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Detection of alpha particle contamination on ultra low activity-grade integrated circuits

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Abstract. We propose to apply the superheated droplet detector (SDD) technology to the measurement of alpha-particle emissivity on integrated circuits of ultra-low activity grade ($< 1\alpha$/khcm^2) for high reliability applications. This work is based on the SDDs employed within our team to the direct search for dark matter. We describe the modifications in the dark matter SDDs with respect to fabrication, signal analysis and characterization, in order to obtain a device with the adequate detection sensitivity and background noise.

1. Introduction

Soft Errors (SE) are non-destructive functional errors induced by energetic ion strikes. An important parameter is the critical charge required to change the logical state of a stored data bit. With the continuous technology downscaling, the decreased node capacitances and operating voltages reduce the critical charge, thereby increasing device sensitivity to SE. Electronic devices in aircrafts, space missions and nuclear power plants are specially selected for their reduced intrinsic SE rate (SER) and resistance against radiation-induced SE.

There are two primary sources of terrestrial SE: alpha-particles (α) emitted from the radioactive impurities in materials nearby the sensitive volume (packaging, solder bumps, etc) and atmospheric neutrons (n) which produce highly ionising charged particles on their interaction with the component materials. The α-induced SER increases more rapidly with decreasing critical charge and can overcome the n-induced SER even with Ultra Low Activity (ULA) materials, i.e., with alpha emissivity below $10^{-3}\alpha\ \mathrm{h}^{-1}\mathrm{cm}^{-2}$ [1].

Although fast and thermal neutron-induced SE reappeared in advanced integrated circuits (IC) [1, 2] they can be kept negligible even below 28 nm with improved Si technology and carrier gases depleted in ^{10}B [3]. Alpha contamination remains therefore a major concern of nanoelectronic companies for commercial, industrial, aerospace and defense applications

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where reliability is mandatory. Qualification methodologies for ULA ICs have included variable-dependent measurements or underground tests (in a place devoid of cosmic radiation with negligible local α- and n-backgrounds). Evidence of any contamination is apparent in less than 6 months underground, but measuring the α-SER with any precision after 1–2 year testing is not possible with any of these methods [4].

Industry roadmaps call for instruments with detection limits of 10^{-3} α $\mathrm{h}^{-1}\mathrm{cm}^{-2}$ in the energy range 1–10 MeV for measurement times of less than 1 week with sample sizes $\sim$1500 cm^2 at a cost $<$ 50 kEUR [5]. These conditions cannot be fulfilled by any of the current commercial proportional counters, since their backgrounds (5 count/h) are a factor of 5 too high [6]. Promising alternatives based on ionisation counters are under development and evaluation for ultra-low background α-emissivity measurements, but no general consensus has been obtained up to now. One of the problems is the internal contamination by radon-emitting isotopes that simulate α's from the sample and moreover the cosmic bias that induces a lab-lab variability of the measurement accuracy [7, 8].

In this work we propose a new approach to measure α-emission rates, based on the superheated droplet detectors (SDD) developed by our team towards the direct search for dark matter (DM) [9]. Similarly to IC, SDD are sensitive to α's and n's. Until now, their development aimed to achieve minimal n-background signal, as events caused by DM mimic n-interactions and are extremely rare ($\ll$ 1 count/y in 1 kg target material). In the proposed application the focus is reversed, having α-detection as its main purpose. As our current SDDs can embed small samples of a few cm^2, we will primarily consider the measurement of individual devices. A target value of $< 10^{-3}\alpha$ h^{-1} for the technique sensitivity is thereby set.

Underground testing of the standard DM SDD demonstrated an intrinsic background in the order of 10^{-4} count/h and 10^{-3} count/h for n and α, respectively [9] with a detection efficiency of $\sim$95% [10]. The background signal being the critical parameter to qualify an instrument's ability for low-level measurements, our SDD has an intrinsic α-background signal 100 times smaller than that of the ionisation counter, and a comparable detection sensitivity.

In this paper we describe the main challenges towards the implementation of the new methodology and report preliminary results.

2. Ongoing research and development

2.1 Detector fabrication

Intensive R&D is underway towards the elaboration of an SDD with a sample embedded in a central position. The close contact between the droplets and the sample is mandatory, as α attenuation by any interface material results in a significant sensitivity loss. On the other hand the introduction of irregularities in a moderately superheated material triggers spontaneous nucleations that produce acoustic noise and reduce detector lifetime. We have recently defined a post-fabrication method based on a liquid detector material and recompression stages that yield a smooth sample-detector interface with a distribution of droplets in the vicinity of the sample. Operation at a lower superheat [11] via modification of the thermodynamic parameters or the superheated liquid is under consideration aiming at further noise reduction.

2.2 Event localisation and discrimination

Alphas emitted by the sample are located in its vicinity, in the central volume of the detector. In contrast, those originating in Rn diffused through the detector walls and from emitters

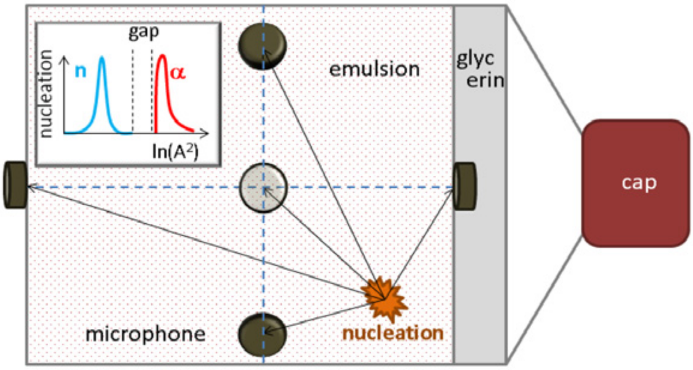

Figure 1. Schematic view of the SDD (in horizontal position) with a 5-microphone arrangement for the spatial localisation of the nucleations. The inset graph represents the amplitude (A) histograms of the acoustic signals corresponding to nucleations induced by recoiling nuclei following neutron interactions (n) and alpha-induced events (α), clearly separated by a gap.

in the detector container are localised near the glass-gel interface [12]. A technique towards the spatial localisation of events was developed based on the analysis of time delays among the signal detection by the various microphones of an array. Tests with a hot probe yielded a spatial resolution of 2 cm^3 that is adequate to identify events originating from a fiducial volume surrounding the sample [13].

Furthermore, the evaluation of the acoustic signals revealed that α- and n-events produce different amplitudes, larger ones corresponding to α's as a result of a greater bubble expansion power from the formation of various proto-bubbles. At signal amplitudes of ∼100 mV there is a 20 mV gap between the α and n- distributions which is clearly resolved by the signal acquisition system (resolution 0.3 mV) [9].

We will proceed with the concomitant application of the localisation and particle discrimination routines in order to extract a signal free from any radiation rather than α's from the volume of interest, thereby decreasing noise and increasing device α-sensitivity. A schematic view of the detection/discrimination system is given in Fig. 1. Current investigations are focussed on the fine acoustic characterisation of the detector (e.g. model of sound propagation in the detector material, reflections in the detector container, dependence of sound speed with thermodynamic conditions) for an improved event localisation.

2.3 Response to alpha particles

Most SDD applications are concerned with the detection of neutrons or heavy recoiling atoms [11], whereas in this work we focus on the detection of α's. Our initial investigations of the intrinsic SDD response to α's were performed using spectroscopy-grade liquid sources that are homogeneously dispersed in the gel during the stirring phase of the fabrication process. Different α emitters (Sm, U and Th) and activities are considered. The nucleation rate as a function of temperature for $^{238/232}$U in a C_2ClF_5 SDD at 1 bar is shown in Fig. 2, which displays a different variation from that corresponding to the local radiation background (measured with an undoped SDD).

Different bubble shapes and sizes and moreover different detection efficiencies were observed for the various emitters. The influence of α energy on the detector response is under investigation using a simplified model of the SDD response that considers the α Bragg

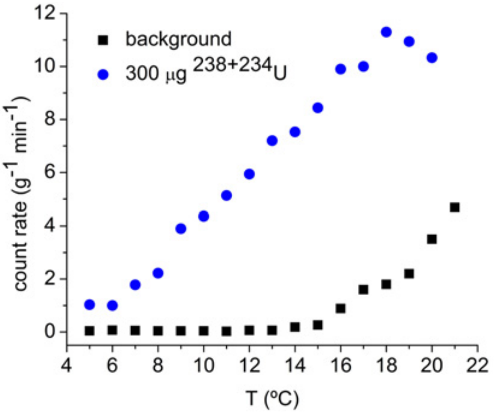

Figure 2. Temperature dependence of the response of a 150 ml SIMPLE SDD, doped with a 1mg/ml U solution and undoped (background).

peak [14] and will be further developed via Monte Carlo simulations coupled to stopping power and energy deposition calculations [15]. The correlation between bubble geometries and the acoustic signals will be evaluated. Such experiments using liquid sources will be explored to extract important parameters (e.g. Harper parameter [16]) for modelling detector response.

2.4 Neutron-induced alpha background

For SDD measurements at ground-level, production of α's within the fiducial sample volume upon neutron interaction with light elements should be addressed. The detector gel was evaluated by Ion Coupled Plasma Mass Spectroscopy with respect to B and Li and for completion, Sm, U and Th. Only upper limits were obtained corresponding to the measurement blanks: 5 ppm Li, 30 ppm B, 1 ppm Sm, 1 ppm U and 10 ppm Th. The upper limits for α emitters correspond to an intrinsic α-background much larger than measured. As for B, the measured upper limit corresponds to a production rate of alphas in the fiducial volume of a $(1.5 \times 1.5)\,\mathrm{cm}^2$ sample, exposed to $\sim 1\ \mathrm{n_{th}\,cm^{-2}h^{-1}}$ thermal neutrons at ground-level [17] of $\sim 10^{-2}\alpha\,\mathrm{h}^{-1}$, which exceeds the order of magnitude of the target values for ULA levels. Measurements with improved detection sensitivity are therefore necessary. Furthermore, the variability of neutron fluence rates (geomagnetic, terrain, altitude, solar, weather) justify an evaluation of the neutron environment at the detector location. Although we favour the application of standard techniques such as Bonner spheres, the SDD themselves can provide an alternative methodology for environmental neutron spectrometry [18].

3. Future developments

Additional questions to be addressed include the investigation of the SDD response to solid α sources, and a series of test measurements at ground-level and underground – the latter intended to qualify the developed methodology. Measurements will initially focus on standard, calibrated α sources and gradually include actual integrated circuits. We are primarily focused on evaluating the following Field Programmable Gate Arrays from

Xilinx [19]: (i) Spartan 6 (45 nm), which has been tested underground with published α-SER values on the order of 135 FIT (1 FIT=1 error per 1E9 hours of use); (ii) Virtex 6 (40 nm), with a particularly low α-SER of 9 FIT/Mb; (iii) 7-series parts (28 nm) with α-SER=22 FIT/Mb; (iv) 20 nm and possibly 16 nm devices (Virtex and Kintex UltraScale). necessary.

Ideally, the underground measurements will be performed at the site where Phase II of SIMPLE was run (GESA room of Laboratoire Souterrain a Bas Bruit) in order to take advantage of the work made in the past towards the reduction and characterisation of the environmental neutron and alpha radiation levels. An effort was made to suppress Rn in the detector by continuous purging of the room air, circulation of the water bath and detector pressurization. The alpha background achieved (measured: $2 \times 10^{-3} \alpha\ h^{-1}$) has order of magnitude of the aimed sensitivity [9]. As the value agrees with estimates of the Rn contribution, we expect to suppress the majority of the background α-events using the spatial localisation algorithms. The environmental neutron field in GESA (originating mainly from radioimpurities in its concrete walls) was reduced by two orders of magnitude with the installation of a water-based shielding [20]. The residual neutron background was characterised in detail using Monte Carlo simulations, their outputs being normalized to the measured activities of U/Th in the experiment materials [21]. The on-detector thermal neutron fluence rate of $\sim 1 \times 10^{-4}\ n_{th}\ cm^{-2}\ h^{-1}$ (calculated) will induce a negligible rate of α-events in the sample region (see Section 2.4). The fast neutron background (calculated: $2 \times 10^{-4}\ n\ cm^{-2}\ h^{-1}$) induces a reduced event rate in the detector (measured: 9×10^{-5} evt h^{-1}) that does not compromise its lifetime and can be rejected based on signal analysis.

4. Conclusions

We propose an innovative approach to the measurement of α-emissivity on ULA-grade integrated circuits, using the SDDs developed by our team for dark matter search. SDDs are of interest because its measured intrinsic α-background signal is two orders of magnitude lower than that of the most promising device under development for industry application, with a competitive sensitivity.

Additional noise reduction is achieved through the simultaneous application of spatial localisation and particle discrimination routines. The anticipated spatial resolution allows the measurement of individual (e.g. discard) devices rather than the large finished wafers evaluated by counters.

The fabrication of SDDs embedding a sample at both reduced spontaneous nucleation rate and high sensitivity is under investigation. Modifications relatively to the standard SIMPLE fabrication protocol are necessary, requiring a revision of the SDD response parameters. The application of liquid sources homogeneously distributed in the detector volume provides a benchmark for the investigation and verification of the physics underlying the detector operation.

In order to evaluate SDD noise at ground-level, the gel contamination by elements with significant (n, α) cross sections must be quantified with detection limits improved relatively to the measurements herein reported. The noise evaluation may benefit from the characterisation of the neutron environment at the SDD location.

In the final phase of the project, samples will be measured in an underground facility for the qualification of the methodology. The neutron background in the GESA room of LSBB has been characterised and is known to be, together with that from α's, appropriately low to conduct the experiment.

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