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An experimental study of antireflective coatings in Ge light detectors for scintillating bolometers

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Abstract. Luminescent bolometers are double-readout devices able to measure simultaneously the phonon and the light yields after a particle interaction in the detector. This operation allows in some cases to tag the type of the interacting quantum, crucial issue for background control in rare event experiments such as the search for neutrinoless double beta decay and for interactions of particle dark matter candidates. The light detectors used in the LUCIFER and LUMINEU searches (projects aiming at the study of the double beta interesting candidates ^{82}Se and ^{100}Mo using ZnSe and $ZnMoO_4$ scintillating bolometers) consist of hyper-pure Ge thin slabs equipped with NTD thermistors. A substantial sensitivity improvement of the Ge light detectors can be obtained applying a proper anti-reflective coatings on the Ge side exposed to the luminescent bolometer. The present paper deals with the investigation of this aspect, proving and quantifying the positive effect of a SiO_2 and a SiO coating and setting the experimental bases for future tests of other coating materials. The results confirm that an appropriate coating procedure helps in improving the sensitivity of bolometric light detectors by an important factor (in the range 20% – 35%) and needs to be included in the recipe for the development of an optimized radio-pure scintillating bolometer.

1 Introduction and motivation

Scintillating bolometers are promising devices for the detection of rare events. A very important issue for these instruments is the light-detector sensitivity, which is crucial to achieve an adeguate background rejection in the most challenging situation (dark matter application and detection of Cherenkov light in TeO_2 bolometers [1]), but important also for the ZnSe [2] and $ZnMoO_4$ [3] scintillating bolometers, which are relevant for double beta decay search. In this work, we refer to the bolometric light detectors that use high impedance neutron transmutation doped (NTD) Ge thermistors as temperature sensors. In particular the light detectors consist of hyper-pure Ge thin slabs equipped with NTD thermistor for the read-out. This structure is convenient due to the simplicity of the detector assembly and very well tested [2, 3]. In order to improve the sensitivity of this kind of detectors there exist several options but in this paper we focus on the use of proper anti-reflective coatings on the Ge side exposed to the luminescent bolometer aiming at an increase of the light collection efficiency. The method here described [4] can be easily adapted to investigate various luminescent crystals and coating materials. In particular, the present article demonstrates and quantifies the positive effect of SiO_2 and SiO coatings on Ge in terms of scintillation light collection emitted by a ZnSe crystal.

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1.1 Consideration on the coating effect

The simplest form of anti-reflective coating is based on the so-called index matching. If a thin layer of material with an intermediate refraction index n_i is interposed between the vacuum and the absorbing medium, then it is possible to calculate the absorbed fraction by using the well-known formula which provides the reflectance for normally incident light at the interface between two media as a function of their refraction indices. It is easy to show that there is an optimum value for n_i, which in case of germanium is equal to 2.36 [4]. A layer with this feature would increase the absorbed fraction up to 69.6%,corresponding to a gain of 35.4% with respect to the bare germanium.
The materials that we have deposited are SiO_2 [4] and SiO. The former has a refractive index of 1.54 in crystalline form (quartz) and 1.45 in amorphous form (fused silica), while for the latter the refractive index is 2.48, at room temperature and at 632 nm. These values lead to calculate an absorbed fraction of 64.5% and 63.1% for crystalline and amorphous SiO_2 respectively, which corresponds to

a gain of 25.6% and 22.7%. For SiO, the absorbed fraction is 69.5% corresponding to a gain of 35.4%. The effect of our coating is however difficult to predict, because of uncertainties in the structure and stoichiometry of the film (which affects the refraction index) and in the temperature dependence of the refraction indices. In addition, the source is not collimated and quite close to the detector (as happens in scintillating bolometers): therefore, the assumption of normal incidence is a crude approximation. Multiple detector source reflections are not taken in to account.

2 Description of the experimental setup

The main idea was to fabricate thin detectors with a coating only on one side, and to make them as symmetric as possible with respect to the two sides in any other aspect. The same light source was then used to illuminate each light detector, in a first cryogenic run (named Run #1) from one side and in a second cryogenic run (named Run #2) from the other side, see Fig. 1. In both runs on the side opposite to that of the light source an X-ray source was placed. The detector-source geometrical coupling was identical in the two runs. The bolometers were equipped with a resistive heater to normalize the detector performance in the two runs. In order to get a redundant confirmation of the results and to overcome inevitable small side asymmetries in the detector configuration, more bolometers of each type have been realized.

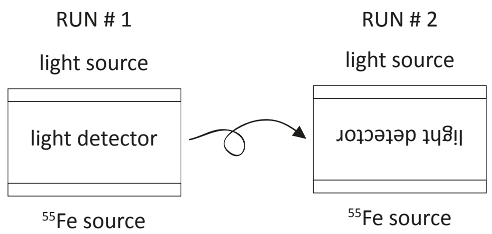

Figure 1. The same light source was enlightening each light detector, in a first cryogenic run from one side and in a second cryogenic run from the other side simply turning the detector itself.

2.1 The light detectors and the sources

Each detector has an energy/light absorber consisting of a hyper-pure Ge square plate, with a side of 15 mm and a thickness of 0.3 mm. After polishing and etching, on four detectors a SiO_2 coating was made on one side of the plate by RF sputtering a SiO_2 target using Argon with 10% Oxygen as a sputter environment. A SiO coating was provide by evaporation in high vacuum on other four detectors. Both SiO_2 and SiO coatings, were $7O$ nm thick. The Ge slab was inserted in a copper holder, with a central square window to accommodate the slab, held by two opposite PTFE clamps establishing a firm mechanical coupling and a weak thermal link towards the copper support (acting as a heat sink for the device). The slab plane is centered with respect to the copper holder thickness. A picture of an individual detector is shown in Fig. 2(a). The thermal signals from the Ge slab were provided by $3x1x0.6$ mm^3 NTD Ge thermistors, showing a resistivity temperature law well compatible with the variable range hopping conduction regime with Coulomb gap, which foresees:

$$R = R_0 \cdot exp\left[\left(\frac{T_0}{T}\right)^{0.5}\right] \tag{1}$$

where $T_0 = 3.83$ K and $R_0 = 6.45\ \Omega$ for the samples here used. A heater, used to stabilize the detector response and to fix a standard excitation allowing to compare the results from different runs, was glued on the opposite side of the Ge slab with a single epoxy dot. The thermistor and the heater, nominally identical, were electrically connected by means of golden wires with a diameter of 50 μm and about 15 mm long. In some detectors, the thermistors were glued on the coated side, while in the others on the bare side. This is the only intentional difference between the four detectors. It was introduced to exclude or at least control a possible effect determined by the inevitable asymmetry due to the presence of the different elements on the two sides. The light sources (see Fig. 2(b)) were made by sending ionizing radiation on four ZnSe slabs obtained by crystalline samples provided by the Alkor Technology Company of Saint Petersburg (Russia). On one side of each slab, one or two drops of an Uranium standard solution were deposited and then dried. Independent measurements of the radioactive source showed that the secular equilibrium of ^{238}U was broken. A source spectral characterization showed ^{238}U α lines at 4.15 MeV (B.R. 21%) and 4.20 MeV (B.R. 79%). A weak doublet from ^{234}U was also observed at 4.77 MeV (B.R. 71.4%) and 4.72 MeV (B.R. 28.4%), with an intensity about 10 times lower than that of the lower energy doublet. Of course, the α particles are fully absorbed by the ZnSe element, and only scintillation light is expected to come out of the opposite side of the slab. We do not expect that a source energy spectrum obtained through light pulses preserves the well-defined energy structure of the source. The light is partially absorbed in the source itself. We expect therefore a smeared structure with a low-energy tail in which however the two main characteristic α energies of the source ($\approx$4.2 and $\approx$4.7 MeV) should be recognizable. On the opposite side of the light detectors a low rate ^{55}Fe source, which provides a main X-ray line at 5.9 keV, was placed for calibration purpose (see Fig. 2(c)).

The detector tower, consisting of an array of bolometric light detector, was installed both in Run #1 and in Run #2 in the experimental vacuum of a dilution refrigerator located in case of SiO_2 in the cryogenic detector laboratory of the University of Insubria, Como, Italy and for SiO in cryogenic laboratory in CSNSM, Orsay, France. The tower was thermally connected to the coldest point of the refrigerator, namely the mixing chamber. In order to read out the thermal pulses produced by light flashes and single particle interactions, each NTD Ge thermistor was supplied with an almost constant current, obtained by applying a total DC voltage bias V_{tot} at the series of thermistor and two 100 MΩ-1 GΩ load resistances, placed at the room temperature and connected symmetrically at the two thermistor sides in order to respect the differential configuration of the front-end electronics. The voltage signals across the thermistors were sent to room-temperature differential low-noise voltage amplifiers and to Bessel analogical filters with 125 Hz cut-off frequency, operating as an anti-aliasing stage. The heaters were connected in parallel to a single wire pair from the mixing chamber to room temperature. A pulse generator was programmed in order to inject every few minutes a square voltage pulse V with a duration of few ms, shorter than the thermal signal rise-time, into each of the heaters (whose resistance is 300 kΩ at the detector operation temperature). The heater pulse represents an excellent method to compare the energy spectra of Run#1 with those of Run#2 and to fix a common energy scale.

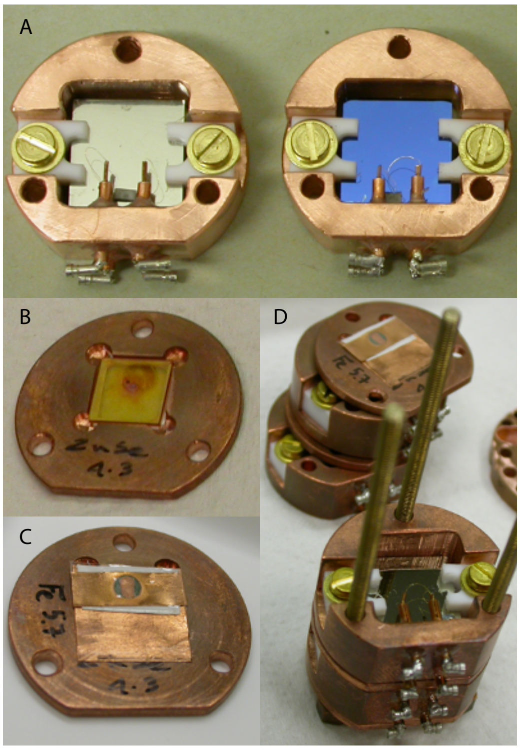

Figure 2. (A) Photograph of an individual light detector seen from both side; (B) photograph of the light source; (C) photograph of the ^{55} source; and (D) photograph of the light-detector tower.

3 Result

For each detector and in both runs, data acquisition was performed at the reported working points without calibration sources placed outside the cryostat. The full waveforms of the signals from the NTD thermistors were acquired and registered, and the method of the optimum filter was applied in order to maximize the signal-to-noise ratio in an off-line analysis. Environmental radioactivity and cosmic rays provided a significant interaction rate in the light detectors, comparable to that due to the light sources, which resulted to be in the range 0.06 – 0.1 Hz. As for the light sources, the rate was in agreement with the amount of uranium solution deposited on the ZnSe slabs. In order to isolate the component due to the light flashes in the energy spectrum of the detectors, we have exploited the well-known fact that the temporal structure of the signal is different for pulses due to the light absorptions with respect to pulses due to the single ionizing particles. In order to compare the detector responses in the two runs, we have used the absolute calibration provided by the ^{55}Fe source, when it was possible; in the other cases the heater signals provide a relative calibration, while the energy scale can be determined by cosmic rays. The operation bias was chosen so as to maximize approximately the voltage signal amplitude. The parameters of the detectors at the chosen working points are summarized in Table 1 and in Table 3.

3.1 Evaluation of SiO_2 coating effect

The gain due to the SiO_2 coating in terms of total energy absorbed by the light detector is apparent. As an example two light spectra collected with the detector LD#3 in the two runs are reported in Fig. 3. Similar plots are obtained for the other detectors. It is confirmed that the SiO_2 coating gives reproducible positive effects on the light collection efficiency, which prevail over any other possible systematic factors that could simulate or fade this result.

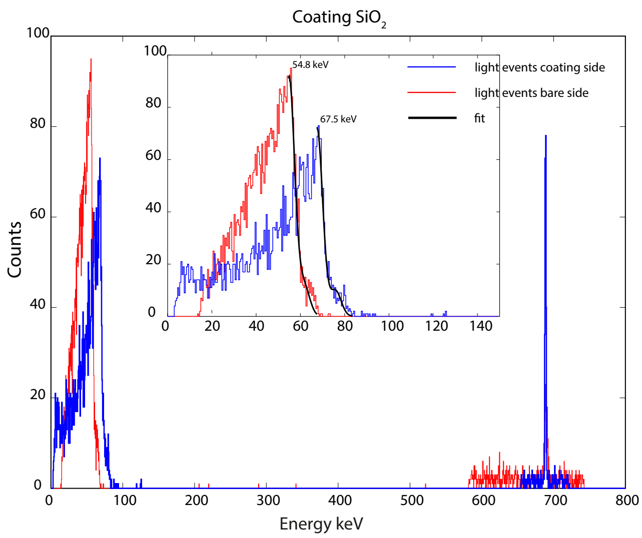

Figure 3. The energy spectra after selection of light pulses through pulse shape discrimination are reported for the detector LD#3, both for Run#1 (blue histogram), correspond to a coated side and for Run#2 (red histogram), bare side, after normalization of the energy scale through the heater peak.

The quantification of the achieved improvement was estimated by fitting the high-energy sides of the light spectra (not influenced by light absorption in the alpha source) with a sum of two semi-Gaussian functions. The distance between the maxima of the two functions was fixed according to the positions of the two main lines of the uranium source described in Section 2. The amplitude of the Gaussian at higher energy resulted always about 10 times lower than the other Gaussian, confirming a known feature of the employed alpha source. The position of the main maximum of the fitting function in Run#1 was compared with that in Run#2, taking into account their statistical uncertainties after energy normalization (which also contributes to the global uncertainty). The results are reported in Table 2, in terms of the percentage improvement due to the SiO_2 coating.

Table 1. Working points of the four SiO_2 coated light detectors in the two runs: V is the voltage across the NTD Ge thermistor, R and T its resistance and temperature respectively.

Detector	Run#1			Run#2		
	$V(mV)$	$R(k\Omega)$	$T(mK)$	$V(mV)$	$R(k\Omega)$	$T(mK)$
LD#1	2.43	433	30.9	2.25	410	31.3
LD#2	1.14	2.08	35.5	1.08	197	35.9
LD#3	6.42	1704	24.6	5.00	3390	22.1
LD#4	2.37	432	31.0	1.65	301	33.1

Table 2. Coating-induced improvement factors in the four light SiO_2 coated detectors.

detector	Improvement factor %
LD#1	18.5 ± 4.0
LD#2	19.8 ± 2.2
LD#3	20.3 ± 0.8
LD#4	20.1 ± 1.8

3.2 Evaluation of SiO coating effect

The same data treatment was applied to SiO-coated light detectors. Unluckily, two of three detectors lost their electrical contact during Run#2. We present here the results obtained with the last detector, namely LD#1, which worked properly in both runs. Taking into account the agreement found among the various SiO_2-coated detectors, we consider these results meaningful and reliable. As shown in Fig. 4 a full particle discrimination was performed and the energy calibration was provided by the 5.9 keV peak due to the ^{55}Fe source. Fitting the end-points of the two light curves as in SiO_2 case, the improvement in light collection can be estimated as 34.3 ± 0.5 %, in agreement with the simple model introduced above.

Table 3. Working points of the four SiO coated light detector in the two runs: V is the voltage across the NTD Ge thermistor, R and T its resistance and temperature respectively.

Detector	Run#1			Run#2		
	$V(mV)$	$R(k\Omega)$	$T(mK)$	$V(mV)$	$R(k\Omega)$	$T(mK)$
LD#1	1.20	239	28.6	0.44	175	30.3

Table 4. Coating-induced improvement factors in the four light SiO coated detector.

detector	Improvement factor %
LD#1	34.3 ± 0.5

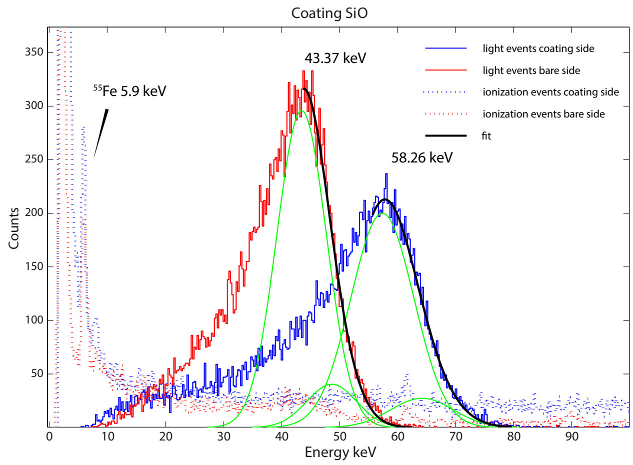

Figure 4. The energy spectra after selection of light pulses through pulse shape discrimination are reported for the detector LD#1, blue histograms correspond to a SiO coated side and red histograms, bare side. Dotted lines correspond to single ionization evens used to set the energy scale through the 5.9 keV ^{55}Fe peak.

4 Conclusions and acknowledgement

The described set-up has allowed to measure unambiguously the positive effect induced by SiO_2 and SiO coatings on the Ge absorbers of bolometric light-detectors in terms of light collection. The measurements were performed at very low temperatures and in conditions very similar to those in which scintillating bolometers normally operate. The increase of the collected light can be explained by the simple model of refractive index matching and consequently SiO coating provides a better performance, with a 34.3% increase of the absorbed light. The results confirm that an appropriate coating procedure helps in improving the sensitivity of bolometric light detectors and needs to be included in the recipe for the development of an optimized radiopure scintillating bolometer.

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