NTLE cryogenic light detectors with planar electrode geometry

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Abstract

The **Neganov-Trofimov-Luke effect (NTLE)** [1] [2] is a promising way to improve the sensitivity of cryogenic light detectors by enhancing the thermal signal in a semiconductor. **This effect in the semiconductor is caused by drifting photo-generated electron-hole pairs while under an electric field and at mK temperatures.** Such cryogenic light detectors are of high importance for **direct dark matter searches** (such as CRESST), **cryogenic neutrinoless double-beta decay searches (0νßß)**, and experiments searching for **coherent neutrino nucleus scattering (CNNS)**; experiments where excellent sensitivity and energy resolution are required. **A novel approach to NTLE light detectors is the use of a planar electrode geometry based on very thin implanted contacts on silicon absorber detectors.** The main difference to previous approaches is that the photo-generated charge carriers are drifted through the bulk of the absorber instead of being drifted across the free surfaces of the absorber, leading to an **improved signal-amplification, signal-to-noise ratio, and charge collection.** In this contribution we will present an update on the development of these detectors at the Astroparticle Physics group of the Technical University of Munich.

Neganov-Trofimov-Luke Effect

The **CRESST** experiment (Cryogenic Rare Event Search with Superconducting Thermometers [3]) is aiming at the direct detection of a nuclear recoil induced by a WIMP (Weakly Interactive Massive Particle). It involves the detection of scintillating light as well as phonon signals within a $CaWO_4$ crystal. The ratio of the two signals' energies allows to determine the nature of the interaction (nuclear recoil like a WIMP or electronic recoil, like most of the background). The light signal can be detected with a second calorimeter. Only about 1% of the energy deposited in a $CaWO_4$ crystal is detected as light. **The sensitivity of the light detectors must be very good for an efficient event by event background discrimination**. Due to the NTLE, the threshold of low temperature light detectors based on semiconductor substrates can be improved significantly by drifting the photon induced electron-hole pairs in an applied electric field which results in additional predictable heat. The gain in heat is described by

[eq. 1] $$G = E_T/E_0 = 1 + eV/\varepsilon_{e\text{-}h}$$

Where 'e' is the charge of the electron, 'V' the NTLE Voltage and $\varepsilon_{e\text{-}h}$ the energy required to create an electron-hole pair. The NTLE allows us to increase the signal to noise ratio [Fig. 1].

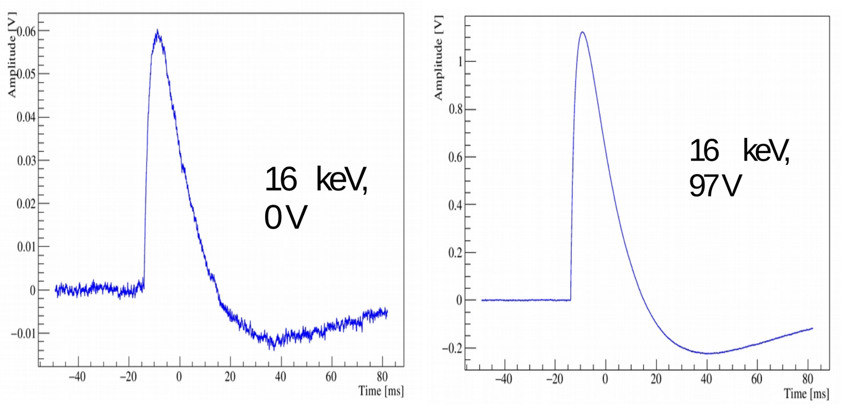

Figure 1: Signals from 430 nm photon flashes (E_{TOT}~16 keV) with 0 V (left) and 97 V applied on a NTLE detector with implanted contacts (right).

NTLE-Detectors with Planar Geometry

One important reason why NTLE detectors are not currently used in experiments is due to charge trapping. This induces degradation (decrease of the signal in time) and a reduced gain compared to the predicted one. This charge trapping can occur because, in the configuration proposed by Stark et al. [4], the drift of the carriers happens close to the free surfaces of the semiconductor wafer where the trapping probability is high (top-left scheme in [Fig. 2]).

In this approach there are no free surfaces since they are replaced by the implanted contacts reducing in this way the trapping of the charges [Fig. 2]. This implies that the photons must penetrate through the cathode which is possible with a very shallow implantation of Boron (<50 nm). The NTLE is proportional to the voltage: the intrinsic silicon being ~300 µm thick implies a very large electric field. It was possible to apply 200 V without noticing any leak current (E > 6500 V/cm). This high electric field ensures a good separation of the electron-hole plasma. Just like in the previous design, a tungsten Transition Edge Sensor (TES) was installed on the silicon device as thermal sensor.

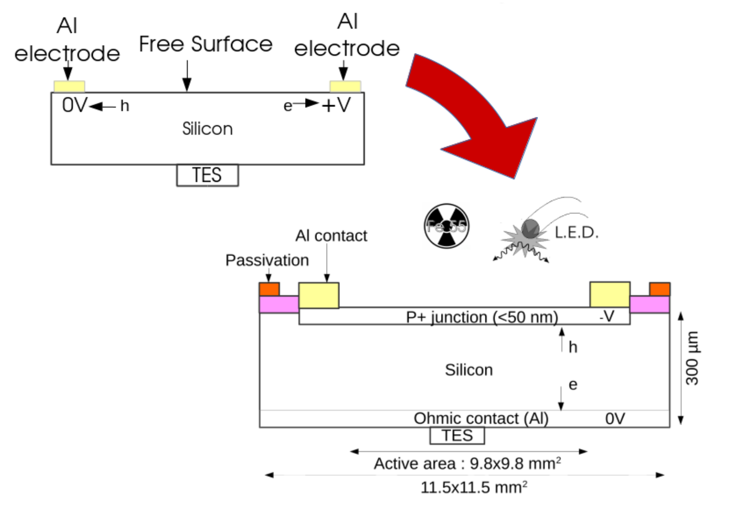

Figure 2: Schematics of the old design (proposed by Stark et al. In 2005 [4]) with parallel stripes (top) and the new detector we propose here with implanted contacts (bottom).

Experiment

The detector was installed nearby an ^{55}Fe calibration source (X-rays at 5.9 and 6.4 keV and electrons at ~ 5 keV) together with an optical fiber transmitting the 430 nm photons emitted by a LED (matching the $CaWO_4$ scintillation properties). The response of the phonon-signals read on the TES was recorded while varying the NTLE voltage [Fig. 3]. The 430 nm pulses together with the X-rays are visible and the amplitude of the pulses increases with the voltage applied because of the NTLE effect. The trigger signal from the LED generator allows to discriminate between LED and other events. The pulses at low energies are due to the electrons emitted by the ^{55}Fe.

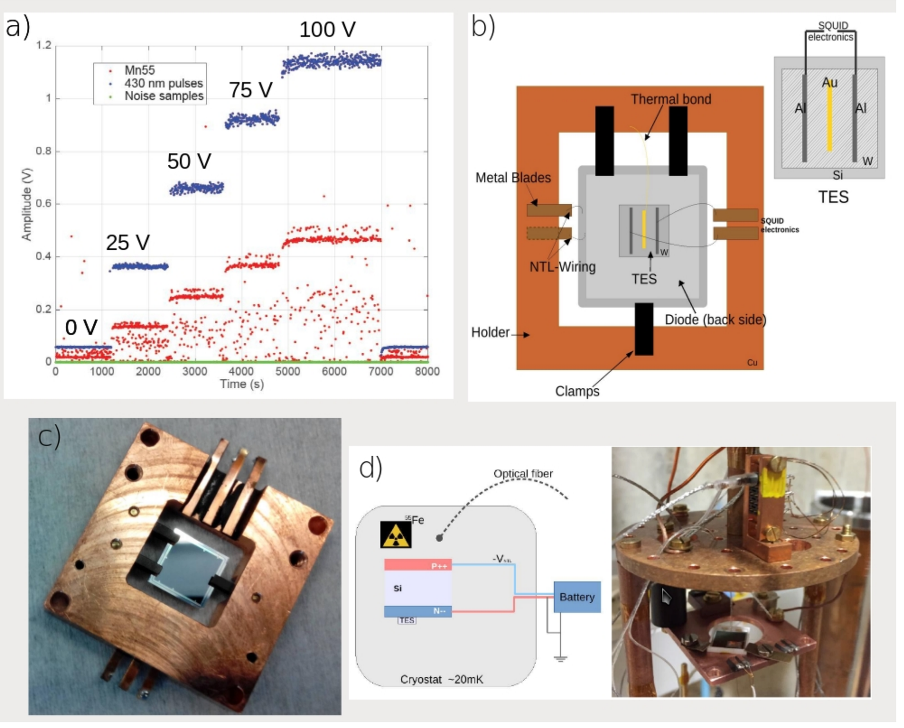

Figure 3: a) Amplitude of the phonon signal as a function of the time for different NTLE voltage applied (values written in bold). b) Scheme of the detector, detector holder and thermal sensor. c) Picture of the 1x1 cm² diodes with holder. d) Set up of the experiment.

Results

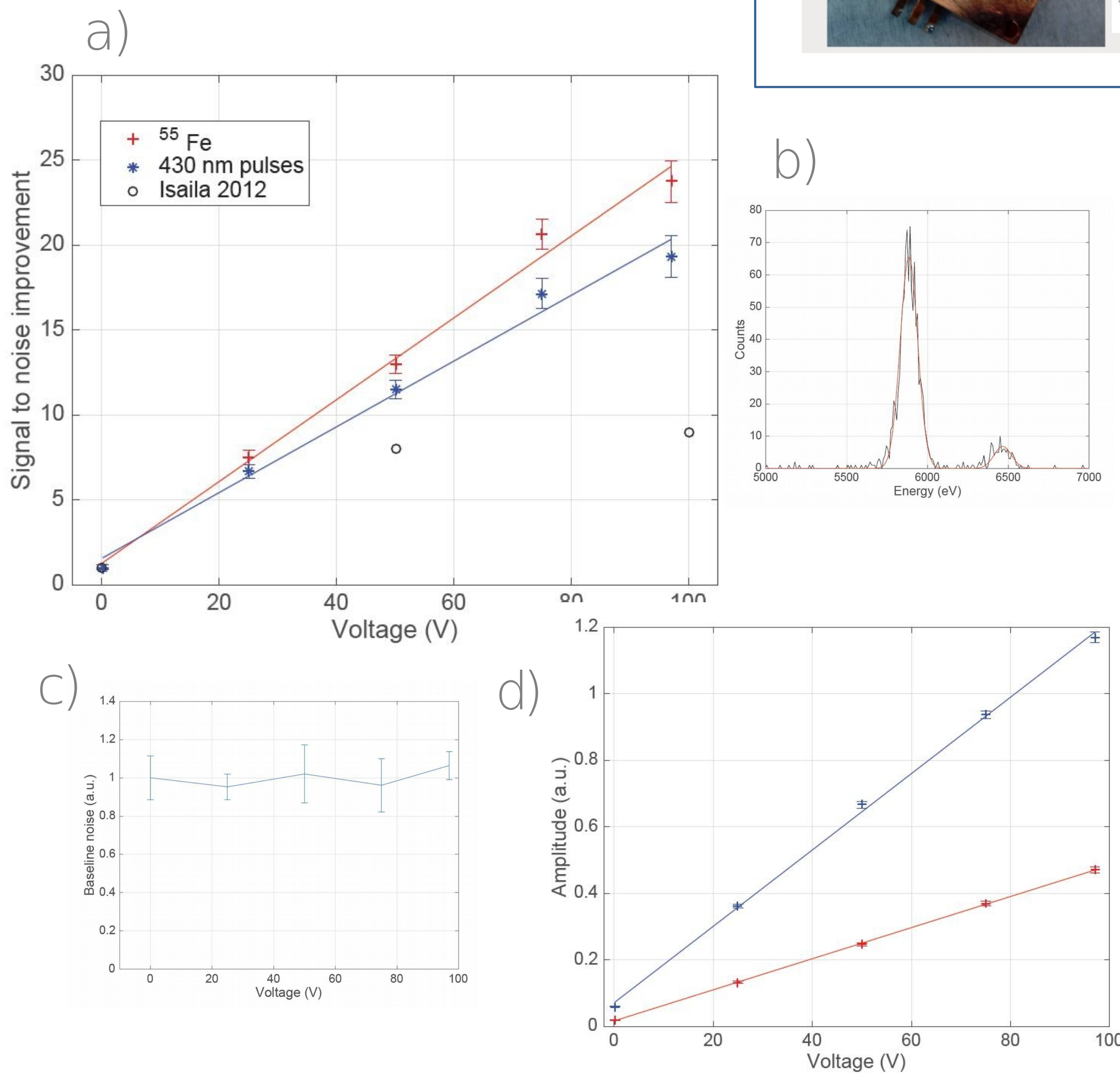

Figure 4: **a)** The amplitude of the pulses increases when increasing the V_{NTL}. The blue dots represent 430 nm photon flashes events (unambiguously determined by the trigger signal from the LED) and the red dots represent events from ^{55}Fe. From the plot, it can be also seen that this increase of the signal with the V_{NTL} follows a linear behaviour for both the photons and the X-rays. This is expected from the theory, but is seldomly obtained by experiments using configurations other than the planar geometry. **b)** In this graph the ^{55}Fe spectral peaks can be seen. The red line corresponds to the Gaussian fit. **c)** Evolution of the baseline for different V_{NTL} applied. **d)** Evolution of the signal-to-noise ratio for different V_{NTL}. The black circular dots correspond to the data obtained for a lateral-field configuration NTL-detector from [5].

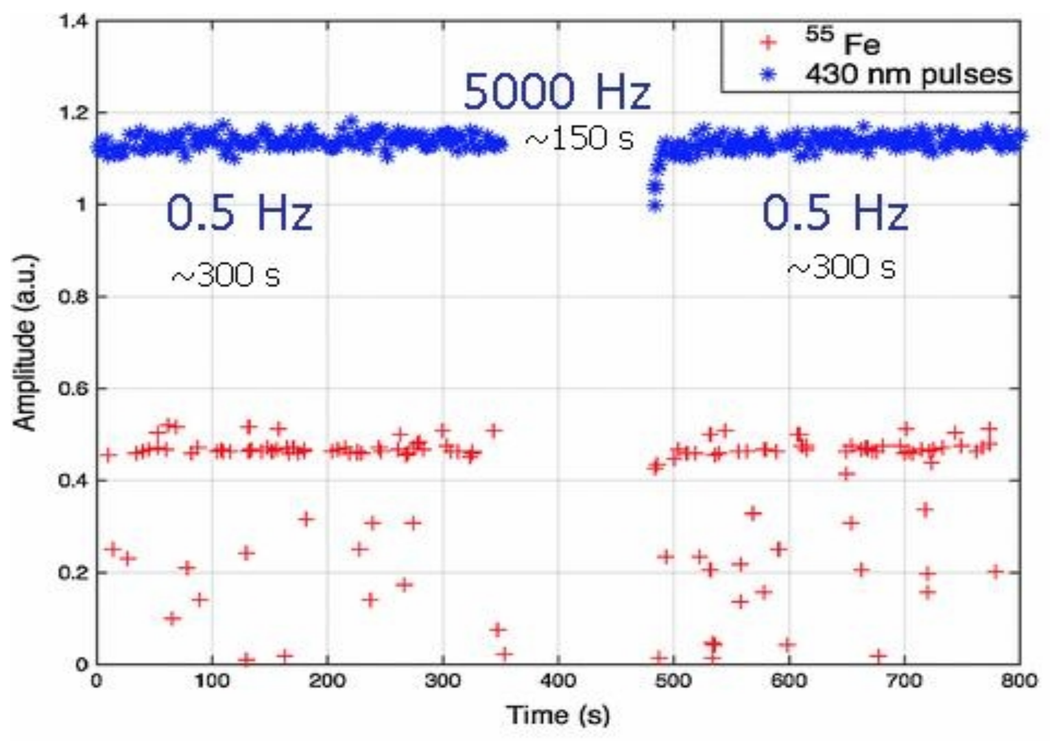

Figure 6: In this graph, the signal amplitude is shown for 430 nm photons (in blue) at 97 V_{NTL} for different photon fluxes. The first 300 s, the flux has a rate of 0.5 Hz. For the next 150 s the flux is increased to a rate of 5000 Hz. After that time, the flux is back to 0.5 Hz. Since the value of the amplitude gets reestablished after setting the detector in pile-up mode (during the high flux), it is possible to determine that the detector does not degrade [6].

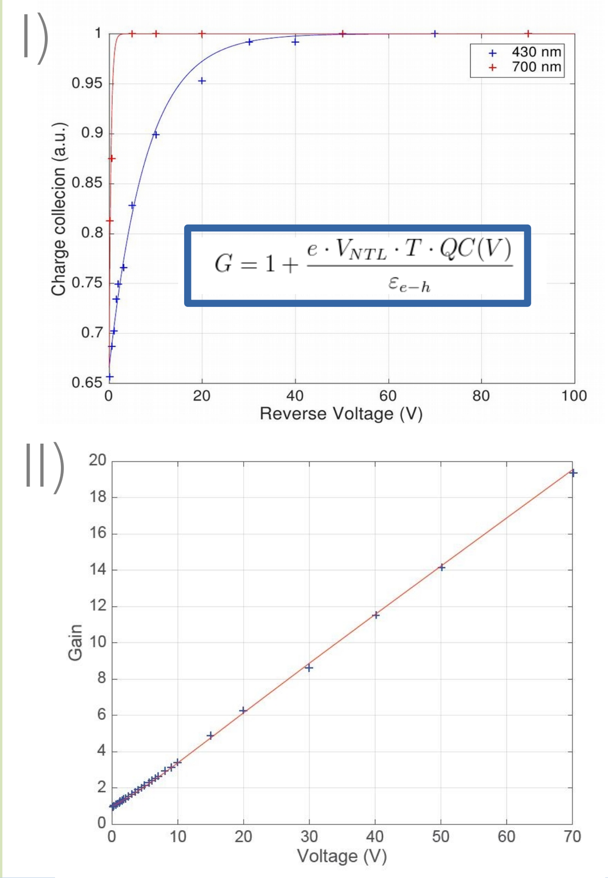

Figure 5: **I)** This graphic shows the charge collection for both 700 nm photons (in red) and 430 nm photons (in blue) plotted against the VNTL. It can be seen that for the photons with larger wavelength, the charge collection is maximal at a much lower V_{NTL} than for the shorter wavelength photons. This occurs due to the fact that the 700 nm photons penetrate deeper into the absorber where the diode is already depleted for low V_{NTL}. This measurement is very important because it provides a better understanding of the gain that can be rewriten as $G = 1 + (e \cdot V_{NTL} \cdot T \cdot QC \ / \ \varepsilon_{e\text{-}h})$. **II)** The plot of the gain for 430 nm photons at different V_{NTL} (blue data points). The red line represents the new fit for the gain for 430 nm photons using the new equation.

Conclusions

The evolution of the thermal gain with V_{NTL} was studied providing information about the value of the ratio $T/\varepsilon_{e\text{-}h}$. The measured gain matches well the predicted one when modifing the equation of the gain providing the value of this ratio. Further experiments should be done to determine the evolution of the transmission T with temperature since the real value for the transmission of the detectors is not known at cryogenic temperatures. The fact that the gain yields values matching the theory is very important because it shows a clear improvement and a better understanding of conventional NTLE-detectors.

Also, for the first time an NTLE detector exhibited an energy resolution close to the theoretical one for X-rays set by Poission statistics. This result is possible because of both the excellent charge collection on the whole surface of the photodiode and the position independence of the diode. Despite the excellent energy resolution, the resolution achieved is still a factor 4 away from the single photon detection of 430 nm photons. Reaching such a resolution would be a great asset because it would constitute the ultimate resolution for a 430 nm light detector.

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