Impact Ionization in SuperCDMS HVeV Detectors

Francisco Ponce[1], W. Page[2], P. L. Brink[3], B. Cabrera[1, 3], M. Cherry[3], C. Fink[2], N. Kurinsky[4], R. Partridge[3], M. Pyle[2], B. Sadoulet[2], B. Serfass[2], C. Stanford[1], S. Watkins[2], S. Yellin[1], B. A. Young[5]

[1]Department of Physics, Stanford University, [2]Department of Physics, University of California, Berkeley
[3]SLAC National Accelerator Laboratory, [4]Fermi National Accelerator Laboratory [5]Department of Physics, Santa Clara University

SuperCDMS HVeV Device

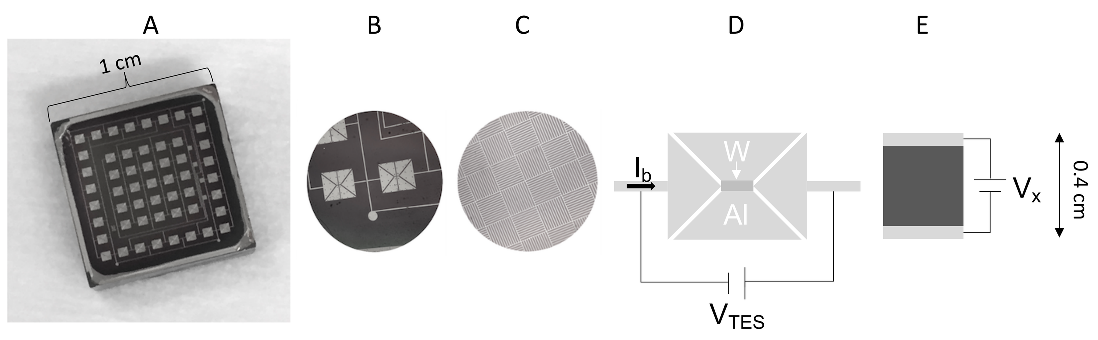
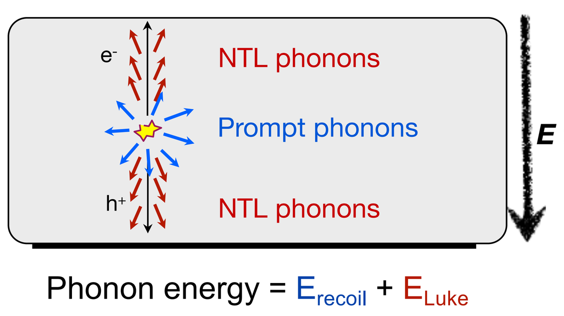


Figure 1: (A) SuperCDMS HVeV device based on the CDMS II and SuperCDMS Quasiparticle-trap-assisted Electro-thermal-feedback Transition edge sensors (QET) advanced athermal phonon sensor technology. (B) An array of QETs covers 13% of one of the (1 x 1) cm² Si substrate sides. (C) A 40 nm-thick patterned Al electrode with 20% coverage (parquet design) covers the opposite side of the detector. (D) Each QET includes a 40 nm-thick W TES coupled to Al fins. The TES is voltage biased at ~ 44 mV for optimal device performance at 30 mK. (D) An amorphous Si layer between the metal films and the Si substrate enables stable substrate biasing to ±140 V (and higher).

Neganov-Trofimov-Luke (NTL) Effect



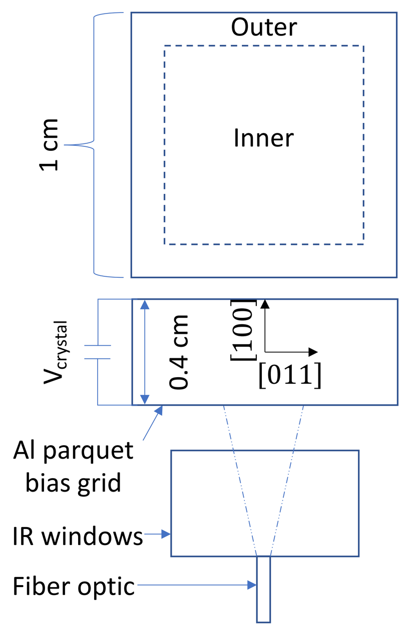


Figure 2: (Top right) Schematic layout of experimental setup. The dilution refrigerator was retrofitted with a single mode fiber optic in order to illuminate the parquet side of the HVeV device with 650 nm (1.91 eV) photons from a pulsed laser. To reduce the amount of IR radiation that reach our detector two 3 mm thick KG-3 IR absorbing windows were installed between the fiber optic output and detector.

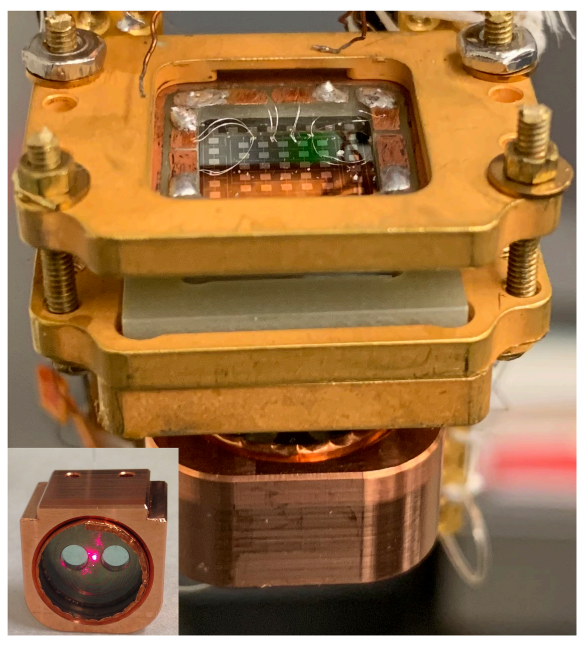


Figure 3: (Left) SuperCDMS HVeV device mounted on mixing chamber stage of dilution refrigerator. KG-3 IR absorbing windows with 350 nm pulse laser visible (inset).

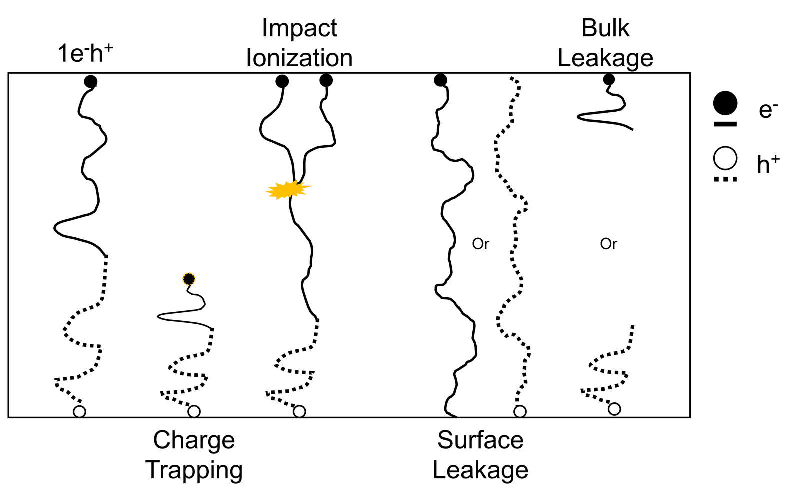


Figure 4: Ideally, each e-h+ pair generated in a single-particle (photon) scattering event will be separated by the applied electric field. The e- and h+ scatter off the lattice as they move through the substrate, converting some of their electric potential energy into Neganov-Trofimov-Luke (NTL) phonons. The phonons are sensed by tungsten TESs on one side of the detector, yielding a quantized peak in the event energy histogram. However, if the e- and/or h+ scatters into an empty state, energy will be lost to the substrate. This effect contributes to the low-energy tails in our observed energy histogram peaks. By contrast, an e- or h+ that collides with a loosely bound charge in the substrate can lead to one additional charge that then undergoes partial NTL amplification. Such "impact ionization" behavior effectively adds energy to the original event and thus contributes to the high-energy tail on a histogram peak. Other noteworthy effects: "Surface leakage" is present when a single e- or h+ is injected into the crystal at the surface and undergoes full NTL amplification (quantized). "Bulk leakage" occurs when a loosely bound charge is freed by either IR or some other mechanism; the freed charge then undergoes partial NTL amplification as it is swept through the crystal by the external electric field.

Analysis Method

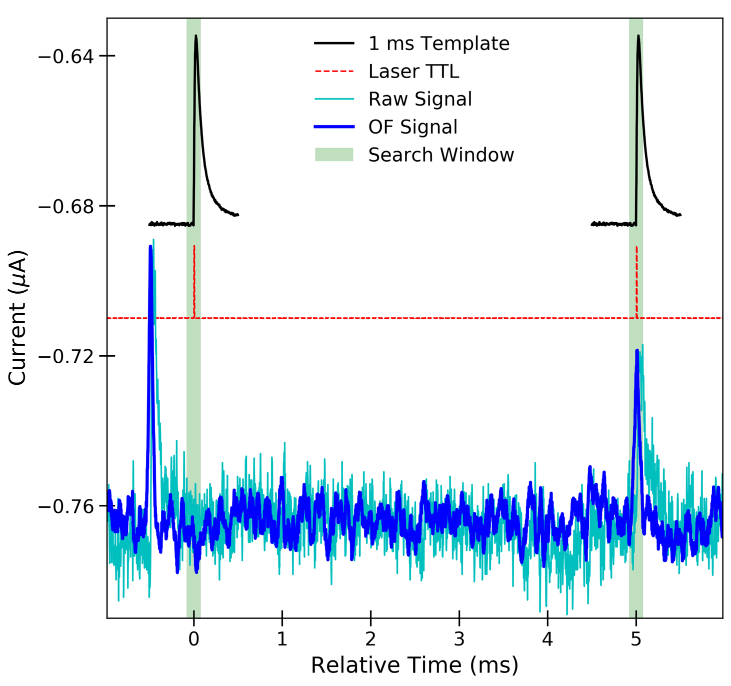


Figure 5: An optimal filter (OF) amplitude as a function of time (blue curve) was calculated by convolving the OF with the trace in the time domain. The energy of an event is taken as the maximum OF amplitude within ± 50 µs (green shade) centered on the laser TTL trigger (red dotted curve).

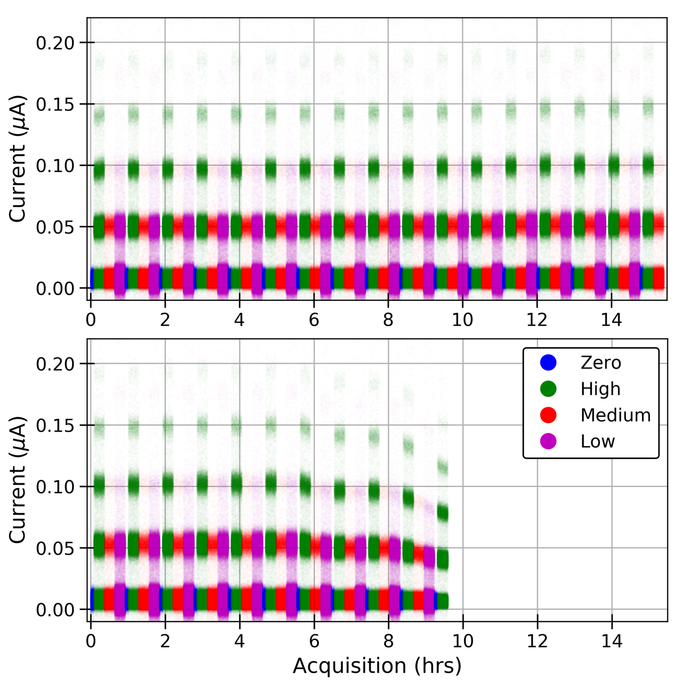


Figure 6: (Top) {Bottom} Detector responsivity over 27 {18} hours of real-time acquisition with a +{-}140 V bias and laser cycled periodically through four intensities: zero, high, medium and low. The detector gain has drifted by less than 6% over 27 hours (top). The refrigerator warmed unexpectedly.

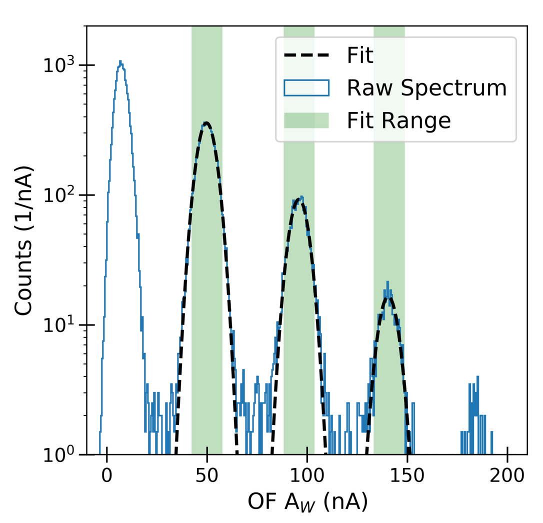


Figure 7: A linear calibration was performed from the centroids of a Gaussian fit (black dashed curve) to the 1, 2, & 3 n_{eh} peaks for the high intensity laser data (blue curve) fitted over a narrow range (green shade).

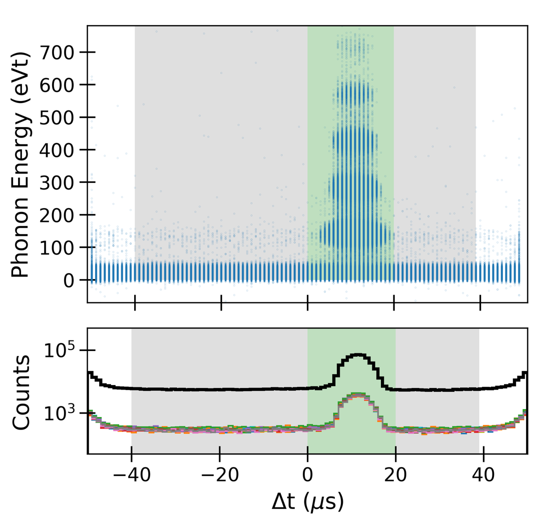


Figure 8: Energy (top) and counts (bottom) of events as a function of the OF estimated arrival time. Non-zero e-h+ pair events cluster together (green). Background spectra are from the zero e-h+ events (gray).

Results

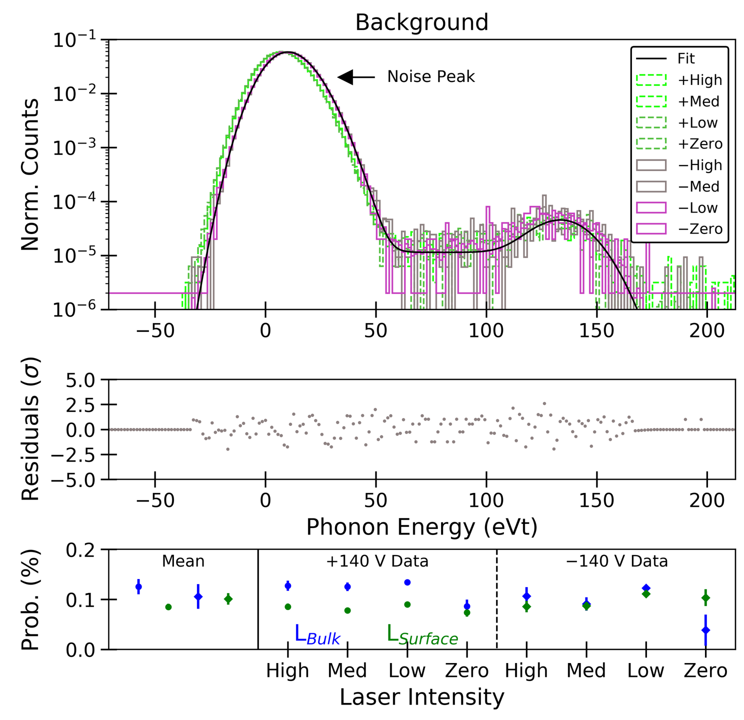


Figure 9: The normalized background spectra (top), one residual (middle) and fitted bulk & surface leakage probabilities (bottom) for all 8 acquisitions. The discrepancy at 0 e-h+ is due to calibration difference. The fitted parameters are nominally identical.

Weighted Bulk Leakage:
0.125 ± 0.015% @ +140 V
0.106 ± 0.025% @ -140 V

Weighted Surface Leakage:
0.085 ± 0.006% @ +140 V
0.101 ± 0.012% @ -140 V

Distorted Gaussian:

$$G_0(x) = \frac{N}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-c_0)^2}{2\sigma^2}} \left(\frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{x-c_0}{\sqrt{2\sigma^2}}\right)\right)\right)^{N-1}$$

Where σ is the standard deviation of the non-distorted gaussian (or detector resolution), c_0 is the shifted centroid of distorted gaussian, and N is fit factor that takes into consideration the search window.

Background PDF:

$$b(x) = L_0\delta(x-c_0) + L_{Bulk}\frac{\Theta(x-c_0)\Theta(c_1-x)}{(c_1-c_0)} + L_{Surf}\delta(x-c_1)$$

Where c_i is the centroid of the i^{th} peak, $L_0 = (1 - L_{Bulk} - L_{Surf})$, L_{Bulk} is the bulk leakage probability, and L_{Surf} is the surface leakage probability.

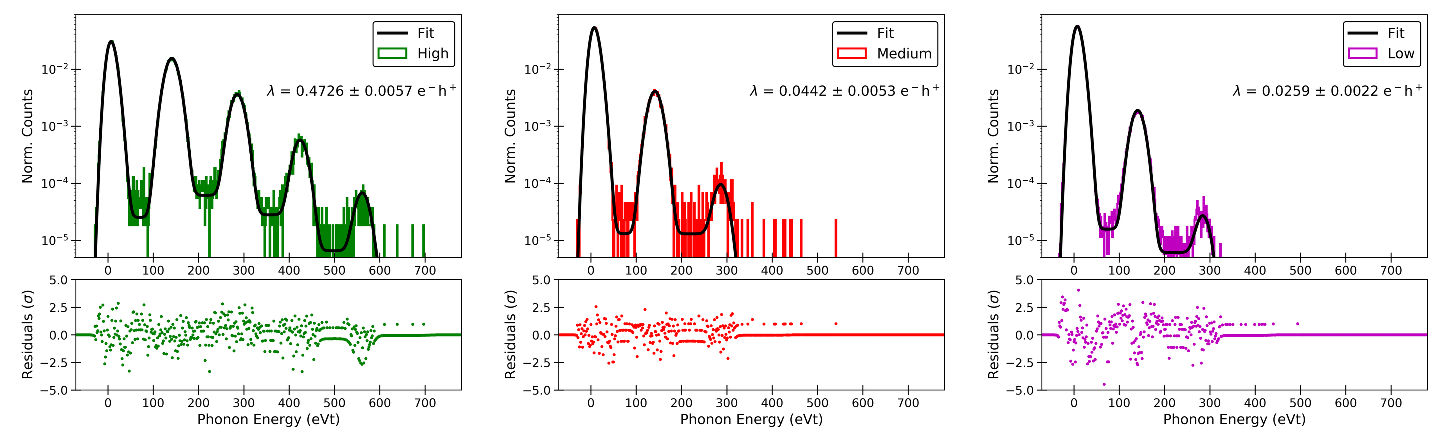


Figure 10: (Top row) Impact ionization and charge trapping fit (black curves) for a single acquisition cycle at +140 V crystal bias with high (green), medium (red), and low (purple) intensity laser. The curves have been normalized by dividing by the total counts in the spectrum. (Bottom row) Residual counts normalized by the individual bin standard deviations. Bins with zero counts were set to have a standard deviation of 1 and thus are seen artificially at zero.

Single e-h+ pair PDF with impact ionization and trapping:

$$^1h(x) = A_1\delta(x-1) + A_-\Theta(x-0)\Theta(1-x) + A_+\Theta(x-1)\Theta(2-x)$$

Where $A_1 = (1 - A_- - A_+)$, A_- is the charge trapping probability, A_+ is the impact ionization probability, and Θ(x) is the Heaviside function.

m[th] e-h+ pair PDF with impact ionization and trapping :

$$^mh(x) = \int_{-\infty}^{\infty} {}^1h(x')\,{}^{m-1}h(x-x')\,dx'$$

$$= A_1^m\delta(x-m) + mA_1^{m-1}A_-\Theta(x-m+1)\Theta(m-x) + mA_1^{m-1}A_+\Theta(x-m)\Theta(m+1-x)$$
$$+ \sum_{i=0}^{m-2}\sum_{j=0}^{m-i}\sum_{n=1}^{m-i} A_{mijn}(n+m-j-x)^{m-i-j}\Theta(n+m-j-x)\,\Theta(x-m+j)$$

Where

$$A_{mijn} = \frac{A_1^i A_-^j A_+^{m-i-j} m!}{i!\,j!\,(m-i-j)!}\frac{(-1)^{m-i-n}(m-i)!}{n!\,(m-i-n)!}\frac{1}{(m-i-1)!}$$

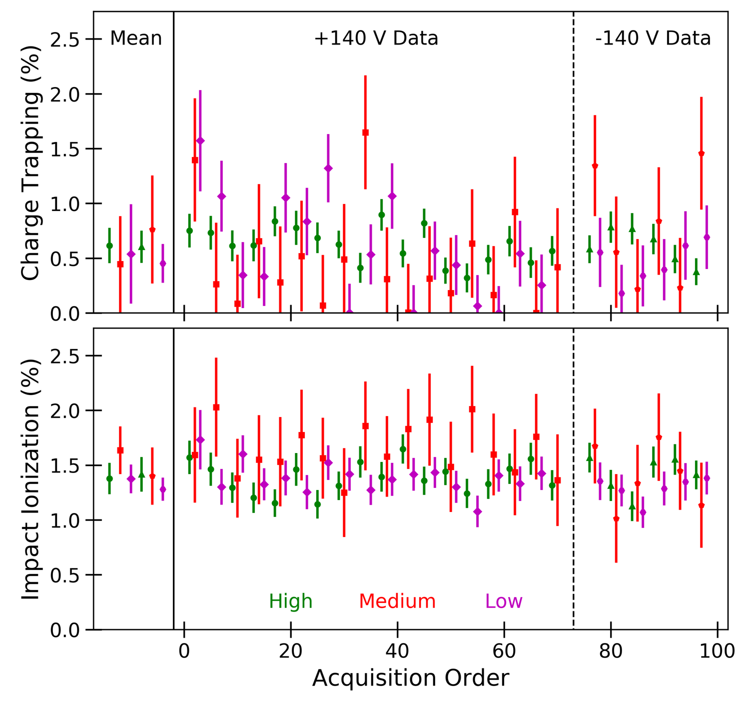


Figure 11: (Top) Tapping and (Bottom) impact ionization probabilities for all acquisitions taken over the course of two days. The weighted average and standard deviations are shown to the left of the black solid line with the individual ±140 V crystal bias data plotted to the right of the solid line separated by the dashed black line. Values were fitted while holding the bulk and surface leakage probabilities fixed using the corresponding values from the background spectrum for each crystal bias and laser intensity in Figure 6 (bottom).

Weighted Charge Trapping Probability:
0.566 ± 0.092%

Weighted Impact Ionization Probability:
1.392 ± 0.101%

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