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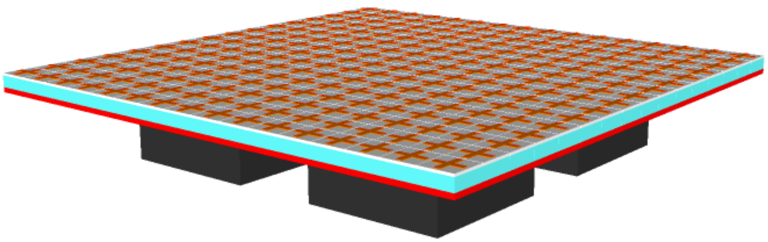
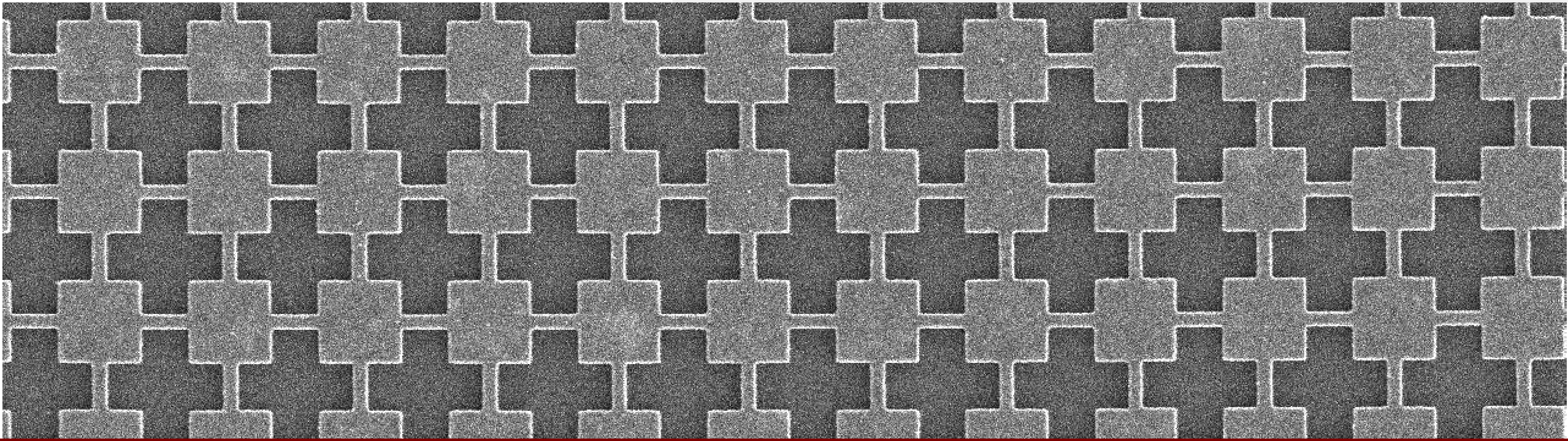
SAND2016-6982C

Nanoantenna-Enhanced Infrared Detectors for Improved Performance and Spectral Tunability



David W. Peters, J. K. Kim, A. Tauke-Pedretti, T. E. Beechem, J. F. Ihlefeld, P. Davids, M. B. Sinclair, J. R. Wendt



U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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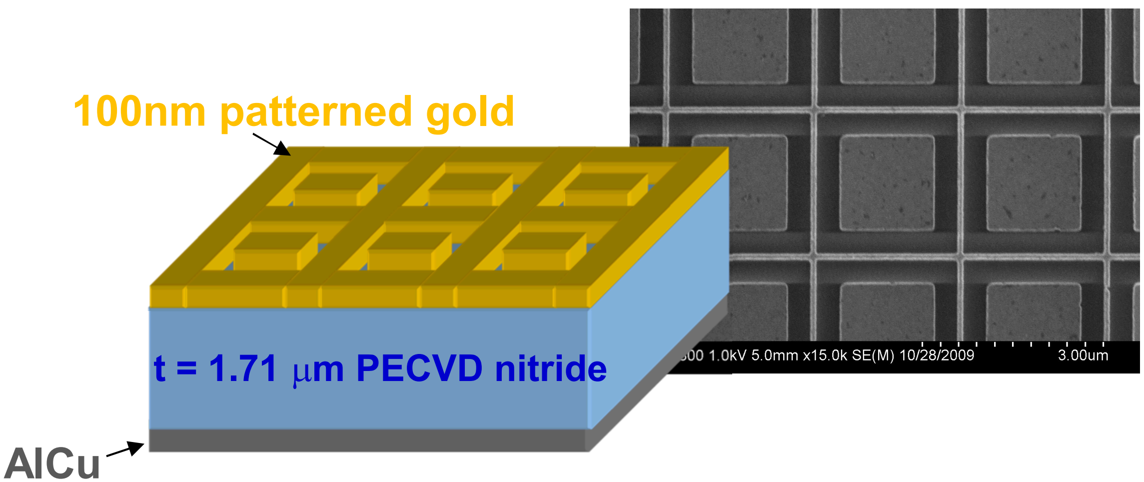
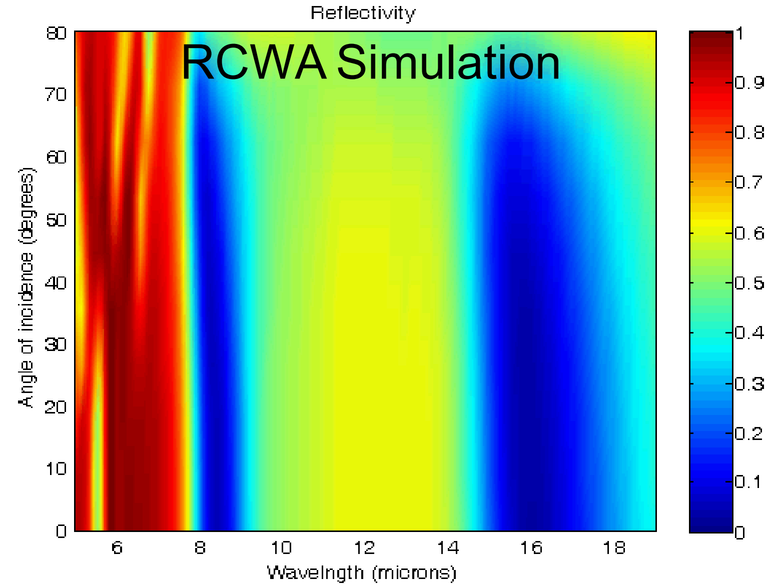
Application-Driven Use of Nanoantennas

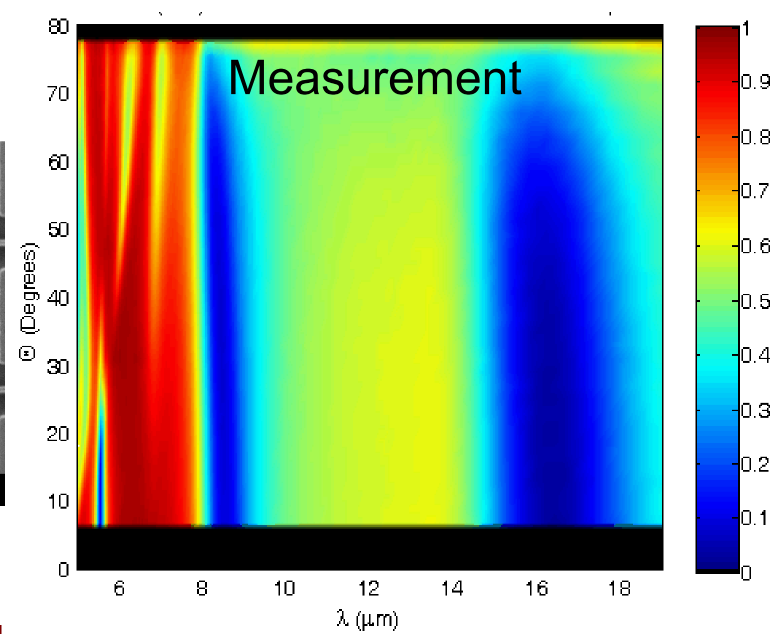
- Nanoantenna/FSS/Metamaterial/Metasurface incorporation into infrared detectors
- Intimate contact allows us to utilize the near field
- Fundamentally changes the detector architecture
  - Improved detector performance
  - New capabilities
- In this talk:
  - Description of concept
  - Modeling results
  - Preliminary measured data
  - Where we are going

Background: Plasmonics and Perfect Absorbers

- Absorption bandwidth is determined by the parameters of the nanoantenna and the materials used.
- Here we see a dual-band perfect absorber.
- Measured absorption is over 99%.
- Note some of the features:
  - No reflection in the design band without a dielectric multilayer AR coat.
  - Absorption band does not change with angle.

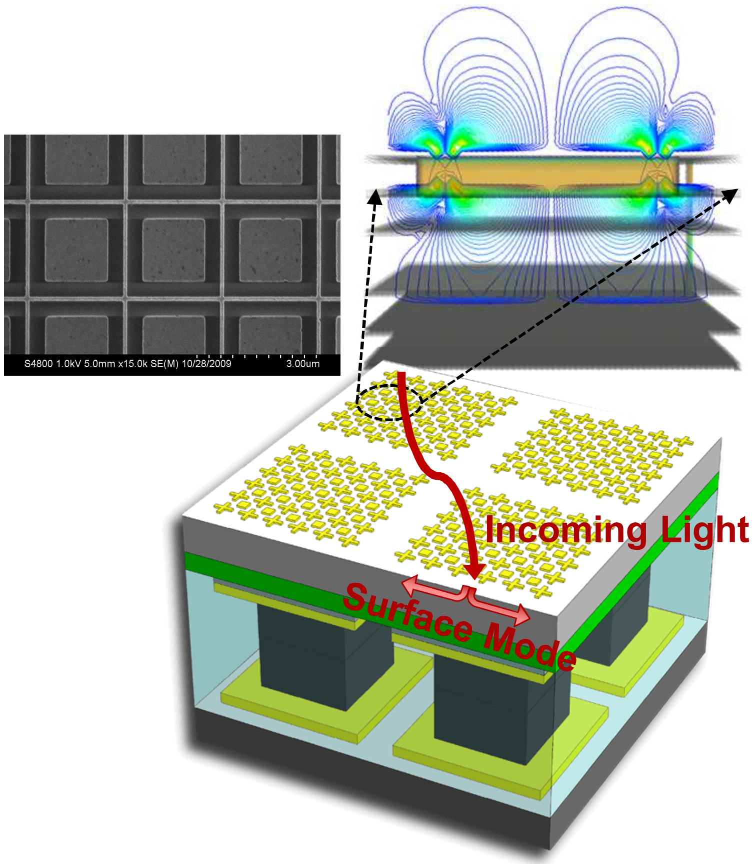






D.W.Peters, *et al.*, *Proc. of SPIE*, vol. 7609 76091C-5, 2010.

Application to an FPA Pixel



- The nanoantenna converts incoming radiation to a surface wave with energy confined to a small volume.
- The pattern may be changed from pixel-to-pixel allowing adjacent pixels to have different spectral or polarization response.
- Confinement allows us to circumvent some current detector limitations.
- Confinement also enables us to look at new detector concepts.
  - 2D Materials
  - Tunable Materials

State of the Art Infrared Detectors

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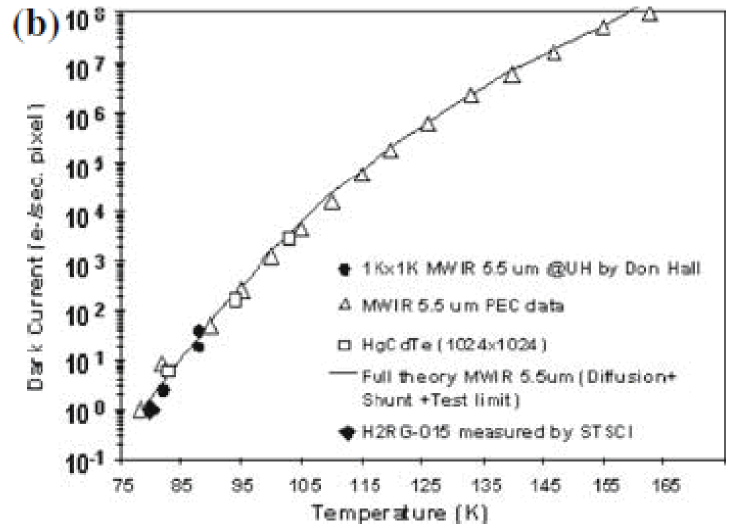
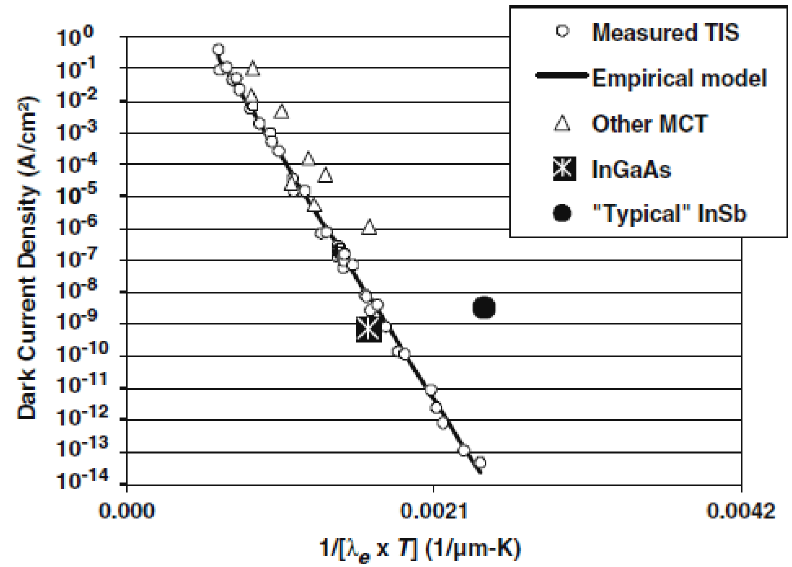
Why bother changing from the current FPA architecture?

- Current architecture has limitations
    - Cut-off wavelength determined at manufacture
    - Noise is nearing its floor for this architecture
- A nanoantenna-based architecture avoids some of the assumptions made in the Rule 07 calculation.

Changes in material composition or architecture tweaks are not going to lead to continued advancement.

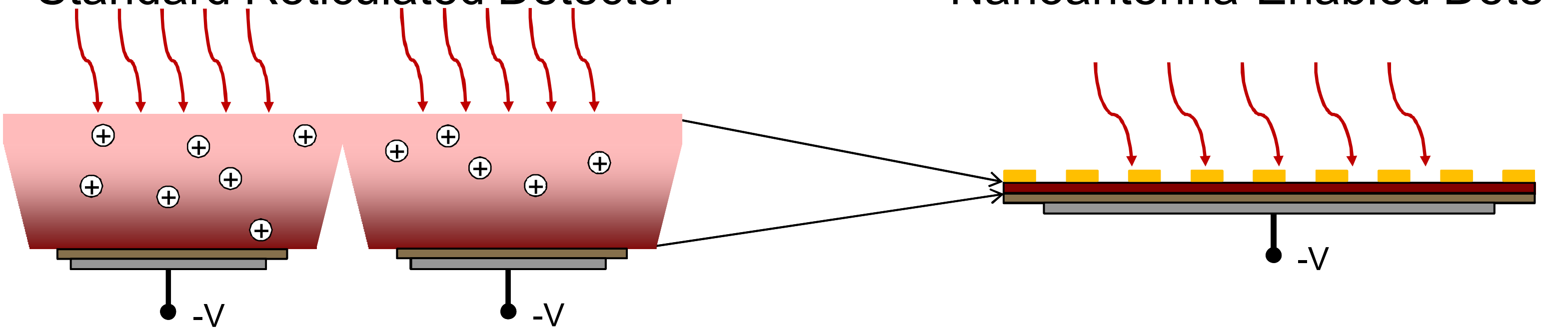




Using Confinement for Improving Detectors

Standard Reticulated Detector

Nanoantenna-Enabled Detector



Dark Current

$$\text{Dark Current } J_{Diff} = \frac{e \cdot n_i^2 \cdot t_{abs}}{N_D \cdot \tau_p}$$

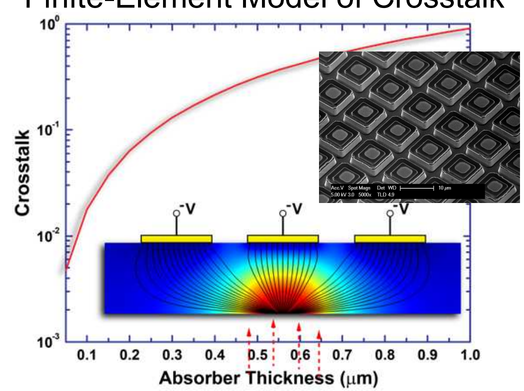
- Leads to noise.
- Is reduced by cooling the detector.
- Is proportional to the volume of active material.

Less volume of active material leads to less dark current.

Crosstalk

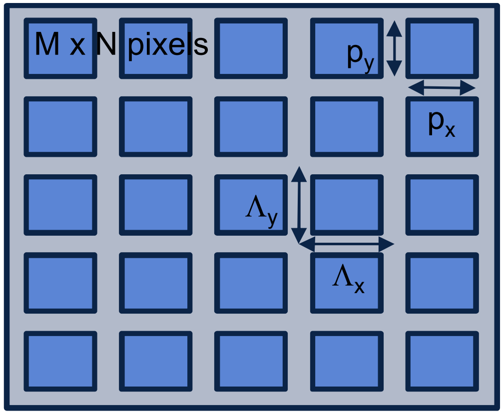
- Causes image blur and loss of resolution.
- Reticulated detectors suffer reduced fill factors.
- Etched sidewalls lead to increased surface recombination/generation.
- Exponential reduction in crosstalk with reduced absorber thickness.
- No loss of fill factor or creation of surface states with nanoantenna detector design.

Finite-Element Model of Crosstalk

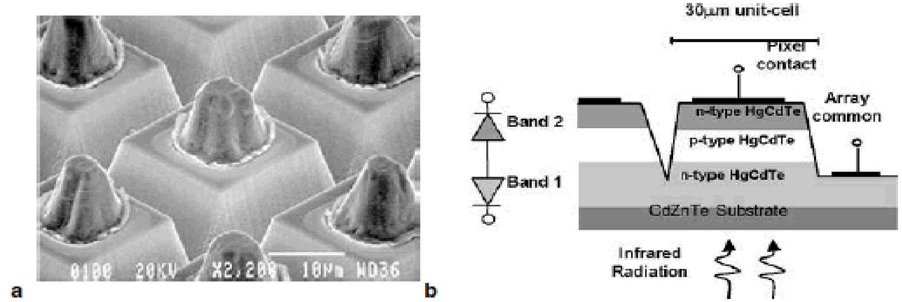


In the IR, the limitation to further reducing pixel size is crosstalk.

Maximizing Active Area Improves MTF and Signal

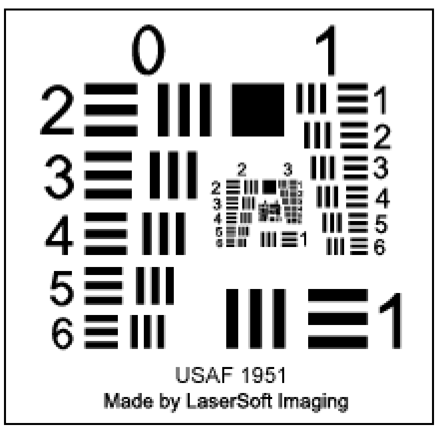


MCT FPA architecture



from E.P.G. Smith, et al, *J. of Electr. Matl.*, 2004.

$$MTF(f_x, f_y) = [\mathrm{sinc}((M\cdot\Lambda_x)\cdot f_x, (N\cdot\Lambda_y)\cdot\eta) * \mathrm{comb}(\Lambda_x\cdot f_x, \Lambda_y\cdot f_y)]\cdot \mathrm{sinc}(p_x\cdot f_x, p_y\cdot f_y)$$



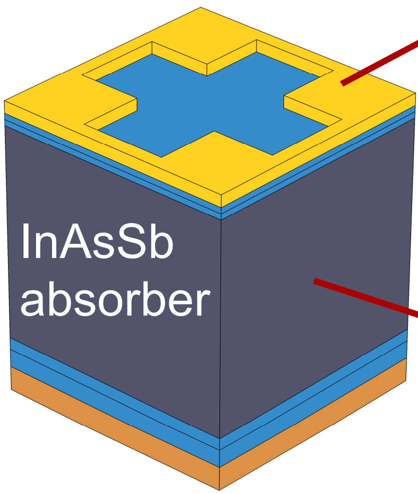
- Ideally for the MTF function, we want Λ_x, Λ_y as small as possible to maximize the MTF (small pixels = better MTF).
- This is clearly impossible, but we can make Λ_x and Λ_y as small as possible for a given p_x and p_y (100% fill factor).

Our architecture gives us near 100% fill factor

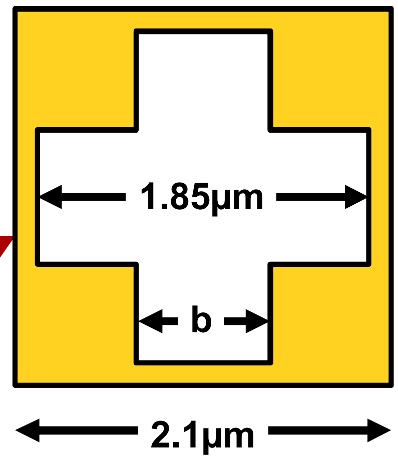
- **Maximizes input signal**
- **Maximizes the resolution**

Nanoantenna Design and Modeling

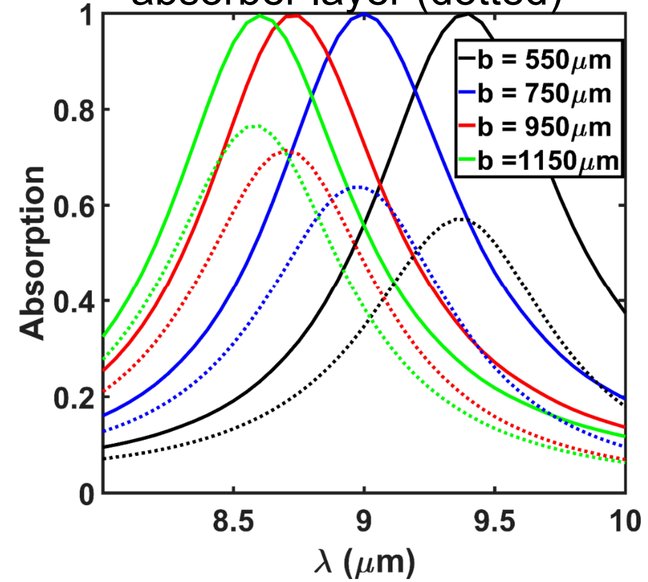
A typical NA design: this one using a crossed-dipole

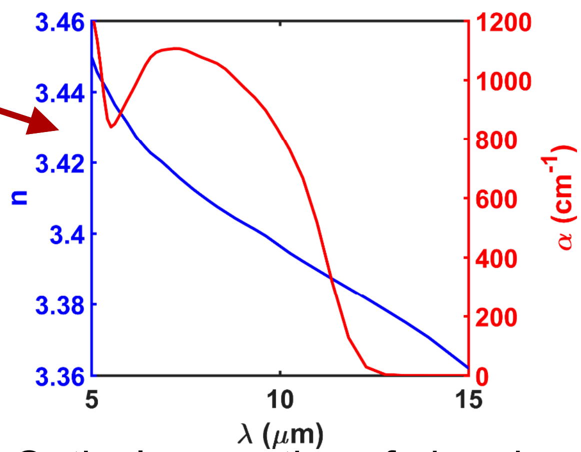


Unit Cell



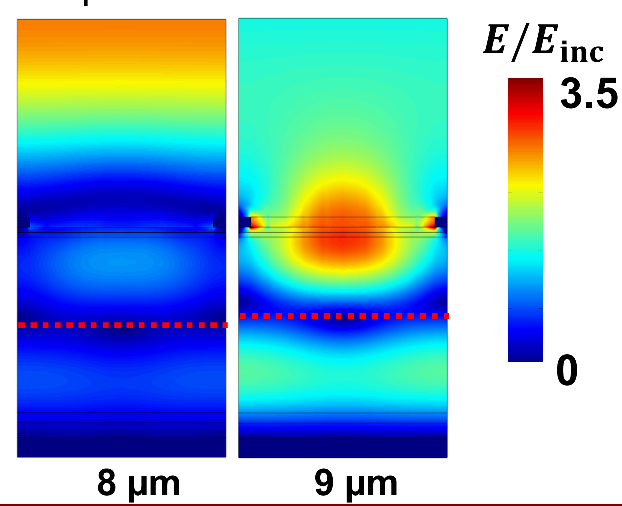
Total absorption and absorption in absorber layer (dotted)





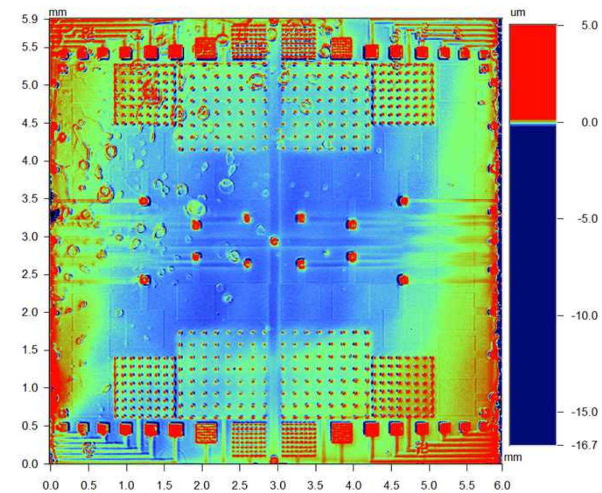
Optical properties of absorber

Field plots on and off resonance

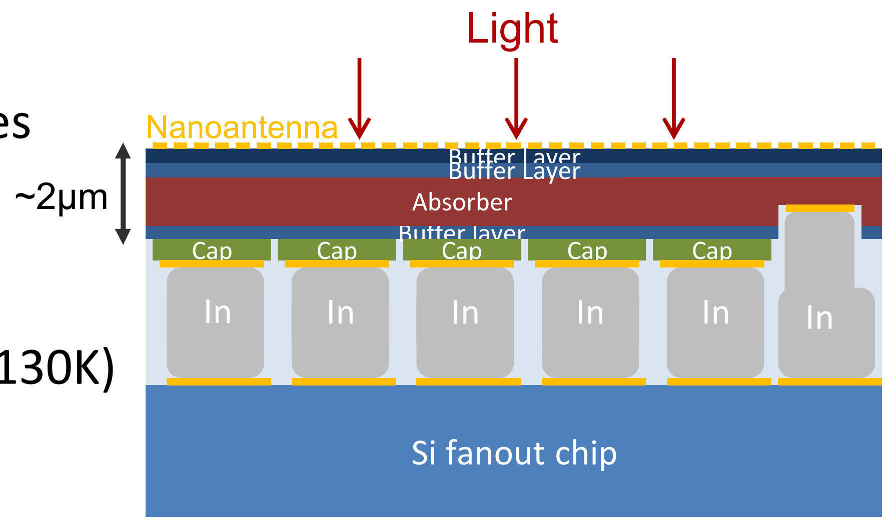


Important Integration Considerations

- Process compatibility
  - Wet chemistries might attack other materials
  - Material synthesis temperatures
  - Order of material deposition
- Integration with readouts
  - Configuration of contacts
  - CTE mismatch between materials
  - Order of integration
  - Mechanical stability of thin structures
- Operational concerns
  - Crosstalk between pixels
  - Operating temperatures will be (80-130K)
  - Accessing controls for pixels

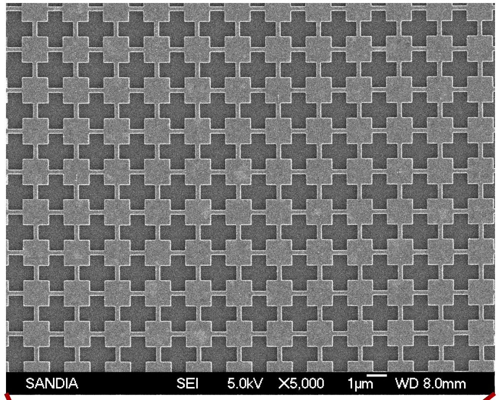


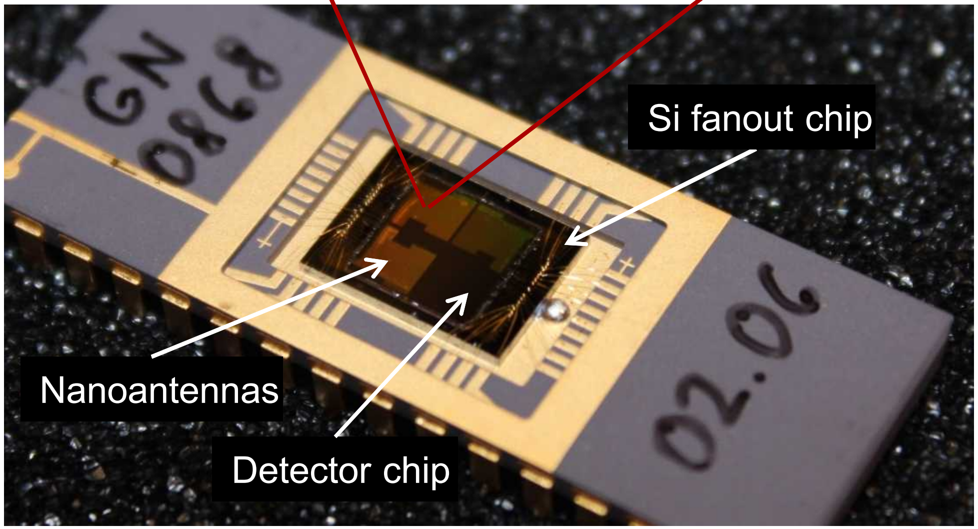
Wyco image of completed die



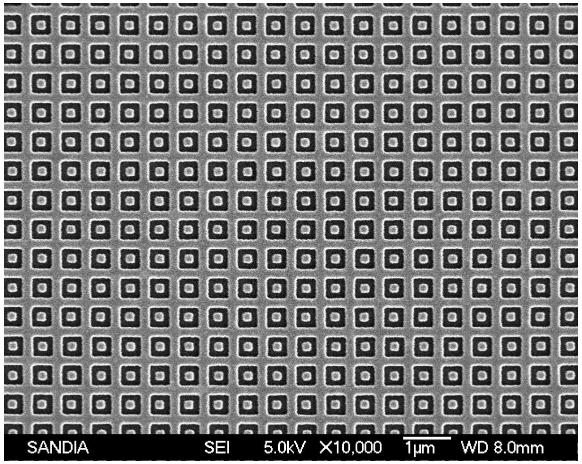
Integration to Fanout Chip

- Integrated test chips which include large area pixels and miniarrays to Si fanout chip
- Post substrate removal patterned chip with nanoantenna using ebeam lithography



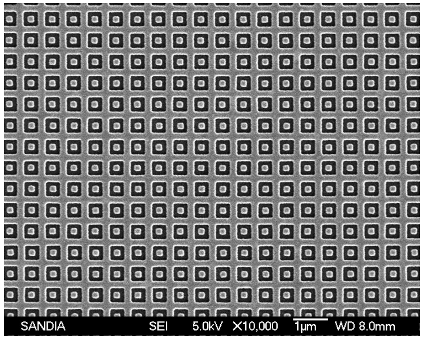


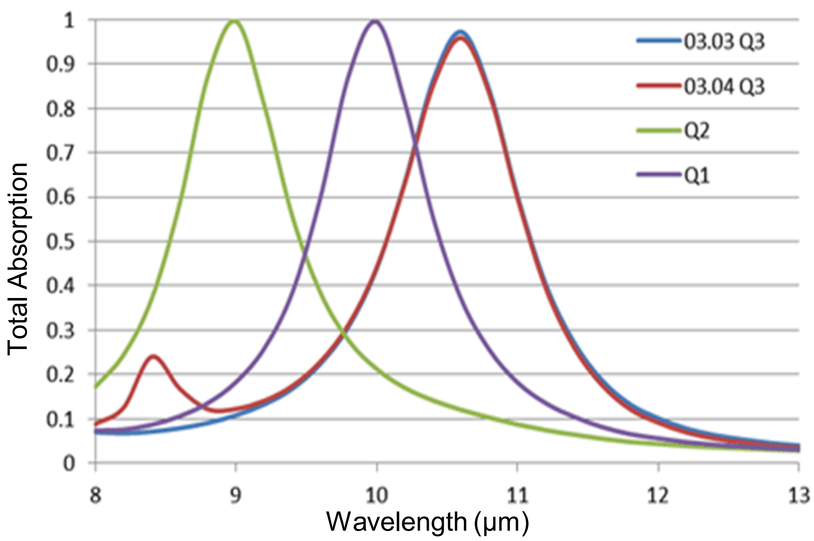
Detectors bonded to Si fanout with patterned nanoantennas

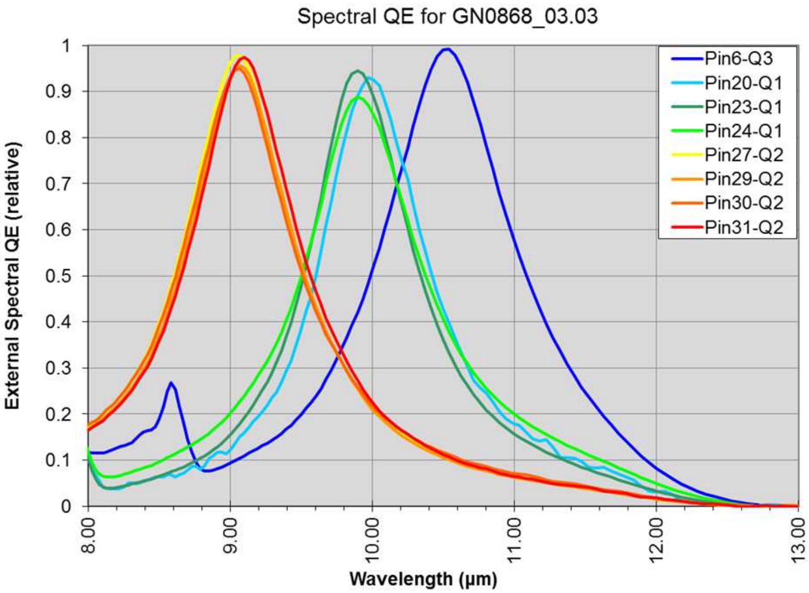


Nanoantenna-Enhanced FPA: MWIR Accomplishments

- Epitaxial growth of two designs for integration with NA for test/evaluation
- Successful fabrication of detectors with integration of NAs using a flip-chip bonding process and selective substrate removal.
- At left: RCWA simulation of total absorption.
- At right: Measurement of external quantum efficiency.







Using Confinement for Spectral Tuning

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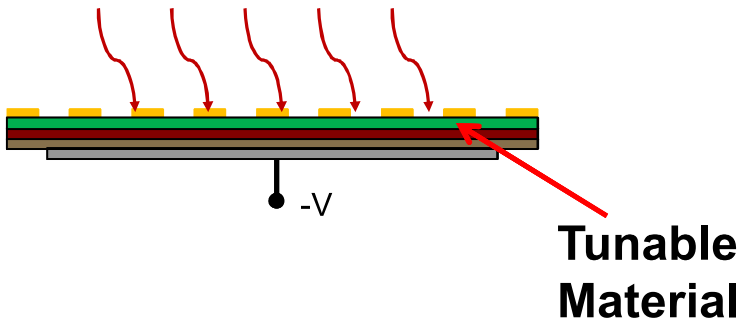
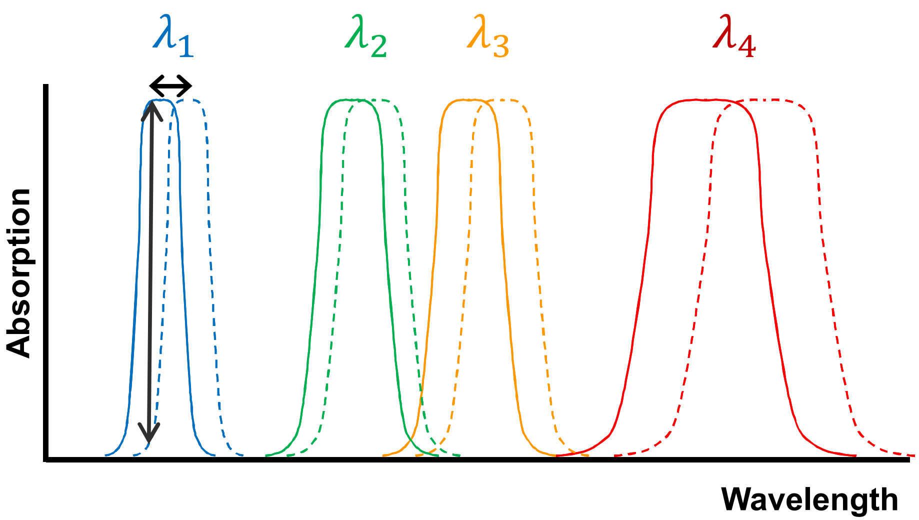
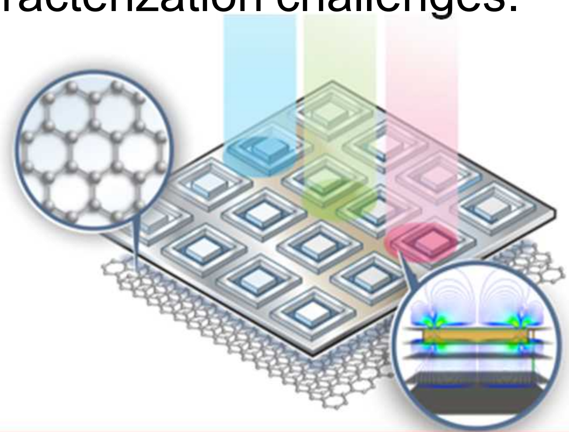
Bias-Tunable Nanoantenna Detector





<u>**Reconfigurable Smart Sensors**</u>

- Use the high-field region to magnify effect of changing material.
- Make 2D materials practical as sensors.
    - Graphene only absorbs 2.3% in a single pass.
- Voltage bias tunability allows on-the-fly changes in functionality (smart sensor).
- Materials science, integration, and characterization challenges.



Plasmonic Tuning

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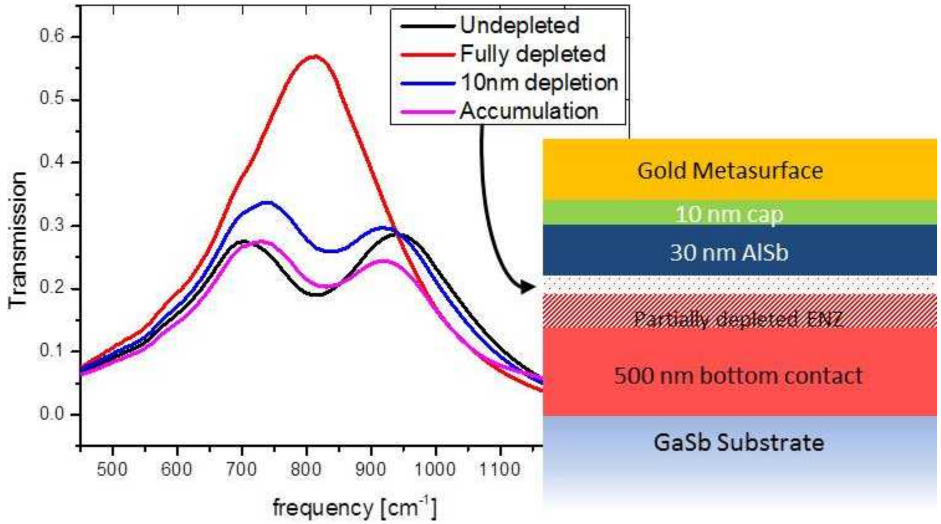
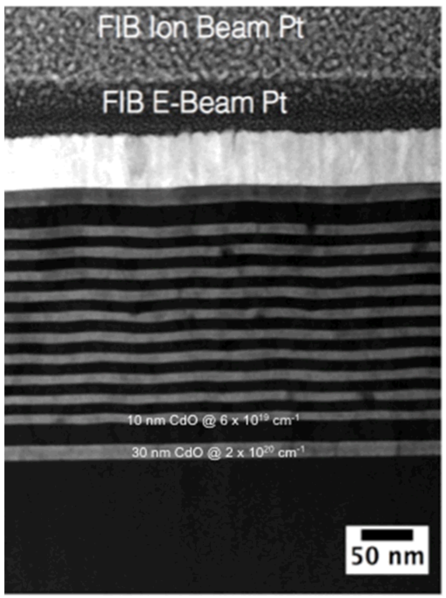
- All Sb-based semiconductor stack prepared with nanoantenna surface
- Gating results in tuning of coupled LWIR response at ~12 µm
- Current semiconductor efforts focused on gate dielectric development (HfO_2) for more efficient depletion





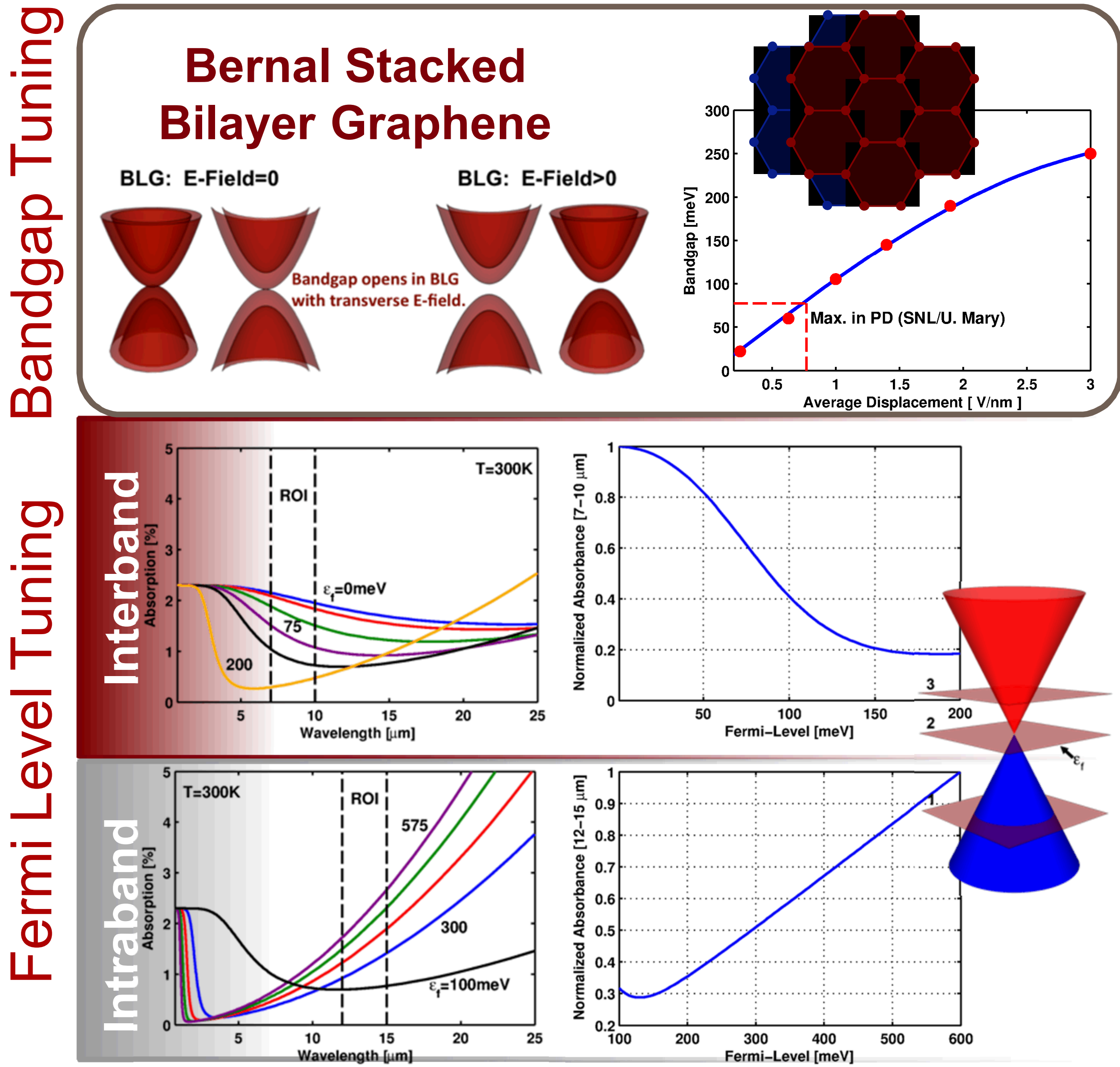
- CdO being investigated as MWIR plasmonic material
- Doping series of epitaxial films obtained from NCSU and Raman used to quantify doping and lattice distortions
- Current semiconductor efforts focused on gate dielectric development (MgO & HfO_2) and in-house CdO preparation

Graphene Spectral Tunability

Graphene has interesting electrically tunable optical properties in the infrared.

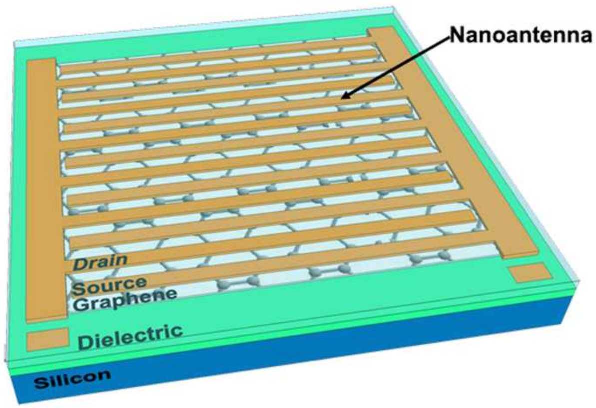
However, it is a 2D material with very low absorption.

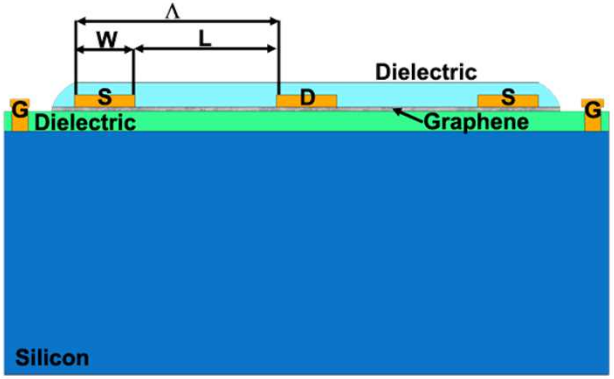
Use a nanoantenna to couple light more efficiently.



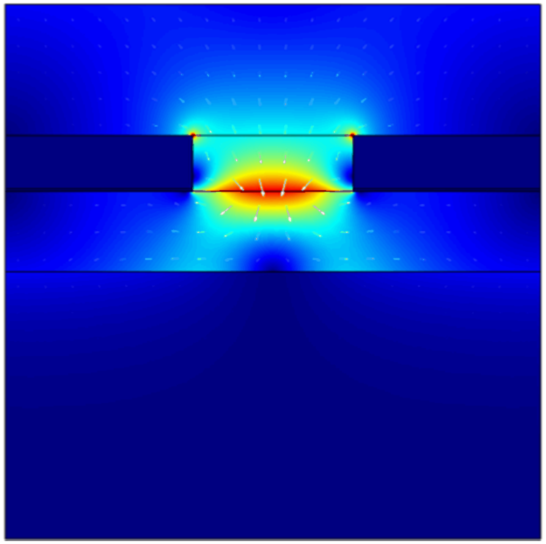
Graphene Detector

Using the top nanoantenna as both an optical coupler and as an electrical contact.



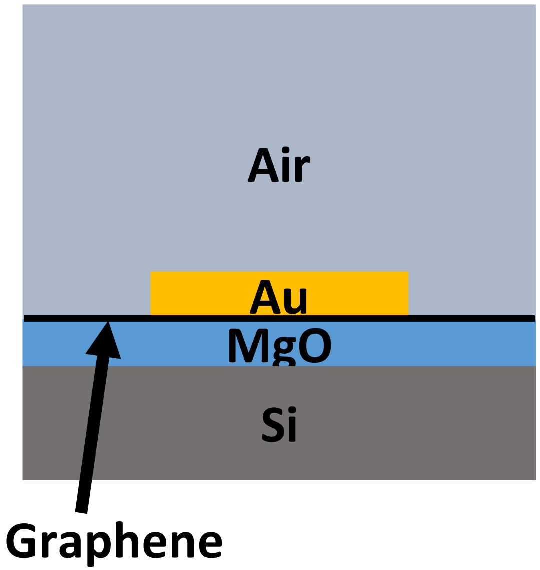


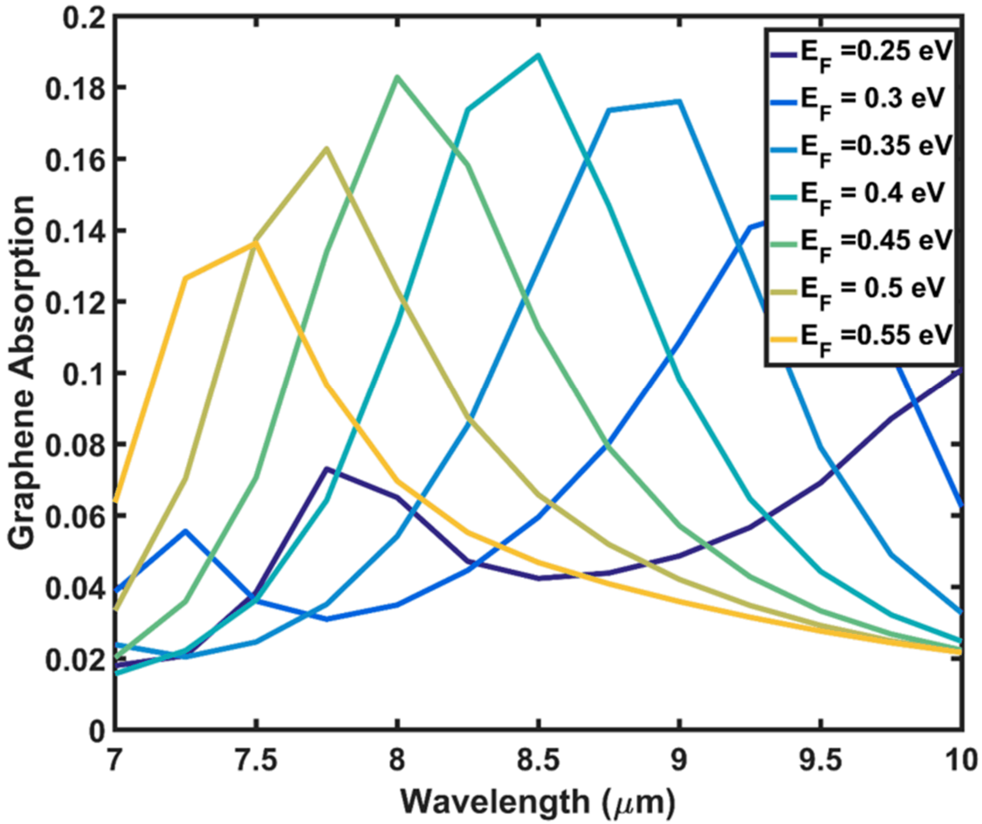
Maximize the optical field in the graphene layer.



Graphene Fermi-Level Tunability

- Tuning absorption through the thermal infrared band by tuning the Fermi level of monolayer graphene.





Summary

- Use a nanoantenna/metasurface/metamaterial to enable advances in performance and allow new capabilities such as tunability.
- Reduced dark current and increased QE in LWIR detectors.
- Options to bring spectral tunability to FPAs.
- Ability to use new detector materials such as graphene.