Snowmass2021 - Letter of Interest

CF Topical Groups: (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other)

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Silicon Photomultipliers as a target for low-mass dark matter searches

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The ability to produce high radiopurity Silicon makes it a desirable candidate for low-background, rare-event searches. Production R&D on Silicon Photo Multipliers (SiPMs), to be used in DarkSide-20k, has also yielded new techniques for reducing the inherent noises associated with SiPMs operating at cryogenic temperatures. We propose a novel SiPM-based, Silicon target, detector design capable of achieving a very low threshold, on the order of 150 eV. This design would be sensitive to WIMP-like particles with masses $< 1\,\mathrm{GeV}$. A tower consisting of multiple wafers, along with the associated integrated electronics, would be constructed using a high-purity copper structure. Housed in a Liquid Neon (LNe) active veto, allowing the SiPM dark rate to be kept below 10^{-3}cps/mm^2, a 1 kg Silicon target could reach a sensitivity better than 10^{-42} cm^2 for both low mass WIMP-like particle and electrophilc dark matter.

1. Introduction

Silicon has proven to be an optimal target for dark matter searches at low recoil energy and correspondingly low WIMP-like particle mass. The combination of low ionization yield and the intrinsically high radiopurity allows it to reach unprecedented background levels [1, 2]. Recent results from the Global Argon Dark Matter Collaboration (GADMC) has shown that it is possible to develop large area ($25\,\mathrm{cm}^2$) SiPM-based photo-detectors operating in liquid argon with remarkably low noises, dark count rate lower than 10^{-3}cps/mm^2, direct cross talk (DiCT) probability lower than 20 %, and with a signal to noise ratio (SNR) in excess of 20 [3–5].

With the knowledge and experience gained through the SiPM R&D process for DarkSide-20k a dedicated low-mass WIMP-like particle detector design is presented here. The proposed detector would exploit a strong pixelization and an active Liquid Neon (LNe) veto to tag the intrinsic and the external background. This detector will be equally sensitive to low mass WIMP-like particle and to electrophilic dark matter. Below we provide a sketch of the proposed detector along with some very preliminary sensitivity projections.

2. Back Side Illuminated SiPMs as an active target for dark matter searches

In standard SiPMs, the incoming photons are converted into charge carriers in the shallow depletion region that extends for 5 µm to 10 µm from the top-side of the device. In Back Side Illuminated SiPMs (B-SiPM) the back-side is what faces the incoming photons, with the depletion region extending for almost the full thickness of the silicon substrate. Typical B-SiPMs have a thickness of the order of 10 µm to 50 µm, however technological processes are available to develop B-SiPMs with thicknesses up to 500 µm with a cell size of a few micrometers. Assuming that the intrinsic SiPMs noises, i.e. DCR and DiCT, are kept to minimum, such B-SiPMs could be an interesting target in experimental searches for low-mass WIMP-like particles.

In SiPMs operating below 100 K, the rate of dark counts due to the thermal generation of carriers is suppressed by more than 7 orders of magnitude with respect to room temperature [3]. Also at this temperature, the main contribution to the DCR is generated in the high field region by the carriers' tunneling. In B-SiPMs the design of the high field region remains unaltered, so it is reasonable to assume that the DCR will not increase. However, special attention will have to be payed in order to avoid increasing the cross-talk probability, and this will be the main R&D challenge.

A charged particle interacting in the B-SiPM's bulk will generate about $250\,e^-$/keV [6]. In the depletion region the recombination probability is low enough to preserve the carriers during their drift toward the multiplication region of the cell. Since the resulting signal amplitude is proportional to the number of cells reached by the carriers, and not the amount of charge arriving at a particular cell, electrons will not disrupt the signals. On average the electrons will drift for 200 µm in a field of $\approx 100\,\mathrm{V/cm}$ and, according to transverse diffusion models [7], we can predict that a point like interaction of 100 eV will affect a minimum of 4 cells (3 µm to 5 µm). The transverse diffusion can be further increased by applying a small magnetic field perpendicular to the drift direction. For electromagnetic interactions releasing an energy above few keV, the ionization cloud will extend beyond the SPAD size, significantly increasing the number of affected cells and the signal amplitude.

3. Detector design

The core of a detector could consist of a monolithic $14 \times 14\,\mathrm{cm}^2$ silicon wafer, containing about 280 B-SiPMs with an area of $70 \times 1\,\mathrm{mm}^2$ and a thickness of the order of 500 µm. The whole unit(die) can be directly grown and diced from a single 8″ wafer. Based on the results of SiPM production for DarkSide-20k we expect the fraction of working pixels on each die to be higher than 85 %.

Each B-SiPM die has an active mass of 20 g. In order to increase the detector exposure, several dies will be mounted on a high radiopurity copper tower, accruing a total active mass of 1 kg of Silicon. The tower will be hosted in a LNe veto, at about 30 K, and at this temperature the SiPMs' dark noise rate is expected to be below 0.5 mcps/mm^2. A "blackout layer" deposited on the SiPMs' surfaces will prevent any undesired detection of photons from Neon scintillation. This protective blackout layer will cover roughly 95 % of the active surface of the detector. The remaining non-blind pixels would then exploit the Neon scintillation, effectively transforming the LNe passive buffer into an active veto.

The high pixelization of the detector (around 14000 channels) will also be useful in tagging non-local events and in searching for delayed coincidences, like the $^{32}\text{Si}-^{32}\text{P}$. ^{32}Si is naturally present in Silicon with a coincidence window of 14 d with a Q-value of 224 keV. Assuming a DiCT probability of 15 %, the DCR pilep-up in 3 τ would be less than a few percent.

Integrated electronics can be developed on two 14×5 cm^2 monolithic silicon boards to be wire bonded to the SiPM array. The BNL group has already shown, in their work on DUNE, the working design of low-power, low-noise, charge amplifiers which feature on-chip digitization and operate successfully in liquid Argon [8]. And, the lower operating temperature of LNe is not expected to pose any issues for the CMOS electronics. The boards will be daisy-chained by means of high radiopurity flat cables, and only a single connection would be required to extract the timing and charge information for all of the hits in the detector.

4. Physics reach

Owing to the high radiopurity of the Silicon substrate, the radioacitve background in the wafers is highly, which suppressed. The largest background for this detector comes from the cross-talk, which enhances the dark rate signal to many photoelectrons. This background follows a Poissonian distribution which is scaled by the total DCR and fewer than 4 counts/yr would have an amplitude larger than 8 photoelectrons. With the previous assumptions on carriers diffusion, a simple toy montecarlo on transverse diffusion predicts that a point like interaction of 8 photoelectrons, corresponding to a visible energy of about 150 eV, would have an acceptance above 80 %. We also note that this could likely be reduced to less than 100 eV by means of a transverse magnetic field. Electromagnetic interactions with a deposited energy a few keV will result in events with a large signal outside the region of interest. The same applies for α's decays with typical energy in the MeV scale. Partially contained electromagnetic or α's interactions will be tagged by the active LNe veto.

The detector would require installation in an underground laboratory to reduce the rate of cosmogenic particles, and a passive shield composed of ultra-pure water and plastic layers would be required to attenuate the residual neutrons and the gamma rays. The careful estimation of the background will require a complete simulation of the detector materials, of the shielding, of the underground laboratory, and of the multi-scatter interactions within the veto and the detector itself. However, the intrinsic constituents of the detector are very radiopure: silicon, copper and neon are proven to reach a contamination level of the ppb scale for the Uranium and Thorium chains. Furthermore, all of the non-stable isotopes of neon have a very short lifetime. Assuming that the remaining background sources can be kept below the dark rate contribution, we can project our sensitivity better than 10^{-42} cm^2 for both low mass WIMP-like particle and electrophilic dark matter.

Furthermore, the anisotropic structure of the semiconductor crystal makes the ionization threshold sensitive to the recoil direction [9]. This produces a modulation in the rate of dark matter events above the detector energy threshold, which can be as large as ±40 % for MeV-GeV mass dark matter [10]. A detector configuration where sets of SiPM are arranged in orthogonal planes enhances the sensitivity to a sidereal modulation signal.

5. Conclusion

A SiPM-based detector using high a radiopurity Silicon target operating in a LNe active veto could achieve a threshold of ≈150 eV. This design would be sensitive both to WIMP-like particles and electrophilic dark matter and allow for further exploration of the parameter space below 10 GeV/c^2. The modest production cost of SiPM wafers and the proposed single-cable readout system allow to easily scale-up the target mass of the detector, making it very competitive with respect to CCD-based technologies and allowing a cross-check of the current silicon best limits [2].

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