLG}}{Slope_{SLG}} = \frac{{n^*}_{BLG}/_2 + \Delta/_2}{{n^*}_{SLG}}$$

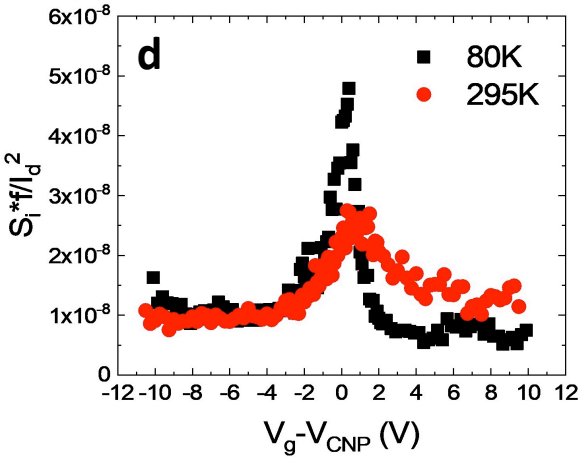
$$\Delta = n_1 - n_2$$

- For SLG:
  - Puddles are pinned at lower temperature
  - Puddles are unpinned at higher temperature.
- For BLG:
  - Increase in n* makes the channel more puddle like (more Type-I).
  - Increased activation energy to escape from puddle to percolation region









Summary

- Noise in graphene channel near CNP can be explained by McWhoter's model with fluctuations in flat band voltage.
- Noise in graphene channel away from CNP is explained by mobility fluctuation.
- Puddles are pinned at lower temperature and depinned at higher temperature for SLG.
- Higher n* value for BLG at CNP makes puddles harder to depin with increasing temperature.

Acknowledgements

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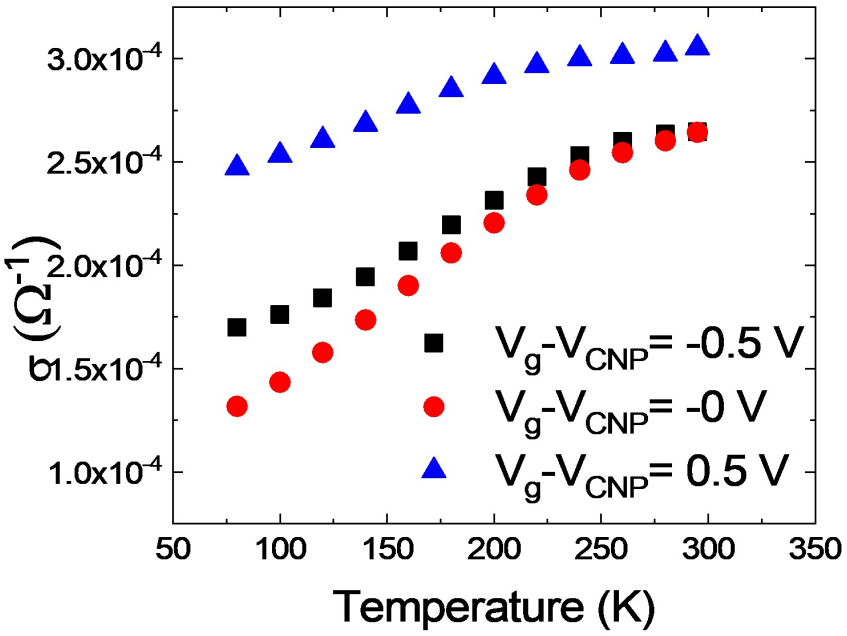
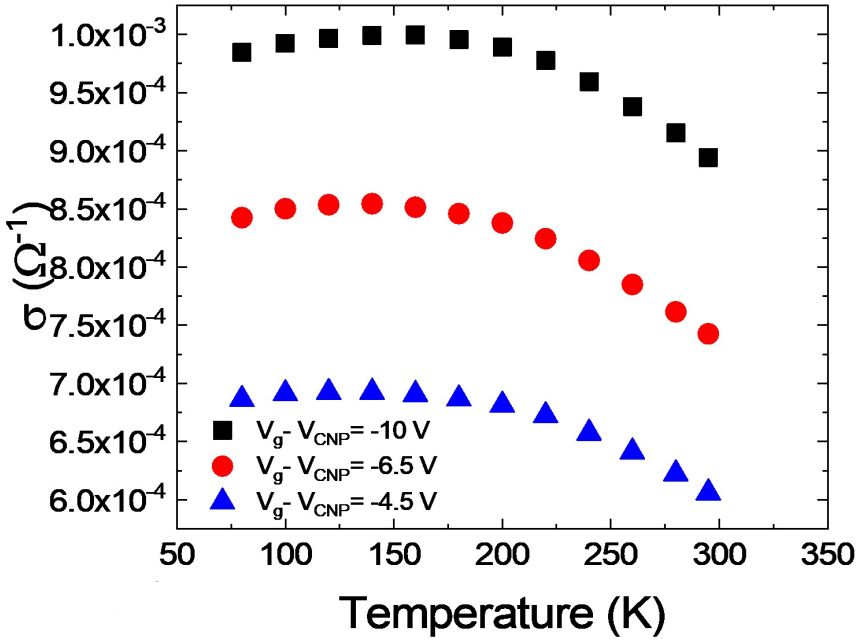
Thank You for your attention!

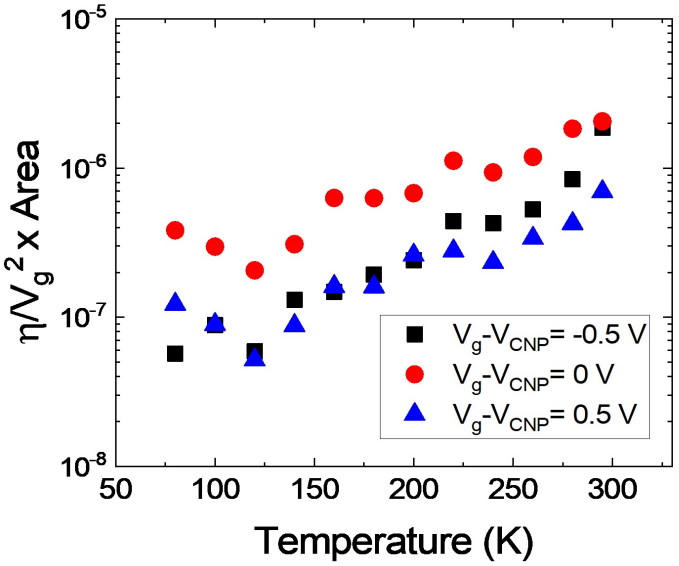
Questions?

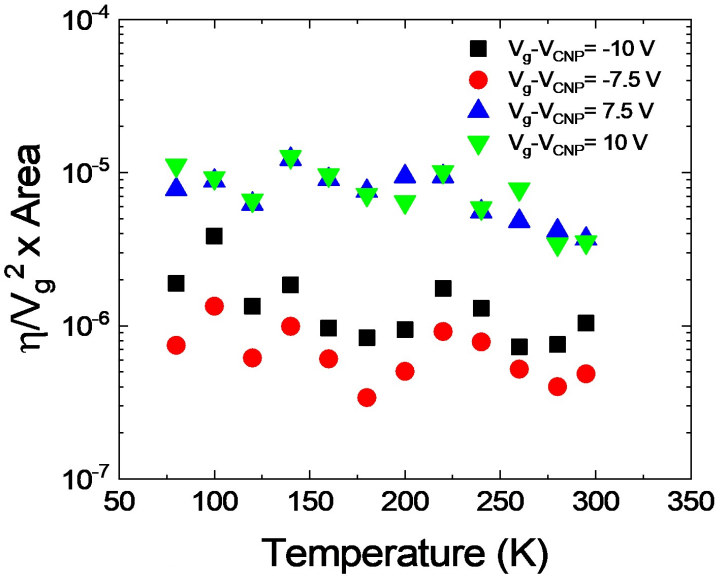
Additional Figures

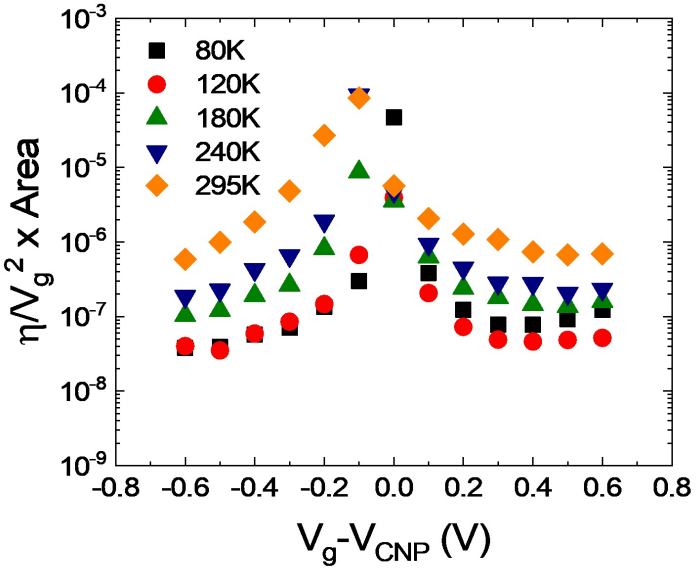




Additional Figures







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