Exceptional service in the national interest

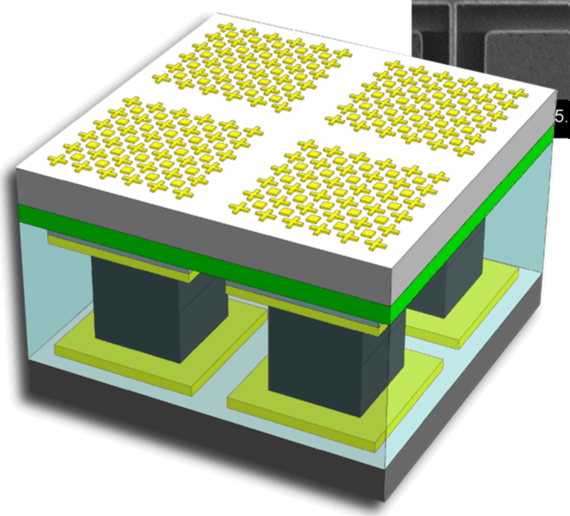
SAND2016-2291C

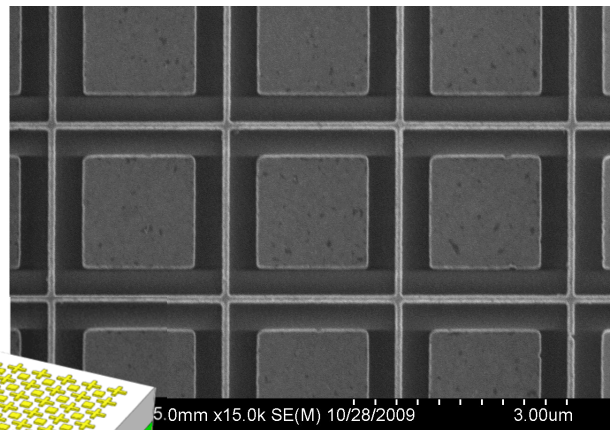
Sandia National Laboratories

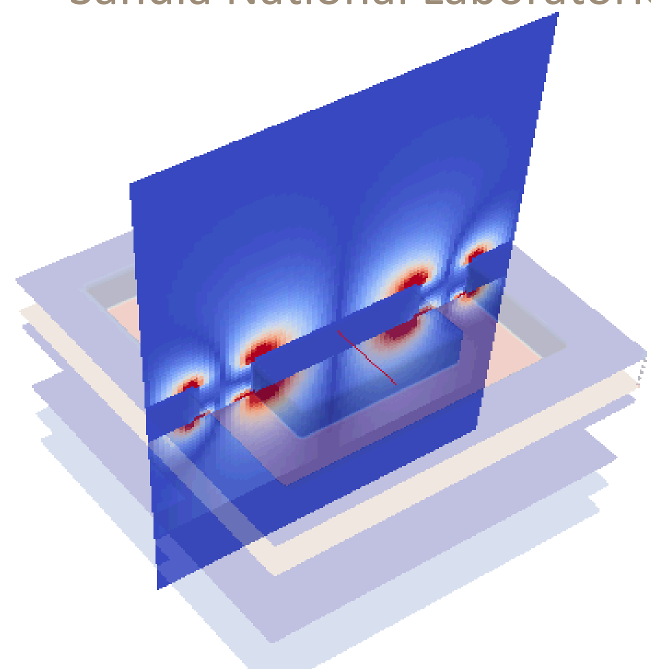
Field confinement using metasurfaces for increased-efficiency III-V infrared detectors

Jin Kim and David Peters

Sandia National Laboratories







U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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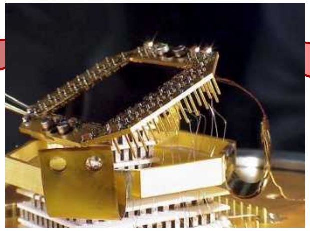
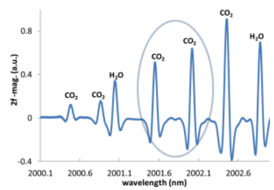
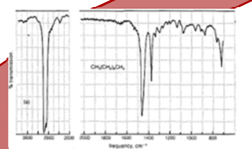
The Steps of Sensing

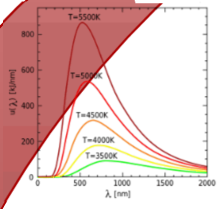
Sense It



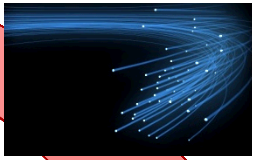
Understand Phenomenology

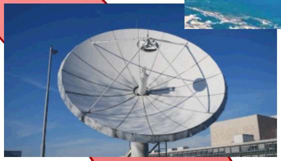


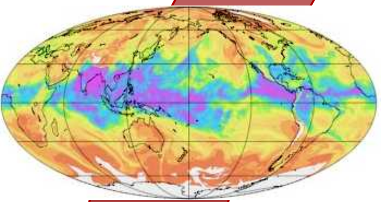


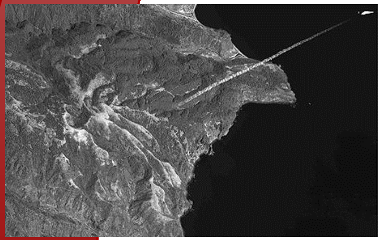


Control, Pre-process and Transmit the Data



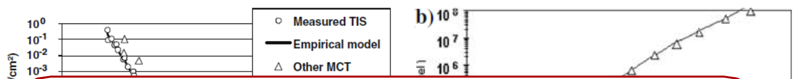






Limits in current technology

- Cut-off wavelength determined at manufacture
- Noise is nearing its floor for this architecture



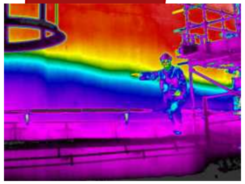
To achieve a radically improved sensor we <u>must</u> look at both new materials and architectures.

Understand the Data

Changes in material composition or architecture tweaks are not going to lead to radical improvement.

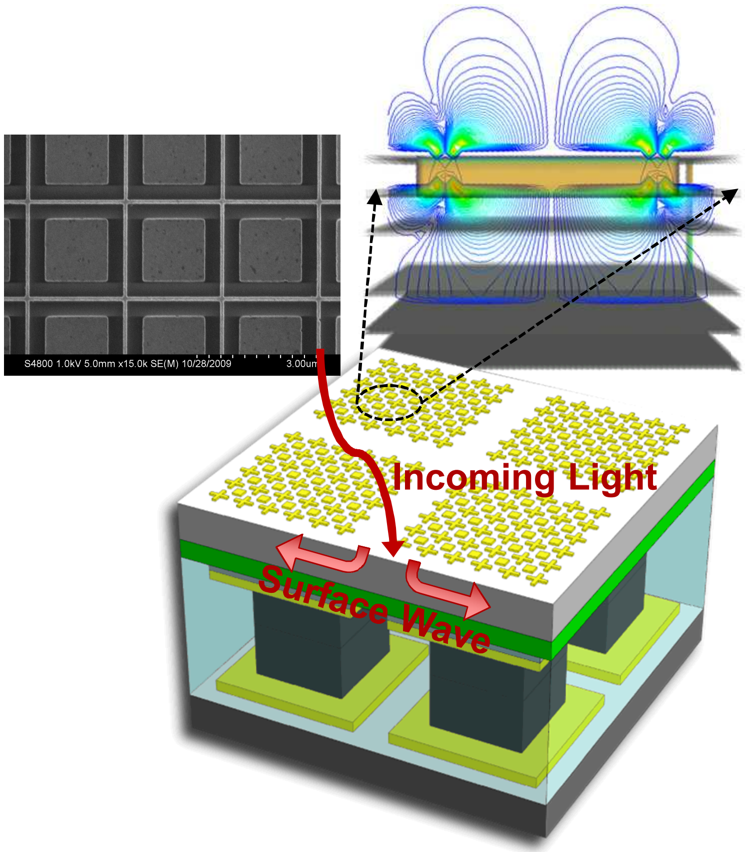
Take Action

Event Occurs



The Enabling Technology: Nanoantennas

What is a nanoantenna?



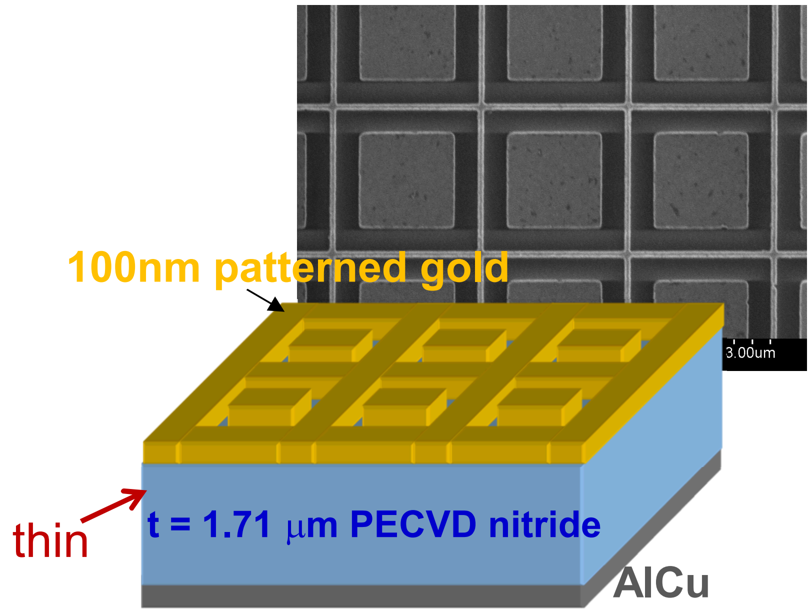
- A subwavelength patterning of metal or high-index dielectric
- The nanoantenna converts incoming radiation to a surface wave with energy confined to a small volume
- The pattern may be changed from pixel-to-pixel allowing adjacent pixels to have different spectral or polarization response
- Built-in A/R "coating"
- Angular insensitivity

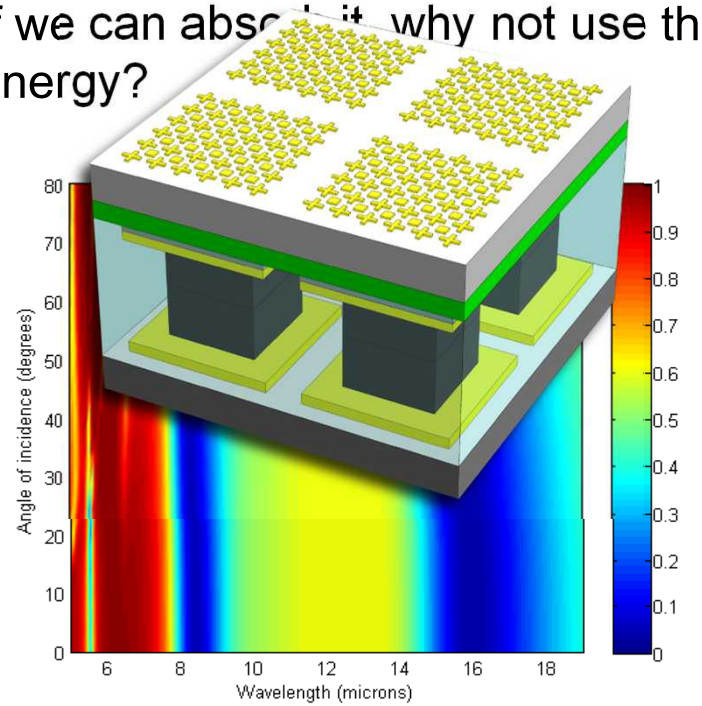
Outline

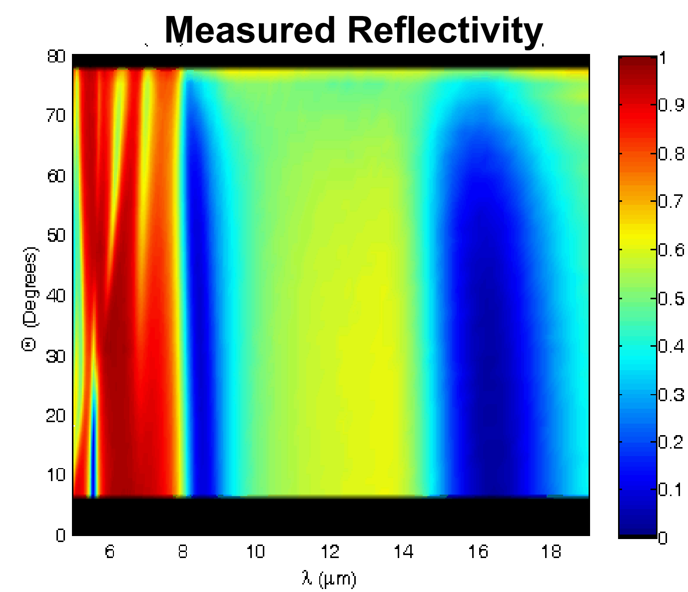
- Background
  - Perfect absorbers
  - Field confinement
- nBn Material
  - Material choices
  - Changes that thin absorber layer allows
- Nanoantenna Development
  - Finite size of pixels
  - Where absorption occurs
- Integration Challenges

Background: Perfect Absorbers

- We designed and made a dual-band perfect absorber.
- Excellent agreement between simulation and measurement. → Great confidence in our models.
- Measured absorption of 99% in two bands.
- A resonant structure.
- If we can abs[illegible] it, why not use that energy?

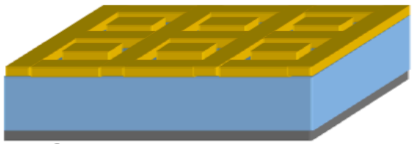






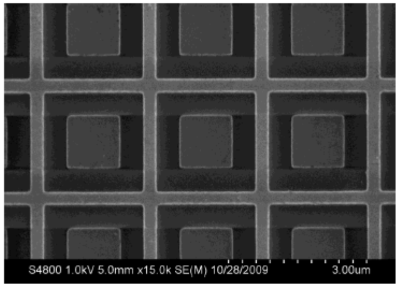
Early Perfect Absorber Work: SiO_2

Patterned Metal

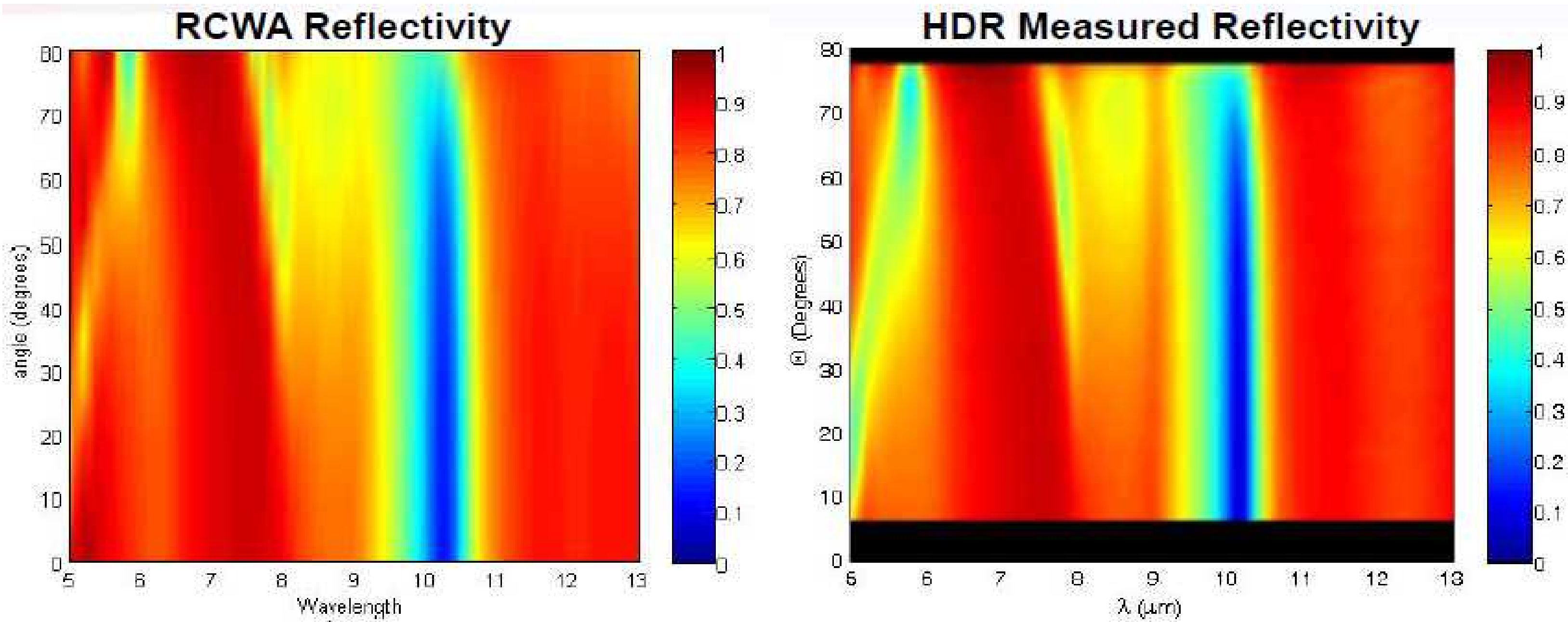


Ground plane

These type nanoantennas consisting of a
patterned metal layer
semiconductor/dielectric
metal backplane
are inherently angle insensitive.



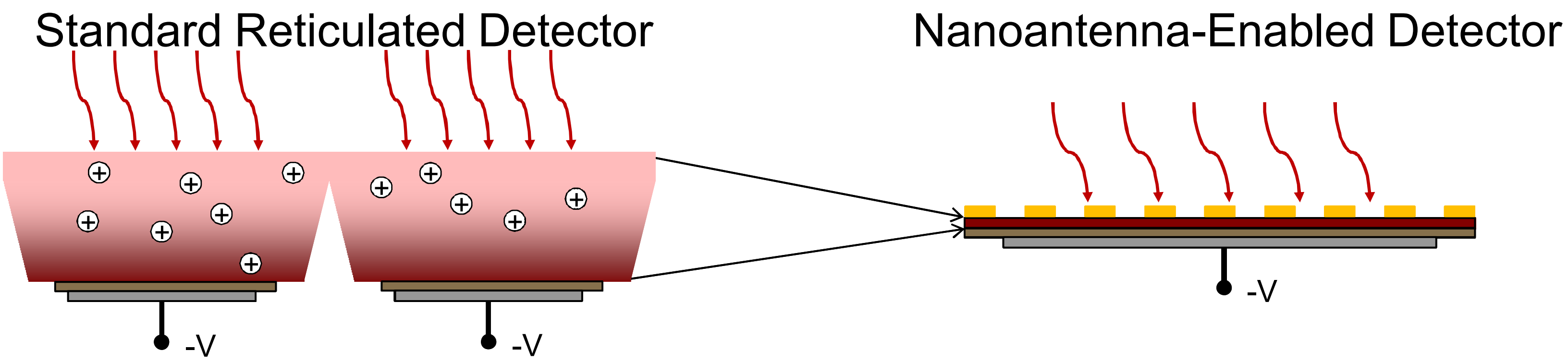
SiO_2



D. W. Peters, G. R. Hadley, A. A. Cruz-Cabrera, L. I. Basilio, J. R. Wendt, S. A. Kemme, T. R. Carter, S. Samora, “Infrared Frequency Selective Surfaces for sensor applications,” Proc. of SPIE, vol. 7298, 7298 3L, Apr. 2009.

D.W. Peters, P. Davids, J.R. Wendt, A.A. Cruz-Cabrera, S.A. Kemme, S. Samora, “Metamaterial-inspired high-absorption surfaces for thermal infrared applications,” Proc. of SPIE, vol. 7609, 2010.

Using Confinement for Improving Detectors



Dark Current

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

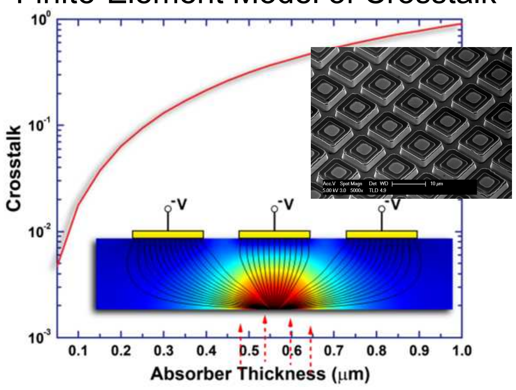
- Leads to noise.
- Is reduced by cooling the detector.
- Is proportional to the volume of active material.

Less volume of active material leads to less dark current.

Crosstalk

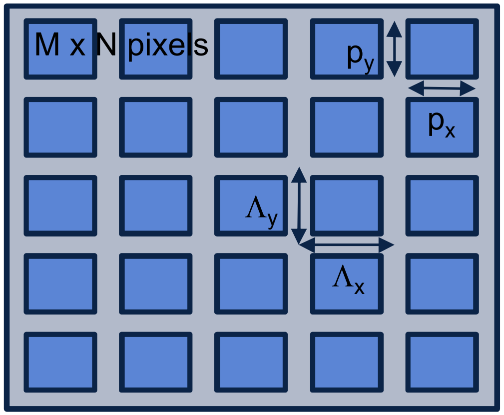
- Causes image blur and loss of resolution.
- Reticulated detectors suffer reduced fill factors.
- Etched sidewalls lead to increased surface recombination/generation.
- Exponential reduction in crosstalk with reduced absorber thickness.
- No loss of fill factor or creation of surface states with nanoantenna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

Finite-Element Model of Crosstalk

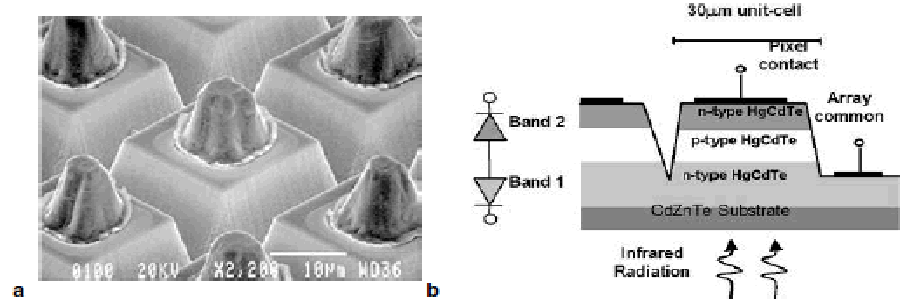


In the IR, the limitation to further reducing pixel size is crosstalk.

Maximizing Active Area Improves MTF and Signal

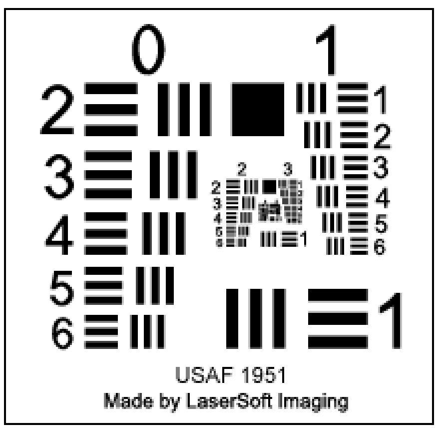


MCT FPA architecture



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).

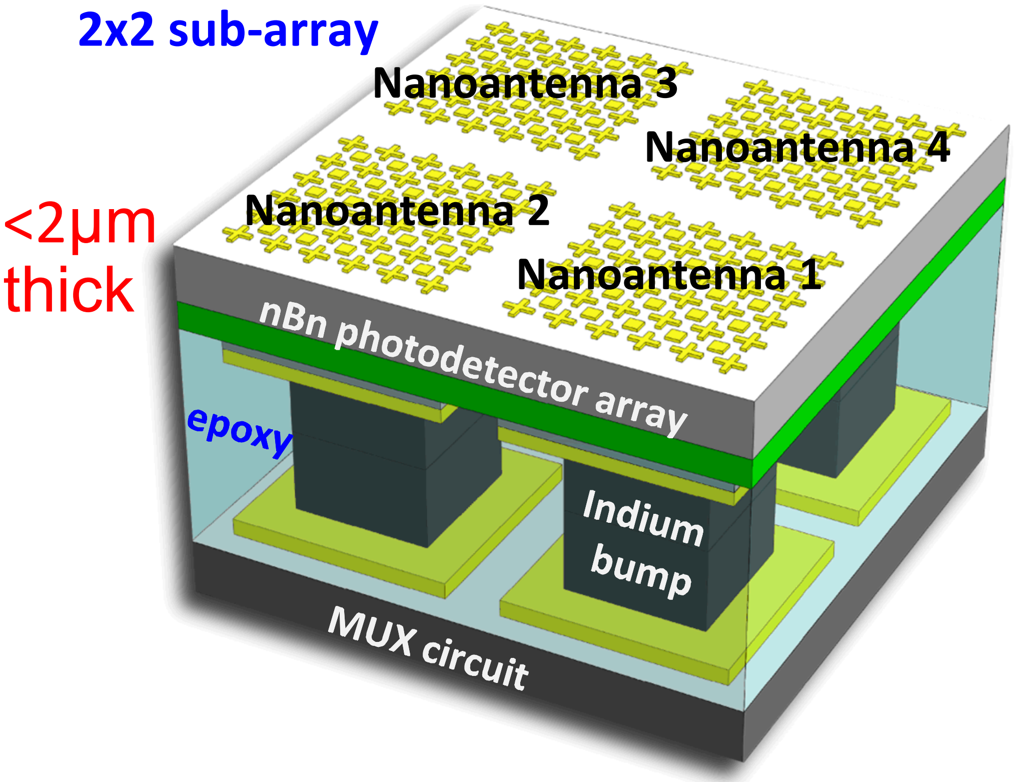
Our architecture gives us near 100% fill factor

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

Our Current Efforts

Demonstrate Plasmonic Field Concentration

- Develop methods to accurately tune resonance
- Achieve high responsivity (QE > 70%): a joint modeling and fabrication effort.



Achieve Dark Current Reduction

- Minimize absorber volume
- Suppress interface parasitics

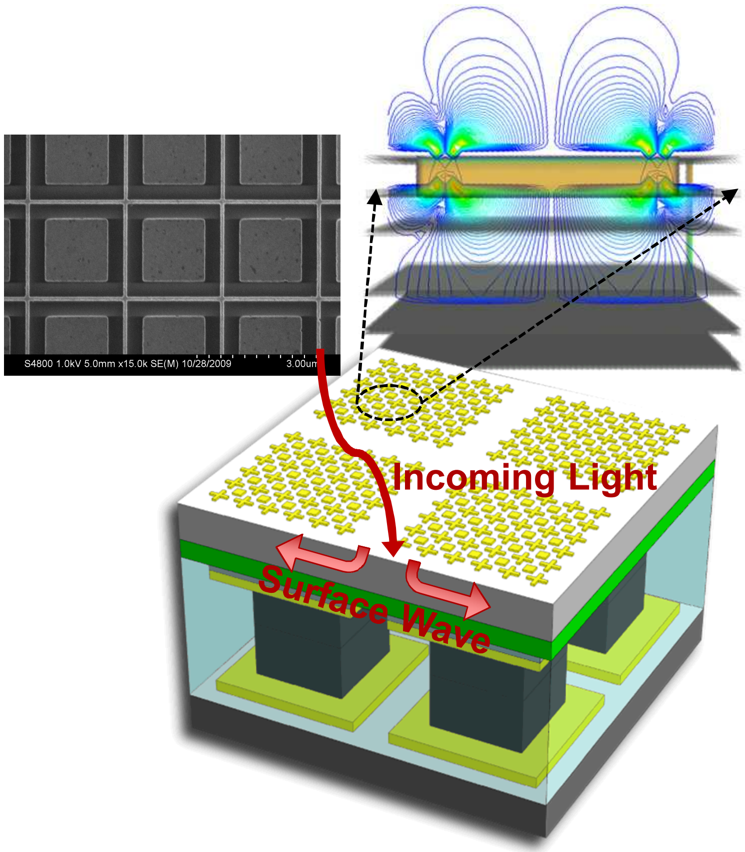
Develop Integration Methods

- Maintain surface flatness
- Ensure uniform lithography
- Manage material stress

Demonstrate Plasmonic Field Concentration

Enabling Technology: Nanoantenna (NA)

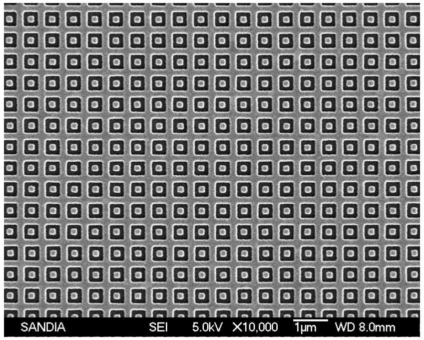
What is a nanoantenna?

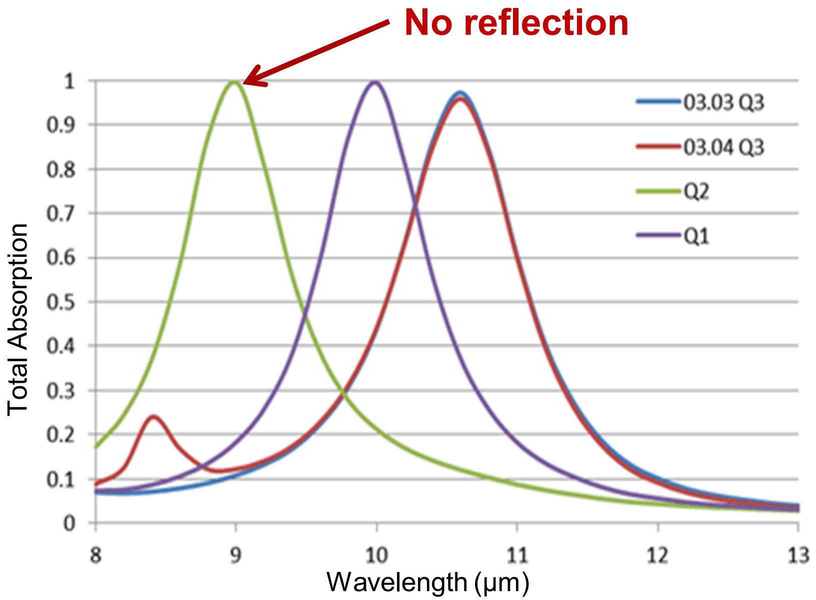


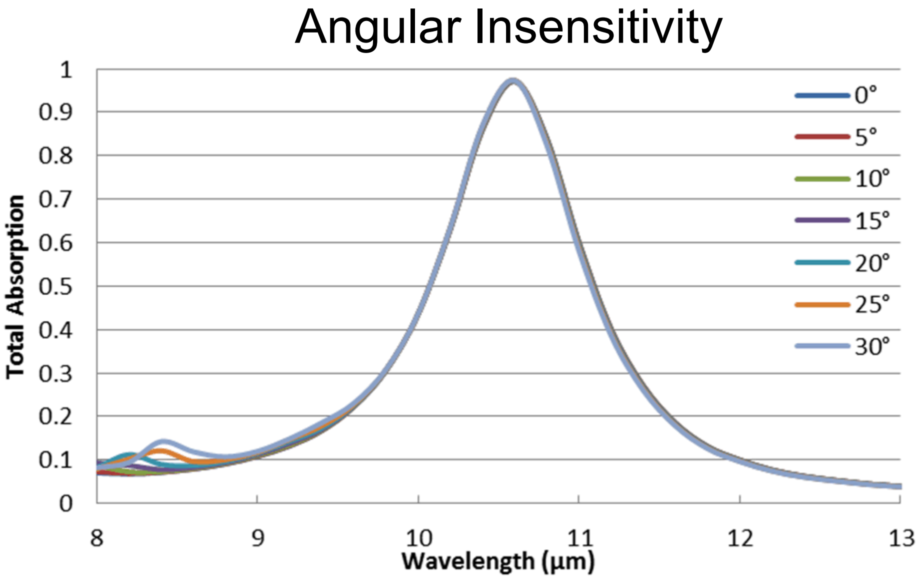
- A <u>subwavelength</u> patterning of metal or high-index dielectric
- The nanoantenna converts incoming radiation to a surface wave with energy confined to a <u>small volume</u>
- The pattern may be changed from pixel-to-pixel allowing adjacent pixels to have <u>different</u> spectral or polarization response
- Built-in A/R "coating"
- Angular insensitivity
- A foundation for tunability

Nanoantenna Optical Properties

- The nanoantenna couples the incoming light to a surface wave with no reflection at the design wavelength.
  - Achieved with a single patterned metal layer.
  - No AR dielectric stack required
- The AR effect does not change with angle as it would with a dielectric AR coat.
- Polarization independence over angular range of interest.

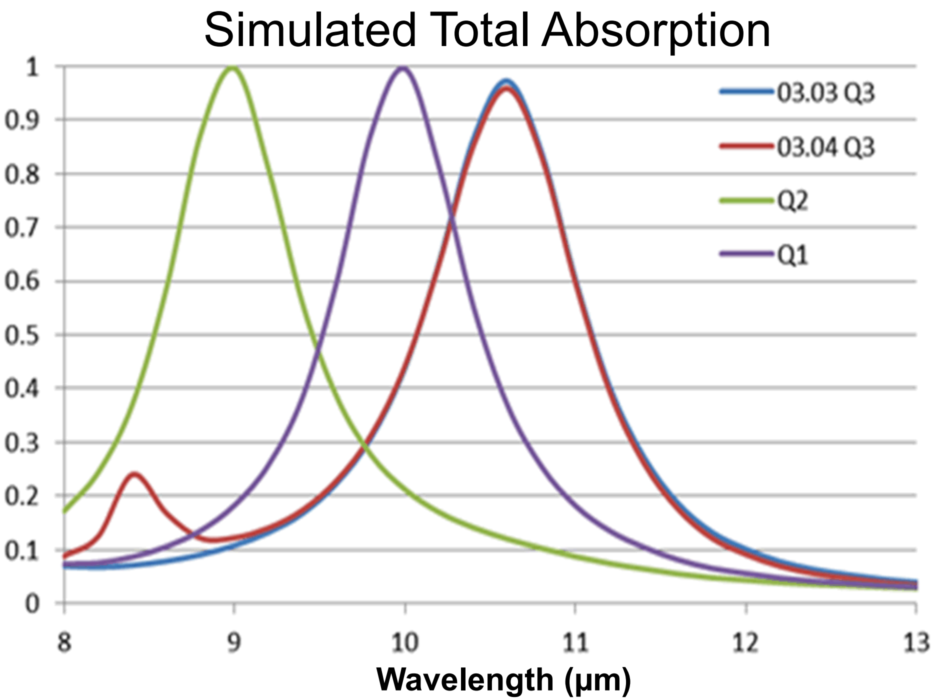


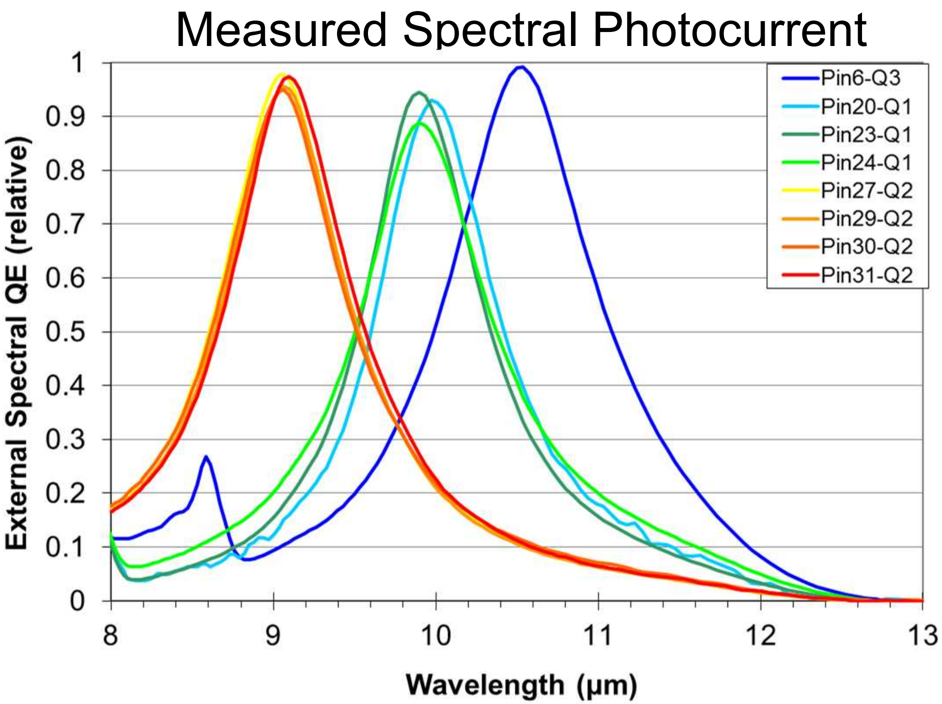




Develop Numerical Model for Tuning NA

- Early work has confirmed good agreement
- Refine nanoantenna model for QE optimization
- Determine relevant material properties

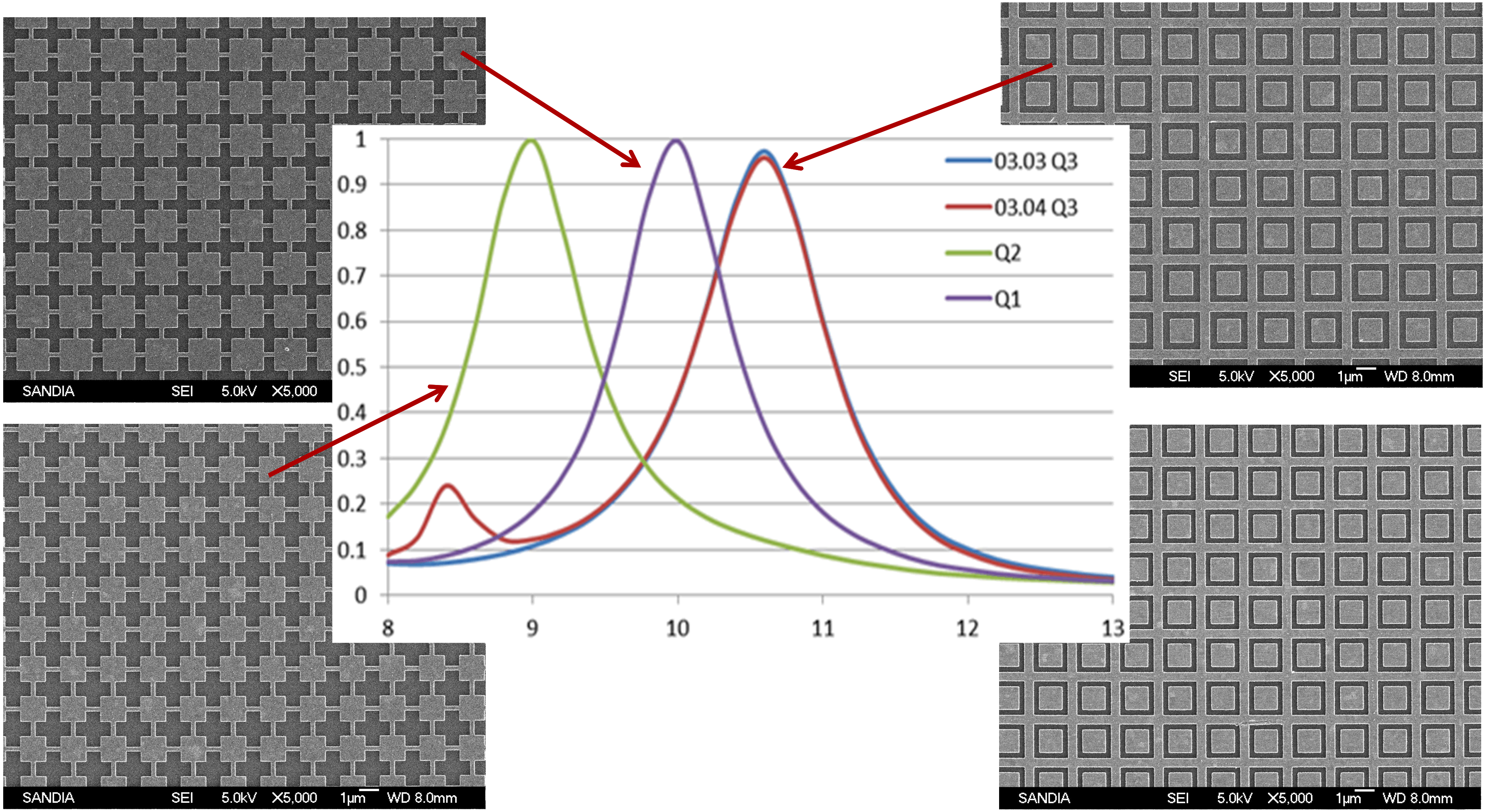




- Calibrated QE is being measured

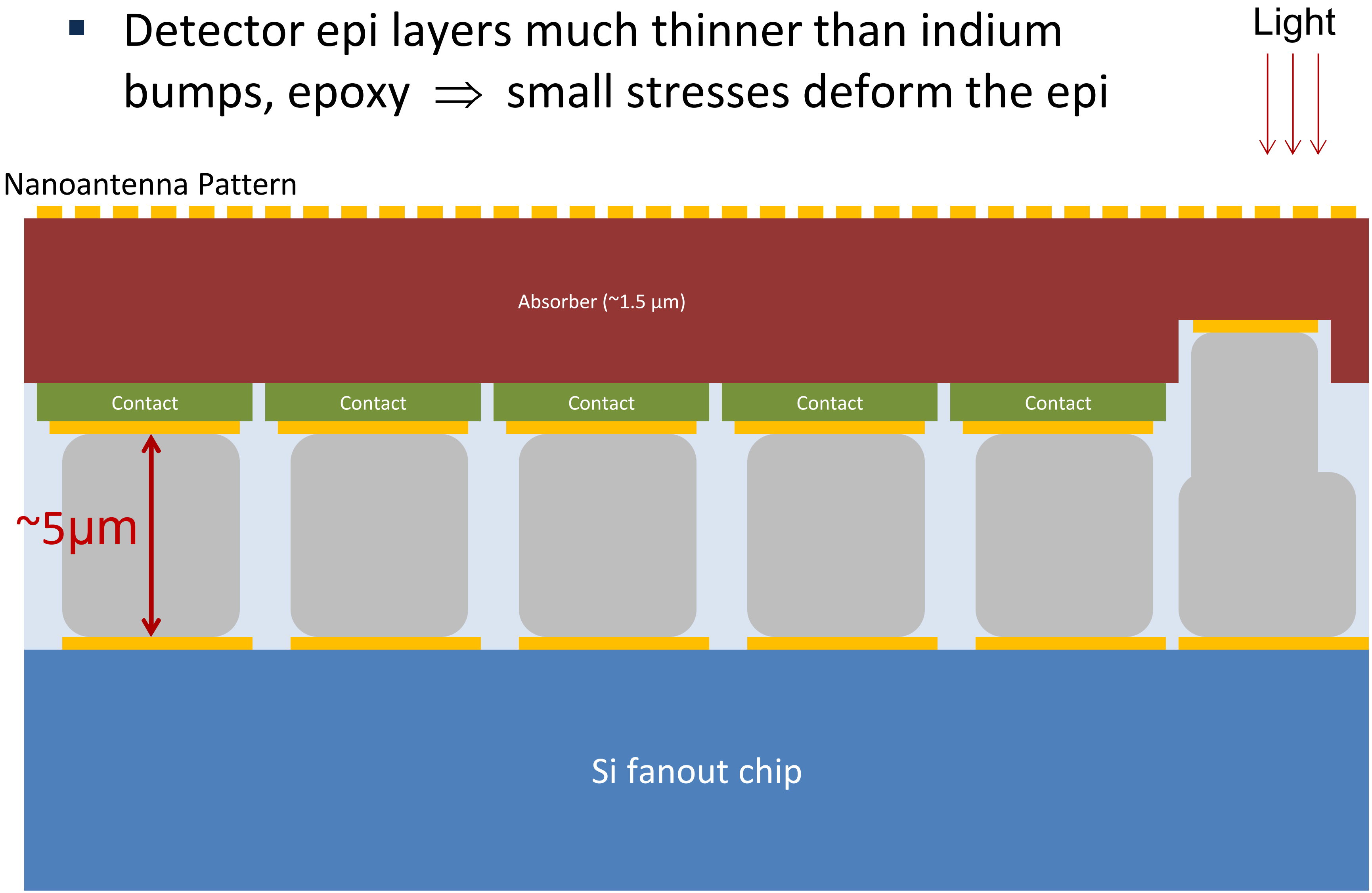
Challenges in the Replication of Design

- Gap feature size difficult to replicate (pitch is accurate)
- Surface flatness difficult to ensure



Challenges in Ensuring Surface Flatness

- Detector epi layers much thinner than indium bumps, epoxy $\Rightarrow$ small stresses deform the epi

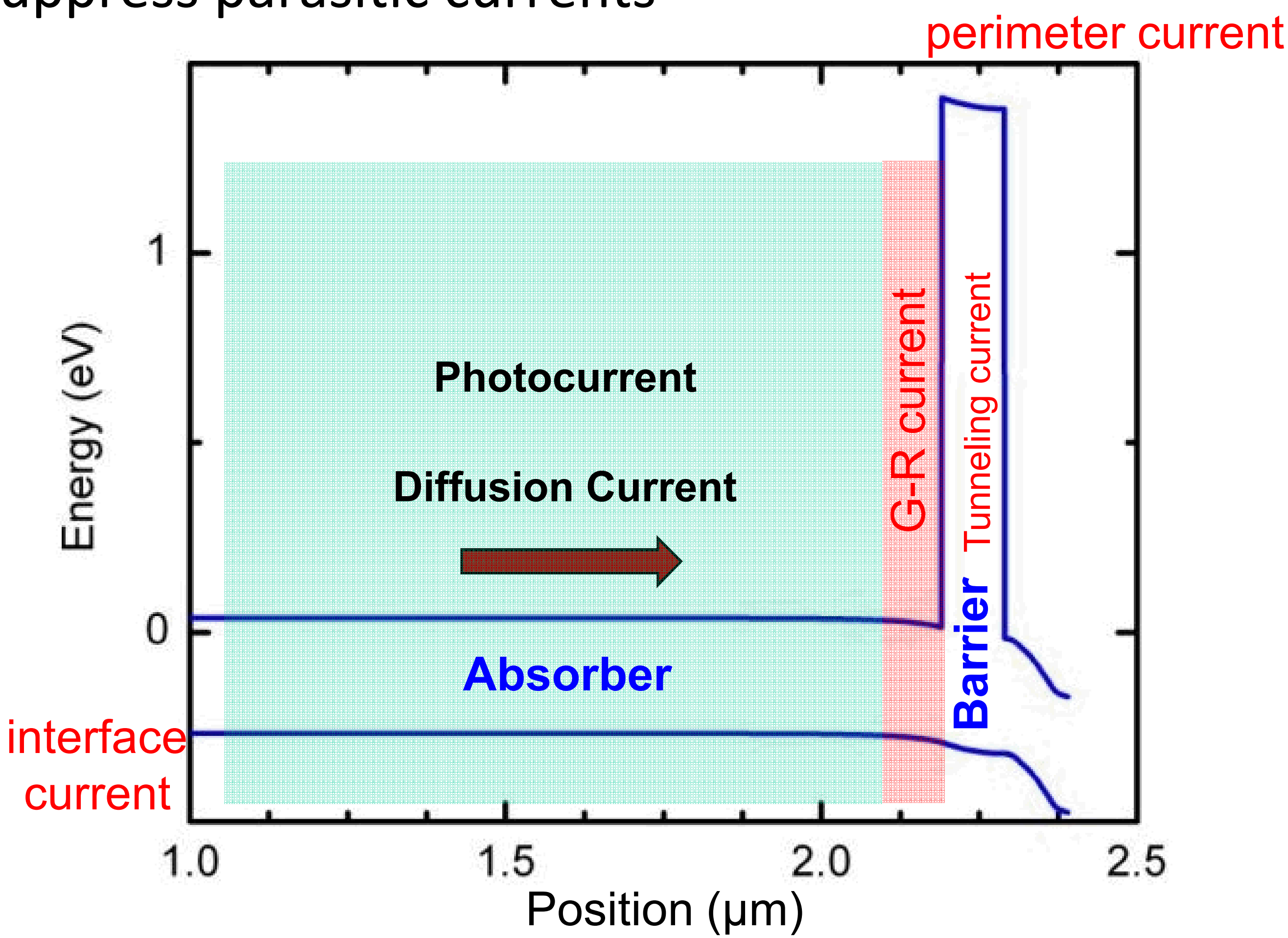


Achieve Dark Current Reduction

Achieve Dark Current Reduction

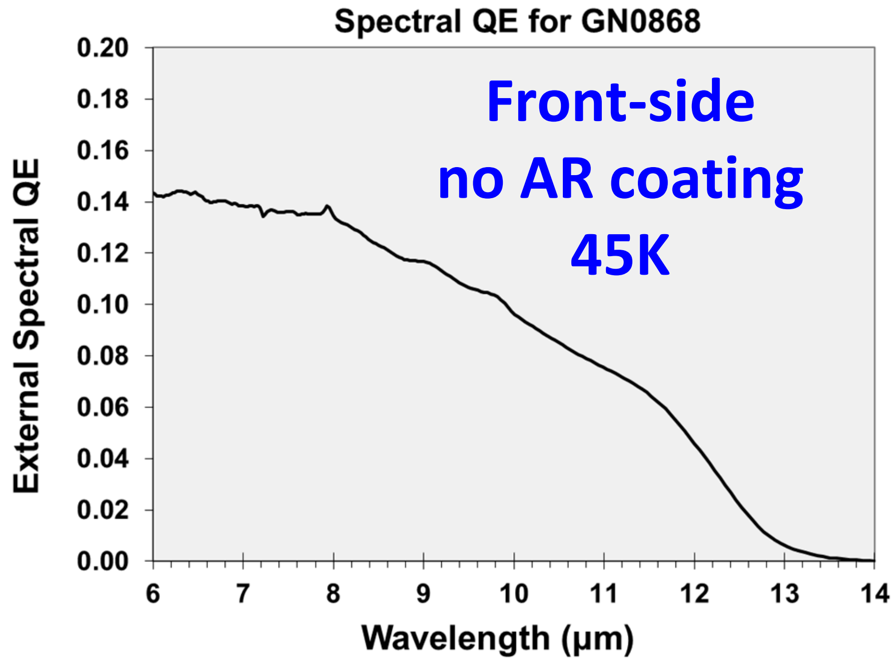
- Based on nBn device architecture
- Minimize absorber volume
- Suppress parasitic currents

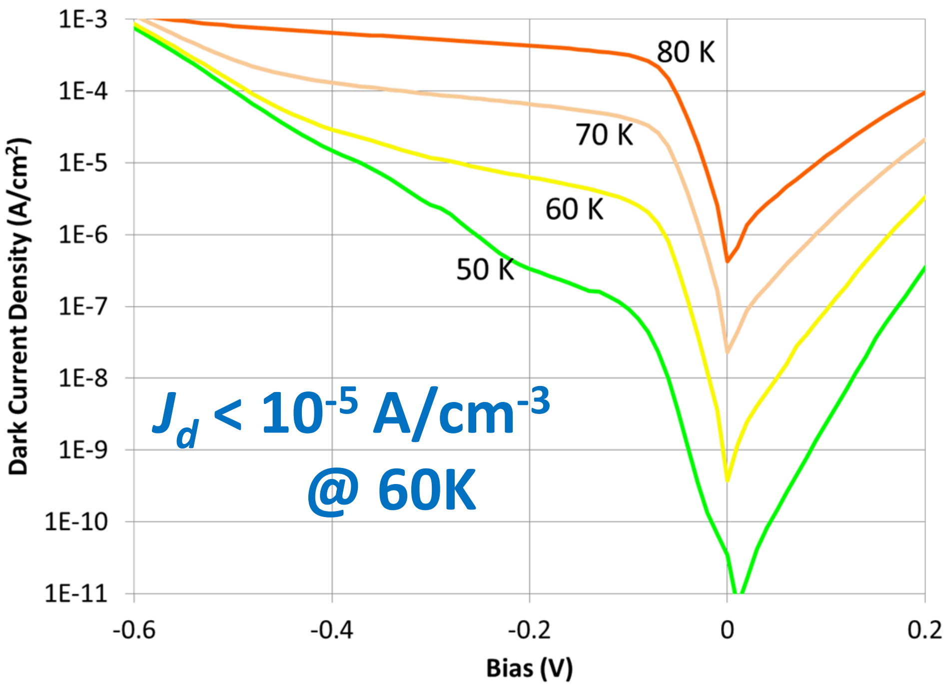
$$J_{Diff} = q\, n_i^2\, W_{Abs}/N_D\, \tau$$



Limitations of Conventional (V)LWIR nBn

- MWIR nBn FPAs very successful
- I_{dark} & QE approaching HgCdTe
- Compatible w/ tuning methods





- High m^*_{hh} limits diffusion length
- QE suffers, especially for VLWIR
- Absorber doping exacerbates the problem
- Very difficult problem to solve

Features of NA-nBn FPA

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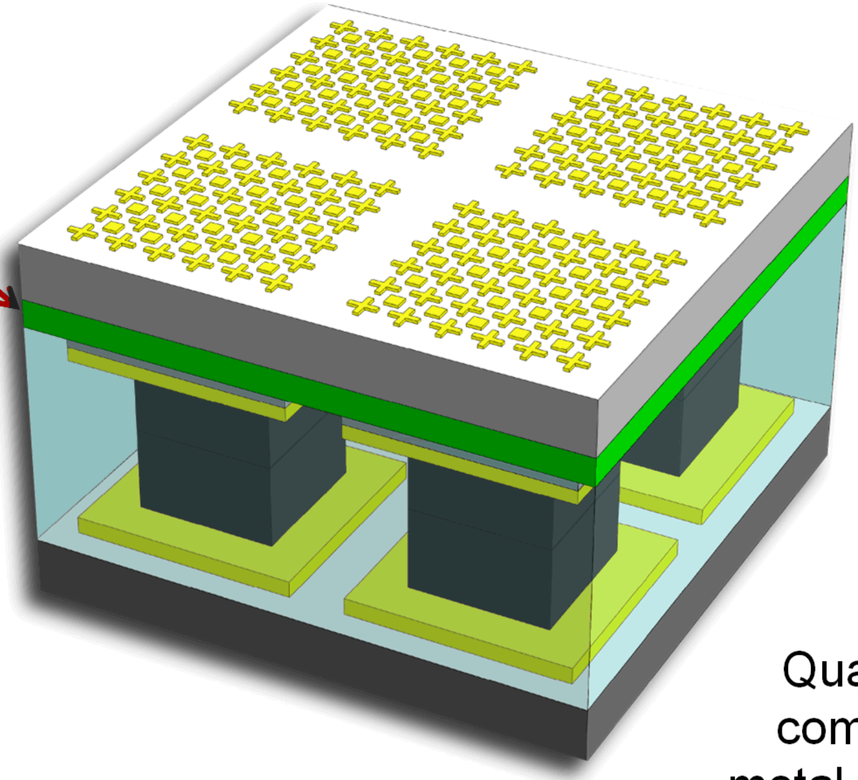
Built-in “AR coating”

Angular insensitivity

Control perimeter current by leaving Barrier intact

Thin absorber ensures high MTF (low crosstalk)

Field concentration ensures high QE

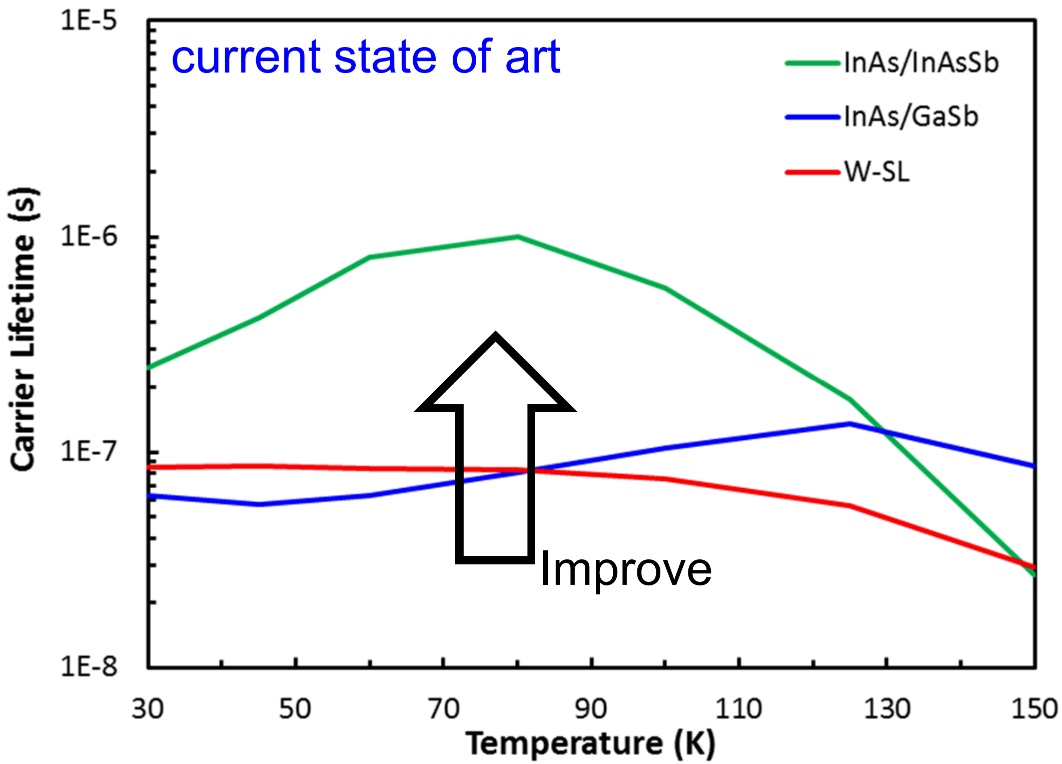


Quantum Efficiency: competition between metal and semiconductor absorption ⇒ Absorbers with stronger absorption desired

Absorber Material Choices

- W-SL: high absorption strength, low mobility
- InAs/InAsSb: longest lifetime, low mobility
- InAs/GaSb: somewhere in between

$$J_{Diff} = q\, n_i^2\, W_{Abs}/N_D\, \tau$$



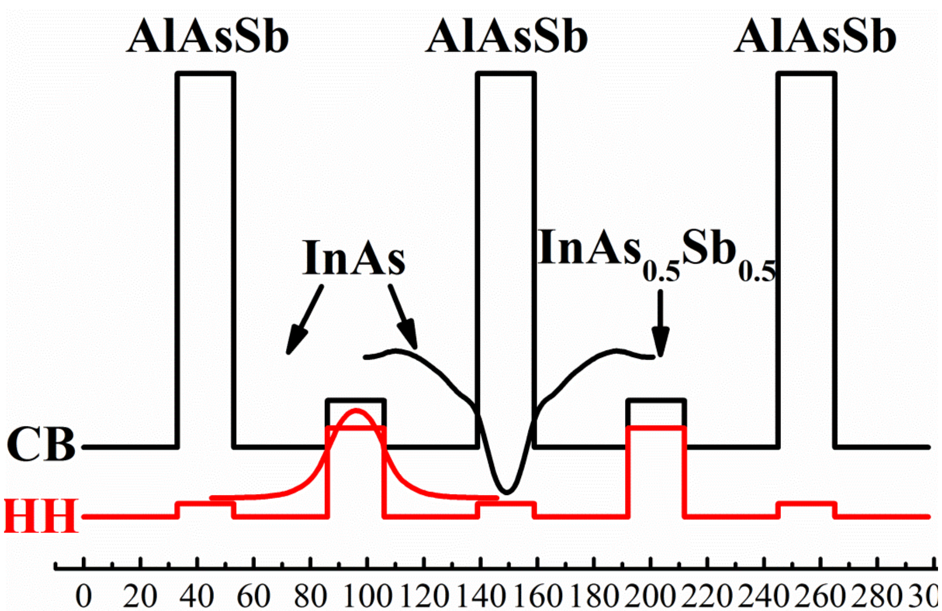
- Down-select in 12 months

W-SL Properties

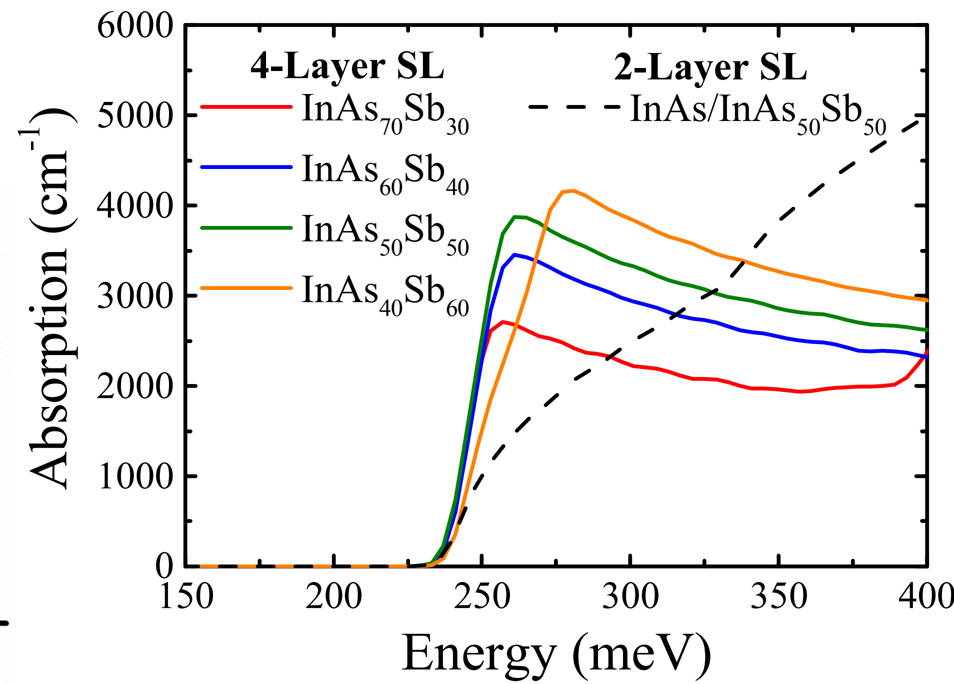
simulation

- AlAsSb bisects electron wavefunction
- Higher e-h overlap than InAs/InAsSb SL
- Induces "resonant" absorption
- High hole effective mass

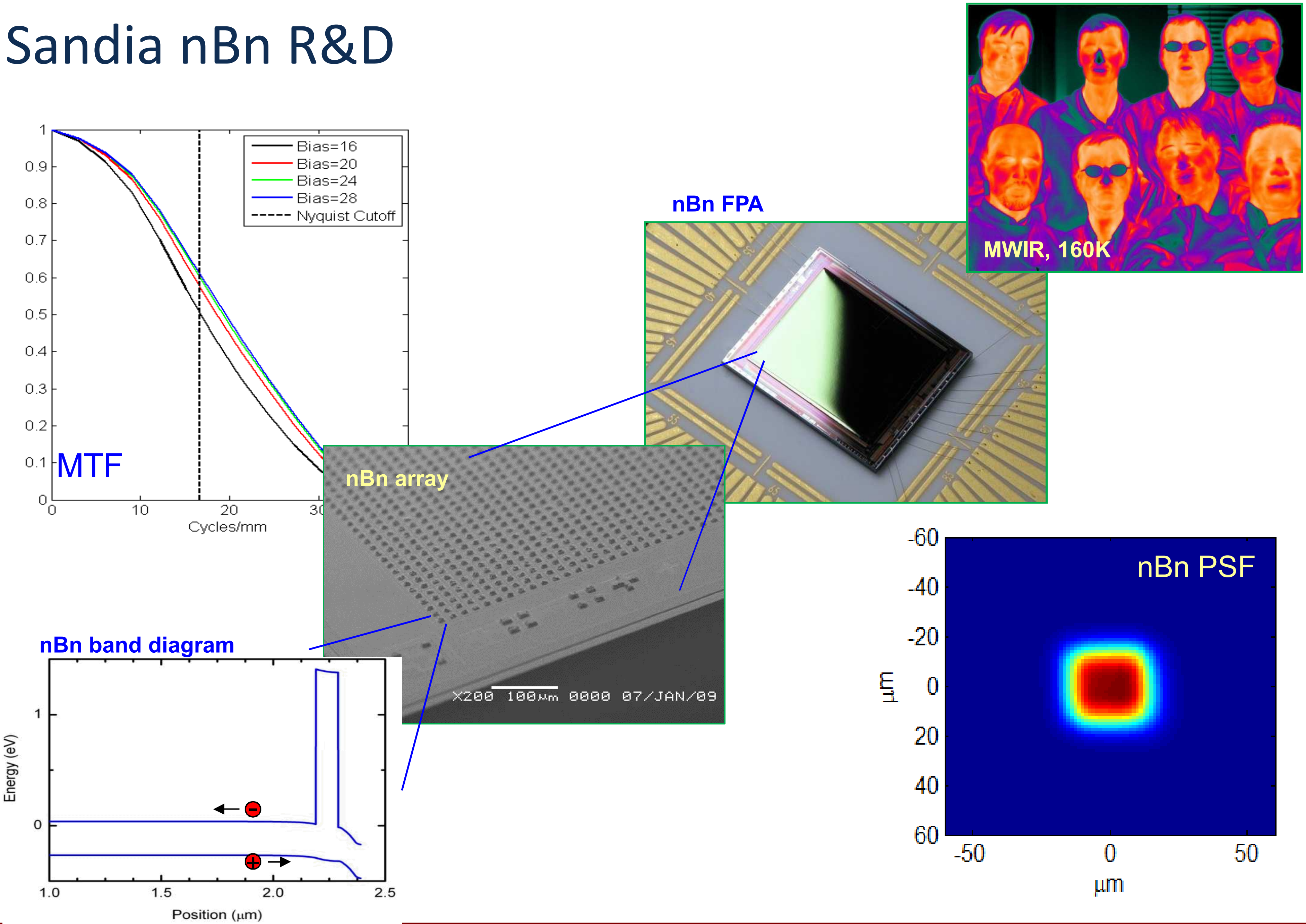
Modified from NRL design



Position (Å)

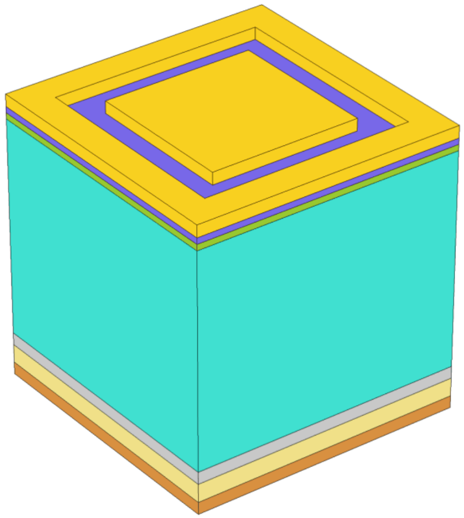


Sandia nBn R&D

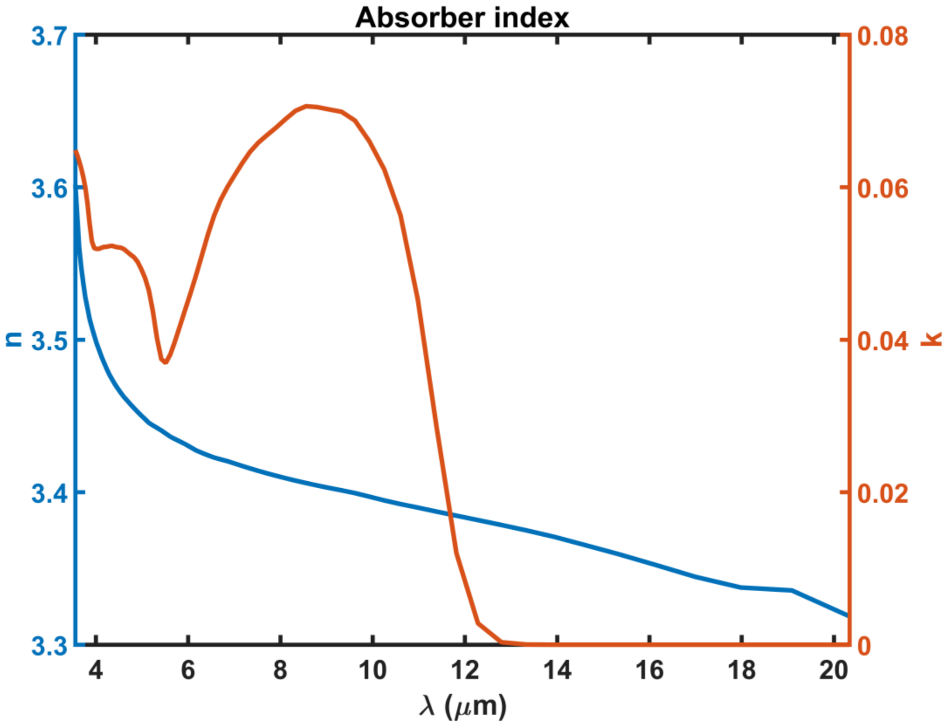


Electromagnetic and Electrostatic Modeling

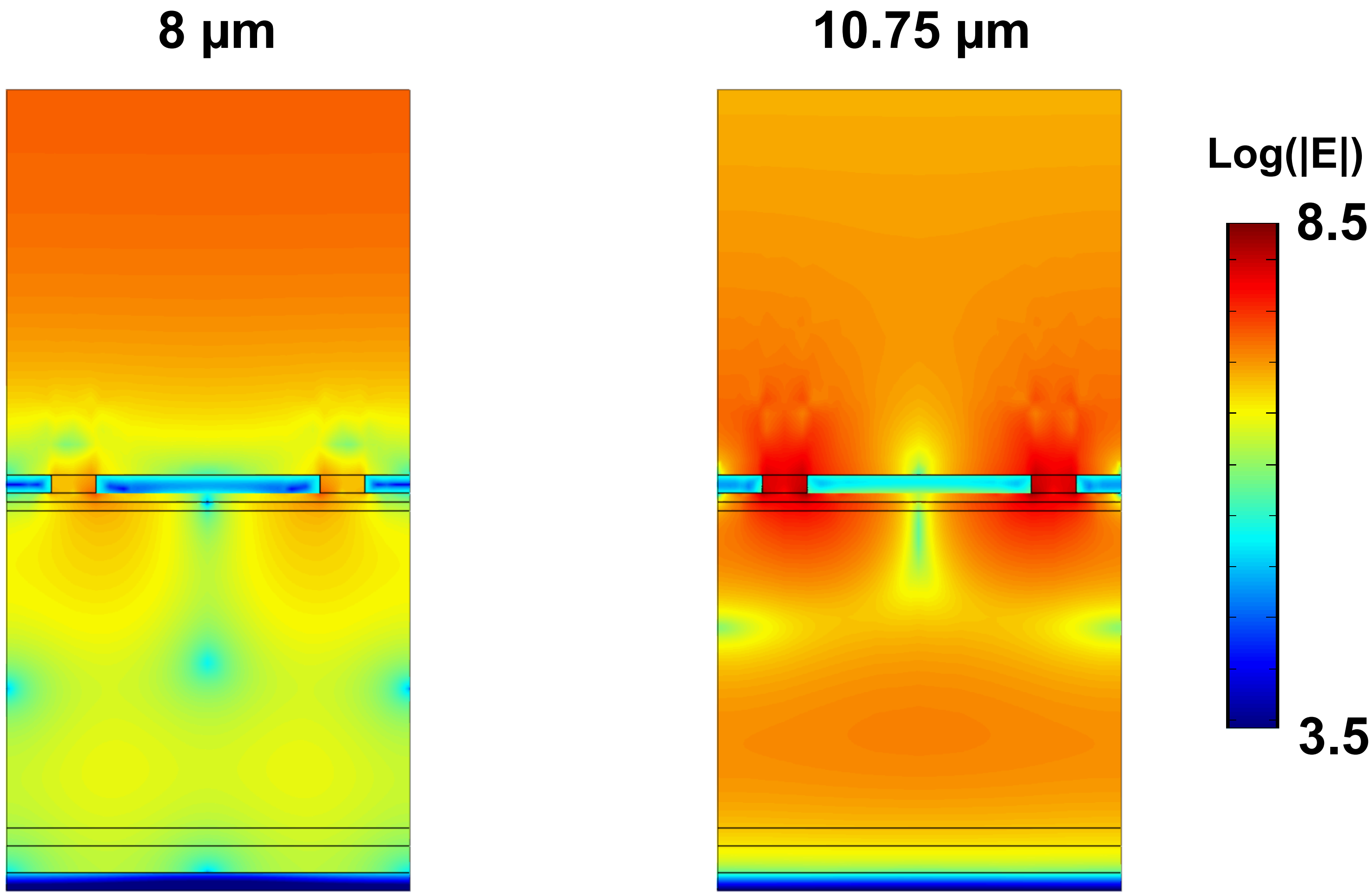
Comsol Device Modeling



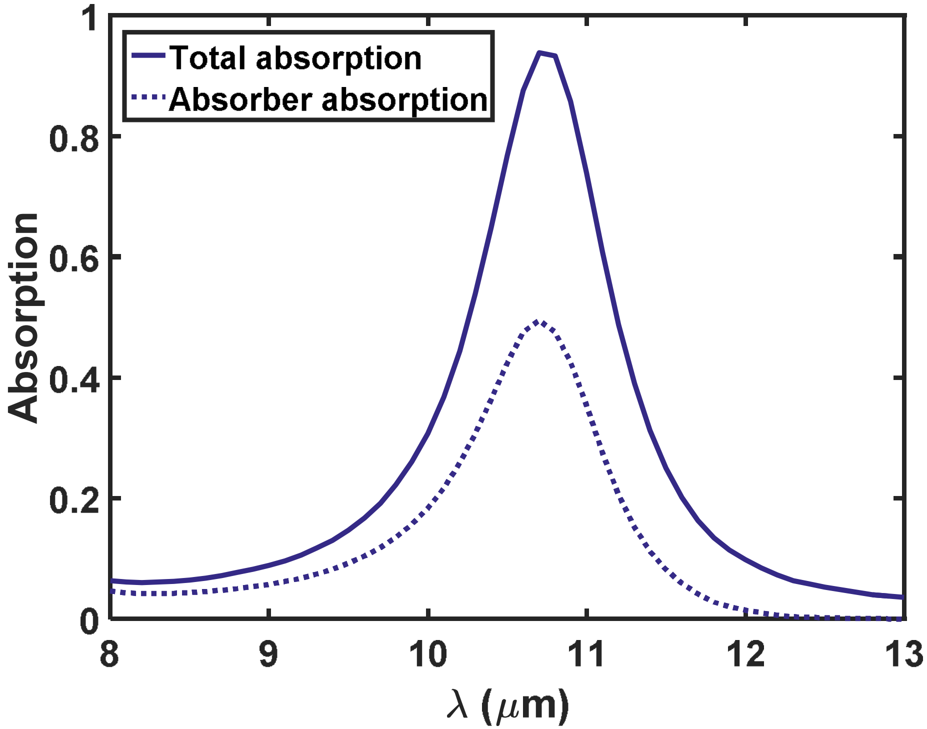
- Gold
- GaSb
- AlAsSb
- Absorber
- AlGaAsSb
- InAsSb
- AlCu

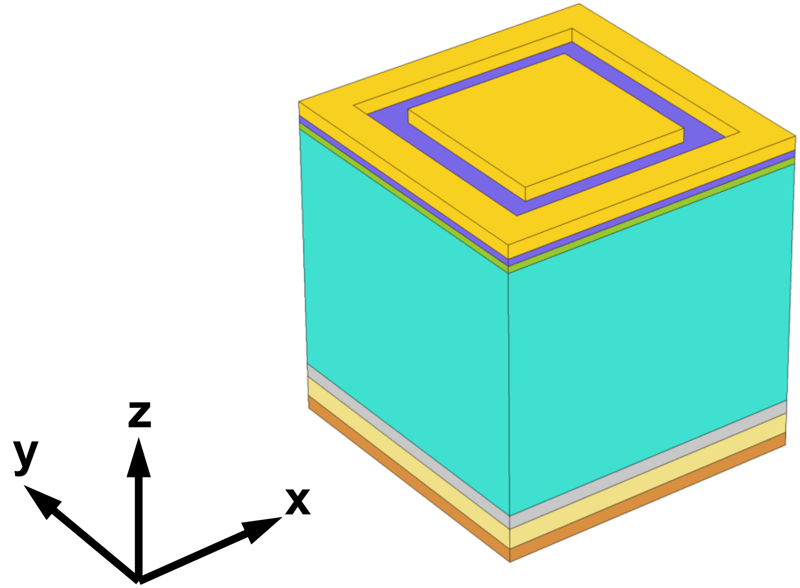


Electric field distribution



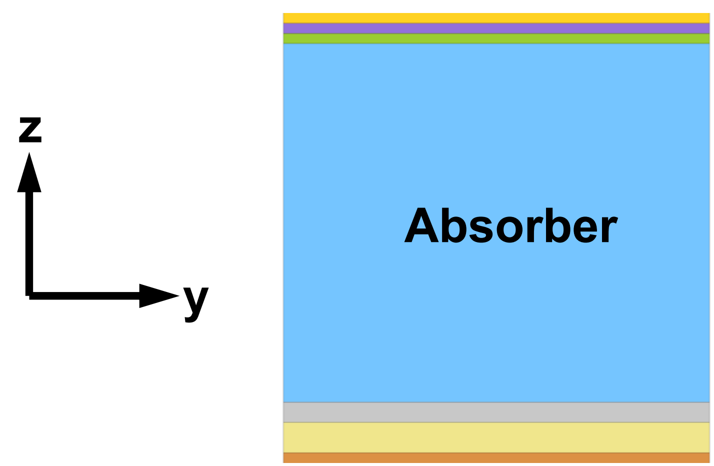
Absorption Location



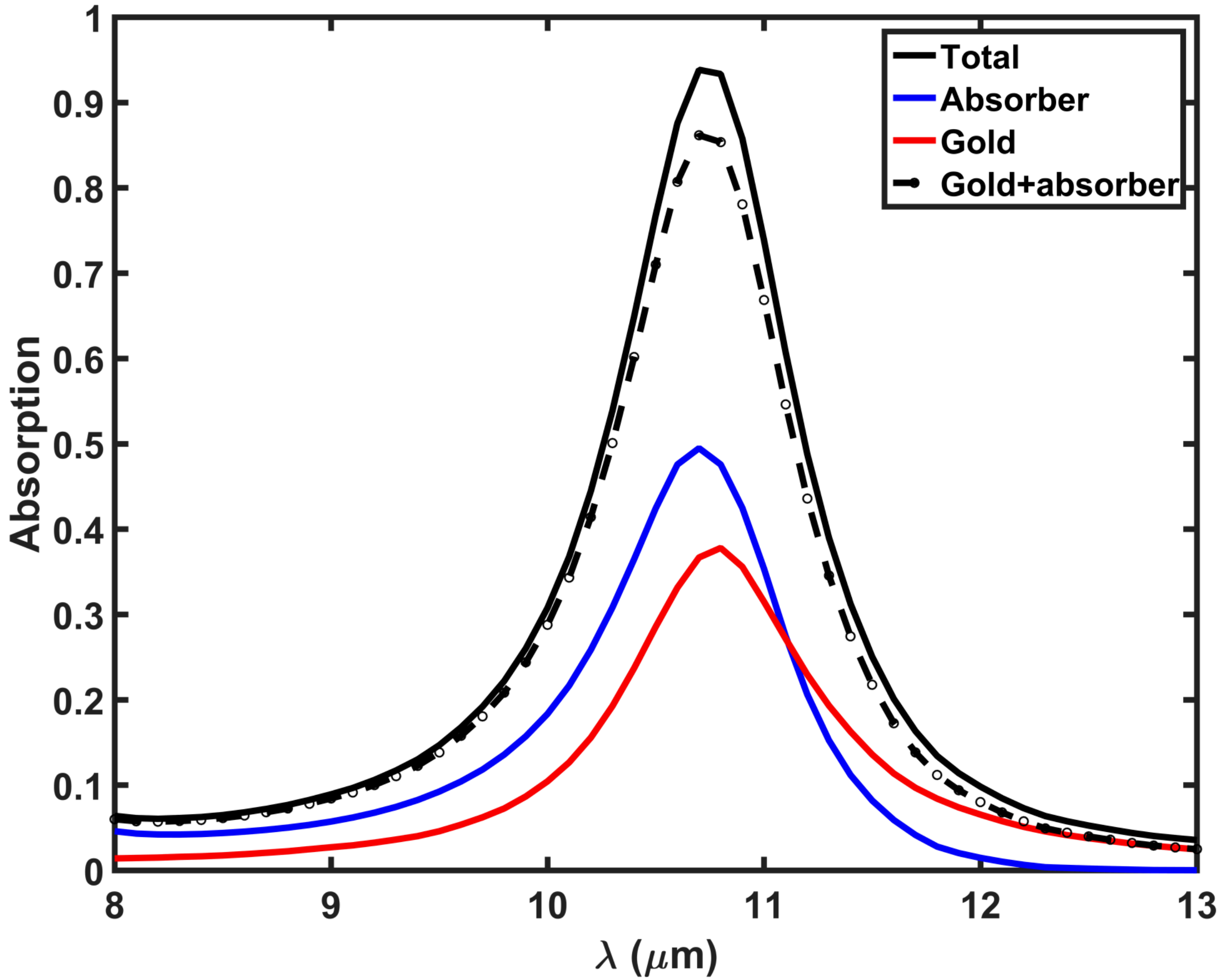


Flux through top and bottom surface:

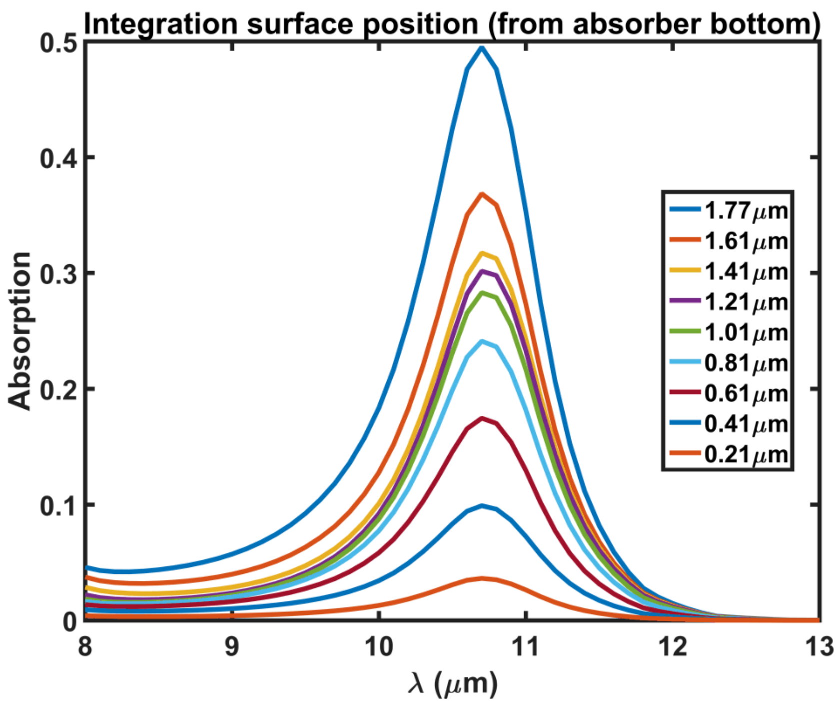
$$A_{\text{abs}} = \int_{top} S_z dxdy - \int_{bot} S_z dxdy$$

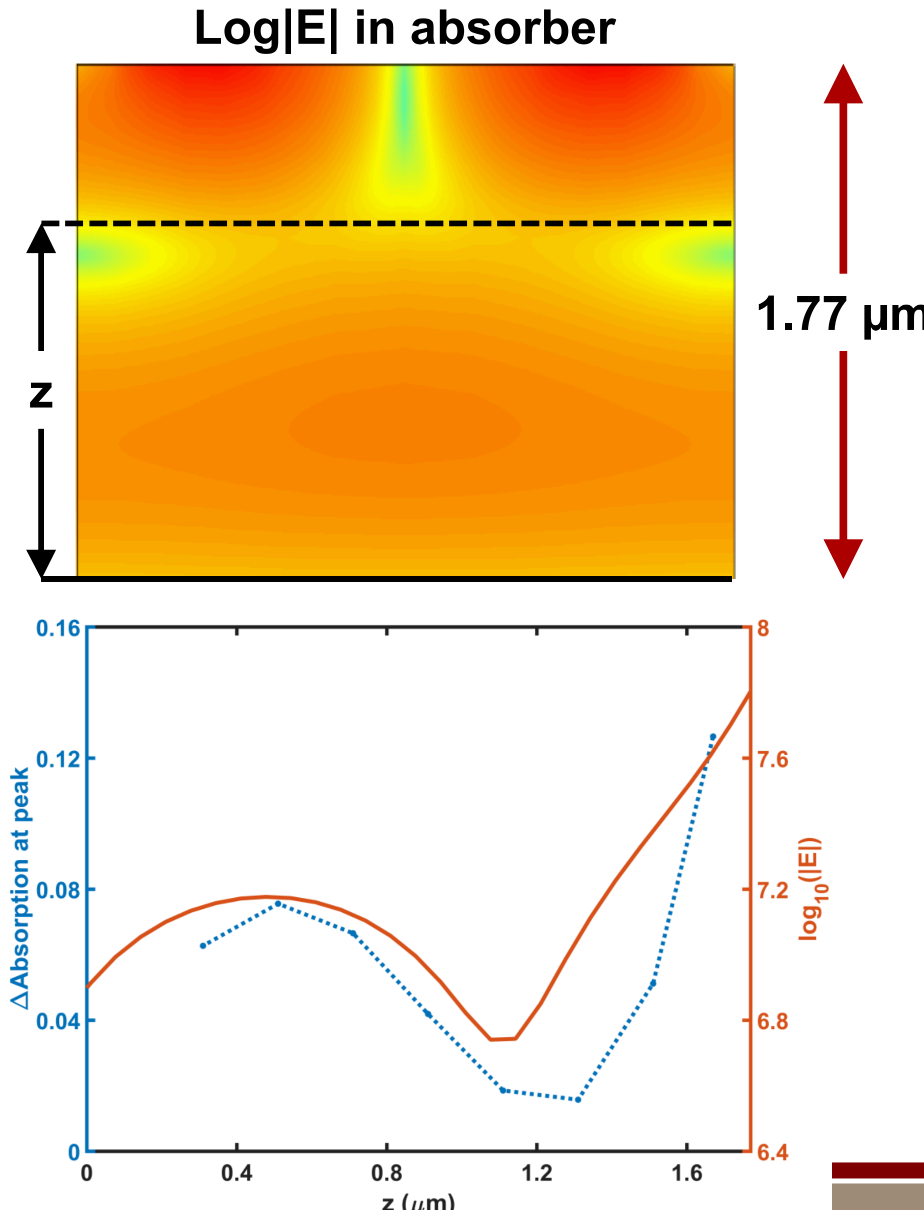


Absorption Location

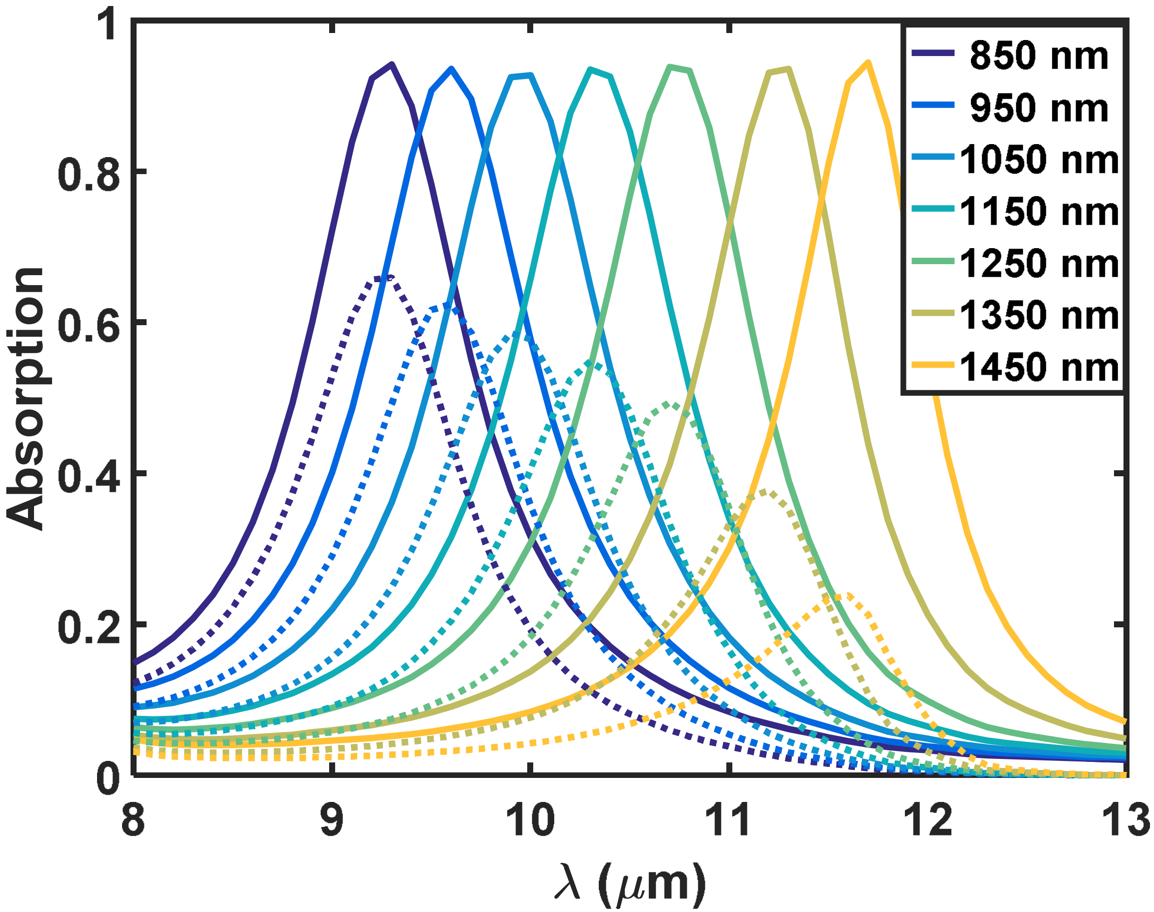


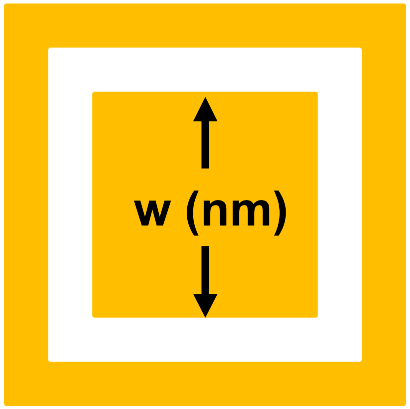
Absorption Location

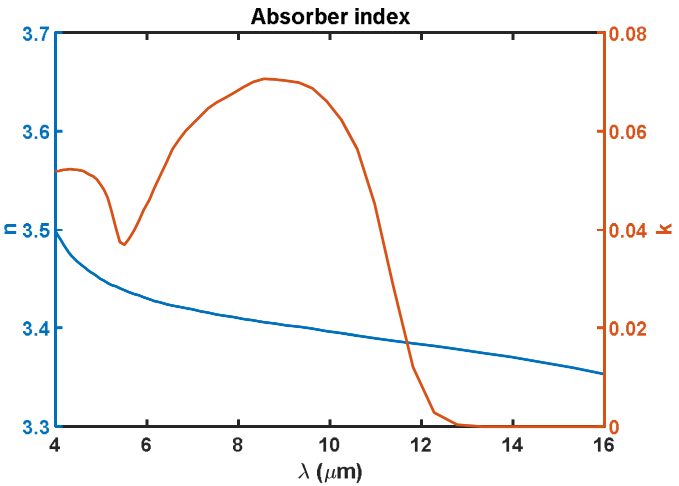




Shifting absorption resonance



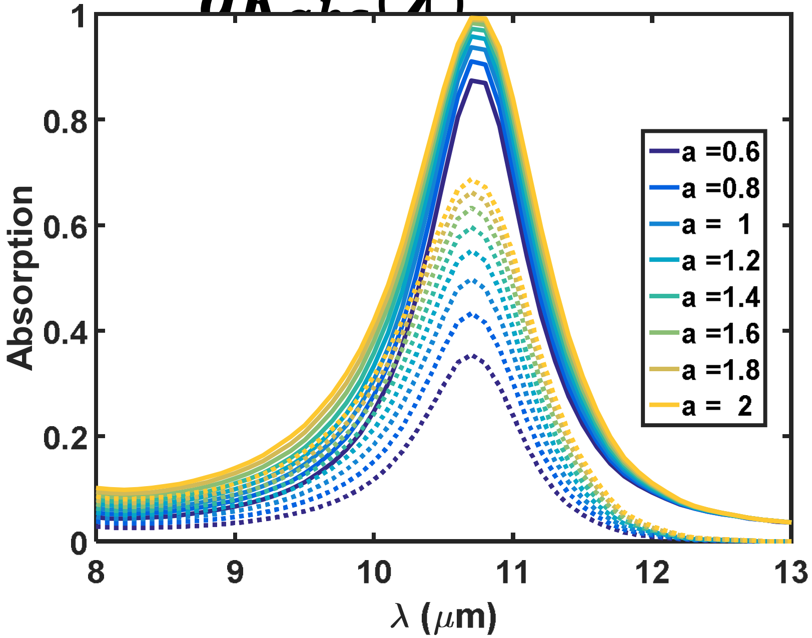


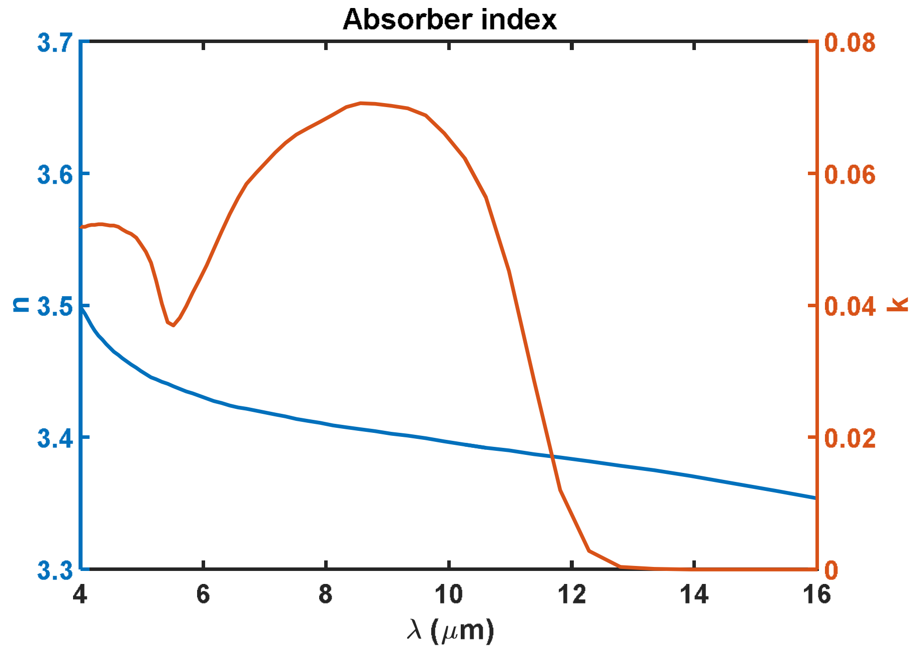


Modifying w allows for shifting of the resonance of the nanoantenna array

Optimizing absorber index

Scaling the absorber index: $k_{\mathrm{abs}} = a k_{\mathrm{abs}}(\lambda)$





Higher absorber k yields greater "useful" absorption

Finite Pixels

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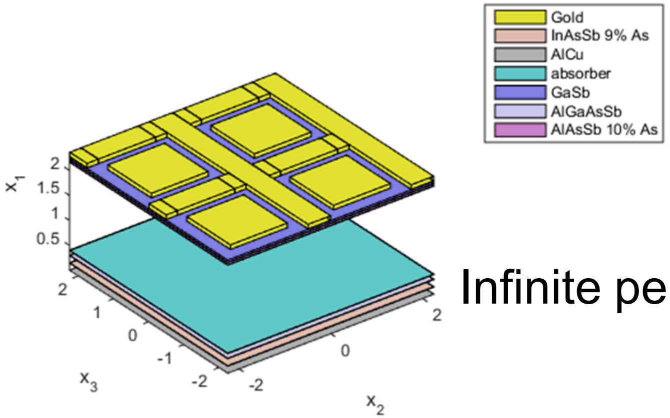
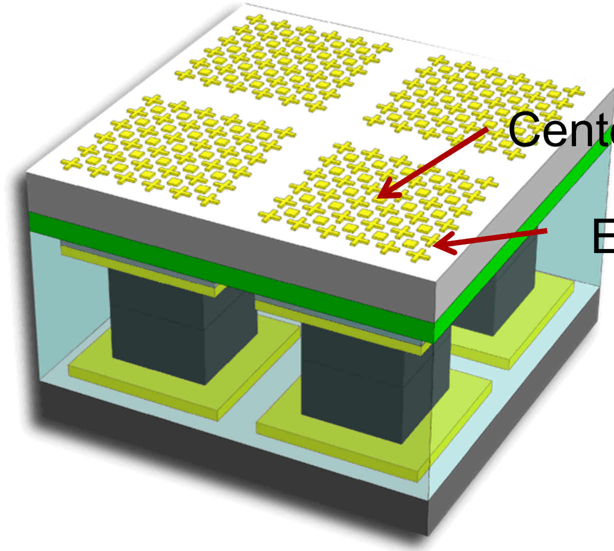
RCWA

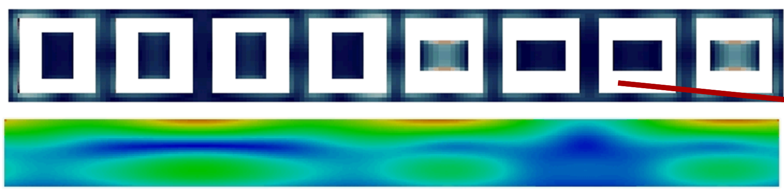


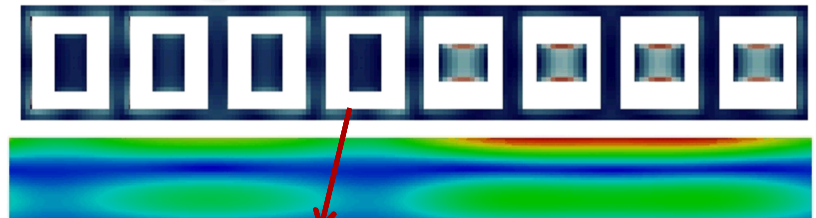
Infinite periodicity

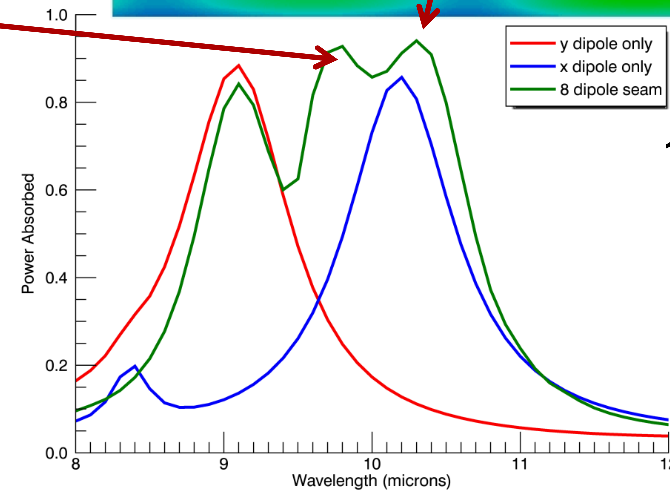


Center emitter

Edge emitter







9.8 um

10.2 um

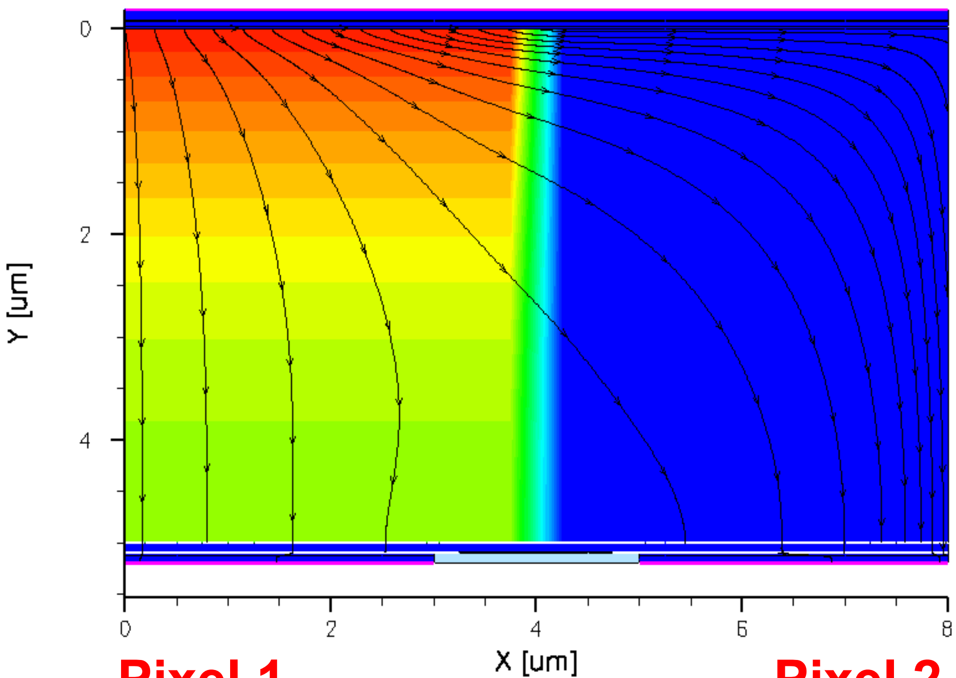
Dipole Seams: effect of non-periodicity on absorption.

Center to edge differences can lead to cross-talk

2-D Numerical Device Simulation Capability

Current Paths

Illumination

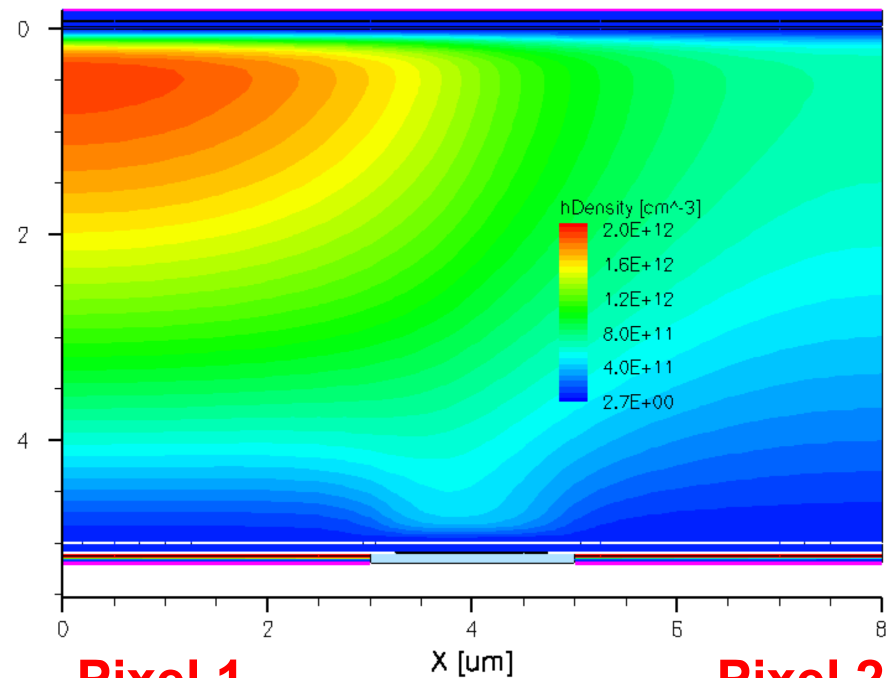


Pixel 1

Pixel 2

Hole Density Contour

Illumination



Pixel 1

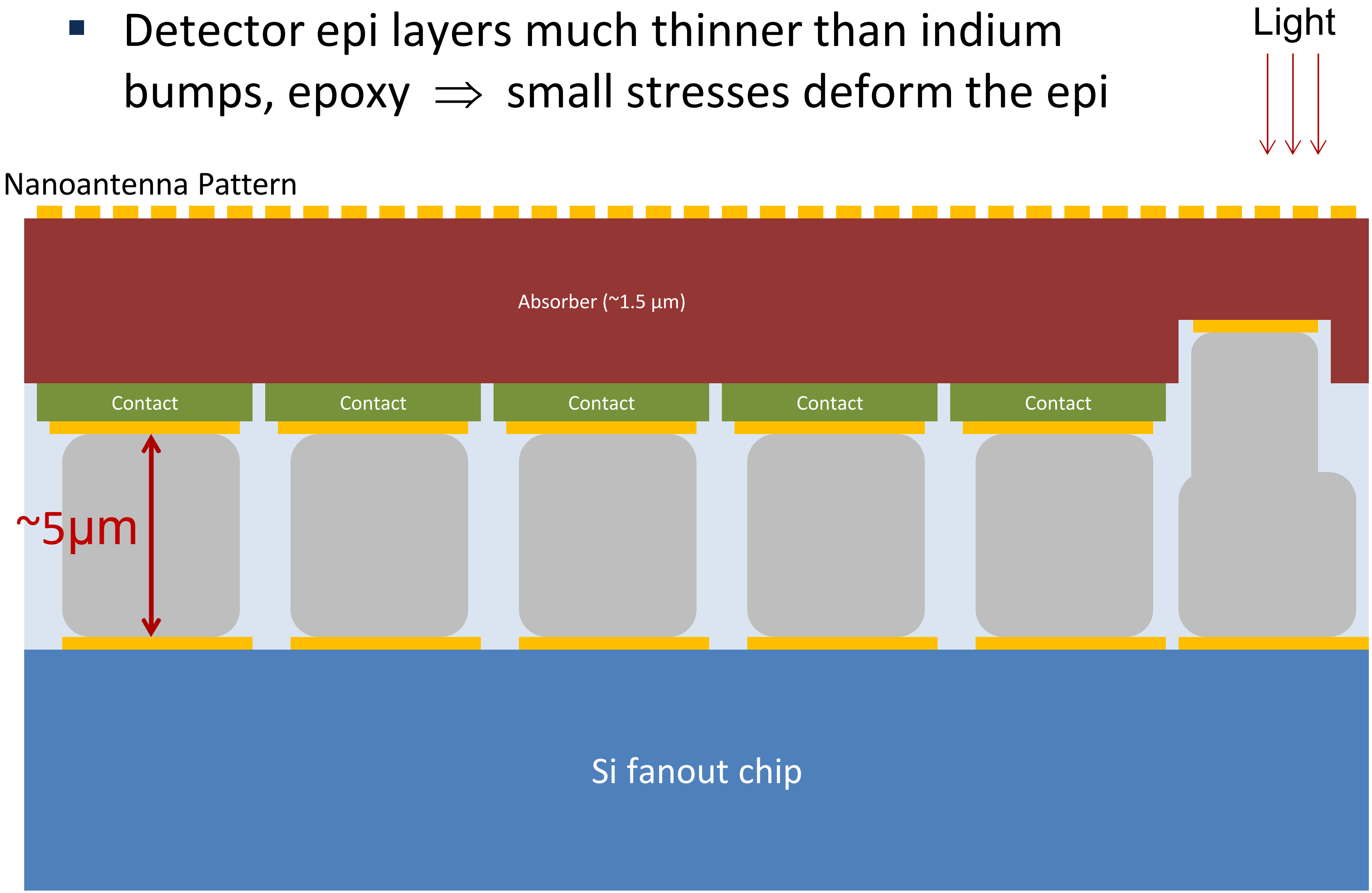
Pixel 2

Useful for analyzing 2-D effects: crosstalk, optical concentrator.

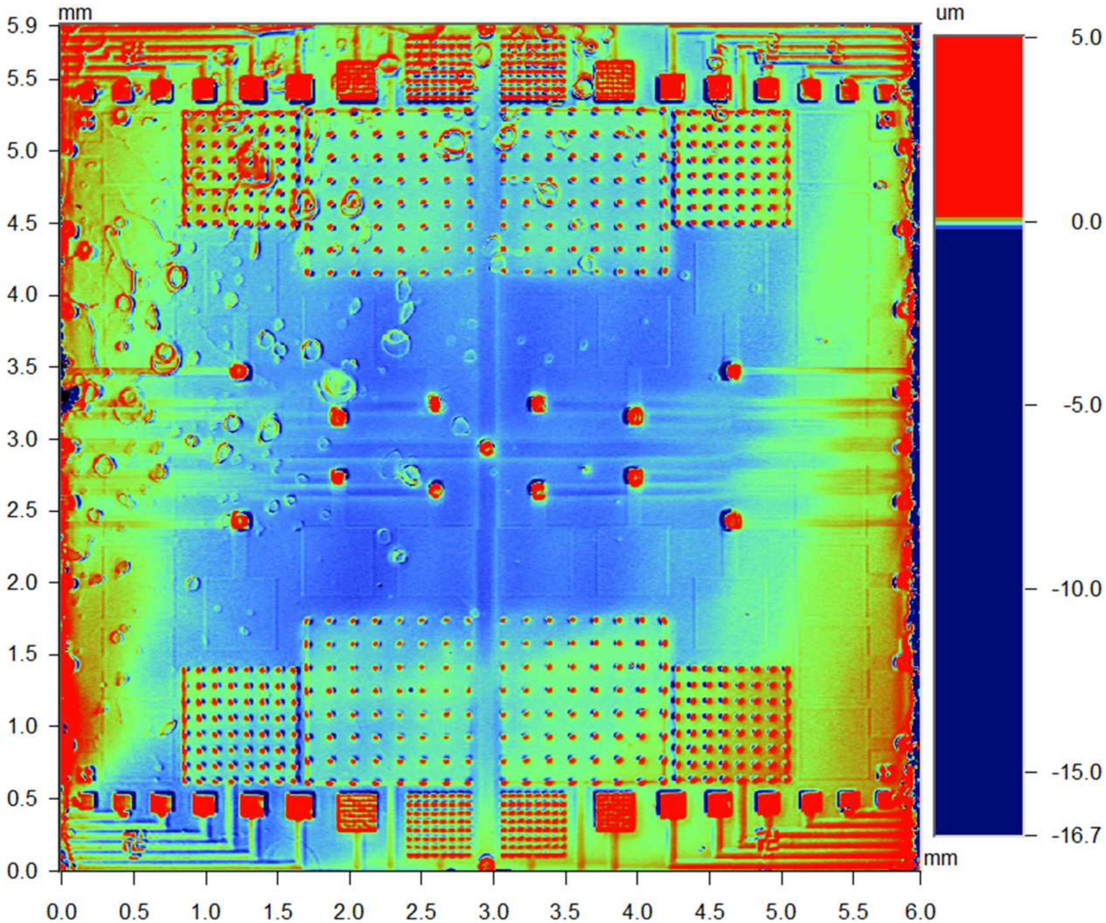
Develop Integration Methods

Challenges in Ensuring Surface Flatness

- Detector epi layers much thinner than indium bumps, epoxy ⇒ small stresses deform the epi



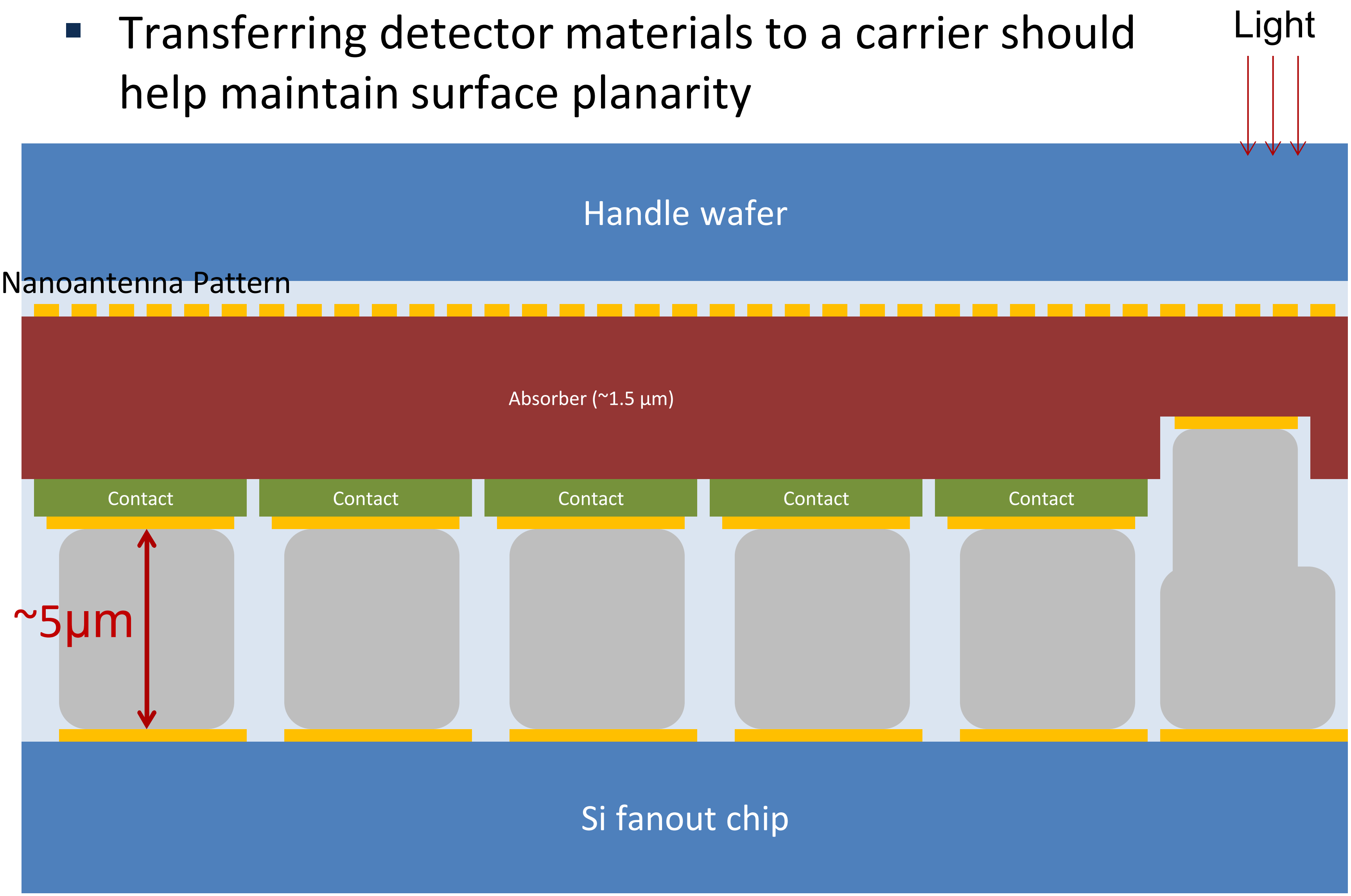
Surface Flatness Issues



- Large topography issues with isolated bumps
  - This creates issues with writing the nanoantennas
  - May hinder detector performance due to material stresses
- Dense arrays show reduced topography
  - Similar to an array for mating to a ROIC

Alternate Integration Method

- Transferring detector materials to a carrier should help maintain surface planarity



Summary

- Overall Goal: Demonstrate significantly better performance (dark current, responsivity, MTF) over conventional IR FPAs
- Goal: Characterize sources and mechanisms of dark current in thin absorbers
- Modeling optical fields and carriers
- Formulated approach, Assembled technology components
- Demonstrated ability to tune nanoantenna to LWIR
- Demonstrated progress toward suppressing parasitic I_{dark}
- Identified areas of greatest technical challenge: integration