Cryogenic detectors made of ultra-pure single crystals of silicon (Si) and germanium (Ge), and biased with \(\sim 100 \text{ V}\) across the crystal, have achieved very low thresholds in the search for dark matter by converting the ionization signal to a phonon signal with substantially improved resolution over that obtained with a charge amplifier. This Neganov-Luke effect is proportional to the applied bias voltage across the crystal. The resulting phonon signal is read out using quasiparticle-trap-assisted electro-thermal-feedback transition edge sensors (QETs). The ultimate ionization resolution for these detectors is achieved by counting individual \(e^-h^+\) pairs.

Si and Ge are indirect-gap semiconductors, since their conduction band energy minima do not occur at zero momentum. For Si the conduction band has six minima, or valleys, located near the mid points along the [100] direction in the Brillouin zone and produce a highly anisotropic electron mass tensor. As a result, an initially localized group of electrons in a small but uniform electric field will spatially separate into three pairs of clusters along each principle axis, each consisting of \(e^-\)'s or \(h^+\)'s transported across the crystal. At high temperatures, in high electric fields, or at high impurity concentrations, electrons occupying one of the three pairs of valleys will form electric field will spatially separate into three pairs of clusters along each principle axis, each consisting of \(e^-\)'s or \(h^+\)'s transported across the crystal. At high temperatures, in high electric fields, or at high impurity concentrations, electrons occupying one of the three pairs of valleys will form electrically localized group of electrons in a small but uniform electric field will spatially separate into three pairs of clusters along each principle axis, each consisting of \(e^-\)'s or \(h^+\)'s transported across the crystal. The resulting phonon signal is read out using quasiparticle-trap-assisted electro-thermal-feedback transition edge sensors (QETs). The ultimate ionization resolution for these detectors is achieved by counting individual \(e^-h^+\) pairs.

The phonon measurement utilizes the QET advanced athermal phonon sensor technology developed for CDMS and SuperCDMS. These sensors are composed of a thick Si (or Ge) crystal patterned using photolithography with aluminum (Al) electrodes connected by tungsten (W). At low temperatures, athermal phonons propagating in the crystal will diffuse into the superconducting Al electrodes on the crystal surface. These phonons are sufficiently energetic to break Cooper pairs in the Al, generating Al electrodes on the crystal surface. The W film is operated between the superconducting and normal states as a Transition Edge Sensor (TES) and the excess quasiparticles raise the temperature and resistance of the film. The TES resistance increase under voltage bias is detected as a decrease in current using SQUID amplifiers.

A test device was constructed on a 1 cm x 1 cm x 4 mm thick Si crystal (0.93 g), oriented with the [100] direction perpendicular to the 1 cm\(^2\) face and the side walls along [110]. The front (non-illuminated) face of the crystal was patterned with equal area inner and outer QET phonon.

FIG. 1. (color online) Photograph of Si detector mounted on mixing chamber stage of KelvinOx 15 dilution refrigerator with phonon sensors on top and bias grid below. A fiber optic illuminates the device from below with 650 nm photons.
channels with a net active Al coverage of 13% on top of a 40 nm thick amorphous Si layer. Two sensors allow vetoing events near the outer edges if there is significant difference in the phonon collection efficiency. The back (illuminated) face was patterned with a 20% coverage (“parquet pattern”) 40 nm Al electrode overlaid on an 40 nm aSi film to allow visible photons to be absorbed near the surface of the bulk crystal. The back electrode was biased relative to the front QETs, creating a field near the surface of the bulk crystal. The back electrode heating, thus allowing us to find the absorbed power as a highly precise measurement of the quantized e−h+ pair peaks generated by the laser.

These data have a quadratic nonlinearity for e−h+ peak position versus amplitude, which we correct using $q_{\text{linear}} = q[1 + 0.016a/(160 \text{ eVt})]$. This small effect is due to the series resistance in the bias circuit, which prevents purely linear electrothermal feedback. We calculate the energy collection efficiency of the device by comparing the inferred energy absorbed from the current change to the absolute energy calibration from the laser. When phonon energy is absorbed, the current through the TES decreases, producing a decrease in current (and therefore a decrease in Joule heating) proportional to the energy absorbed. For our sharp TES transition near 51 mK, this energy input changes the resistance of the device, but leaves temperature largely unchanged, so that the increase in energy input is balanced by the decrease in Joule heating, thus allowing us to find the absorbed power as

$$E_{\text{abs}} \approx - \int_0^T \Delta P + \int_0^T \Delta I dt$$

where $R_I$ is the resistance in series with the TES in the voltage-biased topology, $V_b$ is the voltage bias, $I_0$ is the TES bias current, and we have assumed a sharp TES transition to simplify this expression. We find that the single e−h+ peak shown in Fig. 2 (for summed A+B), with 161.9 eVt from 160 eV Luke gain plus 1.9 eV of the original photon, corresponds to $E_{\text{abs}} \approx 8$ eV, giving a measured efficiency of 5±1%. The systematic uncertainty is due to uncertainties in bias circuit components and operating point resistances.

Figure 3 (top) shows the position of the first e−h+ pair peak across a range of voltages where quantization is detectable for both e− and h+ propagation (positive and negative bias). The linearity with voltage demonstrates that the athermal phonon collection efficiency for Neganov-Luke phonons is independent of both E-field

In typical runs, the crystal is cooled to base temperature, and “neutralized” for ∼24-72 hours, where we ground the crystal and illuminate it with the laser at high intensity (2 mW, 1 ms, and -10 dB optical attenuator). This floods the crystal with e−’s and h+’s, which attach to charge traps. During operation, the Si crystal is biased between -160 and +160 V and illuminated with the laser at low intensity (200 µW, 200 ns, and -50 dB optical attenuator). The trace acquisition can be triggered on the laser internal TTL for low noise acquisition or triggered on a threshold to observe the leakage current of the detector.

For the crystal biased at 160 V, the laser intensity averaging ∼2 photons per pulse and the acquisition system triggering on the laser TTL, a comparison of the total collected energy in eV (eVt) in each QET channel is shown in Fig. 2. The contours show that channel noise is uncorrelated and that the channels measure comparable energies for a given laser pulse. The amplitude of the acquired traces was estimated using a matched filter, with fits shown in the inset of Fig. 2. These data demonstrate a highly precise measurement of the quantized e−h+ pair peaks generated by the laser.

Electron-hole (e−h+) pairs were created in the crystal by illuminating the electrode side with a monochromatic 650 nm pulsed laser (∼1.91 eV photons). The laser power and pulse width along with optical attenuators control the average number of photons per pulse that reach the sensors. The number of observed photons in any individual pulse is stochastic such that the observed detector response is a convolution of a Gaussian with a Poisson distribution. Setting the average number of photons per pulse is stochastic such that the observed detector response is a convolution of a Gaussian with a Poisson distribution. Setting the average number of photons per pulse that reach the sensors. The number of observed photons in any individual pulse is stochastic such that the observed detector response is a convolution of a Gaussian with a Poisson distribution. Setting the average number of photons per pulse that reach the sensors. The number of observed photons in any individual pulse is stochastic such that the observed detector response is a convolution of a Gaussian with a Poisson distribution.

![Figure 2](image-url)

**Figure 2.** (color online) (upper inset) Schematic of 1 cm x 1 cm x 4 mm thick silicon detector (0.93 g) with 160 V grid bias. (lower inset) Pulses for 0, 1, 2 and 3 charges per pulse. (plot) Signal energy difference in the phonon collection efficiency. The back sensors vetoing events near the outer edges if there is significant difference in the phonon collection efficiency. The back electrode heating, thus allowing us to find the absorbed power as a highly precise measurement of the quantized e−h+ pair peaks generated by the laser.

These data have a quadratic nonlinearity for e−h+ peak position versus amplitude, which we correct using $q_{\text{linear}} = q[1 + 0.016a/(160 \text{ eVt})]$. This small effect is due to the series resistance in the bias circuit, which prevents purely linear electrothermal feedback. We calculate the energy collection efficiency of the device by comparing the inferred energy absorbed from the current change to the absolute energy calibration from the laser. When phonon energy is absorbed, the current through the TES decreases, producing a decrease in current (and therefore a decrease in Joule heating) proportional to the energy absorbed. For our sharp TES transition near 51 mK, this energy input changes the resistance of the device, but leaves temperature largely unchanged, so that the increase in energy input is balanced by the decrease in Joule heating, thus allowing us to find the absorbed power as

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Figure 3 (top) shows the position of the first e−h+ pair peak across a range of voltages where quantization is detectable for both e− and h+ propagation (positive and negative bias). The linearity with voltage demonstrates that the athermal phonon collection efficiency for Neganov-Luke phonons is independent of both E-field

![Diagram](image-url)

**Diagram**

In typical runs, the crystal is cooled to base temperature, and “neutralized” for ∼24-72 hours, where we ground the crystal and illuminate it with the laser at high intensity (2 mW, 1 ms, and -10 dB optical attenuator). This floods the crystal with e−’s and h+’s, which attach to charge traps. During operation, the Si crystal is biased between -160 and +160 V and illuminated with the laser at low intensity (200 µW, 200 ns, and -50 dB optical attenuator). The trace acquisition can be triggered on the laser internal TTL for low noise acquisition or triggered on a threshold to observe the leakage current of the detector.

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strength and excitation type throughout this range of biases.

This linearity, coupled with the invariance of the phonon noise with voltage (as demonstrated in Fig. 3), means that as long as this trend continues to higher voltages, we can continue to expect linear gains in signal to noise. In addition, we show that the relationship between mean photon number and laser power is also highly linear and invariant to voltage, allowing us to compare the high voltage and 0 V energy distributions to check the absolute phonon energy calibration.

Figure 4 demonstrates this 0 V calibration, utilizing the measured photon yield as a function of laser power shown in Fig. 3 (bottom) to compare the signal from a 30 photon pulse to the high-voltage data. These 0 V pulses should deposit 1.91 eV per photon or 57 eV into the phonon system (assuming the recovery of all of the gap energy as $e^-$ and $h^+$ recombine at surfaces). Comparison with the first photon peak at 50 V bias which should produce 52 eV of phonons or $1/3$ of the first photon peak at 150 V bias shows agreement is good to $\sim 5\%$, within possible systematics in the zero bias measurement from any residual space charge that would add Neganov-Luke phonon energy or local trapping of $e^-$’s or $h^+$’s which would prevent the gap energy from returning to the phonon system. This good agreement suggests that neither effect is significant.

Figure 5 shows that $\sim 15\%$ of the events are distributed in between the quantized photon peaks. For these events, one or more of the produced ionized excitations did not traverse the entire crystal, and thus its Neganov-Luke phonon production was incomplete, and non-quantized. This can occur if an ionized excitation was trapped in the bulk while drifting. A second possibility is impact ionization, where a drifting excitation scatters off an occupied impurity state releasing a non-paired excitation that drifts across only a fraction of the crystal. Finally, subgap photons produced in coincidence when the laser is pulsed could also interact with filled impurity states, again producing an unpaired excitation.

These three models were fit to the data by a maximum-likelihood fit in which the noise variance, peak separation, mean photon number, impact ionization probability, ionization trapping probability, and the average sub-gap IR absorption number were allowed to vary. Impact ionization events contribute less than $\sim 1/5$ of the fill-in events, which are $\sim 15\%$ of all events in the data. Impact ionization is not a major contribution since it cannot produce any of the events seen between the 0 and 1 $e^-$ $h^+$ peaks. The best-fit models for a typical dataset at 160 V can be seen in Fig. 5 compared to the ideal Poisson model with the probability of these secondary processes set to 0.

These fits were performed both as a function of bias voltage and laser input power. A striking trend is that the secondary process probability (the total amount of fill-in between the peaks) is found to be independent of voltage, which disfavors the trapping model since we expect the trapping length should be a function of the mean field strength in the crystal [14].

In the subgap infrared absorption model, fitting data with different average photon number to the same model requires that the sub-gap IR photon flux be proportional to the average number of above gap photons (proportional to the pulse time of the laser). This is certainly
In addition, as shown in this paper, the spectral infor-
timing, energy efficiency and resolution by a factor of
bias voltage. In addition, a device with two-sided phonon
the signal/noise may continue to improve with increased
of input conditions that we have tested; suggesting that
this device continues to operate linearly across the range
isting CCD-based technologies. We have also shown that
better pileup-rejection (\( e^{-}\)) represents a new generation of gram-scale detectors ca-
\(\sim\) \(\mu\) \(10^6\) GeV.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{(color online) Histogram of summed A+B data from Fig. 2 showing the excellent fit for a Poisson distribution. A small non-
linearity of the number of \( e^{-}\) is shown above, the phonon crystal
energy below (eVt), and an electron-equivalent energy scale (eVee) at bottom using the standard 3.8 eV per \( e^{-}\) pair. \(\lambda_0=\lambda_{DR}=2.0\) Photons
\(\lambda_{THP}=2.3\) Photons \(\sigma=14.0\) eV
=0.33 eVee
=0.087 eVee
\end{figure}

quite reasonable and perhaps even expected. In the fu-
ture, we will modify our fiber setup to be a single-mode
fiber instrumented with IR filters to attempt to sub-
stantially suppress this probable background. These up-
grades will have the added benefit of further isolating the
detector from room-temperature IR not coincident with the
laser pulse, which may dominate the leakage rate.

This letter demonstrates the operation of the first
phonon-based detector capable of resolving single
charges. This detector has a demonstrated resolution of \(\sim\)0.09 \( e^{-}\) in real-time with significantly
better pileup-rejection (\(\sim\)10 \(\mu\)s) and larger mass than ex-
isting CCD-based technologies. We have also shown that
this device continues to operate linearly across the range of
input conditions that we have tested; suggesting that
the signal/noise may continue to improve with increased bias voltage. In addition, a device with two-sided phonon
readout and higher collection efficiency, may improve the
timing, energy efficiency and resolution by a factor of \(\sim\)3.

In the short term, such devices will allow the Super-
CDMS collaboration to measure not only the average
ionization yield of nuclear recoils down to the production of
the first \( e^{-}\) pair in Si and Ge, but also measure the full
probability distribution of the nuclear recoil ionization
yield as a function of recoil energy - essential for nuclear
recoil direct detection dark matter searches based on ion-
ization measurement in the 100 MeV < \(M_{DM}<\) 6 GeV.

In addition, as shown in this paper, the spectral infor-
mation gained with quantization allows a better under-
standing of the physics of athermal phonon detectors us-
ing Neganov-Luke amplification, such as kg-scale Super-
CDMS SNOLAB detectors.

In the longer term such quantization could be used
to distinguish between the background of electron re-
coils from ambient radioactivity and low energy nuclear
recoils. Such nuclear recoils are inefficient at produc-
ing \( e^{-}\) pairs, requiring roughly an order of magnitude
more recoil energy deposition than the 3.8 eV per pair for electron recoils. That extra phonon energy added to the
Neganov-Luke amplification increases the total crystal
energy (eVt) of nuclear recoils over those for electron
recoils with the same number of \( e^{-}\) pairs, thereby
placing such events before and between the first few elec-
tron recoil peaks. This capability could enable a future
upgrade to the SuperCDMS SNOLAB experiment with
sensitivity to the solar neutrino floor, as well as preci-
sion experiments to probe coherent scattering of neutrini-
ons from nuclei. Finally, such quantization could allow
a direct detection experiment to differentiate between a
hypothetical very light dark matter candidate that inter-
acts electronically from a higher mass dark matter can-
didate that scatters off a nucleus but produces similar
ionization.

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