Germanium Internal Charge Amplification (GeICA) for MeV-Scale Dark Matter Searches

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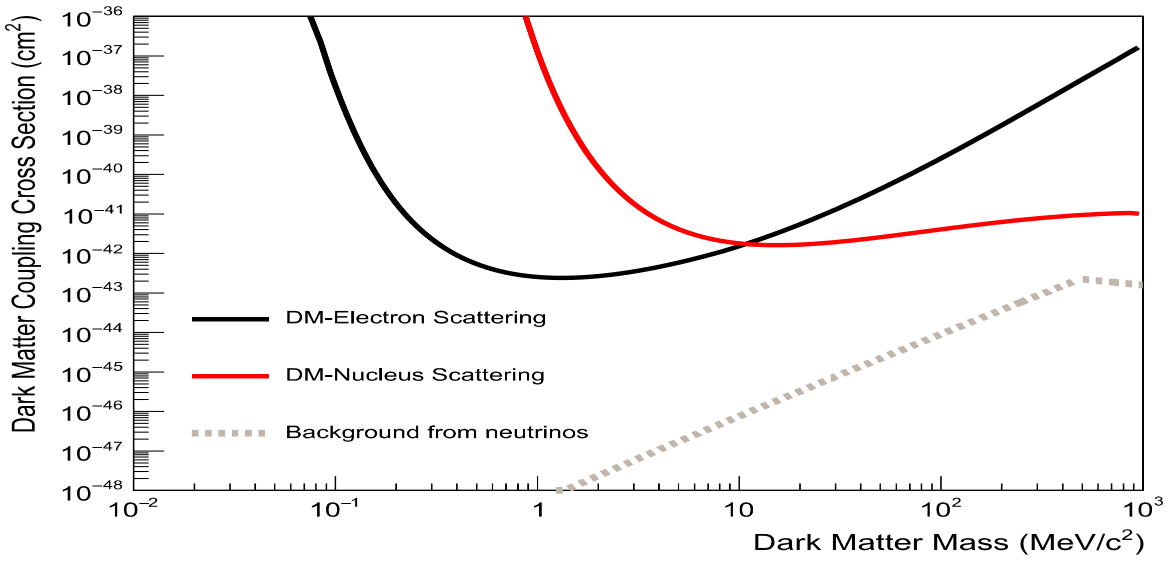
Direct detection of MeV-scale dark matter utilizing germanium internal amplification for the charge created by the ionization of impurities has been published in THE EUROPEAN PHYSICAL JOURNAL C, Eur. Phys. J. C (2018) 78:187.

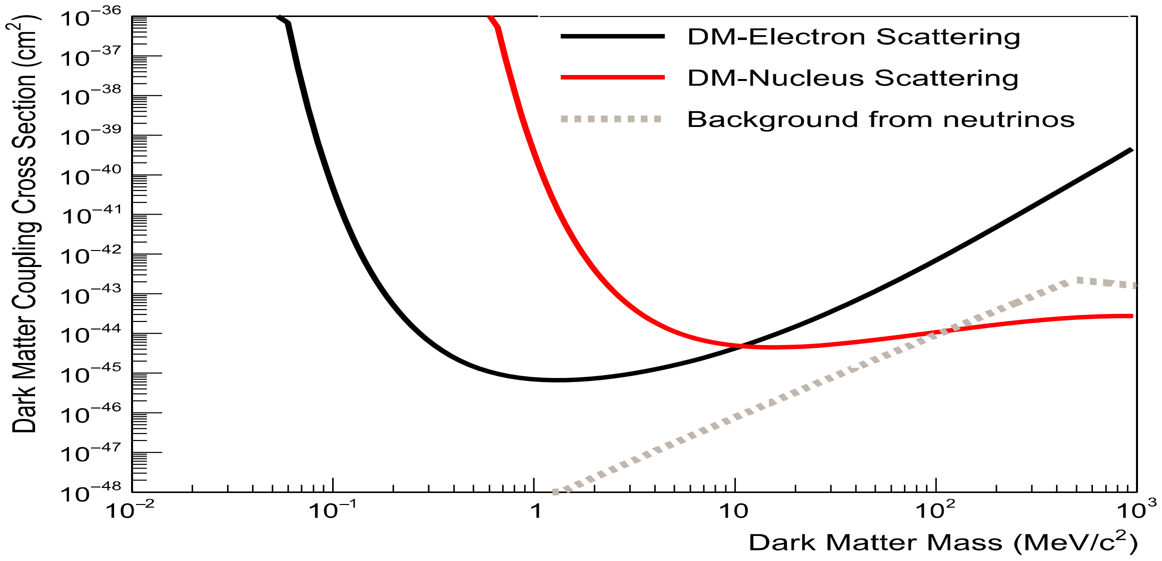
Advantages:

- Extremely low-energy threshold: ~ 0.1 eV or better
- Large in detector mass: ~ 1 kg of germanium crystal
- Very high sensitivity

Disadvantages:

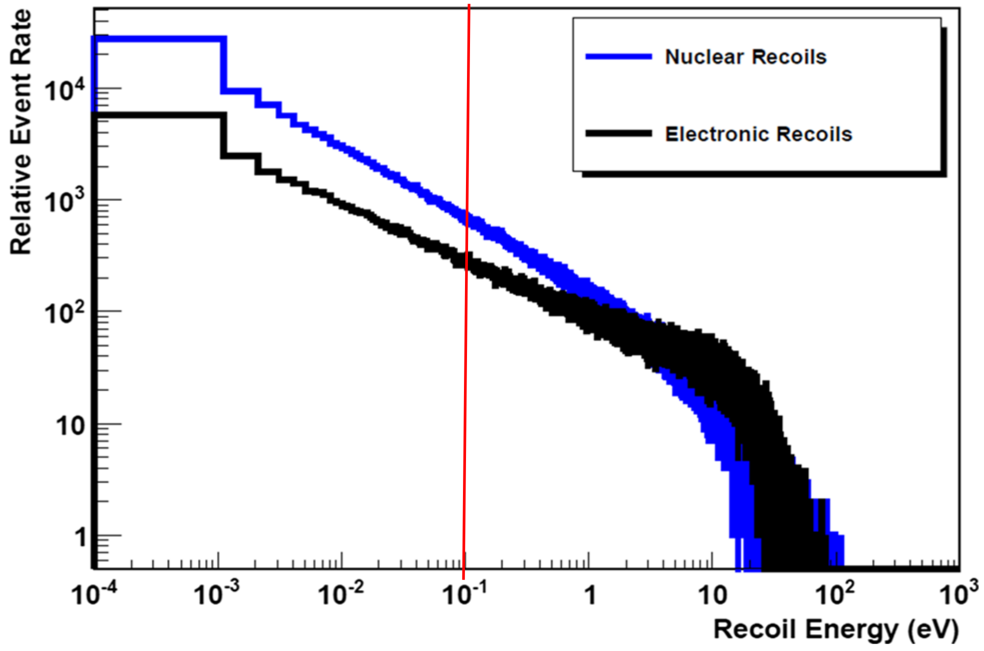
- New technology
- Not commercially available
- Intensive R&D





Left: The projected experimental sensitivity for a day. Right: The projected sensitivity for a year. The calculation was based on a GeICA detector with a mass of 1 kg.

MeV-Scale DM Induced Recoil Energy



Impurity	Boron	Aluminum	Gallium	Phosphorus
Ionization energy (eV)	0.0104	0.0102	0.0108	0.012

Low-energy threshold is required

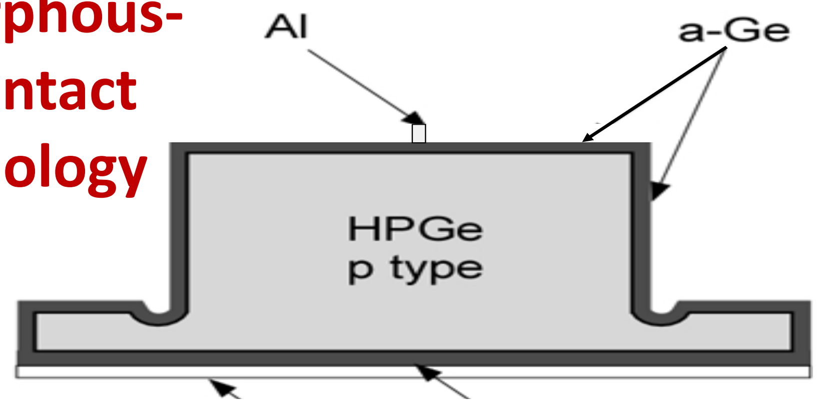
Single e-h pair → **Internal Amplification Through High E-field** → ~1000 e-h pairs

Challenges:
Avalanche breakdown
Electrical breakdown

R&D in progress to demonstrate the critical technology in the lab

Six detectors were made

Amorphous-Ge contact technology



Injection Current and Energy Barrier Height

Shottky Theory:

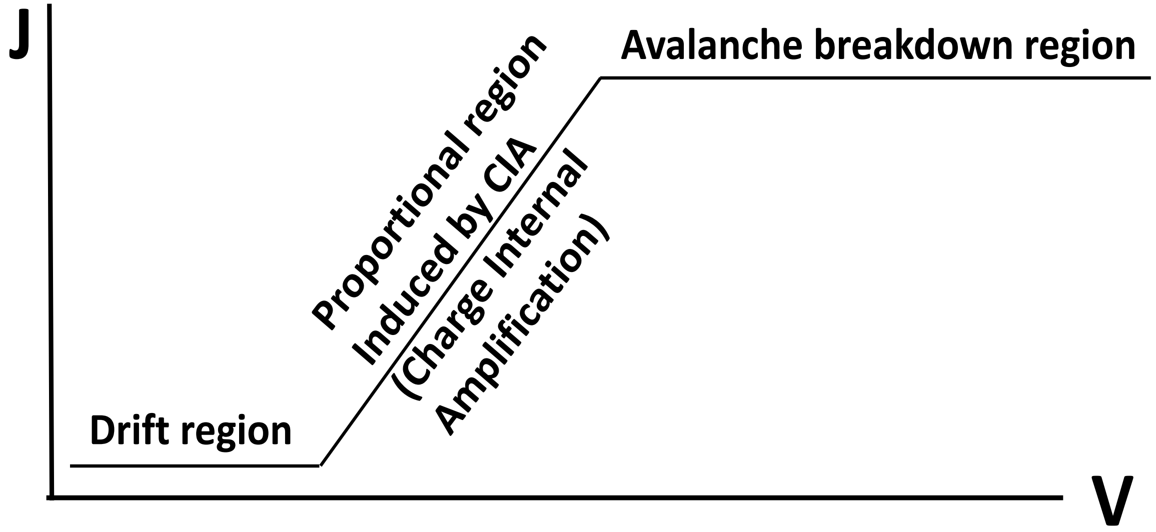
$$J=J_0T^2\exp(-\left\{\varphi-\left[\left(\frac{\varepsilon_0\varepsilon_{Ge}}{N_F}\right)_{\varphi}^{1/2}\times\frac{V+V_{depl}}{d}\right]\right\}/k_BT)$$

Wei et al. [arXiv: 1809.04111] from USD found that

$J_0=2.45\times10^{-5}A/cm^2/K^2$, $\varphi=0.18eV$, $N_F=1.6\times10^{18}/eV^{-1}cm^{-3}$

Leakage current at 4K is expected to be zero

What we have observed in the lab

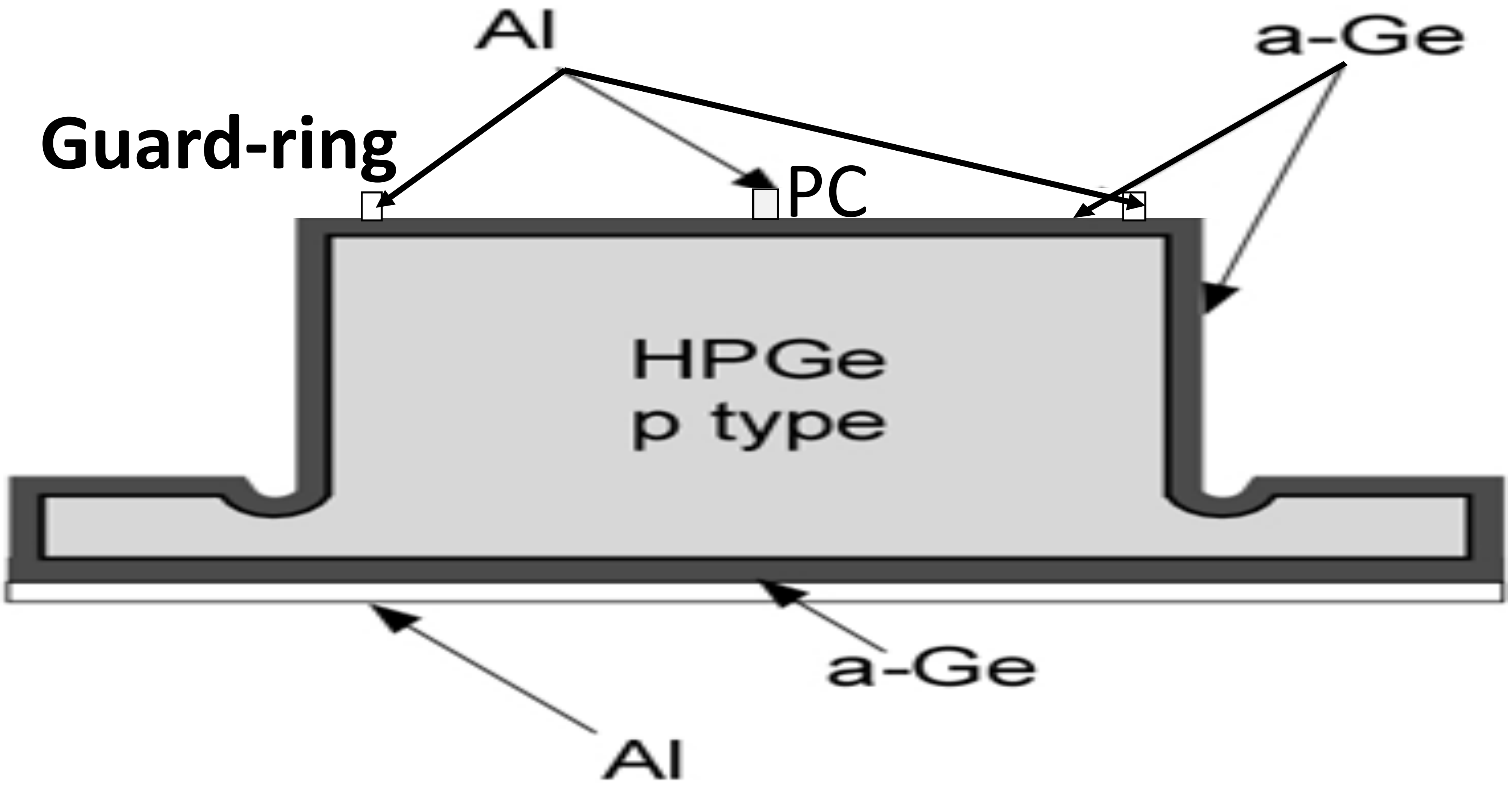


$$M=\frac{1}{1-\left(\frac{V}{V_{bk}}\right)^n}$$

M: Amplification Factor
V: Applied bias voltage
V_{bk}: Breakdown voltage

V_{bk} = 3000 voltage for a point contact of ~1 mm^2
V= 2300 – 2700, M $\approx$ 1000
Average ionization length: ~0.9 μm

Methods



Injection Current and Energy Barrier Height

Dohler and Brodsky Theory:

$$J = J_{\infty}\exp\left(-\left\{\varphi - \left[\left(\frac{\varepsilon_0\varepsilon_{Ge}}{N_F}\right)^{1/2}_{\varphi} \times \frac{V+V_{depl}}{d}\right]\right\}/k_B T\right)$$

Hull et al. (NIMA 538 (2005) 651 found that:
J_{∞}=6.4x10^{6}A/cm^2, where N_F=1x10^{18} eV^{-1} cm^{-3}, $\varphi = 0.30\ eV$

If one requires: $\varphi = \left[\left(\frac{\varepsilon_0\varepsilon_{Ge}}{N_F}\right)^{1/2} \times \frac{V+V_{depl}}{d}\right]$, no energy barrier height anymore

V>100,000 volts

Injection Current and Energy Barrier Height

Shottky Theory:

$$J = J_0 T^2 \exp\left(-\left\{\varphi - \left[\left(\frac{\varepsilon_0 \varepsilon_{Ge}}{N_F}\right)_{\varphi}^{1/2} \times \frac{V + V_{depl}}{d}\right]\right\}/k_B T\right)$$

Wei et al. found that (USD):

$J_0 = 2.45\text{x}10^{-5} A/cm^2/K^2$, $\varphi = 0.18 eV$, $N_F = 1.6\text{x}10^{18}/eV^{-1}cm^{-3}$

If one requires: $\varphi = \left[\left(\frac{\varepsilon_0 \varepsilon_{Ge}}{N_F}\right)^{1/2} \times \frac{V + V_{depl}}{d}\right]$**, no energy barrier height anymore**

V>60,000 volts

What is the value of the barrier lowing term?

$$\left[\left(\frac{\varepsilon_0 \varepsilon_{Ge}}{N_F}\right)^{1/2} \times \frac{V+V_{depl}}{d}\right] = 0.011 \text{ eV for V = 3000 volts}$$

Hull: J = 2.3 pA/cm^2 Wei: 2.4 pA/cm^2

If N_F = 1x10^{17} eV^{-1} cm^{-3}

$$\left[\left(\frac{\varepsilon_0 \varepsilon_{Ge}}{N_F}\right)^{1/2} \times \frac{V+V_{depl}}{d}\right] = 0.033 \text{ eV for V = 3000 volts}$$

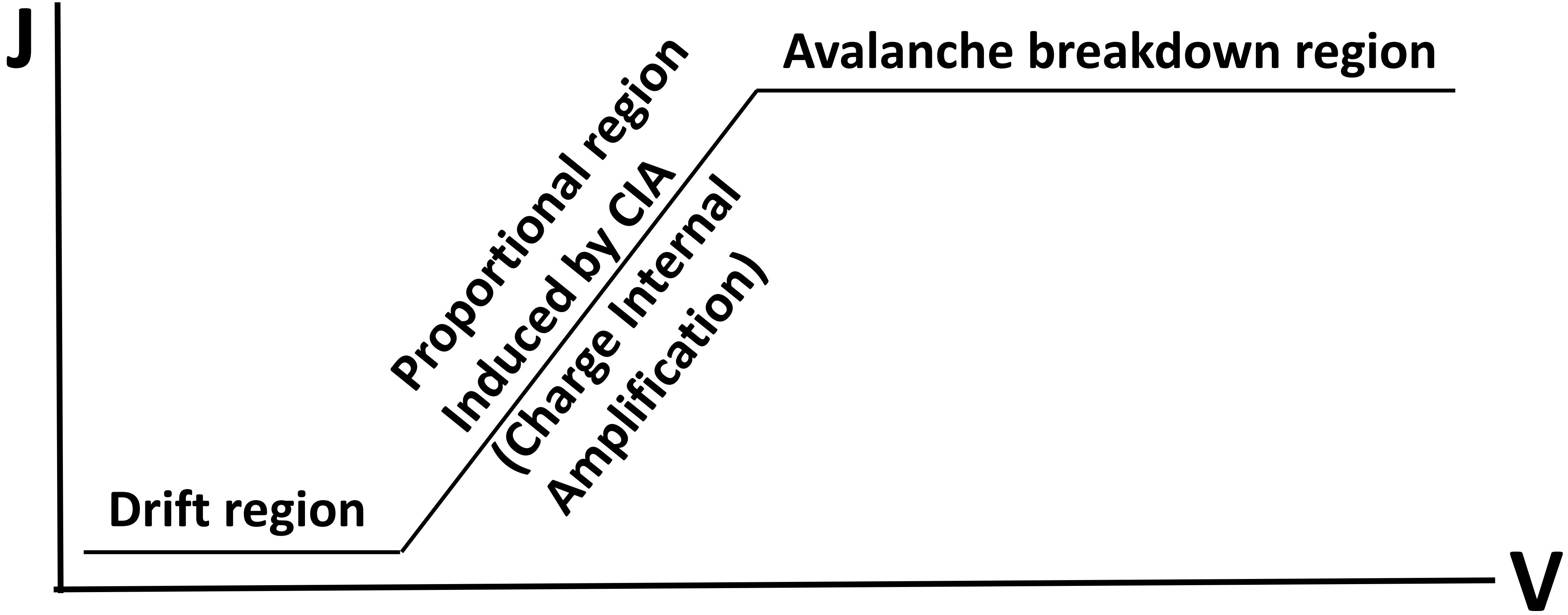
Hull: J = 59 pA/cm^2 Wei: 64 pA/cm^2

What we have observed with USD-W02?

1. Point Contact: Effective area ~ 1.5 mm^2
   - Injection current from ~ 5nA to 100 nA in a range of applied voltage between 2300 V to 2700 V
   - Injection current of 650 nA when the applied voltage is 3000 Volts
   - Second day, Injection current was around 600 – 900 nA when V = 1600 volts
2. Pogo-pin: Effective area <<1.0 mm^2
   - Injection current around 650 nA when V = 1000 volts

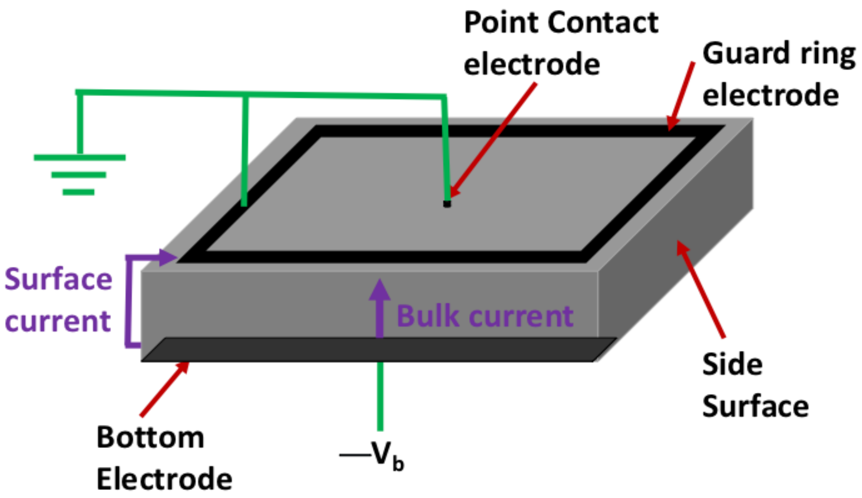
What caused the injection current to be high?

Avalanche Effect causes the injection current to be amplified

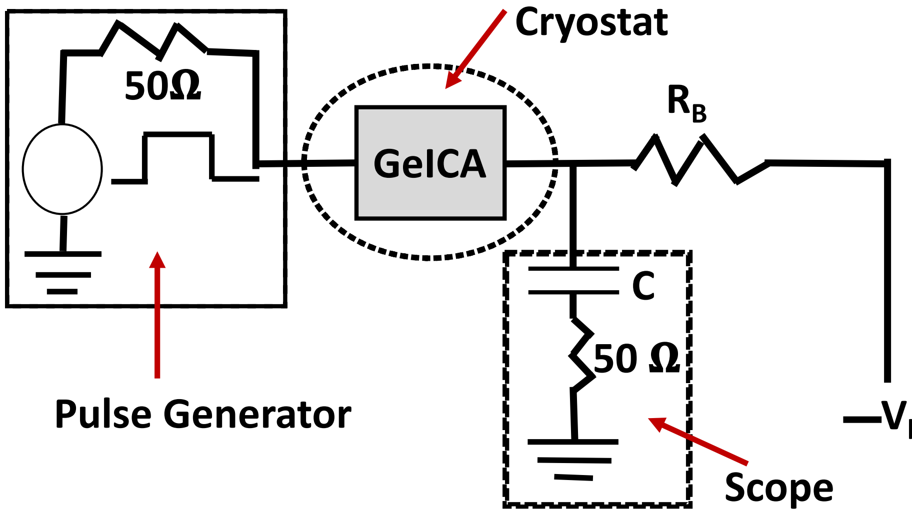


R&D for Achieving a Suitable Electrical Breakdown Prevention Structure

Detector design



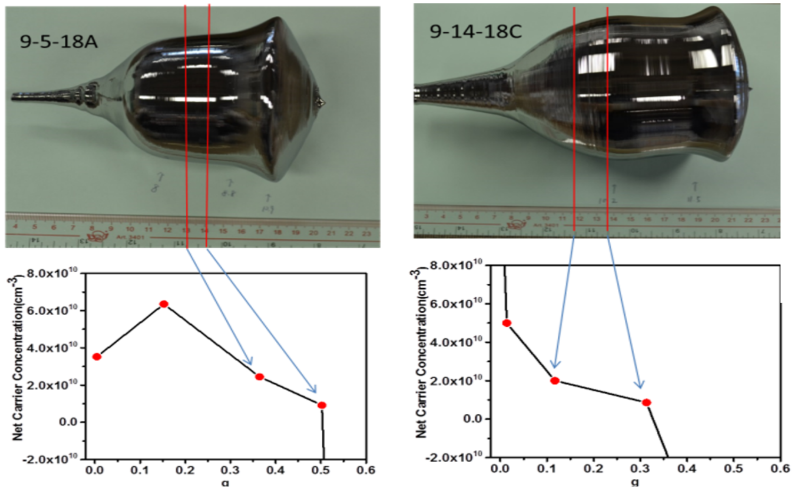
Electronics for calibration



R&D needs in 3 years:

(1) Leakage current test down to ~4K
(2) Fabrication of detectors with 300 grams
(3) Optimization of detector performance
(4) Cryostat design and test
(5) Single e-h pair calibration

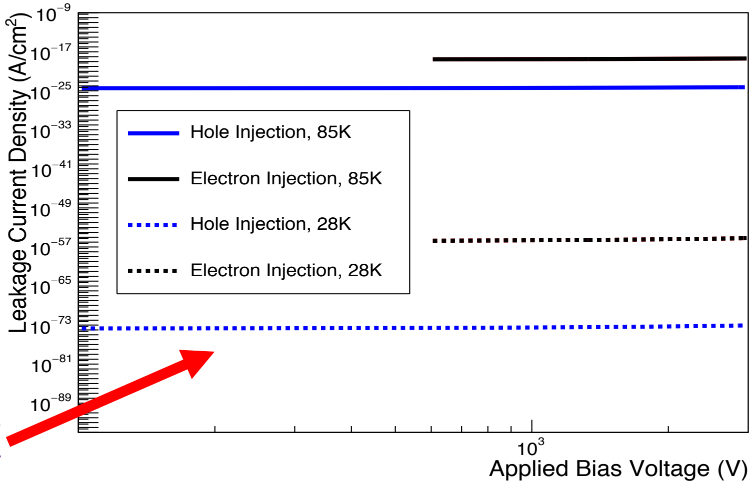
Crystals are grown



Crystal	9-5-18A	9-14-18C
Diameter (cm)	8.7	8.6~10.5
Thickness (cm)	1.1	2.1
Weight (g)	350	900
Impurity Concentration(cm^{-3})	9.1×10^{9}~2.6×10^{10}	6.3×10^{9}~2×10^{10}

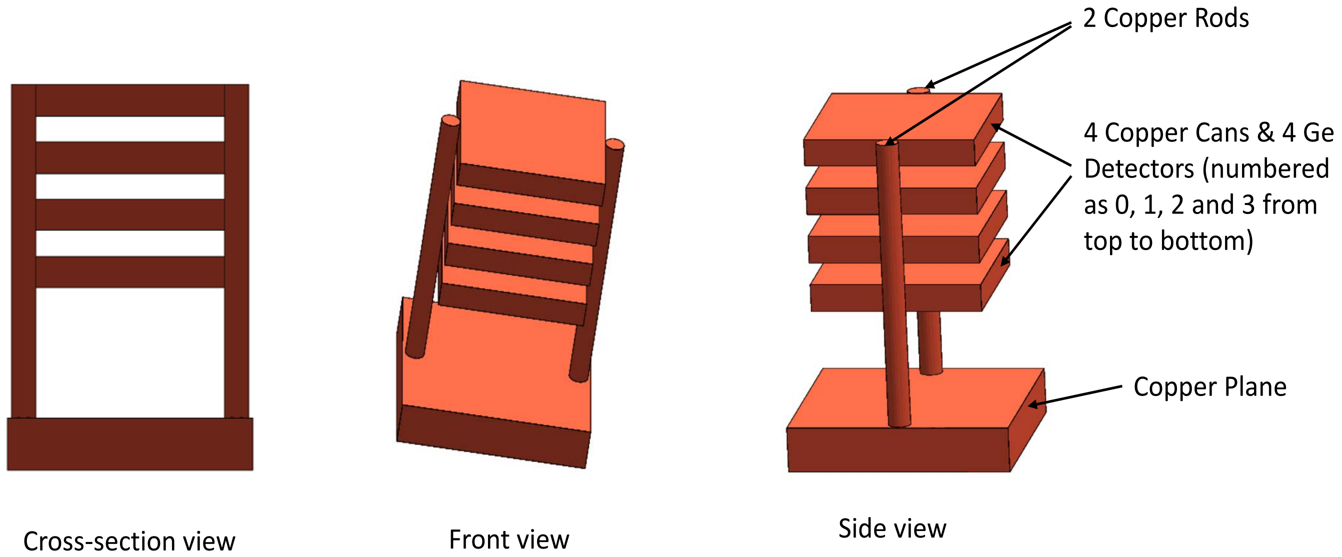
Impurity levels are appropriate

Projected leakage current down to 28K



Monte Carlo simulation of the experiment

Experimental geometry for 4 detectors with a total mass of 1.2 kg



Backgrounds from radioactivity in the region of interest (0.1 eV to 200 eV) is ~0.01 events/kg/year

Ultra low-noise electronics from LBNL

1. **Low noise, low-threshold**
2. **Optimize for down to 0.1 pF detectors**
3. **Minimize cabling**
4. **Reduce external components**
5. **27 eV-FWHM, <4 e-rms achieved**

Phase-Approached Method: **1) GeCIA-0: on-going MC and Fabrication of small detectors (~ 20 grams) to observe charge internal amplification; 2) GeCIA-1: R&D to build four detector (~1.2 kg) at SURF in six years; 3) GeCIA-2: Build an experiment with 10 kg detectors at SURF**