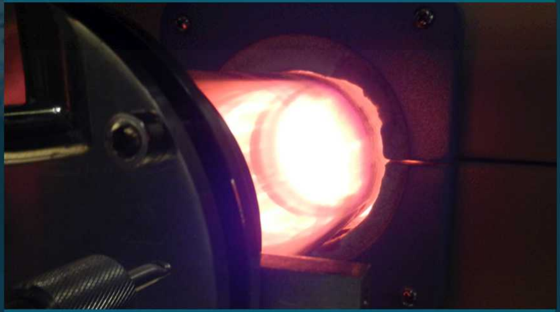
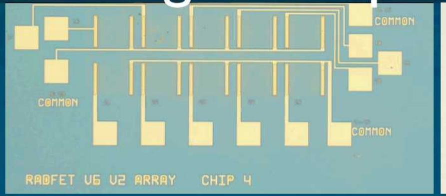
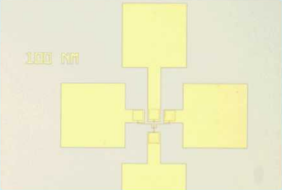
SAND2019-9916C

The Deeply Depleted Graphene-Insulator-Semiconductor Junction:

A versatile approach towards light sensing across the electromagnetic spectrum







Smart Sensor Technologies

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

PRESENTED BY

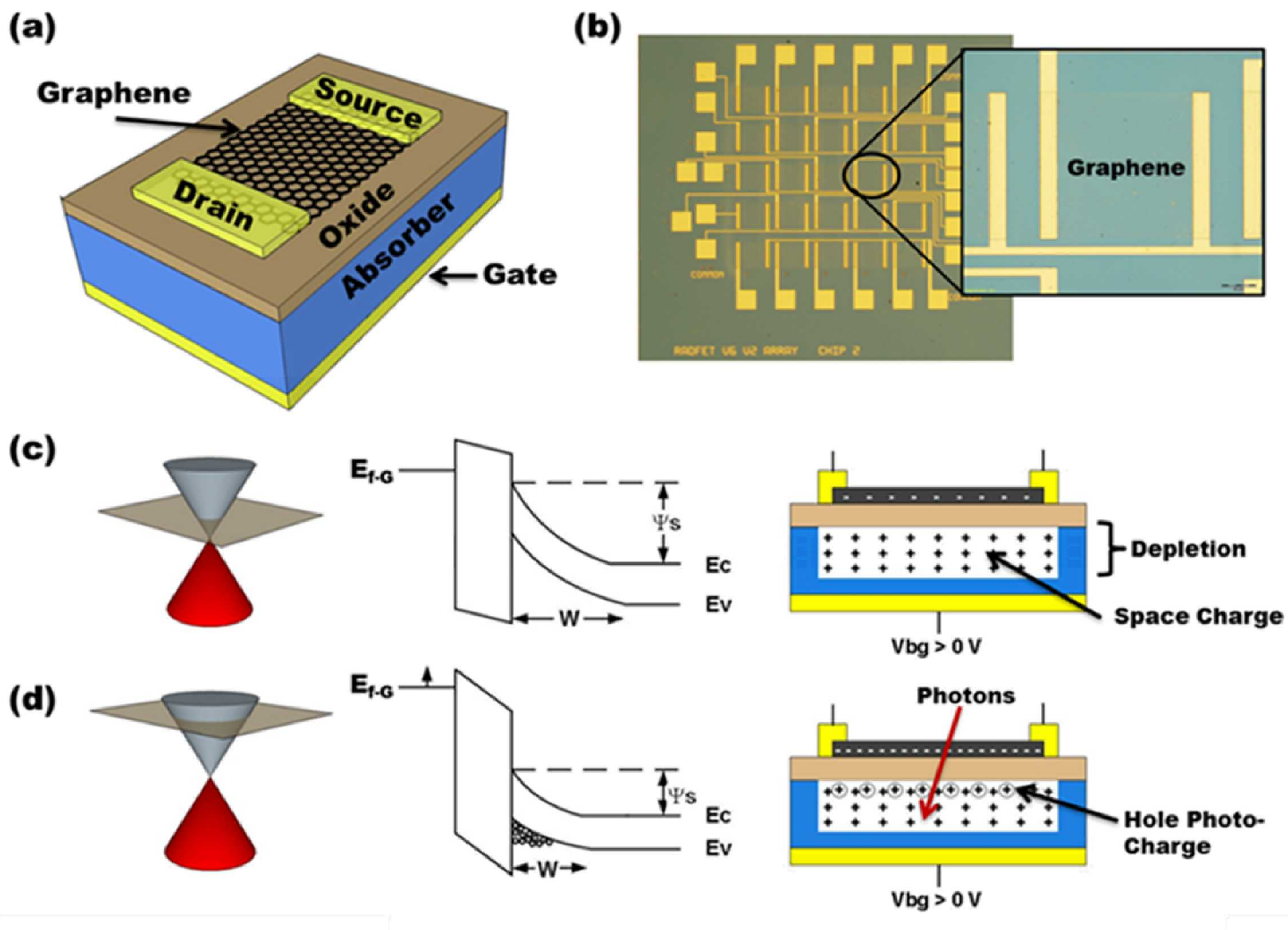
Isaac Ruiz, Michael D. Goldflam, Raktim Sarma, Thomas E. Beechem III & Stephen W. Howell

NAVSEA WARFARE CENTERS CRANE

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.

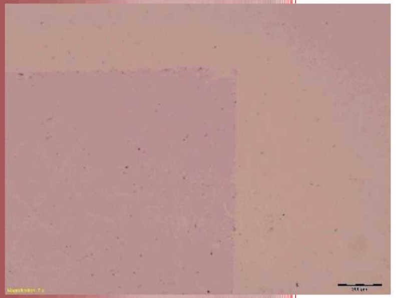
Outline

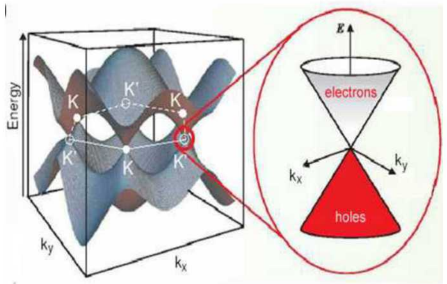
- Motivation
- Background of the D^2GOS Junction Detector
  - Operating Principles
  - Operational Modes
- Optimization of the D^2GOS Junction
  - Reducing interface states
  - Increased Well Lifetime
  - High Responsivity
- Detection in the NIR to Mid IR
  - InGaAs Device Demonstration
  - InAs Device Demonstration
- Detection of Gamma Radiation using a Si based D^2GOS junction



Motivation to use Graphene

Novel 2D Material





- Ultra-High Mobility
- Broadband Optical Absorption
- Tunable Electronic/Optical Properties
- Scalable
- Many demonstrations of sensing across EM spectrum (UV to IR)

Major Issues

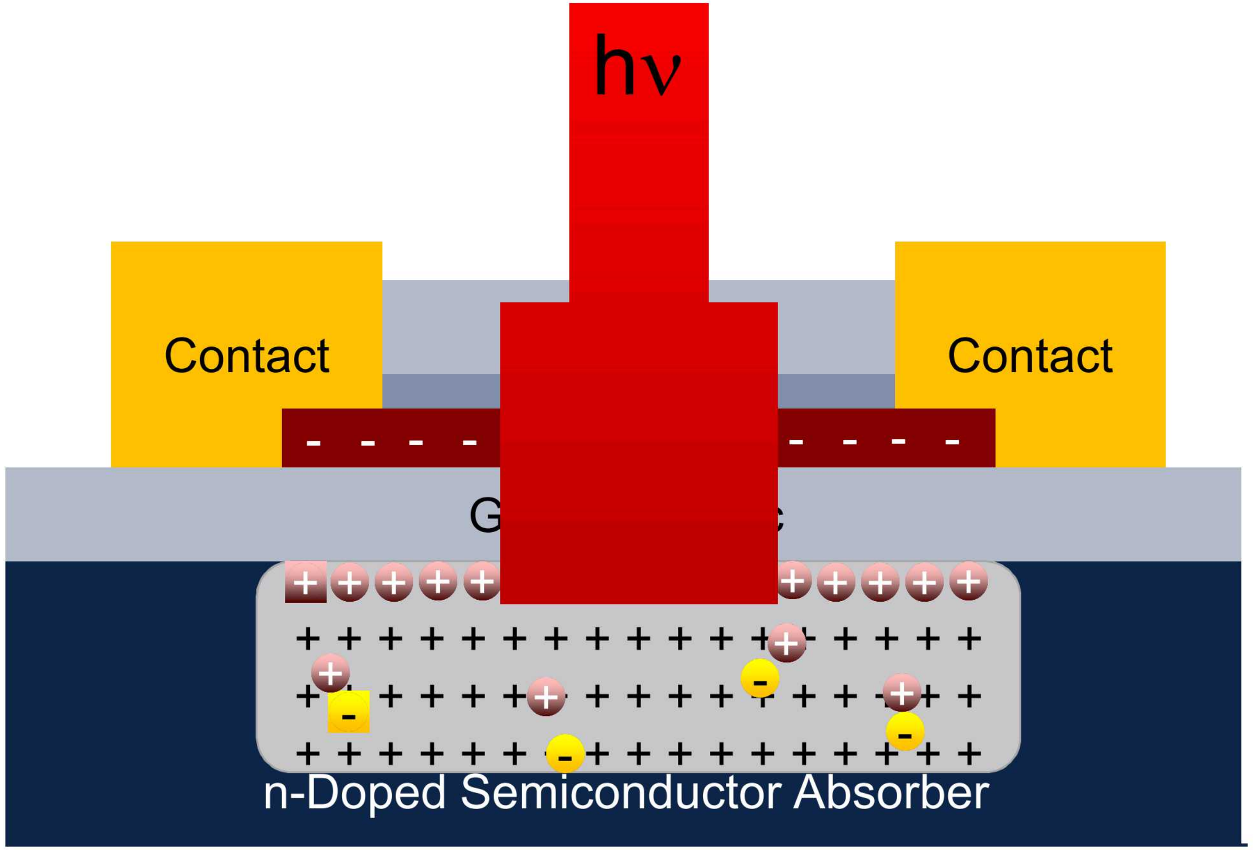
- **Poor Absorber of Light**
  - Atomically thin
    - Low absorption
  - Short recombination length

Solution:

Don't Absorb into the Graphene

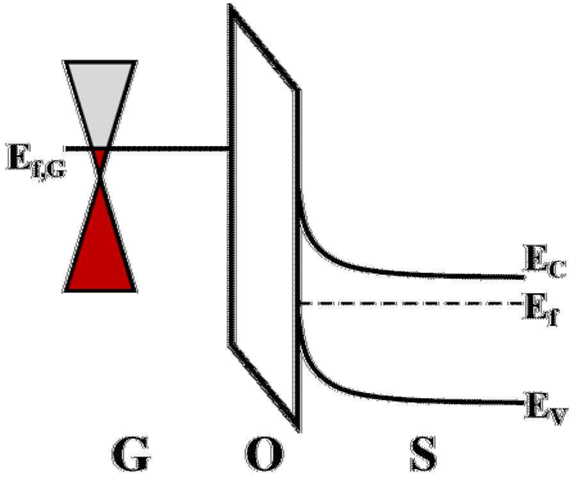
Use graphene a to sense photo-generated generating in a **good** absorber.

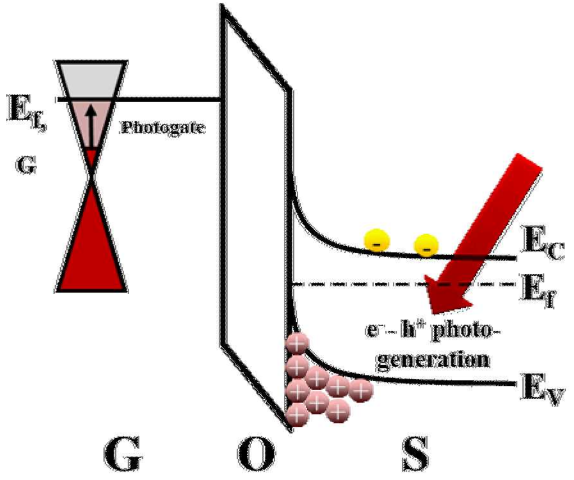
Operating Principle Graphene-Oxide Semiconductor Junction



$V_{bg} > V_{fb}$

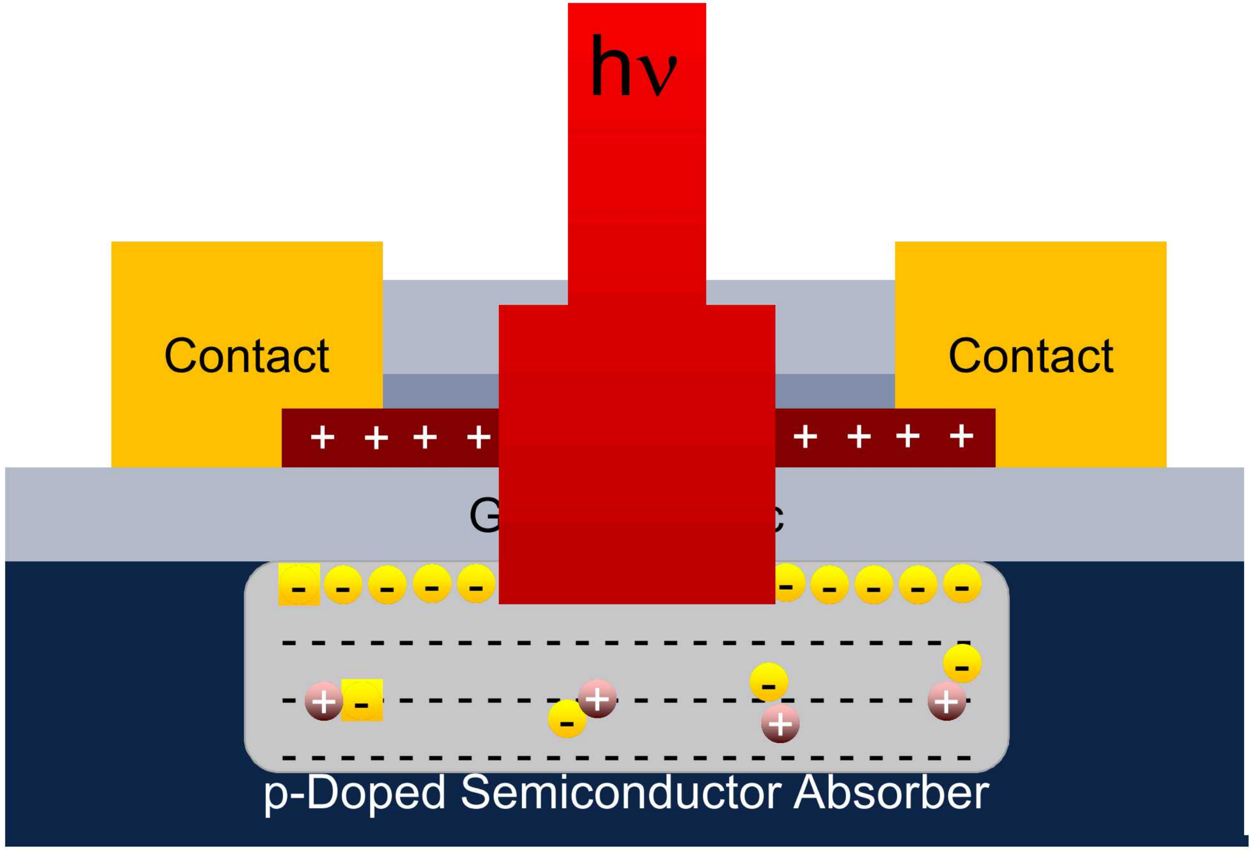
1. Absorber-Oxide-Graphene Junction.
2. Low doped absorber is depleted with an applied back gate voltage.
3. Incoming light creates photo-generated charge in absorber.
4. Built in electric field separates electron-hole pairs.
5. Charge accumulates at semiconductor/Oxide interface.
6. Opposite charge is induced in the graphene channel, which can now be readout directly.



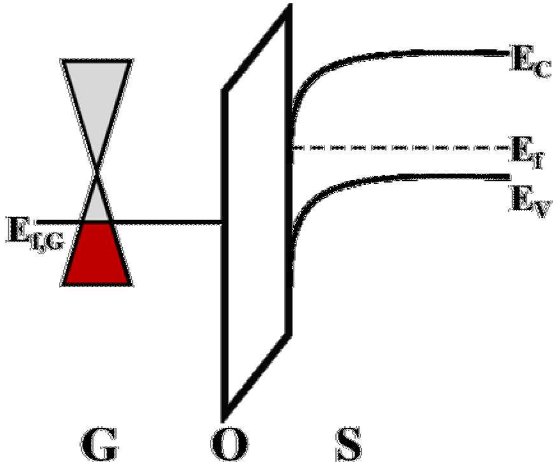


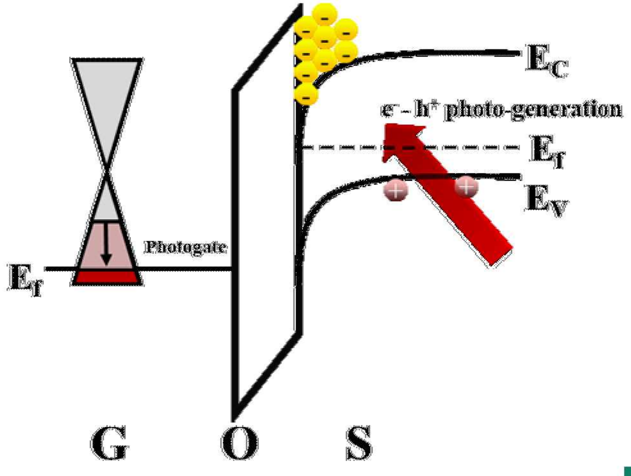
Operating Principle Graphene-Oxide Semiconductor Junction

1. Absorber-Oxide-Graphene Junction.
2. Low doped absorber is depleted with an applied back gate voltage.
3. Incoming light creates photo-generated charge in absorber.
4. Built in electric field separates electron-hole pairs.
5. Charge accumulates at semiconductor/Oxide interface.
6. Opposite charge is induced in the graphene channel, which can now be readout directly.



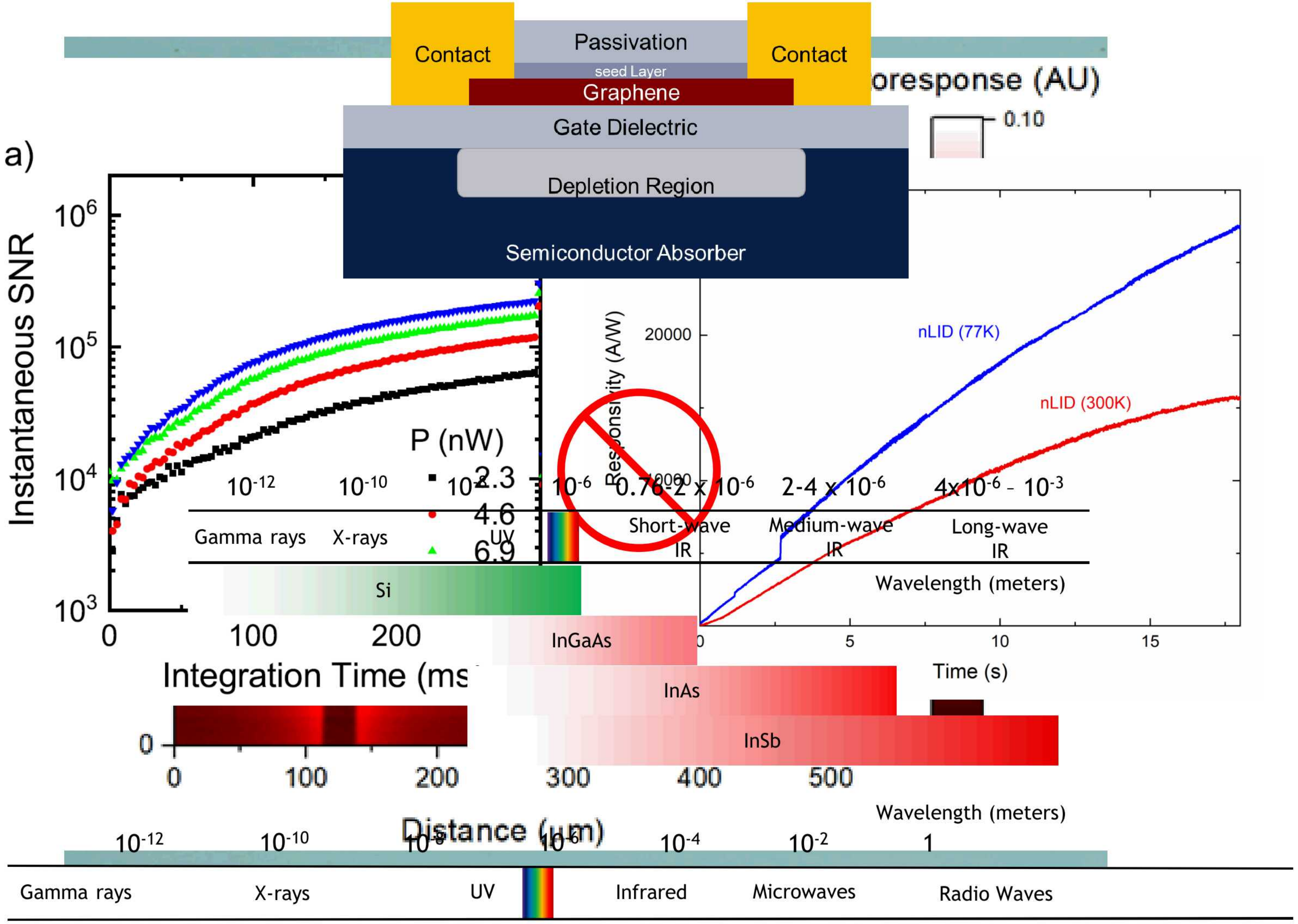
$V_{bg} < V_{fb}$





What are the advantages of the D^2GOS Junction Detector?

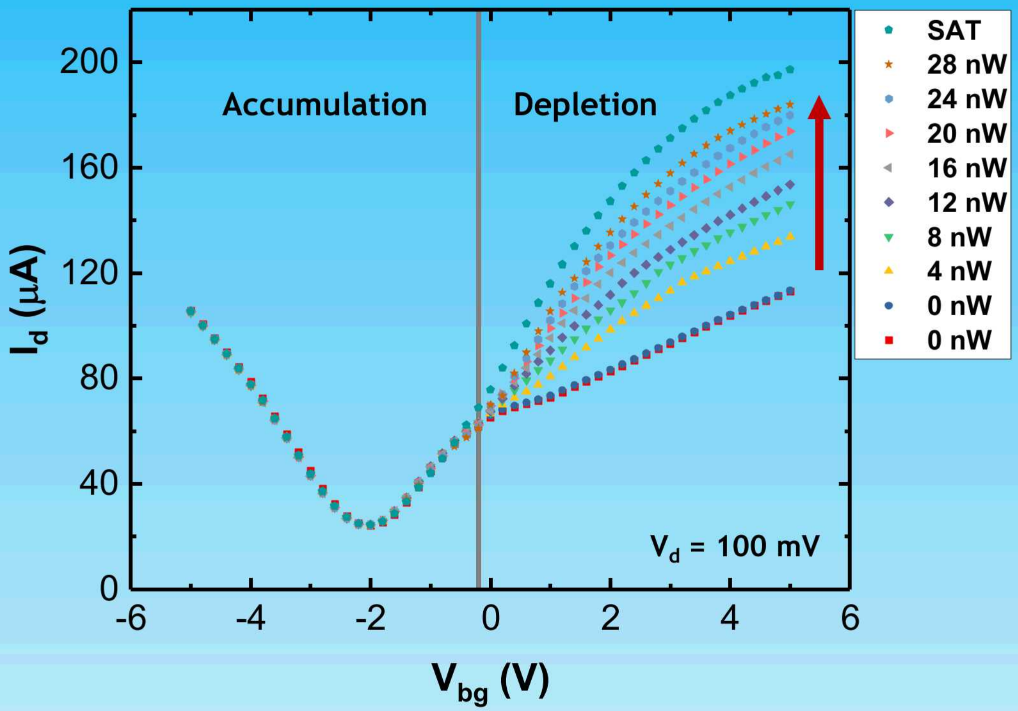
- Scalable
- Can integrate charge like a CCD
- Direct Pixel Readout
- Large Fill factor
- High Sensitivity
  - Demonstrated <1 nW detection
- High SNR
  - Demonstrated 10^2-10^5
- High Responsivity
  - Demonstrated >25,000 A/W
  - Several orders of magnitude higher possible
- Low Operational Power (~mW)
- Absorbing substrate agnostic
  - **By choosing substrate with appropriate bandgap, absorption bandwidth can be selected.**
  - SiC, GaN and AlN for **Gamma - UV**
  - Silicon for **Visible**
  - InGaAs for **Near IR**
  - InAs, InAsSb, InSb for **Mid IR**



Operational Modes

Device Characterization Mode

I_D vs. V_{BG}

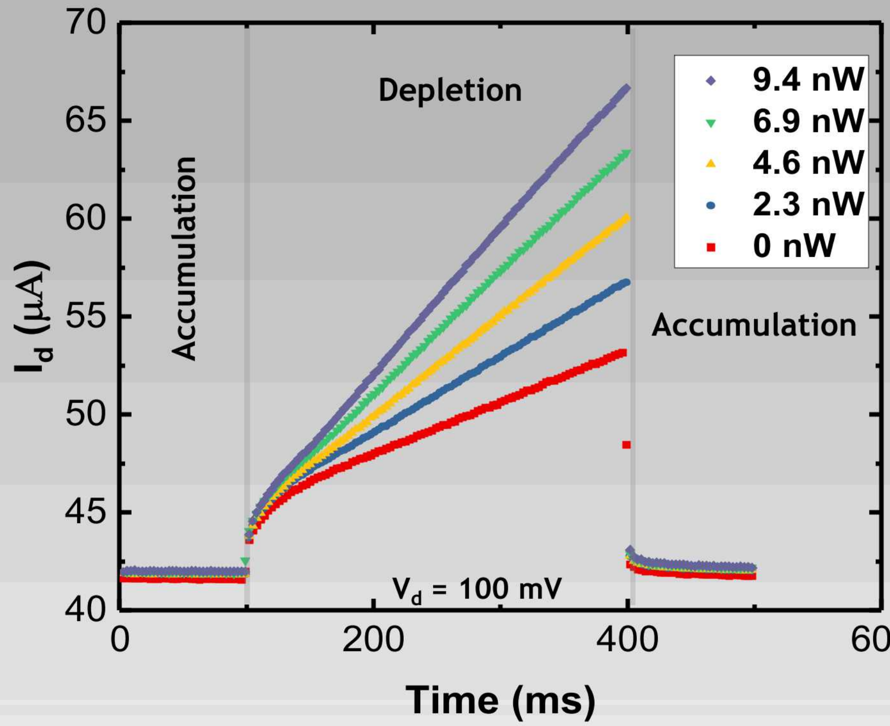


This mode allows for the GOS stack characterization of:

- Graphene's material properties
  - Doping, Mobility and Resistivity.
- Semiconductor material properties
  - Doping polarity and Band Gap
- GOS Junction V_{FB}
- Any induced damage from high energy events.

Detection Mode

I_D vs. Time



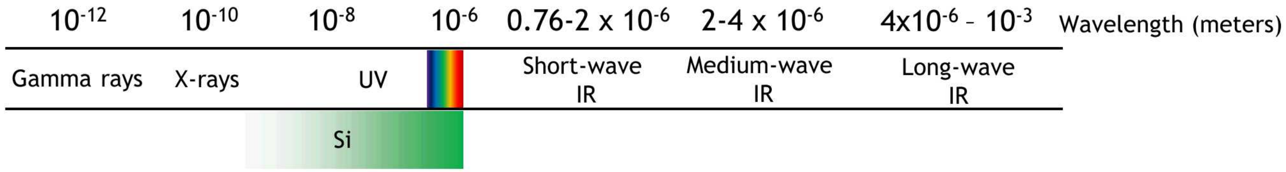
This mode allows for real time detection of light.

- Similar CCD (no charge shuttling).
- Integration of photo-induced charge.

This mode also allows for the characterization of thermally generated charge in the semiconductor.

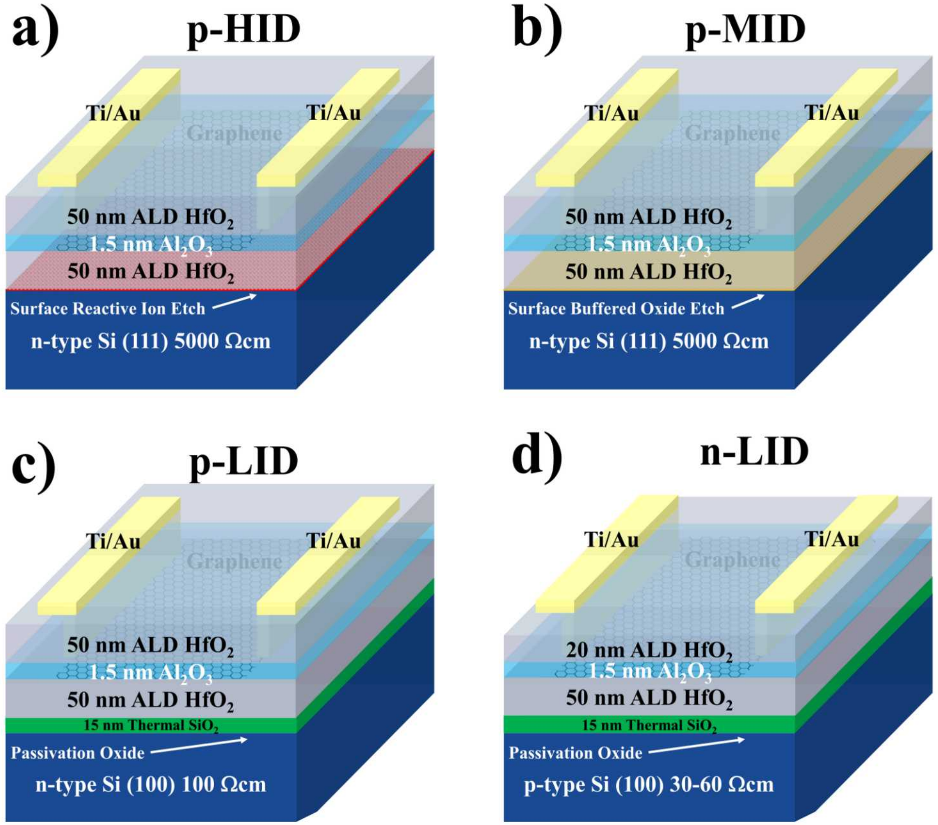
- Primarily Semiconductor/Oxide interface defect density.

Semiconductor/Oxide Interface on D²GOS Junctions in the Visible (635 nm)



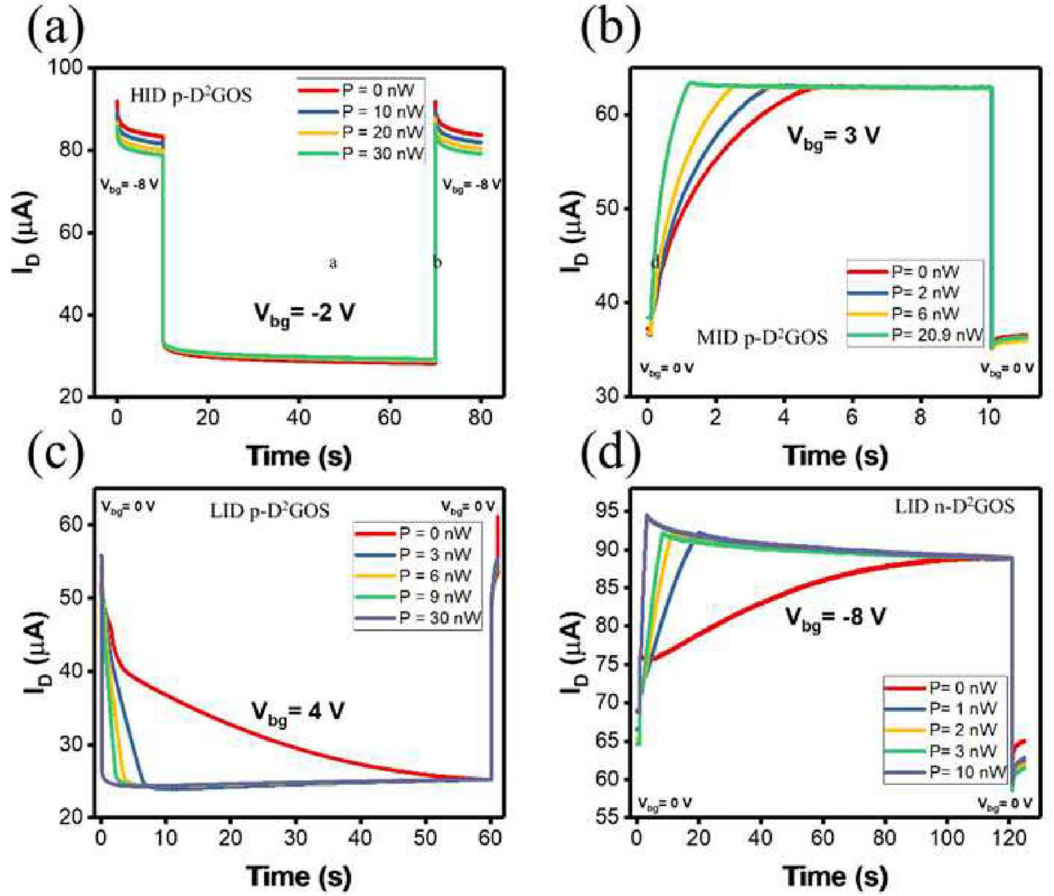
Question:

What happens if we minimize the interface states?



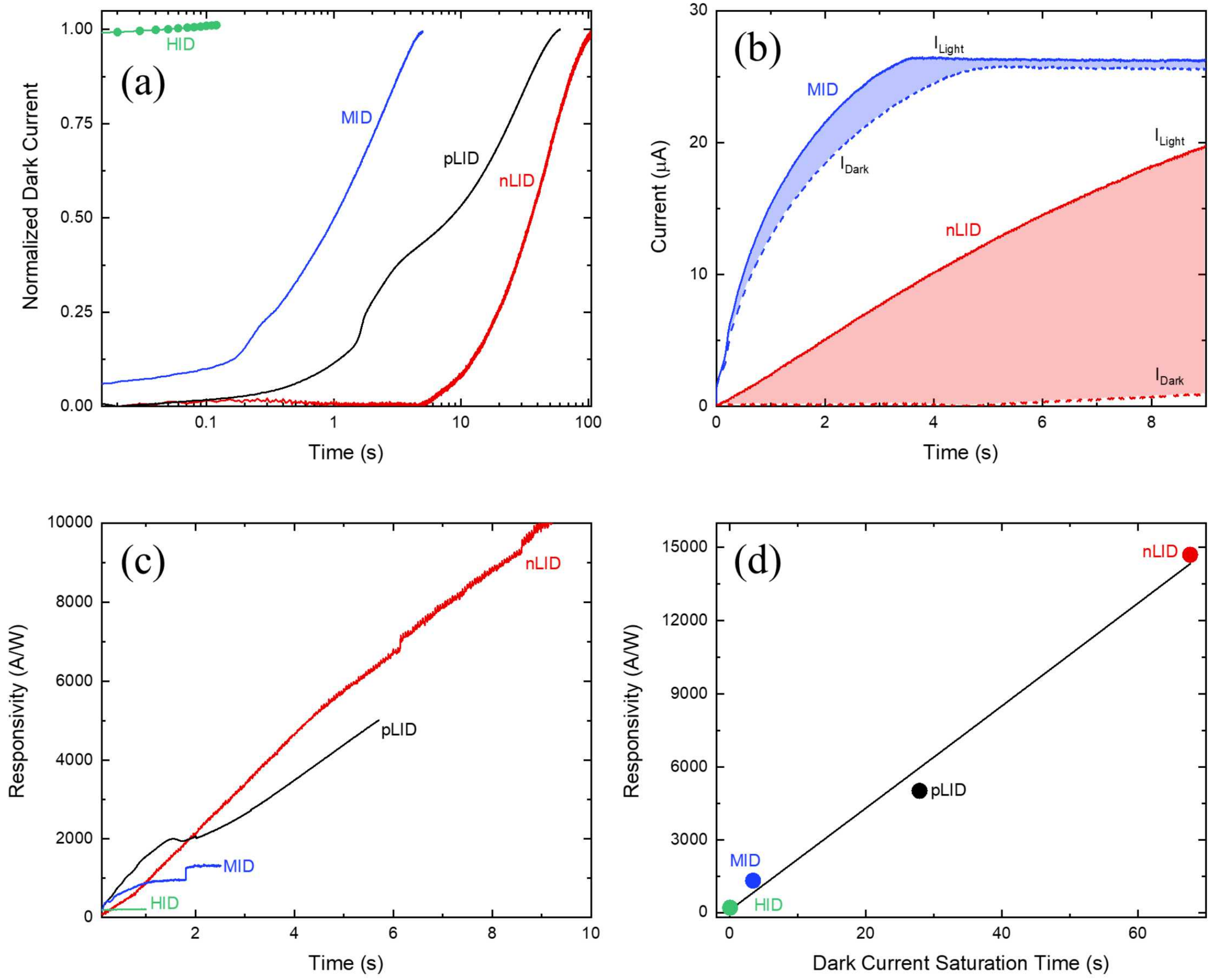
Answer:

Reduction in Interface defect density increases dark well lifetime from 6 seconds to 120 sec!



Variable Interface Defect D^2GOS Junction Performance

Room Temperature Characterization



High interface defect GOS junction is not functional

Low Interface defect GOS junction has much lower dark current

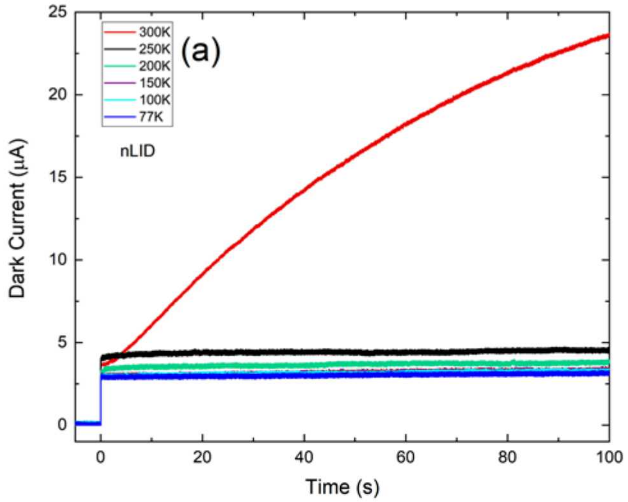
Surface charge generation is the primary source of dark charge

Responsivity is proportional to dark current saturation time.

Responsivity is also a highly dependent on the graphene mobility.

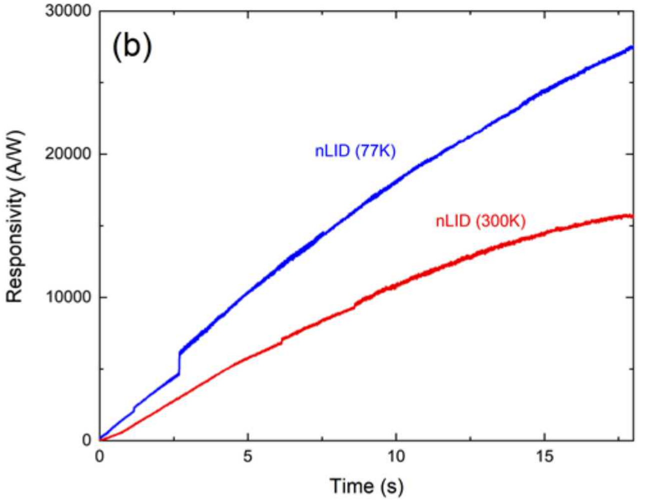
Low Temperature D^2GOS Junction Performance (Visible and 635 nm)

Low Temperature Characterization



Interface charge is quenched between 77K - 250K

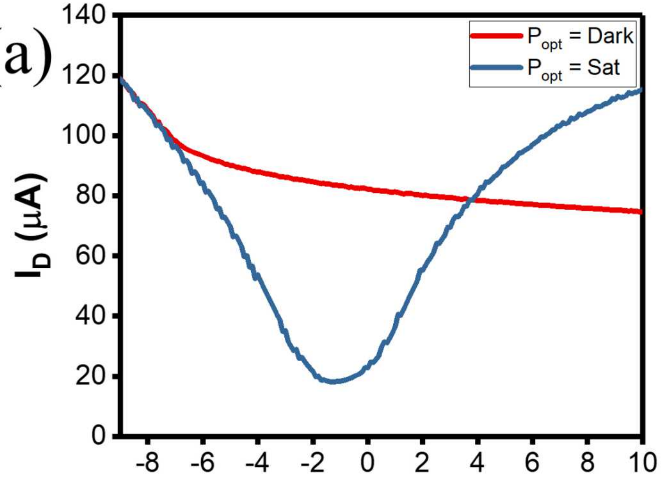
No generated dark current



Reduction in dark current results in almost a 2X increase in responsivity at 77K

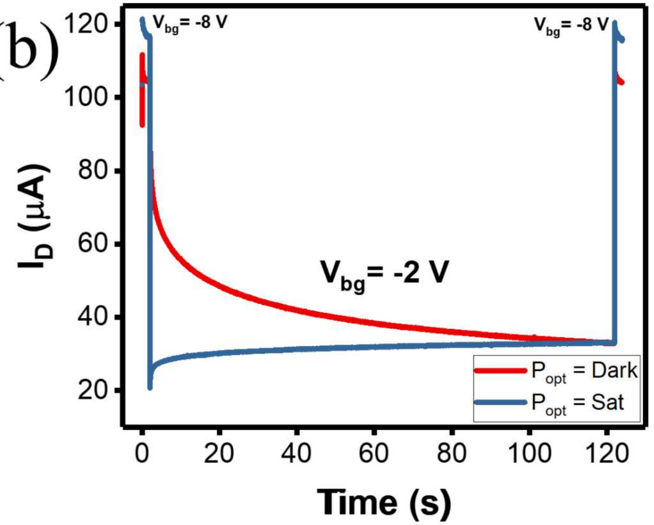
Highly defective interface D^2GOS junction at 77K

(a)



Unresponsive device becomes functional at 77K

(b)



Although the dark current is reduced it is not completely quenched.

How do we move the D^2GOS beyond Silicon (Visible)?

Easy

Graphene is easily transferable to any substrate

GOS Junction/GFET is simple to fabricate on the most common semiconducting-dielectric substrates.

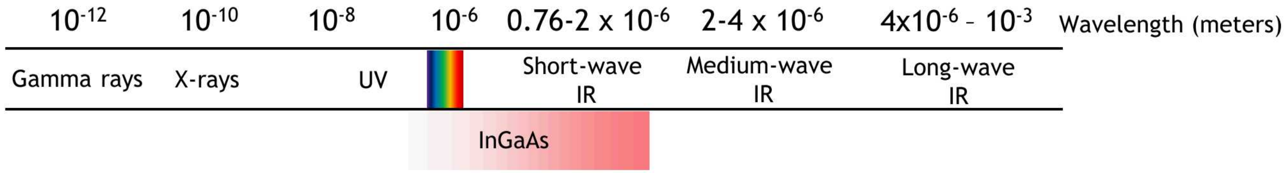
GOS structure must be depletable.

Hard

Semiconductor/Oxide interface must be of reasonably high quality.

Low doping concentration of semiconductor for large depletion width

Demonstration of D^2GOS on InGaAs (E_g ~0.76 eV (~1.6 μm))

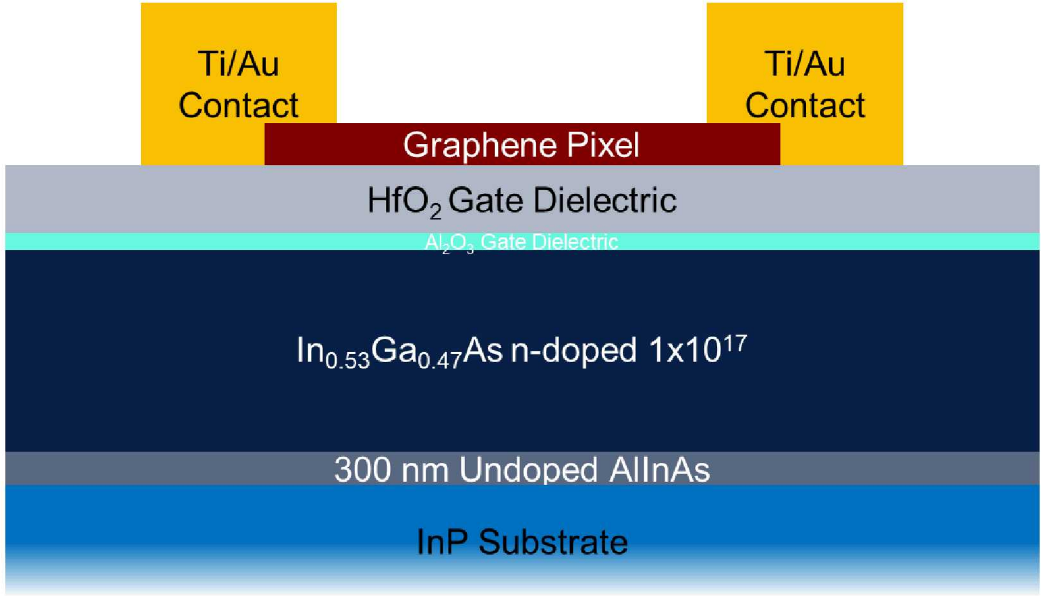


InGaAs Surface Preparation

Remove Native Oxide
BOE Etch 90 sec

Atomic Layer Deposition Recipe
300C N_2 Plasma 1 cycle
Al_2O_3 deposition 12 cycles (TMA)
HfO_2 Deposition 550 Cycles (TDMAH)

Anneal
N_2 gas anneal at 400 C for 15 min

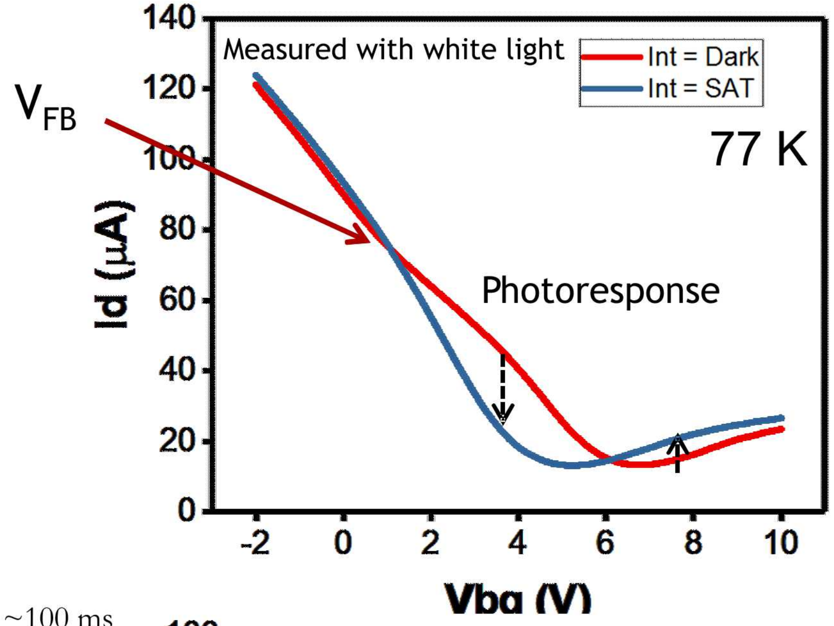


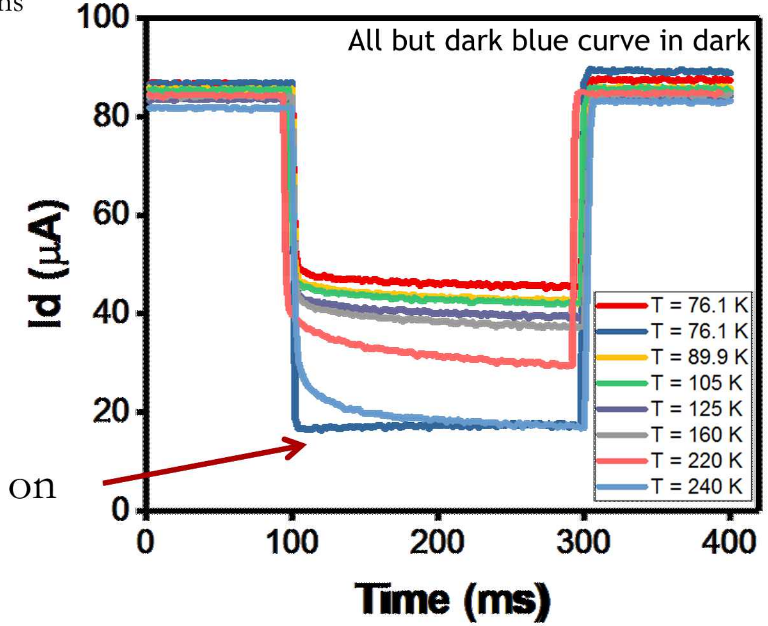
Dark Charge current quenched at 77K

Dark Current quenched up to 160K.

Device functional up to 240K but with ~100 ms well lifetime

Immediately saturates when illuminated

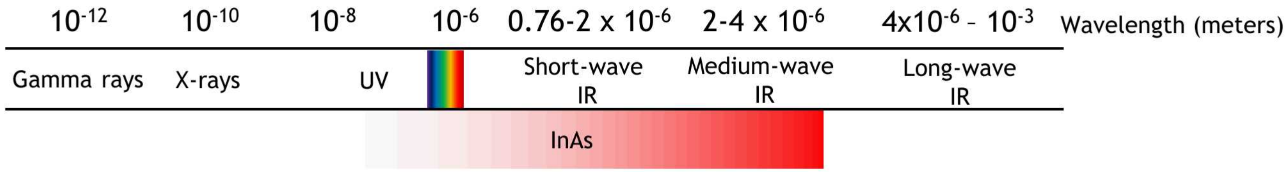




77K with light on

(Illuminated with White light)

Demonstration of D²GOS on InAs (E_g ~0.35 eV (~3.5 um))

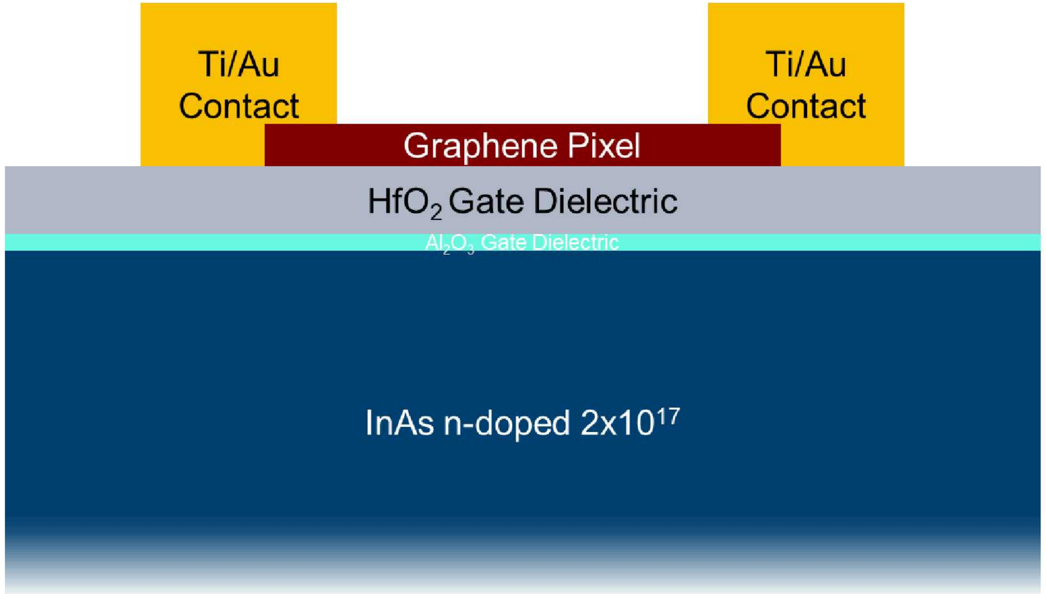


InAs Surface Preparation

Remove Native Oxide
BOE Etch 90 sec

Surface Passivation
(NH4)2SO4 soak for 5 min

Atomic Layer Deposition Recipe
Al2O3 deposition 10 cycles (TMA)
HfO2 Deposition 550 Cycles (TDMAH)



Small photo response in depletion

Dark current appears quenched at 77K.

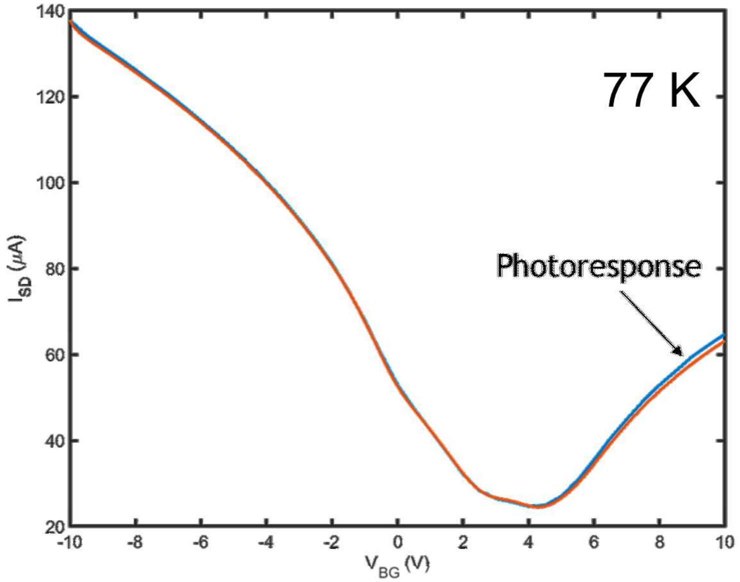
Responsive to light.

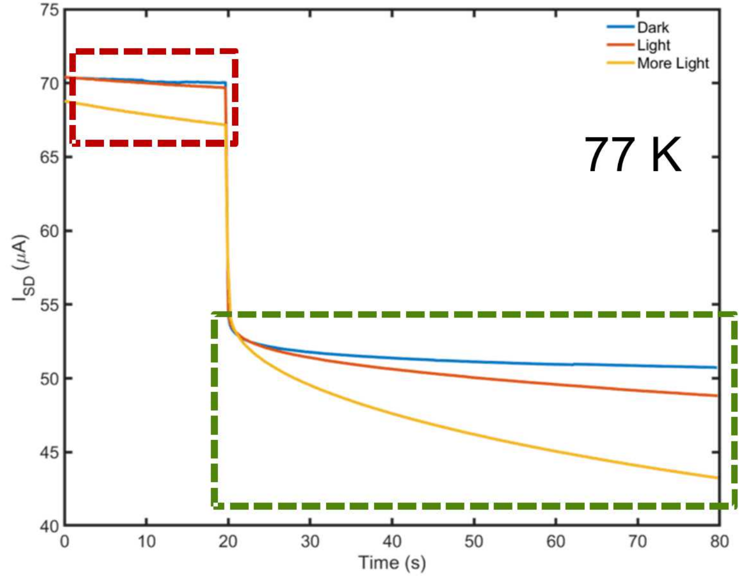
Photo Current proportional to incident light power.

Current not saturating when flood illuminated (Si devices saturated immediately with powers low as 100 nW)

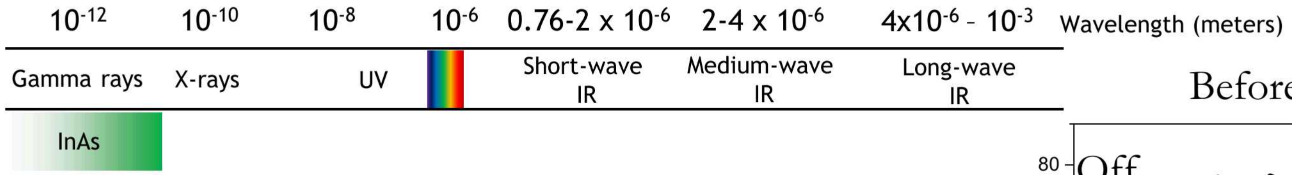
Some photo response in accumulation. Why?

(Illuminated with White light)

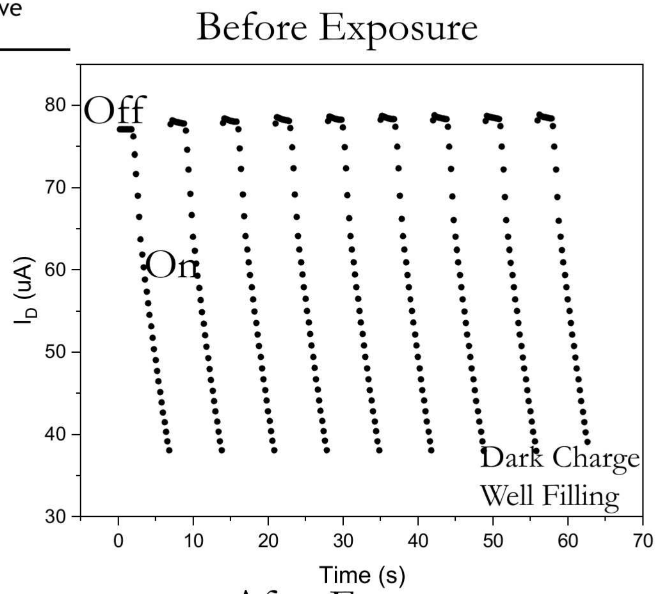


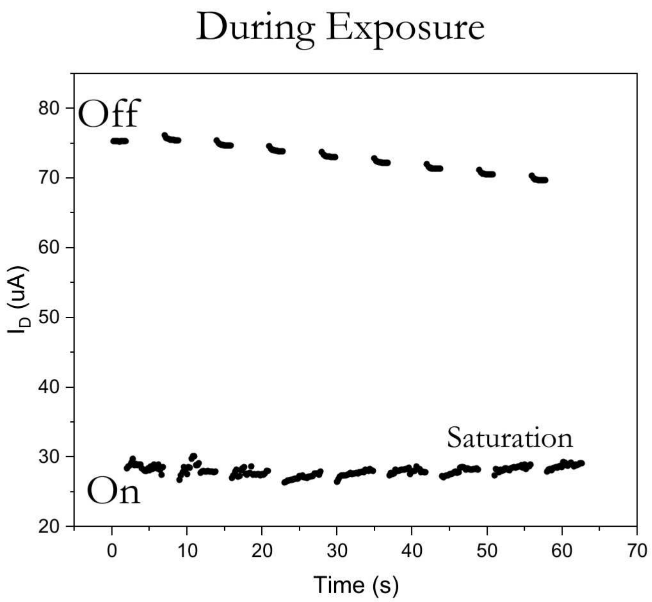


Silicon D²GOS for Gamma Ray Detection



Si D²GOS tested in Gammacell 220R
Cobalt 60 source
1.2 MeV
Sample lowered into Gammacell and exposed at 360°
Sample backgate pulsed at 0 V for 2 sec (Accumulation) and then 10 V for 5 sec (Depletion)





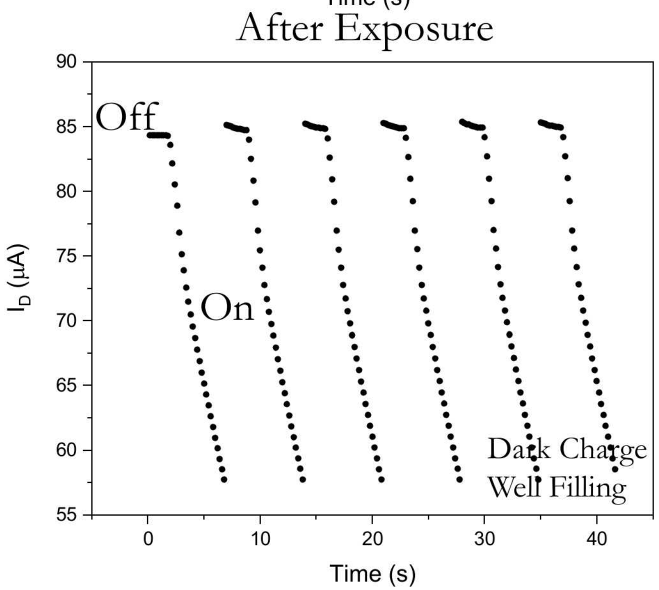
D²GOS Immediately Saturates when biased into deep depletion

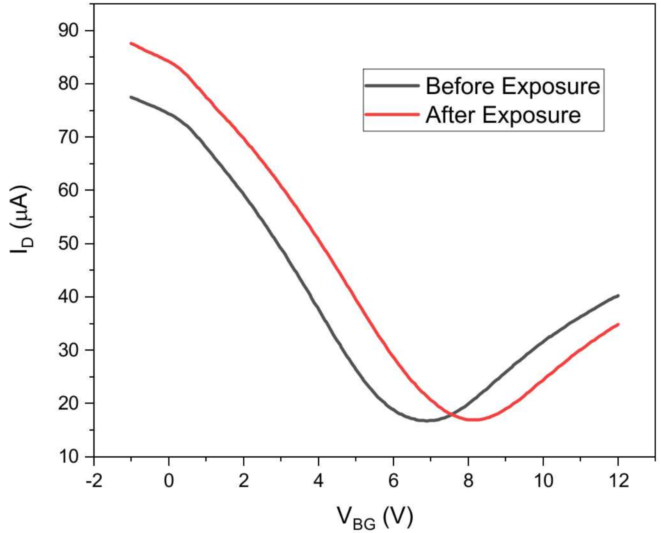
Device not noticeably damaged from high energy gamma exposure

Gate leakage current increase was observed in during On state while Being exposed to gamma radiation.

Returned to normal operation comparable to how it performed before the exposure.

I-V curves showed slight shift but otherwise normal.





Conclusion

Demonstrated a path forward for optimizing D^2GOS Detectors

- Improved Interface
- Improved Graphene Film

Demonstrated D^2GOS on III-V Substrates

- Expanded detection into near and mid-wave IR

Detected 1.2 MeV Gamma Rays in Si D^2GOS junction

- Device was not damaged
- Returned to normal operation after exposure

Thank you

Michael D. Goldflam

Stephen W. Howell

Thomas E. Beechem III

Sean Smith

Joshua Shank

Bruce Draper

Raktim Sarma

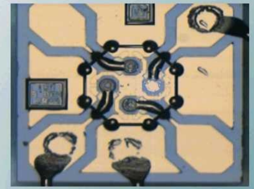
Anthony McDonald

SANDIA's PHOTONIC MICROSYSTEMS

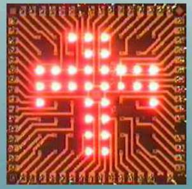
National Capabilities for Advanced Photonics R&D: design, model, fab, package, and test

Materials: Silicon, III-V (Phosphides, Arsenides, Antimonides, Nitrides), Lithium Niobate, Graphene, etc.

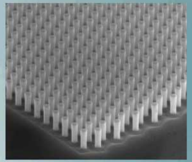
Sources



Single-Frequency Tunable VCSELs



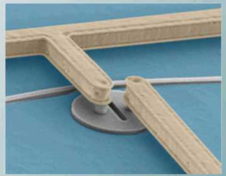
High Efficiency VCSELs



Nanowire Laser

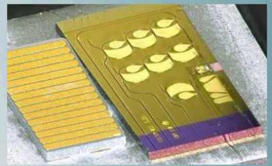
High power GaAs laser

Control / Manipulation

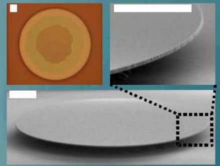


Resonant Optical Modulator/Filter

Array Waveguide Grating Channelizing Filter

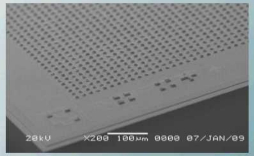


RF Channelizing Filter

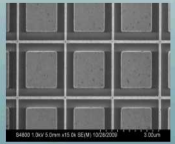


LiNbO3 Freq. Converter

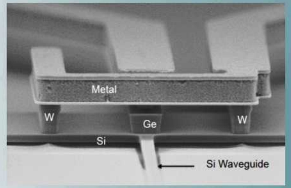
Detection



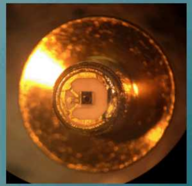
Infrared Detector



Plasmonic Perfect Absorber



Germanium Detector on Silicon

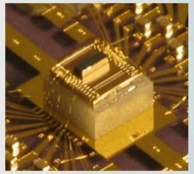


X-ray Detector

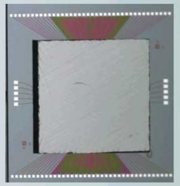
Chip-scaled MicroSystems

Heterogeneous Integration

III-V on CMOS



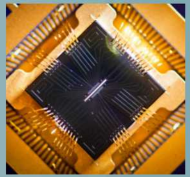
CMOS on Si Photonics



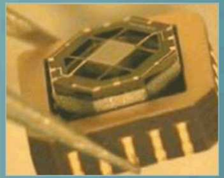
High-speed Optical Transceivers

nBn on CMOS

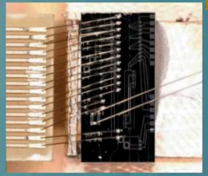
IR Focal Plane Array w/ ROIC



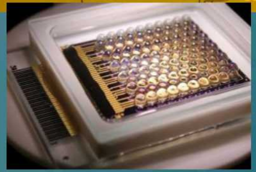
Quantum Surface Ion Trap



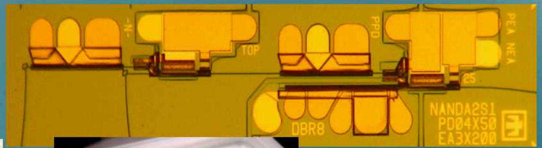
Atomic Clock



Quantum Key Distribution Transceiver



Photovoltaics w/ microlenses



High-speed All-Optical Logic

Collaborate with us!

Visit us:

- On-line: sandia.gov/mesa/nspc

Email contact:

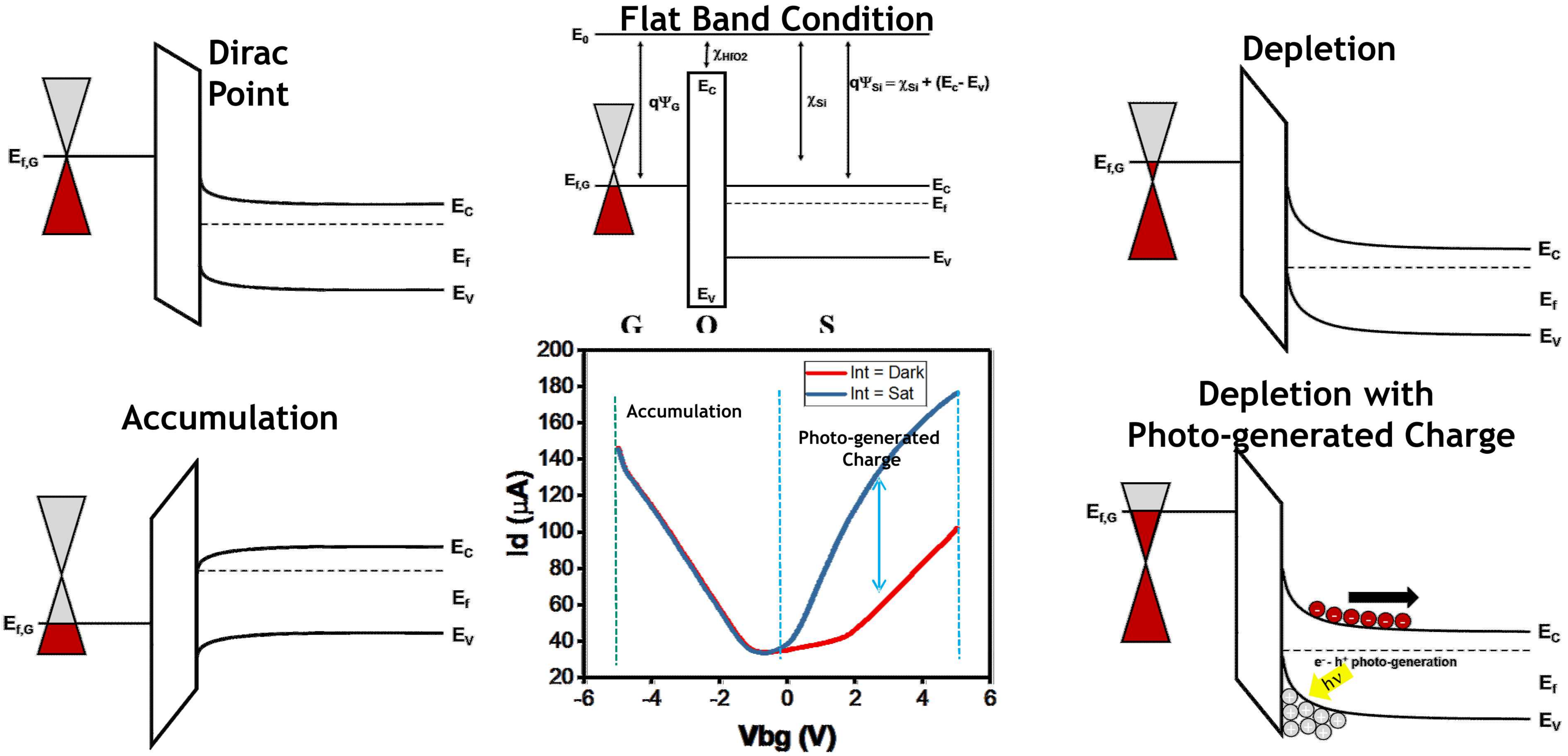
- photonics@sandia.gov

Career Opportunies for staff and students:

- www.sandia.gov/careers
  - Postdoc
  - Staff
  - Student interns (year-round or summer)

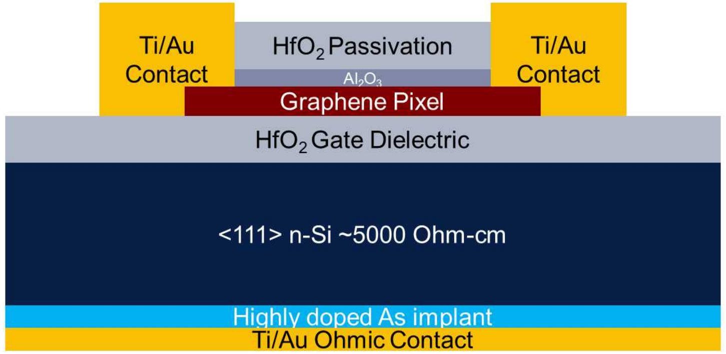
I will be happy to take any questions.

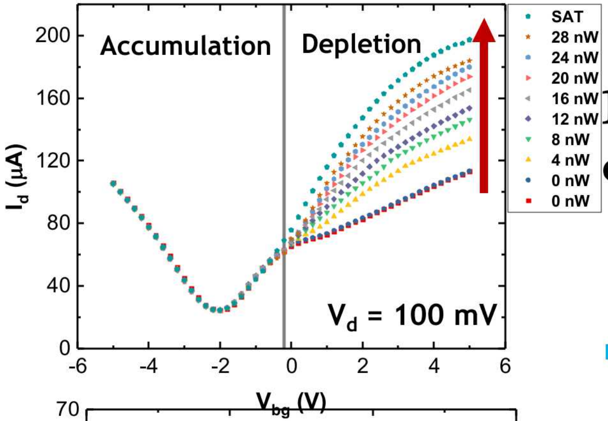
Band Diagram of “intrinsic” graphene D2GOS Junction Detector

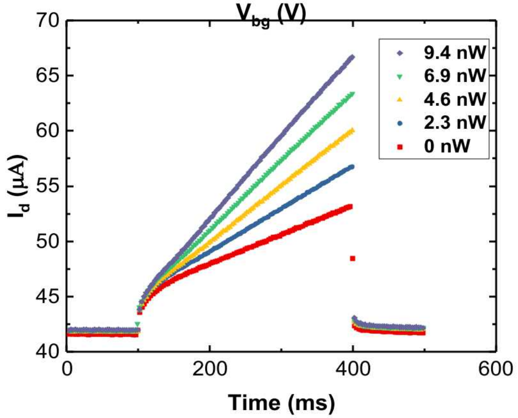


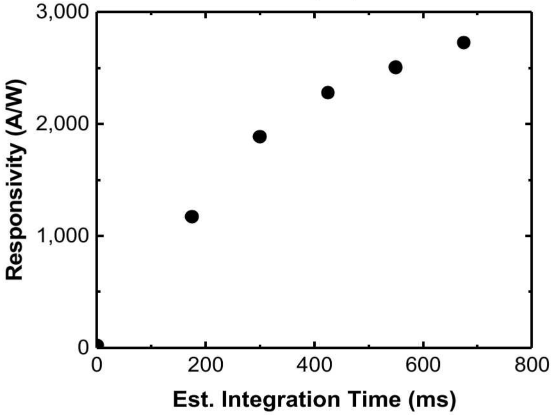
First Generation Silicon Based Devices For Visible Light Detection (635 nm)

- Fabricated on low doped n-doped silicon for absorption in the visible regime.
- Graphene was slightly n-doped, close to intrinsic.
- Demonstrated nW sensitivity.
- High Responsivity
  - > 2500 A/W



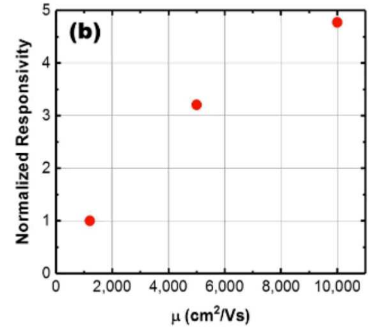






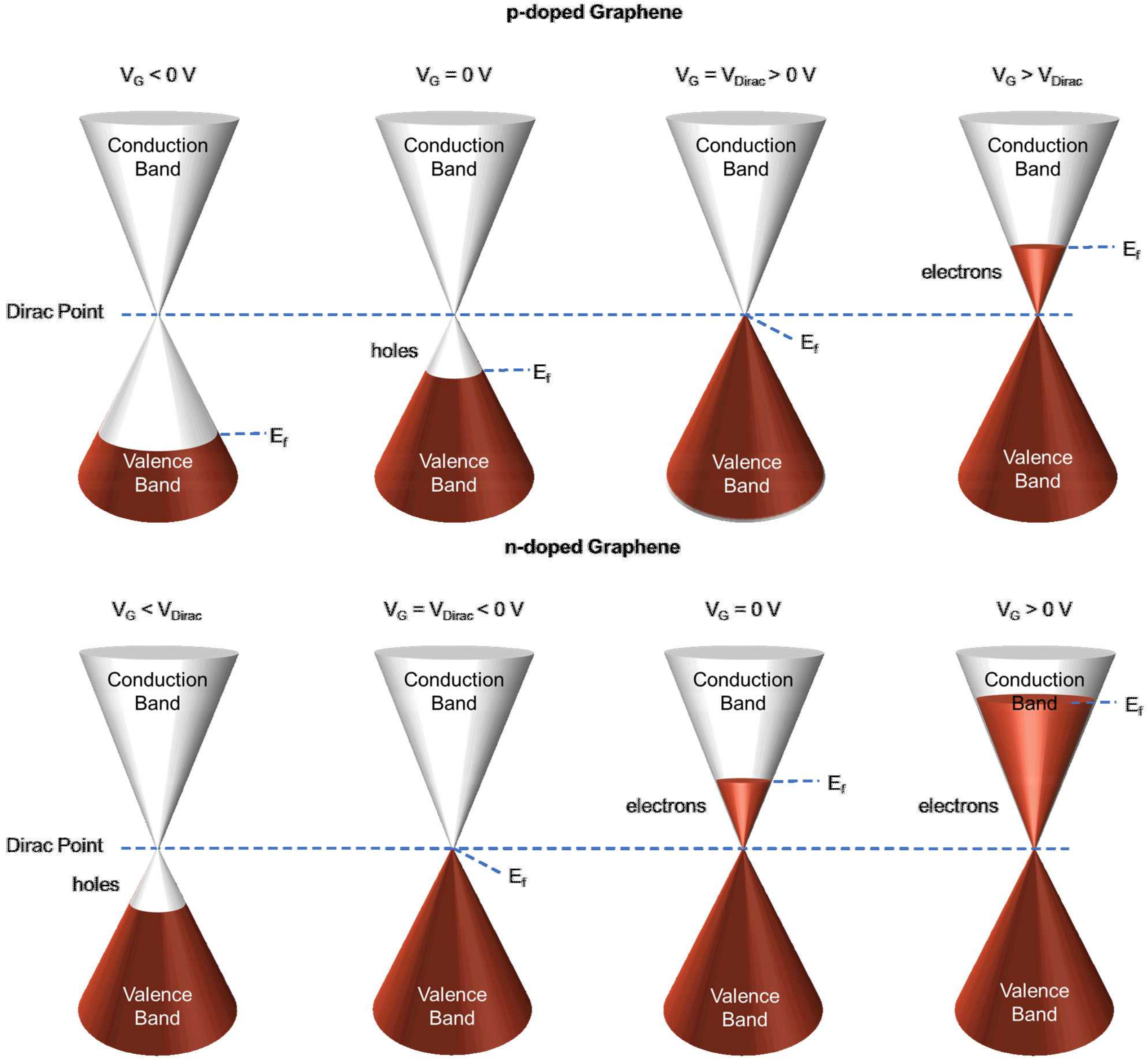
Devices were functional but nowhere near optimized.

- **Problems**
  - Poor interface between Si and HfO2.
    - 111 surface forms bad interface.
    - Potential well fills up quickly (~8 sec)
      - Thermally generated dark charge.
  - Graphene mobility ~1200 cm^2/s.
    - Near low end of CVD graphene quality

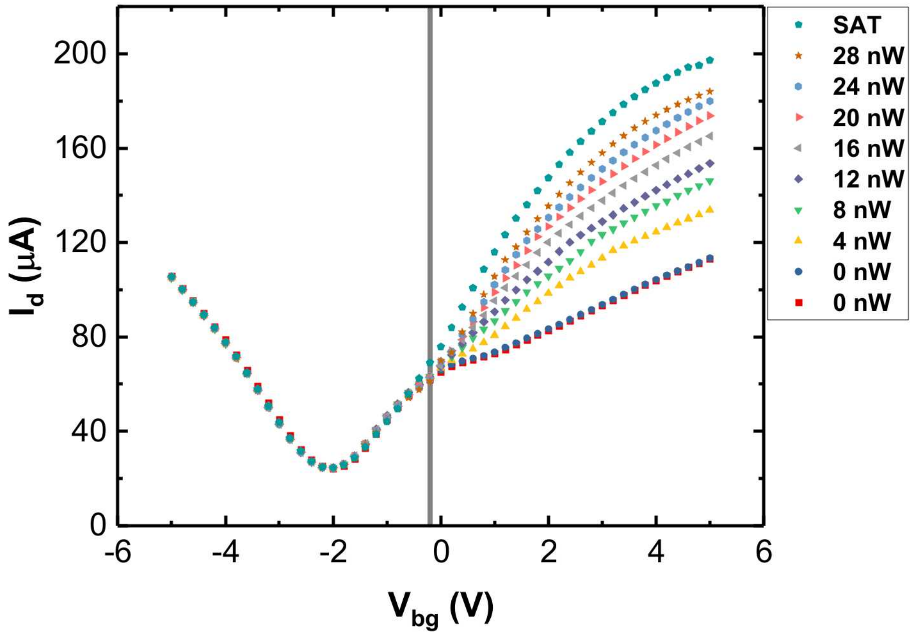


- **Only one of several possible configurations.**
  - N-doped Si
  - N-doped Graphene

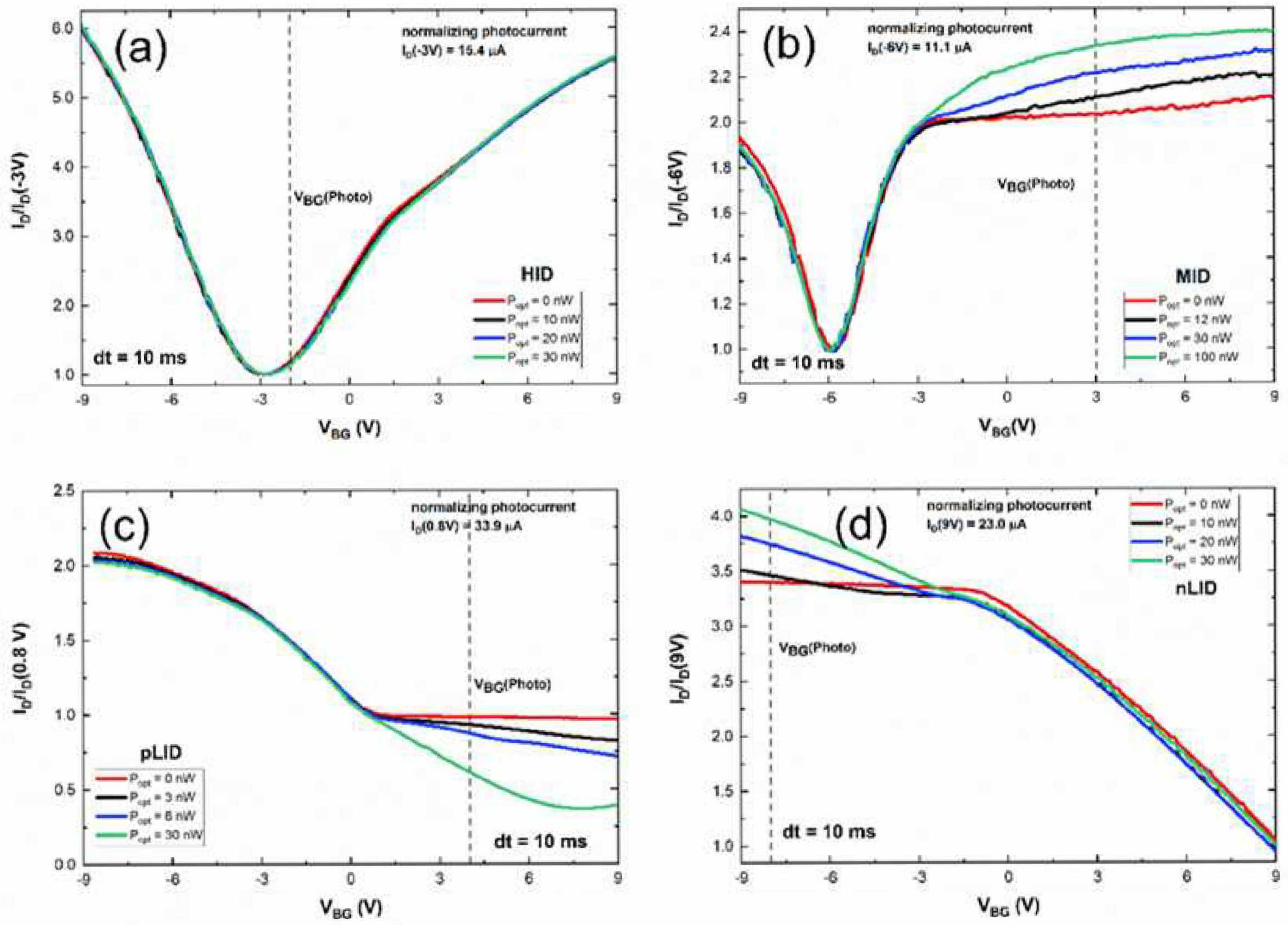
Graphene is Doped



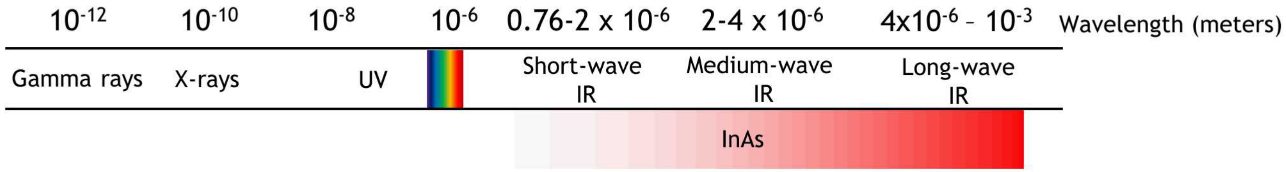
- First Generation Devices were n-doped Graphene on n-Si.
- This provided very predictable, easy to understand $I_d(V_{bg})$ curves.



$I_D(V_{BG})$ of HID, MID, p-LID and n-LID



Demonstration of D^2GOS Junction of InSb (E_g ~0.17 eV (~7.3 μm))

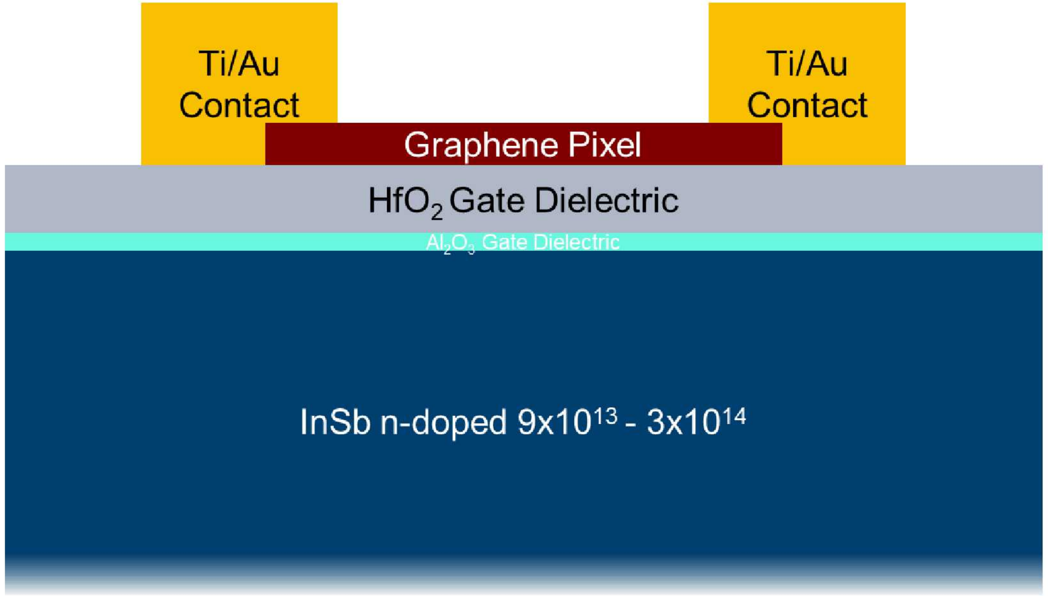


InSb Surface Preparation

Remove Native Oxide
BOE Etch 90 sec

Surface Passivation
(NH4)2SO4 soak for 5 min

Atomic Layer Deposition Recipe
Al2O3 deposition 10 cycles (TMA)
HfO2 Deposition 550 Cycles (TDMAH)



Small photo response in depletion

Dark current appears quenched at 77K.

Responsive to light.

Photo Current proportional to incident light power.

Current not saturating when flood illuminated (Si devices saturated immediately with powers low as 100 nW)

Some photo response in accumulation. Why?

(Illuminated with White light)