Membrane Based Hard-X-Ray Imager

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Outline

- **Introduction:**
  Conventional Photomultiplier tube (PMT)
- **Our Approach: Membrane enabled imager**
- **What is unique about membrane?**
- **Preliminary results**
- **Future plan**

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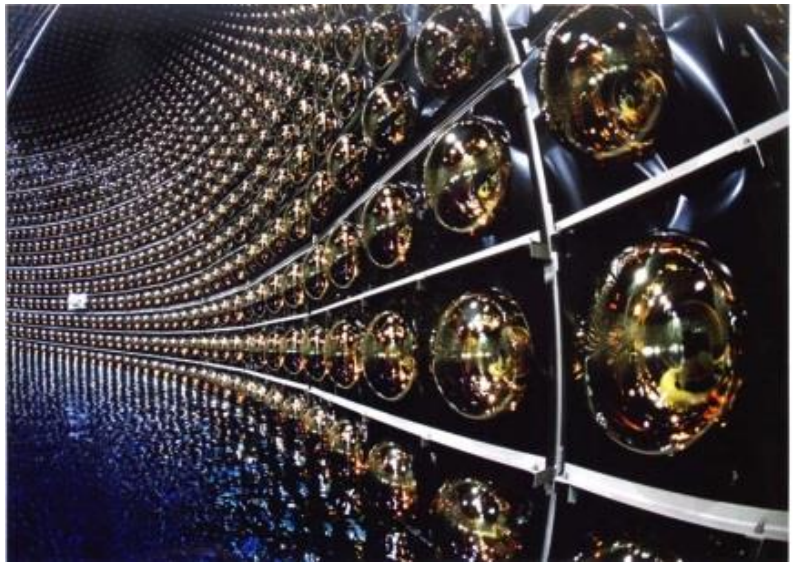
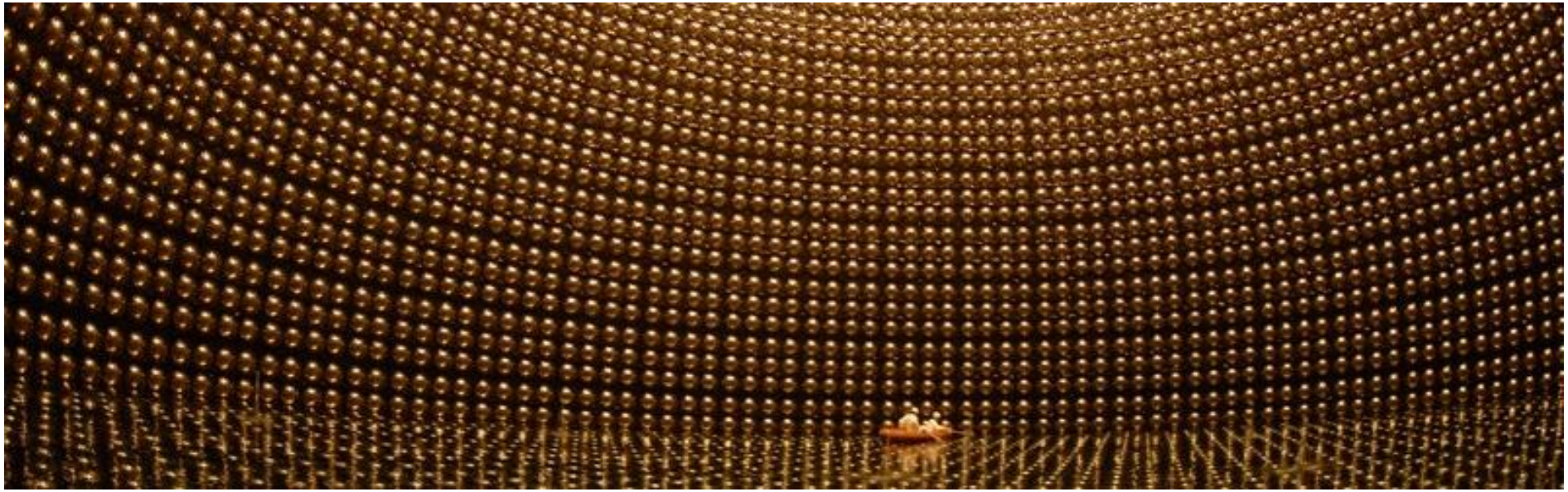
Photomultiplier Tube (PMT) for High-Energy Particle Detection



Single PMT

- Bulky
- Slow reponse
- No spatial information recorded



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Membrane Enabled Imager

------- Based on fast scintillator

Proposed Plan

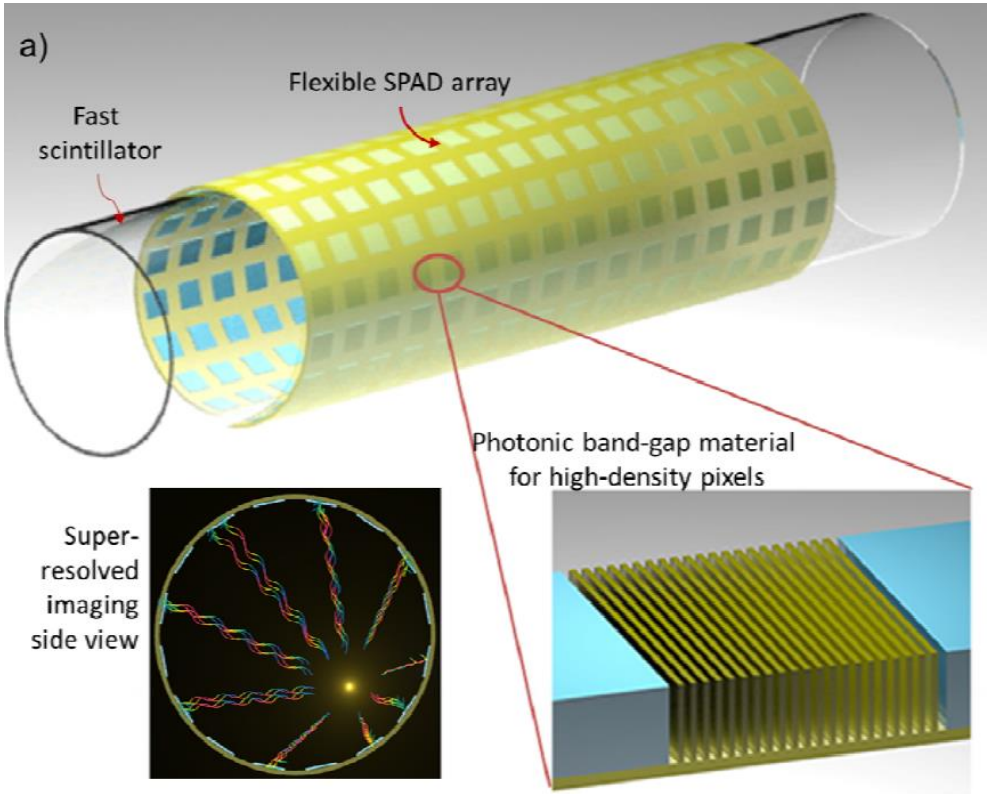
- Flexible Silicon membrane detector array wrapped around the scintillator
- Monte-Carlo method algorithm to achieve super-resolved imaging
- Photonic Crystal structure to realize optical signal isolation

Approach

- Traditional nanofab process to realize p-i-n silicon avalanche photodiode (SPAD)
- Using membrane transfer method to transfer detector array on any unusual substrate

Impact

- Ultra compact, flexible X-Ray Imager
- SOI based silicon membrane p-i-n diode
- 3D tomography single photon level sensitivity
- Low voltage operation mode
- Can be integrated to any mobile systems



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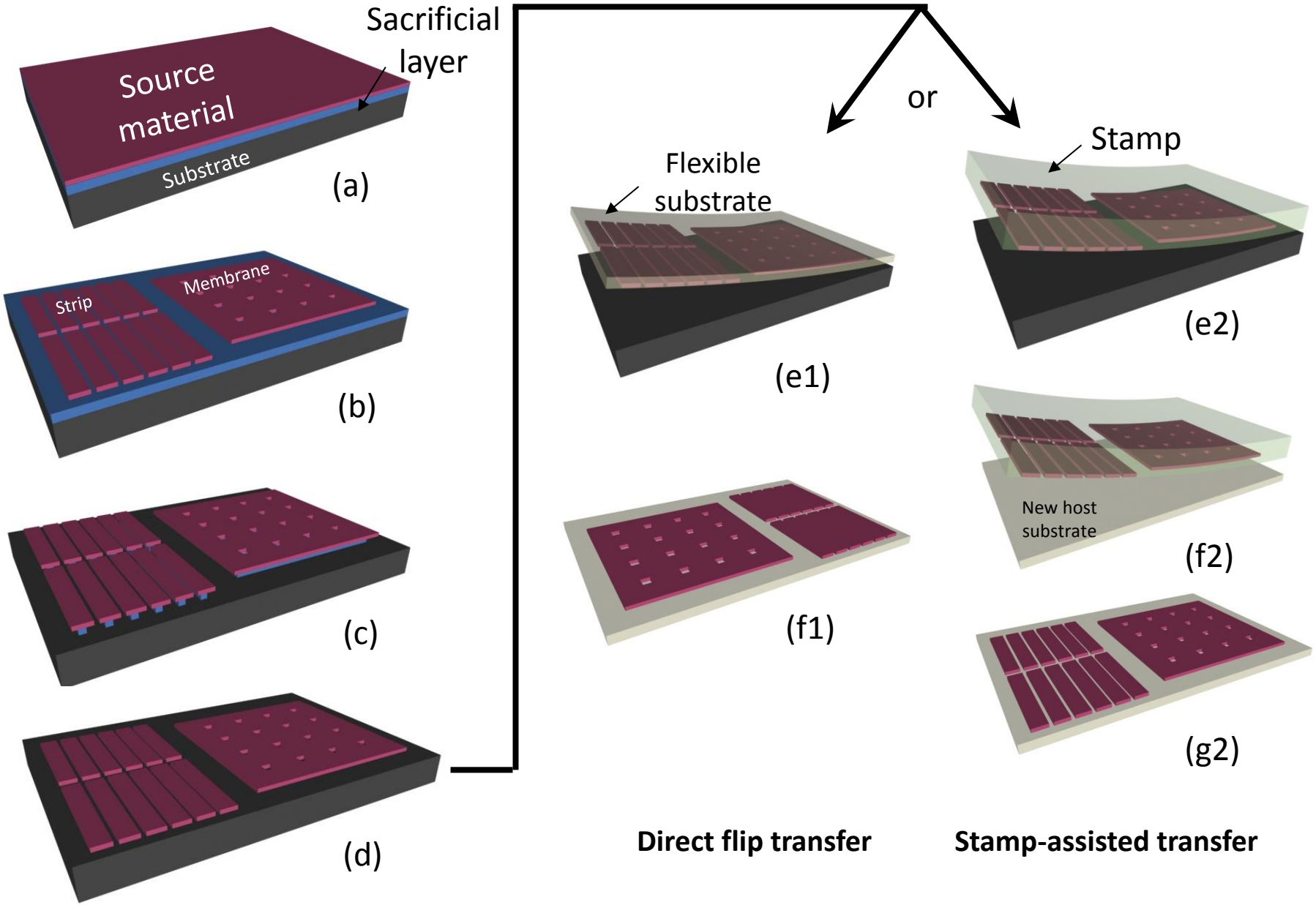
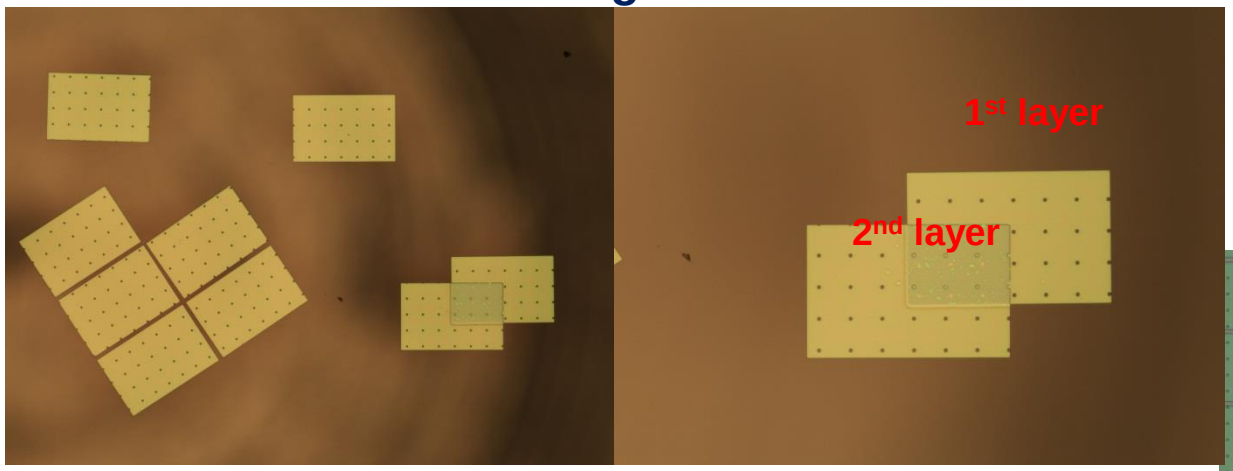
Semiconductor Nanomembranes
release and transfer printing - the general approach



Multiple-times transfer printing/stacking of semiconductor nanomembranes

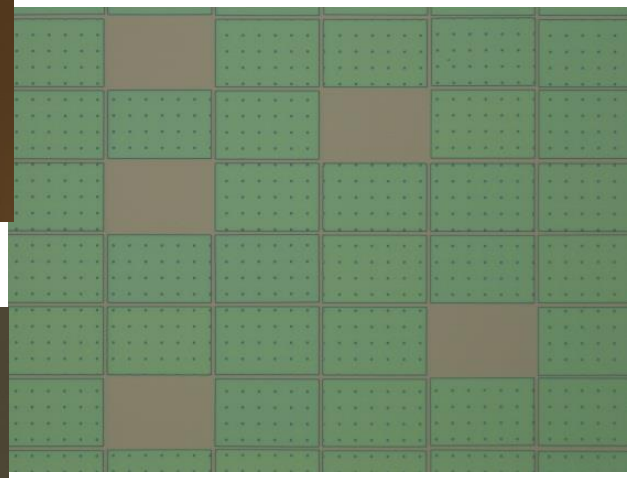
The receiver substrate

Printing twice



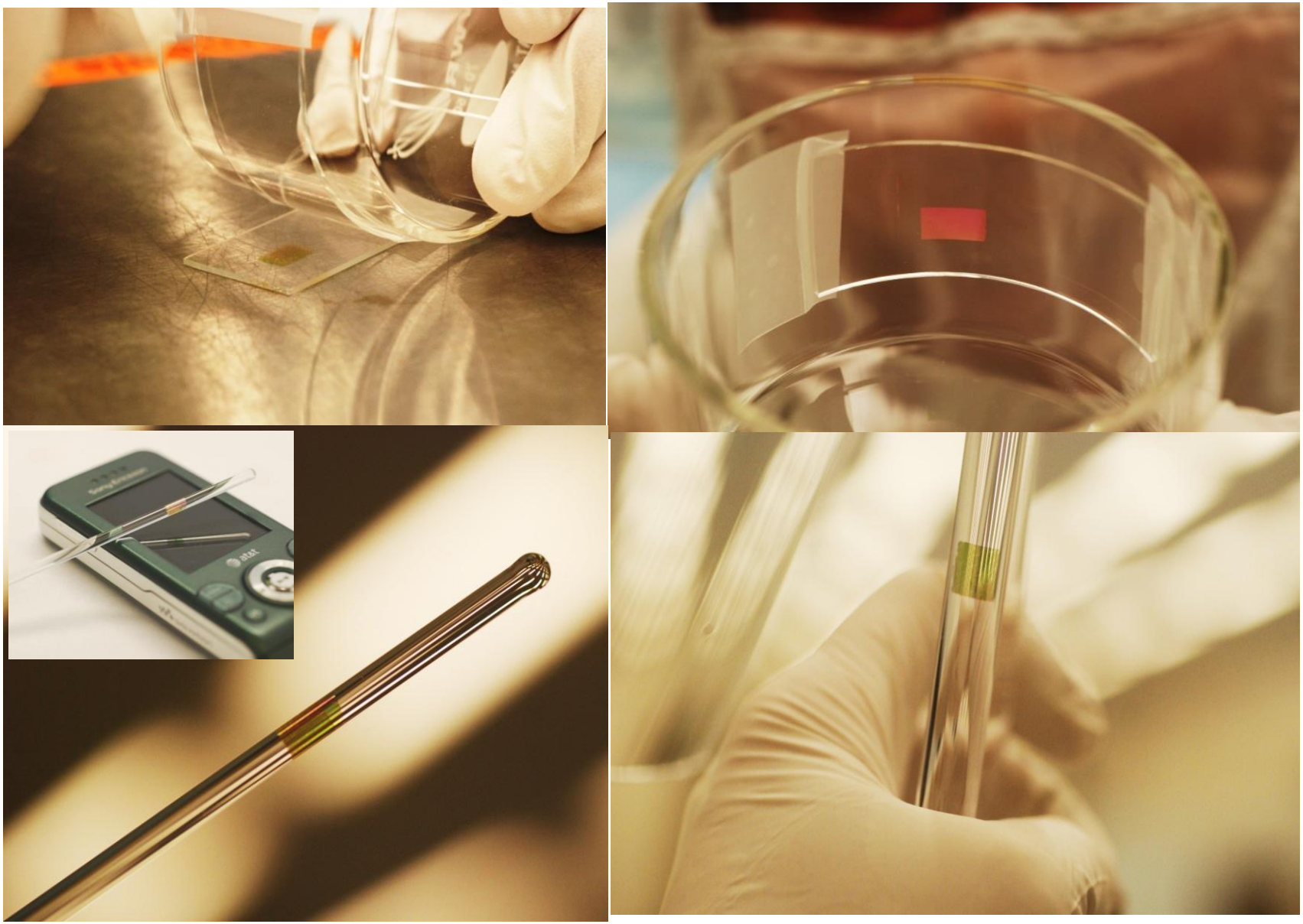
Printing 3 times

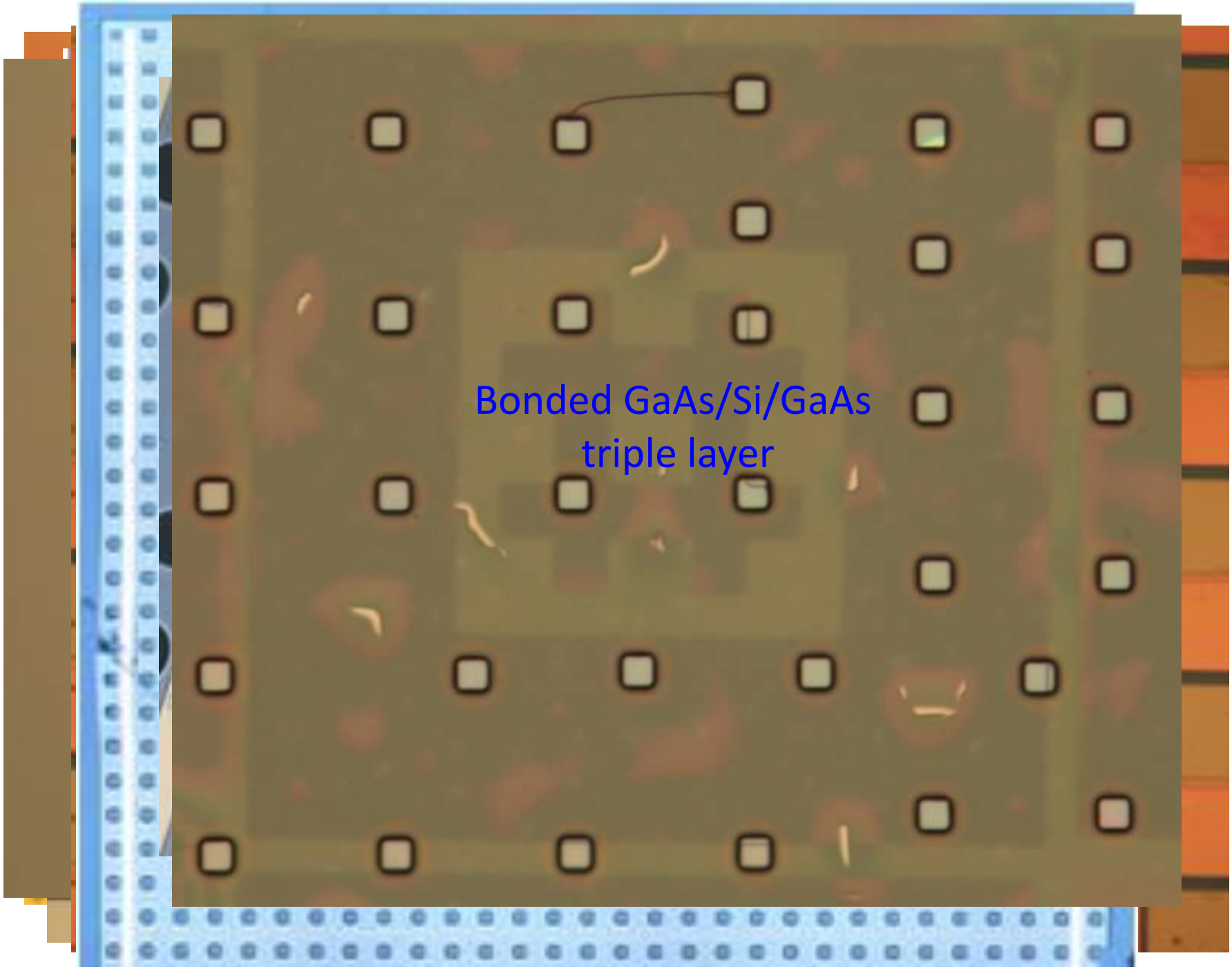
The donor substrate



Selective printing
(300 um x 200 um SiNM)

Single-crystal Semiconductor Nanomembranes are very flexible

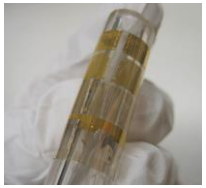



Bonded GaAs/Si/GaAs
triple layer

Development of fast flexible electronics over the last 10 years @ UW- Madison (Si-based only)

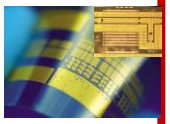
Feb. 2005 — PDMS assisted membrane transfer DC MOSFET and No doping

Jul. 2006 — Flip membrane Transfer. DC MOSFET. Strained Si channel.

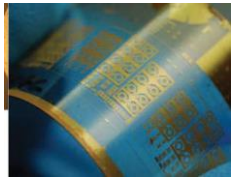


Aug. 2007 — Gate-overlapped channel. Channel length **1.5 µm**. RF NMOS. **f_T=2.04 GHz. f_{max}=7.8 GHz.**

Jul. 2009 — Flexible RF Si switch **f_{-3dB} = 20 GHz**



Nov. 2010 — Local alignment method. L_{ch} = 1 µm. RF NMOS. f_T=3.8 GHz. f_{max}=12 GHz.



Feb. 2013 — Strained Silicon RF NMOS. Lch = 1.5 µm f_T=5.1 GHz. f_{max}=15.1 GHz.

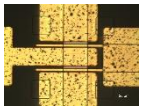
Dec. 2015 — Nanotrench Siilcon RF NMOS. L_{ch} = 200 nm f_T= 5 GHz f_{max}= 38 GHz

2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016

Mar. 2005 — SOD doping DC MOSFET

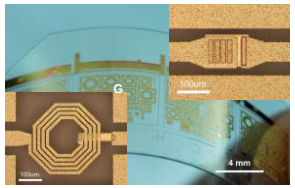
Jun. 2006 — Solid source diffusion. RF NMOS f_T=515 MHZ (UIUC)

Nov. 2006 — Ion-implantation doping. RF device f_T=1.9 GHz. f_{max}=3.1 GHz.

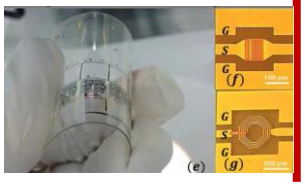


Mar. 2008 — Strain-sharing channel. DC MOSFET.

Jan. 2010 — Flexible RF inductors and capacitors f_{res} = 13.2 GHz Q = 35 @ 3 GHz



Aug. 2015 — Improved RF inductors and capacitors f_{res} = 25.1 GHz Q = 117 @ 3 GHz



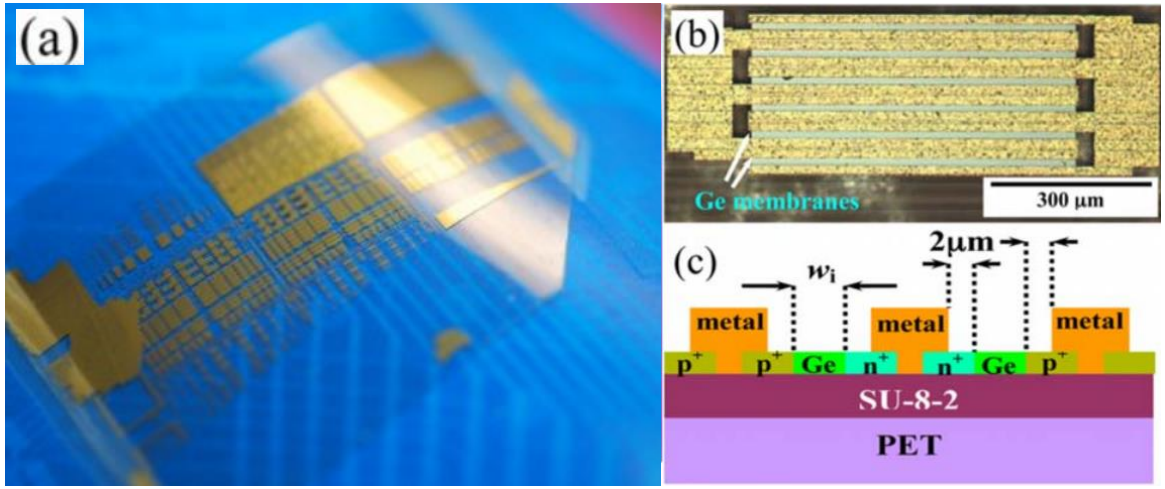
Dec. 2015 — Stretchable Transmission line F_{-1dB} >40 GHz

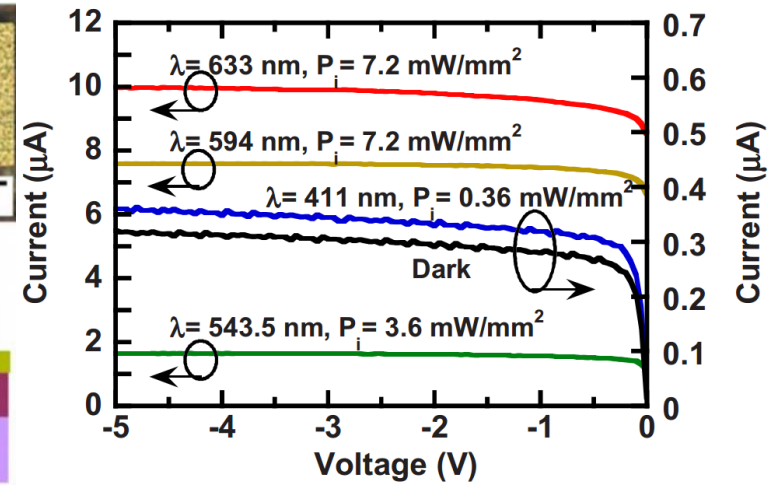
Flexible RF active devices
Flexible RF passives

J. Phys. D: Appl. Phys. *45*, 143001 (2012)

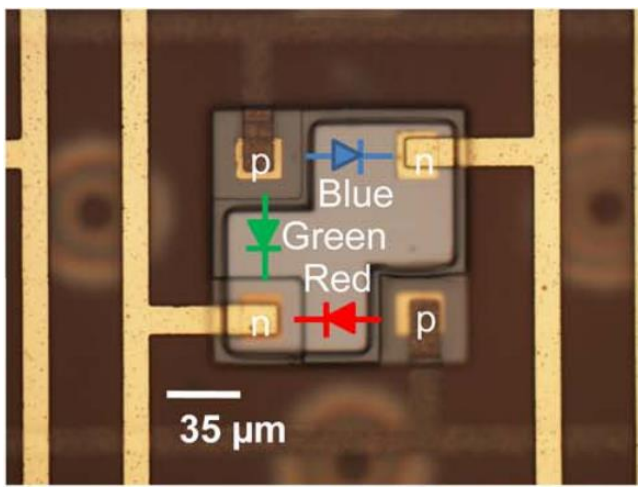
Nanomembrane based photodetectors

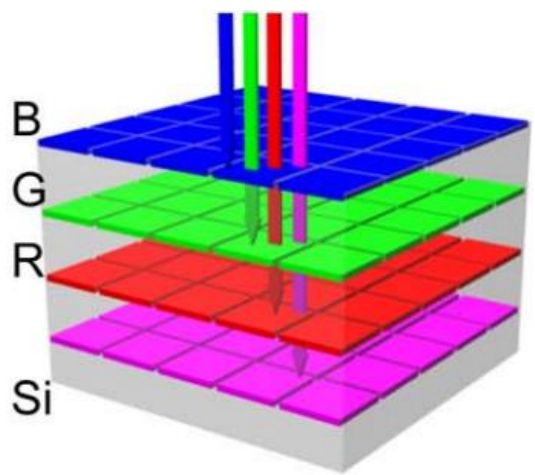
◆ Lateral junction based Ge p-i-n photodiode

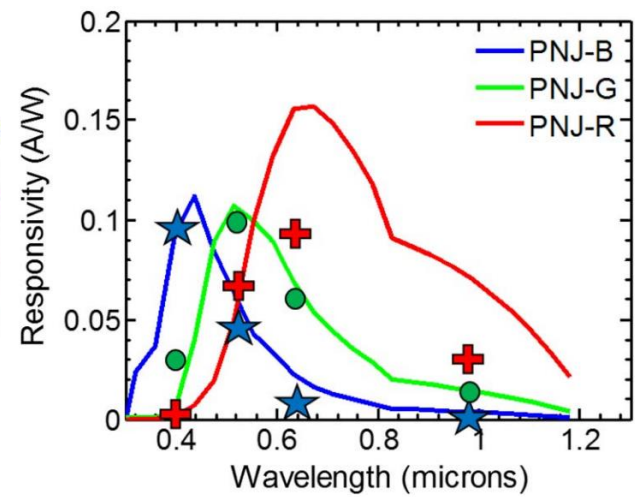




◆ Membrane stacked Silicon RGB color photodiode







- Z. Ma et al, Appl. Phys. Lett. 94, 013102 (2009)
- Z. Ma et al, IEEE Photonics Journal., 2015, 7, 1–6

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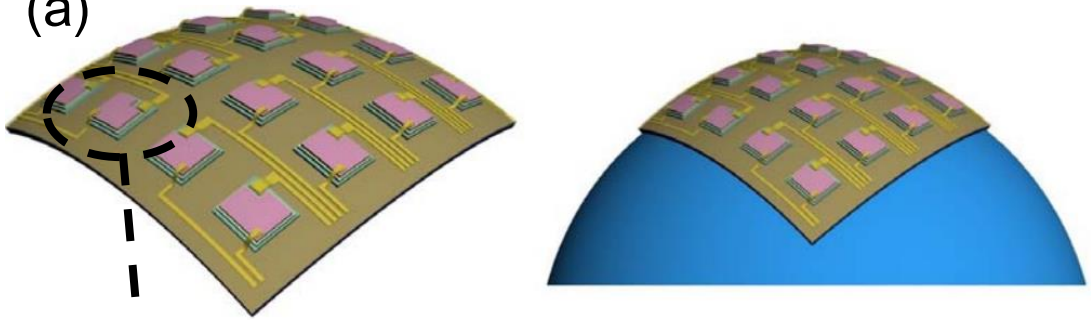
Membrane-based photodetector (vertical)

Virtual Fab Process

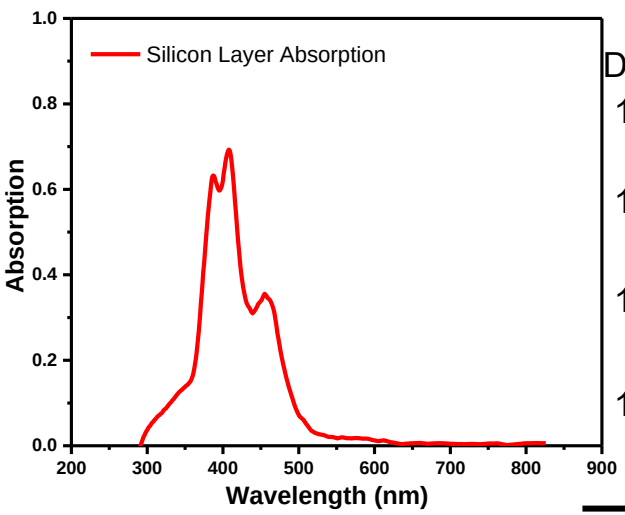
- Tune the doping profile of p-i-n diode by Athena, Silvaco™
- Device transfer after fab process
- Backside illumination, which means 100% photo sensing area

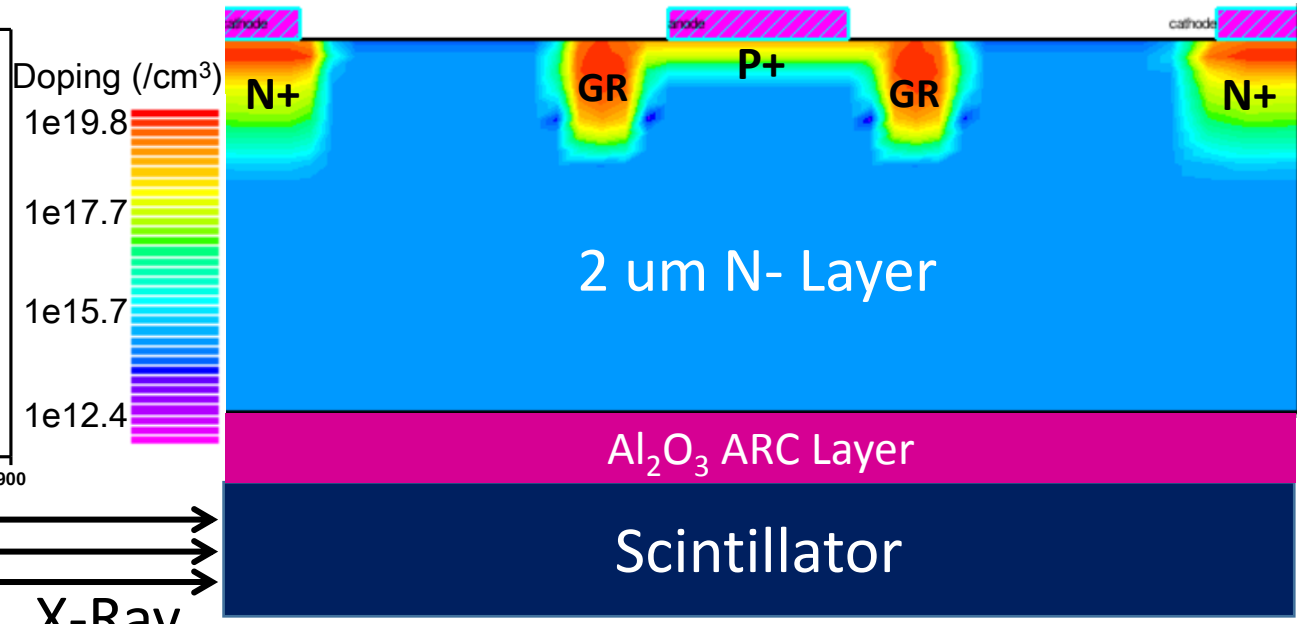
(a)



◆ Schematic SPAD Array on flexible substrate

(b)





X-Ray

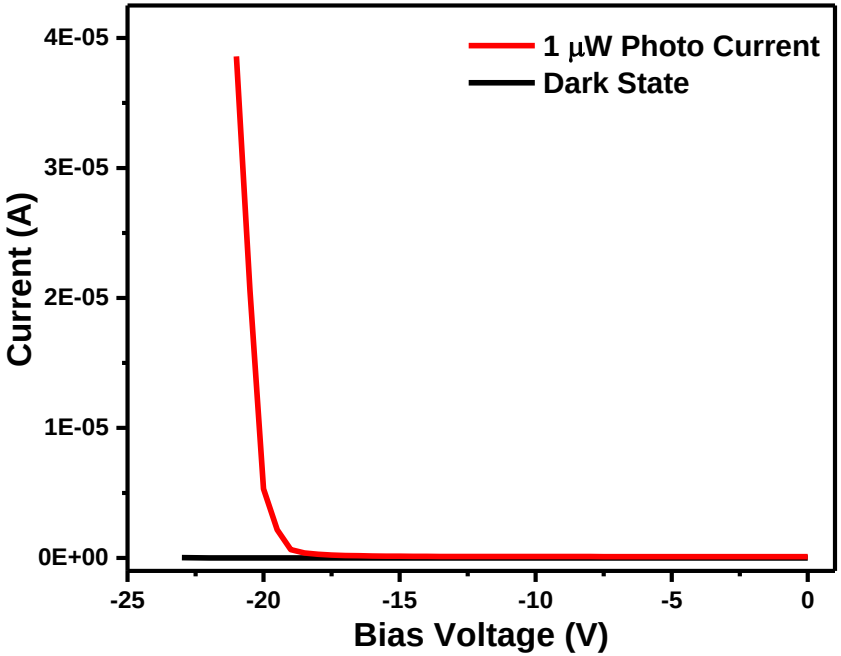
420 nm

◆ SILVACO Simulated Doping Profile of SPAD

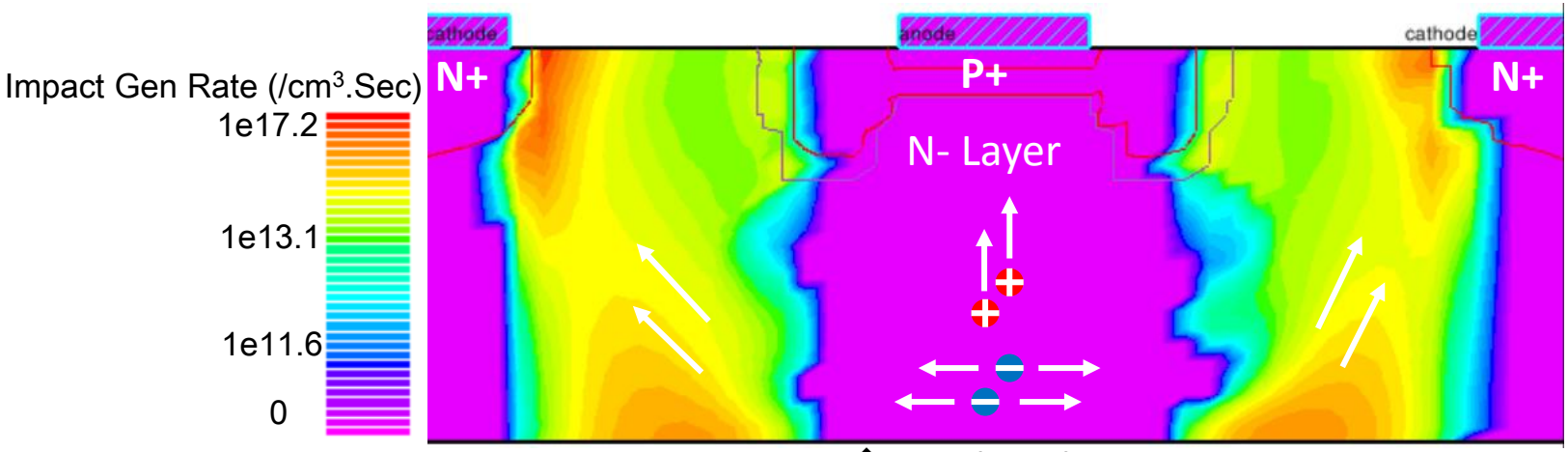
Membrane-based photodetector (vertical)

Vertical p-i-n APD

- Carrier generated near the surface, then accelerated by high electric field
- P+ region protected by guard ring, to prevent electric field breakdown
- Device can be performed in the avalanche mode, gain value of 40 is achieved by far
- Potentially can performed as single photonGeiger counter

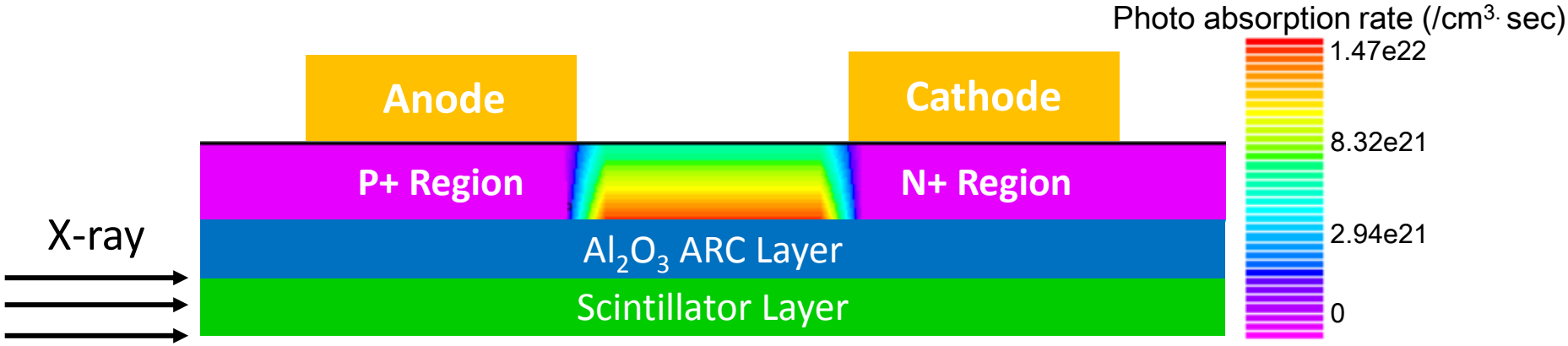


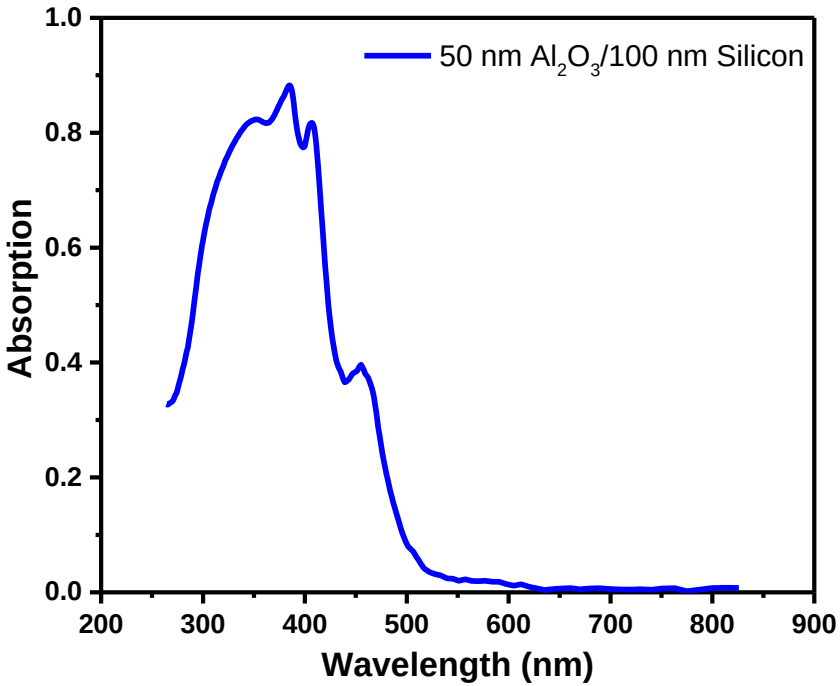
◆ Simulated IV Response of silicon SPAD



◆ Analyzed Impact Generation Rate

Membrane-based photodetector (lateral)

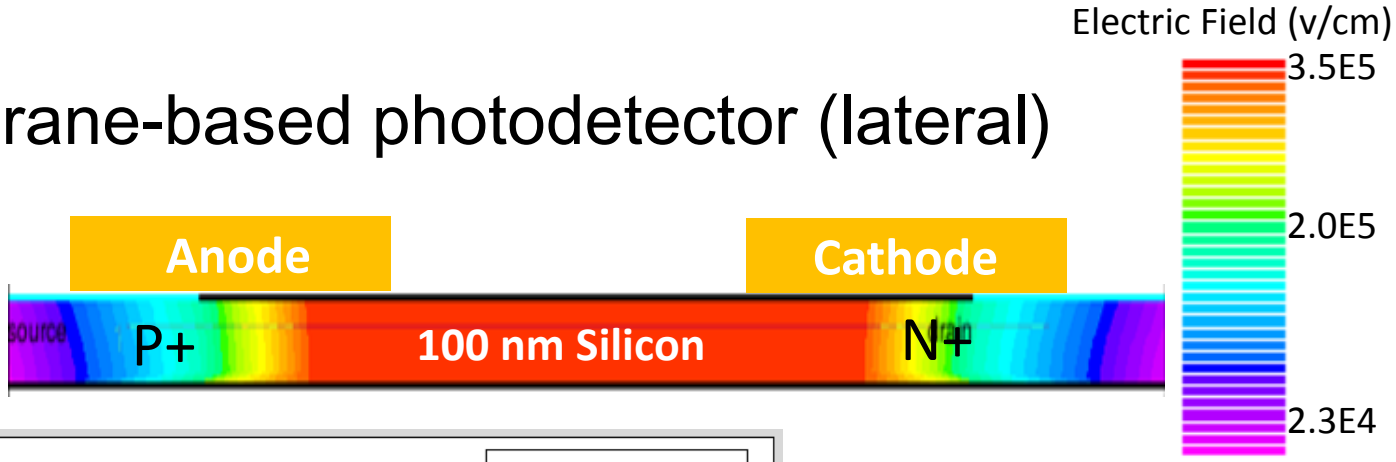


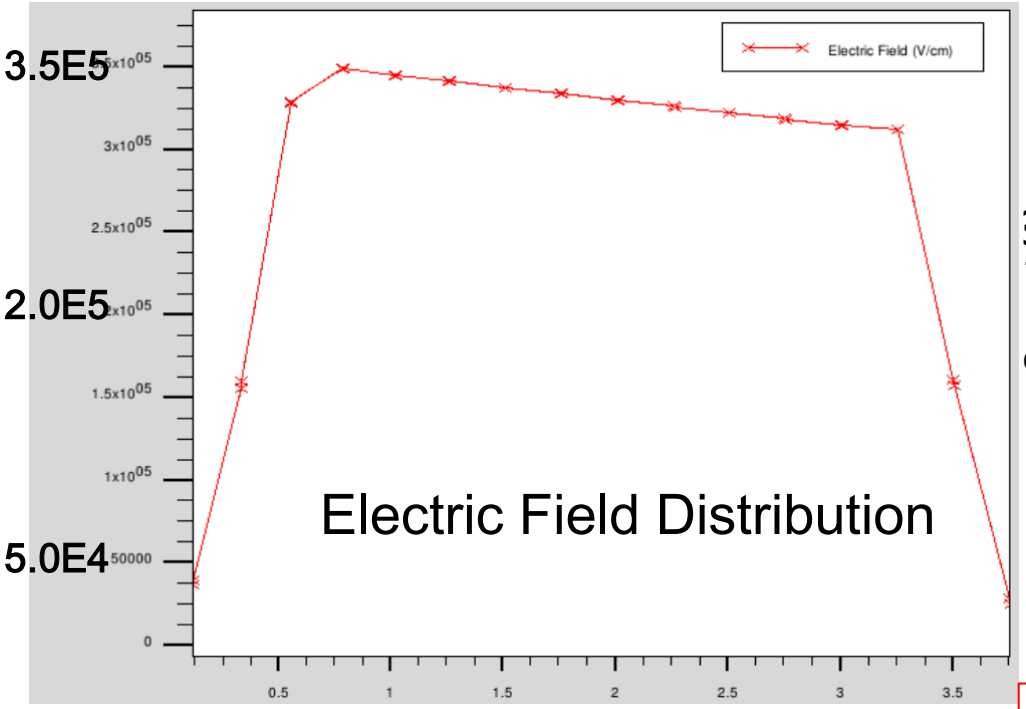


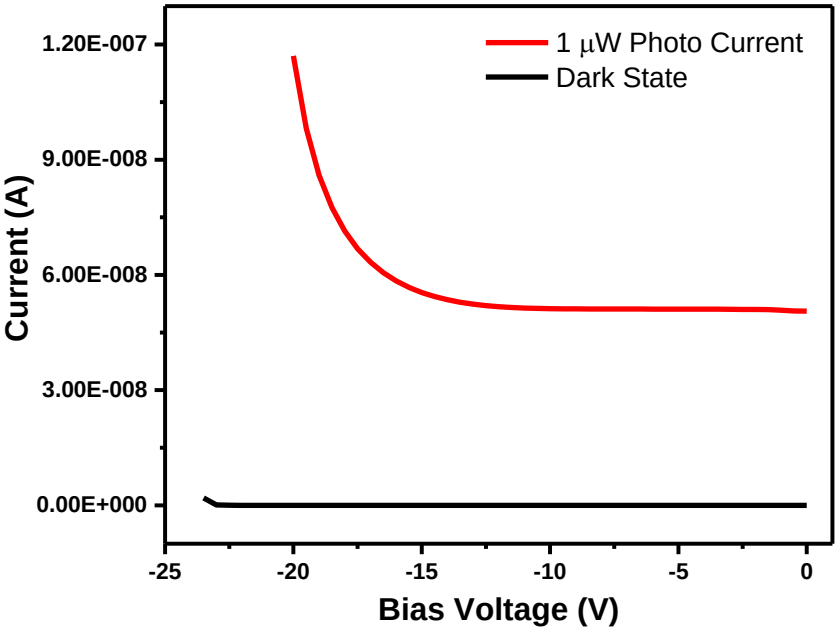
Lateral p-i-n APD

- Close to 80% of light signal can be absorbed
- Absorption and carrier multiplication region are overlapped, optimized for short wavelength
- Ultrathin membrane (~100 nm), easy for membrane transfer printing process

Membrane-based photodetector (lateral)







◆ Photo Sensing Region E Field Enhanced

- Dark current is suppressed by sheet resistance, compared to the vertical p-i-n diode
- Membrane surface can be well controlled by employing ALD layer
- Carrier absorption and multiplication region overlapped for short wavelength (420 nm)

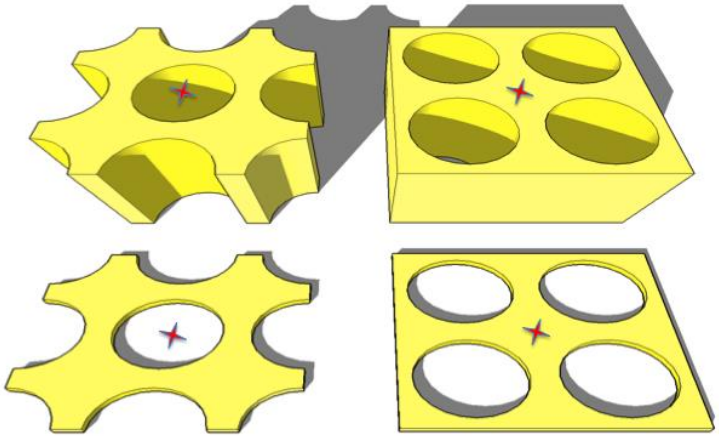
Photonic crystal design

for easy identification of particle positions

➢ Apply the nano-fab of Scintillators to make the Scintillator Photonic Crystal

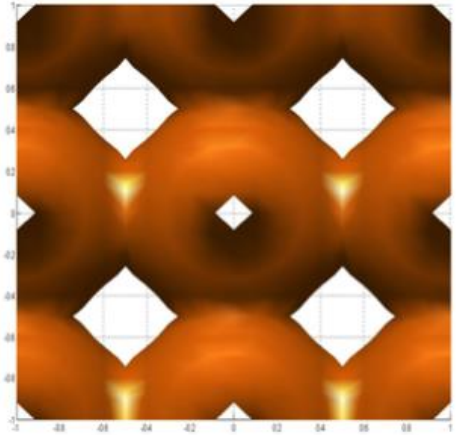
2-D & 3-D Structure Visualization

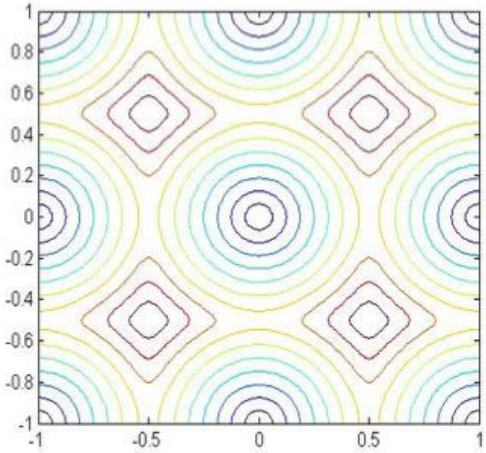
Point source in air hole Point source in Dielectric



2-D & 3-D Frequency Contour Figures as comparison…

Top view of 3-D Freq. Cont.

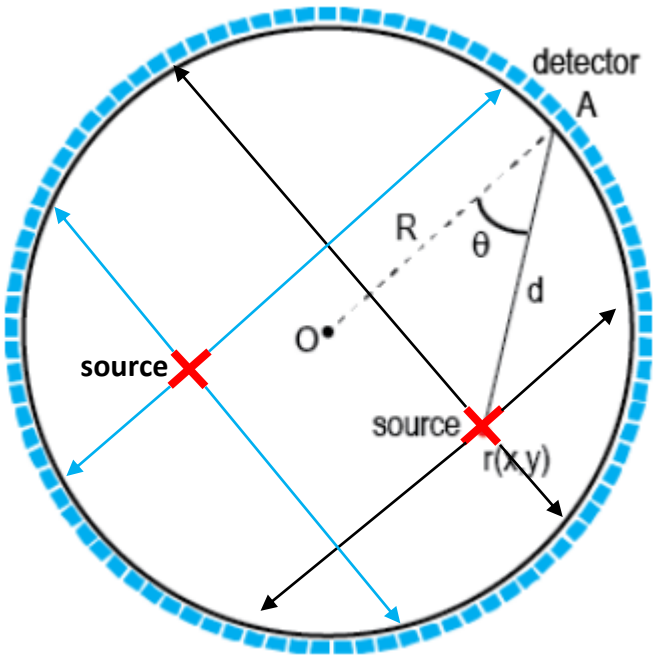


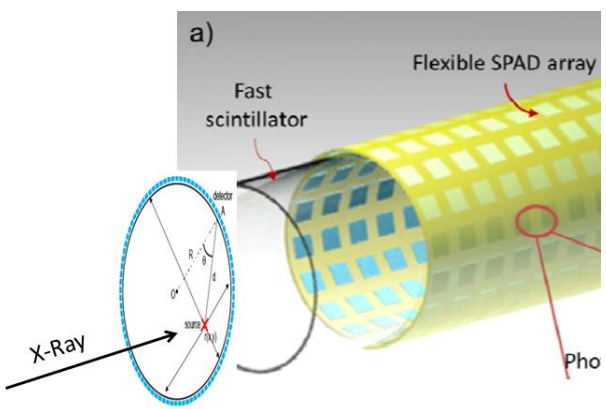


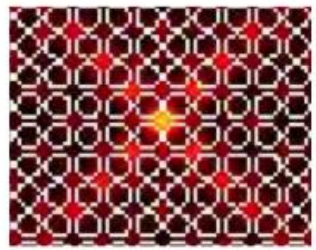
Softwares used for simulations

- Maxwell FDFD (Finite-Difference Frequency-Domain)
  - Matlab based package
  - Solves frequency domain Maxvell's equations
- MPB (MIT photonic bands)
  - Computes band structures (dispersion relation)
  - Solves definite-frequency eigenstates of Maxwell's equation
- MEEP FDTD (Finite-Difference Time-Domain)
  - Solves time domain Maxvell's equations
  - Transmission / Reflection spectra

Photonic-crystal based scintillator

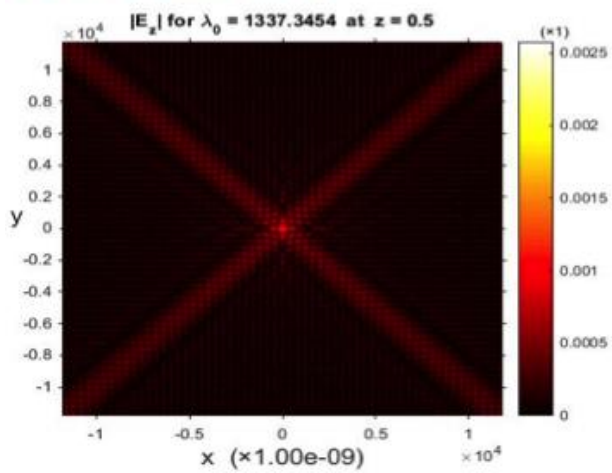


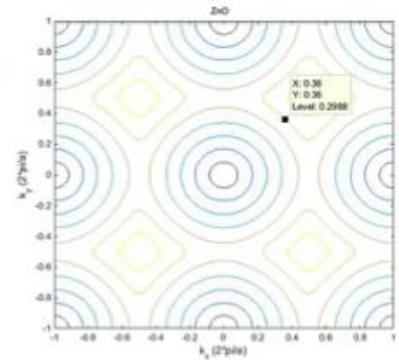


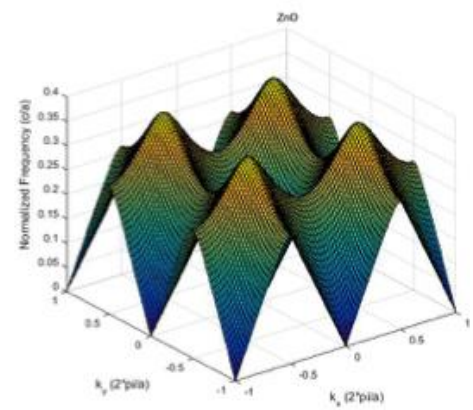


Self Collimation in 2D ZnO PhC
Point source Located in dielectric

- Self collimation is achieved 2D ZnO PhC where ε = 4.004 (n = 2.001), air hole radius; r =0.30a, ʎ =a/0.2988 (CENTER DIELECTRIC)







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Task of First Year:

- Develop fabrication process for SPAD.
- Design, fabricate and measure the single device on rigid substrate.
- Optimization of algorithms for super-resolved X-ray imaging.
- Finalize the design of photonic-crystal based scintillator.