SAND2024-10201C

IEEE RESEARCH AND APPLICATIONS OF PHOTONICS IN DEFENSE

14-16 August 2024 ▪ Miramar Beach, FL, USA

www.ieee-rapid.org

Characterization of Hot-carrier Enhanced Pixels for Out-of-band CMOS Camera

Matthew E. Spotnitz, Zachary Piontkowski, Raktim Sarma, Nicholas J. Karl, Mason J. Risley, Deanna M. Campbell, ***Evan M. Anderson,*** *and D. Bruce Burckel*

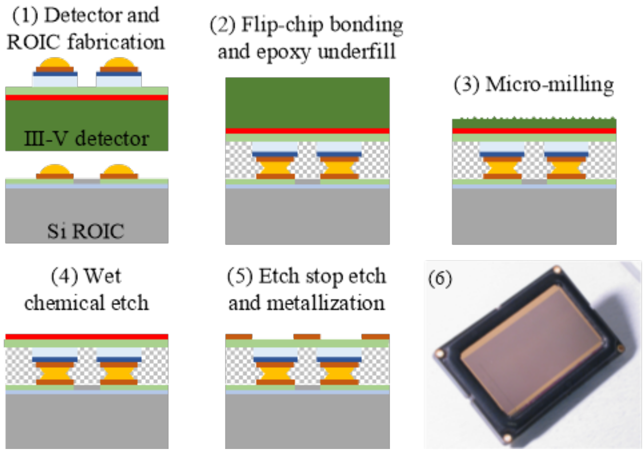
Sandia National Laboratories

15 August 2024

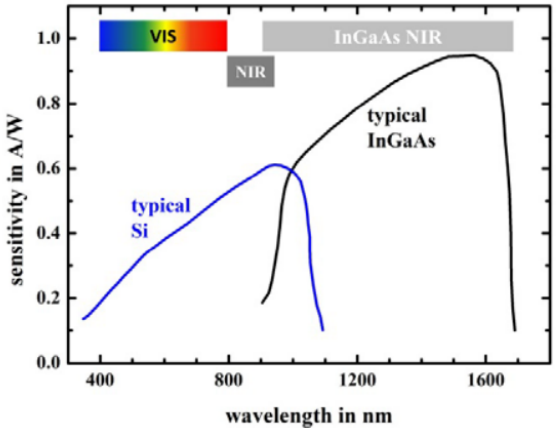
RAPID Research and Applications of Photonics in Defense | IEEE Photonics Society | IEEE

Infrared (IR) Imaging

- Many defense applications require IR detection
- InGaAs and HgCdTe work, but are comparatively expensive with complex heterogeneous integration (though certainly well-developed, ongoing area of research)
- Capitalizing on robust, inexpensive Si manufacturing for IR detection is desirable



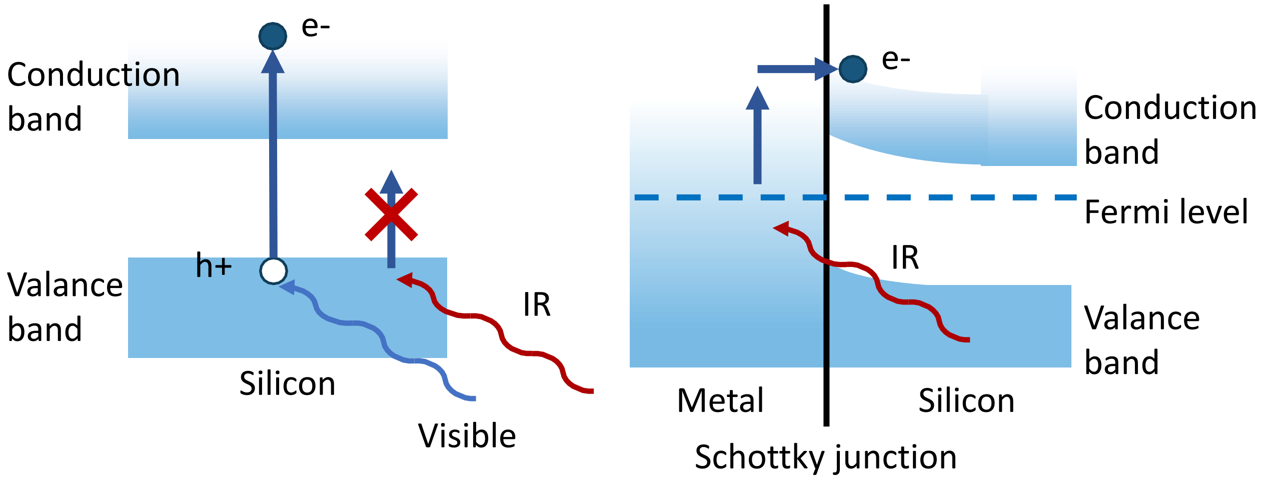
M. G. Wood et al., *in CLEO, Technical Digest Series* (2023).



M. Vollmer et al., ETOP Proceedings, TPE09, (2015)

Band Structure and Light Absorption

- Silicon band gap is too wide for IR beyond ~1100 nm
- Schottky barrier allows hot-carrier injection for IR beyond Si band gap
- Inefficient processes to excite and extract carriers

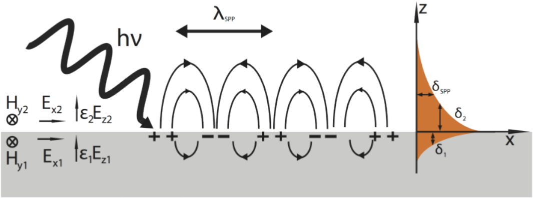


Type and structure	Barrier height (eV)	EQE
Au NPs/n-Si pyramid	0.8	0.9%
Al/ n-Si pyramid	N/A	3.5%
Au grating/n-Si	0.5	0.05%
TPs based Au/n-Si	0.8	1.8%
Au/n-Si waveguide	0.76	0.03%
TPs based Au/p-Si	0.32	2.84%
Au grating/p-Si	0.32	1.04%
Au/p-Si waveguide	0.33	0.09%
Au/oxide/Si	3.8	13.5 % (4 V bias)

Zhu et al., Appl. Phys. Rev. 8, 021305 (2021)

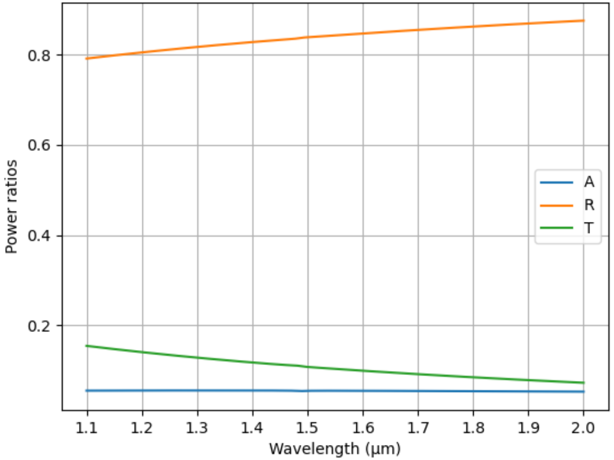
Plasmonic Resonances to Boost Sensitivity

- Photoelectric effect generates carriers in metal
- Metasurface designed to resonantly excite a plasmon in metal
- Increase absorption at desired wavelength

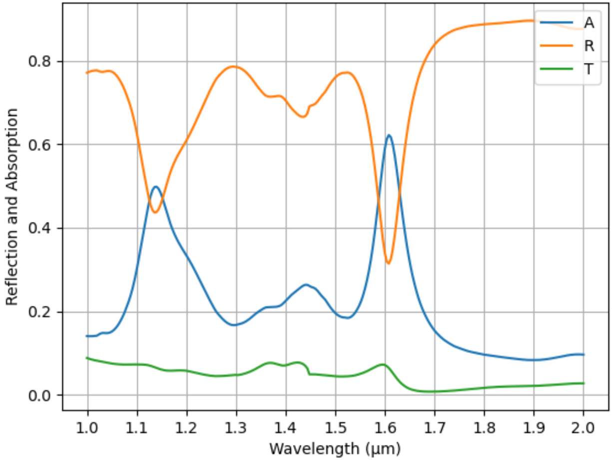


https://en.wikipedia.org/wiki/Surface_plasmon

Simulated Unpatterned Schottky Diode



Simulated Plasmonic Metasurface



Photonic Designs: Sample Geometry Defines Resonance

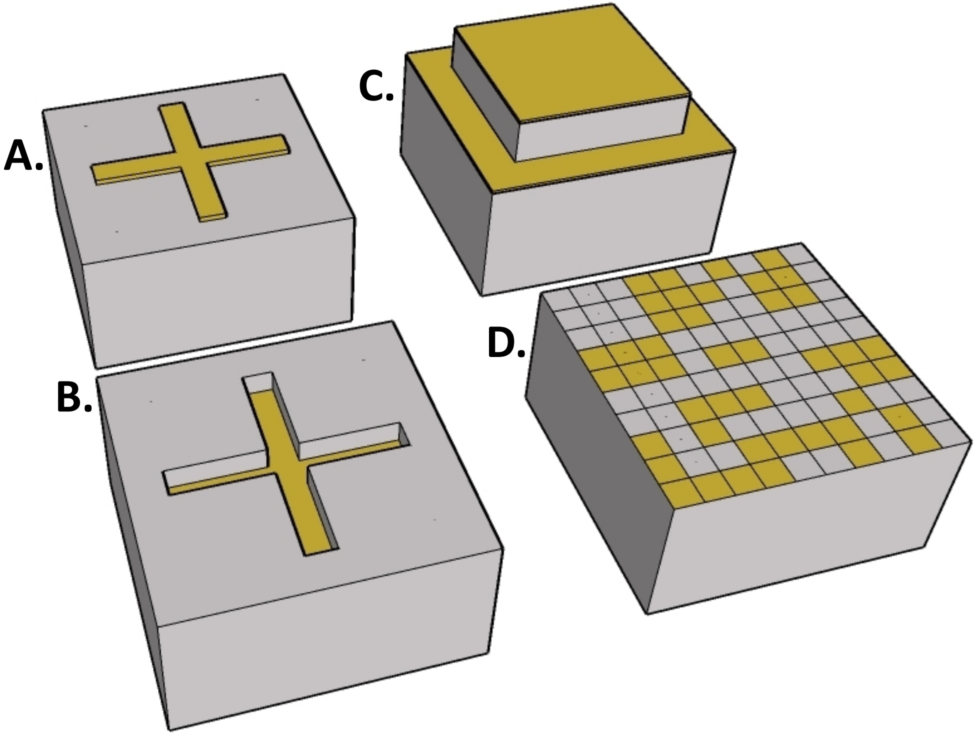
- Large variable space of design options!

A. Canonical Cross
  - Resonant antenna to excite a dipole for a photoconductor

B. Embedded Cross
  - Increase metal/semiconductor interfacial area to improve carrier extraction

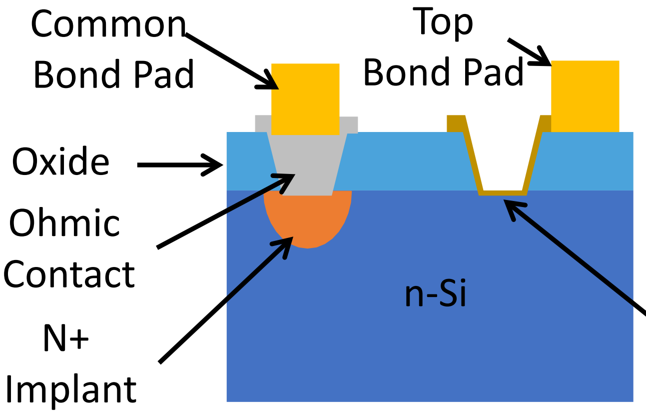
C. Square Mesa
  - Continuous metal enables photodiode
  - E.g. Li & Valentine, Nano Lett., 14, (2014)

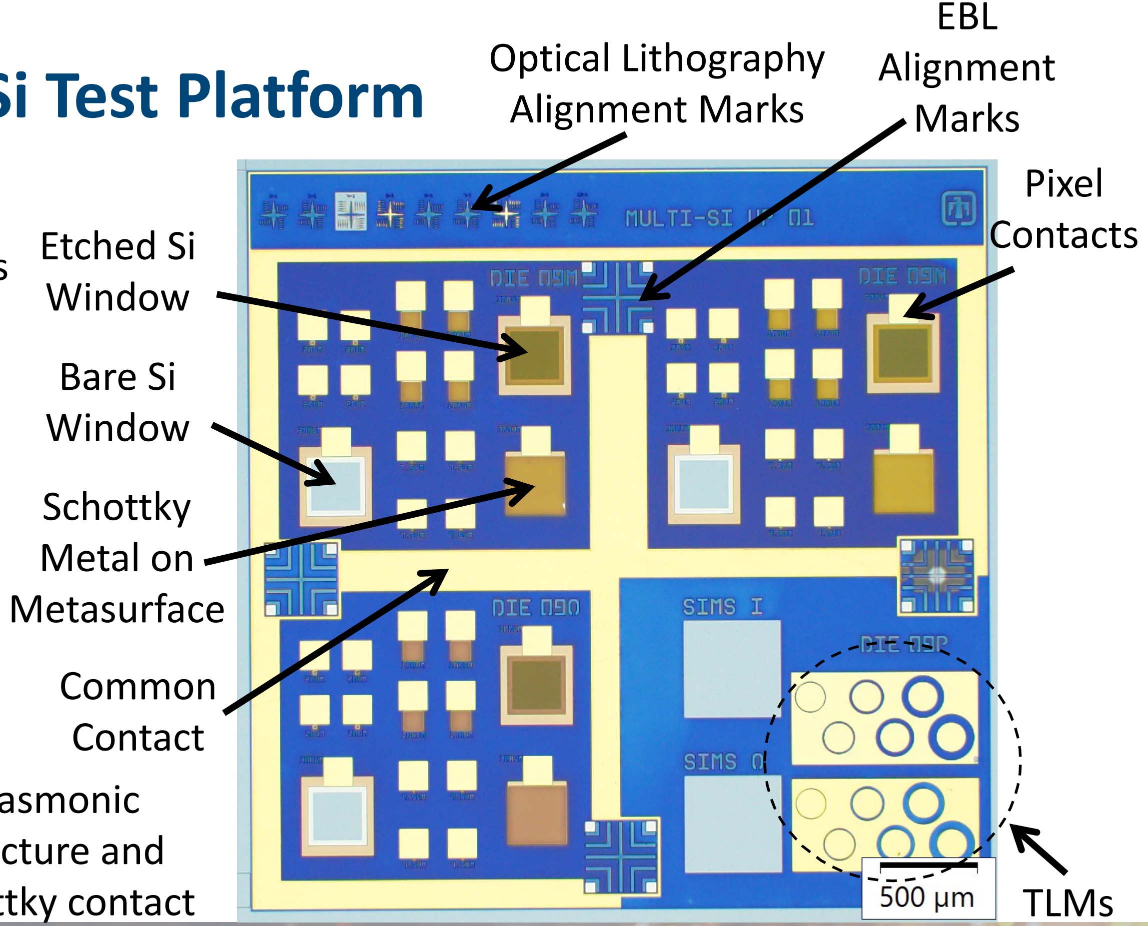
D. Genetic Algorithm
  - Iterate over generations of design modifications to maximize absorption
  - Enables unintuitive geometries
  - E.g. Sarma, et al., Crystals, 12, (2020)



Accelerate Learning: Si Test Platform

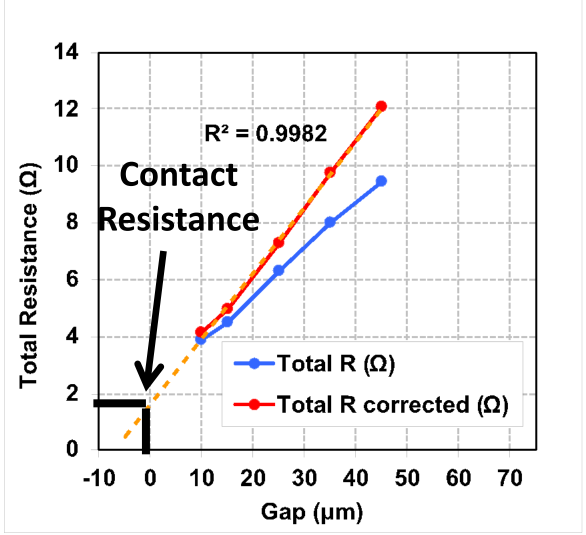
- Variety of device sizes and structures for electrical and optical measurements
- Electron beam lithography for nanoscale metasurfaces with optical lithography for high throughput

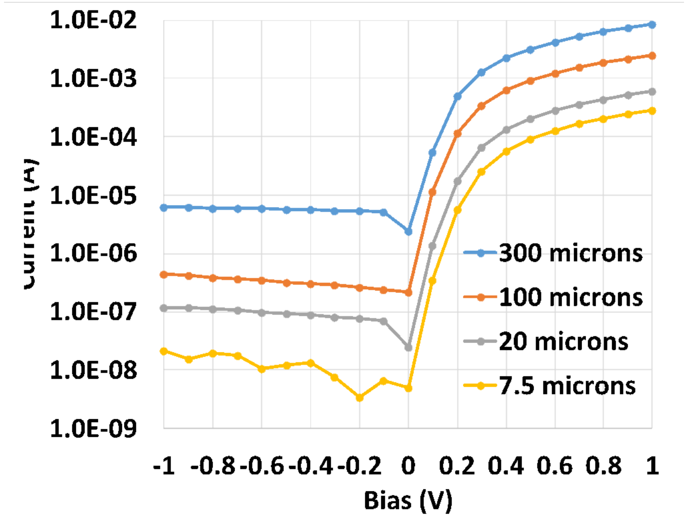




Testbed Electronically Suitable for Optical Devices

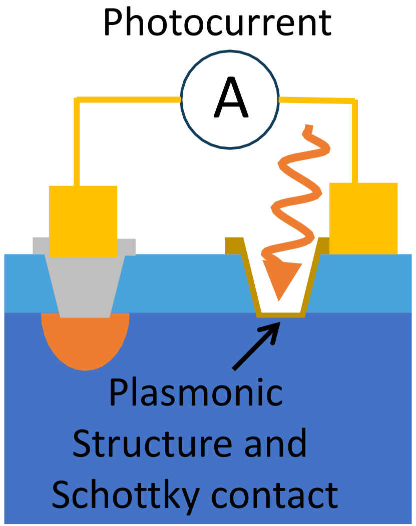
- Acceptable Ohmic contacts with ~1.4e-5 Ω-cm^2 contact resistivity and ~110 Ω/□ sheet resistance
- Ti/Au monolithic diodes are rectifying at room temperature for all device sizes

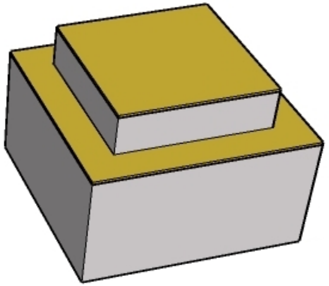


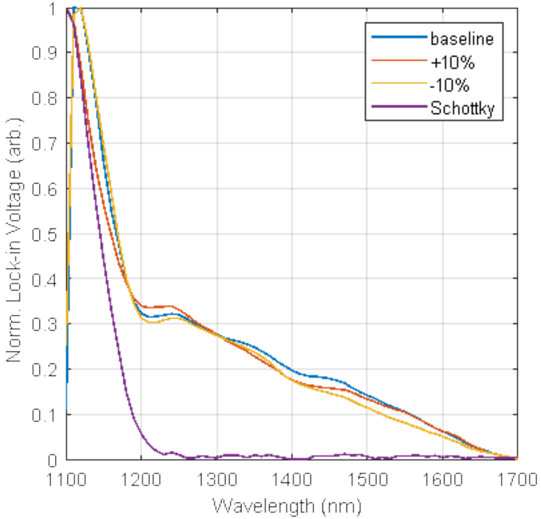


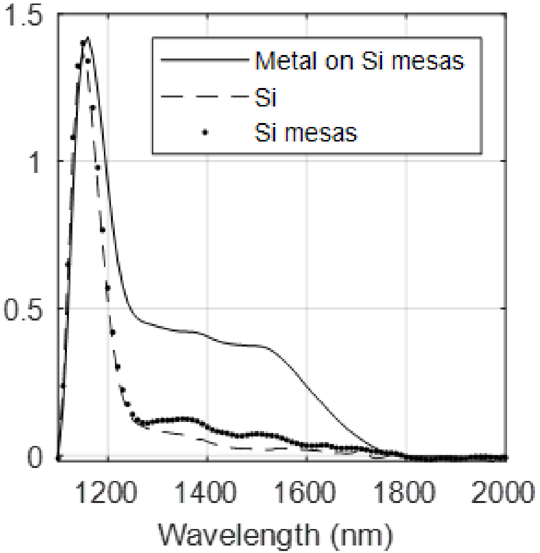
Broad Out-of-Band Response with Square Mesas

- Minimal response for monolithic Schottky metal and bare Si, as expected
- Response insensitive to minor changes in lateral dimensions
- Suspect fabricated geometry doesn't match designed geometry









Summary and Conclusions

- We've developed a CMOS-compatible testbed for Si-based metasurface IR detectors for out-of-band detection
  - Enables electronic and optical characterization of resonant metasurface designs to rapidly explore large variable space
  - Initial testing validated ohmic contacts and Schottky contacts needed for hot carrier photodiodes
  - Initial optical testing showed out-of-band absorption in square mesas, with further fabrication development in progress to match simulated wavelength resonance

This work was supported by the Laboratory Directed Research and Development Program at Sandia National Laboratories and was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.