SINGLE: single photon sensitive cryogenic light detectors

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Abstract.
Thermal detectors operated at few mK as calorimeters are a powerful tool for the study of rare particle physics processes. In order to implement particle identification, light detection can be effectively performed by means of other thermal detectors operated as light sensors. This configuration can be used also in large scale, thousand-channels setups, but the light sensors must be sensitive enough to detect few, possibly a single, photons. The SINGLE project described here aims at producing silicon based, large area devices that can be operated as thermal detectors with single-photon sensitivity, and demonstrate the reliability of the performance, scalability of the production process and integrability with present and next generation cryogenic experiments for the search for rare events.

1. Introduction
Thermal particle detectors are used as calorimeters in rare events physics (neutrino-less double beta decay, direct dark matter detection, rare nuclear processes, coherent neutrino interactions), where the excellent energy resolution and the wide choice of materials are important features. The simultaneous detection of the energy deposited in the target material and the amount of emitted light is a powerful tool to identify and reject background events in modern and future detectors [1, 2], but the amount of light to be detected can be as small as few optical photons for some materials and setups. An example is the detection of cherenkov light produced by relativistic electrons in non-scintillating crystals. This light signal can be used to discriminate between electron or gamma radiation and alphas or nuclear recoils, that are not expected to produce any cherenkov radiation [3]. Given the production yield, internal reflection and absorption and the lack of any optical coupling between the main crystal and the light detector (any thermal connection between the two detectors would spoil the performance of both devices), the number of photons impinging on the light sensor is of the order of few tens [4]. Very performing light detectors, with single photon sensitivity, are thus required.

2. State of the art
The experimental conditions where these detectors are expected to operate are particularly challenging. In order to convert the energy deposited by a particle interaction in a measurable temperature variation, thermal detector are operated at cryogenic temperature, in the tens of mK range, inside a dilution refrigerator that provides the required cooling power to maintain a stable working point. Due to the limited available cooling power at such low temperatures,
experimental volume and heat loads are an issue, especially in setups including hundreds of detectors. Standard light detectors with single photon sensitivity aren’t a viable solution for many reasons. Photomultiplier tubes are too bulky to be integrated in a compact and modular detector design, where each main absorber crystal is coupled to a photodetector. Moreover the heat load generated by the large output current couldn’t be sustained by the refrigerator. Silicon photomultipliers (SiPM) present similar limitations, due to the presence of bias and front-end electronics. Active surface areas are also typically too small: modern thermal detectors can be as large as 5x5 cm², requiring active surfaces of the light detector in the 2000-10000 mm² range to optimise the geometric efficiency. Finally, the correct functioning of the described light sensors at few mK isn’t documented in the literature.

Given these limitations, the most effective choice is to use thermal detectors as light sensors as well. Germanium, silicon and SOS (Silicon on Sapphire) slabs are the substrates that have been used as photon absorbers, instrumented with different types of temperature readouts, including NTD (Neutron Transmutation Doping) thermistors, TES (Transition Edge Sensor) and MKIDs (Microwave Kinetic Inductance Detectors) [5, 6, 7]. With these technologies, very small energy thresholds can be achieved, as small as 100 eV. However, single photon sensitivity and reproducibility on a large scale has never been demonstrated.

3. The SINGLE detector design
SINGLE is an INFN founded R&D project. Its primary goal is the development of large area (up to 10000 mm²), single optical photon sensitive light detectors that can operate at 10 mK as thermal detectors and can be easily integrated in next-generation ton-scale cryogenic experiments. The photon absorber will be a silicon substrate, 625 μm thick, cut from a high resistivity, electronics grade wafer. The choice of silicon has many advantages: the small heat capacity, compared to germanium, allows for the use of thicker substrate, making the detector sturdier and easier to build and handle, thus suitable for large area applications. Moreover, the silicon is typically cheaper than other options, and can profit from the huge know-how of semiconductors industry, both for the instrumentation and for the deposition of anti-reflective coatings, for the sake of reproducibility and reduction of large scale production costs.

For what concerns the temperature read-out, SINGLE mainstream option is the use of NTD thermistors, glued to the silicon surface with epoxy adhesive. NTDs are simple germanium based devices, whose steep resistance-temperature curve is exploited to convert temperature variations into electric signals. High impedance at the working point and large dynamic range allow the use of relatively simple front-end electronics for their readout, and reproducibility on large scale makes them suitable (and in fact the typical choice) for large scale rare events experiments. The sensitivity of NTDs is relatively limited, and typical noise contributions when coupled to silicon are in the hundreds of eV range.

In order to achieve the single photon sensitivity, SINGLE will therefore exploit the Neganov-Luke effect [8, 9] in a novel way. The silicon absorber is equipped with implanted electrodes that, when a bias voltage is applied, generate an electric field. The electron-hole pairs generated by photons absorption drift in the electric field, and the kinetic energy acquired by the electrons is converted into a large thermal signal via interaction with the silicon lattice, effectively amplifying the original energy deposition by a factor proportional to the applied voltage. The shape of the electric field is optimised by designing the electrodes in such a way that:

- charges are fully collected at the electrodes to avoid space charge accumulation that would reduce the gain and produce a time dependent degradation of the performance;
- depending on the magnitude of the applied voltage, secondary charges can be produced by impact ionisation inducing an avalanche effect and further increasing the signal-to-noise ratio;
electrical connections are minimised and simplified to reduce the space needed for the integration of the device in a close-packed array of detectors.

4. Roadmap and preliminary results
The SINGLE project roadmap is based on a phased approach, with a time scale of two years. Preliminary results have been obtained with small (2×2 cm²) prototypes [9] biased with relatively low voltage in 2015, showing the feasibility of the approach and that the technology is promising. The main parameters to be upscaled are:

- absorber area: the final goal is to build 10×10 cm² square detectors, with the size and shape calibrated on a typical present generation thermal detector setup and limited by the size of industry standard silicon wafers (6”). Other limiting factors will be investigated during the upsizing process;
- electrodes design: studies will be performed on the opportunity to implement a modular, multi-pixel design to operate the detector in a Geiger mode;
- bias voltage: the voltage applied to the electrodes to amplify the thermal signal will be gradually increased in order to study the different regimes the detector operation mode undergoes, from the simple collection of the primary charges to a proportional model with non-linear amplification to a saturation (Geiger) mode;
- production process: in order to apply this technology to large scale projects, the feasibility of a large production of reliably performing devices will be demonstrated.

In order to implement this phased approach, the required instrumentation will also be gradually upgraded. The cryostat where the detectors are hosted has been equipped with a number of dedicated channels for the high voltage supply, rated up to 2 kV. Dedicated measurements will be performed to evaluate the dark current of the detectors as a function of the voltage, a possibly limiting factor due to its contribution to the heat load on the cryogenic system. A dynamical characterisation of the current-voltage curve will also be performed to verify the onset of the different charge multiplication regimes. Once the electrodes design will be finalised, a campaign of anti-reflective coatings characterisation will be planned, with dedicated relative and absolute efficiency measurements.

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