FBK roadmap towards the next-generation of 3D-integrated SiPM and SPAD technologies

A. Gola, F. Acerbi, A. Ficorella, S. Merzi, L. Parellada Monreal, E. Moretti, G. Paternoster, M. Penna, M. Ruzzarin, O. Marti Villareal, N. Zorzi.

Fondazione Bruno Kessler, Trento (Italy)

***Abstract*—While modern SiPM technologies have achieved remarkable performance in several fields, there are still several challenges in the technology development. Among them, further improving the timing performance for ToF-PET and HEP experiments, enhancing radiation hardness and building high-performance single photon imagers. Thanks to a recent upgrade of its microfabrication facilities, FBK is currently working on 3D integration technologies, which could significantly improve the performance parameters cited above. We are currently working in parallel on technology developments with different TRL. In addition to a more traditional, medium density TSV approach, FBK is working on an advanced TSV concept, allowing independent, single cell connection without relevant loss of Fill Factor. Moreover, FBK has introduced a radical redesign of the microcell structure to build Backside-illuminated, NUV-sensitive SiPMs, potentially approaching 100% Fill Factor even with small cell size below 15 um. (**_Abstract_**)**

Keywords—SiPM, SPAD, 3D integration, TSV, Backside illumination. *(key words)*

I. INTRODUCTION

Over the last few years, FBK Silicon Photomultiplers (SiPM) demonstrated state-of-the-art performance in several fields, spanning from medical imaging to Big Science experiments to Industrial applications. Using FBK NUV- and VUV- sensitive SiPM technologies, CTR of 58 ps FWHM [1] and of 51 pd FWHM [2] was achieved in the readout of the LYSO:Ce,Ca and of the the BaF_2 scintillators, respectively, in the ToF-PET application. Research demonstrated that, to achieve these results, it is important to combine excellent SiPM electro optical performance with optimized, high-frequency, readout electronics [1].

As regards the SiPM, it is well known that the most important factors determining the time resolution are the Photon Detection Efficiency (PDE) and the Single Photon Time resolution (SPTR). PDE approaching 70% at 410 nm (Fig. 2), combined with crosstalk probability of less than 5% at maximum PDE, was recently achieved by FBK with the NUV-MT technology, featuring metal filling of the Deep Trench Isolations (DTIs) that separate adjacent microcells in a SiPM [4]. Reducing the size of the detector generally improves the SPTR by minimizing the Transit Time Spread (TTS) of the signals coming from the SiPM and by reducing the detector output capacitance, which limits the slope of the rising edge of the signals. This suggest that segmentation is a promising approach to further improve the time resolution of next-generation SiPMs, as demonstrated by studies on the topic [3]. In this context, FBK has recently measured an SPTR of less than 30 ps FWHM with a 1x1 mm^2, NUV-HD SiPM, featuring a special layout optimized for timing and illuminated with light at 390 nm (Fig. 1).

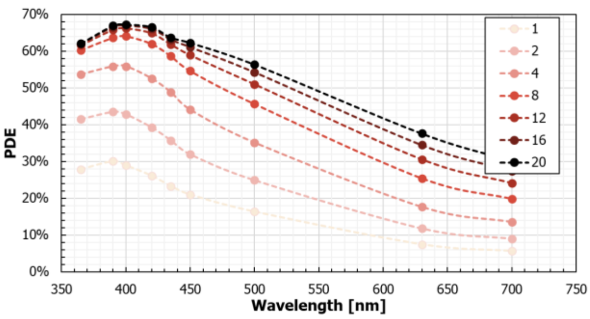

Fig. 2: PDE vs. wavelength measured on the 45 um cell of the NUV-HD-MT SiPM technology, developed jointly by FBK and Braodcom Inc.

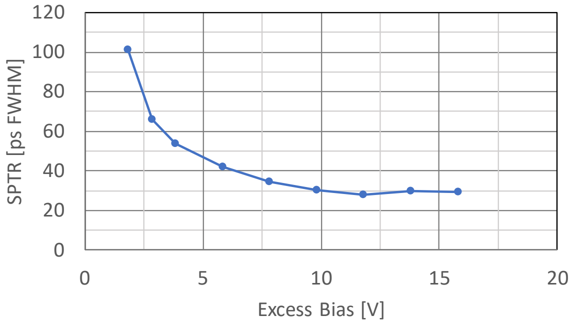

Fig. 1: SPTR measured on a 1x1 mm^2 NUV-HD-MT device with a special layout optimized for timing, using a high-frequency amplifier developed at FBK.

In the field of Big Physics experiments, FBK SiPM technologies have shown extremely low DCR of less than 0.01 cps/mm^2 at 77 K [5], which is an enabling technology for experiments requiring very large detection areas, such as DarkSide-20k experiment [6]. State-of-the-art PDE of 24% at 189 nm was also reported in cryogenic conditions [7]. Currently, an important challenge in the field is increasing the PDE at short wavelengths to levels comparable to the PDE at 400 nm and further extending the sensitivity to even shorter wavelengths, for example 128 nm, for the direct detection of the liquid Argon scintillation light. SiPM / SPAD radiation tolerance is another very important topic for scientific applications and determines the feasibility of using this type of detectors in HEP experiments and in space. Several studies are ongoing in the field [8], including the ones carried out by FBK [9][10]. The main effect of irradiation on the SiPM parameters is the increase of the DCR caused by bulk damage from NIEL. While the R&D is still ongoing, preliminary results indicate that there is a slight advantage in employing customized SiPM / SPAD technologies, characterized by lower peak value of the electric field in the multiplication region. On the other hand, this type of incremental improvement does not provide the breakthrough in SiPM

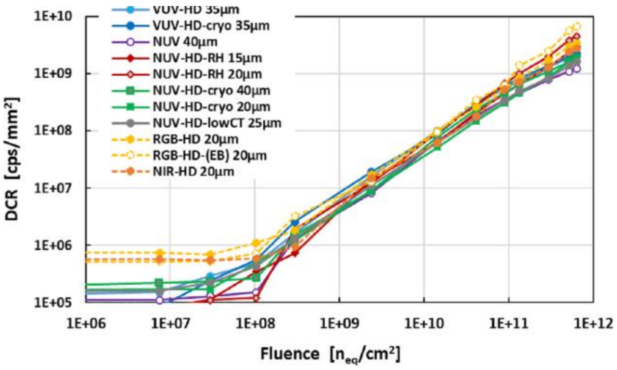

Fig. 3: DCR measured at 5 V excess bias on different FBK SiPM technologies after irradiation as a function of the irradiation dose, up to 10^12 1 MeV n_{eq}/cm^2.

radiation tolerance required by the most demanding applications, considering that the differences between very different SiPM technologies are generally limited to less than one order of magnitude (Fig. 3). A very interesting research topic is the investigation of the potential benefits of switching off noisy microcells after irradiation [11]. However, studies on SPAD DCR population after irradiation on custom SiPM technologies are still very limited. FBK has fabricated dedicated test structures and scheduled an irradiation test in early 2024 to investigate this topic.

Based on the considerations reported above, to improve the performance of its next generation of custom SiPM / SPAD technologies, FBK is currently working on several fronts. An important part of the future R&D is related to 2.5D and 3D integration techniques between sensor and readout electronics. This will be possible thanks to the recent upgrade of FBK microfabrication facilities to support this type of technologies [5] and defines a clear roadmap towards the segmentation of the SiPM active area into smaller and smaller groups of microcells, eventually down to the single SPAD.

II. MINI-SIPM AND 2.5D INTEGRATION

FBK is currently working on the development of medium-density TSVs to support the segmentation of the active area of the SiPM into miniSiPM [12], all fabricated on the same silicon die (monolithic miniSiPM array), with a pitch in the order of 1 mm^2 and almost local connection to the readout electronics through a passive interposer (2.5D integration) (Fig. 4). Thanks to the enhanced signal integrity allowed by the TSV and to the reduction of the detector capacitance, an SPTR performance better than the 30 ps reported above is expected, which is extremely interesting for the PET application, even without requiring the complexity of full 3D wafer stacking techniques. The 2.5D integration currently seems the sweet spot between complexity, cost, and performance, especially for applications requiring high TRL technologies and large sensitive areas (PET, Big Physics experiments) at a reasonable cost. Indeed, one of the advantages of the 2.5D integration is that the readout layer, which is typically more expensive because it requires a full CMOS process with around 40 lithography steps, can have a much smaller area than the sensing layer, which only requires approximately 10 lithography steps. The 2.5D integration process is currently being explored by FBK in the context of two, recently started, EU-funded projects [13], [14].

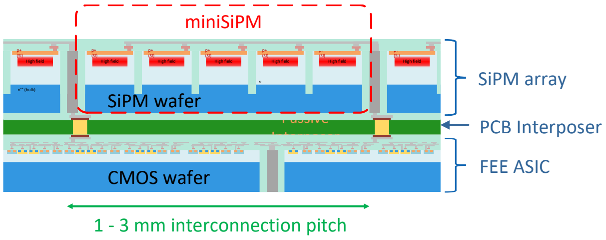

Fig. 4: Representation of a 2.5D integration scheme exploiting the medium-density interconnection TSVs being developed at FBK.

III. SINGLE-CELL TSV AND 3D INTEGRATION

FBK is also working on more advanced interconnection concepts for applications requiring the ultimate performance. FBK has recently started the development of a new microfabrication process to achieve single-cell access in frontside illuminated SiPM technologies, without any loss of active area because of the TSVs. This Single-SPAD TSV, S2TSV, approach is shown in Fig. 5. We exploit the fact that the SPADs in a SiPM are inherently separated by Deep Trench Isolation (DTI). After applying a glass carrier wafer, we thin down the SiPM wafer until each SPAD is electrically isolated from its neighbors. With a contact etched on the backside for each microcell, this cube-like SPAD constitutes its own TSV. The remaining bulk silicon below the depleted volume is low-resistivity and does not affect the electrical performance. A common bias is brought to all SPADs from a common metal grid on the topside while a redistribution layer (RDL) is optionally formed on the backside.

Thanks to the RDL, it is possible to group several SPADs together forming very small SiPMs, which we can call microSiPM (µSiPM), with significantly greater design flexibility compared to the medium-density TSV approach and without any loss of PDE. The design freedom allowed by the S2TSV approach is currently being investigated in the context of the DIGILOG project [15], to find the best trade-off and design parameters for the ToF-PET application. In this case, the segmentation flexibility and the power of local ASIC readout, which are typical features of a dSiPM, will be combined with state-of-the-art SPAD performance of the NUV-HD-MT SiPM technology reported above, which is typically improved compared to more standard CMOS SPADs technologies.

On the other hand, the S2TSV approach is also very effective to independently connect each SPAD the readout electronics for even more advanced applications, such as single photon imaging in the field of quantum applications, which are being investigated by FBK in the context of the

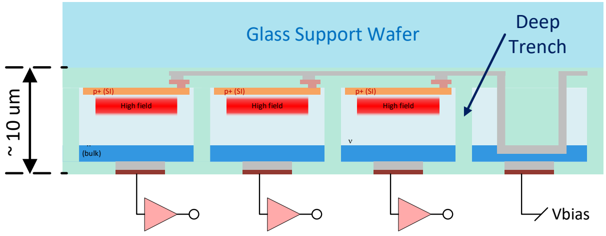

Fig. 5: Single SPAD TSV concept, exploiting the DTI separating the SiPM microcells to form a backside connection below each SPAD, without losing FF.

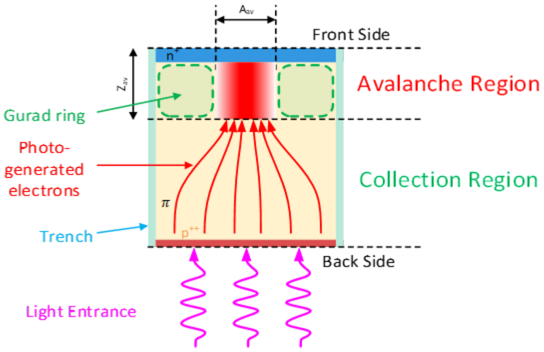

Fig. 6: Schematic representation of the new NUV-BSI SiPM SiPM microcell being developed at FBK, featuring a clear separation between the avalanche and multiplication region and a charge focusing mechanism.

NQSTI PNRR project [16]. Furthermore, as mentioned above, single SPAD access might be useful to improve SiPM radiation hardness by disabling the noisiest cells in the SPAD population.

IV. NUV-BSI SIPMS

Finally, to provide non-incremental improvements of the SPAD electro optical characteristics and to achieve truly next-generation performances, FBK is working on a more radical redesign of the microcell, aimed at building Backside Illuminated, NUV-sensitive SiPMs. The new microcell structure is represented in Fig. 6. It features a clear separation between the charge collection and multiplication regions. A charge focusing electric field drives the photogenerated charge into a much smaller avalanche region. Thanks to the focusing mechanism, there is ample space close to the front side of the wafer for the virtual guard rings, while the fill factor on the backside approaches 100%. The expected advantages of the NUV-BSI structure include:

- (i) very high Fill Factor (FF) up to 100% and very high Photon Detection Efficiency (PDE) even with a very small cell size.
- (ii) excellent linearity and dynamic range with microcell pitch below 15 um and recharge time constant below 10 ns.
- (iii) almost uniform light entrance window, suitable for advanced optical stack, such as laser annealing and plasma doping, and extended sensitivity at short wavelengths, suitable, for example, for the new cross-luminescence scintillators and VUV light detection.
- (iv) low gain and, thus, low external optical crosstalk probability.
- (v) it is the most suitable technology for 3D integration to the readout ASIC, even at the single microcell level, as it does not require the use of Through Silicon Vias (TSVs).

Finally, we observe that the NUV-BSI structure could provide a generational improvement also in radiation hardness. Indeed, under the assumption, supported by experimental evidence, that the DCR after irradiation is dominated by field-enhanced thermal generation, the NUV-BSI decouples, for the first time in FBK technologies, the size of the light sensitive region, which is bigger, from that of high field region, which is significantly smaller, correspondingly reducing the sensitivity to radiation damage in the bulk at the same level of PDE.

V. CONCLUSIONS

3D integration techniques have the potential of providing very interesting solutions to the large number of challenges that SiPM technologies need to face in the near future. These challenges include improved timing performance for ToF-PET and HEP, enhanced radiation tolerance, extended VUV sensitivity and support of new applications, such as single photon imaging with hybrid, 3D integrated detectors. FBK is actively working on these topics through a layered R&D approach, including higher TRL developments, such as medium density TSVs, and more challenging, non-incremental developments, such as single-SPAD TSVs and NUV-sensitive BSI SiPMs / SPADs. The activities are supported by different, publicly funded projects and several silicon runs are ongoing, with the first experimental results expected for early 2024.

REFERENCES

[1] https://doi.org/10.1016/j.nima.2021.165247
[2] https://doi.org/10.1088/1361-6560/abf47
[3] https://doi.org/10.1016/j.nima.2021.165247
[4] https://doi.org/10.1088/1748-0221/18/05/P05040
[5] https://doi.org/10.3390/s19020308
[6] https://www.lngs.infn.it/en/darkside
[7] https://doi.org/10.1051/epjconf/202022702002
[8] https://doi.org/10.1016/j.nima.2023.168578
[9] https://doi.org/10.1016/j.nima.2022.167488
[10] https://doi.org/10.1016/j.nima.2022.167791
[11] https://doi.org/10.1117/12.2665157
[12] https://doi.org/10.1016/j.nima.2023.168042
[13] https://petvision.org/
[14] http://www.cosmoport.xyz/
[15] https://gepris.dfg.de/gepris/projekt/500540345?language=en (DIGILOG project)
[16] https://www.nqsti.it/