# New Concepts of IR Single-Photon Detectors

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# Outline

- IR SPADs: Geiger-mode avalanche gain
- Nanowire detectors: Phototransistive gain
- Ideal single-photon detector:

  Both gain mechanisms in one device → true PMT-like characteristics with high IR detection efficiency
- Summary

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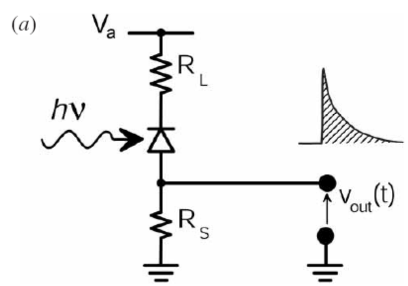
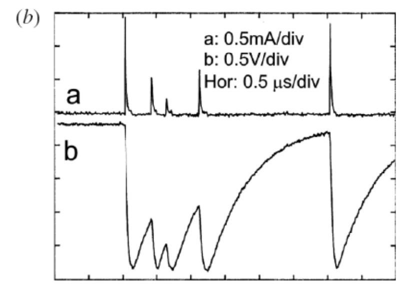
# Challenges for Geiger Mode APDs

- Must be operated with quenching circuits
  - Difficult to make large array
- Dark count and after pulsing
- Excess noise and timing jitter
- Reliability, degradation, and property drift

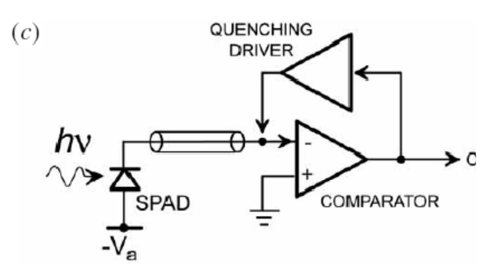
# Geiger Mode APDs

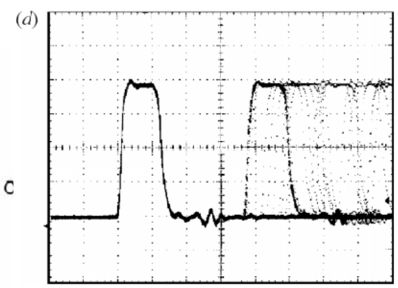
Passive quenching:



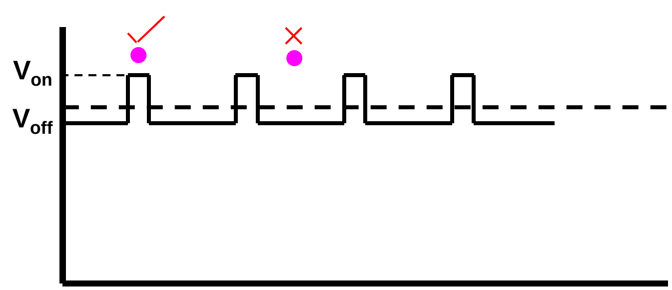




Active quenching:



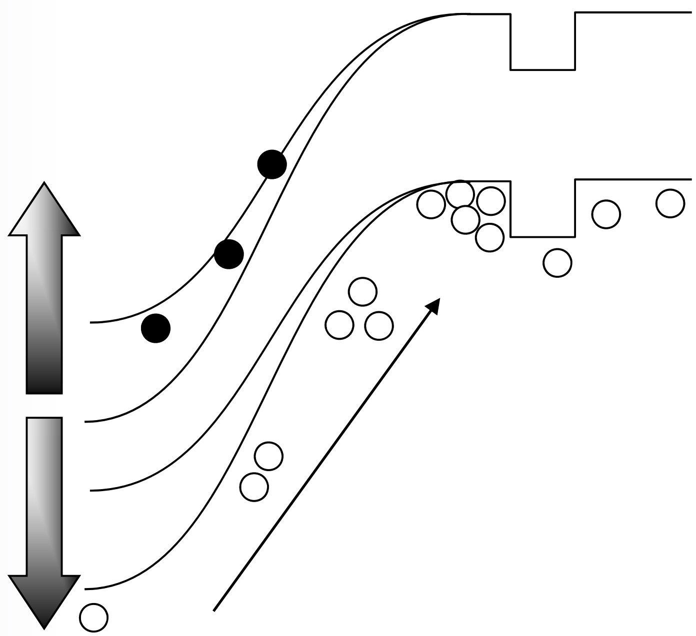




Gated mode operation:

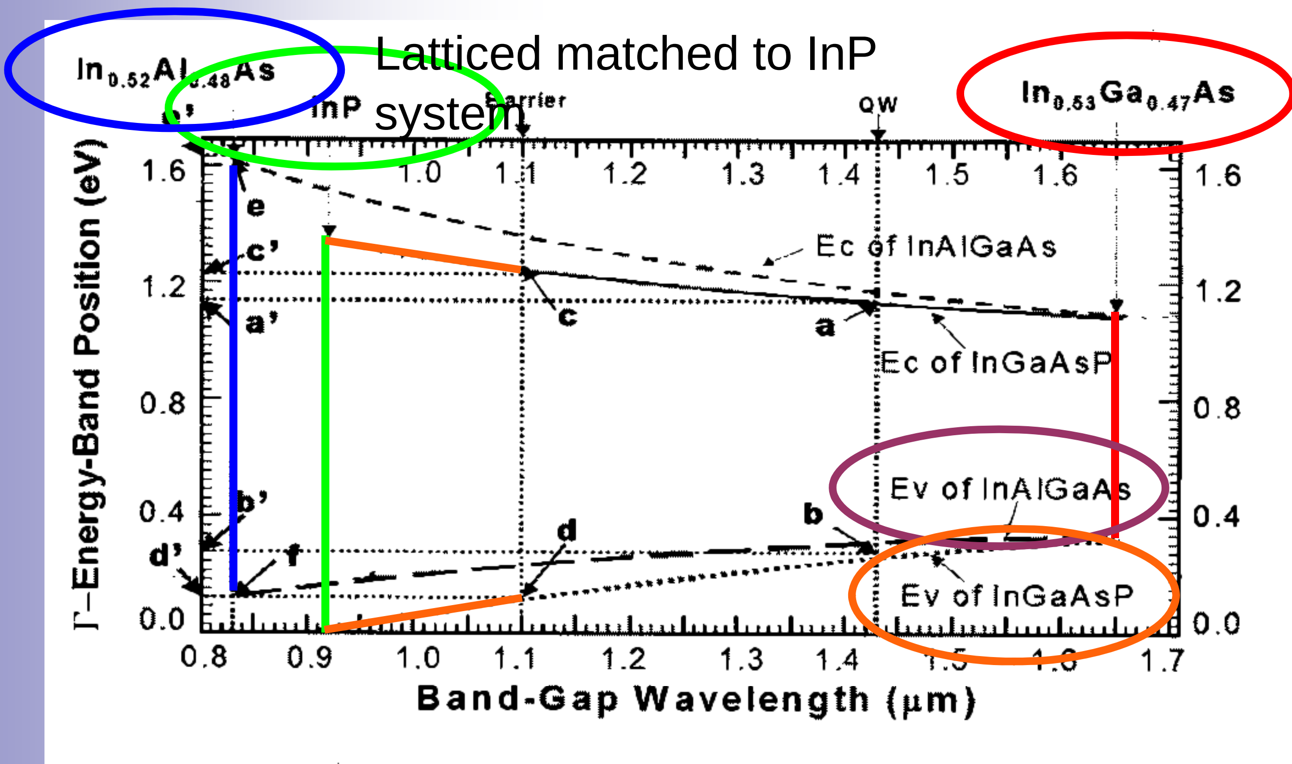


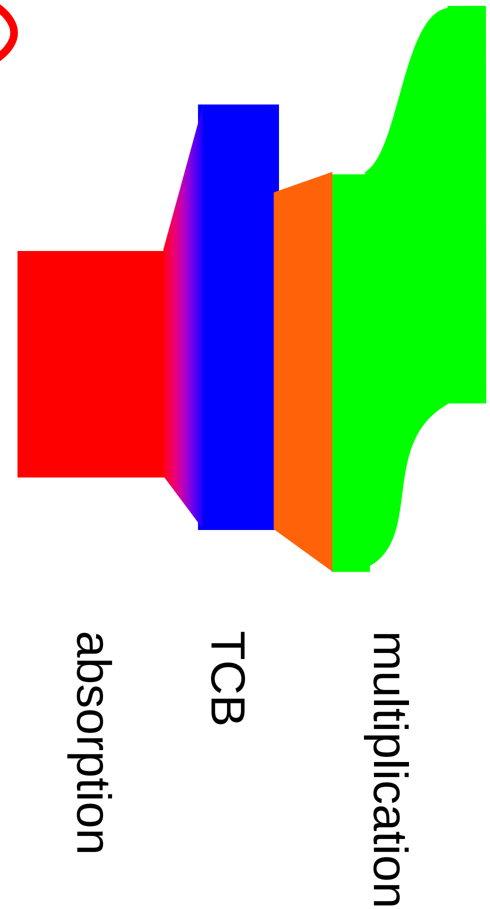
# Self Quenching and Self Recovery

- Use band offsets to form energy barrier "TCB" (transient carrier buffer)
- Avalanche carriers collect at barrier
- $E_m$ is reduced below $E_{br}$, quenching device
- Carriers slowly escape from barrier, recovering device

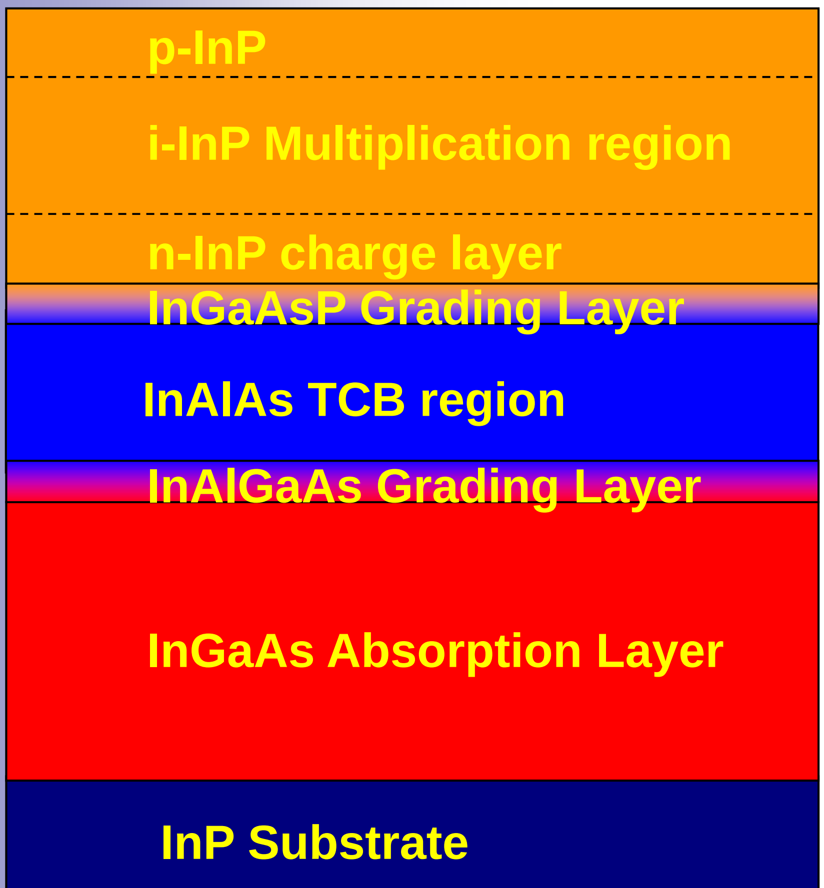


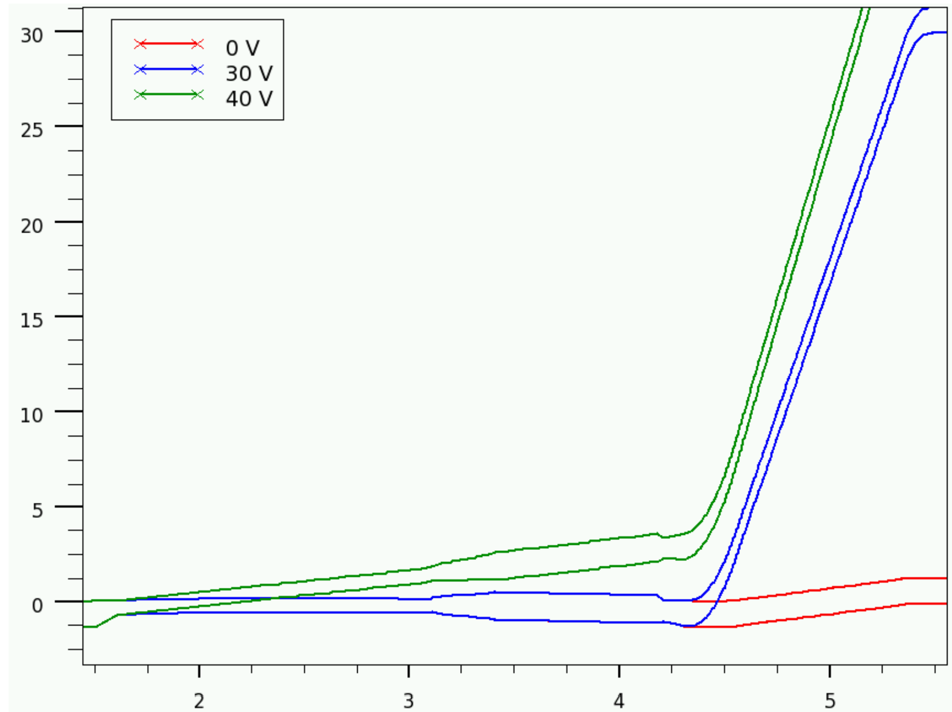
# Implementing the Self-Quenched SPAD Using Band Gap Engineering



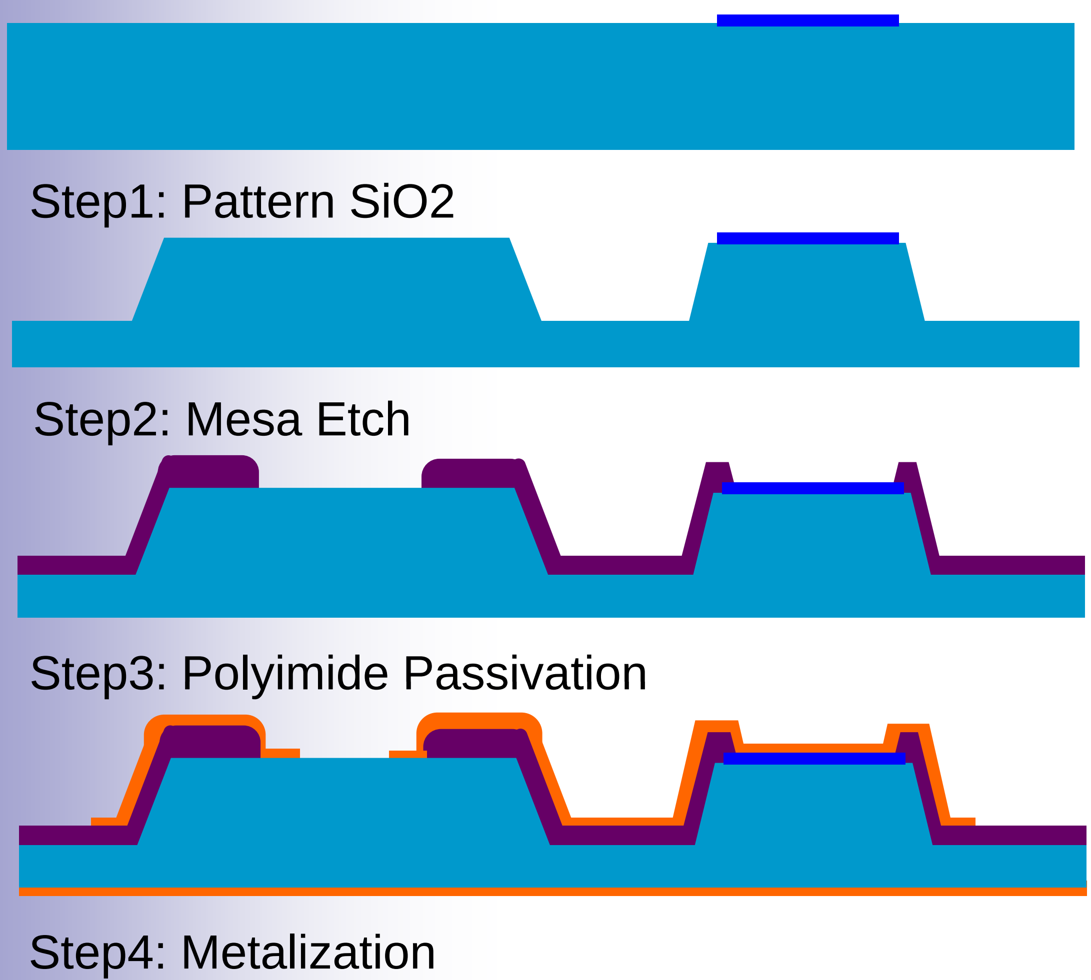



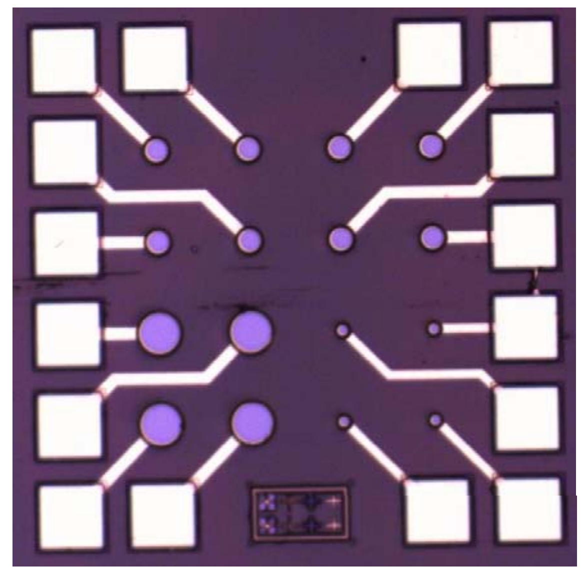
# Device Structure and Bandstructure Simulation



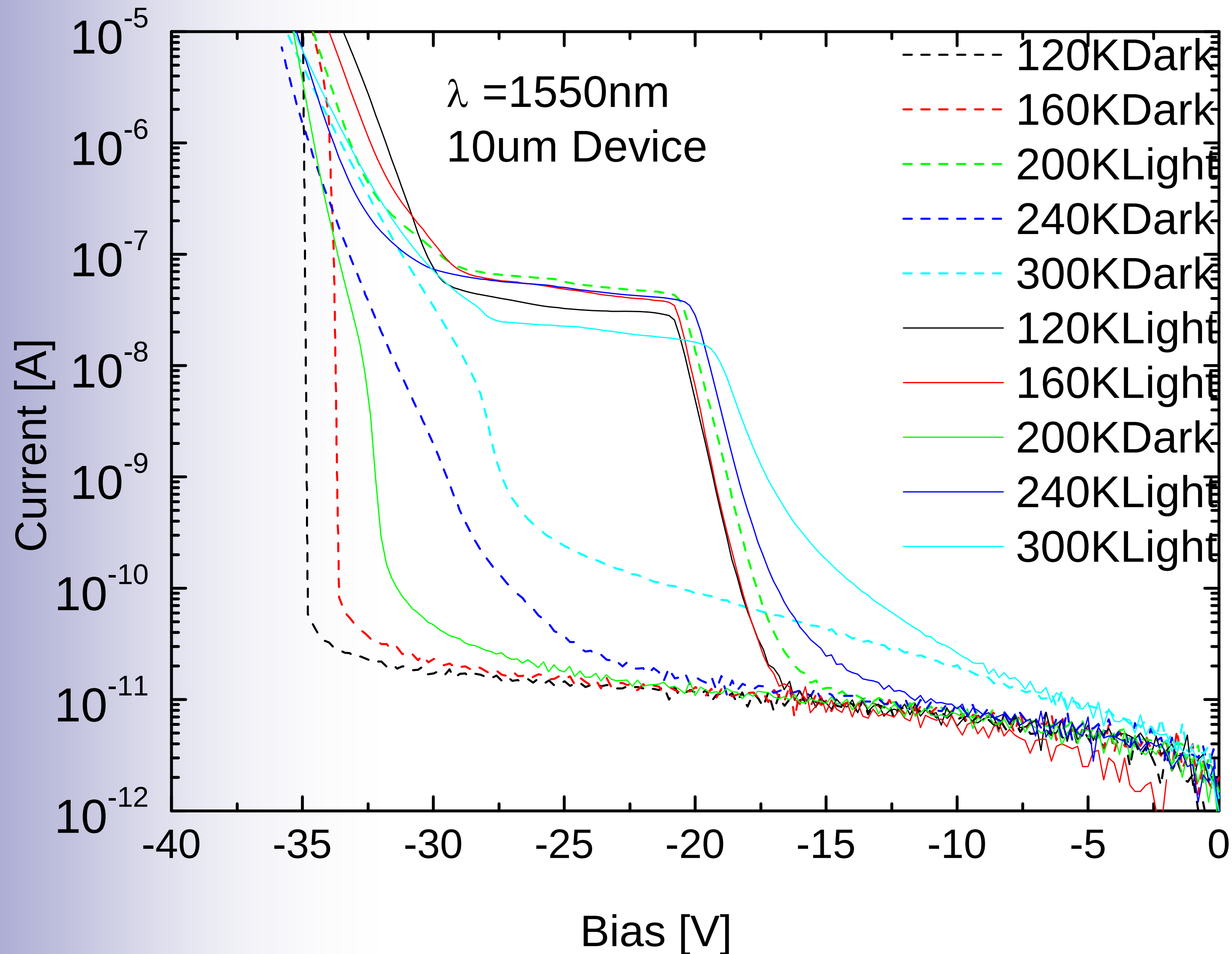



# Process Flow

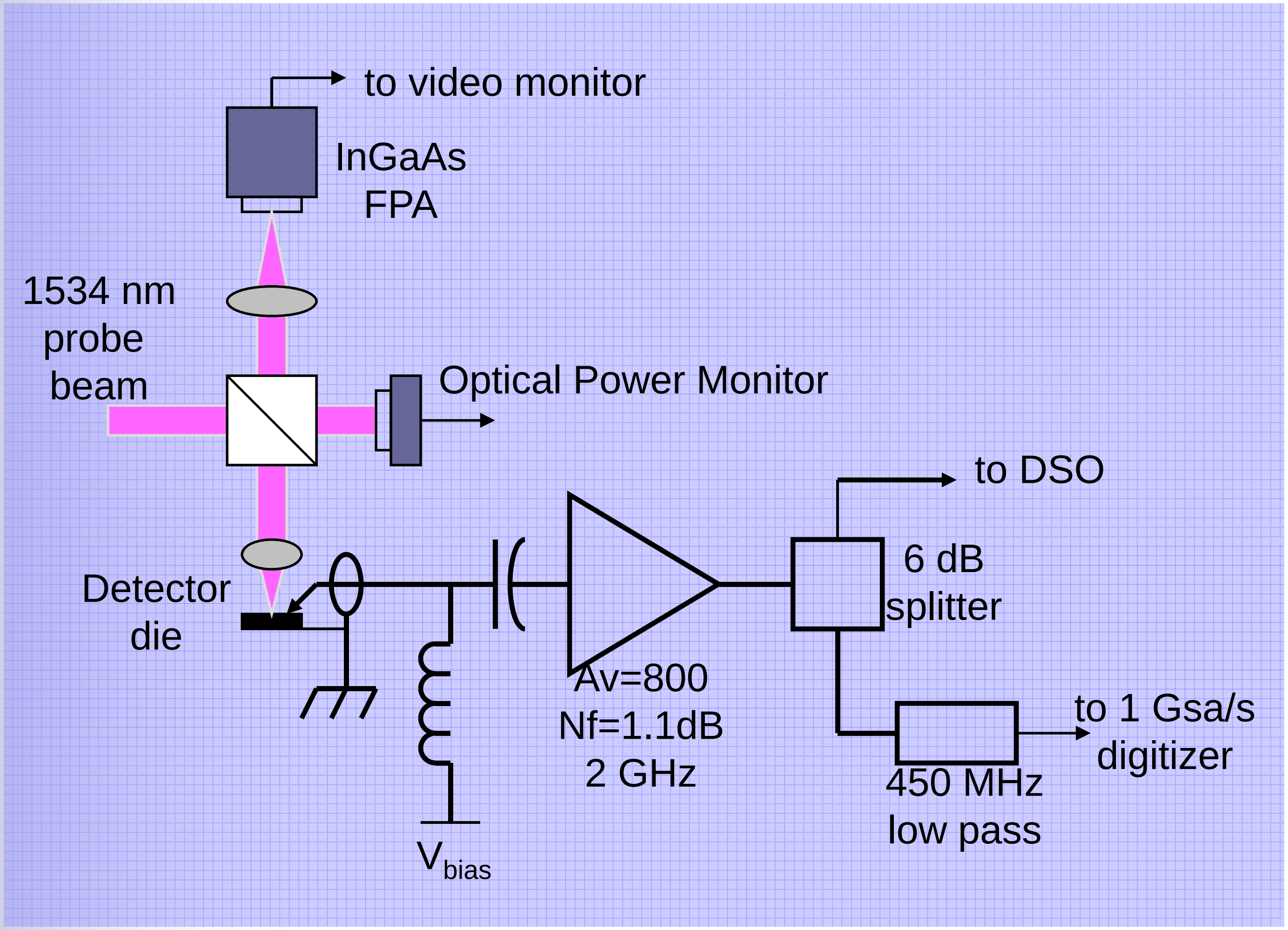


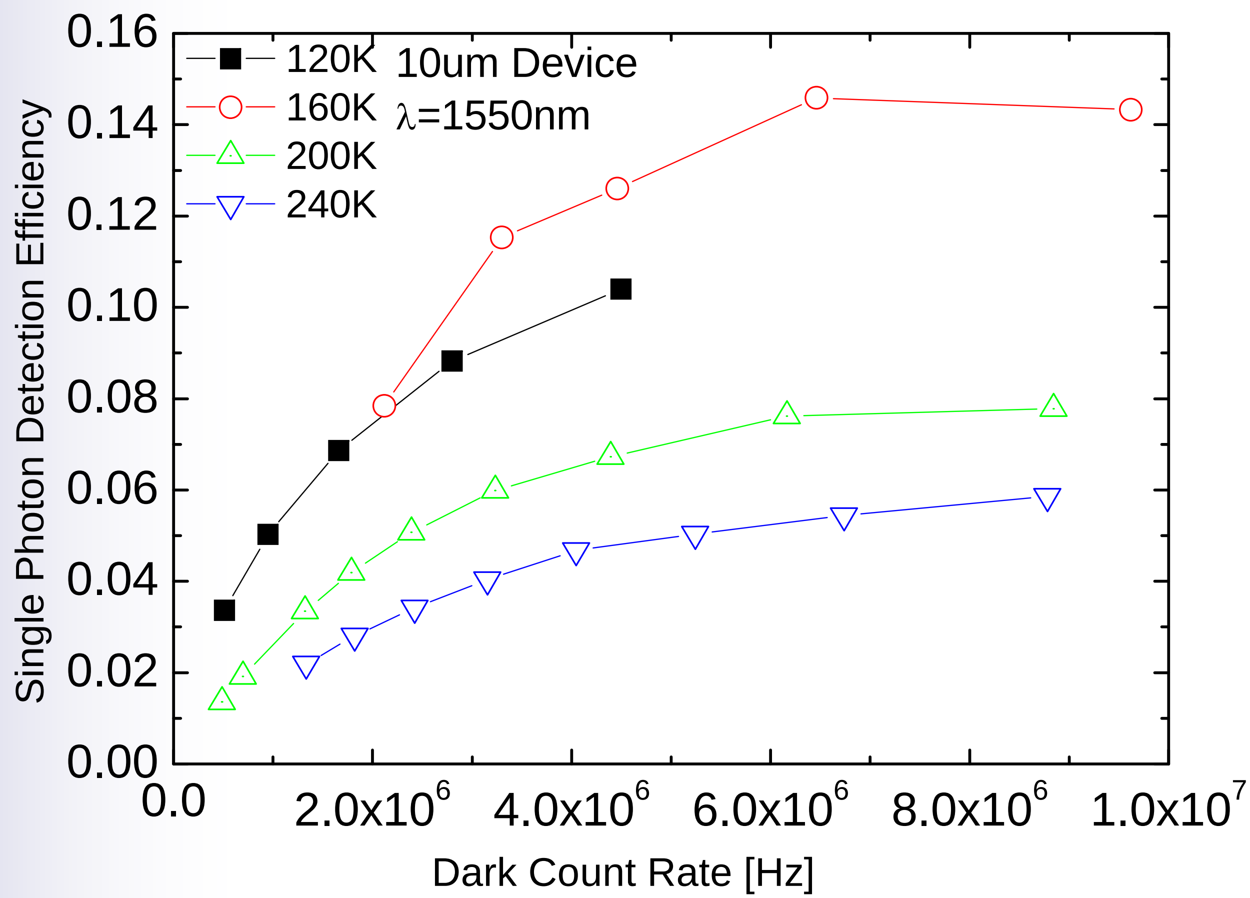
# I-V characteristics



# SPAD Characterization Setup

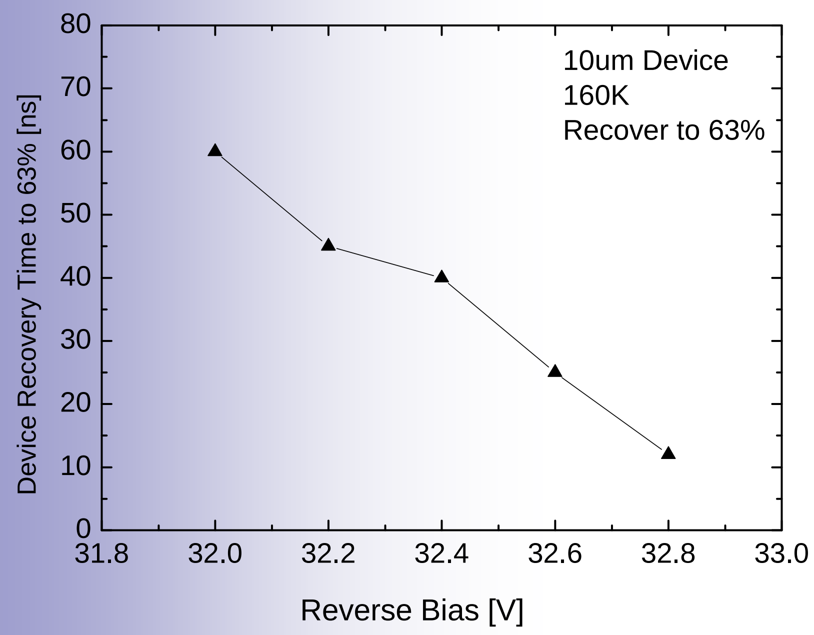


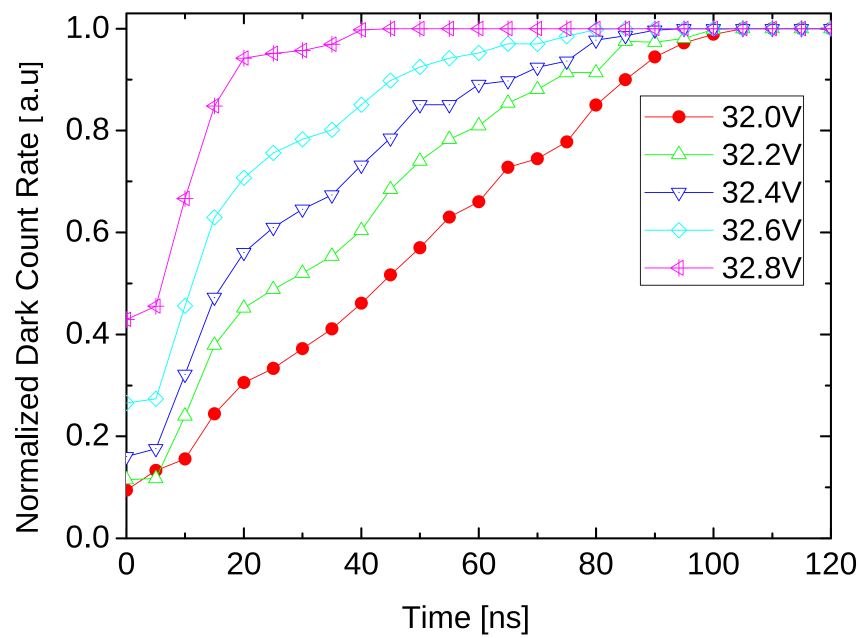
# Single Photon Detection Efficiency vs Dark Count




Poor device passivation causes very high after pulsing rate, limiting the device performance.

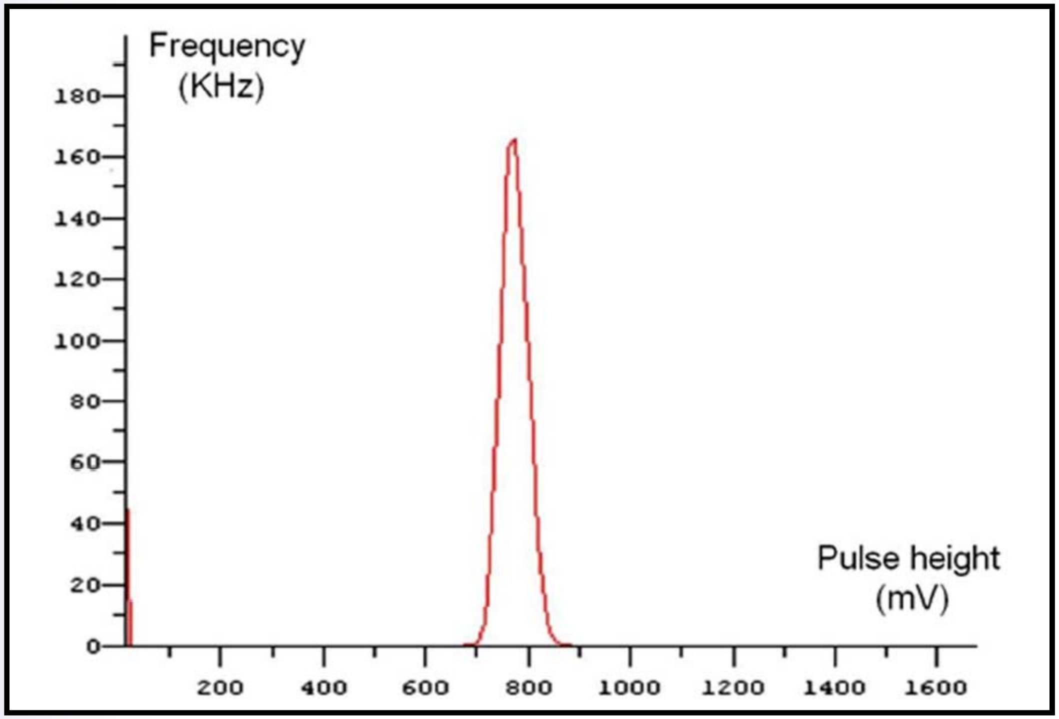
# Self-Recovery Time




- Recovery time decreases rapidly with the overbias (bias above breakdown).
- Recovery time eventually approaches the carrier (hole) escape time as determined by the (valence)band offset (80meV in current design).

# Pulse Height Histogram




- The avalanche pulse height has very narrow distribution.
- The excess noise factor measured by signal intensity at a gain of $5 \times 10^5$-$10^6$: 1.001 – 1.003
- The excess noise (by total charge contained in the pulse): ~1.007

K.Zhao, A.Zhang,Y.Lo and W.Farr, Applied physics letter 91,2007

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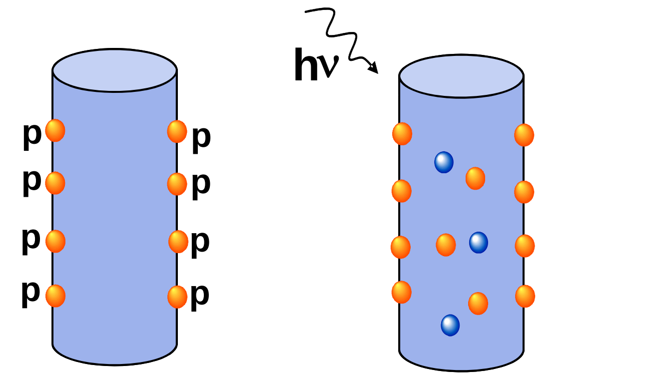
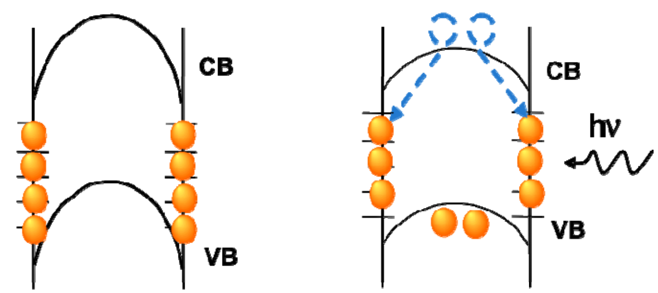
# Phototransistive Gain (P-Type)

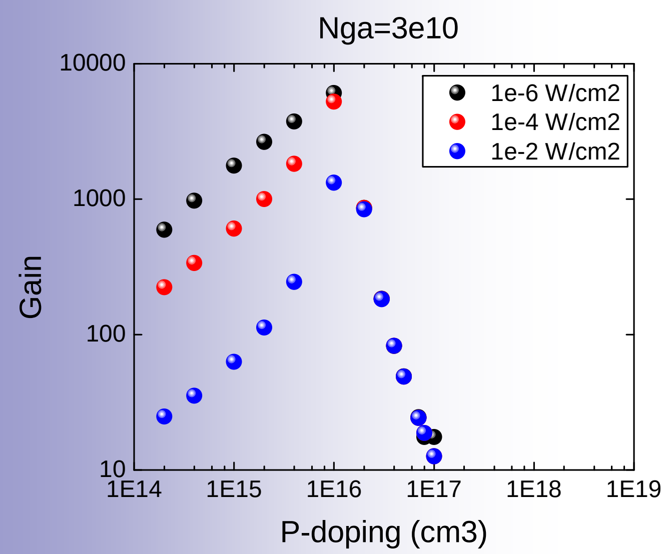
1. Without light, NW is depleted of majority carriers due to large number of surface states
2. When illuminated, e/h pairs generated in body of NW
3. Due to the lateral electric field, minority carriers move to surface and recombine with trapped majority carrier
4. Photogenerated majority carriers are confined to the center of the wire and generate photocurrent with applied bias
5. Photocurrent stops when majority carrier recaptured at the surface
6. Gain occurs when the lifetime of majority carriers is much longer than their transit time.

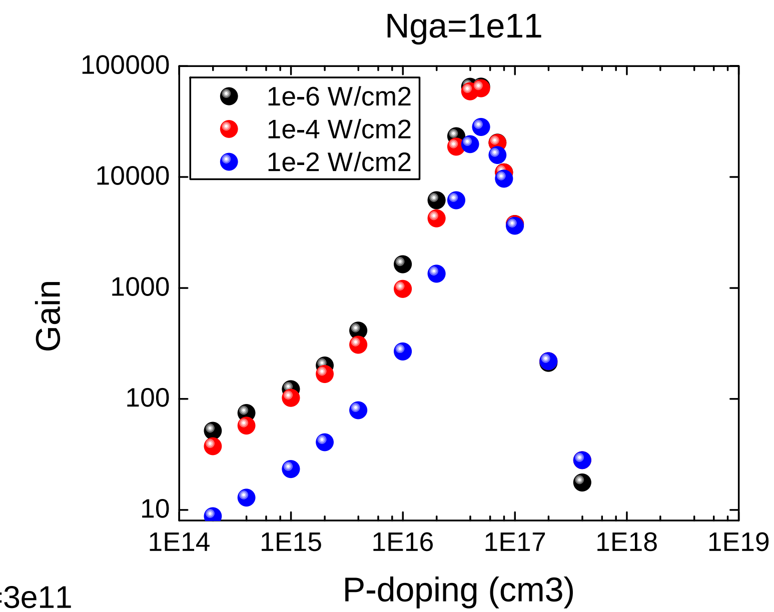


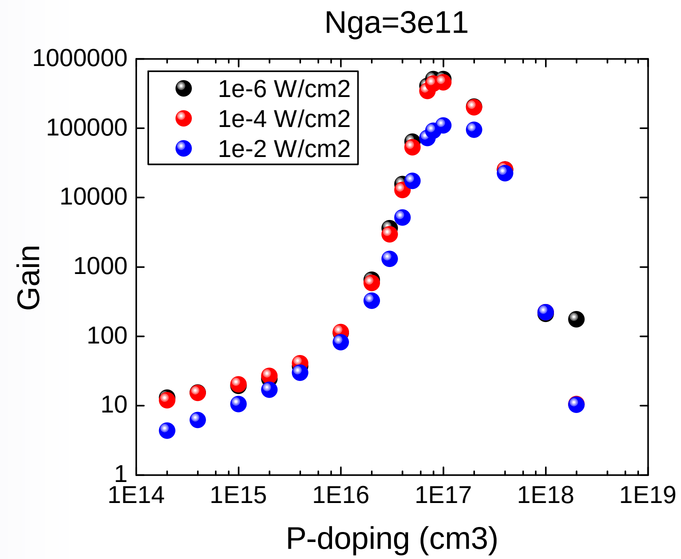




$$Gain_{dc} = \frac{\tau_c}{t_t}$$

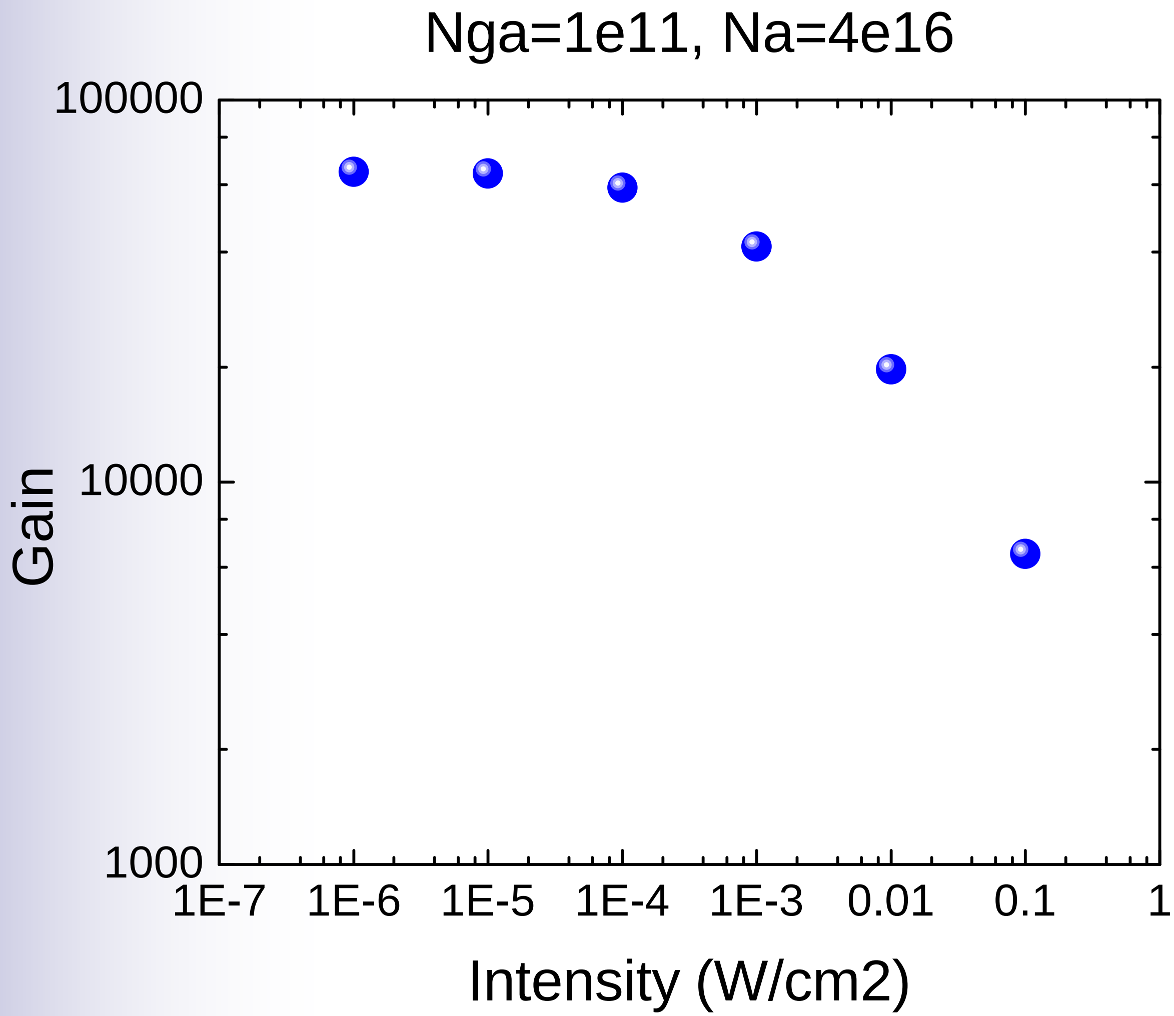
# Gain vs Doping in the Wires



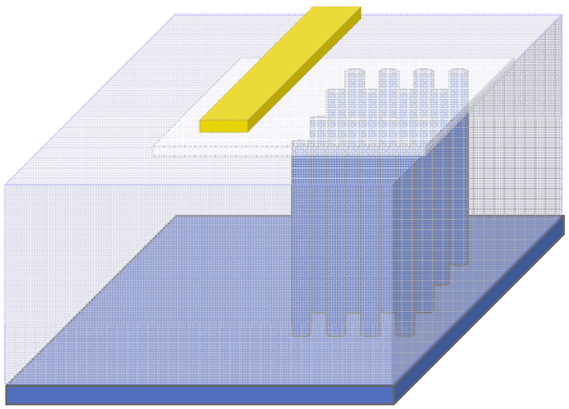



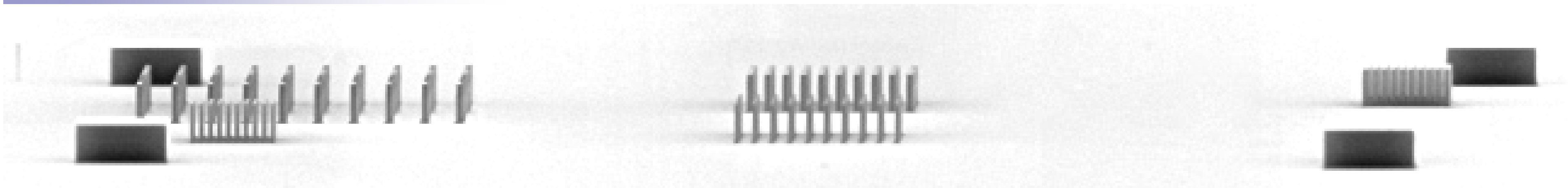
# Gain Saturation



# Advantages of Top-Down Fabrication

- Top-down approach for etching NW's advantageous for:
  - Control of geometry (diameter, height, pitch)
  - Exact placement of wire
  - Control of exact number per contact
  - Single crystalline NW
  - Doping through conventional methods

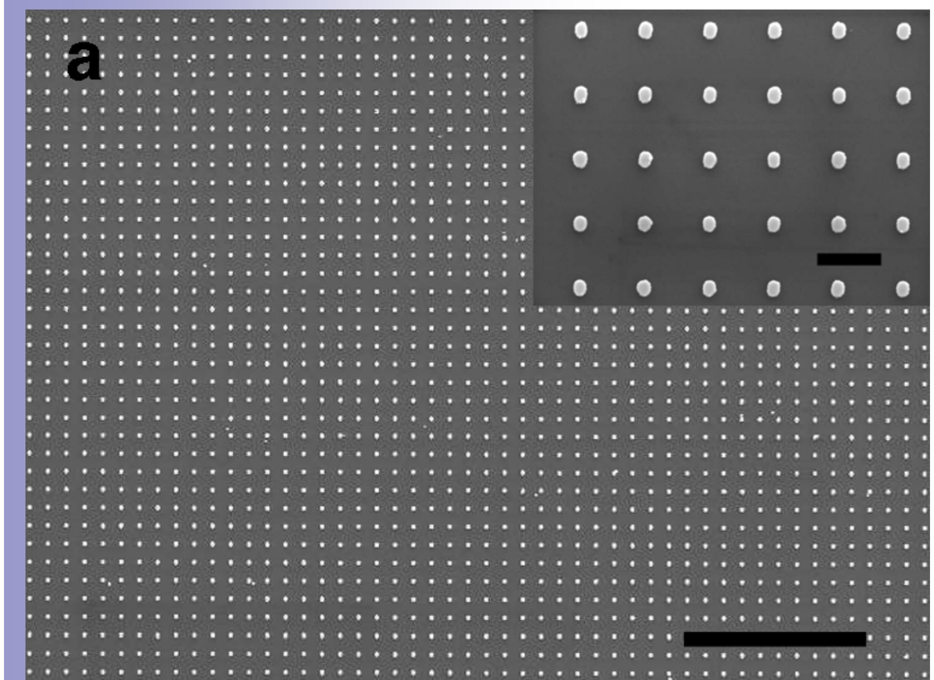




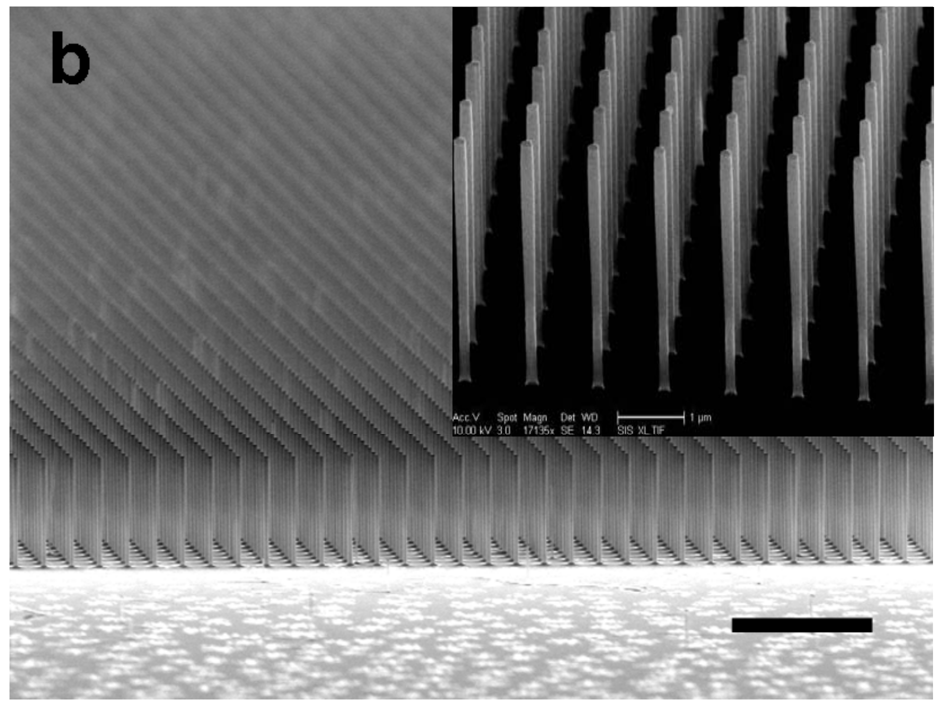
# NW Fabrication Using Nanoimprinting

- Nanowire diameter: 200 nm
- Pitch: 1 um
- Physical fill factor: ~ 3%

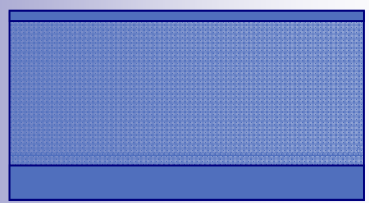
**Before etch**



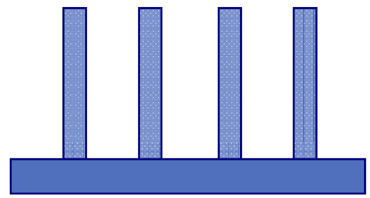

**After etch**



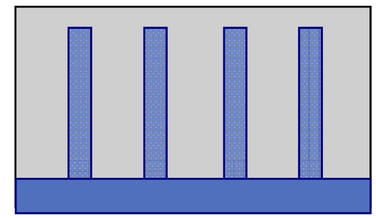
# Vertical Device Fabrication



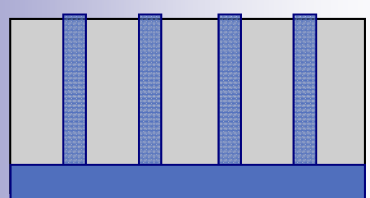
1. Epi Si wafer



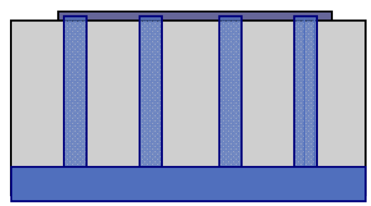
2. E-beam pattern Ni dots and RIE/ICP etch ($SF_6/C_4F_8$)



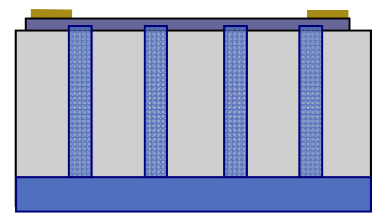
3. Spin on dielectric (PMGI, PI, SOG)



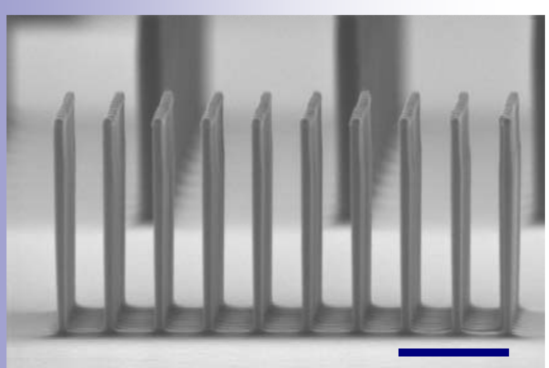
4. Plasma etch to expose wire tips



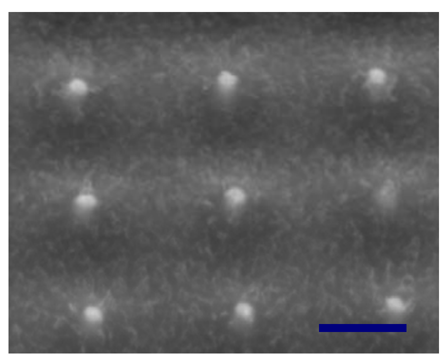
5. Pattern and deposit ITO transparent contact window



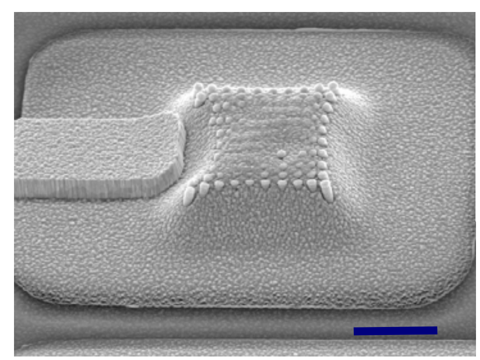
6. Pattern and deposit Ti/Au contacts



1μm

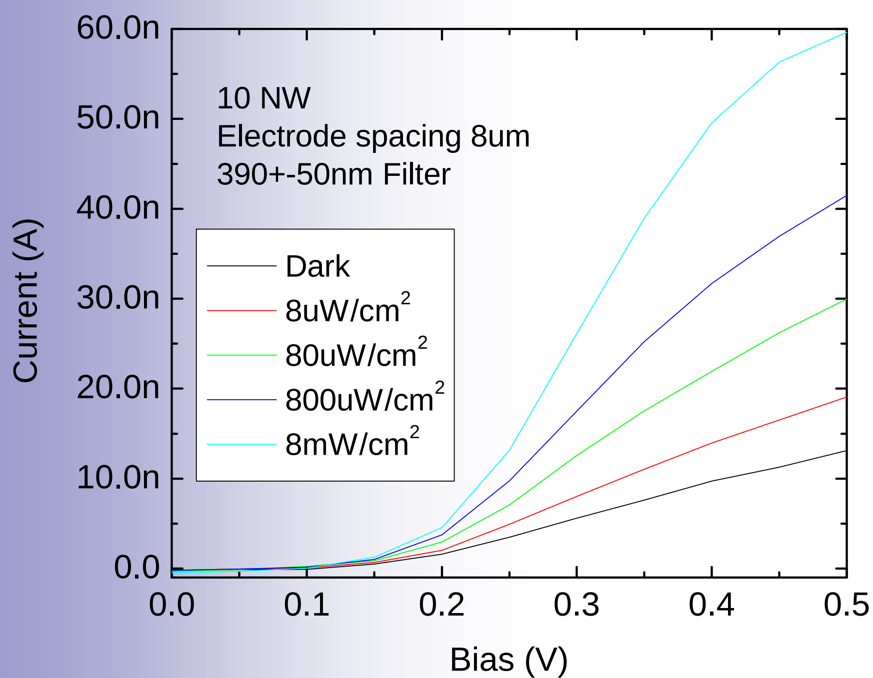


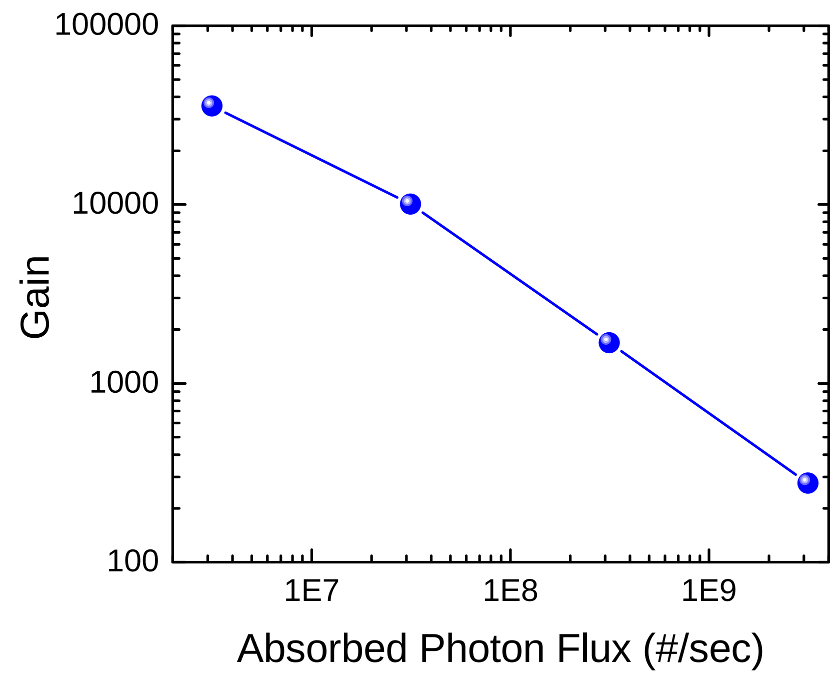
1μm



5μm

# Room Temperature Photoresponse

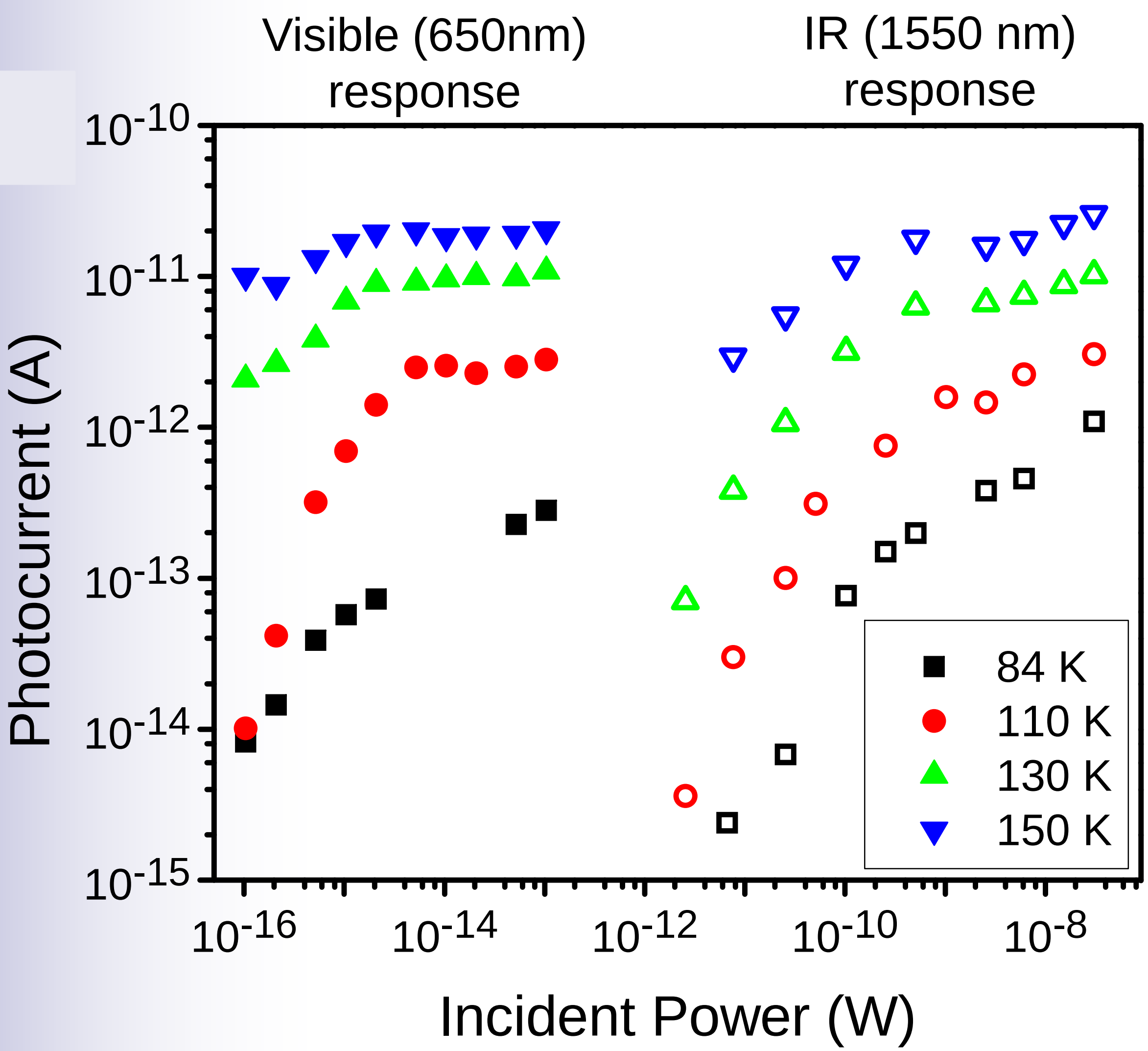



$$G = \frac{\tau_c^h}{t_t^h} = \frac{I/e}{\eta_{QE} P_{opt} / h\nu}$$

$G_{@0.5V}$>35,000

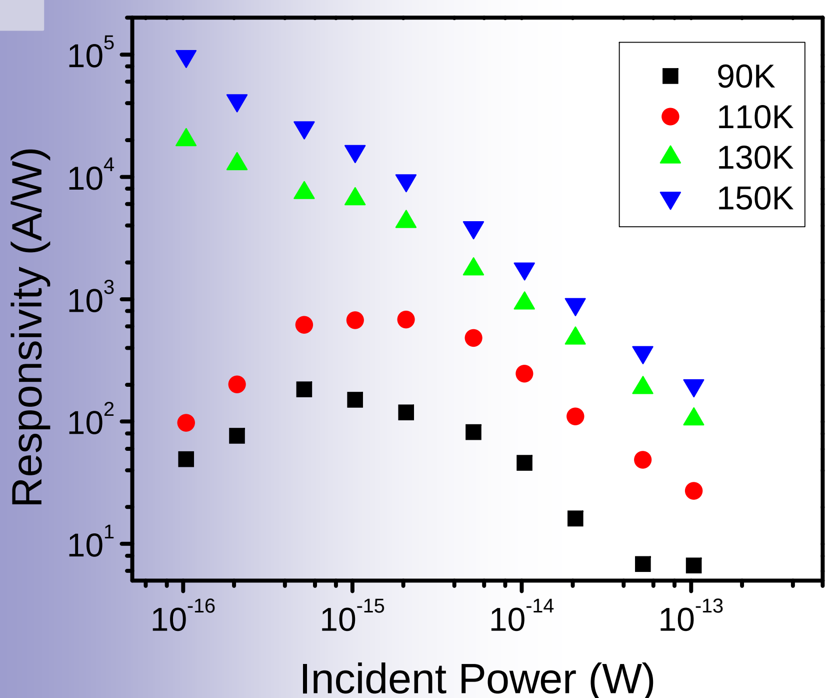
# Photoresponse



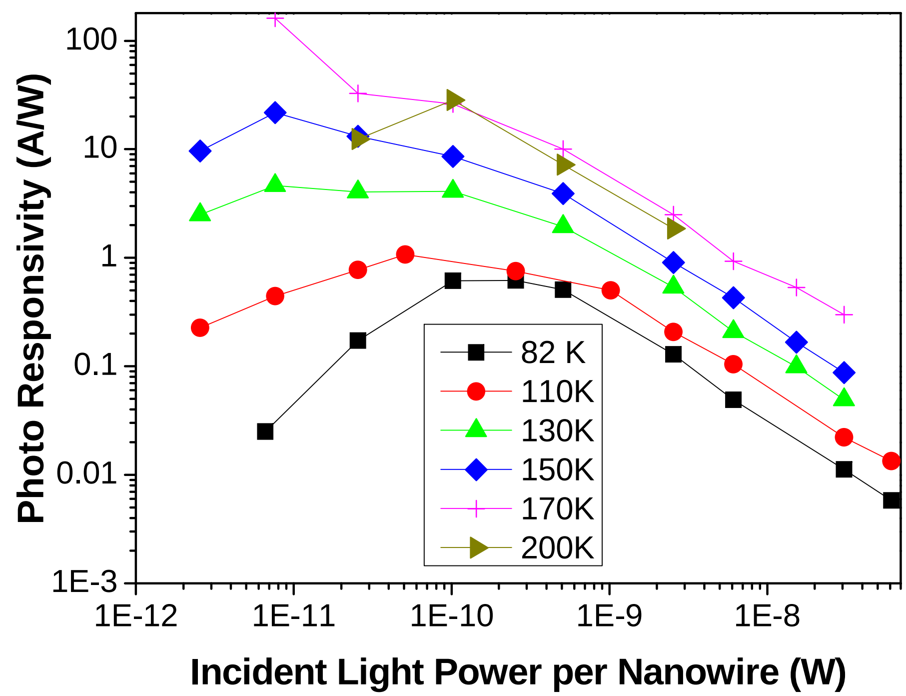

Power: net incident power over 1um$^2$ area.

# Gain vs Incident Power

Visible (650nm) response




IR (1550 nm) response



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# Comparisons Between SPADs and NW Detectors

| Geiger-mode SPADs | NW Detector |
| --- | --- |
| Avalanche gain | Phototransistor gain |
| Biased above breakdown | Low bias √ |
| Extremely sensitive to bias and temperature | Much less sensitive to bias and temperature √ |
| High detection efficiency √ | Low detection efficiency |
| High single-photon data rate (GHz) √ | Low single-photon data rate (< MHz) |
| Dark count/after pulsing | Less dark count √ |
| Lower reliability | Higher reliability √ |

- Can we combine the designs to achieve the merits of both?
- That is, to achieve a multiplication gain of 100-1000 and a phototransistor gain of 10-1000 for a net gain of $10^{5-6}$. This will behave like a PMT with high IR detection efficiency.

# Device Concept