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Plasmonics and Nanoantennas for Infrared Detectors

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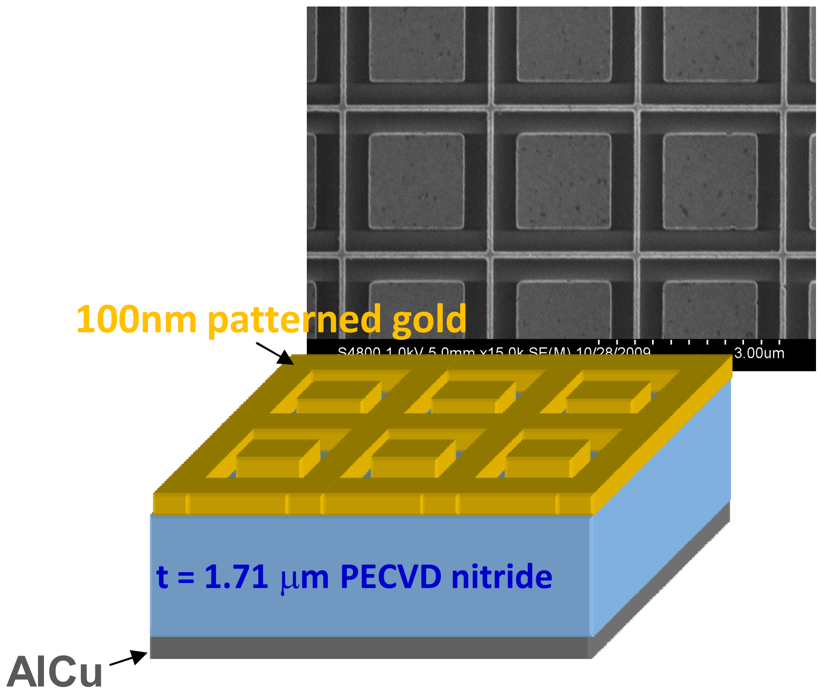
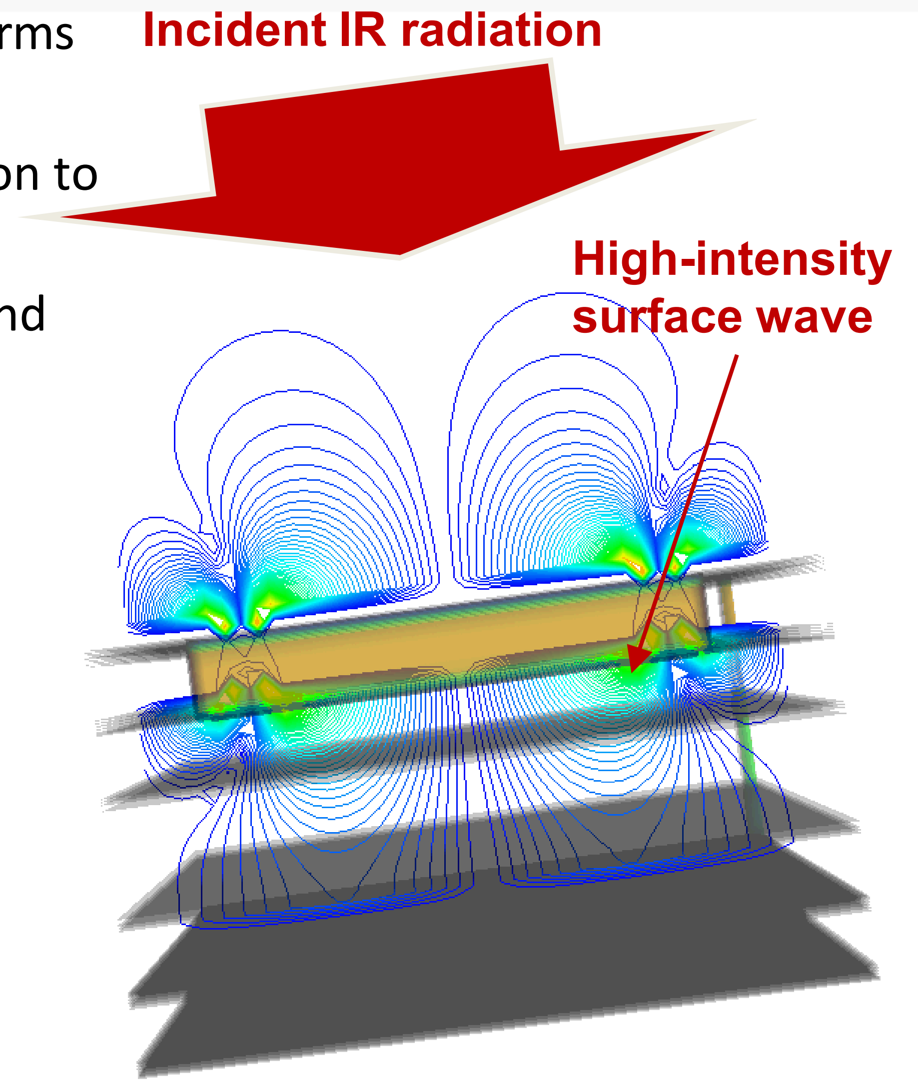
Outline

- “Perfect Absorbers” and their application
- Application of nanoantenna concept to active devices
- Advantages over traditional detectors
- Our fabrication
- Results

Nanoantennas as Perfect Absorbers

- Plasmons are electromagnetic waveforms with high field concentrations.
- Nanoantennas couple incident radiation to plasmons with near 100% efficiency.
- We have used this efficient coupling and field concentration to form “perfect absorbers” in the thermal infrared.





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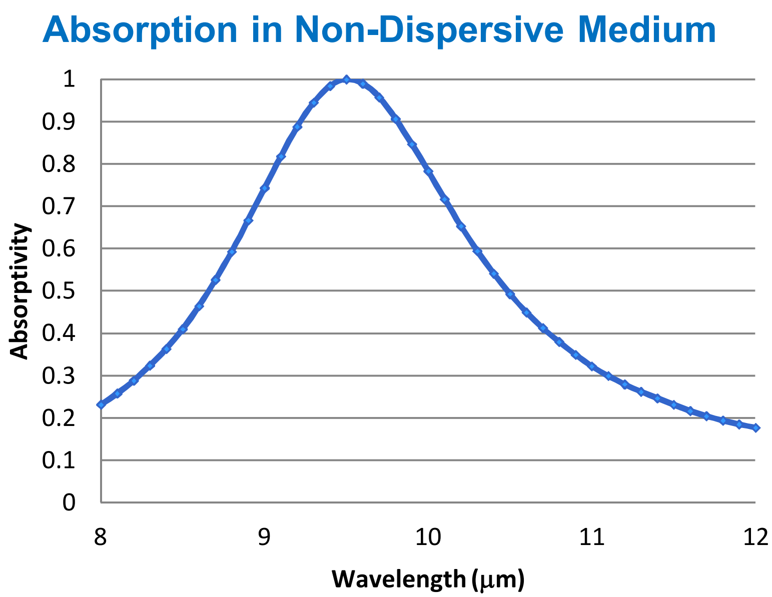
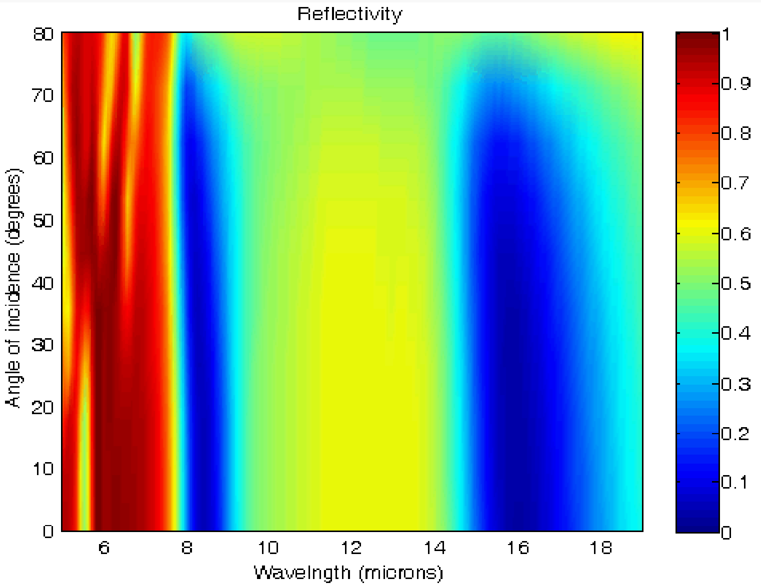
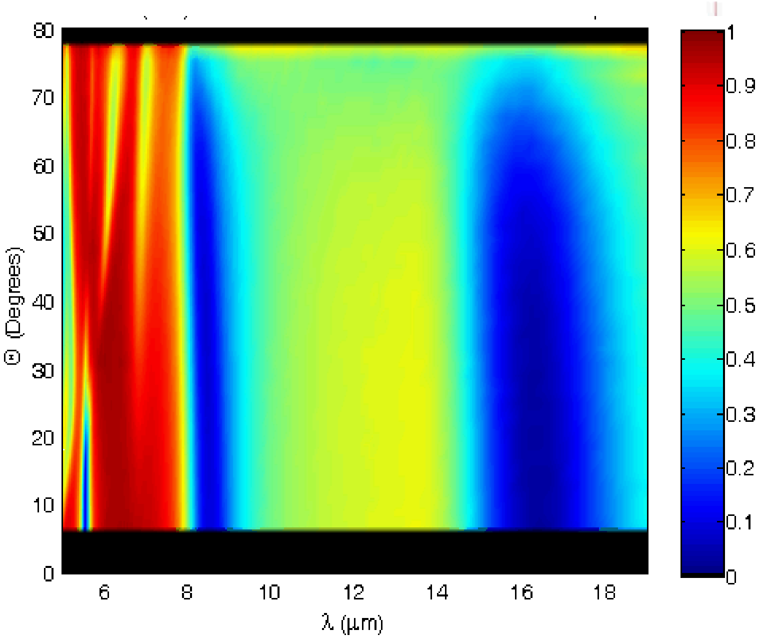
Nanoantennas as Perfect Absorbers

- **Absorption bandwidth is determined by the parameters of the nanoantenna and the materials used.**

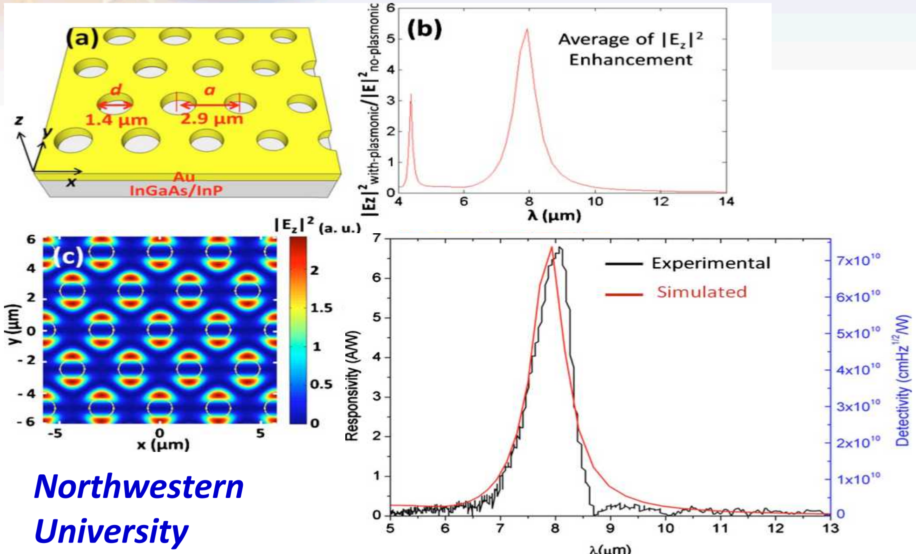


- **We have excellent agreement between simulation and measurement. → great confidence in our models.**



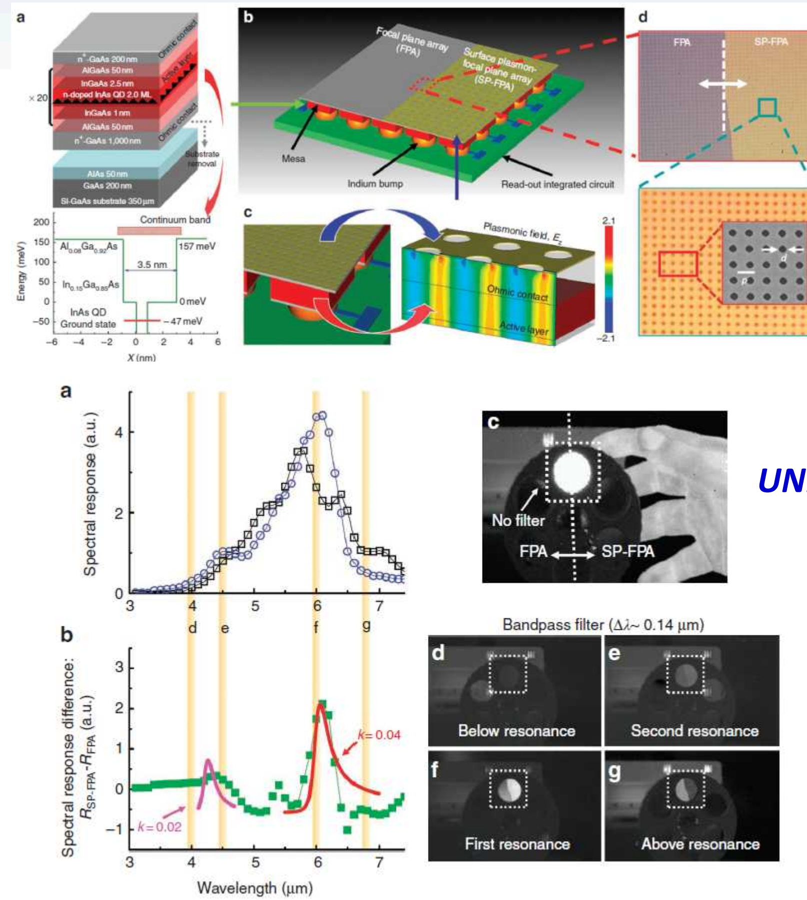


Related Work



Northwestern University

Wei Wu, Alireza Bonakdar, and Hooman Mohsenib, "Plasmonic enhanced quantum well infrared photodetector with high detectivity," *Appl. Phys. Lett*. 2010.



UNM

S. J. Lee, Z. Ku, A. Barve, J. Montoya, W.-Y. Jang, S. R. J. Brueck, M. Sundaram, A. Reisinger, S. Krishna, and S. K. Noh, "A monolithically integrated plasmonic infrared quantum dot camera," *Nature Communications*, 2011.

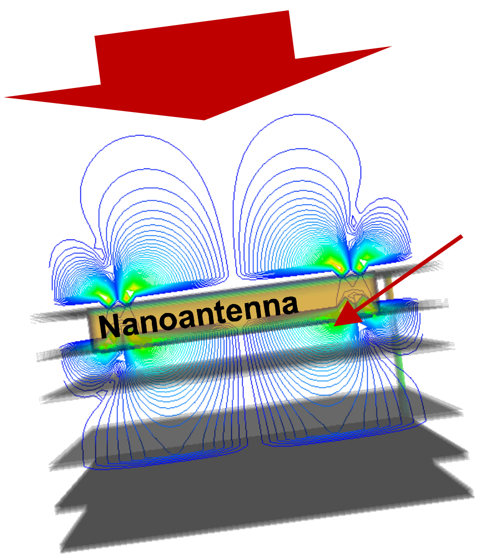
Nanoantenna-Enhanced Infrared Detection

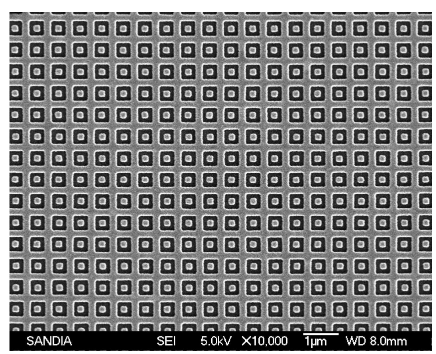
A method to improve all detector platforms by changing the way the energy interacts with the detecting layer.

Use nanoantenna to convert to tightly confined surface waves. ➔ You only need active material where there is energy.

Order of magnitude thinner active layer than traditional FPA!

The concentration of the incident energy in the layer under the nanoantenna allows us to greatly modify existing detectors and envision new devices.





Fabricated device: the nanoantenna covers the entire surface

We are applying nanoantennas to

- **III-V MWIR detectors**
- **bilayer graphene LWIR detectors**
- **germanium SWIR detectors.**

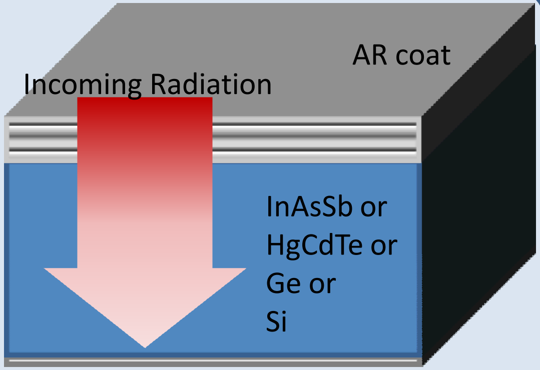
Nanoantenna-Enhanced Infrared FPA

A method to improve all detector platforms by changing the way the energy interacts with the detecting layer.

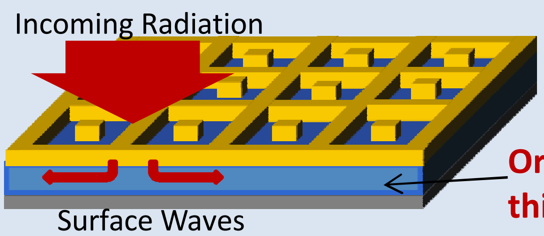
Traditional FPA Pixel:

Active layer must be thick enough to absorb incoming radiation.

Thick active layer leads to dark current and crosstalk.



Our pixel: Use nanoantenna to convert to tightly confined surface waves. ➔ You only need active material where there is energy.

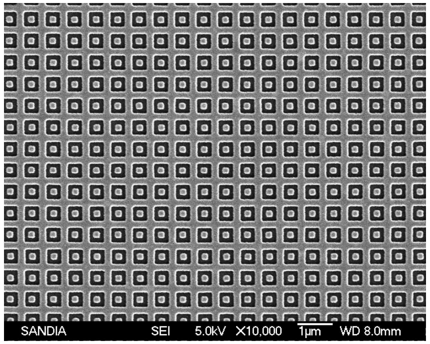


Very thin active layer leads to

- Less dark current
- Less crosstalk
- Faster operation

The nanoantenna gives us

- Spectral or polarization filtering by changing pattern from pixel to pixel
- Built-in wide-angle antireflection coating
- Built in EMI protection
- A material-agnostic device



Fabricated device

We are currently applying nanoantennas to nBn, QWIP, Ge, and bilayer graphene detectors.

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Replacement of a Thick Absorber Layer with a Nanoantenna-Enabled Thin Absorber

This is one single pixel of a traditional MWIR FPA.

Its thickness is determined by the material absorption. You need at least enough material to absorb a wavelength of the light.

Since these materials tend to be high index, you need an AR coat on top.

A thin layer would allow us to:

1. Lower the dark current (higher temperature operation)
2. Strain material more: higher cutoff
3. Obtain higher yields

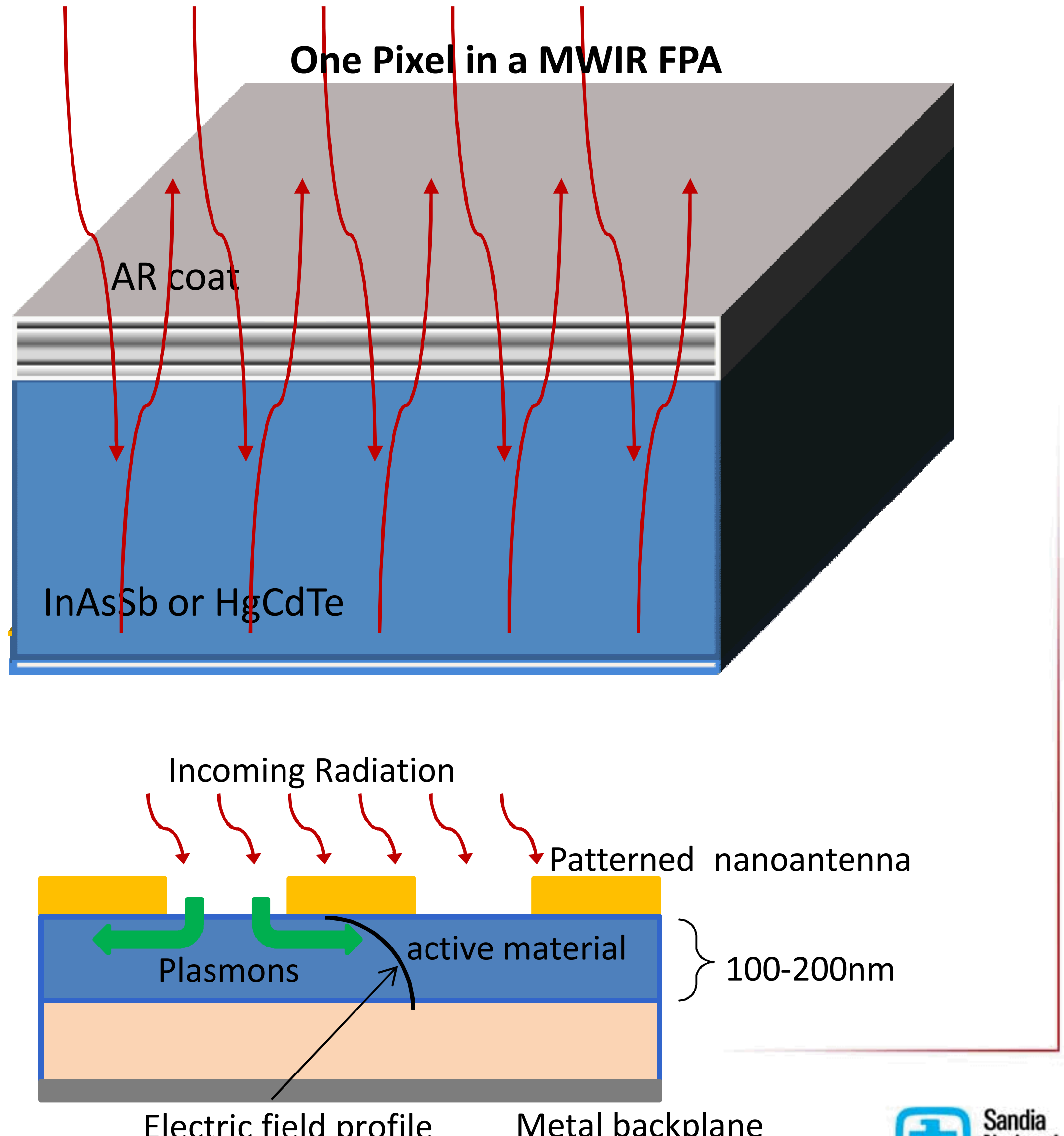
But a thinner layer would not let us absorb the incident radiation efficiently.

No AR coat would lead to much reflection.

The nanoantenna solves both issues:

It couples incoming radiation to plasmons with no reflection.

The plasmons are highly concentrated so only a thin layer is required.



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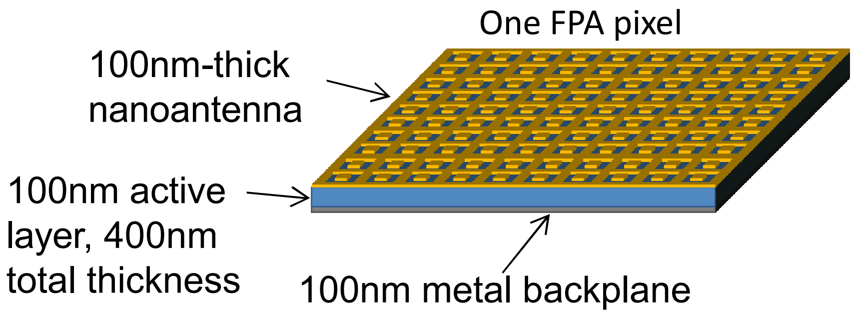
Advantages of a Thinner Active Layer

Integrate subwavelength nanoantenna with active material (MCT or InGaSb) for high-performance FPA.

InGaAsSb photodetectors are made at Sandia.



What does thin buy you?

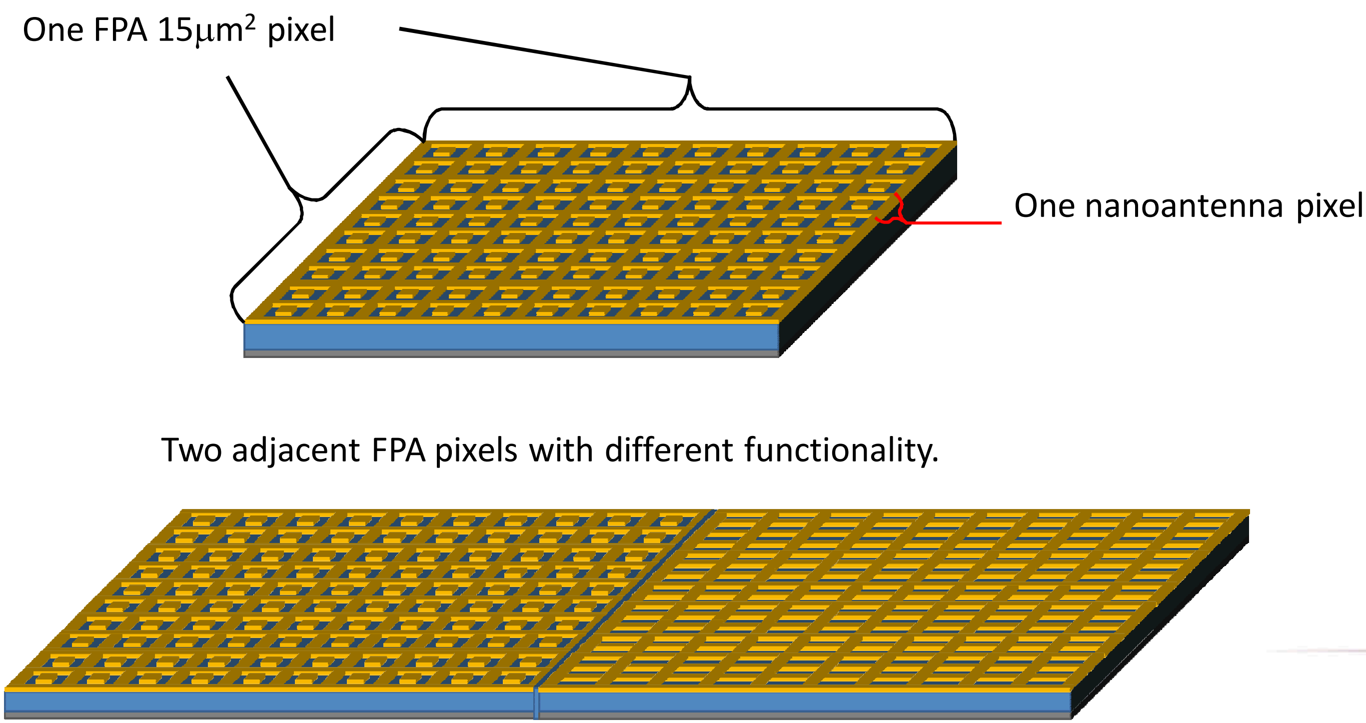
Volume of active material (MCT or nBn) required goes down by over an order of magnitude.

Less material ➔ lower dark current ➔ better performance at a fixed temperature or equal performance at a higher temperature (less cooling required).

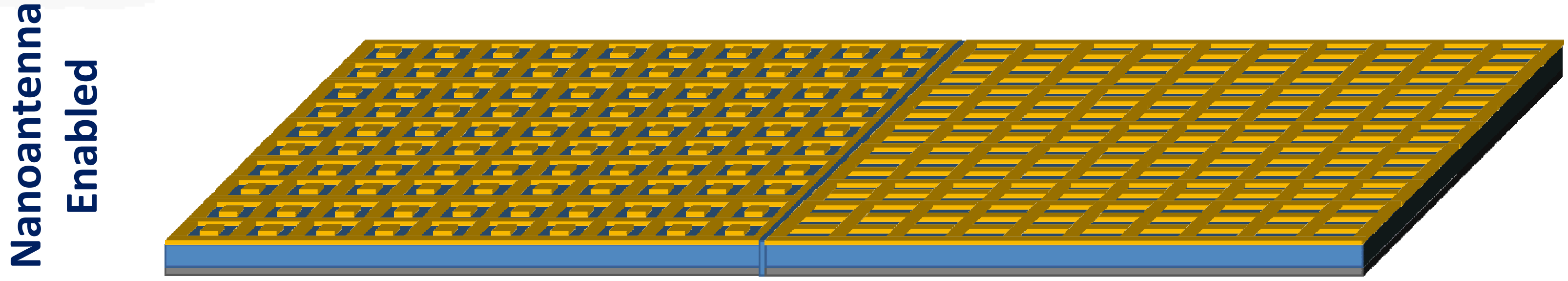
- Thin layer allows more freedom with strain of the material. In the case of nBn, we can push the cutoff wavelength higher by tenths of microns.
- Less material deposition = easier fab/higher yield/fewer dead pixels. Should lead to lower cost detectors.

Advantages of the Nanoantenna Structure

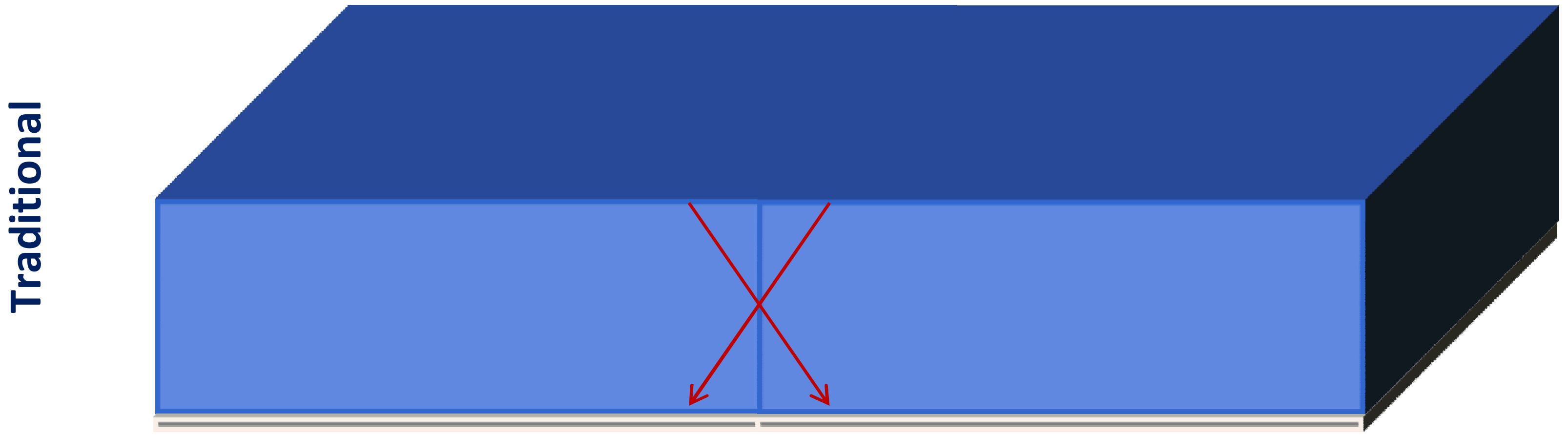
- **Top and bottom contacts allow direct connection.**
- **Filtering can be changed from FPA pixel-to-pixel simply by changing the antenna pattern (Spectral or polarization). This is difficult to do with thin films.**
- **Small antenna unit cell allows multiple unit cells per FPA pixel (for broadband).**



Maximizing Active Area



Thin absorber layer means that isolating adjacent pixels does not require the same area.



Traditional design requires more dead area between pixels to avoid crosstalk.

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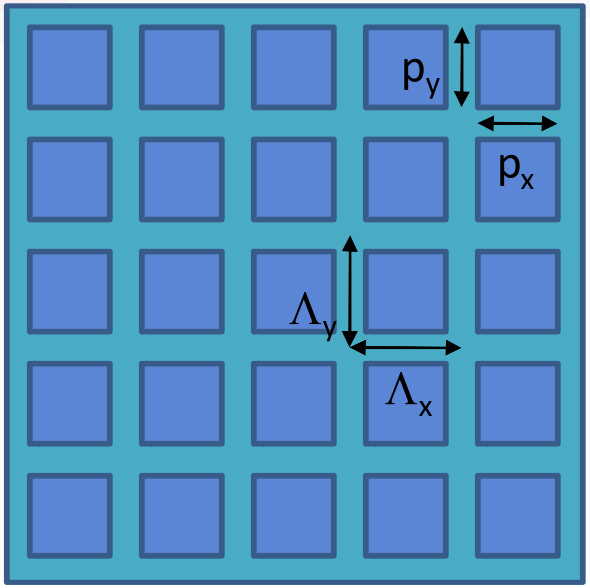
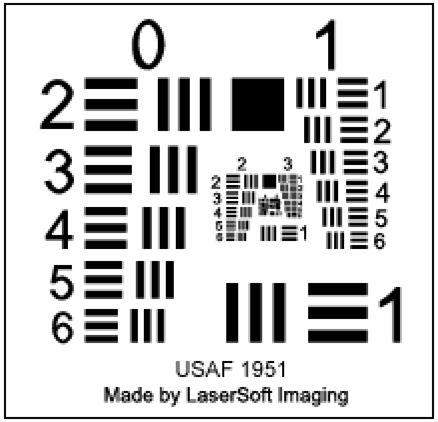
Maximizing Active Area Improves MTF



M x N pixels



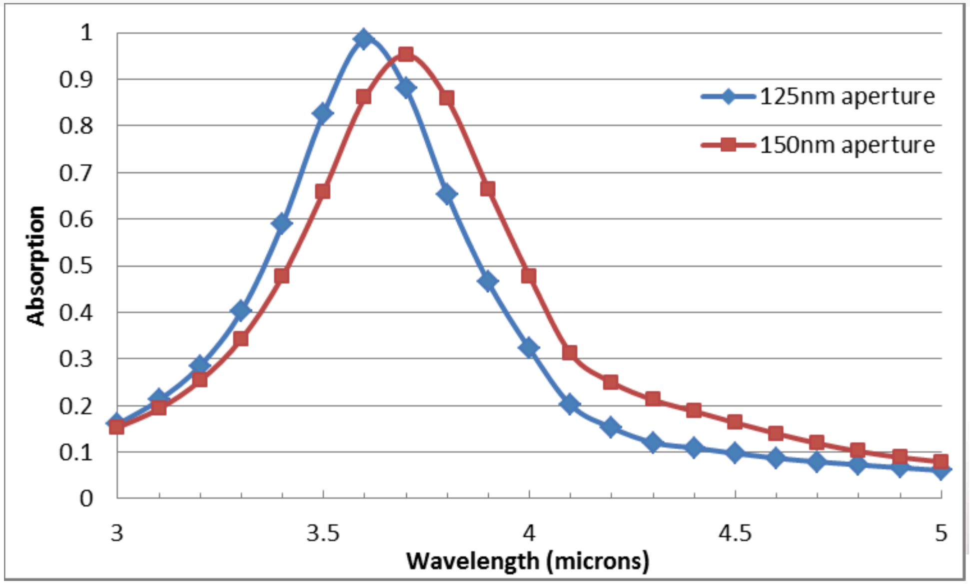
$$MTF(f_x, f_y) = [\mathrm{sinc}((M \cdot \Lambda_x) \cdot f_x, (N \cdot \Lambda_y) \cdot \eta) * \mathrm{comb}(\Lambda_x \cdot f_x, \Lambda_y \cdot f_y)] \cdot \mathrm{sinc}(p_x \cdot f_x, p_y \cdot f_y)$$

Ideally for the mathematical MTF function, we want Λ_x, Λ_y and p_x, p_y as small as possible to maximize the MTF.

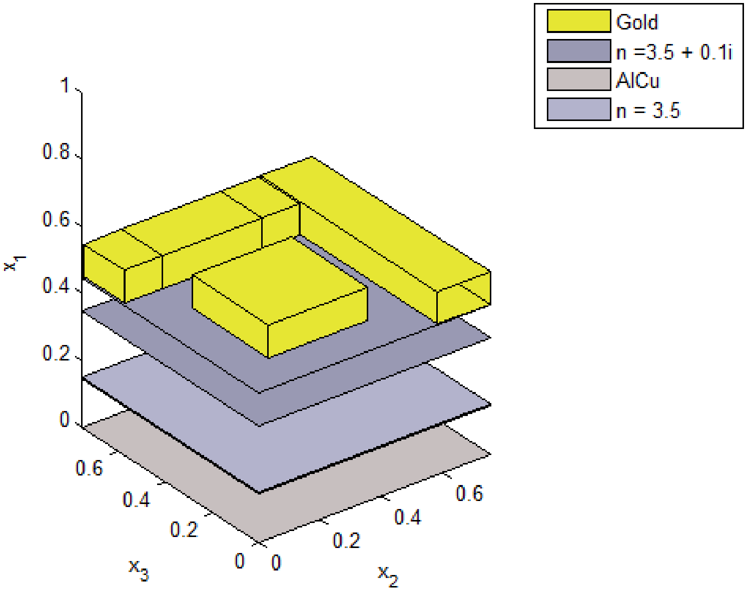
This is clearly impossible, but we can make Λ_x and Λ_y as small as possible for a given p_x and p_y.

Optical Design of Nanoantenna

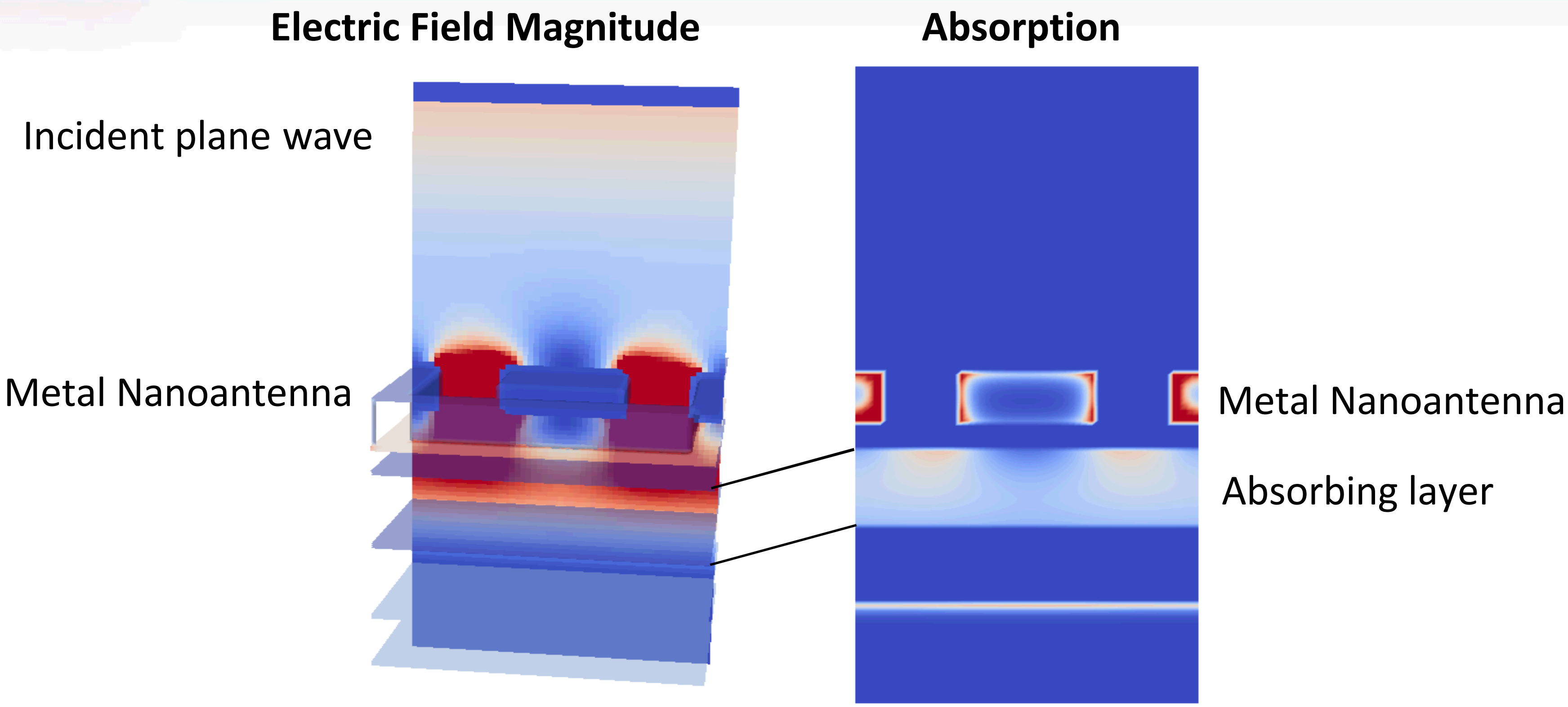
RCWA used to optimize the lateral parameters and layer thicknesses for a desired wavelength and maximum absorption.



Peak of absorption curve is in the 3.5μm to 4.0μm range: middle of the absorption band for the active material we will be using.



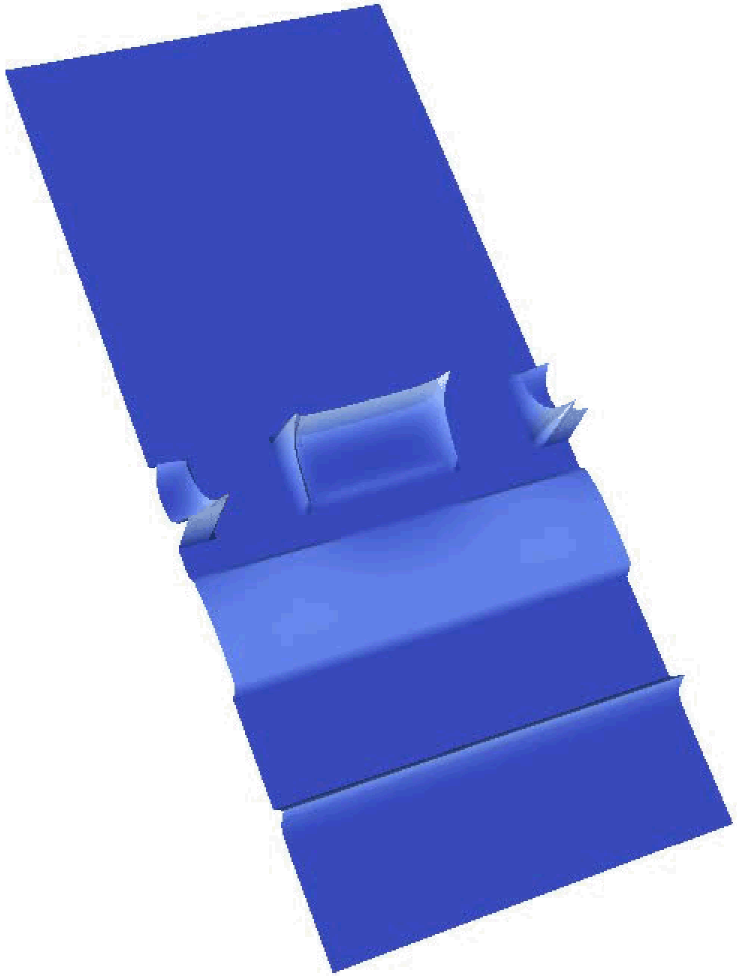
Optical Fields and Absorption



High electric fields generated around the nanoantenna; order of magnitude stronger than plane wave, concentrated in a couple hundred nanometers of surface.

Absorption at edge of metal and throughout active layer.

Absorption as Function of Wavelength



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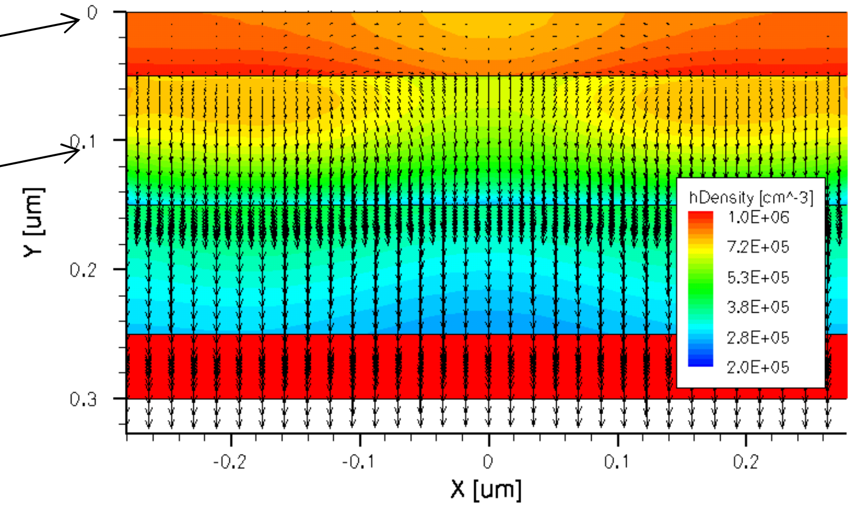
Electrical Modeling

Bottom of nanoantenna metal

Active layer



Shows flow of carriers and if there is recombination at surfaces.

Useful to optimize the design of the epi stack.

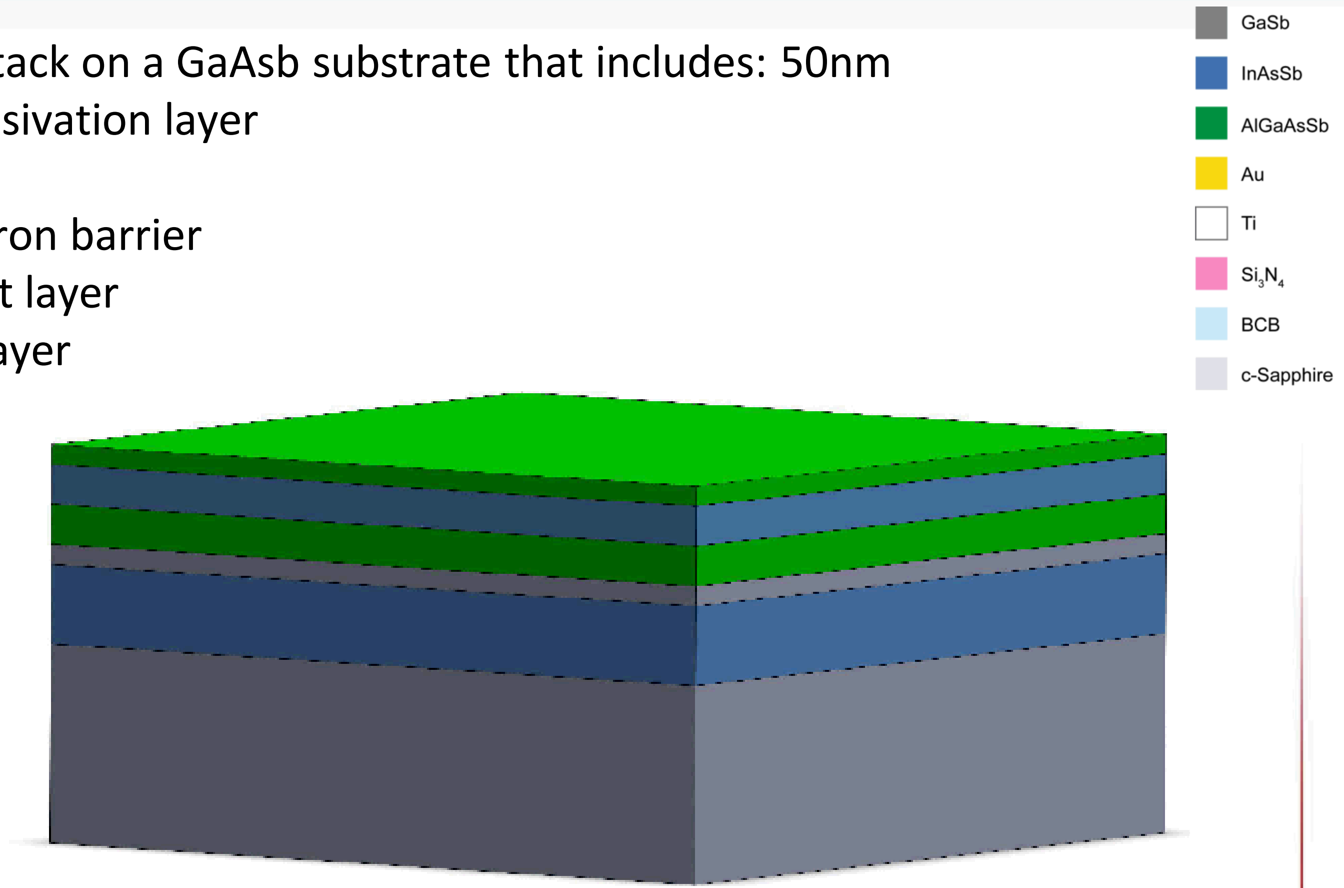
Led to incorporation of buffer layer.

Fabrication

Not only is the active layer thinner than in a traditional detector, but it is sandwiched between the patterned metal nanoantenna and a metal backplane. This requires the development of a new process flow. I'll describe one of the ones that we have developed.

Fabrication Process Flow

An example of a growth stack on a GaAsb substrate that includes: 50nm $AlGa_{0.15}AsSb$ absorber passivation layer
100nm InAsSb absorber
100nm $AlGa_{0.15}AsSb$ electron barrier
50nm p-type GaSb contact layer
100nm InAsSb etch stop layer



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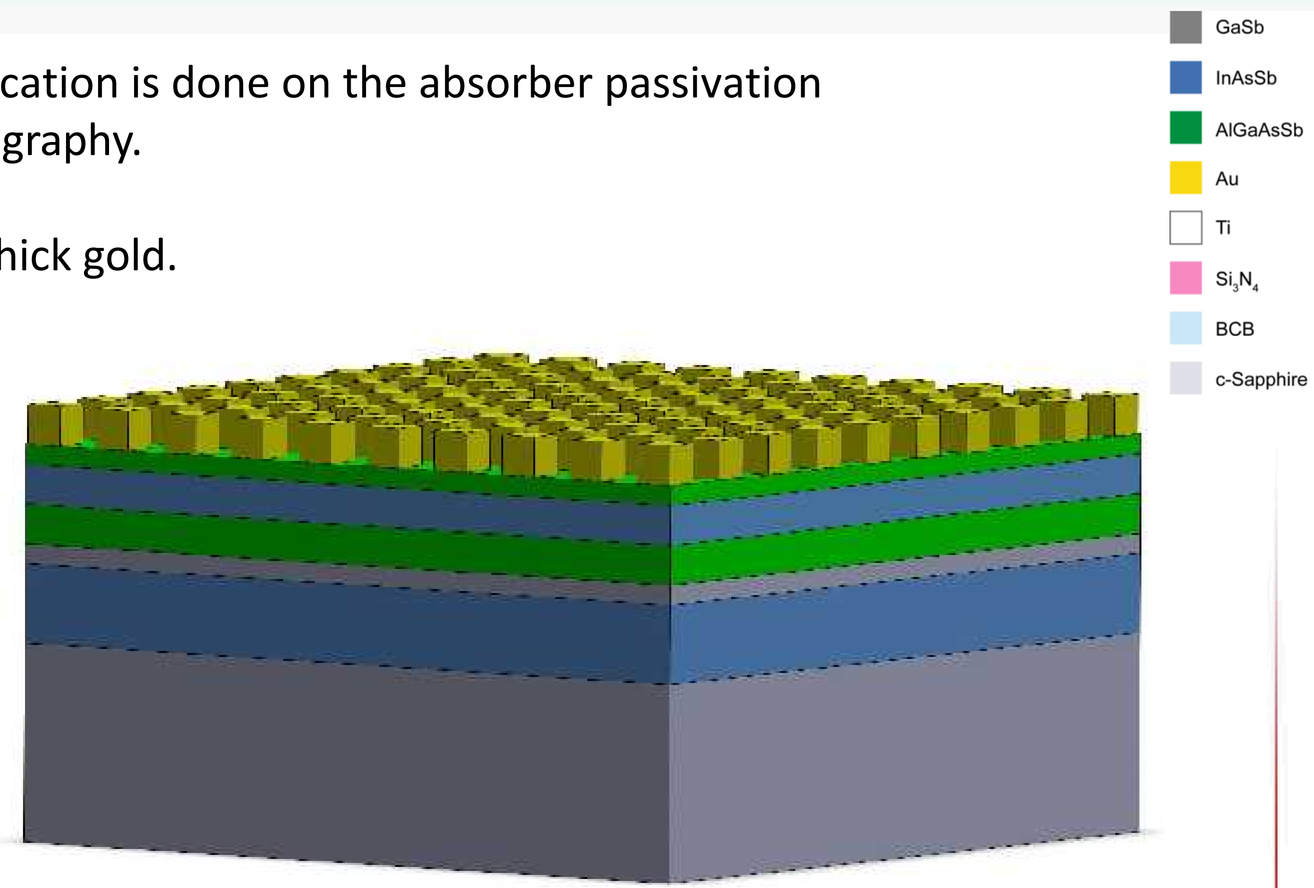
Fabrication Process Flow

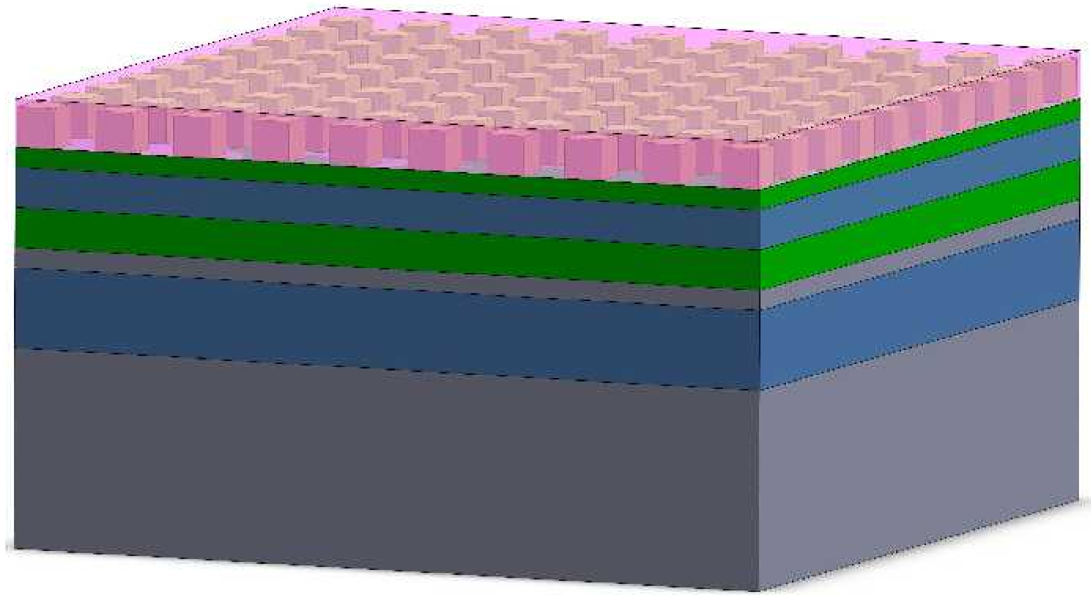
Nanoantenna (NA) fabrication is done on the absorber passivation layer using e-beam lithography.

The antenna is 100nm thick gold.



Fabrication Process Flow

The NA is encapsulated with 300nm of Si_3N_{4}--. The nitride provides a well-defined environment surrounding the antenna, in addition to providing an adhesion layer for the BCB.



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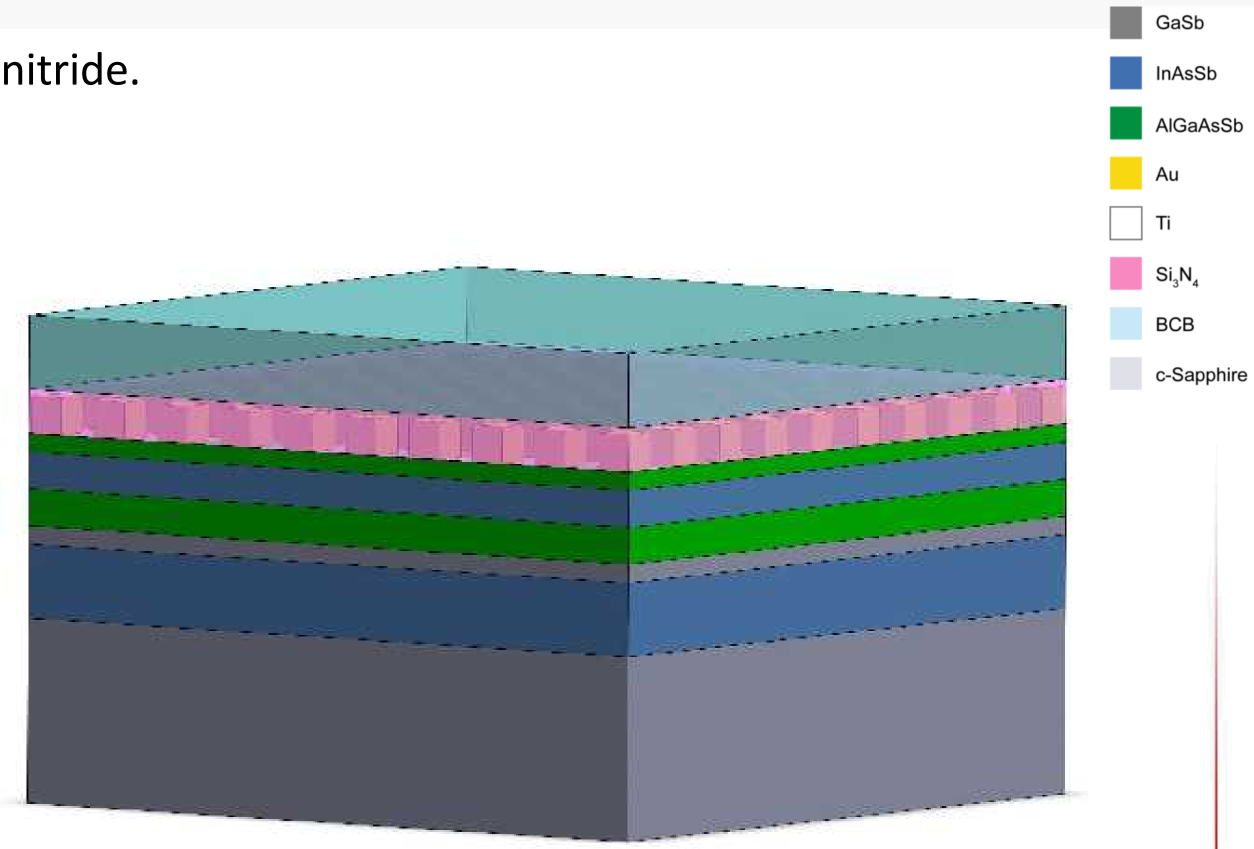
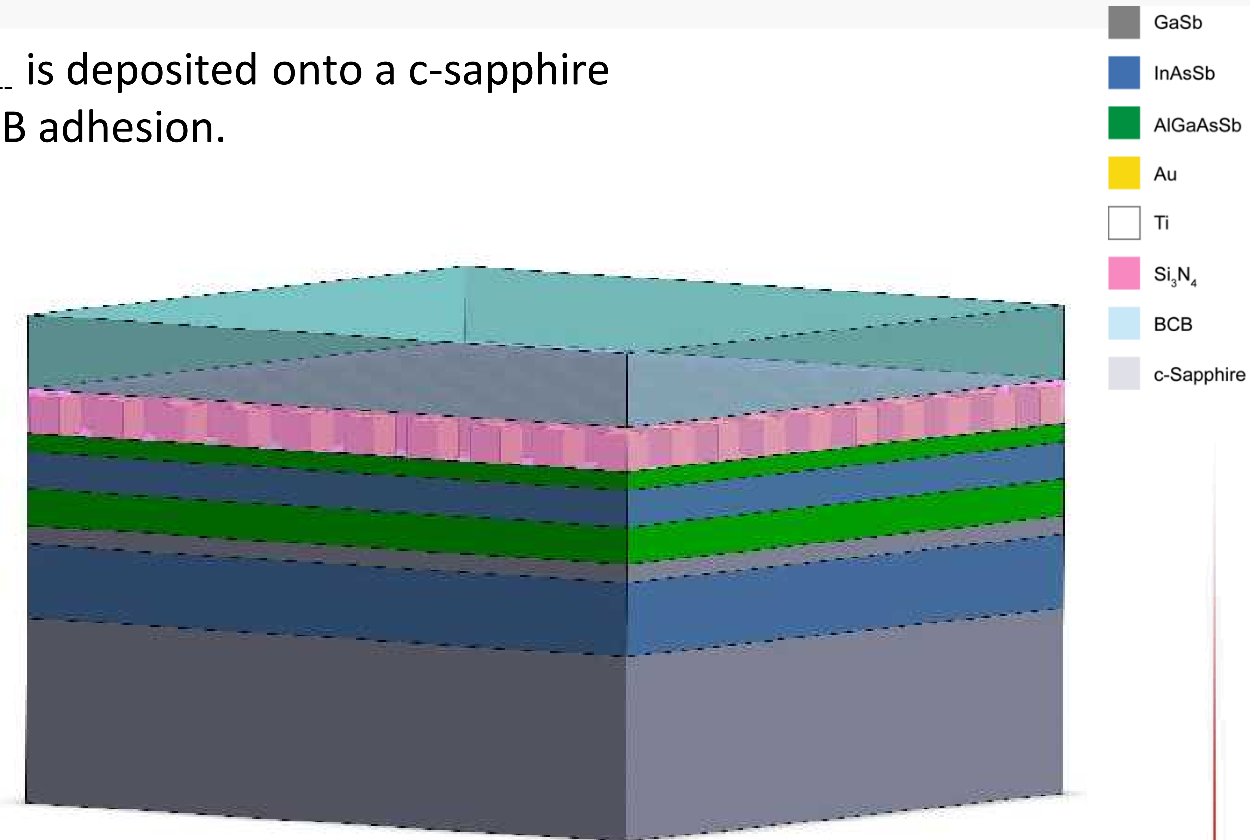
Fabrication Process Flow

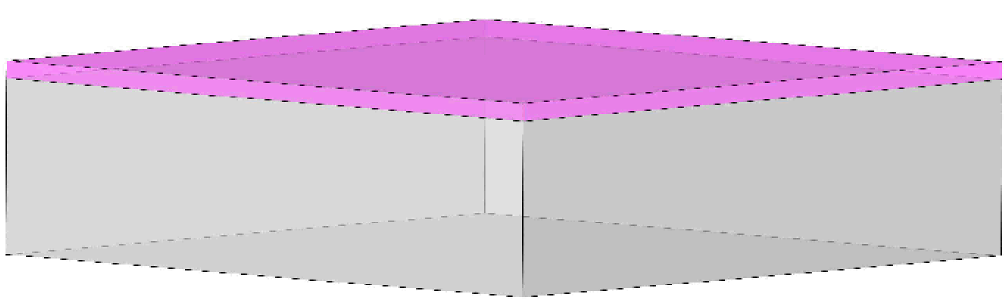
BCB is spin coated onto the nitride.



Fabrication Process Flow

A coating of 100nm of Si_3N_4-- is deposited onto a c-sapphire handle piece to promote BCB adhesion.

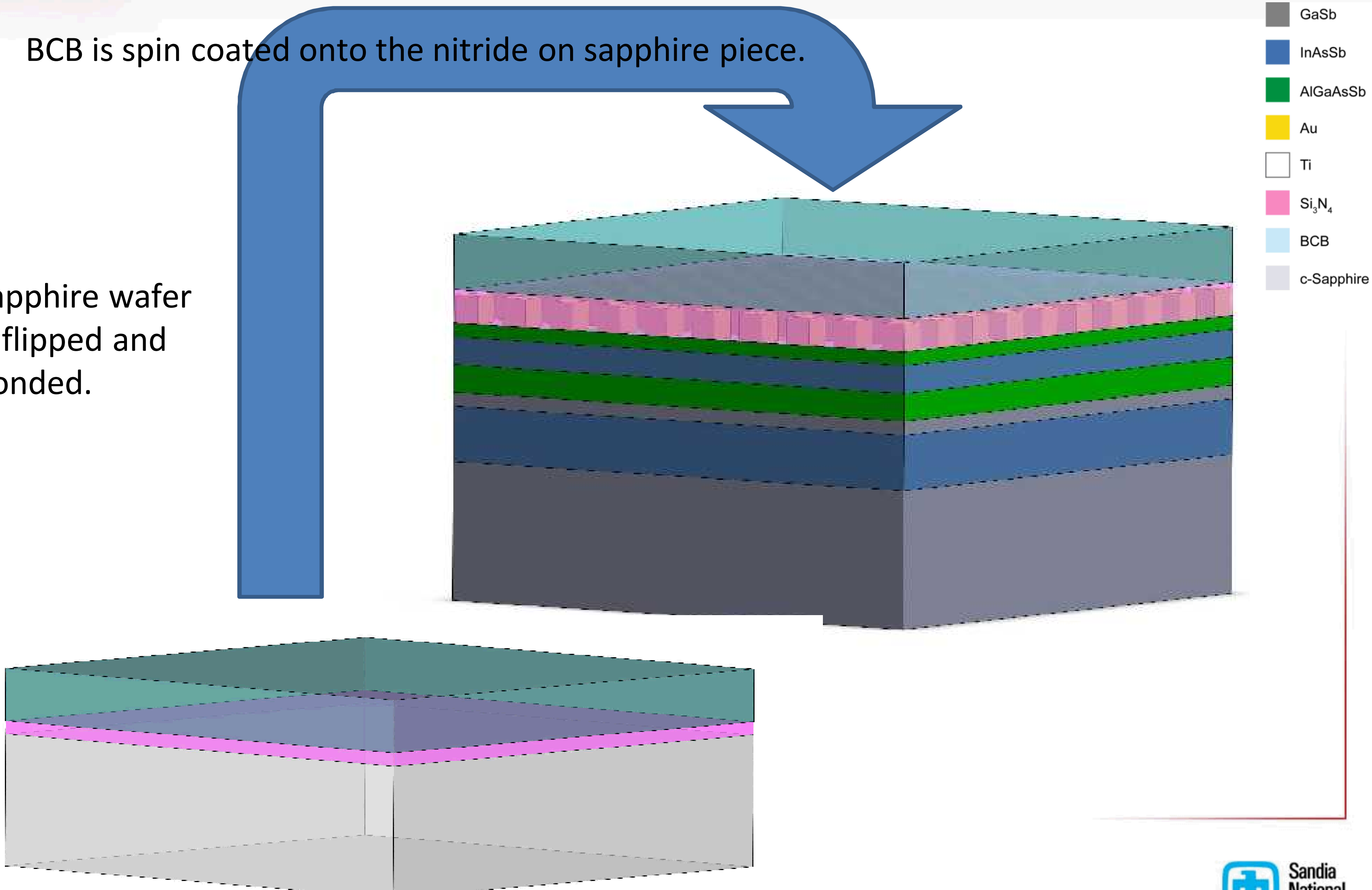




Fabrication Process Flow

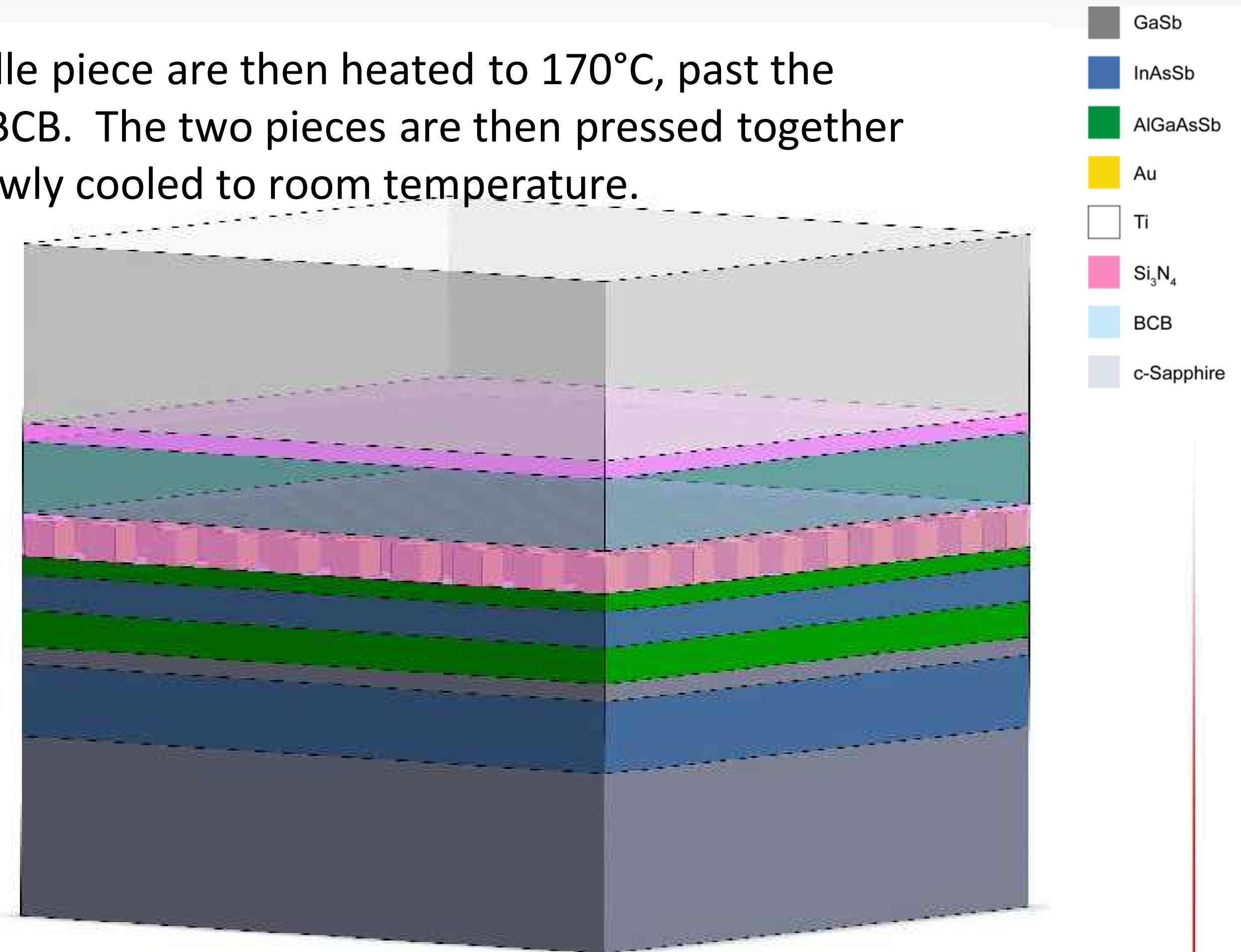
BCB is spin coated onto the nitride on sapphire piece.

Sapphire wafer is flipped and bonded.



Fabrication Process Flow

The NA sample and the handle piece are then heated to 170°C, past the glass transition point of the BCB. The two pieces are then pressed together into intimate contact and slowly cooled to room temperature.



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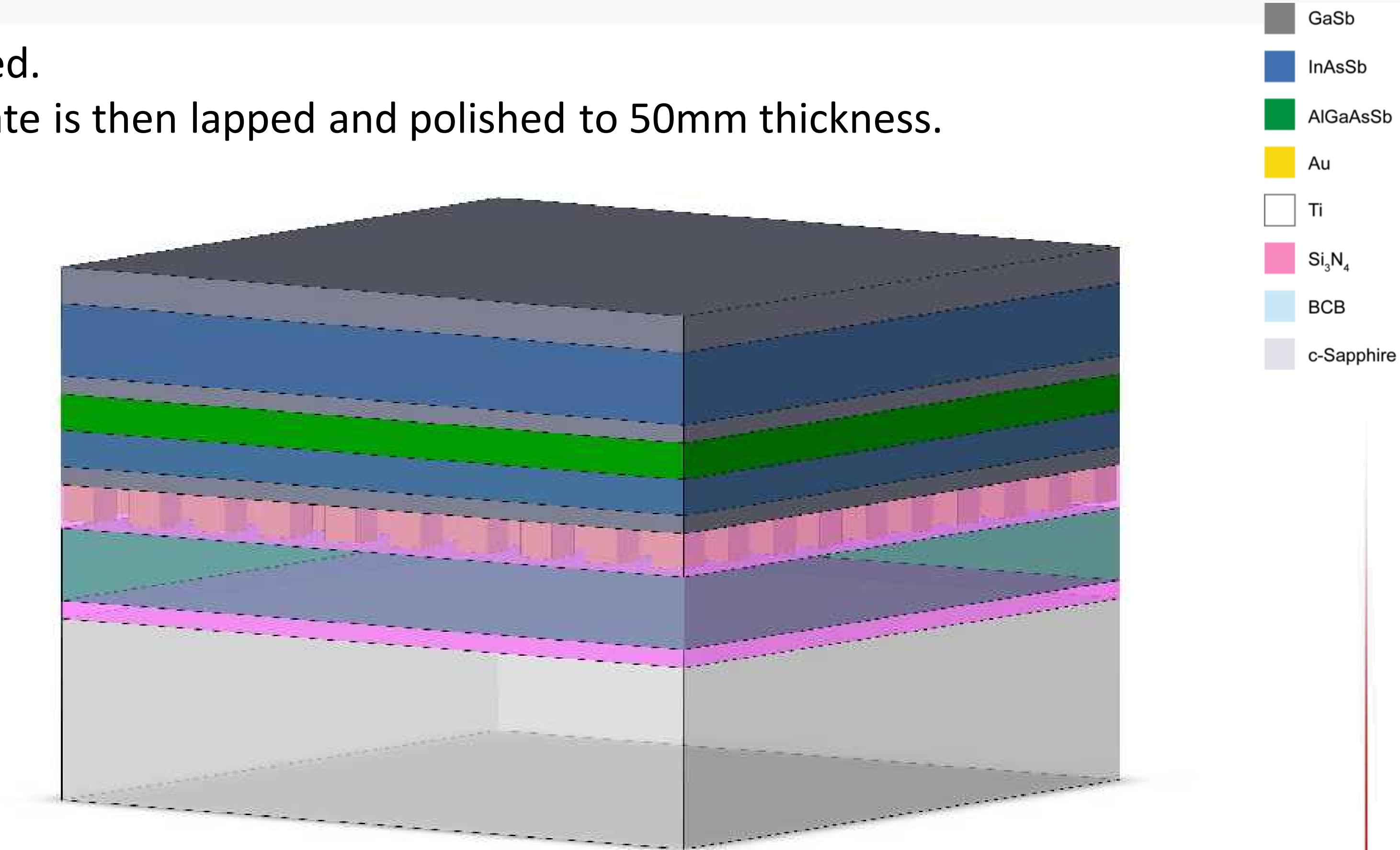
Fabrication Process Flow

Figure now flipped.

The GaSb substrate is then lapped and polished to 50mm thickness.



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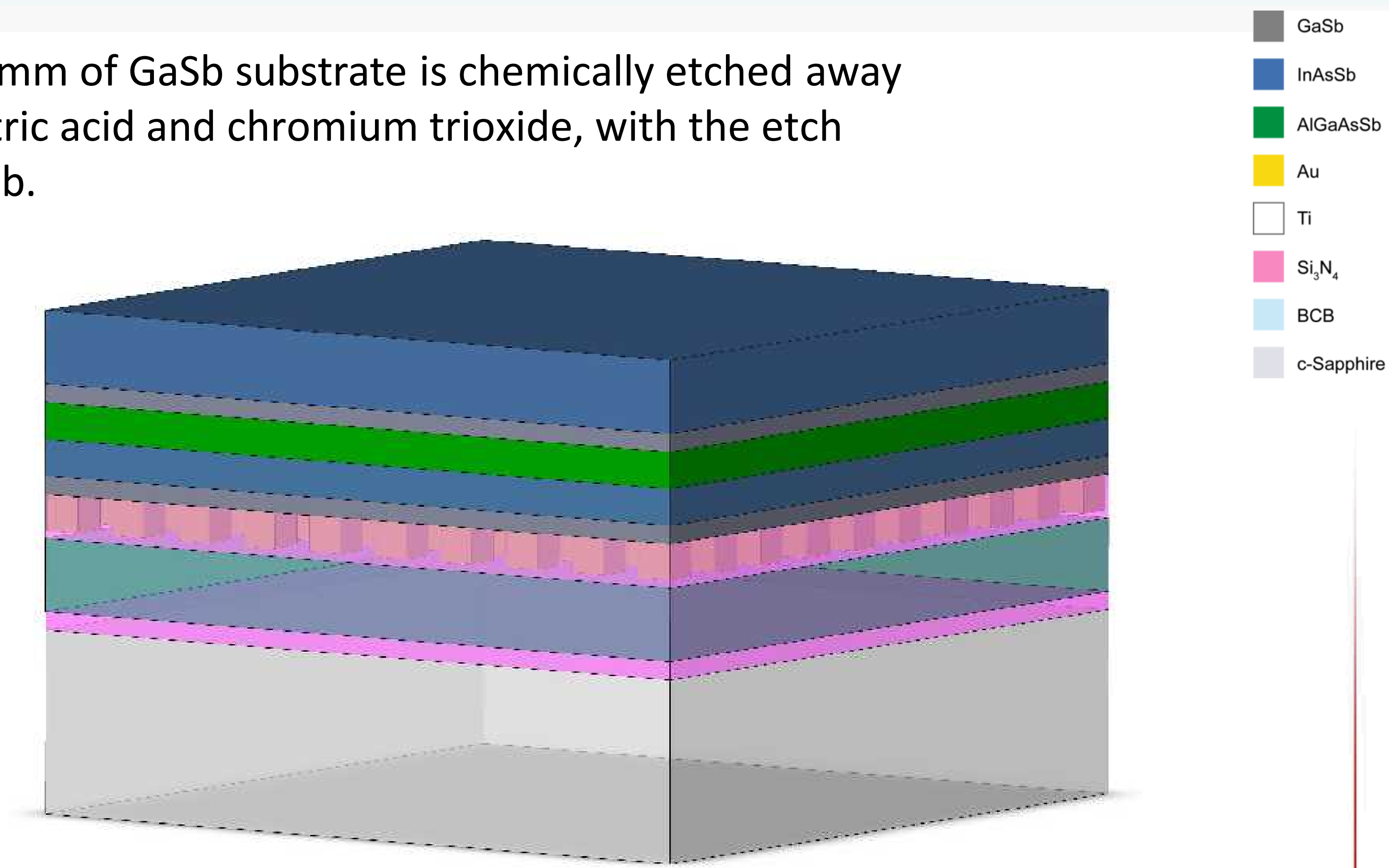
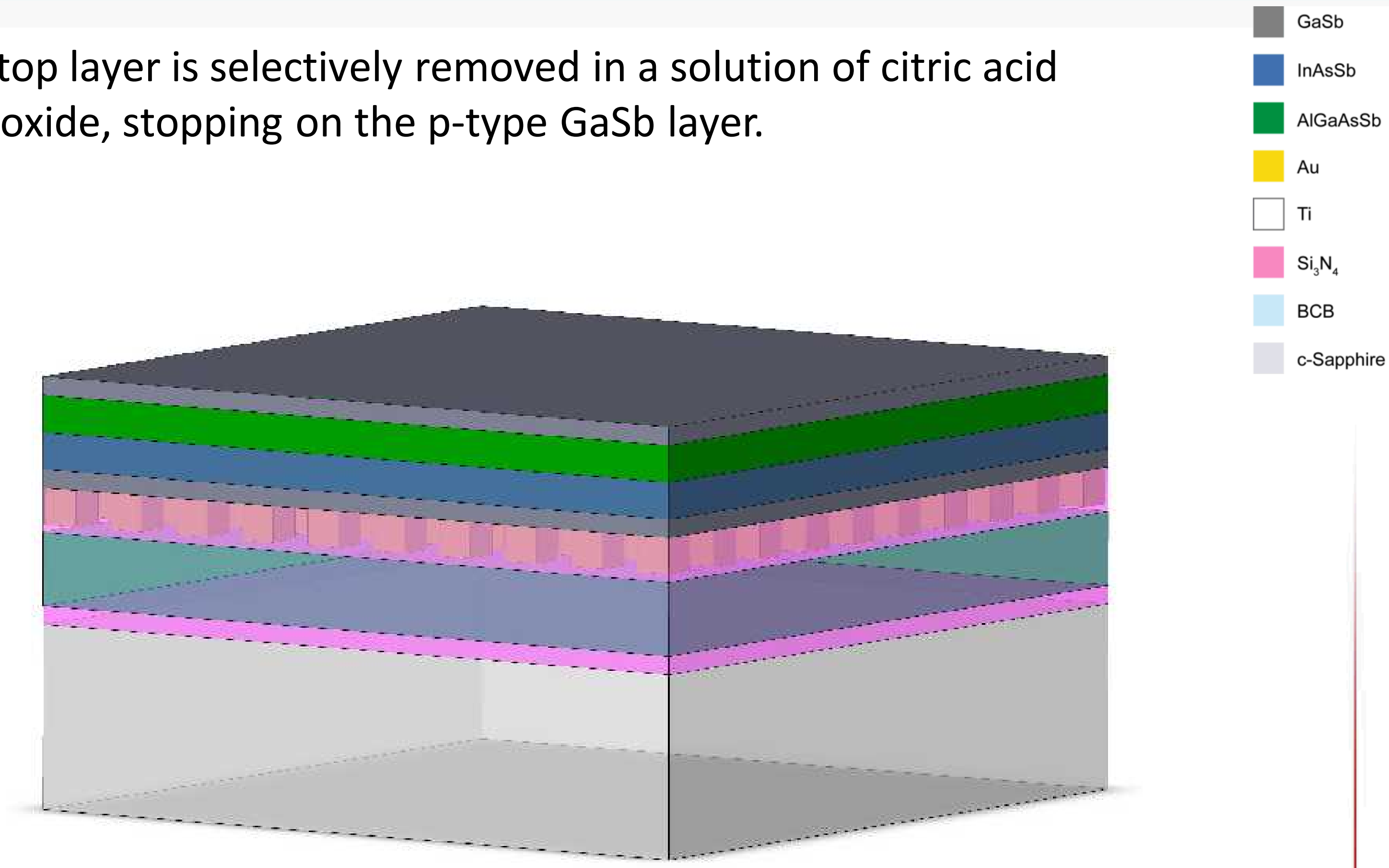
Fabrication Process Flow

The remaining 50mm of GaSb substrate is chemically etched away in a solution of citric acid and chromium trioxide, with the etch stopping on InAsSb.



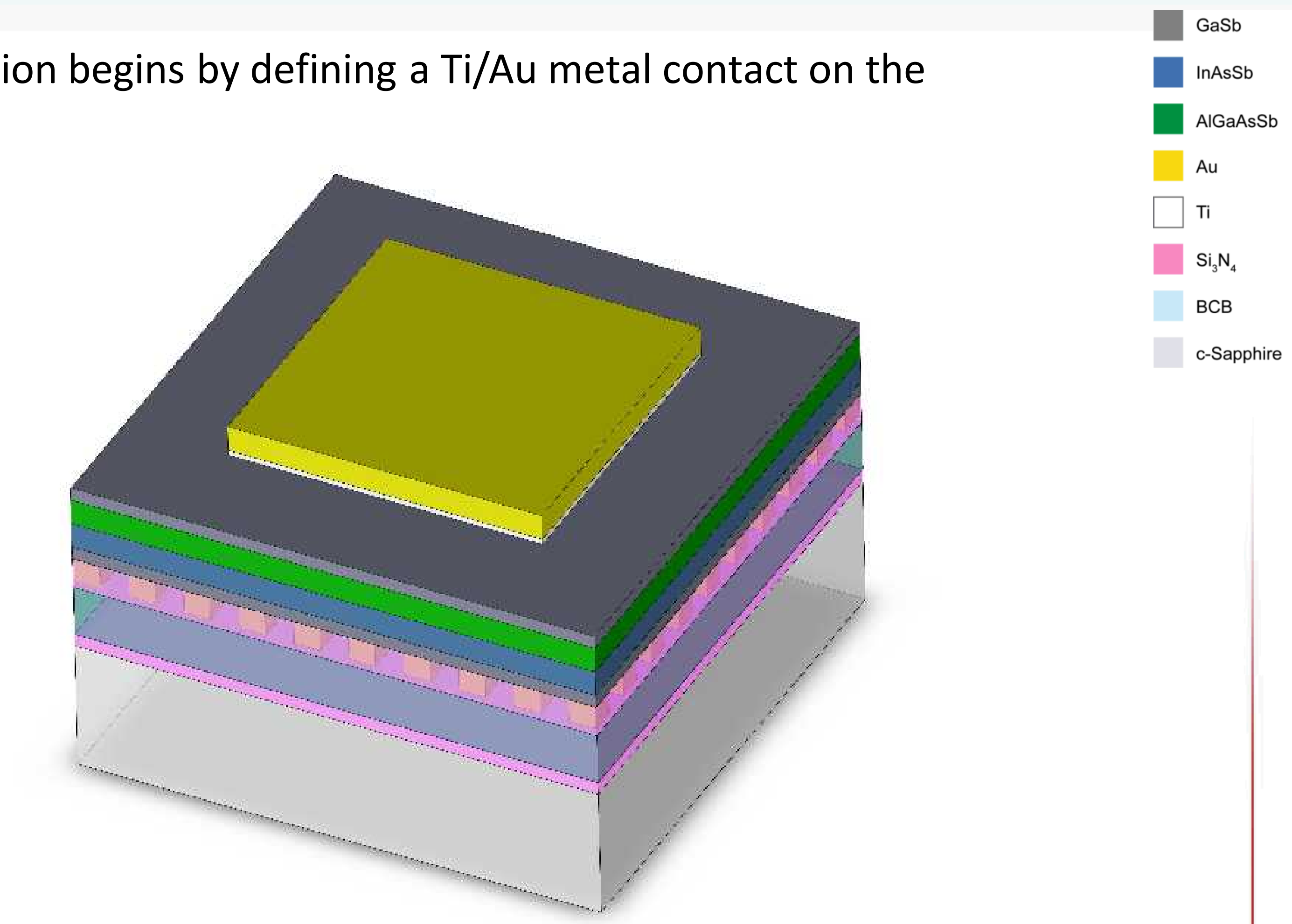
Fabrication Process Flow

The InAsSb etch stop layer is selectively removed in a solution of citric acid and hydrogen peroxide, stopping on the p-type GaSb layer.



Fabrication Process Flow

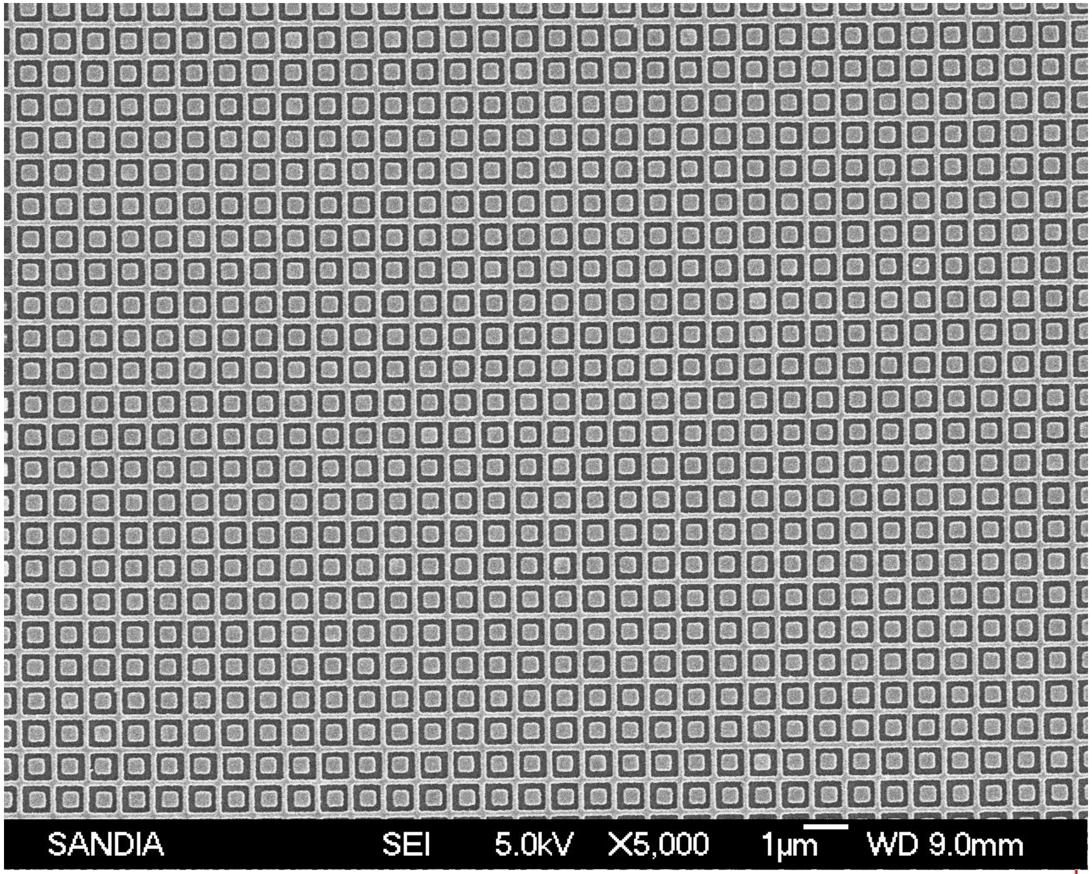
The FPA pixel fabrication begins by defining a Ti/Au metal contact on the GaSb surface.



Fabricated Device

We have written nanoantenna patterns.

Substrate removal and epoxy underfill have proven to be difficult processes.

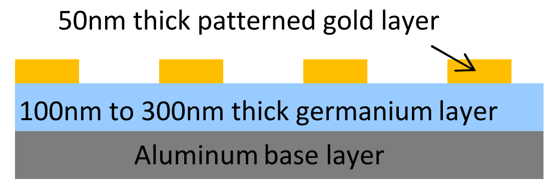


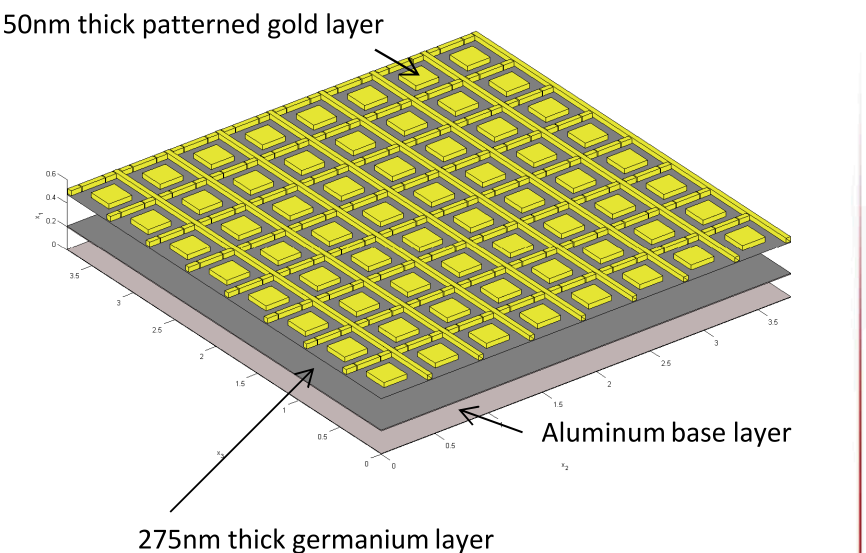
Germanium Detector

As with the other designs, this one involves a detection material between two metal layers. Since it is for the near-IR, the detector layer is quite thin. The metal top and bottom layers act as contacts.

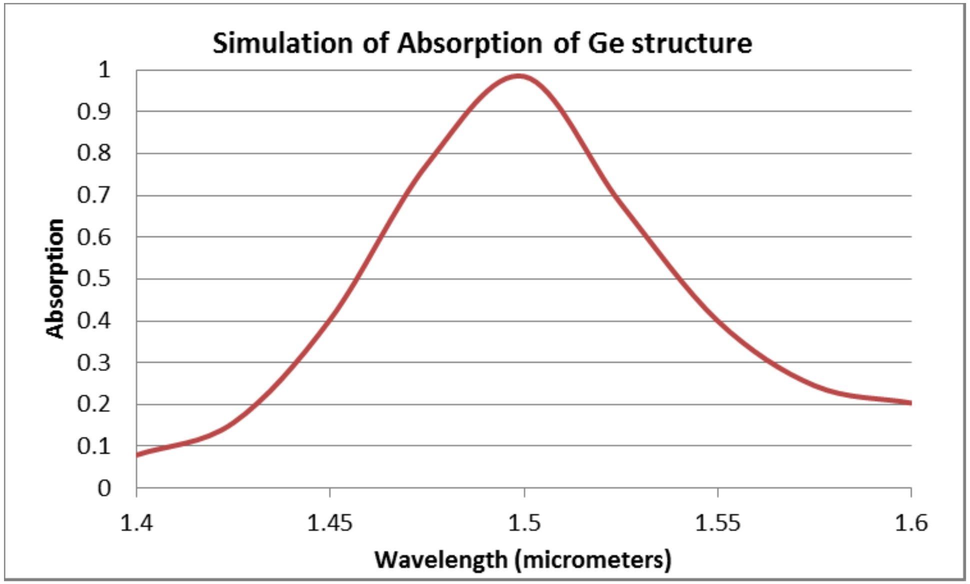
As it is thin, it is very fast as carriers move to a metal electrode quickly. Since the metal wire grid is not a large solid piece of metal, the capacitance should also be low.

We designed and simulated a structure with dimensions below to work at 1.5μm.





Period of nanoantenna = 475nm
Gold square width = 220nm
Width of continuous gold bars = 50nm



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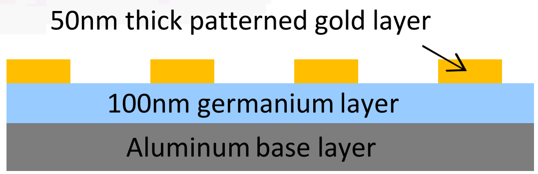
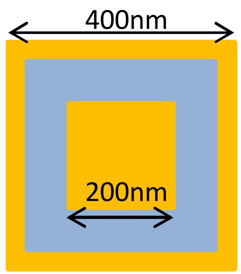
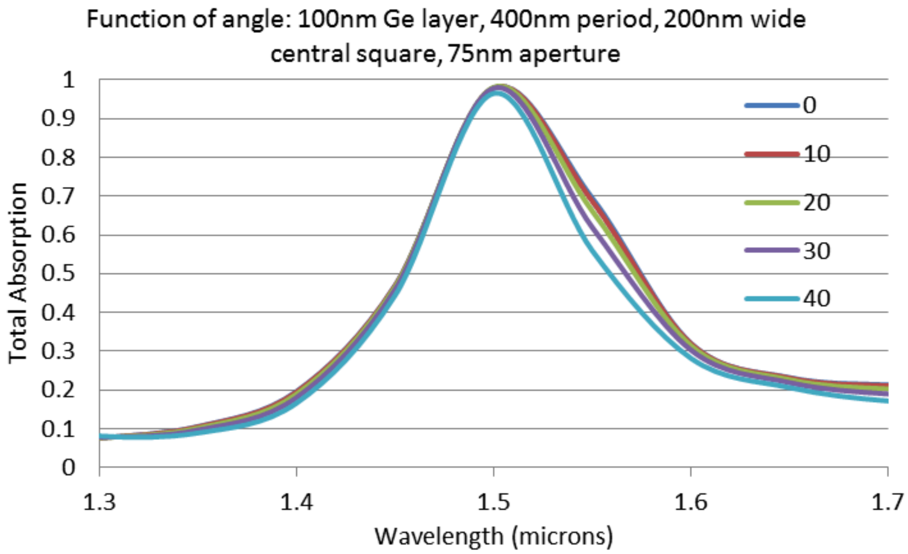
Thin Version

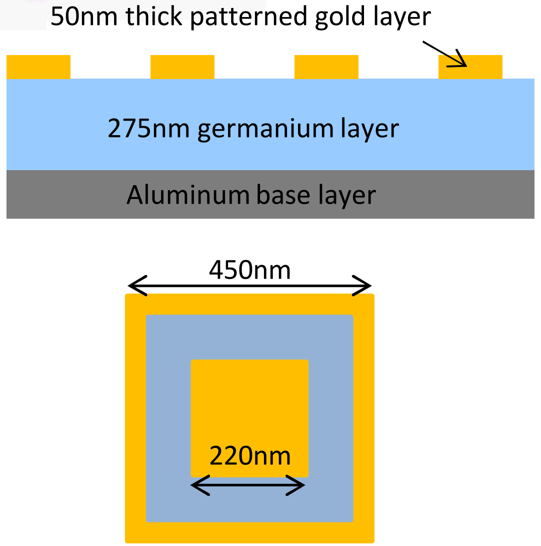




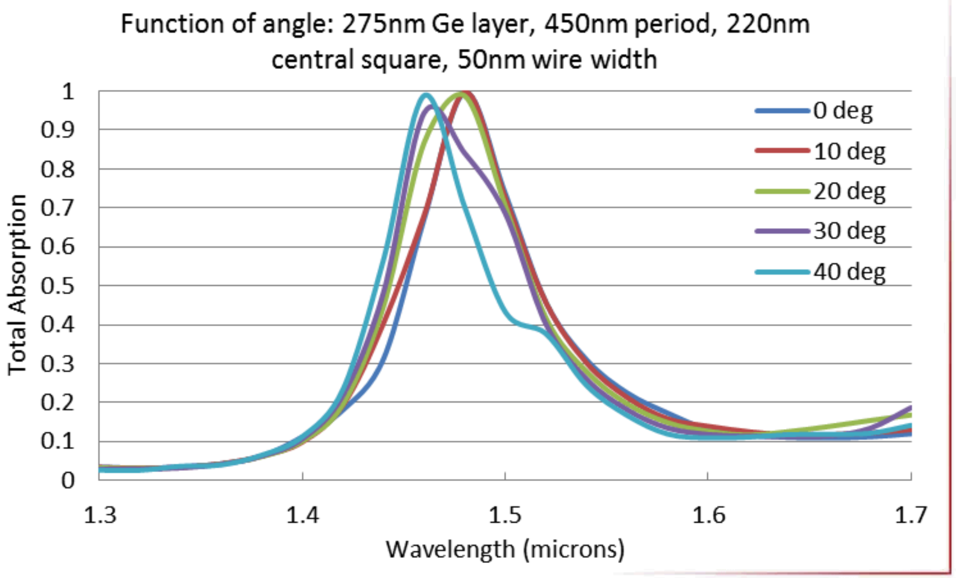
On this one I simulated a broader band (lower left), but the main feature is at lower right. There is virtually no change from normal out to 40deg. In any practical imaging system, this is more than enough.



Thick Version



In this version we see a shift with angle of the peak and also a change in lineshape. I am not sure if there are two modes that are excited or what. Probably worth looking at the fields to see what the difference is.



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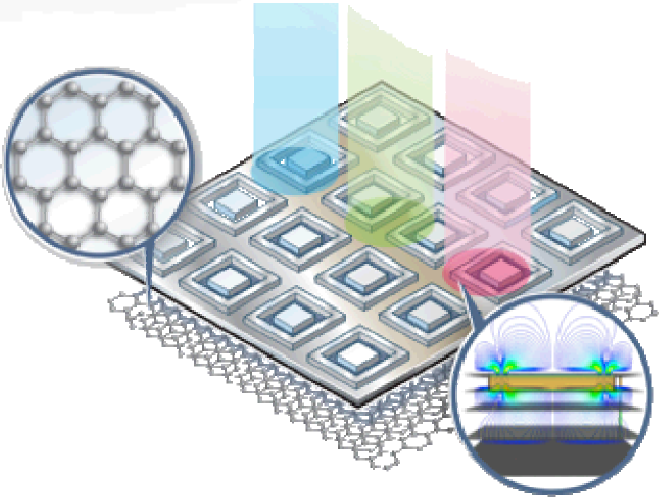
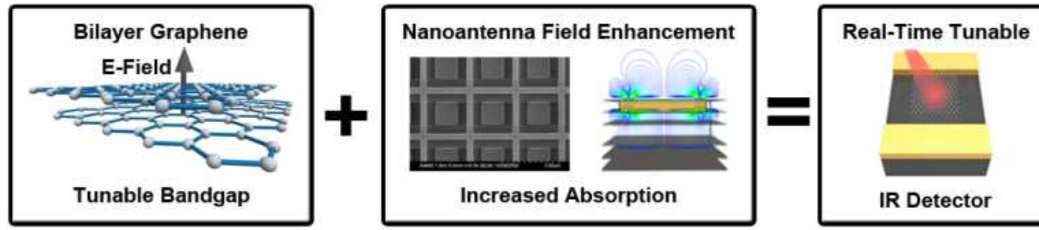
Nanoantenna-Enabled Bilayer Graphene Detectors

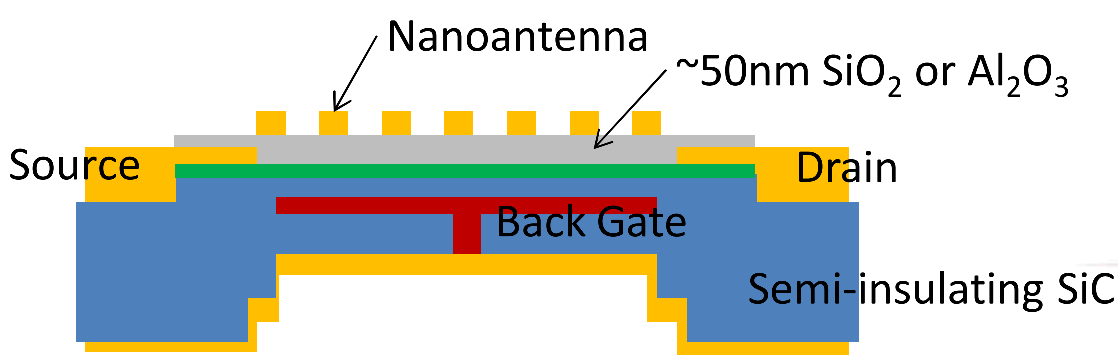
IR detection with a real-time voltage-tunable bandgap.





The 2 atomic layers of bilayer graphene only absorb 4.6% of an incident plane wave.

We can concentrate the light with the nanoantenna for **10X** greater efficiency.



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Summary

The nanoantenna concept allows for a new detector architecture for many IR detector platforms: irrespective of material.

Very thin active layer leads to

- Less dark current
- Less crosstalk
- Faster operation

The nanoantenna gives us

- Spectral or polarization filtering by changing pattern from pixel to pixel
- Built-in wide-angle antireflection coating
- Built in EMI protection
- A material-agnostic device

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