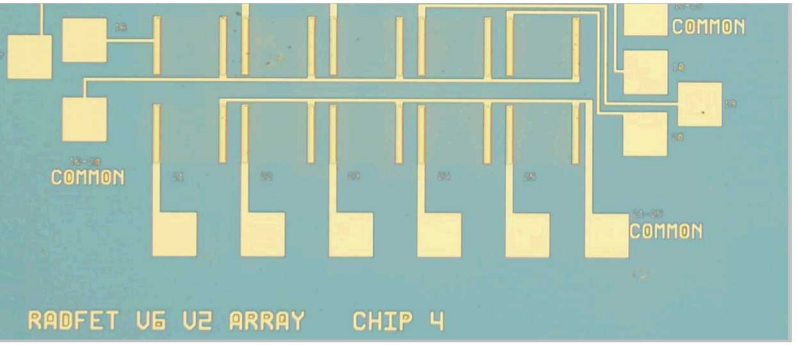
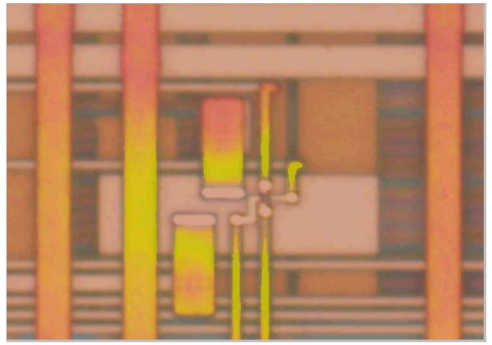
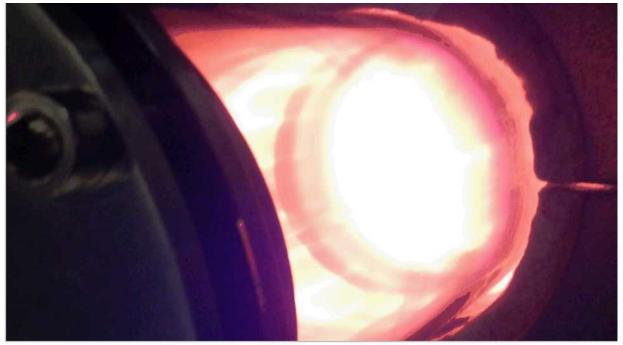
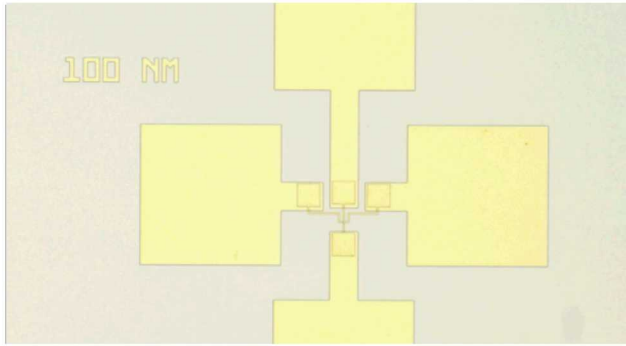
SAND2018-7092C









Characteristic Transconductance of P-Type and N-Type Deeply Depleted Graphene-Insulator-Semiconductor Junction Photodetectors

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

Smart Sensor Technologies

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

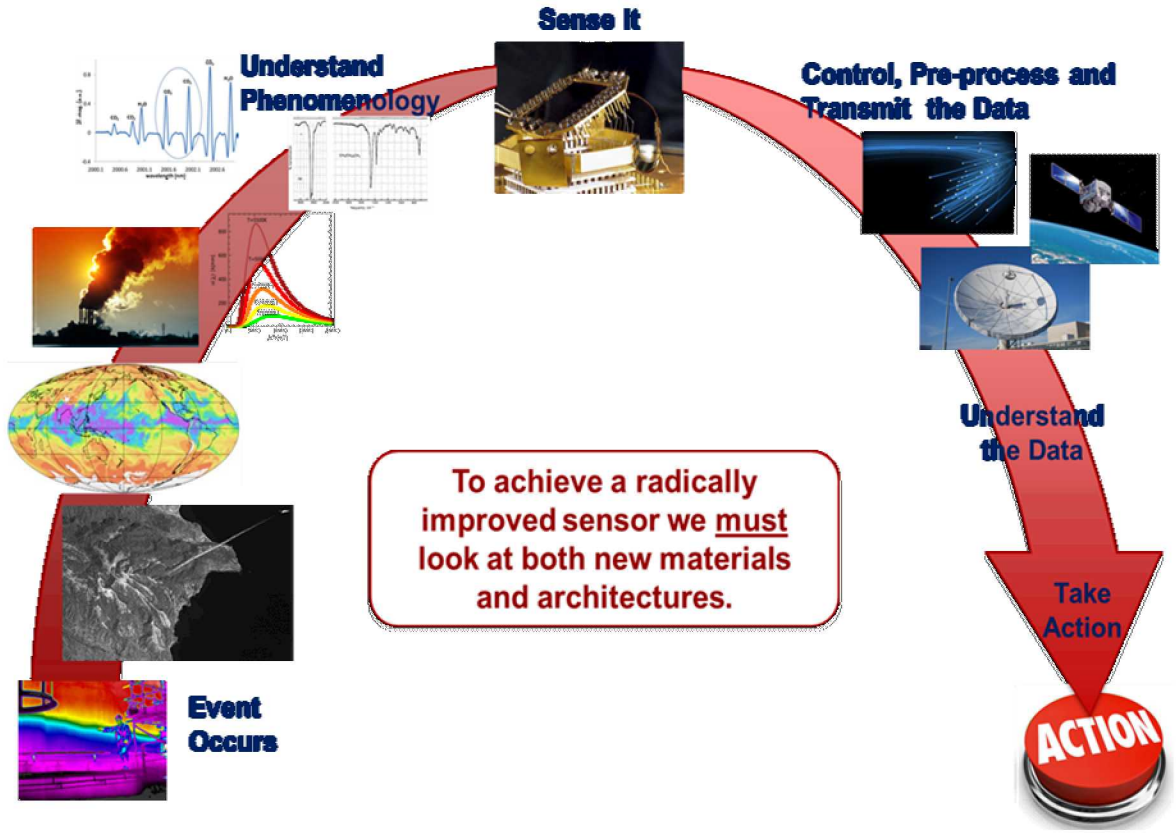
- Motivation
- Background of the D^2GOS Junction Detector
  - Operating Principles
  - First generation device performance
- Improving the D^2GOS Detector
  - Reducing interface states
  - Well Lifetime measurements
- N-type and P-type D^2GOS Visible Detectors
  - Semiconductor doping
  - Graphene doping
  - Experimental Demonstration
- Demonstration of D^2GOS in the near Infrared

Smart Sensors Technology Grand Challenge

Goal: Develop the foundation for a new infrared detector that will lead to an order of magnitude improvement in noise, higher resolution, and real-time spectrally tunable pixels.

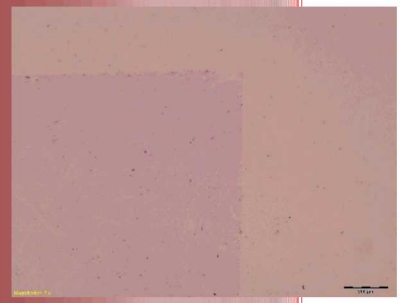
Thrusts:

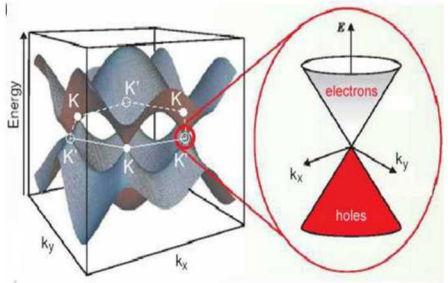
- Tune the Resonance
  - Control the resonance of nanoantennas
- Tune the Detector
  - Control absorption into materials
- Improve Performance



Motivation

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

ically thin

absorptio

Shor bination th

contact doping

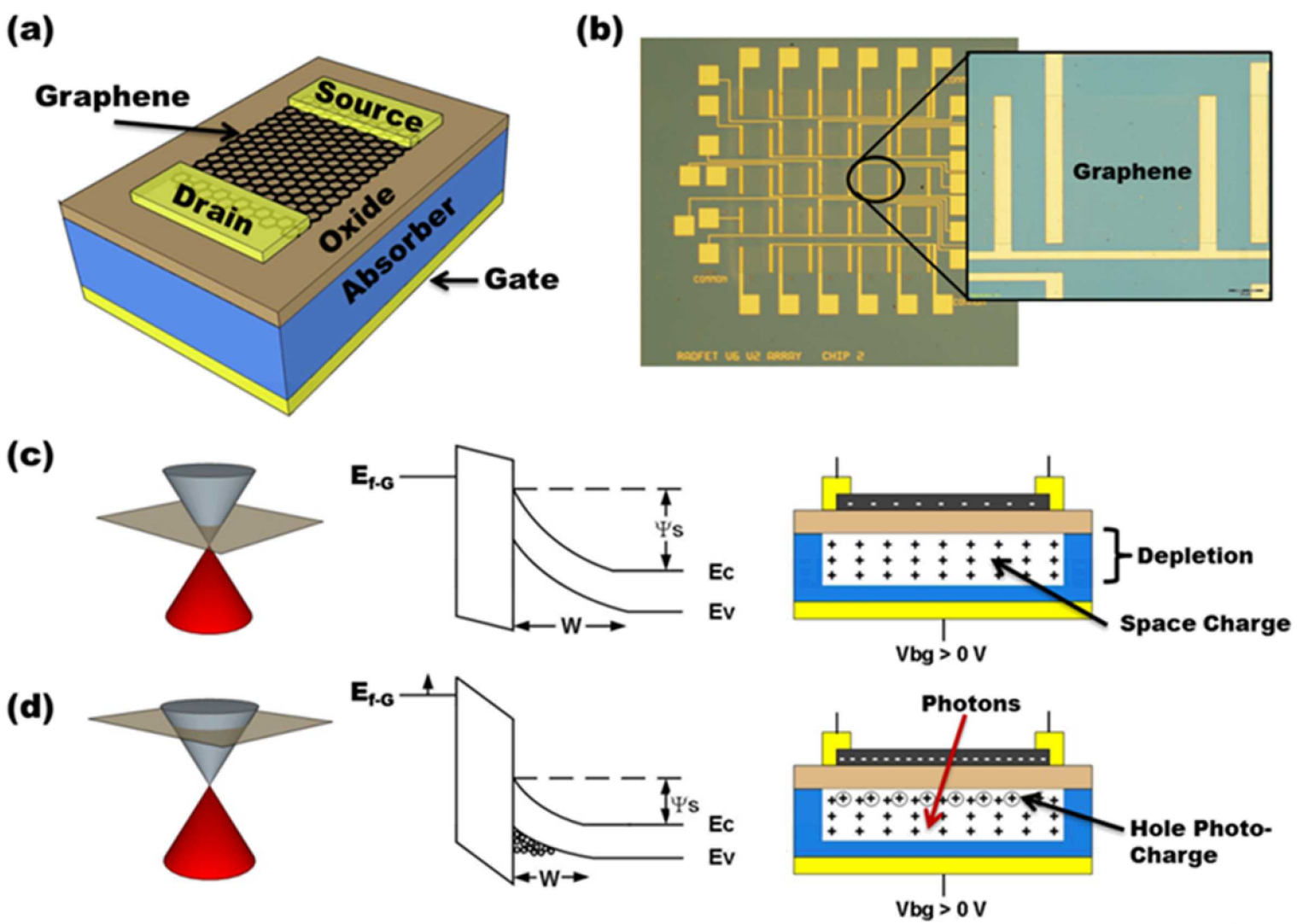
Solution:

Don't Absorb into the Graphene

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

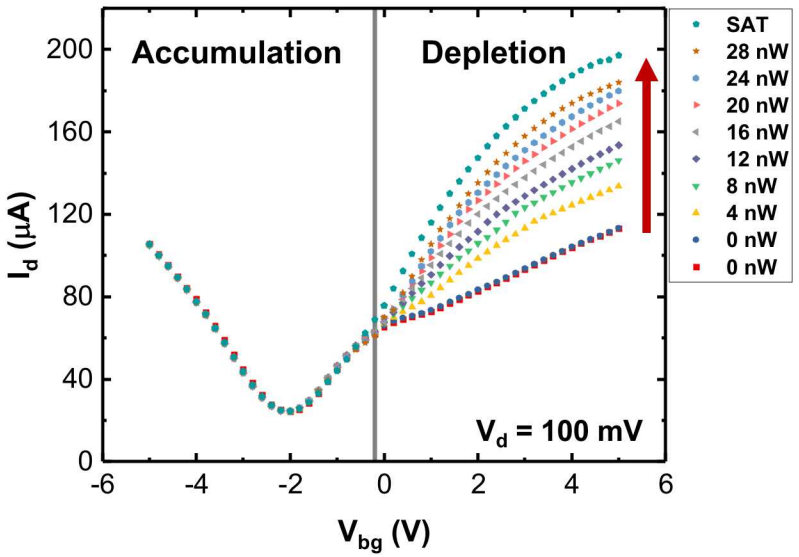
What is the Deeply Depleted GIS Junction and how does it Work?

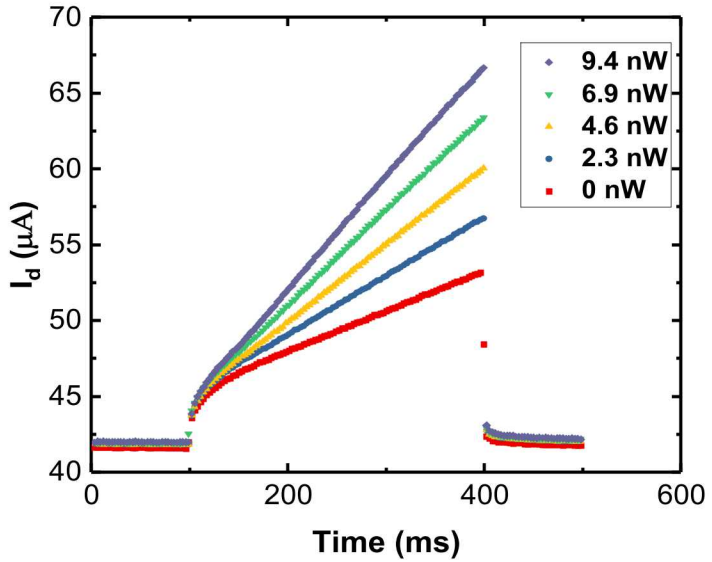
1. Absorber-Oxide-Graphene Junction.
2. Low doped absorber is depleted with an applied back gate voltage.
3. Incoming light creates photo-generated charge in absorber.
4. Built in electric field separates electron-hole pairs.
5. Charge accumulates at semiconductor/Oxide interface.
6. Graphene FET senses accumulated charge

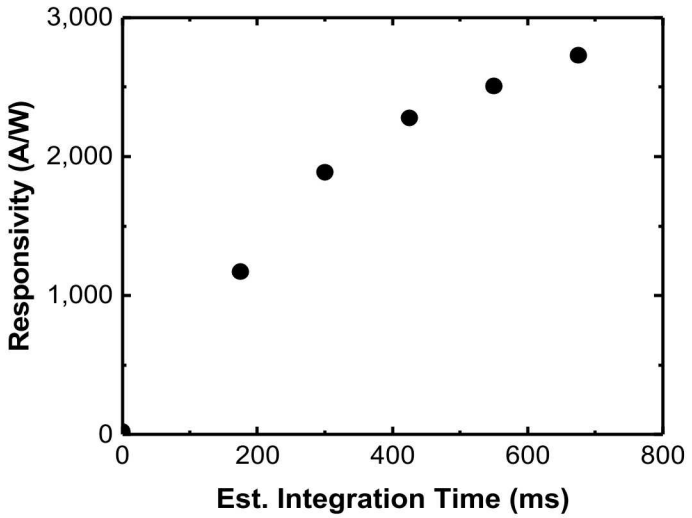


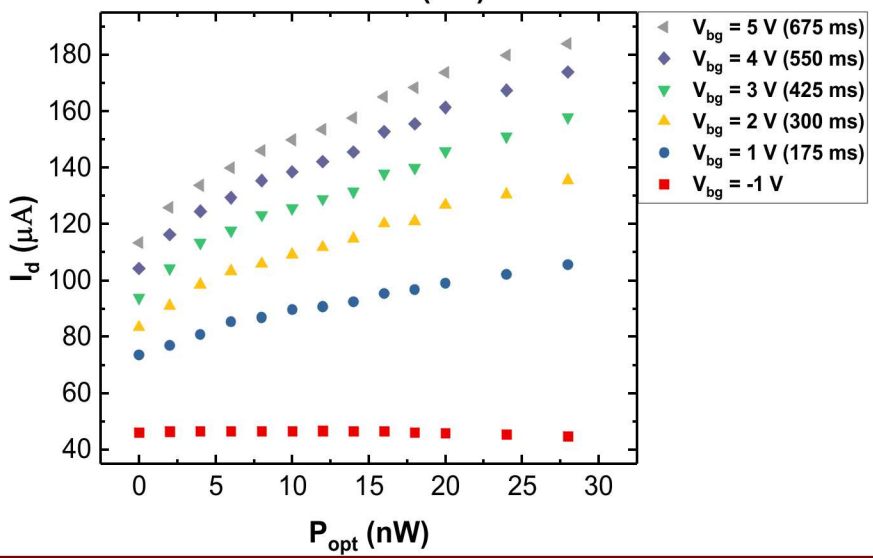
Howell, S.W., Ruiz, I., Davids, P.S., Harrison, R.K., Smith, S.W., Goldflam, M.D., Martin, J.B., Martinez, N.J. and Beechem, T.E., 2017. Graphene-Insulator-Semiconductor Junction for Hybrid Photodetection Modalities. Scientific reports, 7(1), p.14651.

First Generation Devices









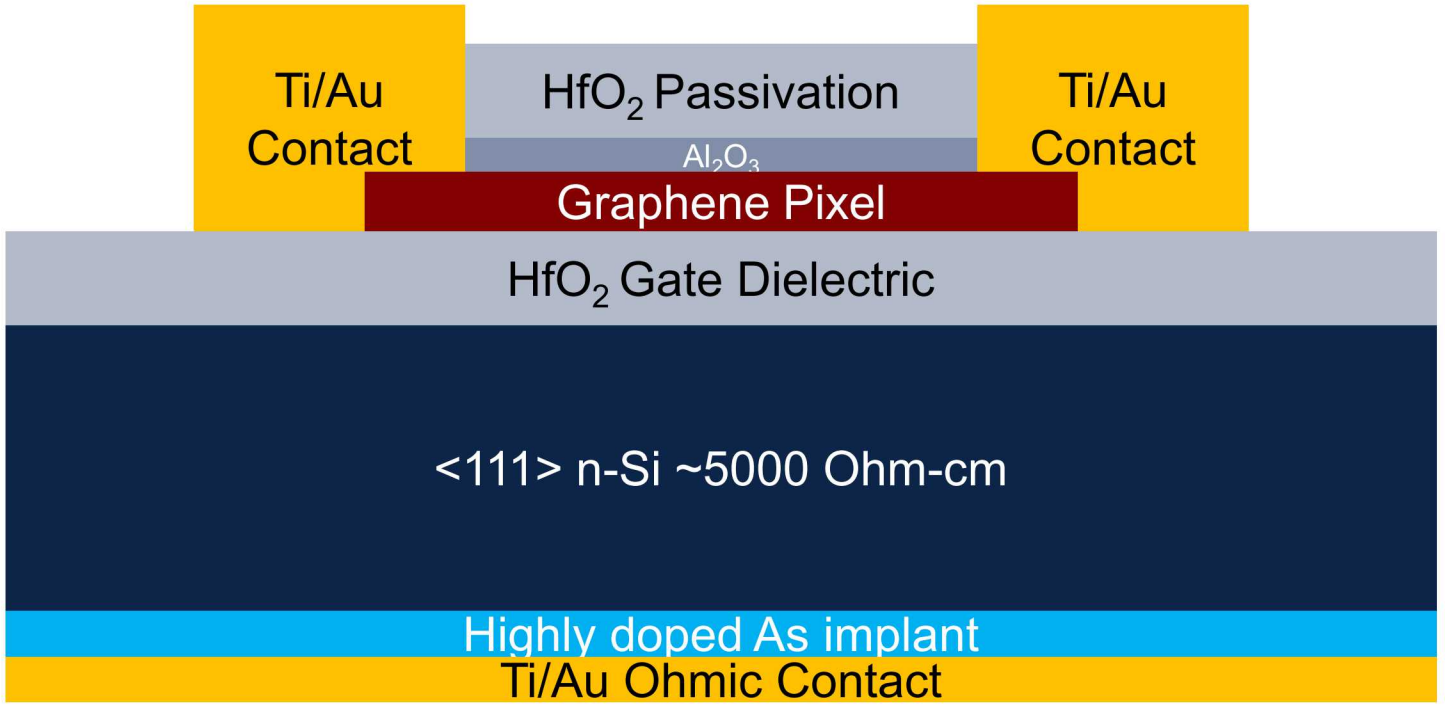
- Fabricated on low doped n-doped silicon for absorption in the visible regime.
- Graphene was slightly n-doped, close to intrinsic.
- Demonstrated nW sensitivity.
- High Responsivity
  - 2500 A/W

Howell, S.W., Ruiz, I., Davids, P.S., Harrison, R.K., Smith, S.W., Goldflam, M.D., Martin, J.B., Martinez, N.J. and Beechem, T.E., 2017. Graphene-Insulator-Semiconductor Junction for Hybrid Photodetection Modalities. Scientific reports, 7(1), p.14651.

First Generation Device Architecture

- **Devices functioned but nowhere near optimized.**

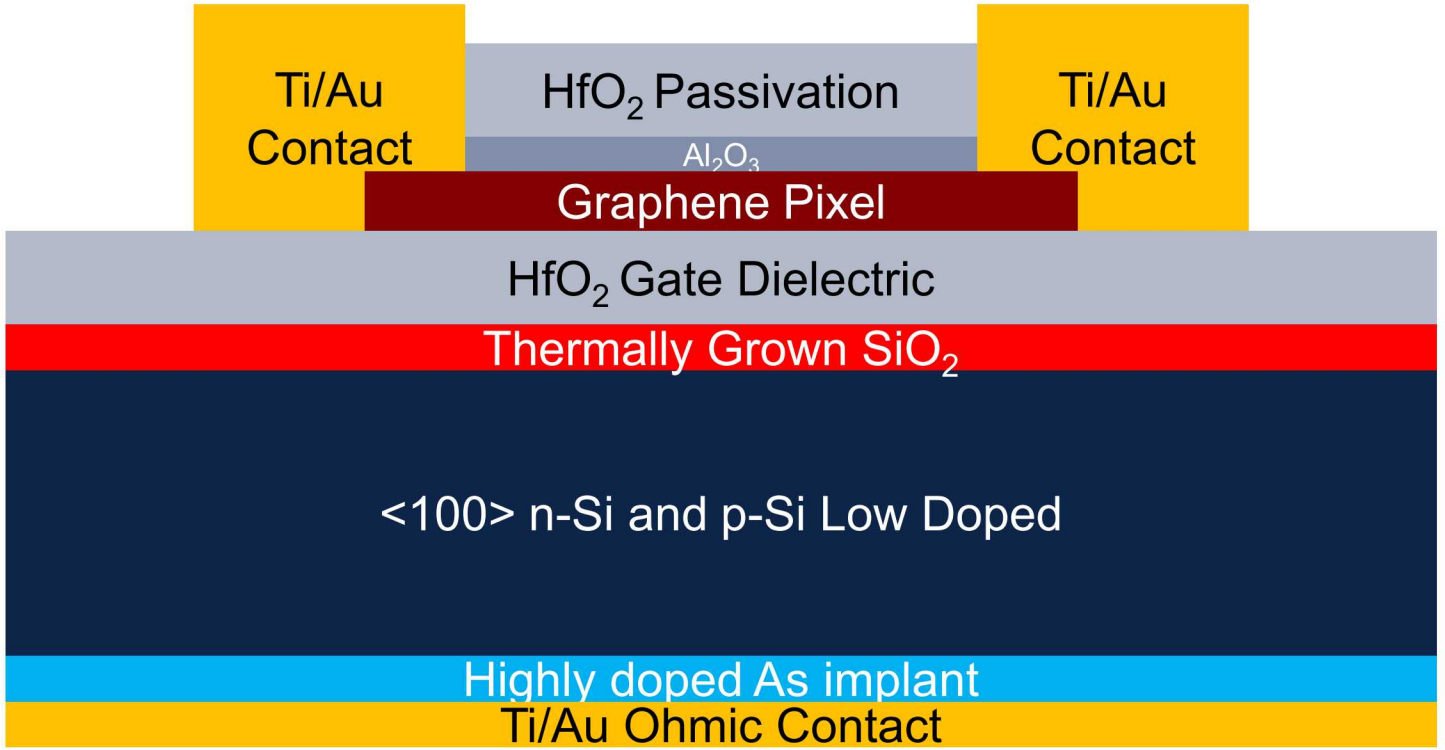
- **Problems**
  - Poor interface between Si and HfO2.
    - 111 surface forms bad interface.
    - Potential well fills up quickly (~8 sec)
  - Graphene mobility ~1200 cm^2/s.
    - Near low end of CVD graphene quality
- **Only one of several possible configurations.**



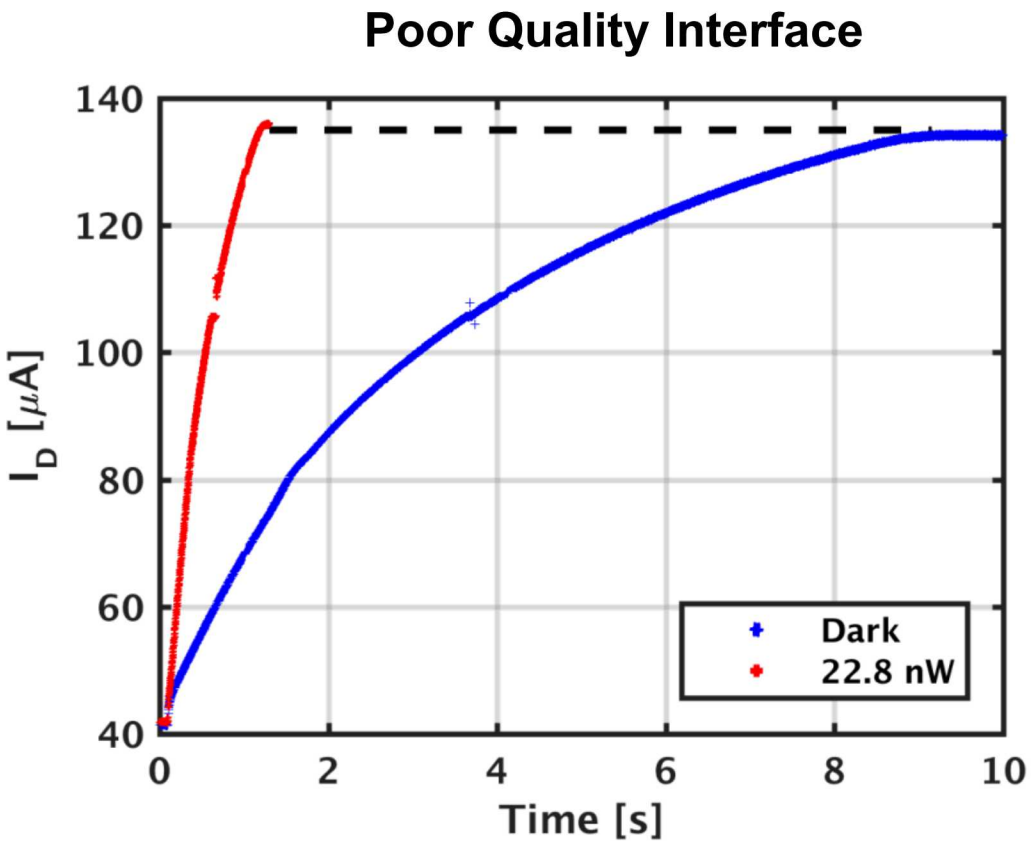
Next Generation Device Architecture

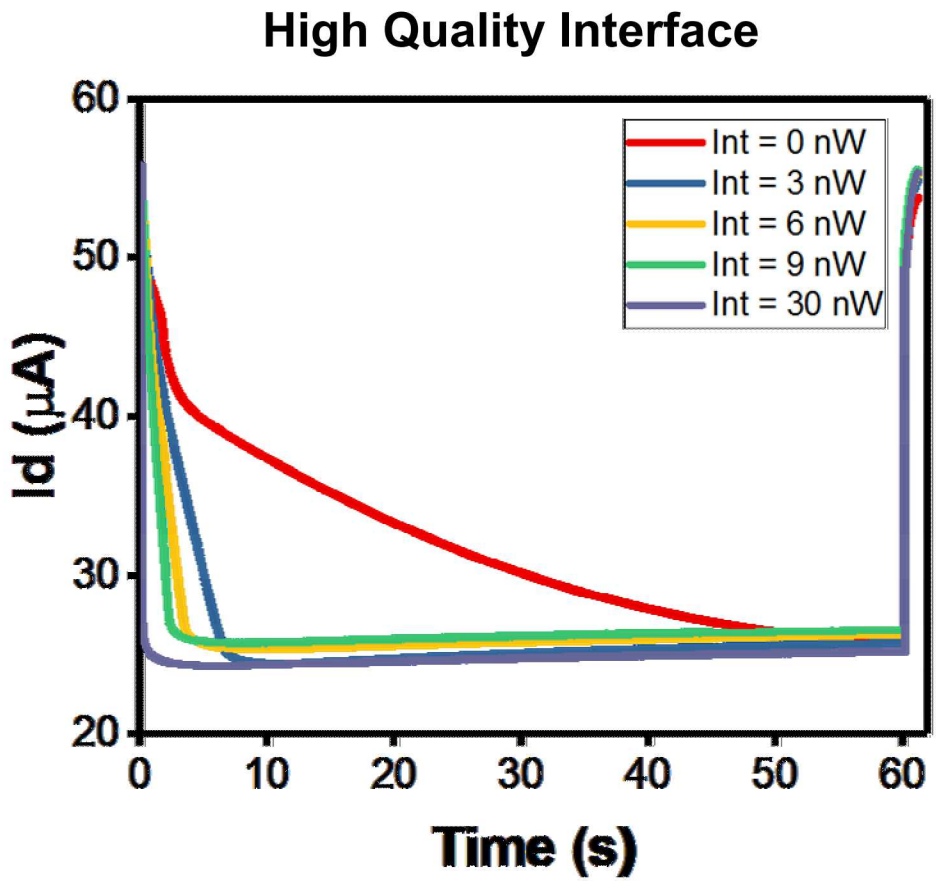
- **Start designing for optimization**
  - ✓ Lower Interface States
  - ✓ Different Absorbers
  - ✓ Graphene Doping
  - ○ Increased graphene mobility

- **Explore the possible configurations of substrate doping and graphene doping.**



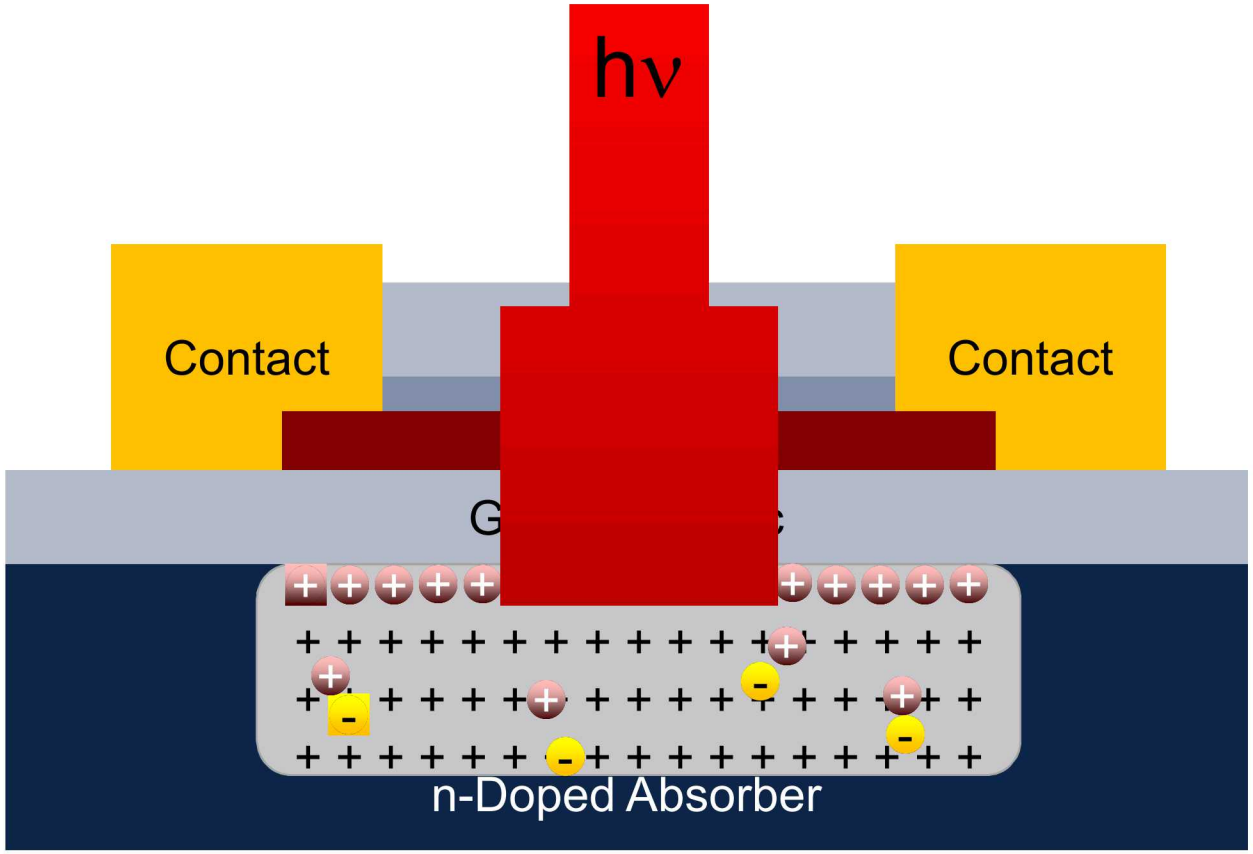
High Quality Interface Effect on Well Filling



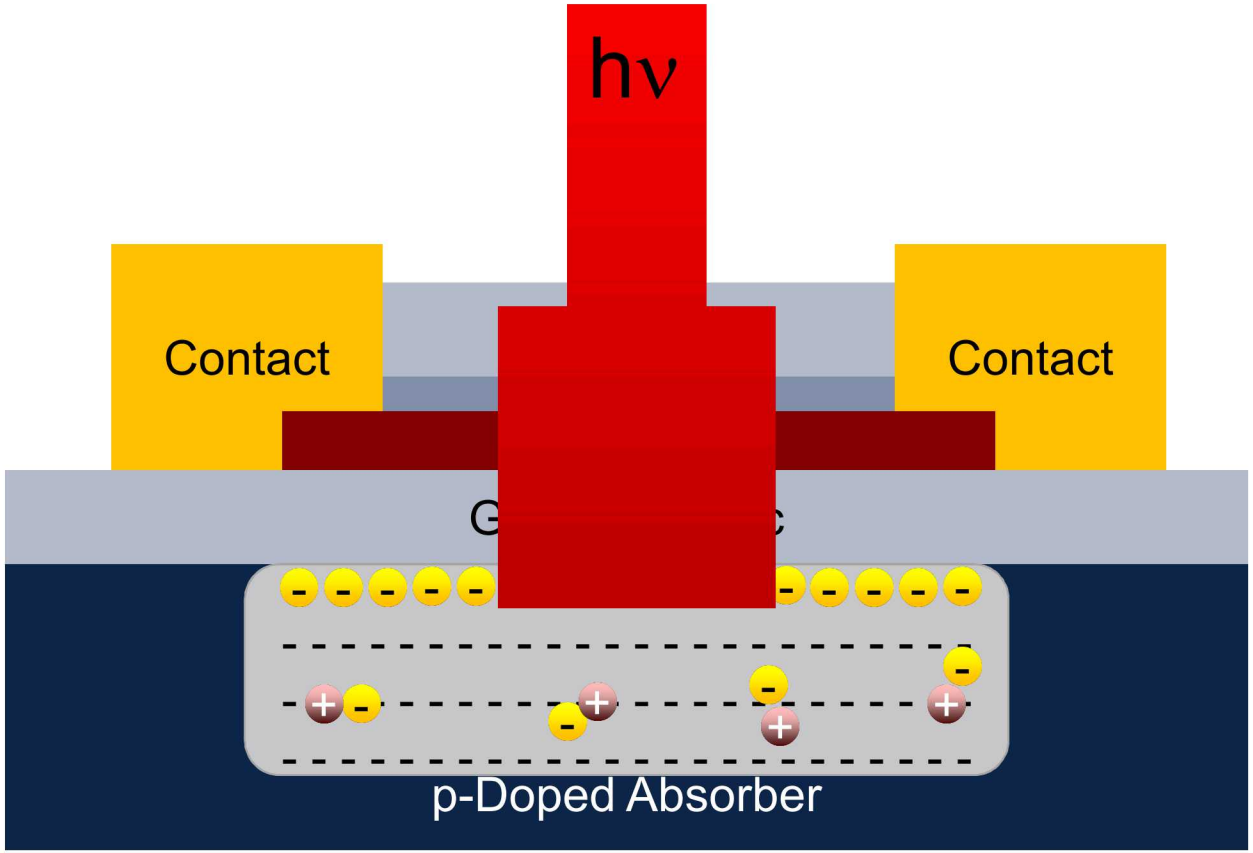


Note: This device architecture allows for direct visualization and read-out of the charge collecting at the absorber/oxide interface.

P-Type and N-Type D^{2}GOS

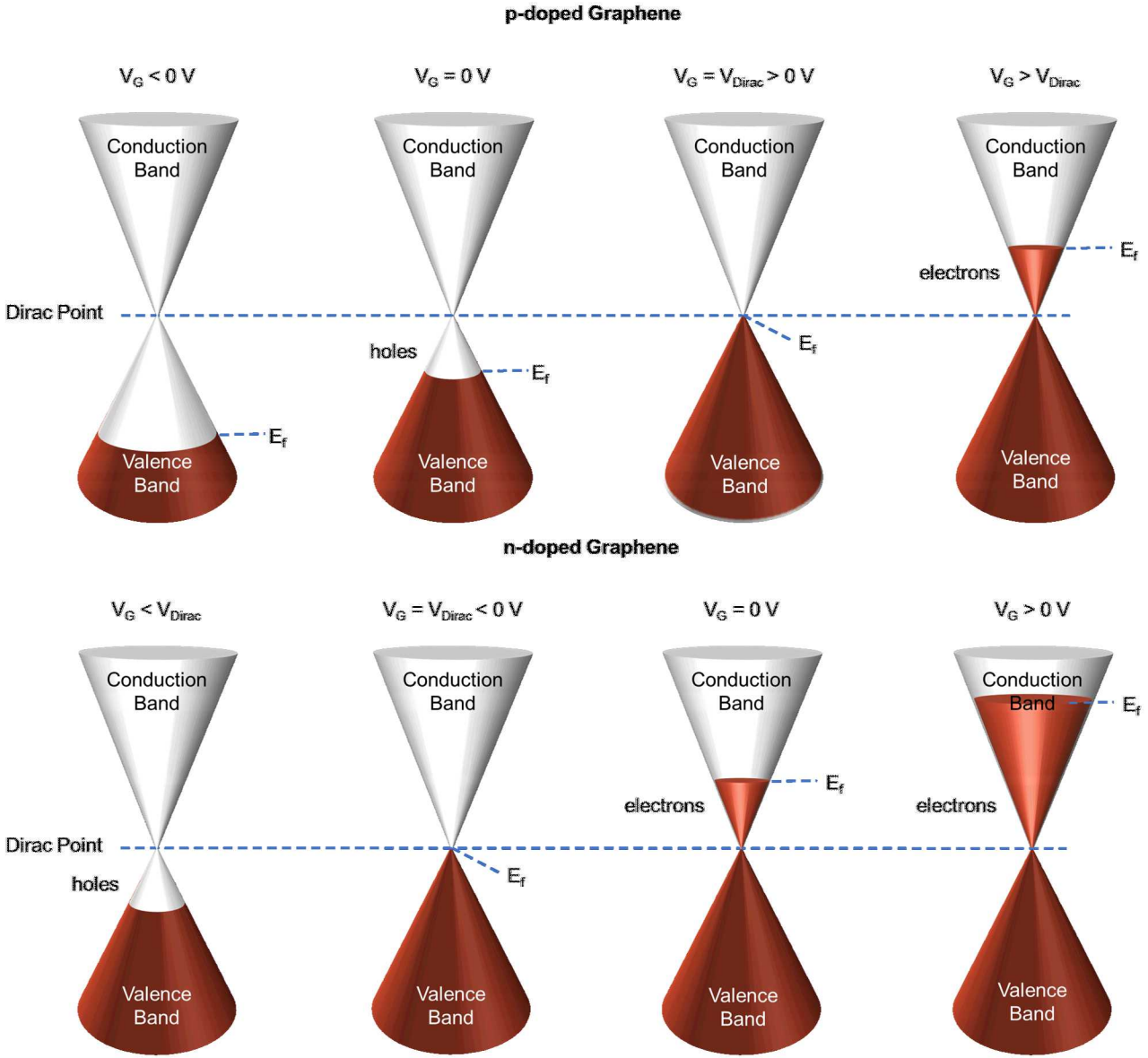


$V_{bg} > V_{fb}$



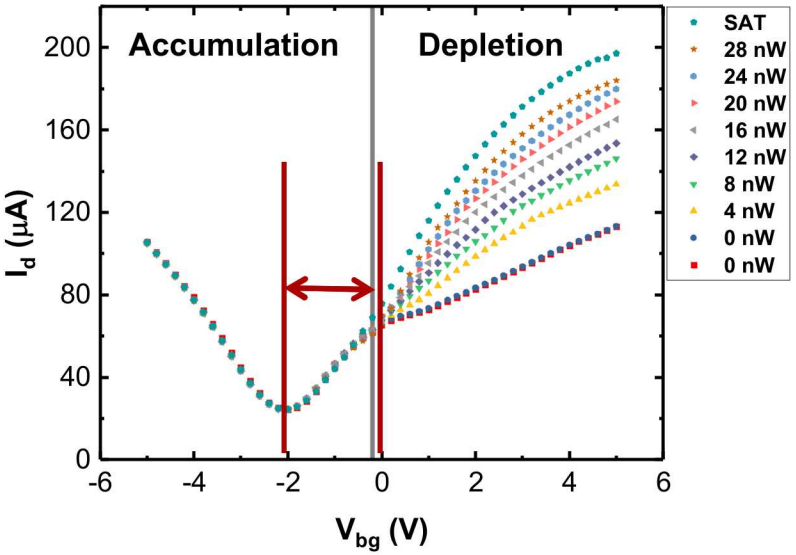
$V_{bg} < V_{fb}$

Graphene is Doped



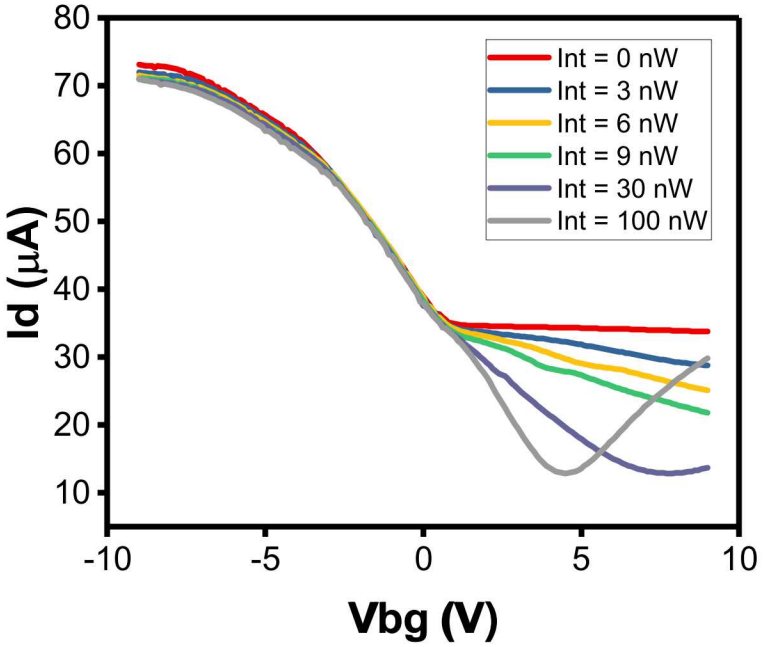
First Generation Devices were n-doped Graphene on n-Si.

This provided very predictable, easy to understand $I_d(V_{bg})$ curves.

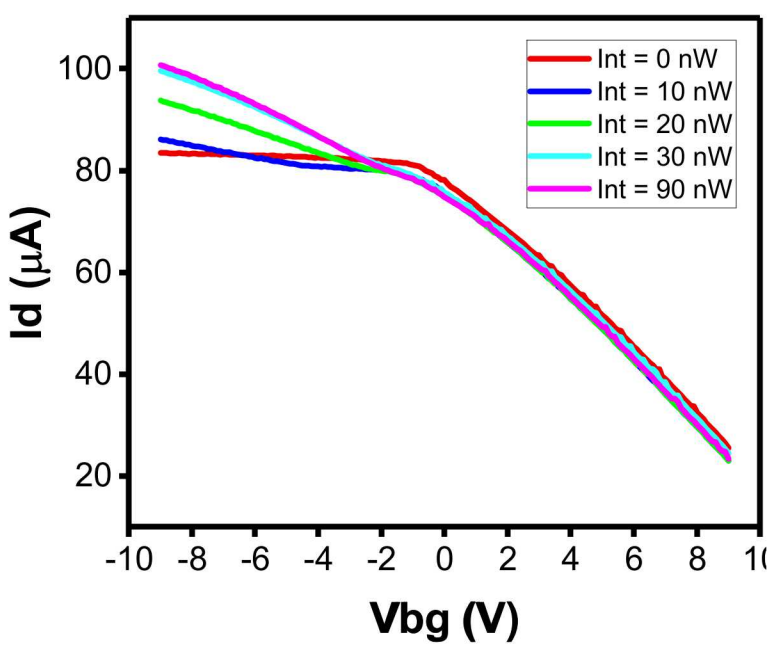


N and P doped Graphene on n-Si and p-Si

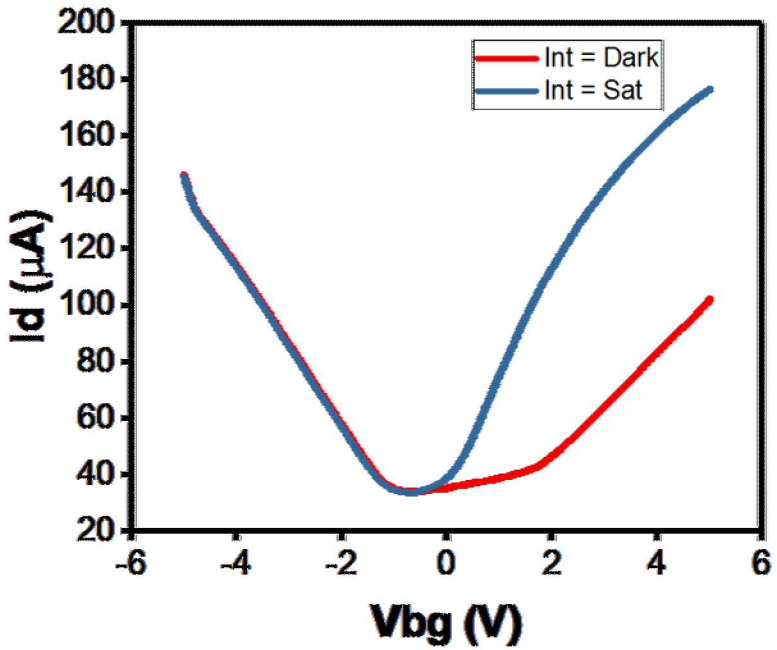
p doped Graphene on n-Si



p doped Graphene on p-Si



n doped Graphene on n-Si

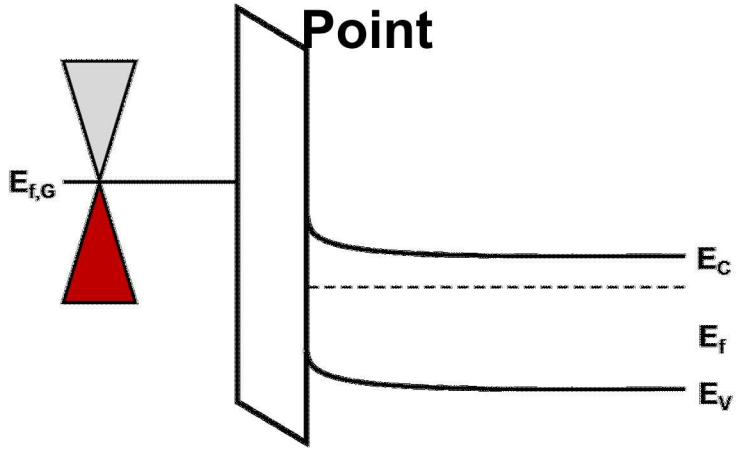


Missing Example of n doped Graphene on p--Si

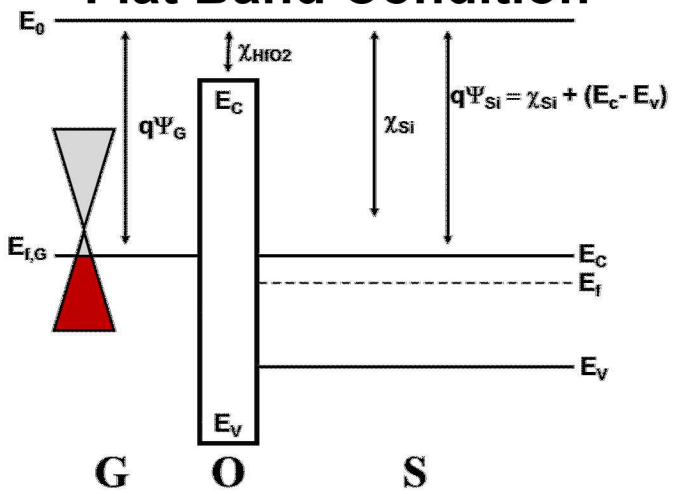
Band Diagram of “intrinsic” graphene D²GOS Junction Detector

Sandia National Laboratories

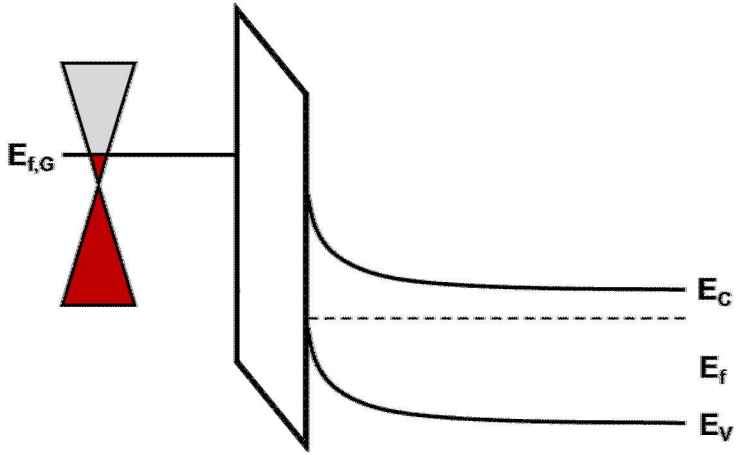
Dirac Point



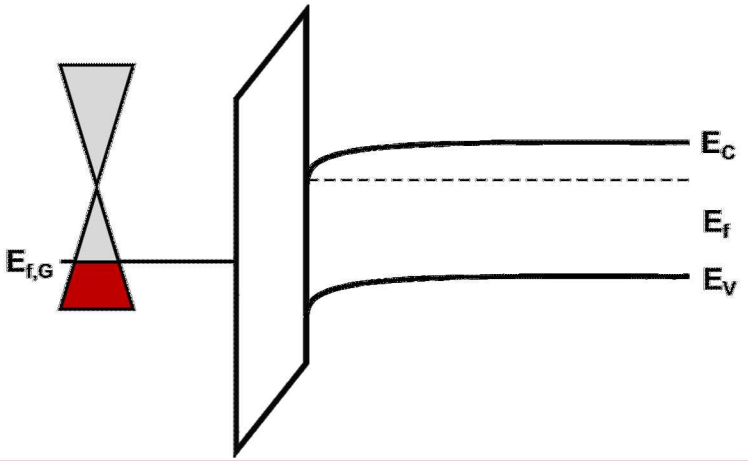
Flat Band Condition

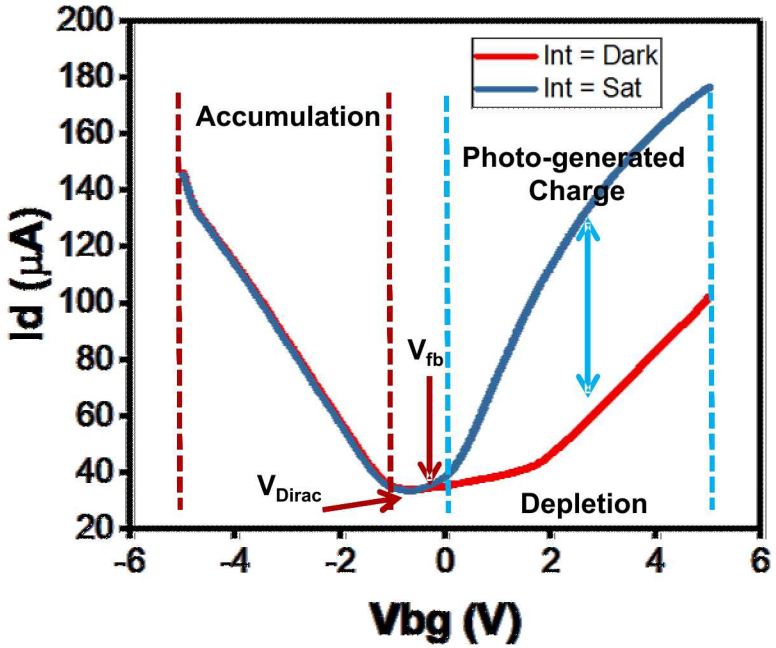


Depletion

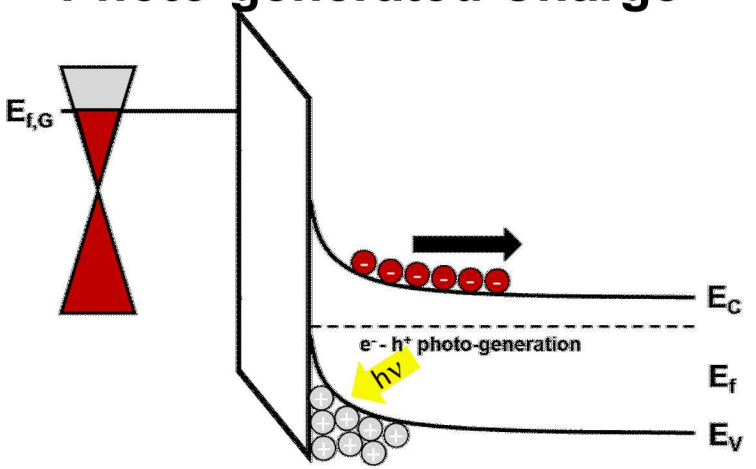


Accumulation



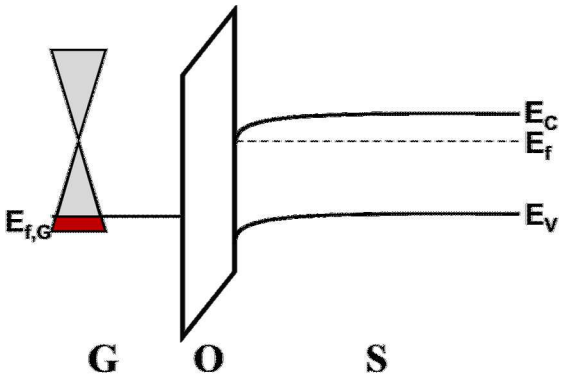


Depletion with Photo-generated Charge

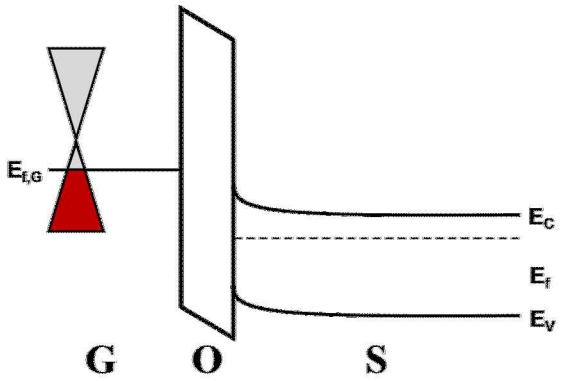


$I_d(V_{bg}$, integration time) for p-doped graphene on n-Si

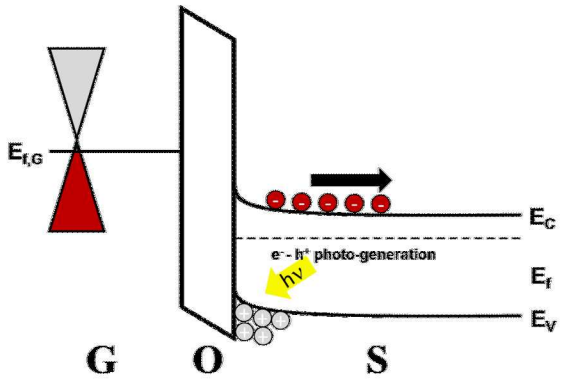
$V_{bg} < V_{fb}$
Accumulation

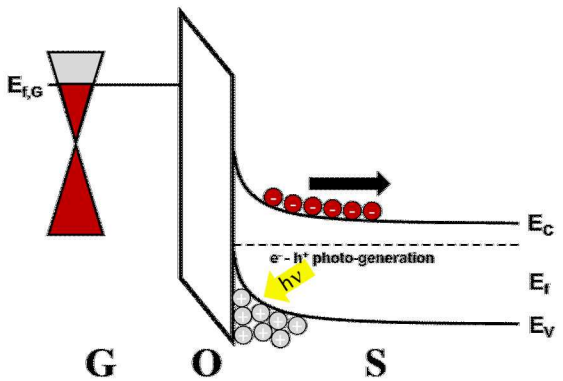


$V_G = V_{Dirac} > V_{FB}$
Depletion

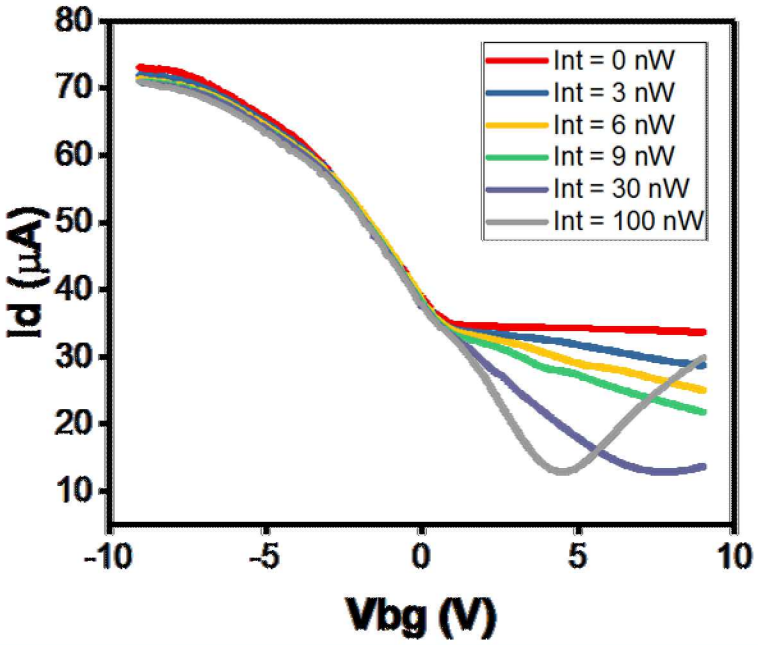


$V_G = V_{Dirac} > V_{FB}$
Dep. w/Photo-gen. Charge

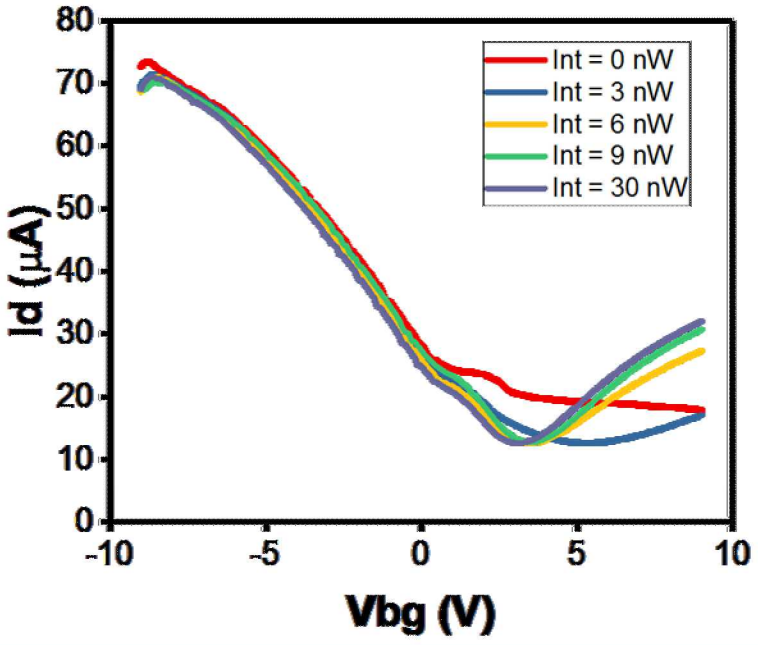




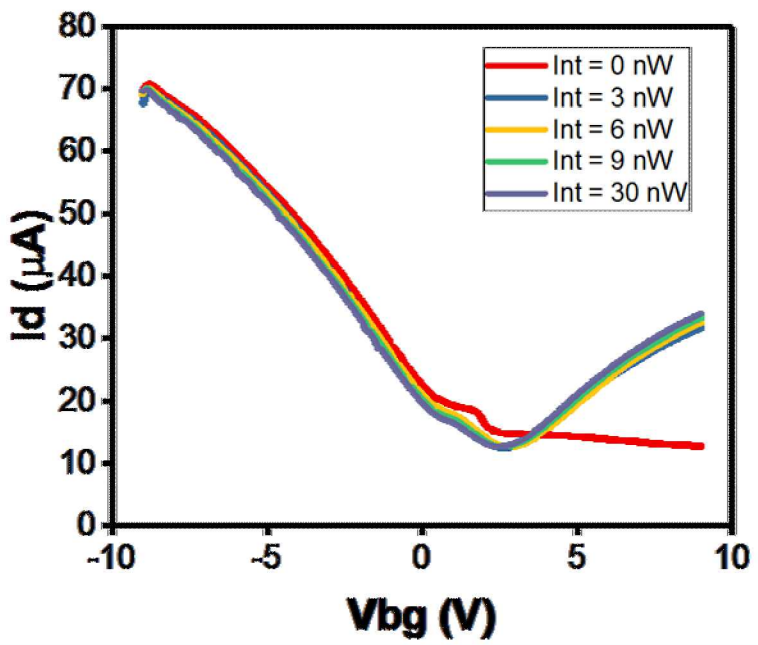
dt = 10 ms



dt = 100 ms

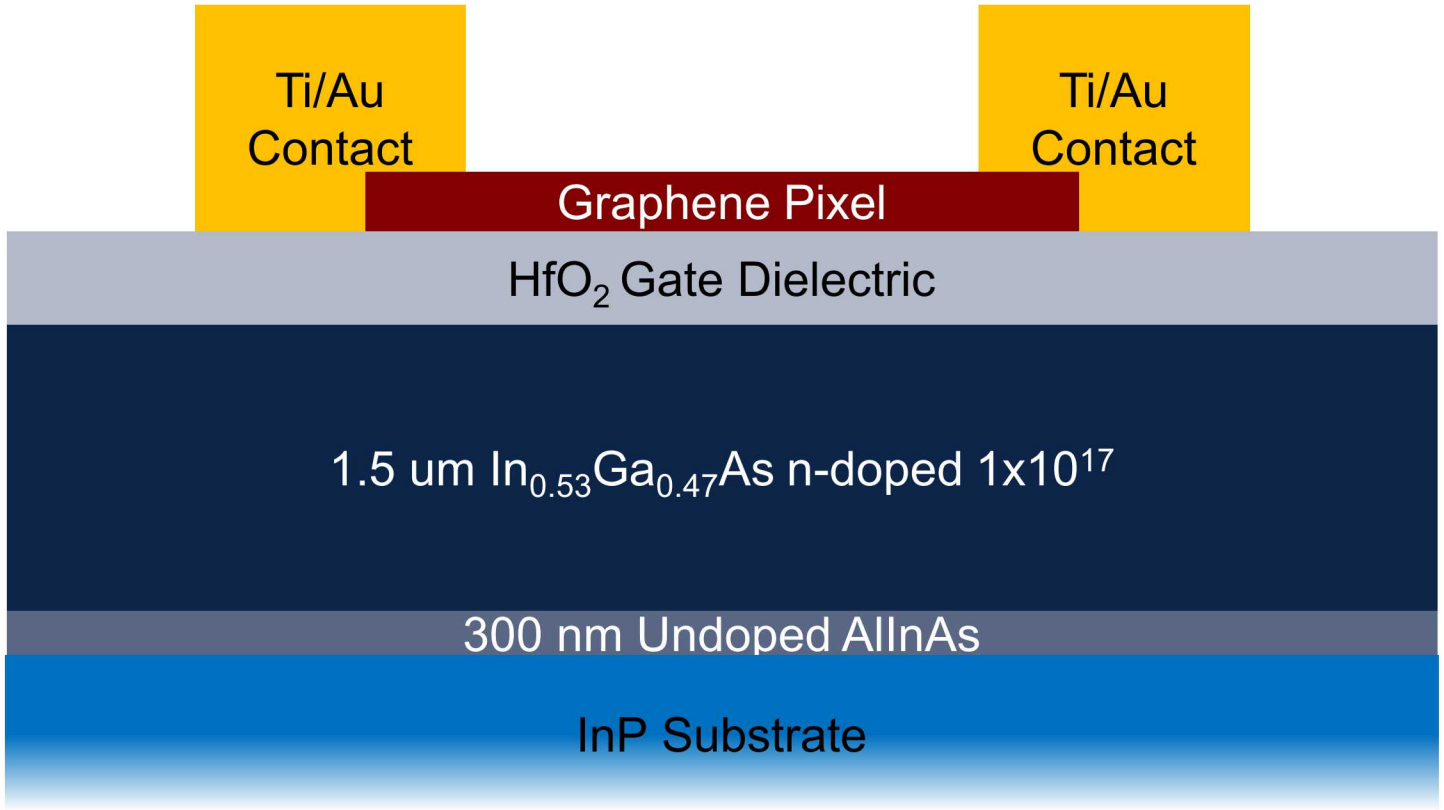


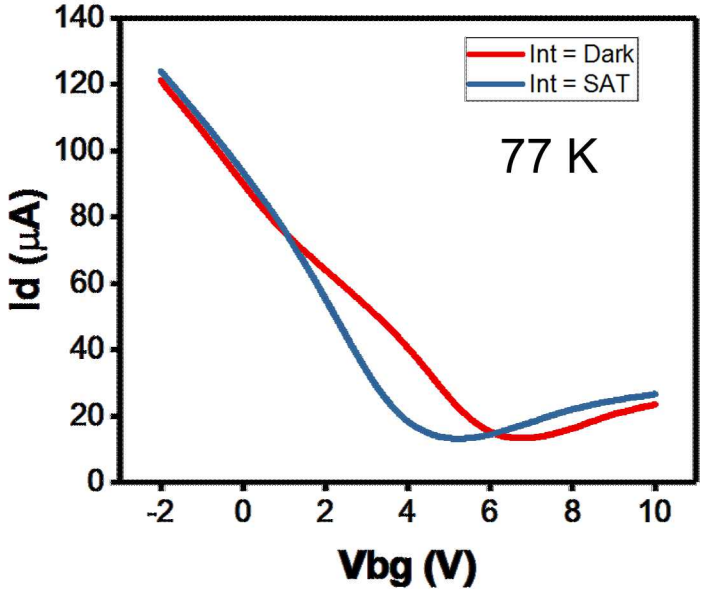
dt = 300 ms



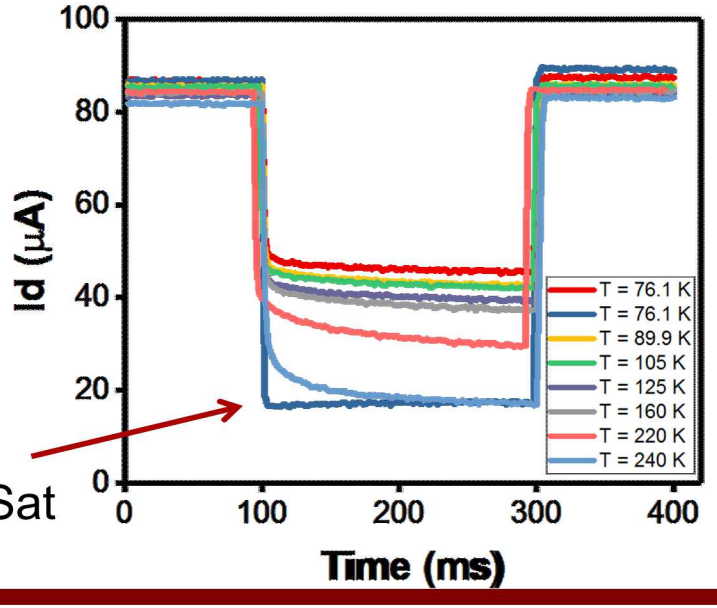
Demonstration of D^2GOS on Shortwave IR Substrate

E_g ~ 1.6 um





77 K
Int. = Sat



Conclusion

- Demonstrated a path forward for optimizing D^2GOS Detectors
  - Improved Interface
  - Determining different operation modes due to graphene and substrate doping.
- Increased well lifetime to over a minute compared to 9 sec.
- Demonstrated D^2GOS on III-V absorber for the first time.

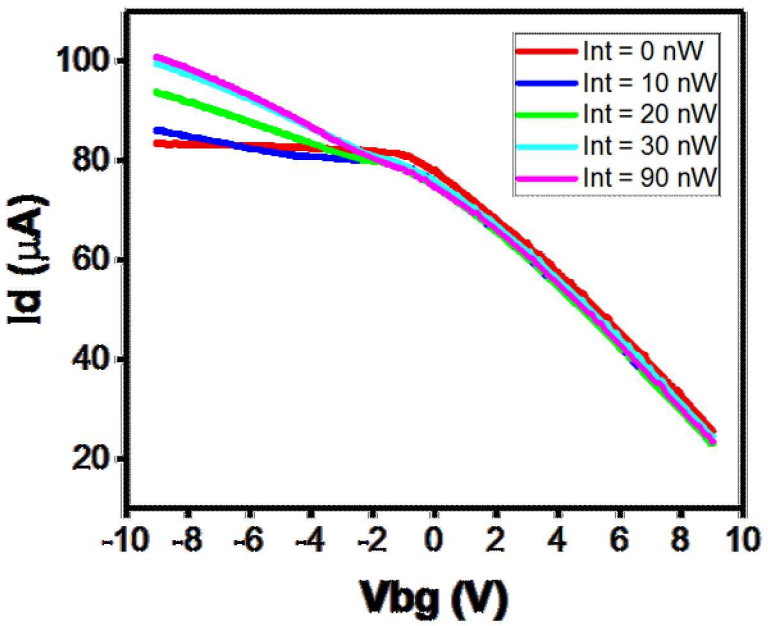
Thank You

Sandia National Laboratories

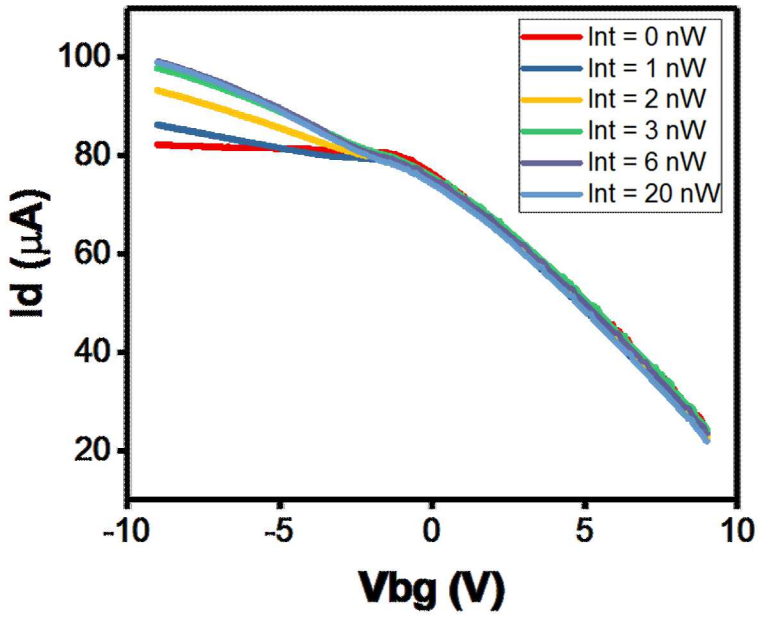
Questions?

$I_d(V_{bg}$, integration time) for p-doped graphene on p-Si

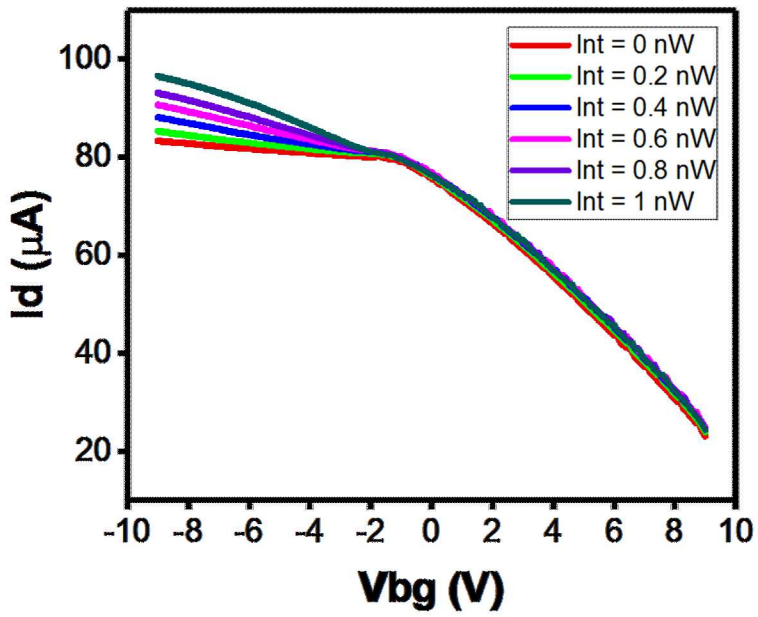
dt = 10 ms



dt = 100 ms

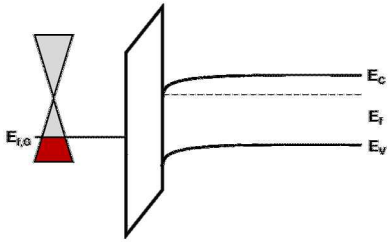


dt = 300 ms

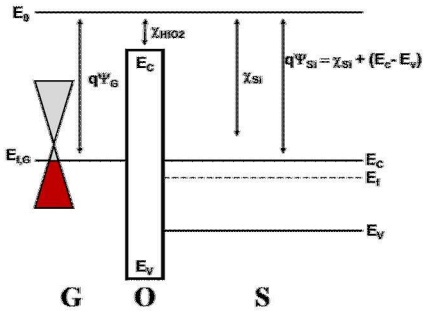


D²GOS Band Diagram

N-SI, Intrinsic Graphene

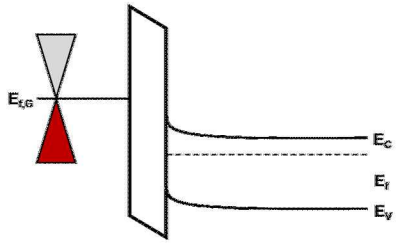


Accumulation



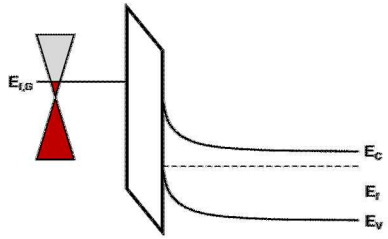
Flat Band Condition

Dirac Point

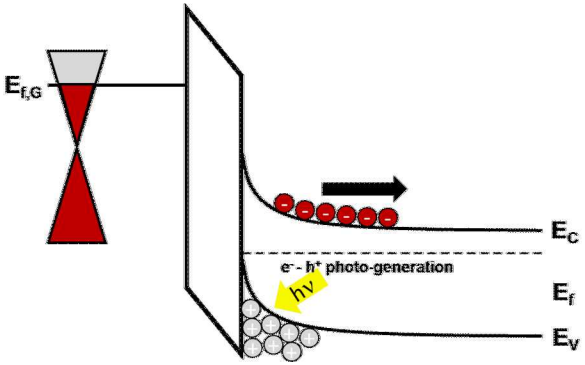


Dirac Point

Flat Band Condition



Depletion



Depletion with Photo-generated Charge

P-Si, Intrinsic Graphene