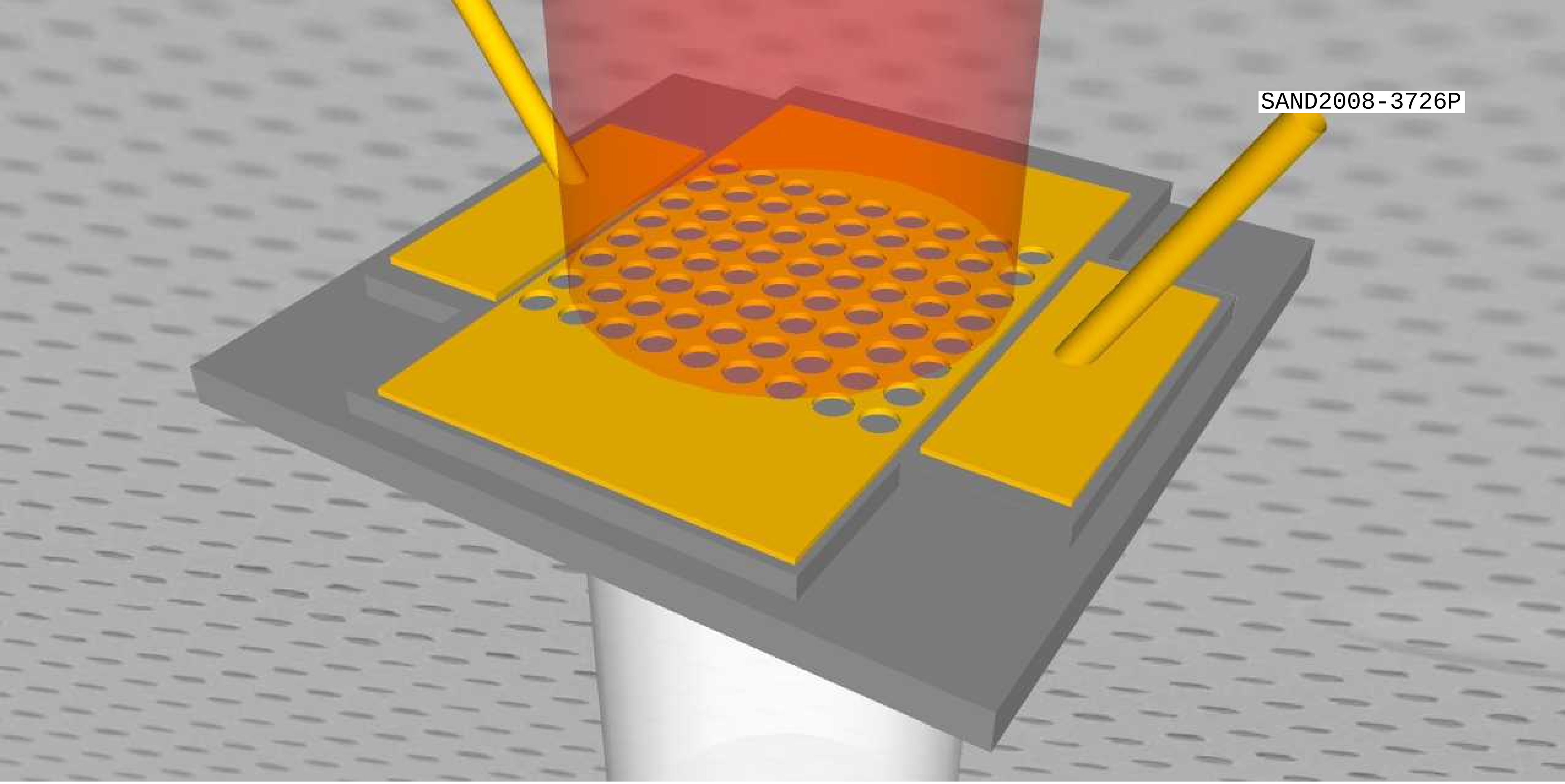

Electrically Tunable Mid-Infrared Extraordinary Optical Transmission Gratings

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Sandia National Labs

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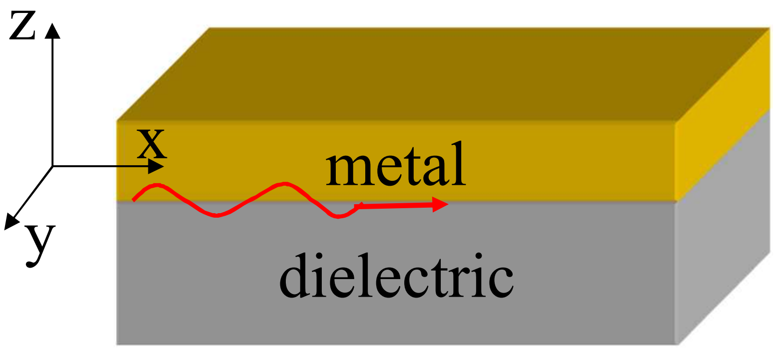
Surface Plasmons



$$k_{sp}^2 = \left(\frac{\omega^2}{c^2}\right)\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}$$

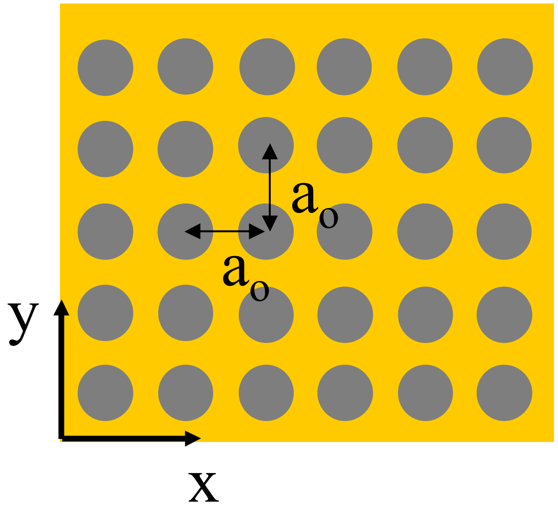
Surface Plasmon
Dispersion Relation

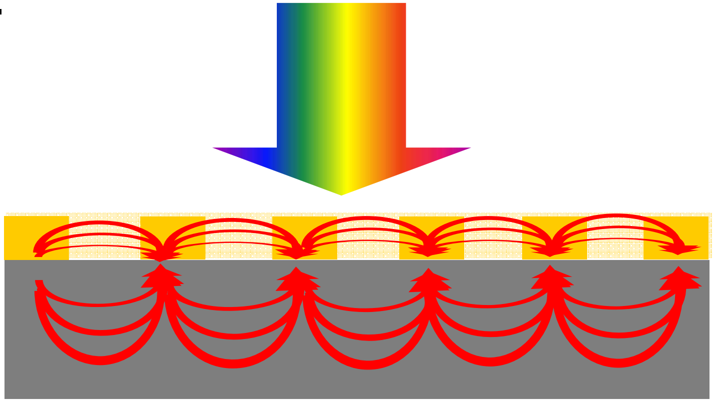
$$\vec{k}_{xphoton} = \frac{\omega}{c}\sin\theta \quad < \left|k_{sp}\right| = \frac{\omega}{c}\left(\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}\right)^{1/2}$$

- Surface Plasmons are hybrid excitations
- Collective charge oscillations in metal coupled to EM waves at metal/dielectric interface
- Can find SP dispersion relation by solving Maxwell's Eqs at metal dielectric interface
- Cannot couple directly to SP from free space

Periodically Modulated Metals

- Periodic metallic gratings or meshes have a 'crystal' momentum associated with the reciprocal lattice vector of the periodic modulation.
- Periodicity of subwavelength structures allow for coupling of incident light to metal/dielectric interface mode.





$$\vec{k}_{sp} = \vec{k}_x \pm i\vec{G}_x \pm j\vec{G}_y \qquad \vec{G}_x = \vec{G}_y = \frac{2\pi}{a_o}$$

$$\sqrt{i^2 + j^2}\,\lambda = a_0\sqrt{\frac{\varepsilon_s\varepsilon_m}{\varepsilon_s + \varepsilon_m}} \approx a_0\sqrt{\varepsilon_s} \quad for \ |\varepsilon_m| >> |\varepsilon_s|$$

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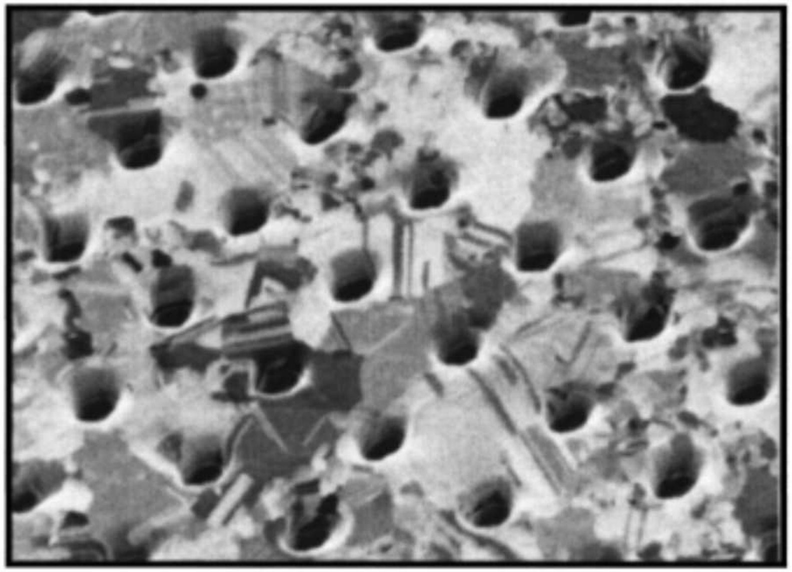
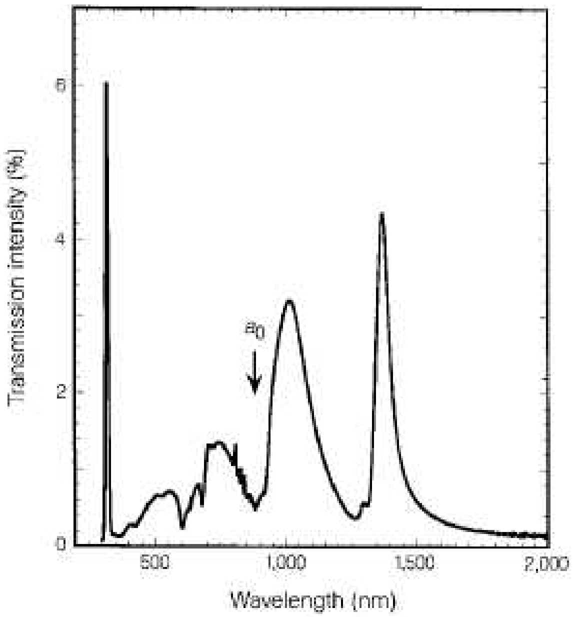
Introduction to EOT

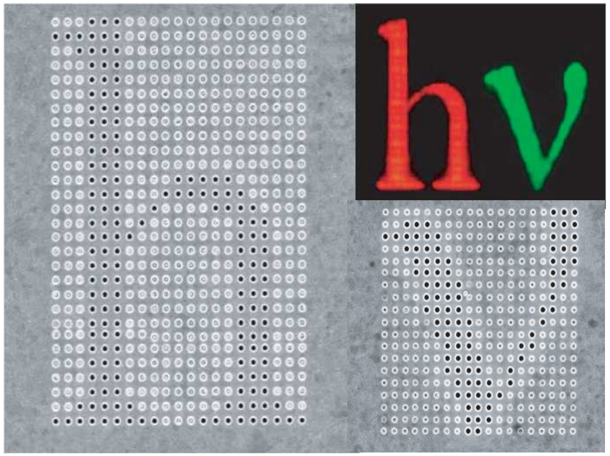
- Ebbesen, et al. Nature (1998)
  - A periodic array of apertures gives enhanced transmission at certain frequencies
  - When normalized for un-metallized area, see >100% transmission!!

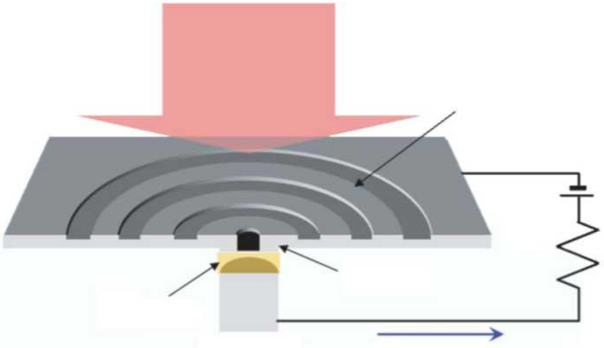




Applications for EOT

- Displays
  - C. Genet and T.W. Ebebsen, "Light in Tiny Holes", *Nature*, **445**, 4 (2007).
- Detector Coupling
  - T. Ishi, et al, "Si nano-photodiode with a surface plasmon antenna" *Jpn J. Appl. Phys.* **44**, L364 (2005).
- Enhanced Sensitivity detection
  - A.G. Brolo, et al. "Enhanced fluorescence from arrays of nanoholes in a gold film" *J. Am. Chem. Soc.* **127**, 14936 (2005).





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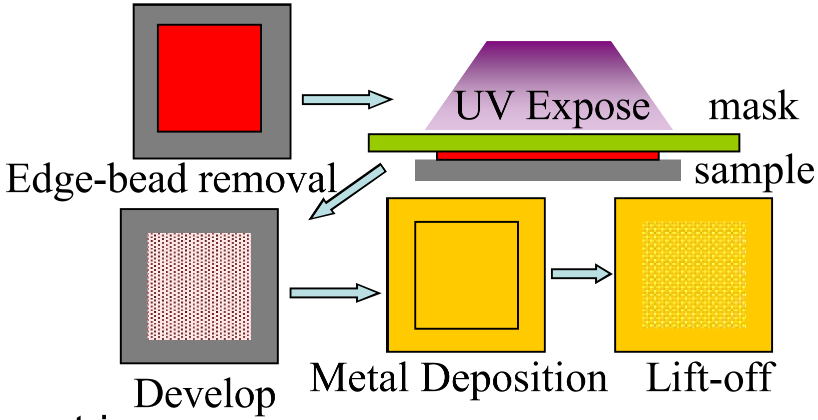
Mid-Infrared Plasmonics



- Advantages and Opportunities!!
  - Fabrication advantages
    - Testbed for interesting physics/novel geometries
  - Gas sensing, communication, countermeasure applications
  - Integration with semiconductors (transparent in MIR)

If Plasmonics is the intersection between Photonics and Electronics, we must be able to integrate SPs with Semiconductors –> MIR is ideal for this!

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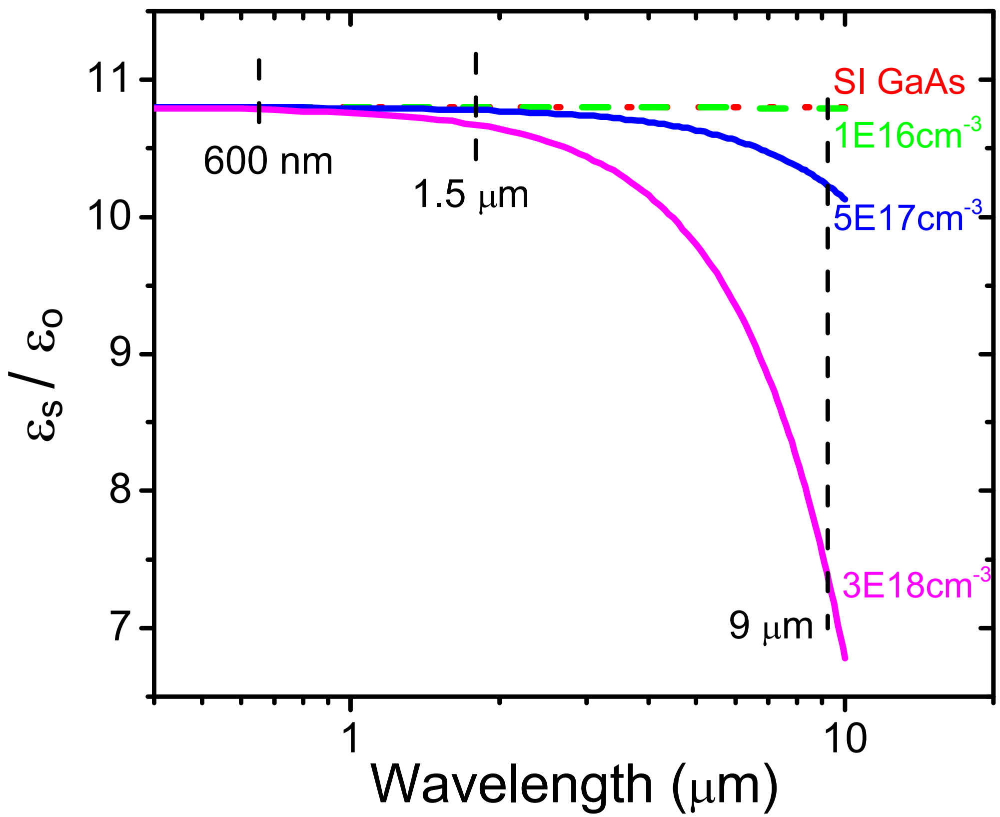
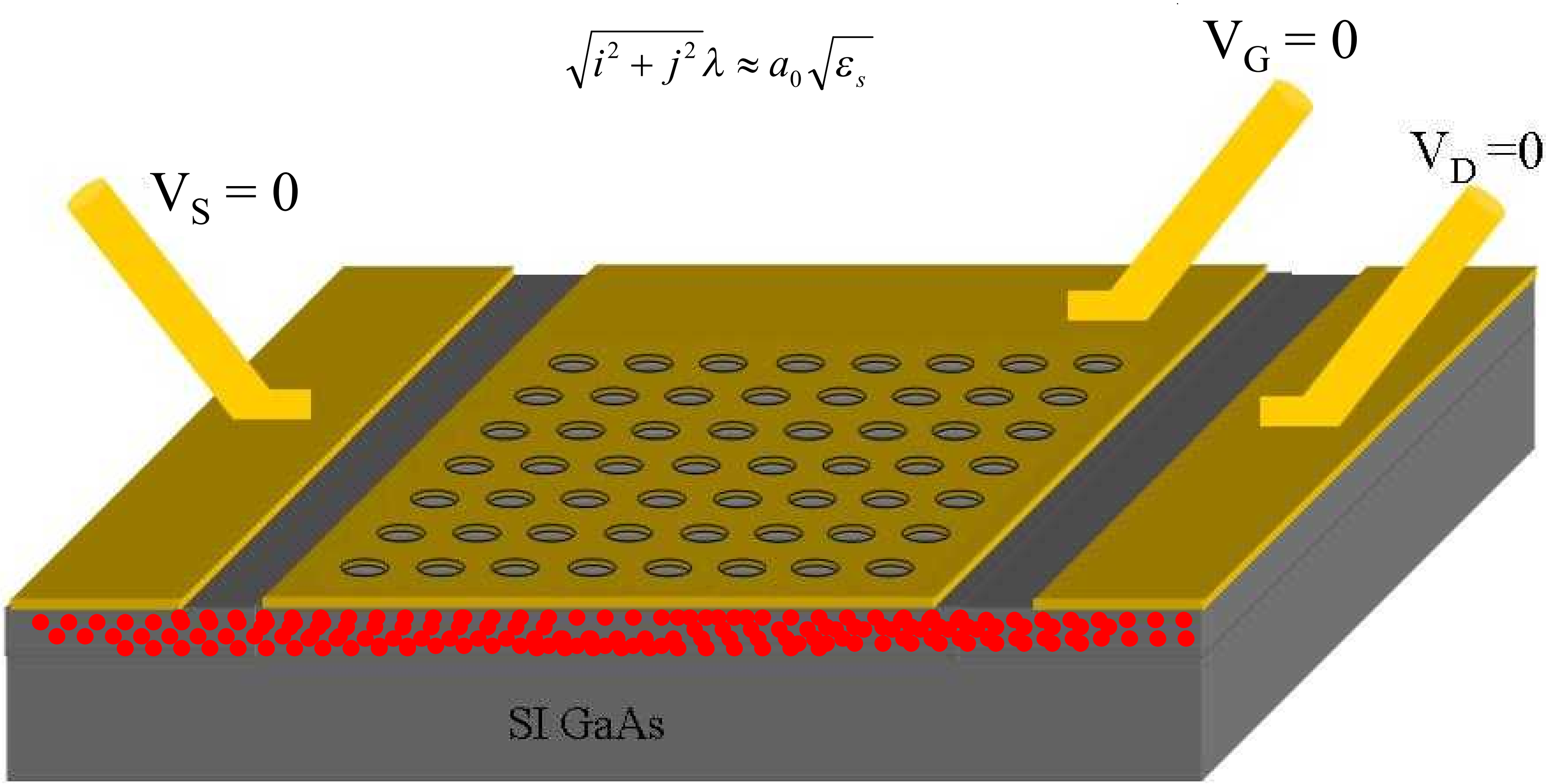
Why mid-IR? (II)



- Semiconductor dielectrics vary as a function of carrier concentration
- Carrier concentration can be tuned electronically (MESFET, MOSFET)
- Carrier concentration can be tuned optically
- Tunable optical components

$$\varepsilon(\omega) = \varepsilon\left(1 - \frac{\omega_p^2}{\omega^2}\right) \quad , \quad \omega_p^2 = \frac{4\pi n e^2}{m^*}$$

Proposed Tunable EOT Device (ETFET)



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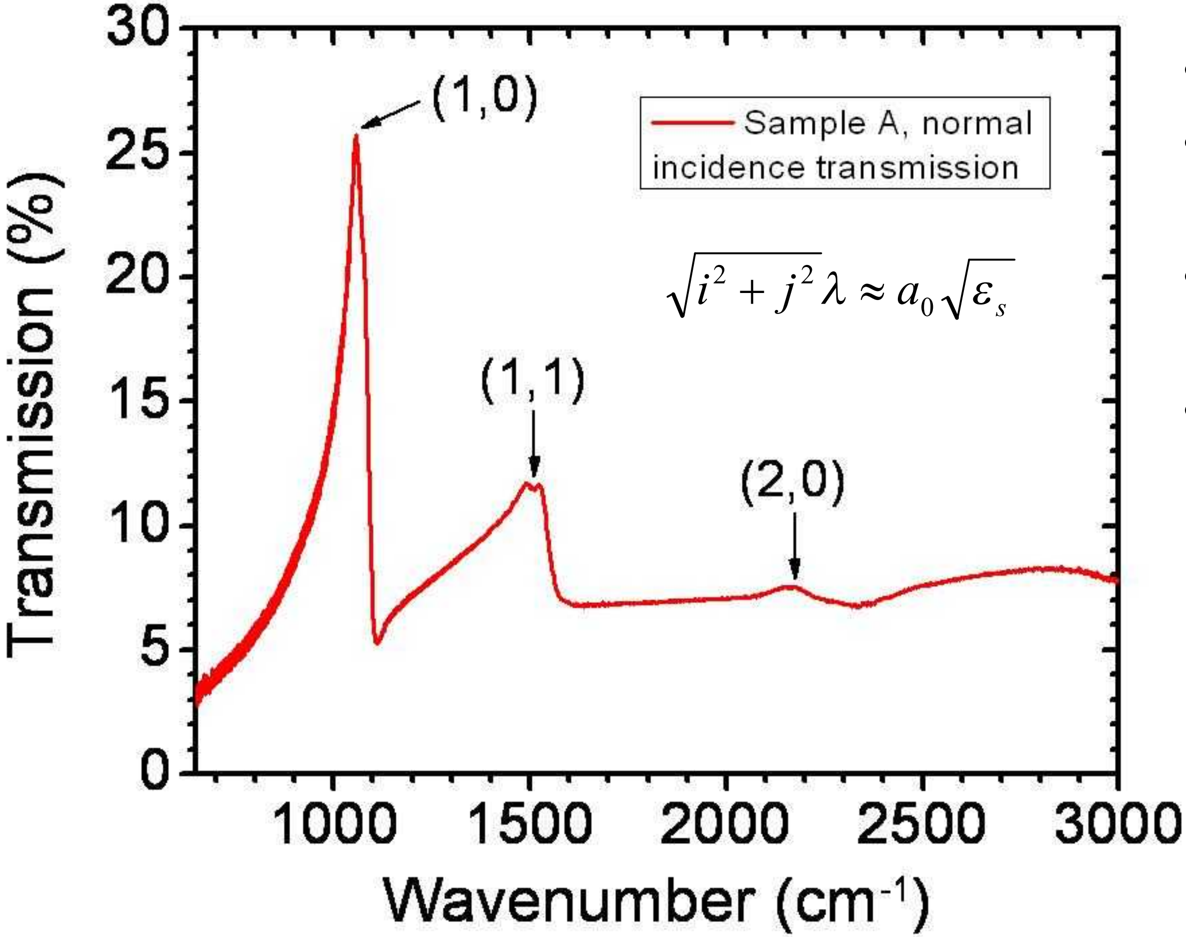
Transmission Spectra



- >25% Transmission!
- Metal covers 78% of sample surface
- Working in EOT regime (>100% transmission)
- Transmission includes losses from:
  - free carriers
  - interface scattering
  - reflection
  - imperfect collection

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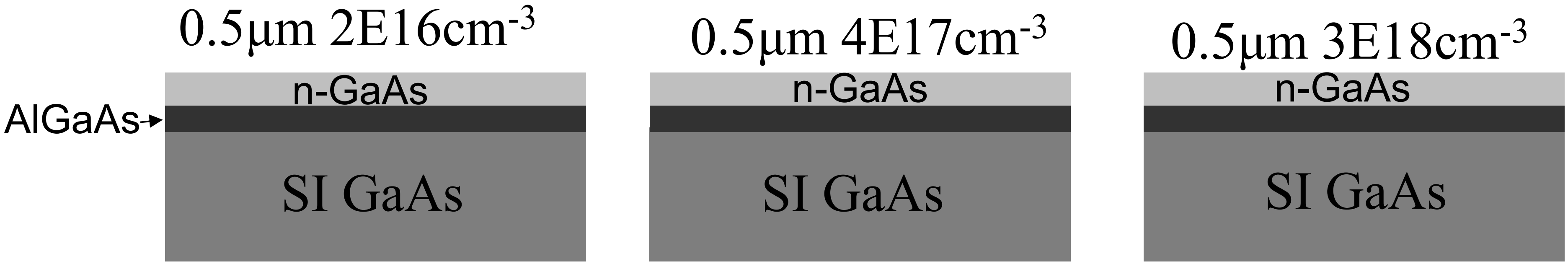
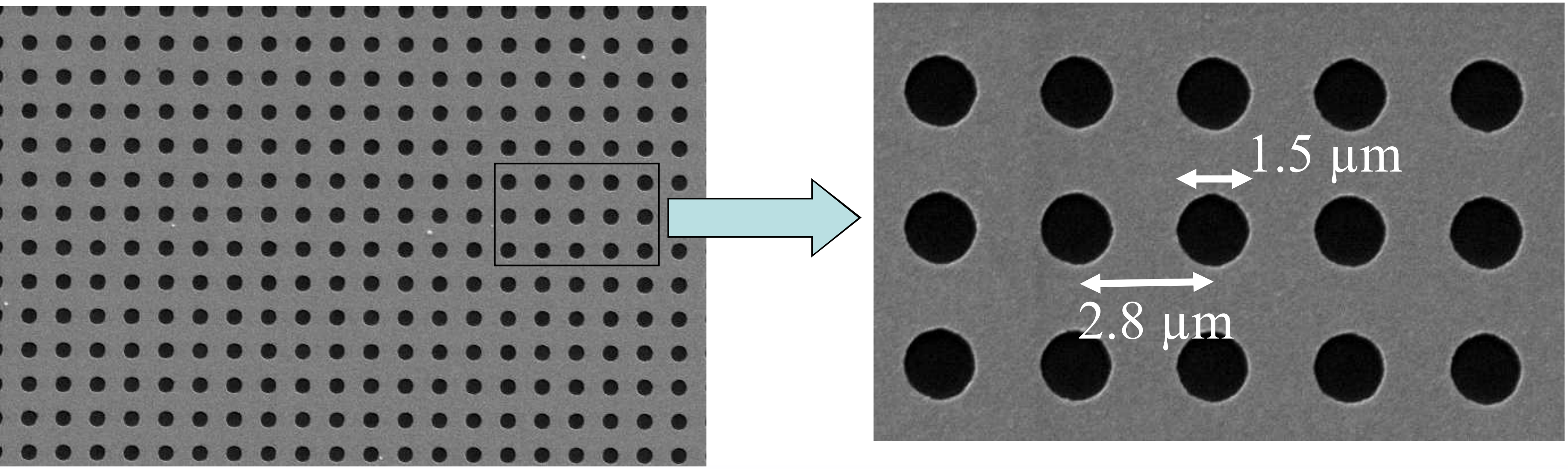
Samples Studied



Sample A Sample B Sample C



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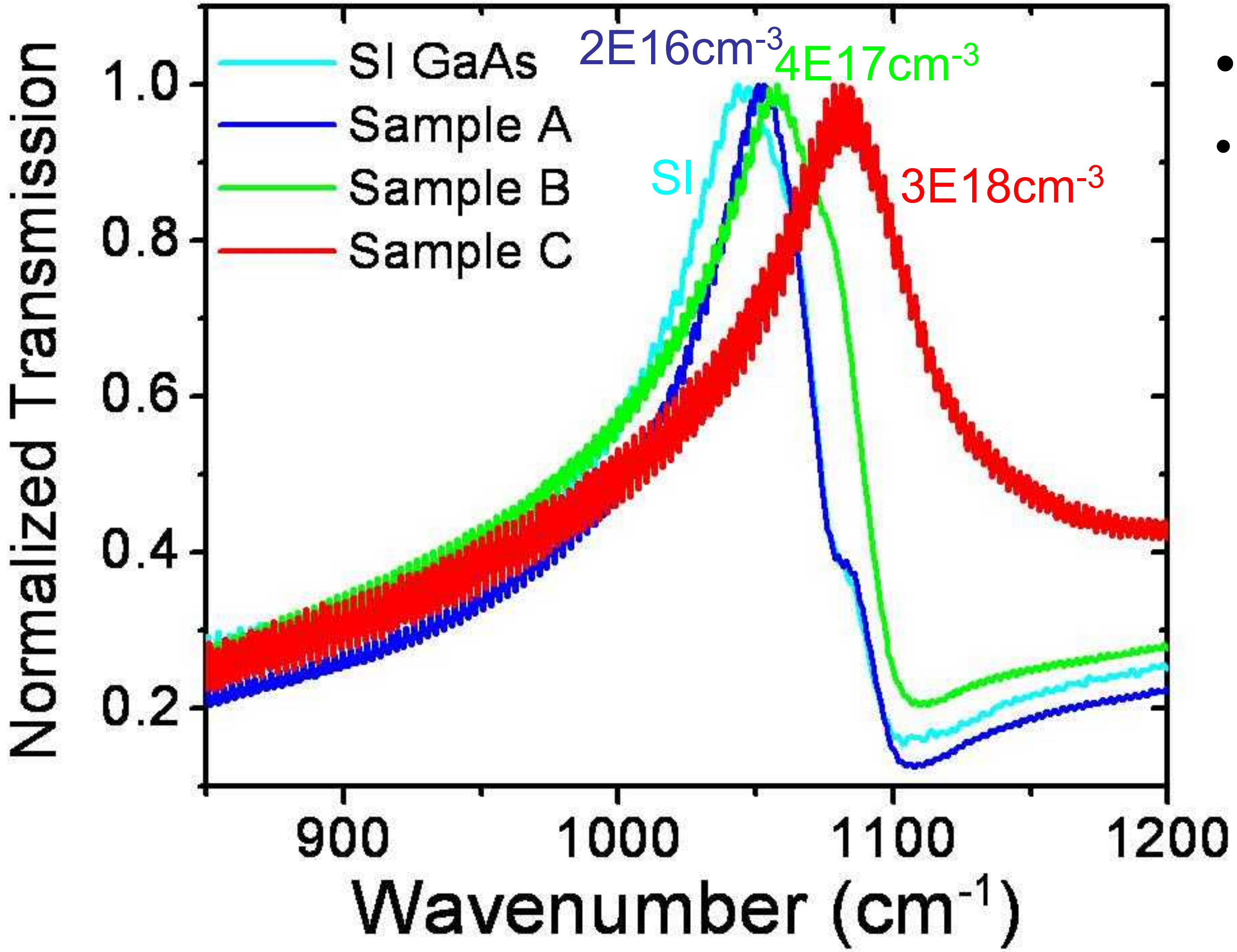
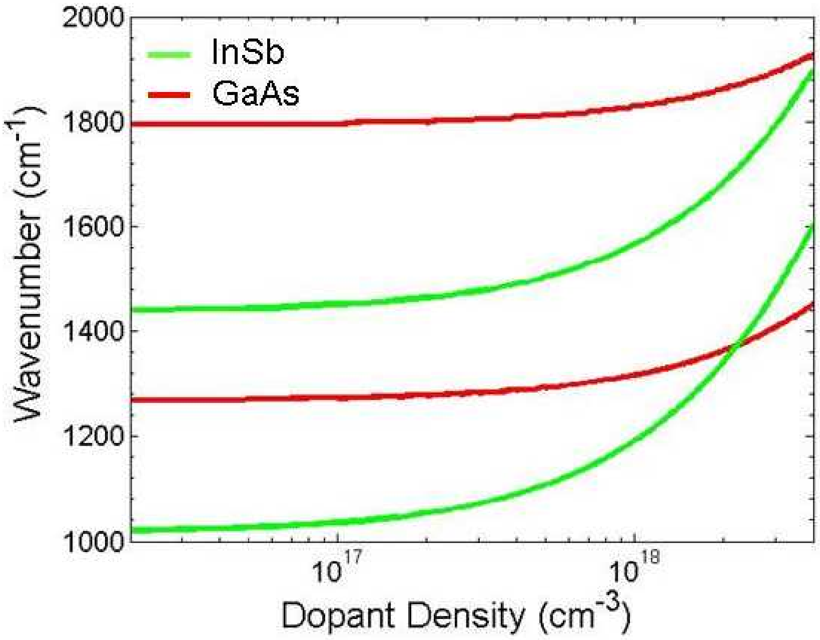
Doping dependent transmission



- Shift of 37 cm^{-1}
- *Appl. Phys. Lett.*, ***90***, *p.191102 (2007)*

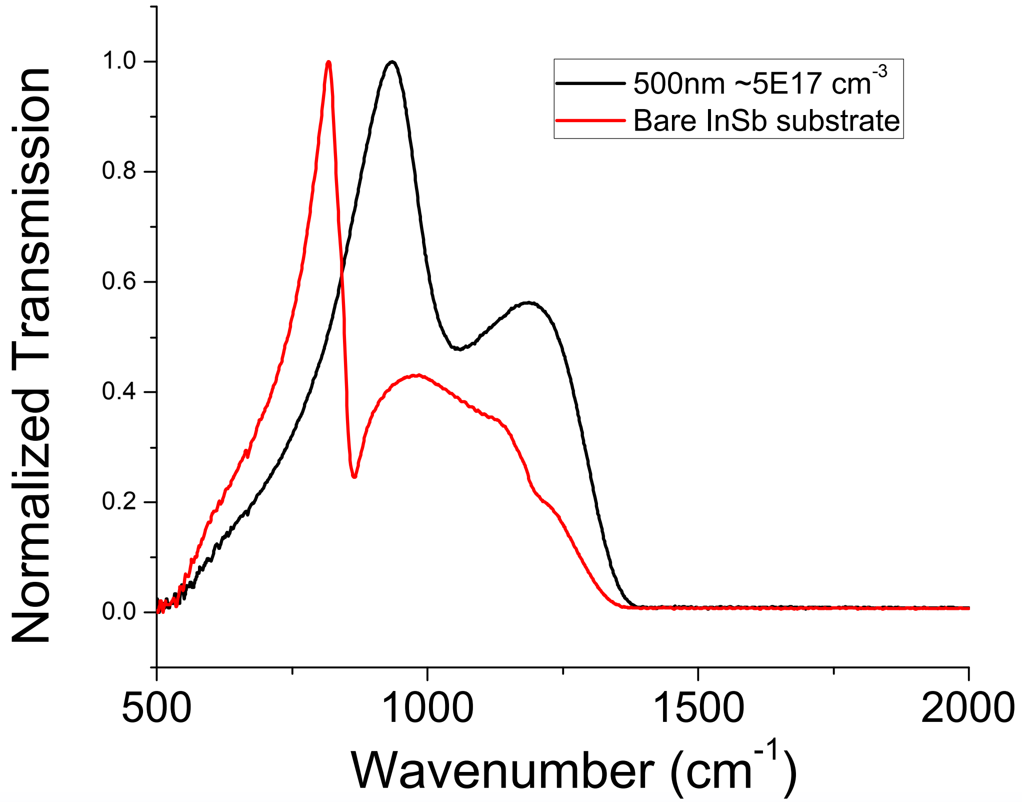
Moving towards Sb-based materials

- Why?
  - Lower effective mass → stronger dependence of *n* on carrier density
  - ~3x temperature coefficient of refractive index compared to GaAs



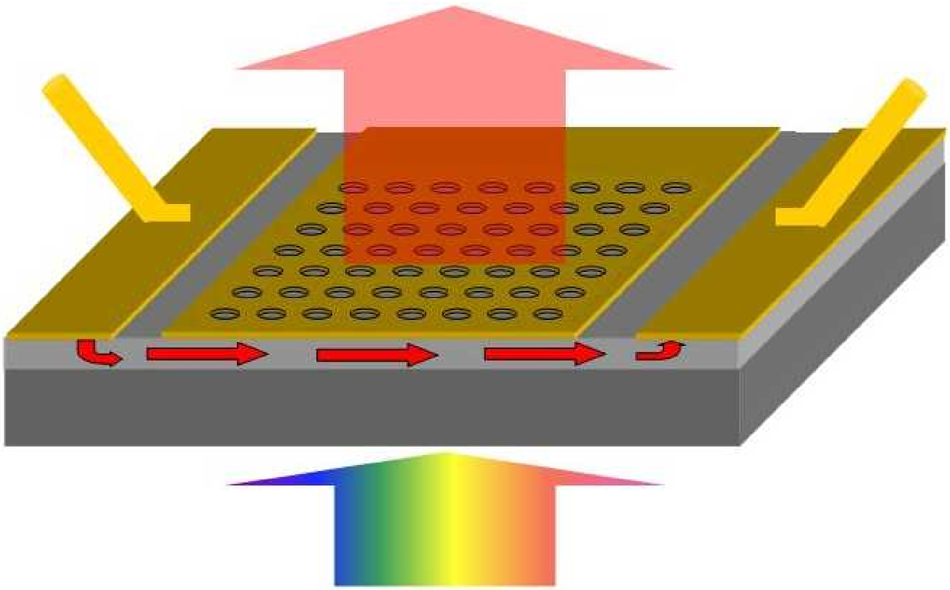
InSb Carrier Tuning

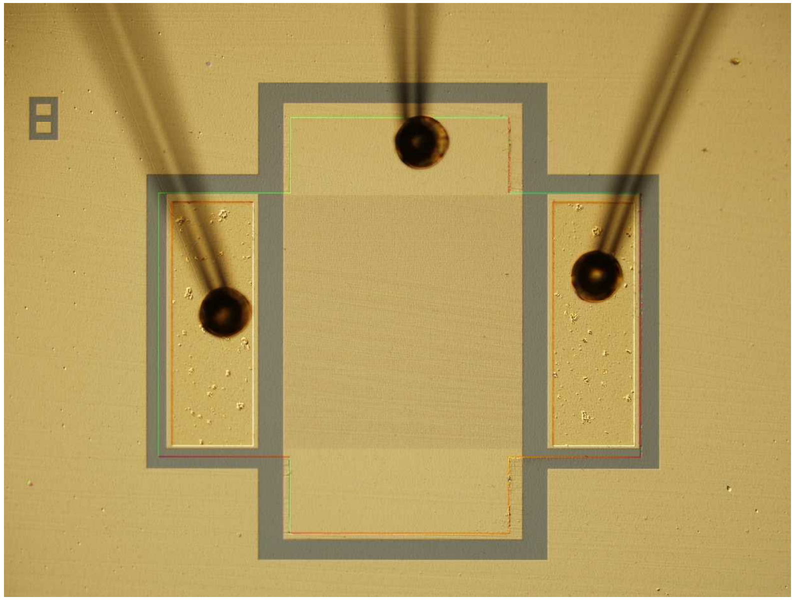
- Shift of 110cm^{-1}, almost 3x of GaAs for an even smaller shift in doping



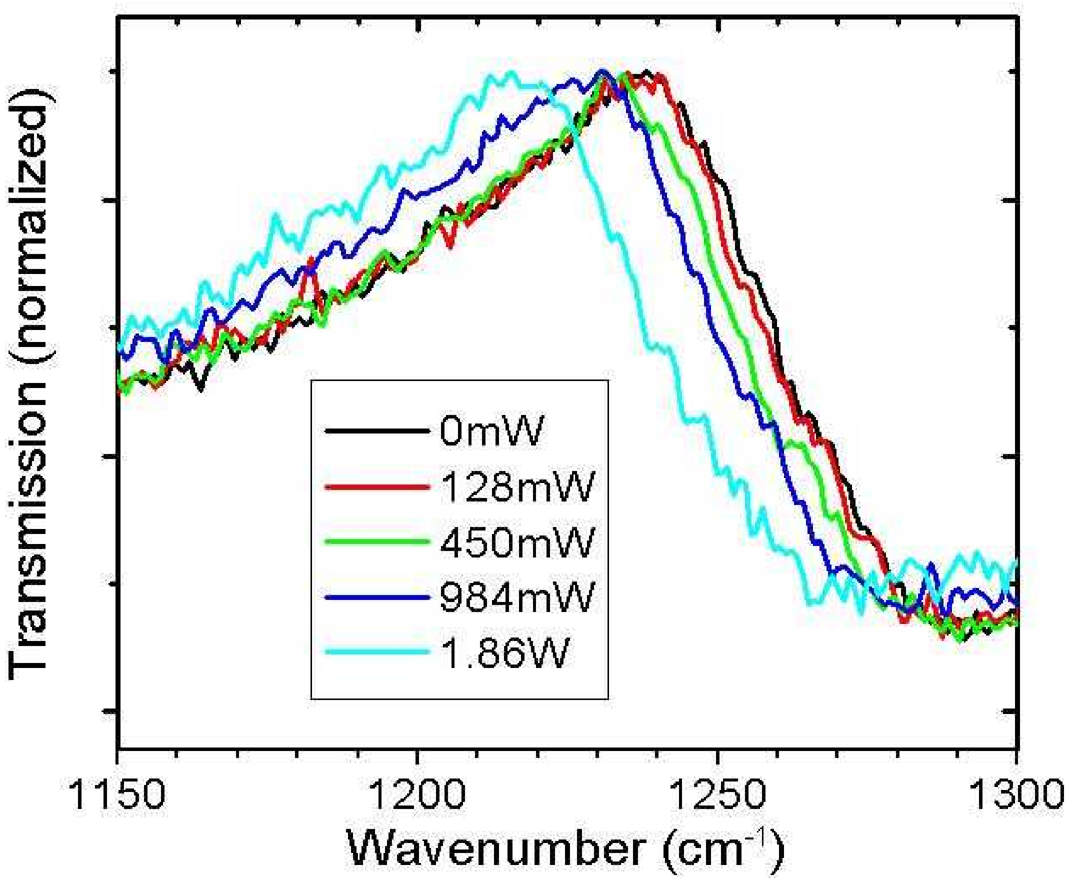
Active Control of EOT Gratings

- Pass current from source to drain of ETFET





Control of EOT Peak Position



- 25 cm-1 shift in SP resonance
- Minimal added losses

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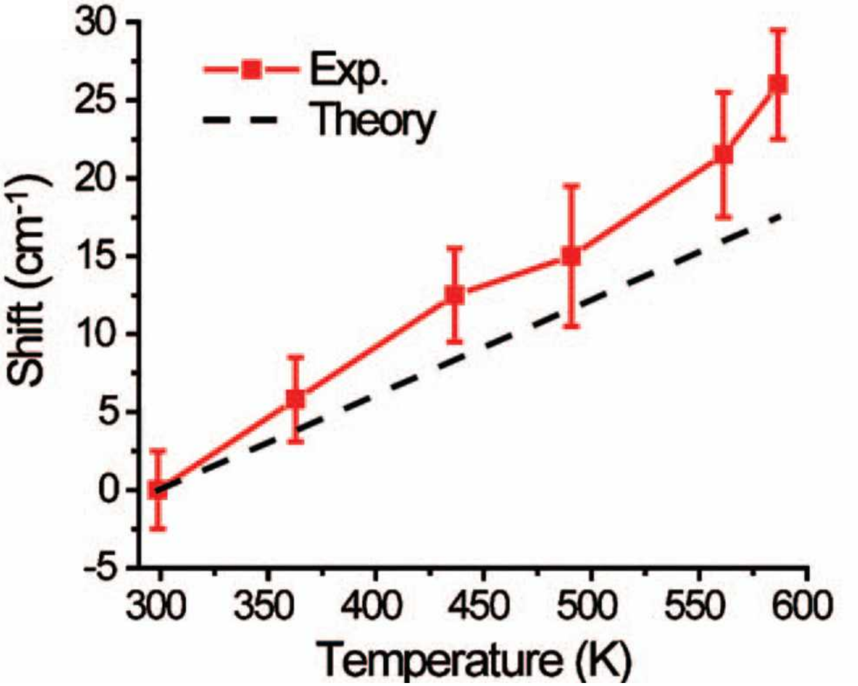
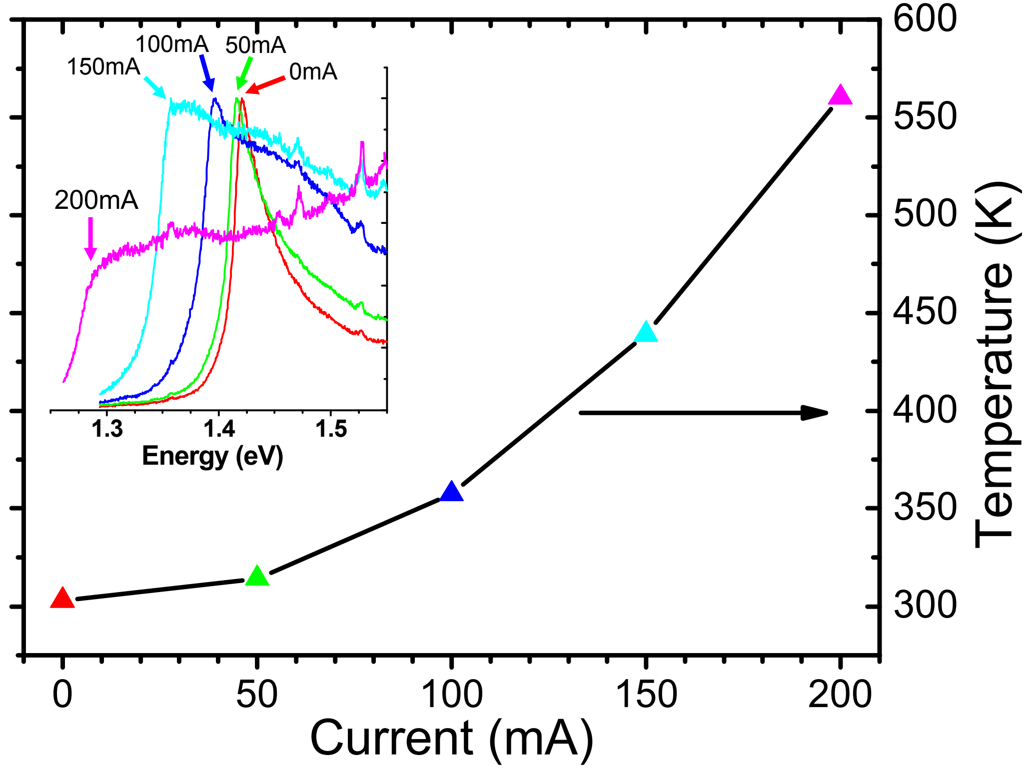
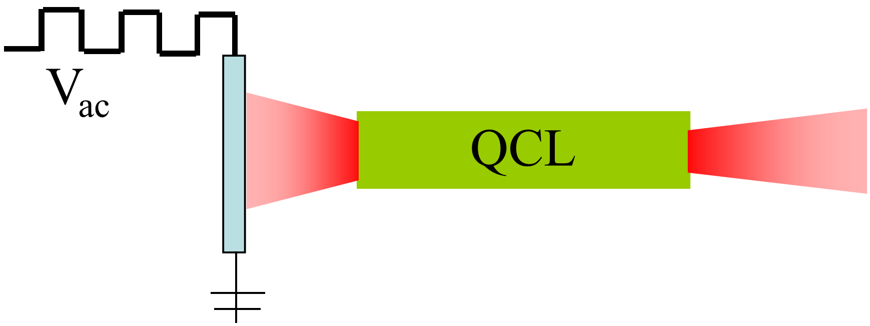
Current Tuning of EOT Gratings



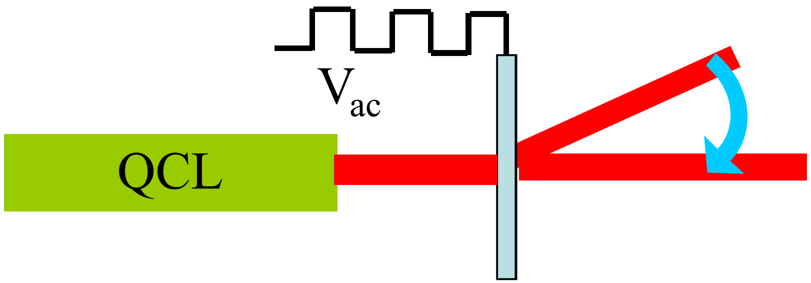


Applications

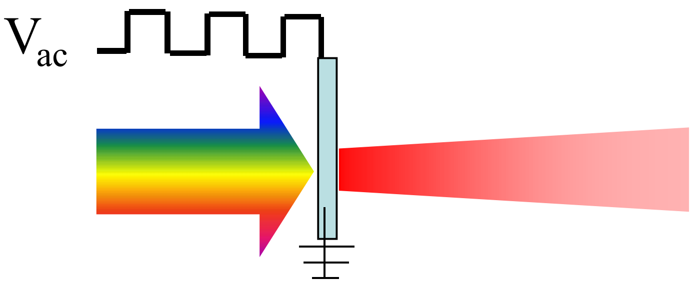
- Tunable mirrors



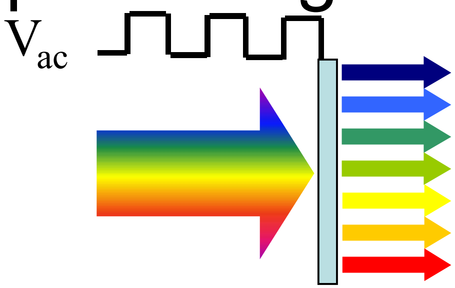
- Beam steering



- Tunable Filters



- On-Chip Sensing



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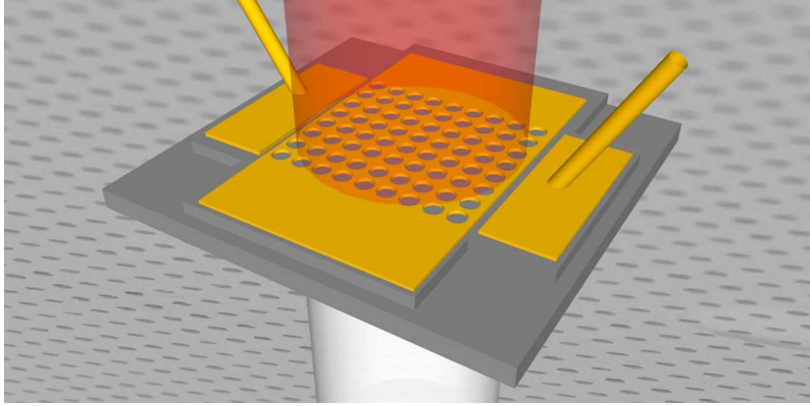
Conclusions



- Demonstrated doping tunable mid-IR EOT grating structures
- Proposed and showed feasibility of “ETFET” dynamic & versatile SP architecture
- Active electrical control over SP excitation frequencies in Mid-IR plasmonic structures

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