SAND2016-6393C

Exceptional service in the national interest

Sandia National Laboratories

Creating Wide Band Gap LEDs Without P-doping

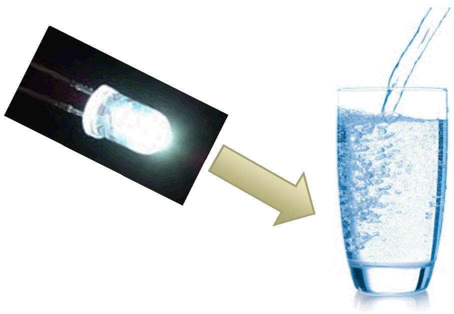
Sapan Agarwal, Jeramy R. Dickerson, Jeffrey Y. Tsao

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

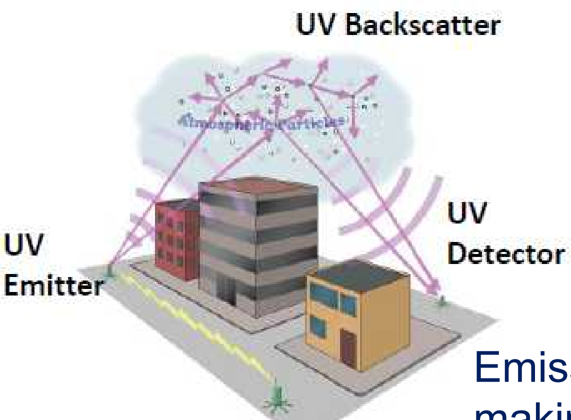
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Want Deep UV LEDs & Lasers for Many Applications

Water Purification – 260 to 280 nm



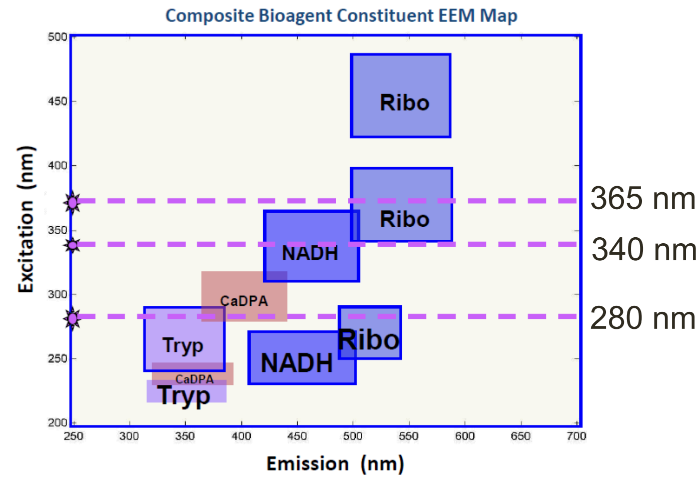
Covert non-line of sight short range communications <280 nm



Gary Shaw (MIT LL)

Emission rapidly decays, making it difficult to intercept and jam

Fluorescence based biosensing



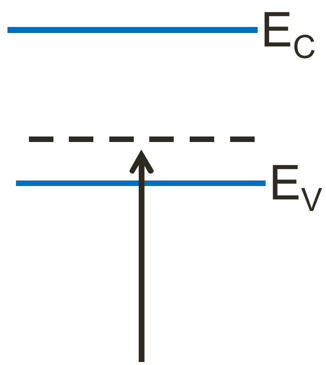
Anthrax spore:

- **Tryptophan (protein)**
- **CaDPA (spore cortex)**
- **NADH (coenzyme)**
- **Flavins (coenzymes)**

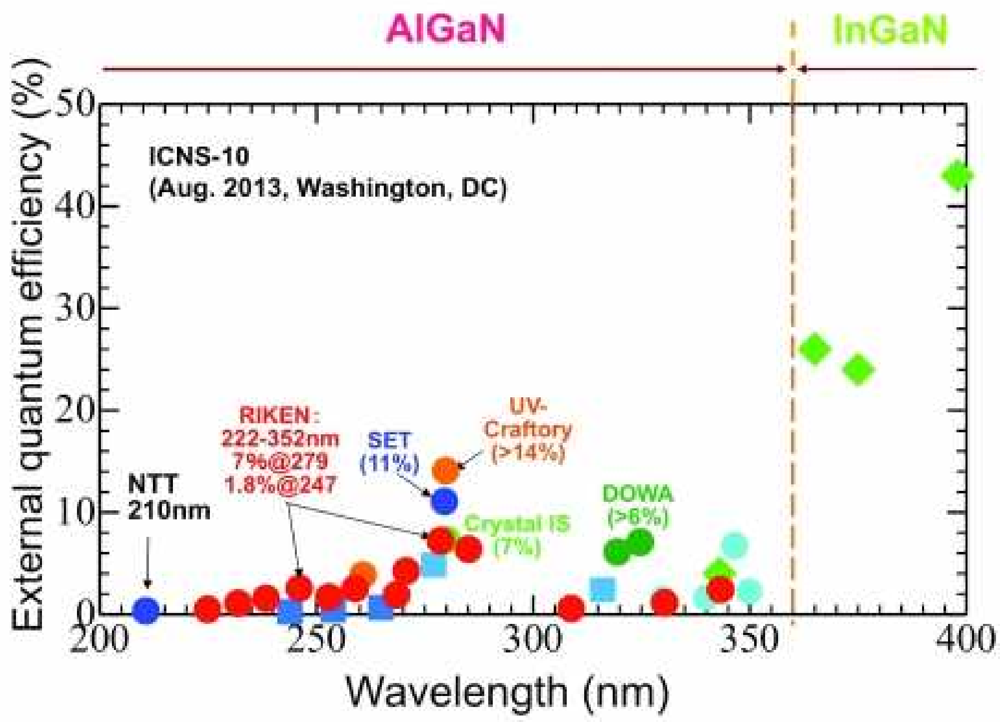
Steve Campbell (MIT LL)

- Chip scale atomic clock
- Lasers for trapped ion quantum information processing

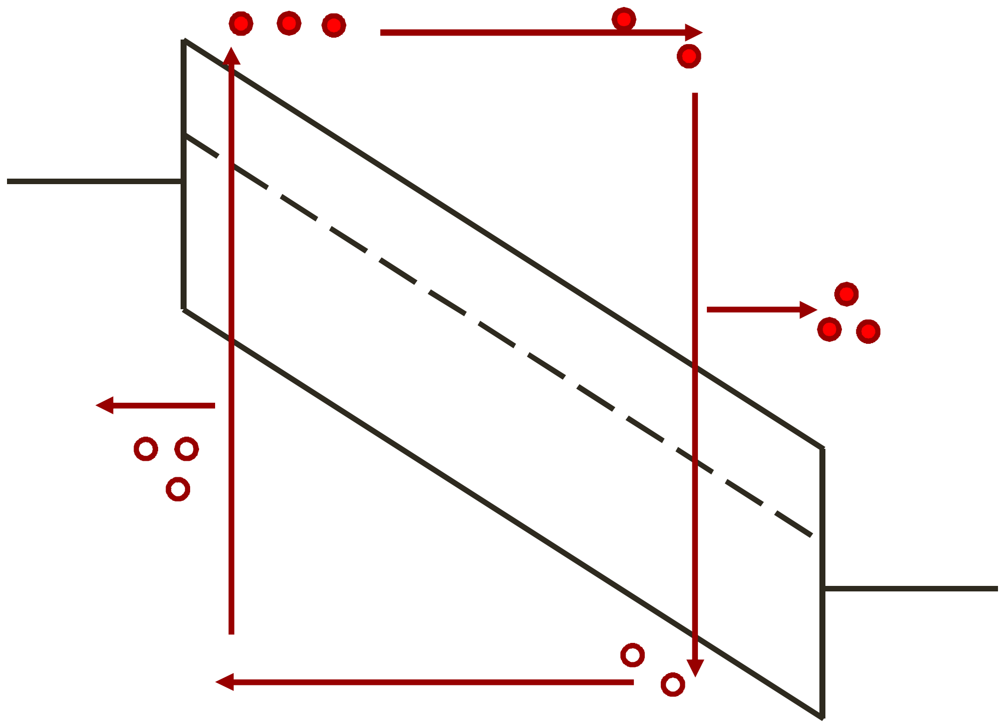
P-Doping is Challenging in Wide Band Gap Semiconductors like AlN



Due to the large band gap, dopant levels are too far from the valance band to effectively thermalize



Use Avalanche Breakdown to Create Holes

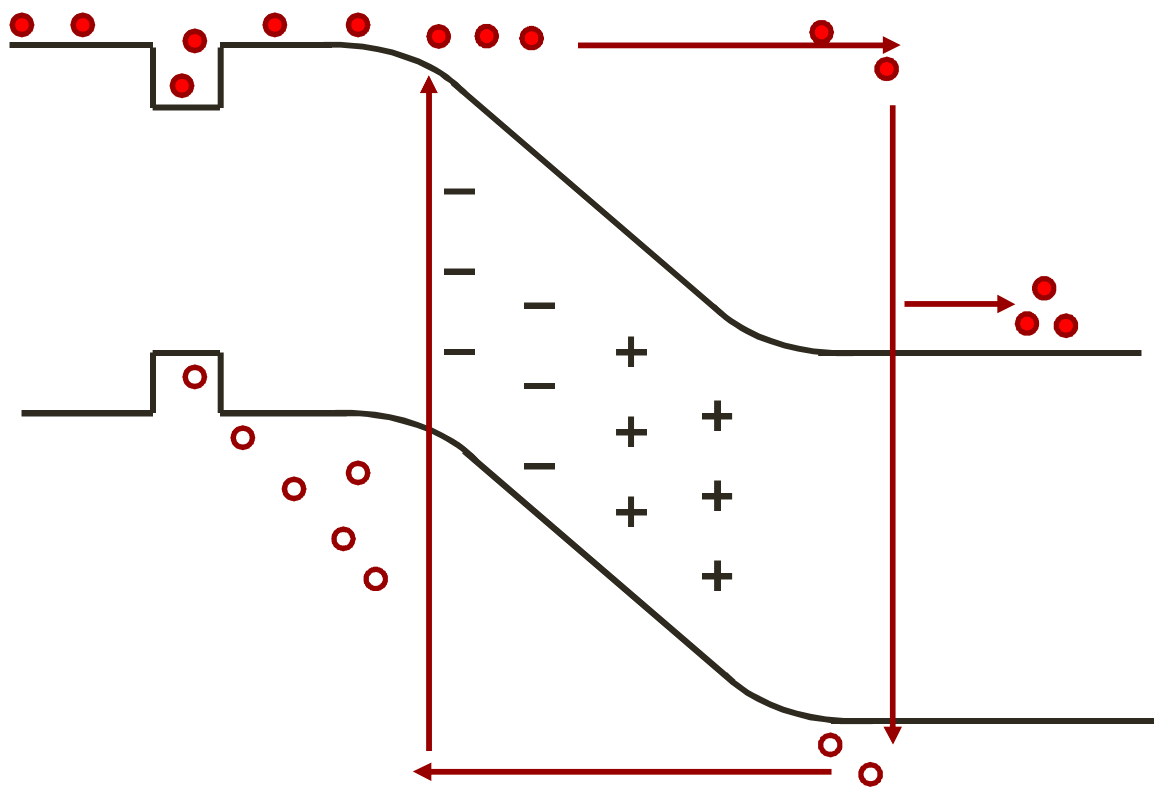


All the holes escape to the contact!!

This killed earlier attempts at Avalanche LEDs:

- T. D. Thompson, "A blue emitting ZnSe LED operating by impact ionization," *Semiconductor Science and Technology,* vol. 6, p. 1015, 1991.
- B. L. Crowder, F. F. Morehead, and P. R. Wagner, "Efficient Injection Electroluminescence in ZnTe by Avalanche Breakdown," *Applied Physics Letters,* vol. 8, pp. 148-149, 1966.

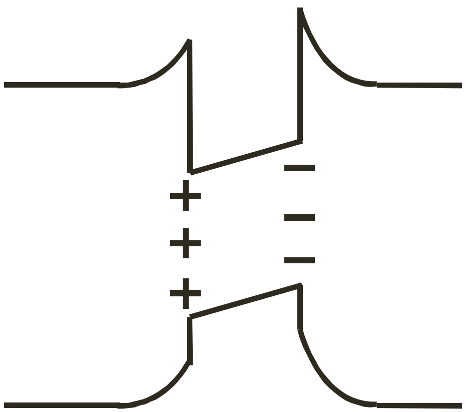
Need A Depletion Region

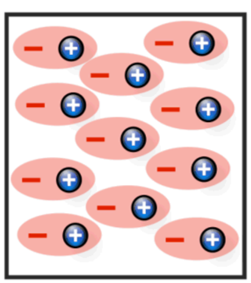


Want the voltage drop buried inside a device so that quantum wells can trap the generated holes

Use Polarization Charge?

Polarization Can Provide
Negative Charge





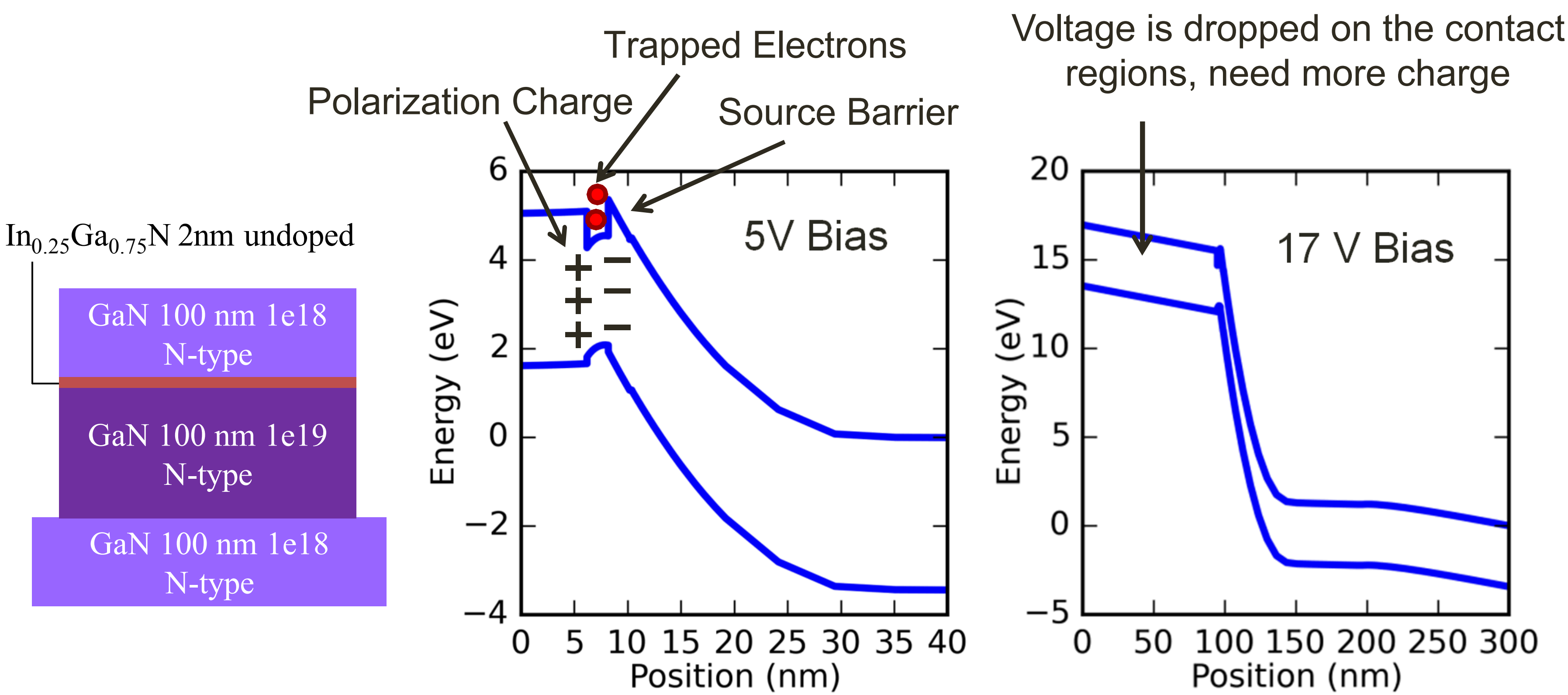
Charge Needed for Avalanche Breakdown

- GaN breakdown field ~ 5 MV/cm
- Assume a sheet charge
- Need 4.3×10^{-6} C/cm^2 = 2.7×10^{13} carriers/cm^2

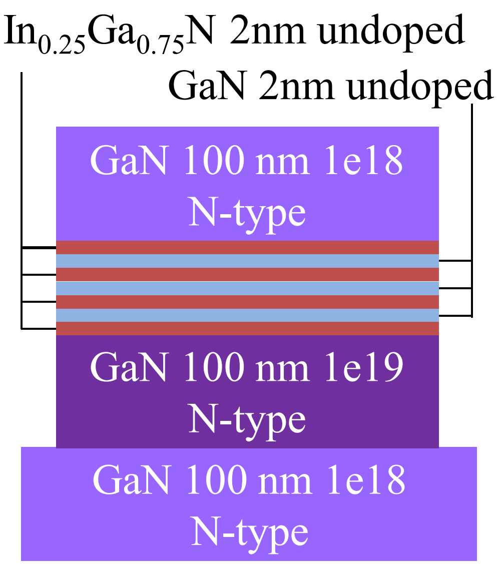
Potential Polarization Charge

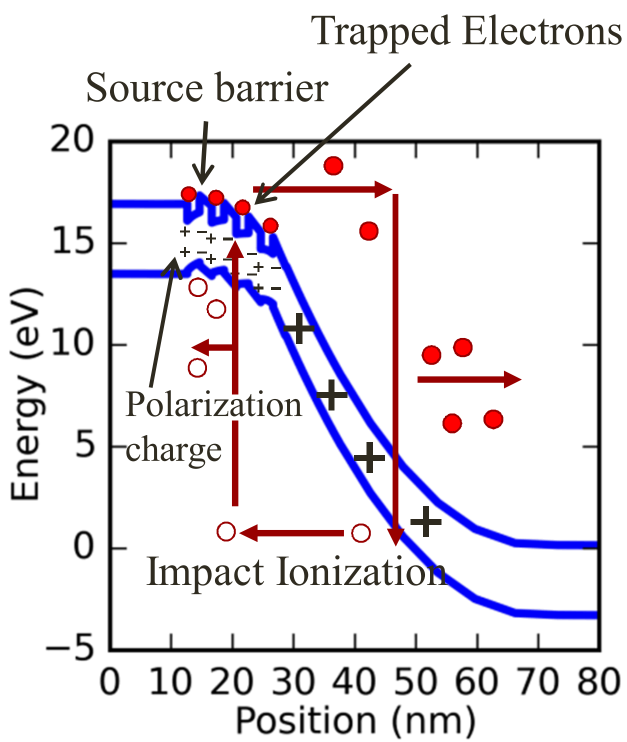
- Consider GaN / $In_{0.25}Ga_{0.75}N$ Heterojunction
- Polarization Charge = 2×10^{13} carriers/cm^2

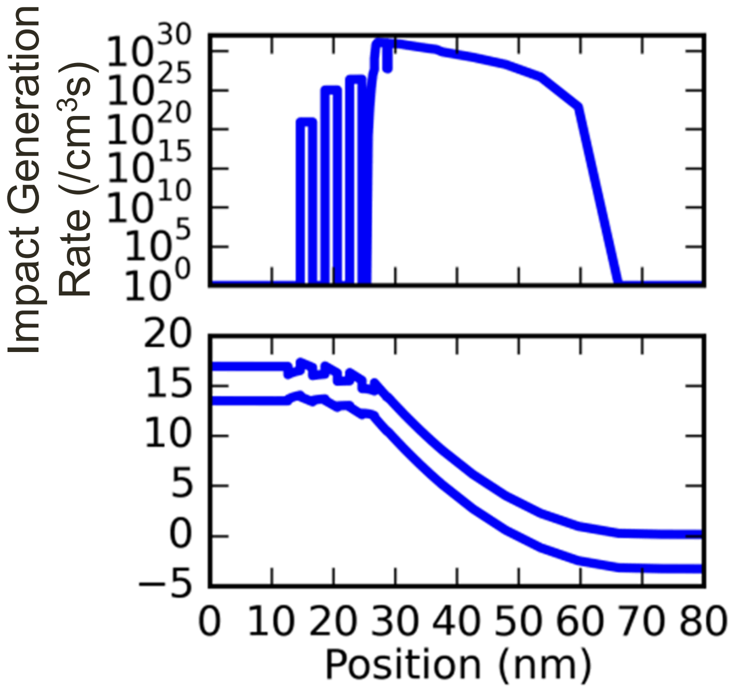
Use Quantum Wells to Trap the Remaining Charge



Use Multiple Wells to Trap Sufficient Charge



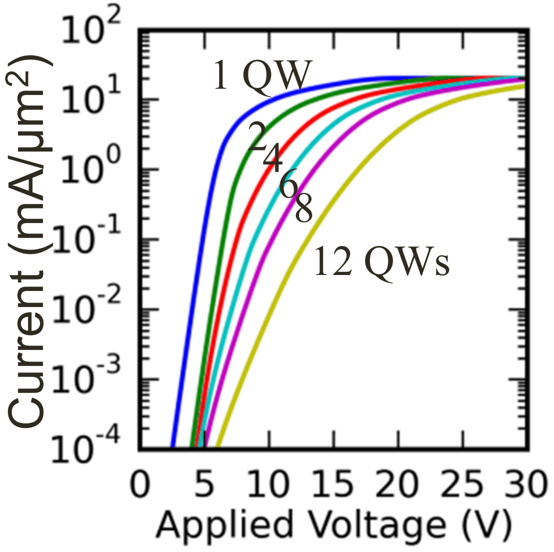




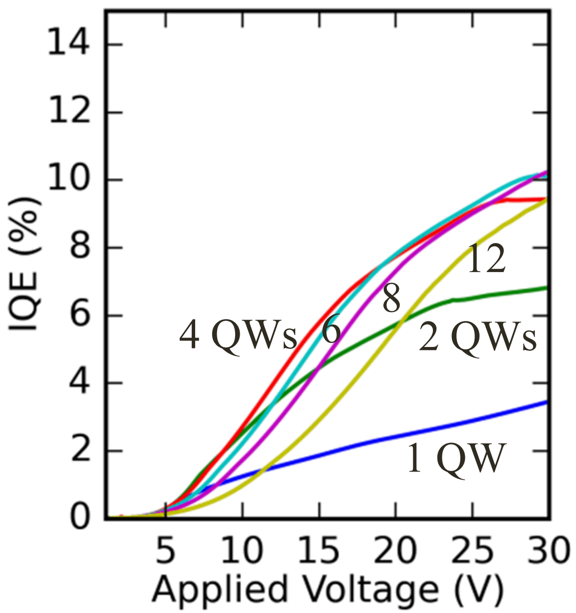
Local field impact ionization approximation, might be different when accounting for electron temperature

Use Multiple Quantum Wells

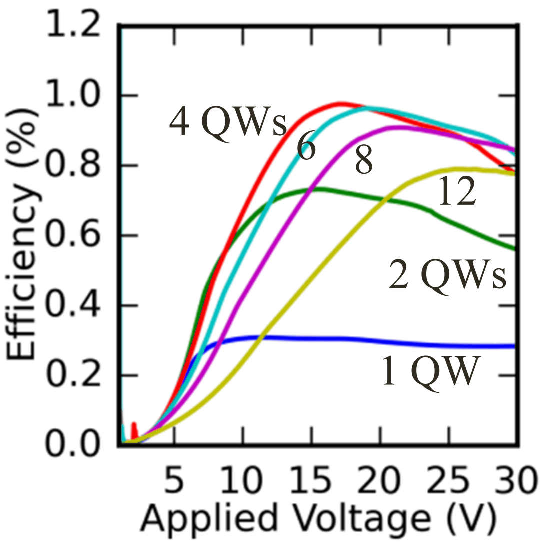
Current vs Voltage



Internal Quantum Efficiency

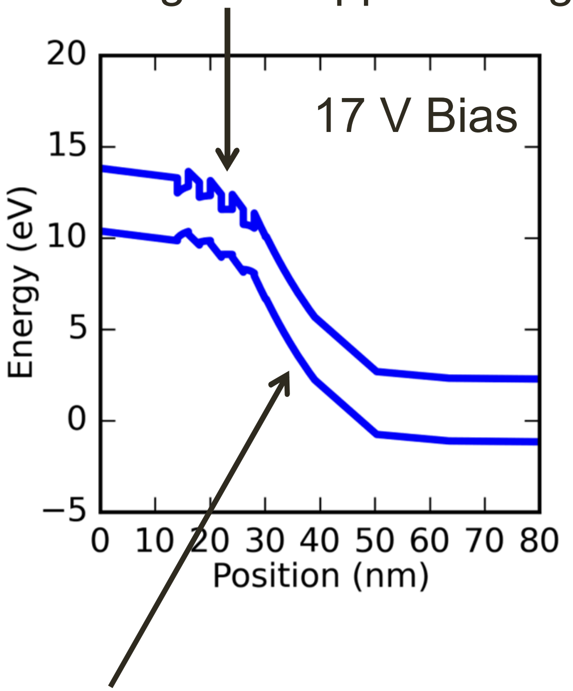


Wall Plug Efficiency Assuming 100% Light Extraction

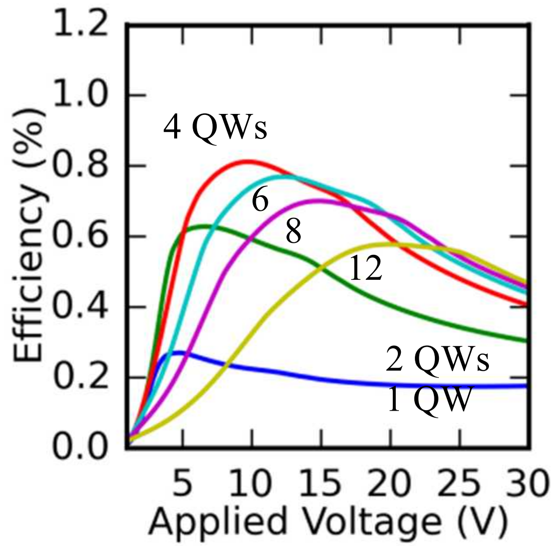


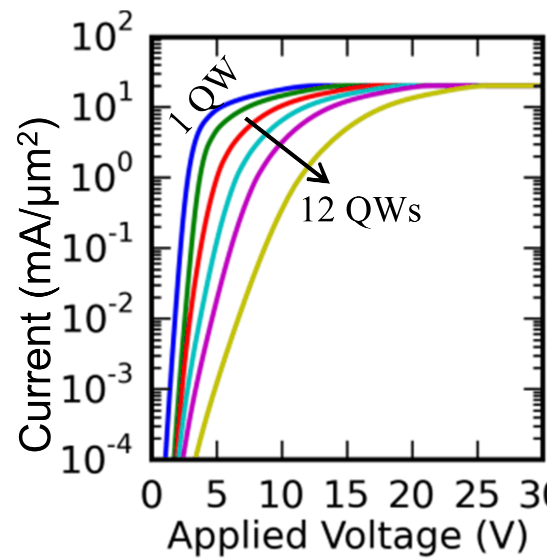
Increasing Doping Doesn't Reduce Depletion Thickness

Additional voltage dropped across quantum wells, reducing the trapped charge



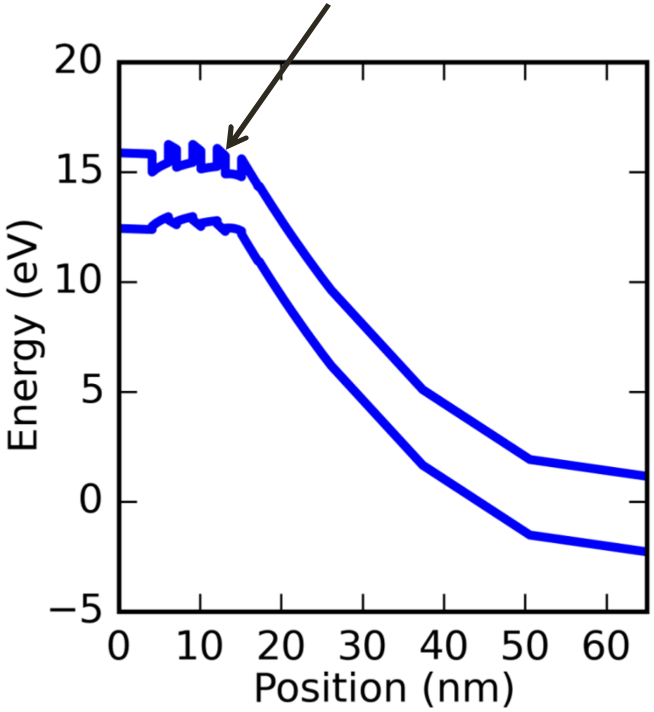
Increase doping from 1e19 to 2e19



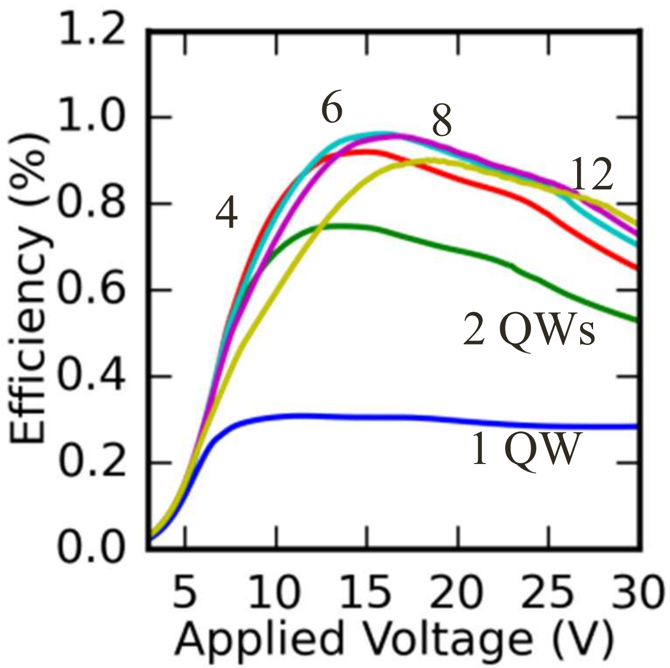


Tunneling Limits Barrier Thickness

Shrink barriers from 2nm to 1nm,
Electrons tunnel out, limiting charge



1e19/cm^3 doping,
2nm wells / 1nm barriers



Conclusions

- Can use impact ionization to generate holes
- Need depletion regions to help contain generated holes
- Polarization charge + quantum wells enable depletion regions
- Generating the high fields required is still challenging