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High Bit Rate Germanium Single Photon Detectors for 1310 nm

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John A. Seamons

Malcolm S. Carroll

Sandia National Laboratories

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Outline

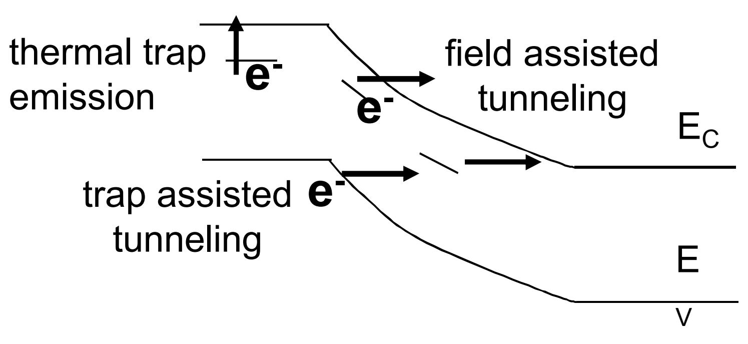
- **Motivation and applications**
- **Methodology**
- **Ge Avalanche Photodiode (APD) measurements**
- **Summary**

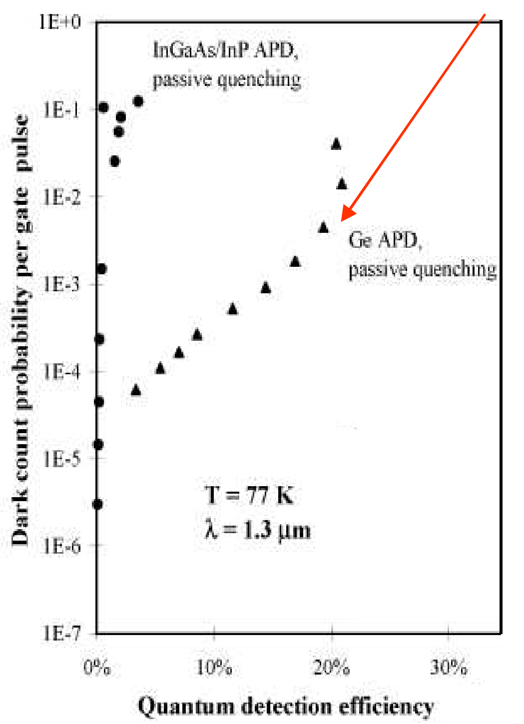
Motivation and Applications

- **Potentially enhanced maximum count rate for 1310 nm**
  - **Ge has over an order of magnitude fewer charge trap density compared to currently available state-of-the-art InGaAs/InP**
  - **Performance at 1550 nm may be enhanced.**

after-pulsing limited for Ge?

after-pulsing



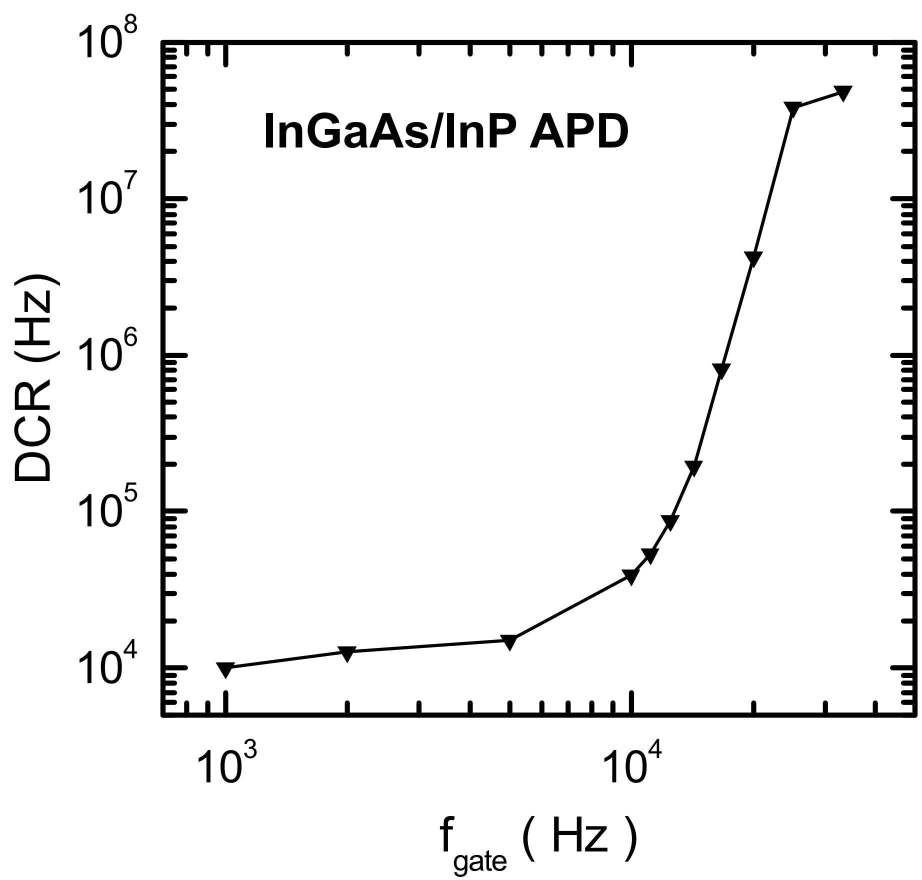


Ribordy et al., AO (1998)

- **Single photon detection desired**
  - **Quantum key distribution (QKD) on dark fiber**
  - **Eye safe LIDAR imaging**
  - **Single molecule fluorescence detection**
  - **Quantum commutation with linear optics**

After-Pulsing

- **After-pulsing causes increased dark count rates (DCR)**
- **After-pulsing is trap related**
  - **InP has traps which limit the performance at high frequency**
  - **Ge has fewer traps which motivates this work**



Tosi, Proc. Eur. Solid-State Dev. Res. ***36****, 335 (2006)*

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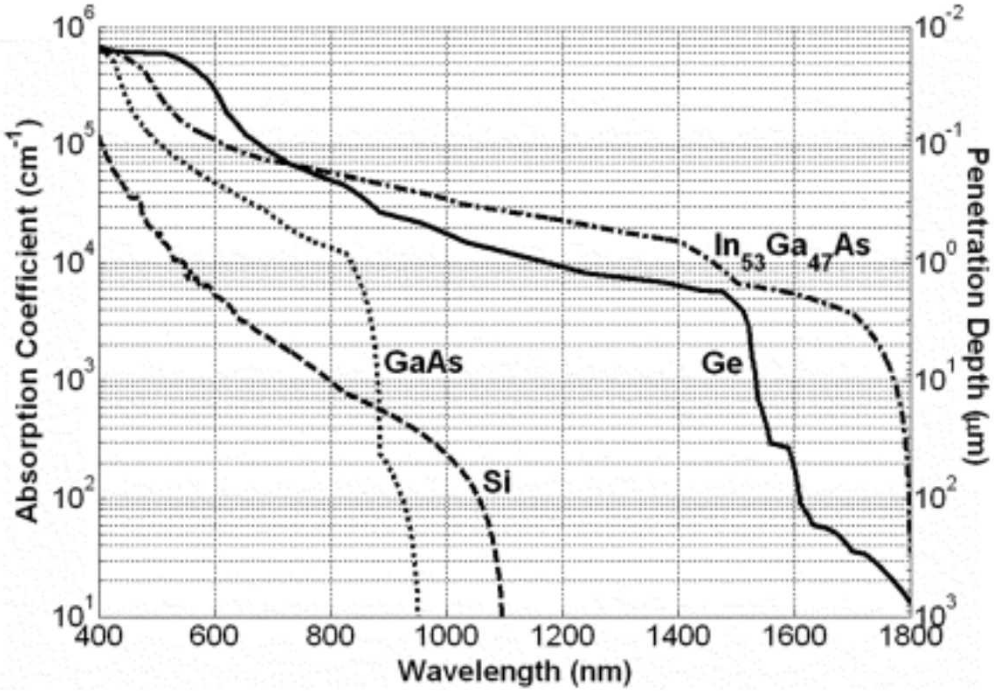
Absorption Coefficients

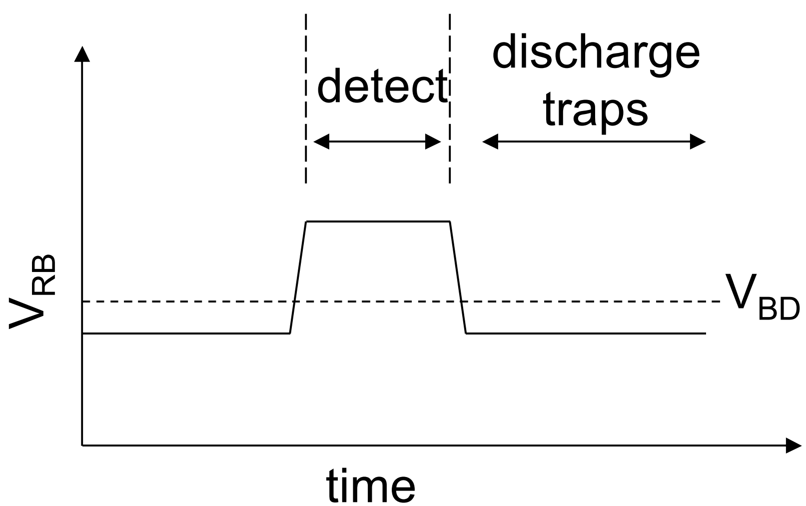
- Ge has long been ignored for single photon detection in the Near-infrared because of the telecommunications need at 1550 nm.
- QKD may use existing dark fiber at 1310 nm
  - Reopening the usefulness of Ge



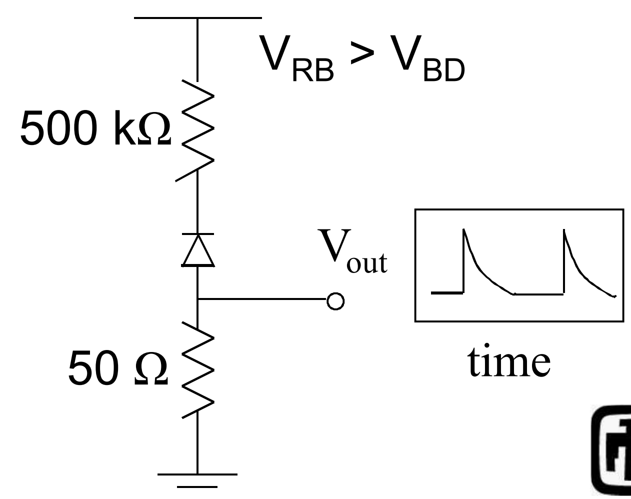
*O.I. Dosunmu, IEEE J Sel Top Quant, **10(4)**, 694 (2004)*

Geiger Mode Operation

- High fields produce avalanche breakdown triggered by single e$^-$
- GM operates APD above breakdown (V_{BD})
  - Single photon sensitivity
- After-pulsing can be suppressed with gated operation
  - Allows time for trap discharging after avalanche fills them
- Geiger pulse can be passively or actively quenched
- The window of sensitivity is when the junction is at high field during the time before the next thermally generated dark count



passive quenching configuration



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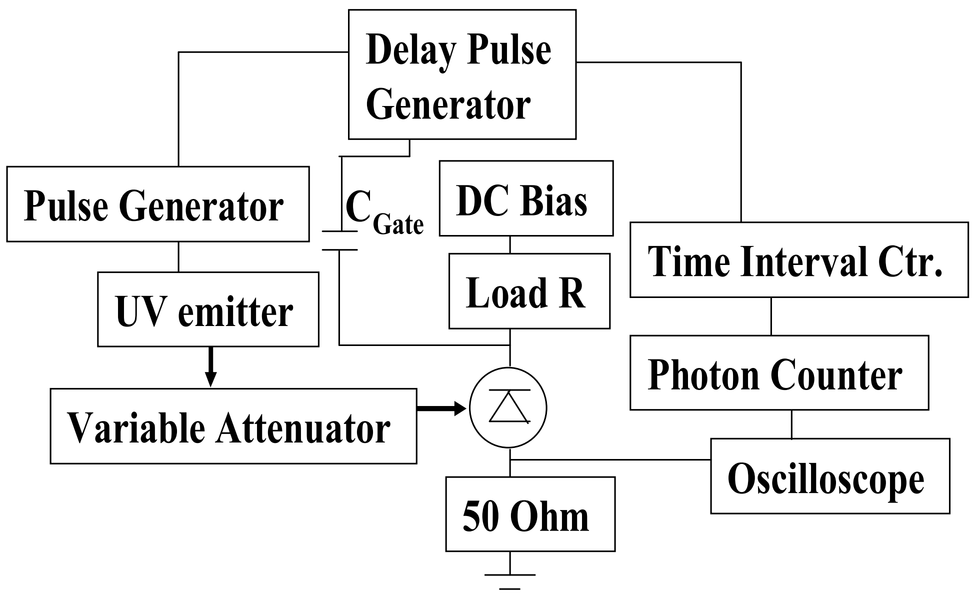
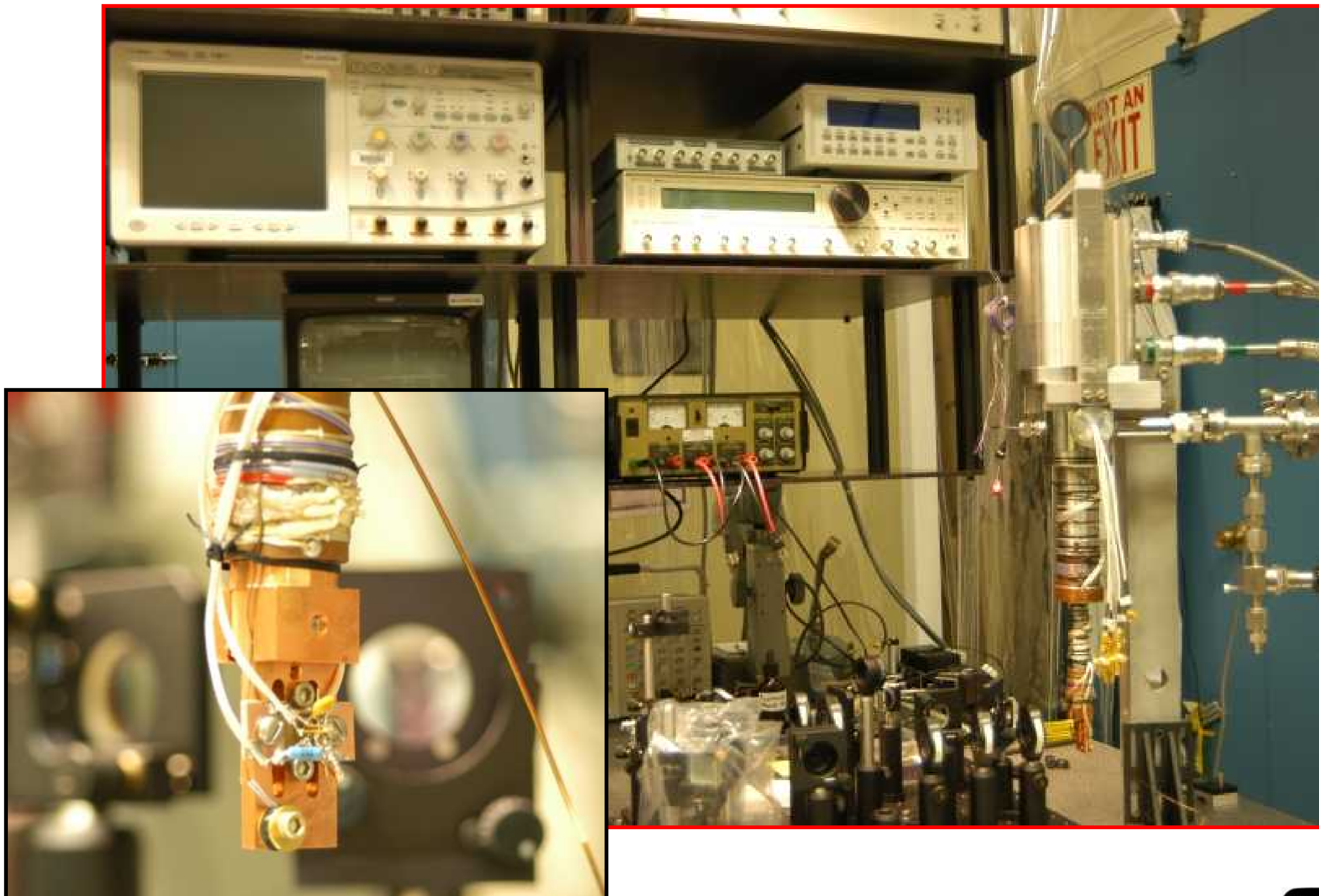
Geiger Mode Setup

- Geiger-mode (GM) operation measurement setup
  - Gating circuit and gate pulse required
    - Gate frequencies typically 1 kHz -100 MHz
    - Gate widths from 4 ns to 10 μs
  - Detection efficiency (DE) and DCR



Cryostat Setup

- **Temperature range** 16 K - 350 K
- **Electrical connections** 50-ohm coax. cables



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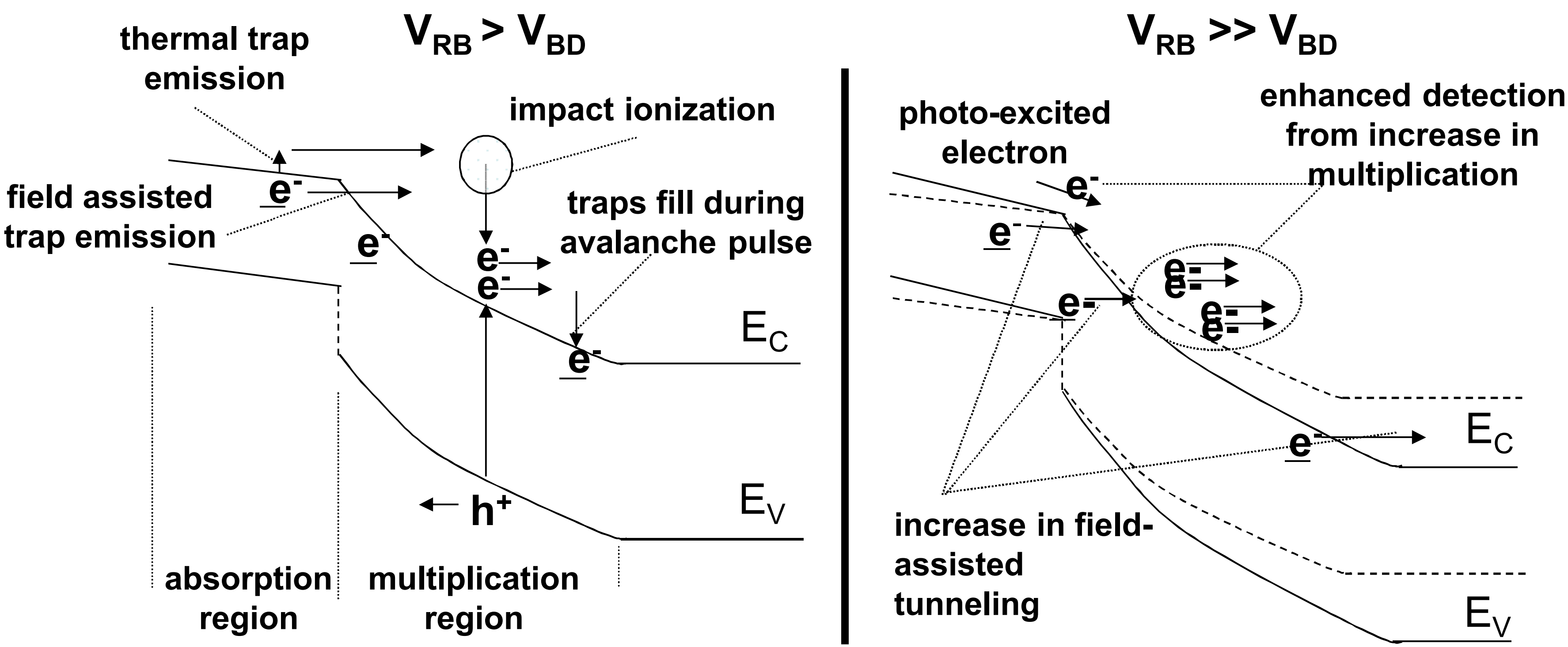
Reverse Bias and DE

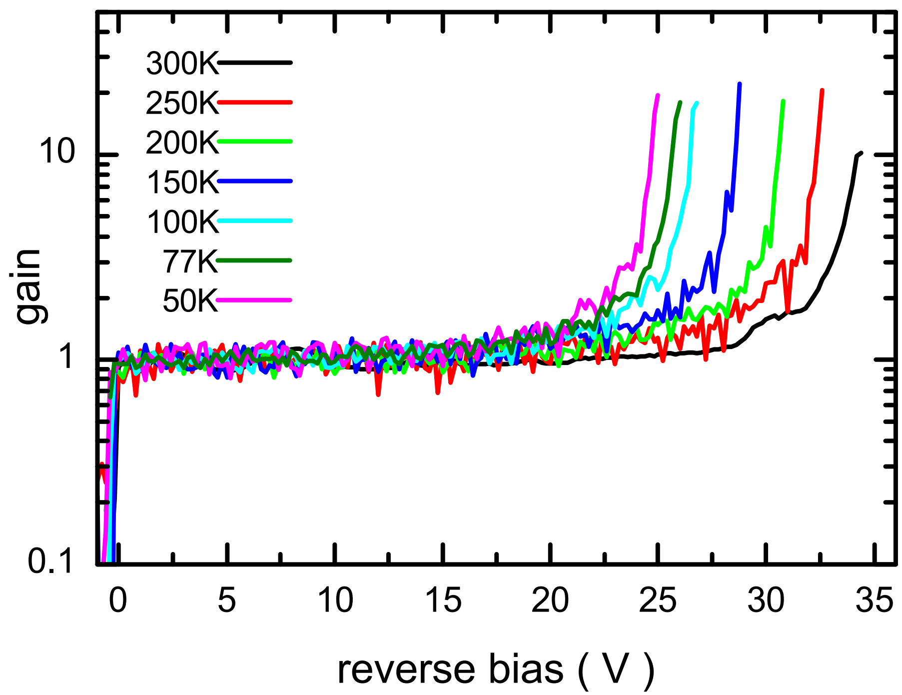
- DE increases with increasing reverse bias (V_{RB})
- Field assisted trap tunneling increases with V_{RB} limiting DE
- DE for NIR devices is typically around 10-30% before dark counts overwhelm signal



Ge APD Multiplication

- **Avalanche photodiodes (APD) produce internal gain due to high field impact ionization**
- **Linear mode results in 10-100 x gain**
  - **Insufficient for single photon detection**

10mW optical power incident on Ge APD



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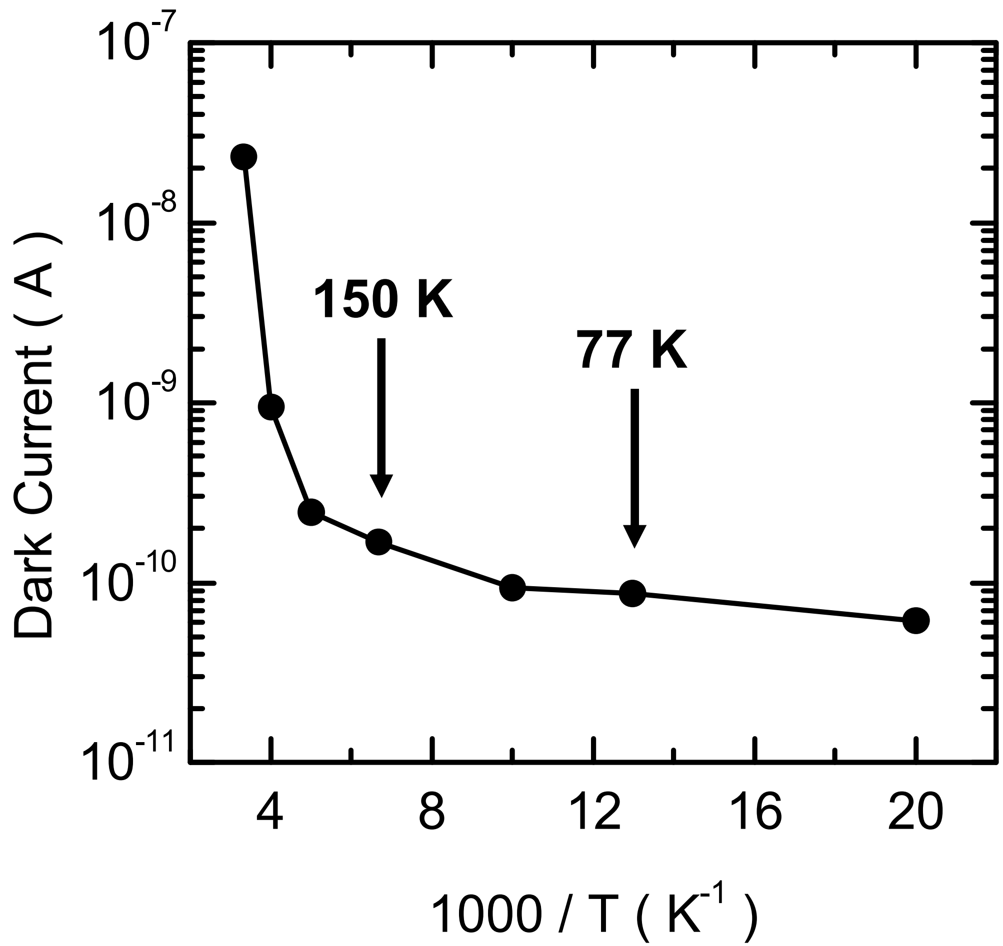
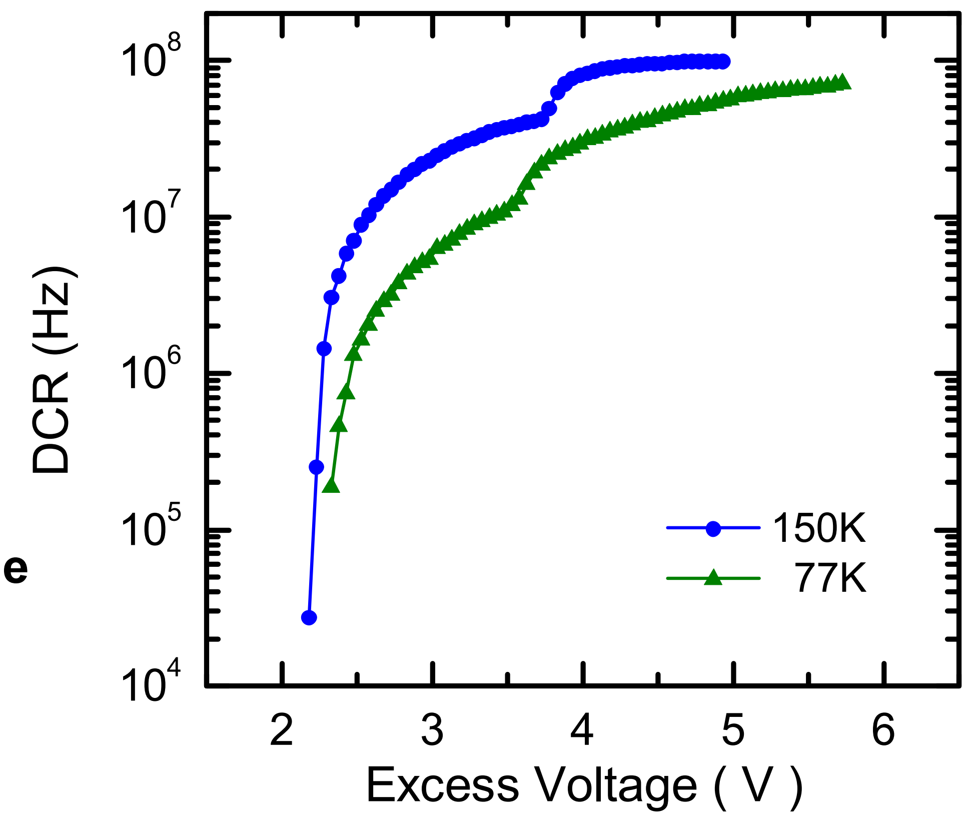
Dark Current

- **Arrhenius plot of the dark current in commercial Ge APD**
  - **Steep decrease in the thermally generated carriers as T^{-1}**



Dark Count Rate

- DCR at 1 kHz ensures after-pulsing is not measured
- Weaker than expected T dep. for thermally generated carriers
  - Tunneling mechanism is dominating the DCR below 150K
- Even at this low f_{gate} the DCR for this APD is higher than common for Ge



$$DCR = \frac{N_{counter}}{T_{on} f_{gate}}$$

$$f_{gate} = 1kHz$$

$$T_{on} = 20ns$$

Excess voltage is VRB - VBD

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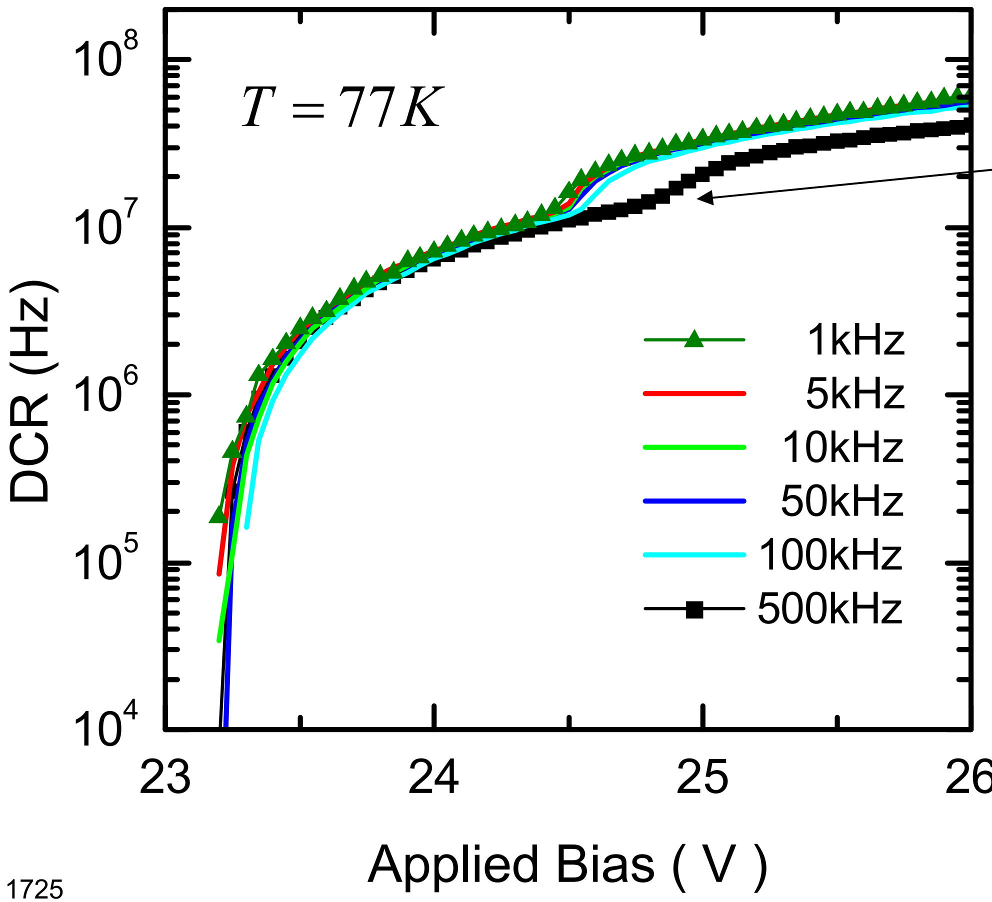
DCR at 77 K

- **Increasing f_{gate} to check for after-pulsing**
- **Tunneling mechanism still dominating the DCR up to 500 kHz**



increased charging of minority carriers shifting V_{BD} with high f_{gate}

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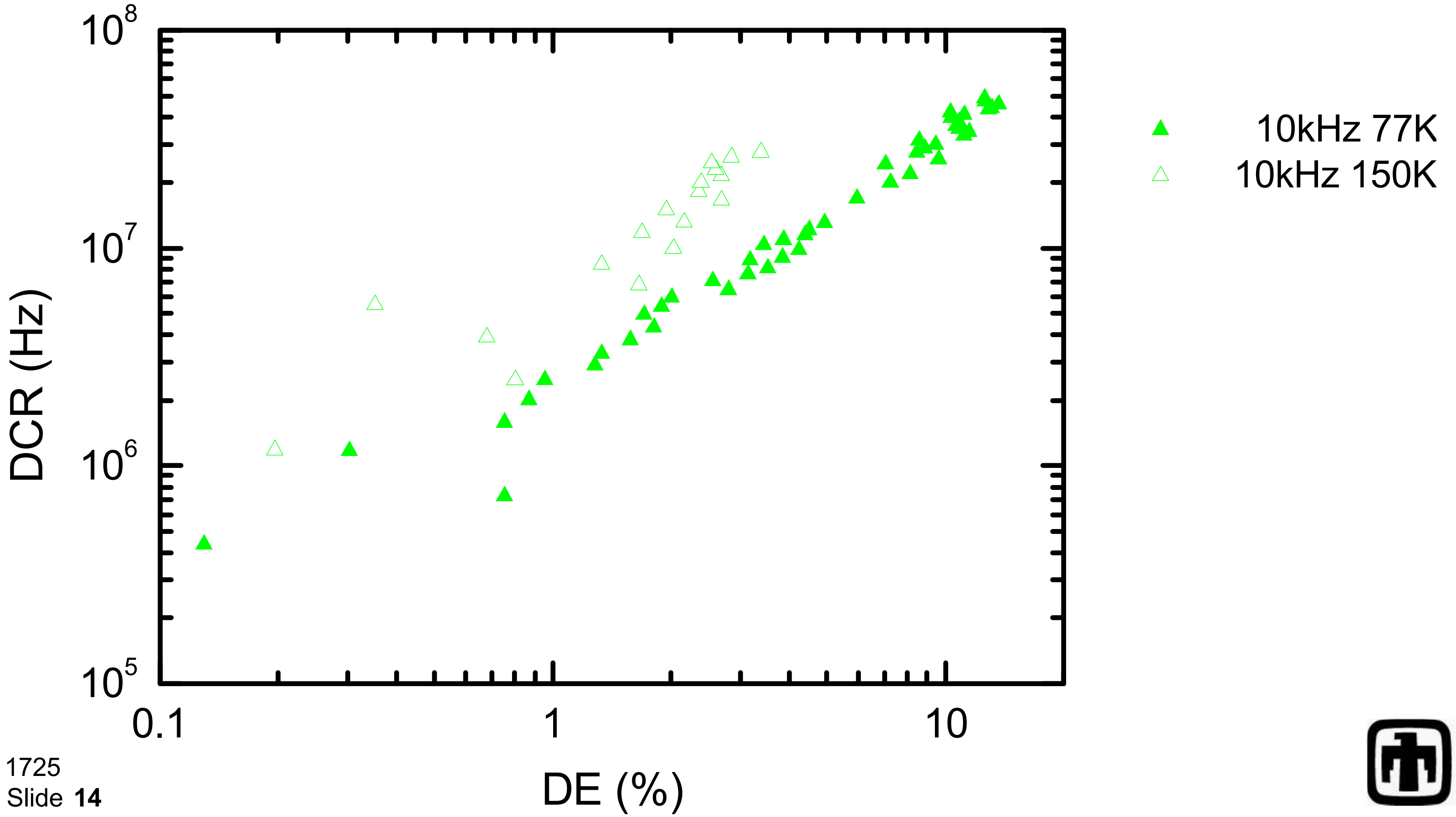
Detection Efficiency

- The Judson Ge APD was not designed for GM
  - Low quantum efficiency (51%) at low T
- DE reaches 15% with 1 photon per gate



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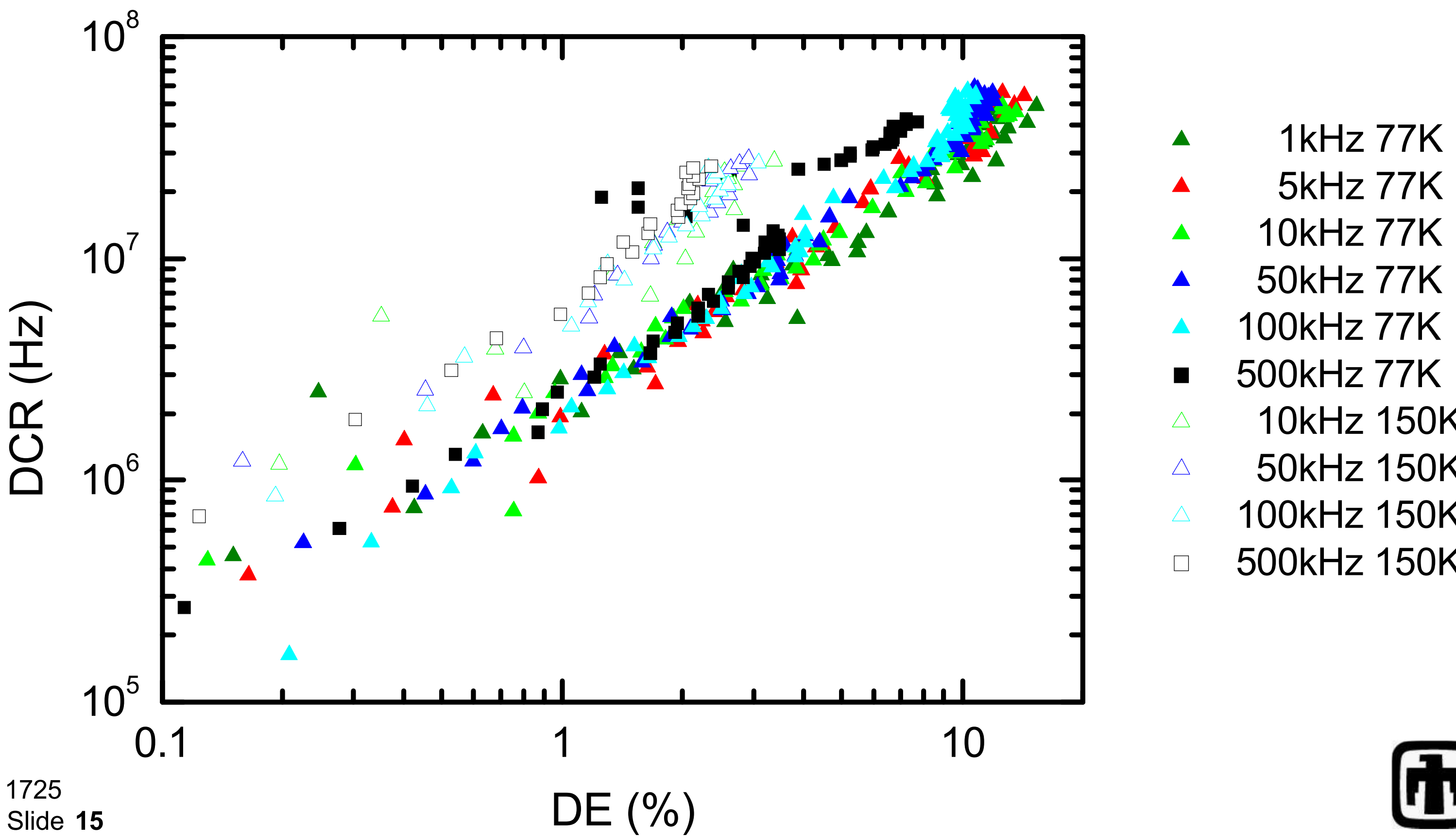
Detection Efficiency

- The Judson Ge APD was not designed for GM
  - Low quantum efficiency (51%) at low T
- DE reaches 15% with 1 photon per gate
- Minimal high frequency penalty



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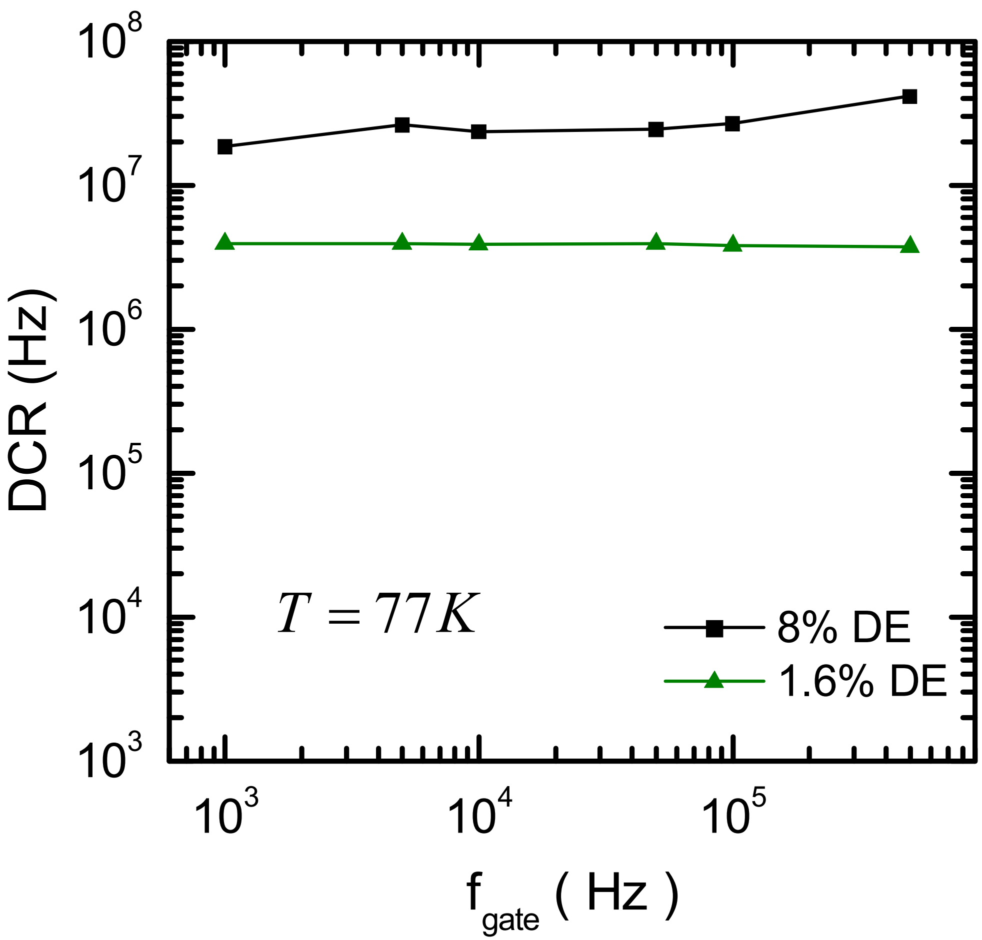
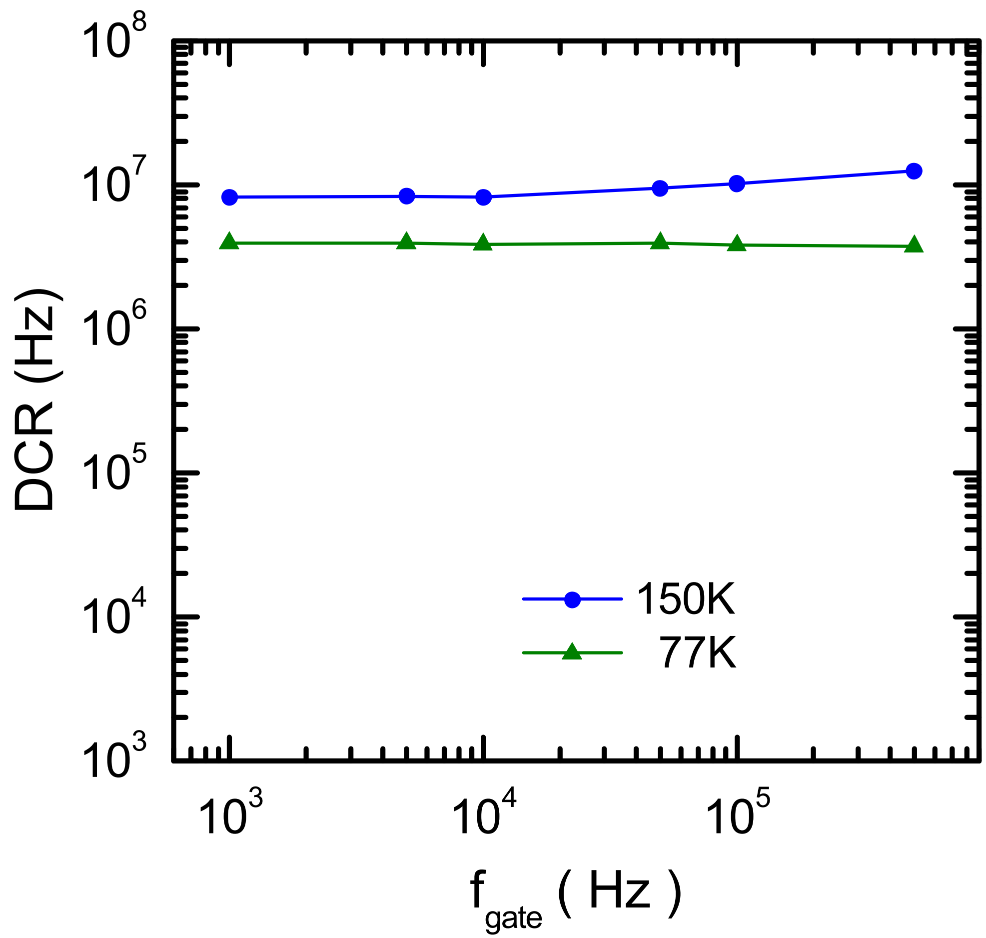
DCR with Fixed DE at 77K

- Ge APD exhibits only a slight increase in DCR at 1.6% DE
- Slight increase in DCR at 8% DE with f_{gate} could be after-pulsing



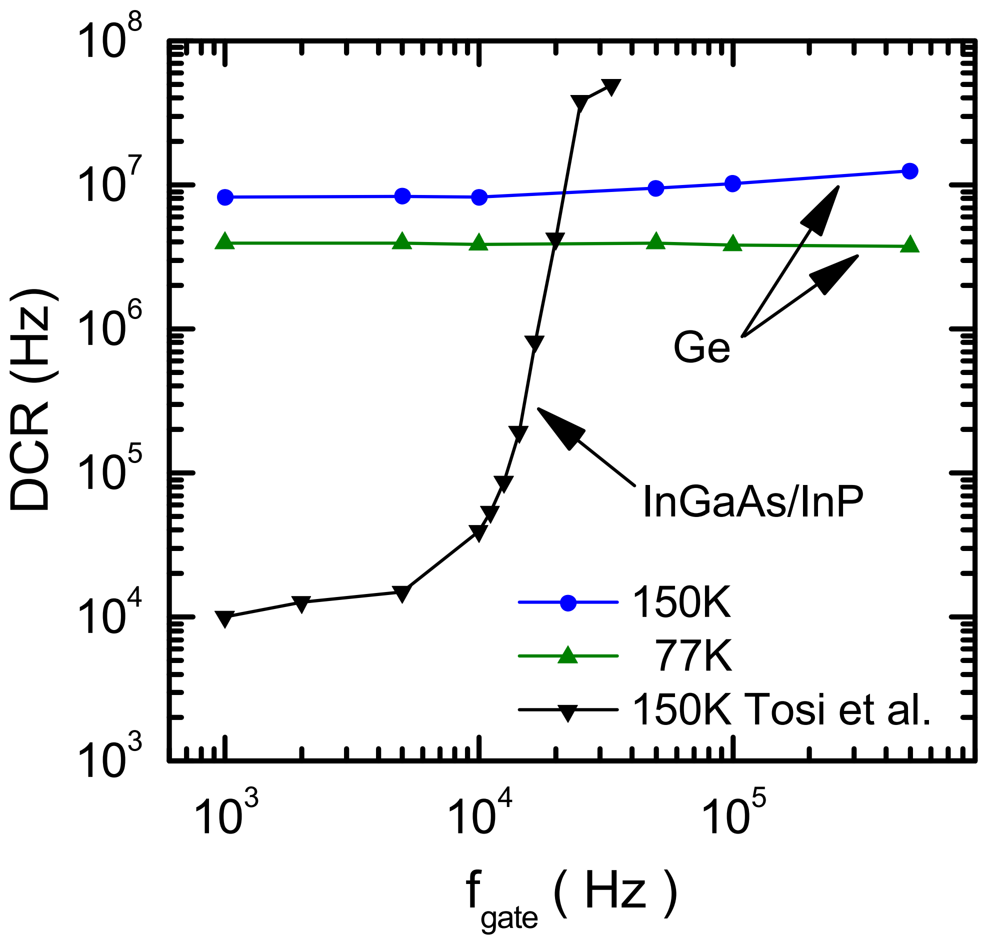
DCR at DE = 1.6%

- **Ge APD exhibits only a slight increase in DCR at 1.6% DE**
- **Increase in DCR at 150K with f_{gate} could be thermally generated after-pulsing**



DCR of Ge and InGaAs/InP

- Ge APD exhibits only a slight increase in DCR at 1.6% DE
- DCR in InGaAs/InP APD demonstrate characteristic increase with f_{gate} at an unspecified DE



*Tosi, Proc. Eur. Solid-State Dev. Res. **36**, 335 (2006)*

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Summary

- Commercial Ge APD has been used to demonstrate single photon detection

- QKD applications at 1310 nm that can be cooled to ~100-220K range may be best suited for Ge
  - Ge heterostructure engineering could significantly raise $T_{operation}$

- DCR while high in this device, showed little increase with f_{gate} up to 500 kHz
  - Unlike InGaAs/InP DCR, that increased nearly 4 decades by 20 kHz

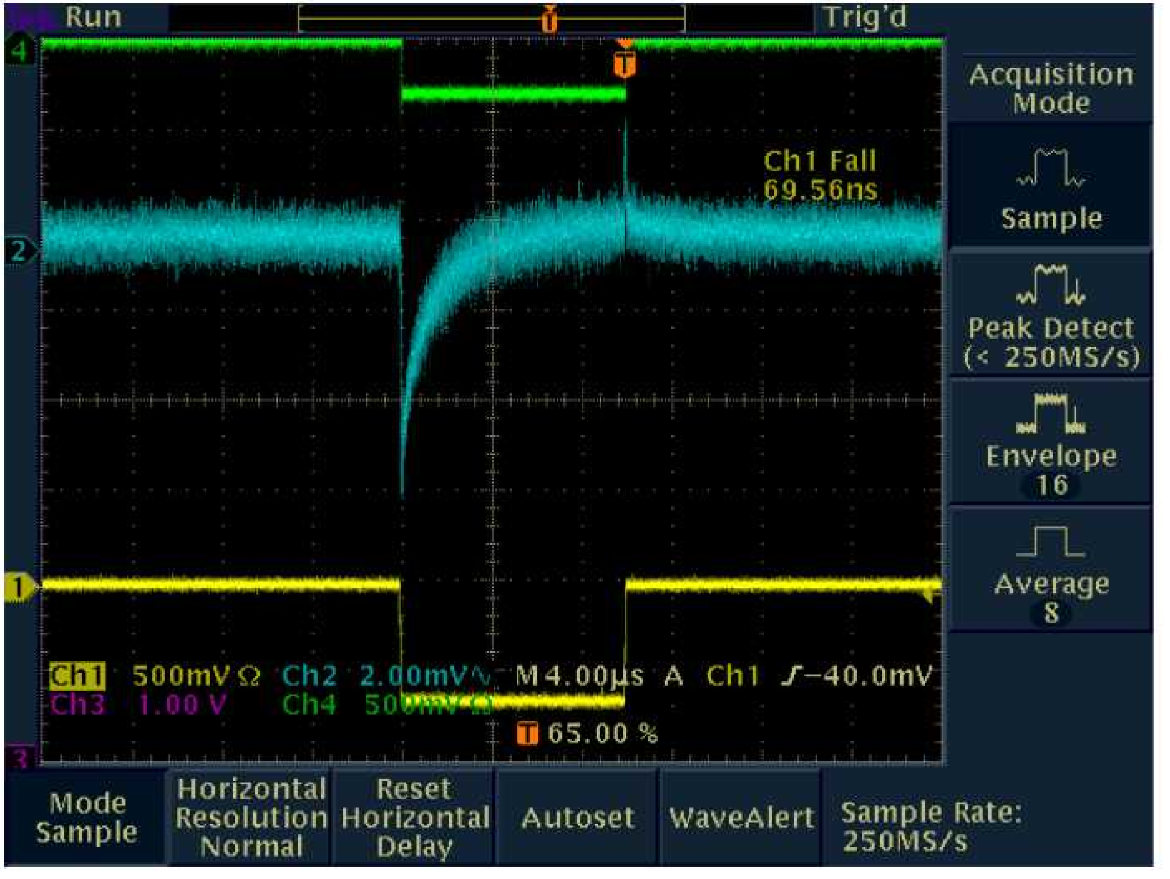
- Future work includes Ge APD designed for GM and possibly a heterojunction design.

Acknowledgement

- **Darwin Serkland**
  - **Sandia National Laboratories**
  - **Use of the lab and equipment**

- **Tom Bauwer (check name and spelling)*********************************
  - **Sandia National Laboratories**
  - **Wiring the cryostat**

Oscilloscope Showing SPAD Operation



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