From graphene plasmon hotspots to low-loss hyperbolic metamaterials: Applications and techniques for super-resolution imaging in the mid-infrared

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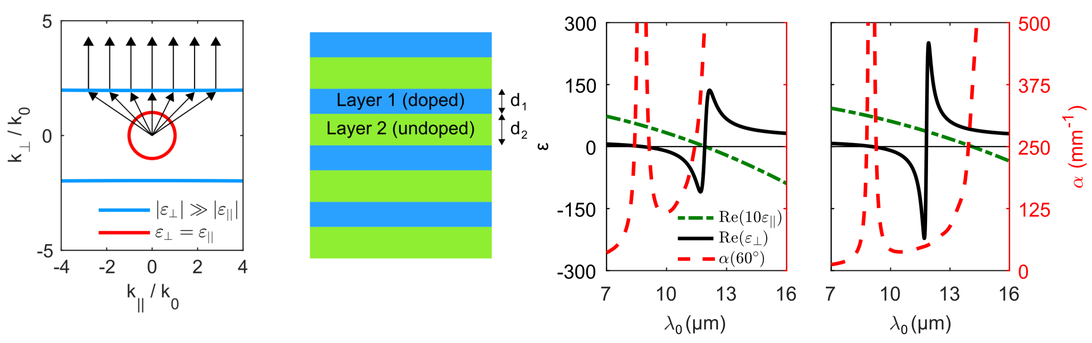
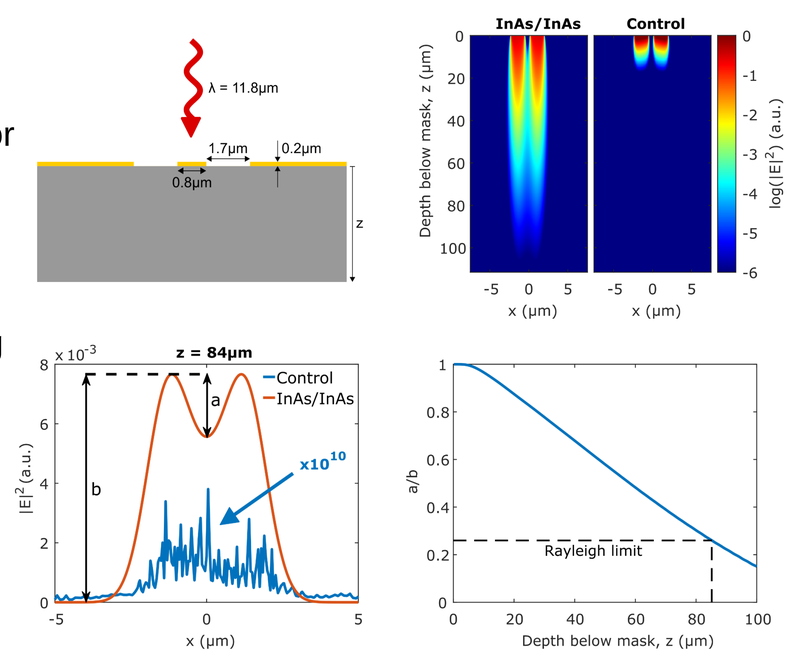
Introduction

- Many applications require imaging below the diffraction limit
- **Long wavelengths** limit conventional mid-infrared imaging to microscale
- Metamaterial superlenses bypass this limit by preserving near-field
- Scattering-type scanning near-field optical microscopy (s-SNOM) **beats diffraction limit** by **~λ/1000** in mid-infrared
- These methods enable investigation of **sub-wavelength** optical phenomena e.g. surface plasmons

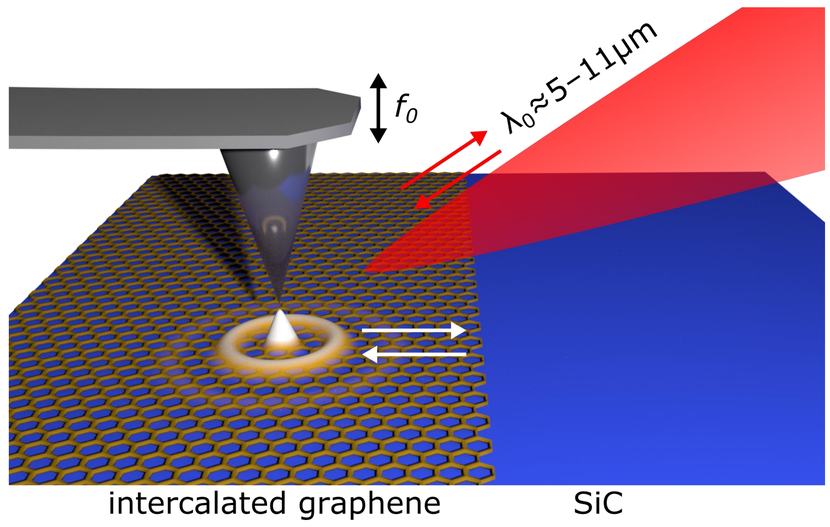
Low-loss metamaterial superlens design[1]



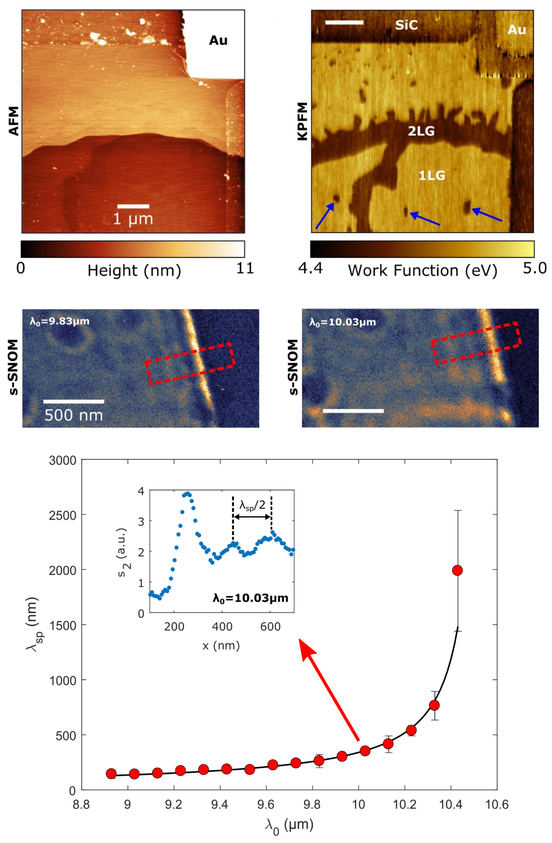
- Metamaterial "**superlenses**" beat diffraction limit, but suffer high losses
- New high electron mobility design provides **stronger anisotropy ($\varepsilon_\perp$> 250)**
- Can vary layer thickness ratio d_1/d_2 to **tune out-of-plane dielectric resonance away from losses**
- Strong anisotropy provides **near diffractionless propagation**
- Sub-wavelength imaging (< λ_0/15) at superlens thicknesses up to ~85μm (~8λ_0)
- **~10x further** than reported for "classical" metamaterials[2]
- Currently being fabricated using MOVPE
- Experimental validation to be performed with s-SNOM



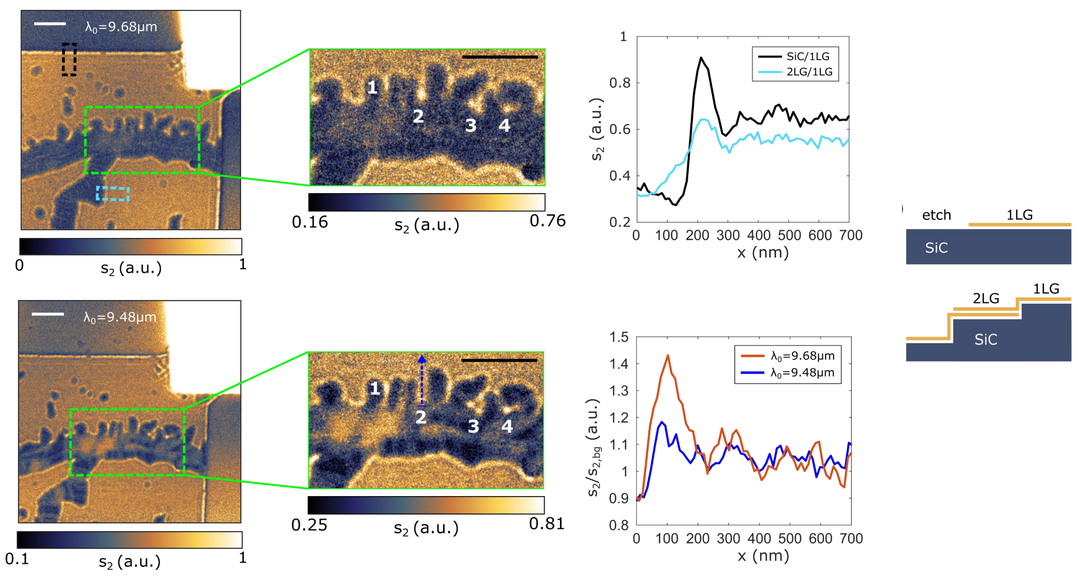
Graphene plasmonics[3]



- S-SNOM focuses light to sharp oscillating probe tip ~10nm
- Tip acts as **"lightning rod"** to greatly enhance and localise interaction with sample
- **Wavelength-independent** resolution[4]
- **H_2-intercalated graphene** (1LG) is good medium for traveling plasmons[5]
- S-SNOM launches plasmons into graphene
- Interference of plasmons **modulates** s-SNOM signal
- Wide tuneability of QCL allows to precisely measure plasmon dispersion from reflections at **1LG/SiC boundaries**
- Dispersion curve gives local measurement of E_F=298±4 meV



- Bilayer (2LG) strips produce tuneable plasmon reflection hotspots



Conclusions

- Super-resolved imaging is fundamental to investigating nanoscale systems
- New **ultra low-loss** superlens design using high mobility materials boosts image propagation by **10x**
- Widely tuneable mid-IR s-SNOM can be used to **launch and detect plasmons**
- Measured plasmon dispersion in graphene to recover **local Fermi energy**
- Observed tuneable **plasmon reflection hotspots** from bilayer/monolayer interfaces

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References

[1] W. S. Hart et al., Ultra low-loss super-resolution with extremely anisotropic semiconductor metamaterials, *AIP Advances* **2018**, 8, 025203

[2] A. J. Hoffman et al., Negative refraction in semiconductor metamaterials. *Nat. Mater.* **2007**, 6, 946-950

[3] W. S. Hart et al., Wide-Band Nano-Imaging of Plasmon Dispersion and Hotspots in Quasi-Free-Standing Epitaxial Graphene, **2018**, arXiv:1805.10102 [cond-mat]

[4] H. Amrania et al., New IR imaging modalities for cancer detection and for intra-cell chemical mapping with a sub-diffraction mid-IR s-SNOM, *Faraday Discuss.*, **2016**, 187, 539-553

[5] J. Chen et al., Strong plasmon reflection at nanometer-size gaps in monolayer graphene on SiC, *Nano Lett.* **2013**, 13, 6210-6215