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Characterization of VUV sensitive SiPMs in LXe

T. Tsang, for the nEXO collaboration

***Abstract* – Many future tons-scale noble liquid detectors depend on the advanced Silicon Photomultipliers (SiPMs) that have good photodetection efficiency at the vacuum ultraviolet wavelength (VUV). The Next-generation Enriched Xenon Observatory (nEXO) experiment with a 5 tons liquid xenon time projection chamber (TPC) will use ~40,000 SiPMs for the direct detection of the 178 nm xenon scintillation light. We highlight the development works undertaken by the photodetector group in the nEXO collaboration on the performance characterization of Hamamatsu and FBK VUV sensitive SiPMs in purified liquid xenon.**

I. Introduction

The nEXO experiment is a neutrinoless double beta (0νββ) decay search in ^{136}Xe based on the ultra-low background liquid xenon technology.[1] 0νββ is a hypothetical nuclear decay, where two neutrons decay into two protons and two electrons but emits no antineutrinos. The observation of this process would have a fundamental impact on the standard model of particle physics and would imply that the neutrinos have mass and are Majorana particles with its own antiparticle. The nEXO plans to build a single-phase time projection chamber filled with 5 tons of 90% enriched liquid xenon (LXe). The rare 0νββ event detection is achieved by detecting both scintillation light and ionization charge signals. Together with cold electronics sitting inside the LXe to improve the signal-to-noise ratio, this allows nEXO to achieve an energy resolution of 1% for the decay of ^{136}Xe. The sensitivity of the experiment is related to the energy resolution, which itself depends on the accuracies of the measurements of the number of drifting electrons and VUV scintillation photons. The collaboration has selected VUV sensitive SiPMs for the direct detection of scintillating light in LXe at 178 nm.[2] For low light level VUV photons detection at an extremely low 0νββ event rate, dark noise and correlated avalanches adversely impact the detector performance, particularly the energy resolution.[3] The SiPM being characterized are Hamamatsu VUV4 and FBK VUV HD-LF, see Table I.

II. nEXO SiPM Characterization Campaign

The performance of SiPMs has improved significantly over the past decade, including high >10^6 gain and excellent single-photon resolution capability. However, commercially available SiPM do not fulfill all requirements. The nEXO collaboration has been driving the dedicated development of VUV sensitive SiPMs for many years. They can now be produced in high radiopurity, a necessary requirement for the 0νββ detection. The SiPMs will be immersed in LXe, placed in the high-field region, covered the back surface behind the field shaping rings of the TPC field cage with a total photosensitive area of ~4.5 m^2. To characterize the VUV SiPMs, the photodetector groups within collaboration have built dedicated ultrahigh purity xenon liquefaction systems and started an extensive SiPM characterization campaign to ensure they meet the nEXO design performance, see Table II.

TABLE I. VUV SiPMs under consideration

vendor	pixel size (μm)	area (mm^2)	$V_{breakdown}$ (V) (LXe)	fill factor	charge gain (x10^6/volt)	$C_{junction}$ (nF/cm^2)
HPK	50	6x6	45.5	0.60	0.58	3.7
FBK	30	4x(3x3)	29.0	0.73	0.5	8.7

TABLE II. nEXO requirements on SiPM parameters

parameters	requirement
PDE at 178 nm	>15%
DCR	<50 Hz/mm^2
Correlated noise	<20%
Electronics noise	<0.1 SPE
Active area/photodetector	>1 cm^2
Radiopurity	<1%, nBq/cm^2
Junction capacitance	<5 nF/cm^2
Pulse width (after shaper)	<100 ns
Timing resolution	<500 ns

To achieve the desired energy resolution which is limited by the dark noise of the light channel, >3% of the scintillation photons must be detected, and PDE >15% is required. Therefore, comprehensive light map simulations are preformed to fully understand the propagation and the overall scintillation photons collection efficiency in the fiducial volume of the nEXO detector. However, silicon is very reflective at the VUV wavelengths. The strong interplay between the reflectance and PDE on SiPM is very important, see Figure 1, where strong spectral oscillations are observed due to the thick intrinsic SiO_2 layer at ambient which is expected to be much reduced in LXe because of a better index match.

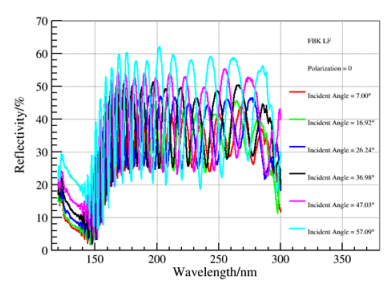

Fig. 1. (a) Reflectivity of FBK bare wafer and SiPM measured in vacuum at room temperature.

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When SiPMs are submerged in purified LXe, a typical dark current versus over-voltage (IV) is shown by the solid line in Figure 2(a). This dark current is slightly higher than the corresponding IV at the same temperature in vacuum, dotted line of Figure 2. We speculate that the extremely low dark current of the SiPM (low DCR as well, I_{dark}=DCR×q×G) allow one to detect the weak background scintillation light from LXe in an ordinary laboratory environment. We characterize the photoelectron responses in LXe by using a picoseconds UV-LED system at 268nm. We obtain the charge gain by collecting a series of single-photoelectron spectrum for each overvoltage and fit the Gaussian width of photoelectron distribution, see Figure 2(b). One photoelectron charge gain >0.5x10^6 and SPE resolution <<0.1 are observed.

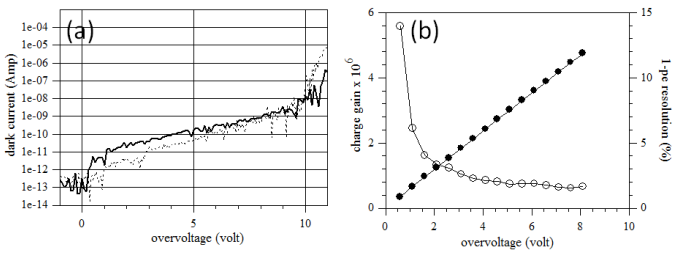

Fig. 2. (a) A typical dark IV plot of a SiPM (HPK VUV4) in LXe (solid line) and in vacuum at 166K (dotted line), and (b) the corresponding 1-photoelectron charge gain and resolution in LXe.

The absolute PDE of SiPMs have been characterized by using 3 different VUV light sources in different photodetector groups within the nEXO collaboration: (1) a scintillation source in gaseous Xenon, (2) a filtered Xenon flash lamp and (3) an optical harmonic generation scheme. Although large difference on PDEs are measured among different SiPMs which remains to be resolved, the possibility of achieving >15% PDE in the VUV wavelengths in LXe is encouraging. Conversely, the single photoelectron spectrum using 268 nm photons is clearly observed in LXe, while similar charge spectrum using 177 nm light pulse but in vacuum at 166°K is also evident, see Figure 3.

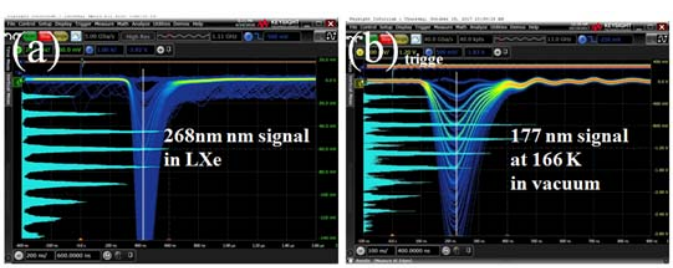

Fig. 3. A typical time-correlated single-photoelectron charge signal and the corresponding charge spectrum of a SiPM (a) in LXe with 268 nm 900 picosecond light illumination, and (b) at 166K in vacuum with 177 nm 60 picosecond light pulse.

It is known that SiPMs are insensitive to external magnetic fields, less known is their performance in strong external electric fields, such as within the TPC field cage of the nEXO detector. Our nEXO photodetector group has studied the effect of SiPM in external electric fields up to 30 kV/cm at a temperature of 149°K.[4] No observable change in the basic operation parameters (gain, PDE, and correlated noise) are found; ensuring their use in experiments such as nEXO.

We note that many other system performance parameters on SiPM must be investigated in LXe, such as the uniformity on the breakdown voltage, dark noise, correlated avalanches, after-pulses, absolute PDE, and a practical light readout scheme by grouping SiPMs in series/parallel/hybrid connection in order to achieve a better SPE resolution and reduced capacitance, Equally important are to optimize the photon transport in the detector possibly by encasing the internal of the liquid xenon detector and the SiPMs with VUV anti-reflective coating to maximize the light collection efficiency. Additional efforts are to study the angular dependence of the PDE in LXe, and to estimate the total systematic photon collection error budget

III. CONCLUSIONS

Promising VUV sensitive SiPM candidate that would meet the requirements of nEXO have been identified. Additional improvement on their performance including larger over-voltage range and lower radiopurity are expected in future SiPMs wafers. Using a simple model and considering the competing effects of increasing PDE and correlated noise with overvoltage, nEXO is expected to reach and possibly surpass the estimated 1% energy resolution. Looking forward, work is in progress to build a light detector module using the VUV sensitive SiPMs in LXe. In addition, design work on readout electronics using cold ASIC is currently in progress to address the large-scale SiPM integration issues, with the goal to have a prototype light detection module for nEXO in the near future.

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