Ultra high-level Radiation Monitoring with Thin Metal Nano-Layers (NanoRadMet)

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ABSTRACT

Advanced Beam Profile Monitor (BPM) devices based on the Secondary Electron Emission (SEE) principle are being developed for the CERN proton irradiation facility (IRRAD) to provide real-time information about the beam position and profile. In IRRAD, a 24 GeV/c proton beam is extracted from the CERN Proton Synchrotron (PS) accelerator to perform radiation hardness tests on materials, electronic components and detectors. The fabricated prototypes were tested at the CERN CLEAR facility with 200 MeV electrons. This paper summarizes the new fabrication technology and the improved performance of these new devices featuring more than 200 times less material thickness in comparison to the previous fabrication technique.

Keywords: Beam-line instrumentation; secondary electron emission; radiation-hard detectors; radiation-induced secondary-electron emission, microfabrication, thin-films

1. INTRODUCTION

Beam monitoring instrumentation is essential for the IRRAD proton facility, where about thousand samples are irradiated, with a total accumulated proton fluence typically exceeding 10^{18} p/cm^2, every year. To successfully perform these tests, a precise monitoring of the proton beam profile is essential. Therefore, flexible Printed Circuit Boards (PCBs) patterned with a matrix of sensing pixels, were used as Secondary Electron Emission (SEE) Beam Profile Monitors (BPMs) since several years. This work comes to improve the BPM devices by expanding the knowledge about the physics behind the SEE principle and using it to develop a completely new fabrication process featuring a simplified and more efficient structure, with the most promising sensing material, substrate and design. The old devices were manufactured with a standard flex-PCB technology, ~0.6 mm thick, composed of multiple copper layers sandwiched with epoxy glue. These stacked layers were originally considered to multiply the signal. Moreover, radiation-induced damage effects were observed in the sensing region of the device and, sometimes, inducing its failure during operation. Compared to the old BPMs, the new prototypes described here, are more than 200 times thinner, and therefore less invasive when interacting with the beam. They are expected to present an enhanced radiation tolerance thanks to the employed microfabrication technology and have a higher sensitivity because of the usage of aluminum as sensing material which has, intrinsically, higher secondary electron yield (SEY) than copper. The main outcomes of this work include, besides an advanced understanding of the sensing principle of the BPMs, also a series of working prototypes based on a newly developed microfabrication process with nanometre aluminum (Al) layers on thin polymeric substrates. The validation of their functionality with experiments in dedicated test-benches and a particle beam, is also presented in this paper. These experiments are the prerequisite to have operational BPM devices for the IRRAD facility after the CERN Long Shutdown 2, as well as, to investigate their usability in very low energy beams as of interest for more general-purpose applications (e.g. industry, medicine).

2. STATE OF THE ART

Standard beam instrumentation devices are generally not designed to be used in an irradiation beam-line. To cope with this problem, custom-made standard BPM devices consisting on rectangular-shaped, flexible PCBs, patterned with a matrix of metallic sensing pads on the one end, and a multi-pin connector on the opposite one, have been developed for the IRRAD facility at CERN (see Fig. 1(a)) [1].

Secondary Electron Emission (SEE), on which the BPM's working principle is based, occurs when a high-intensity beam impinges on a metallic foil and electrons of the energy below 50 eV (Secondary Electrons (SE)) are produced. The number of SEs ejected from the foil is proportional to the local beam intensity [2]. The SEs are then converted into an electrical signal, which is measured and recorded by dedicated electronics. An online web-application, finally displays the current from every metallic pad resulting in two-dimensional beam profiles.

These monitoring devices are installed on every irradiation system of the IRRAD facility and are exposed to the beam together with the samples to be irradiated. Although they have proven to work well during the run 2014 to 2018 of IRRAD, multiple drawbacks has been identified about their functionality.

The standard IRRAD BPMs have shown damages (detaching, burning and bumps) on the region traversed by the beam, because of the usage of epoxy glue between the sensing and isolating layers. Moreover, when all the irradiation systems of IRRAD are positioned in beam, the sum of all BPMs can add almost 2 mm of copper and 8 mm of polyimide to the total material budget, thus significantly contributing to the multiple scattering in the beam-line. Other than the damage, the devices become highly radioactive after long time exposure, something of special concern when the facility staff needs to access the irradiation area or replace a broken device.

The main challenge that the devices are facing is the high radiation levels that they should withstand, particle fluences equivalent at least, to one year of operation in the facility (~10^{18} protons). Moreover, the beam monitoring in IRRAD must be permanent and real time, because these data are also used by the CERN Control Centre (CCC) to tune the beam extraction parameters (e.g. shape, position, charge).

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The BPMs should be made of materials that have short radioactivity, in order to minimize the exposure of the operators and users, relatively low cost and easy manufacturing. Moreover, they have to be on the one hand thin to avoid the multiple scattering and any interference with the projectile beam, while on the other hand thick enough to allow easy handling.

The innovative idea about the new BPMs is the manufacturing process. In comparison to the old devices, which are fabricated in macroscopic scale (millimetres), the new BPMs are made in nanoscale level (nanometres). The field of microfabrication related to metal deposition on polymeric substrates is still very in its infancy, which led us to a careful selection of each step of the manufacturing process: e.g. deposition techniques and equipment, sensing material and substrate, were chosen after strict validation.

The other ground-breaking idea about the new BPM devices is the R&D approach. The initial study of the SEE from surfaces exposed to atmospheric pressure (e.g. in air), instead to the widely studied vacuum, allowed to better target the parameters affecting the SEE and to use these information to provide feedback and optimize the production.

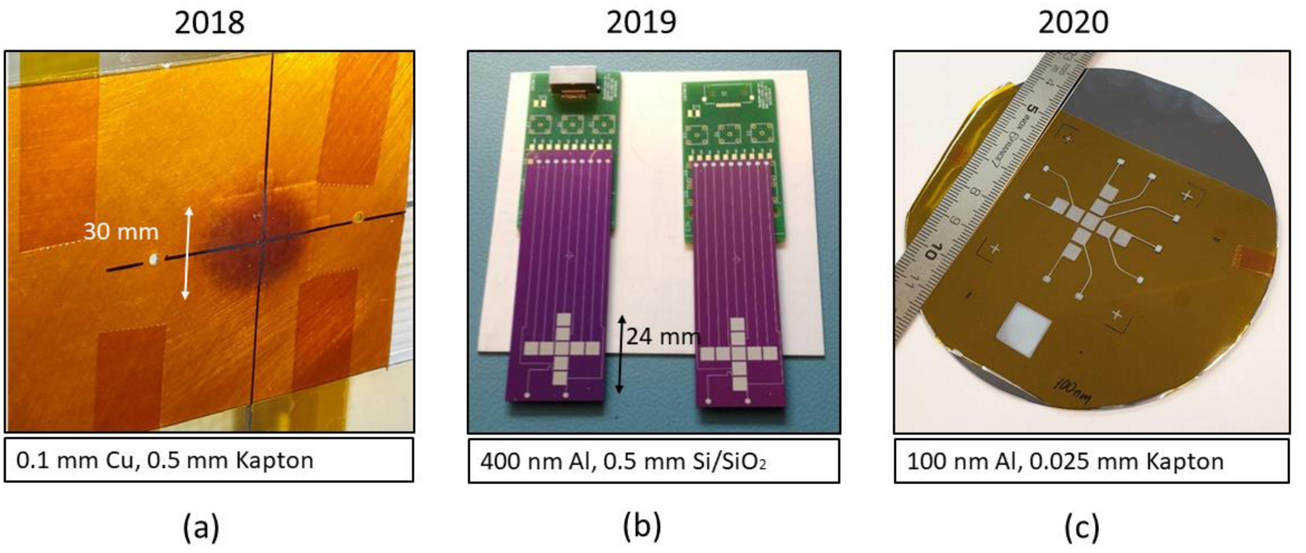
The new BPMs feature improved characteristics with respect to the older version. They are more than 200 times thinner (less invasive) more durable, because of material processing. Last, but not least, during the irradiation of both old and new BPM devices at the CERN CLEAR [3] electron facility, a higher response to the beam was also observed.

4. PROJECT RESULTS

Fig. 1 shows the evolution of the BPMs starting from the version used in the last run of IRRAD in 2014-2018 (left-hand side), then the intermediate version of 2019 (center) and the latest and most promising delivery of 2020 (right-hand side).

The initial production runs with microfabrication technologies, started in the Centre of Micro and Nano technology (CMi) of EPFL in 2018, when the first prototypes on silicon substrate (intermediate version 2019 in Fig. 1) were produced and confirmed the perspective of microfabrication [4].

The intermediate version devices (2019) were produced on standard Si/SiO_2 wafer substrates and had been tested methodically to study different configurations of the metal layers and thus, serving as guideline for optimizing later productions. More specifically, the experimental results showed that multiple metal layers nor isolation of the sensing material influence the signal intensity. An example of a beam profile, recorded during the experimental runs with the 2019 devices at the CLEAR facility with 200 MeV electron beam, is shown in Fig. 2.



(a) (b) (c)

Fig. 1. BPM evolution through the last years. (a) PCBs patterned with a matrix of sensing pads from copper in multiple layers. (b) Silicon wafer substrate patterned with Al (left) and additional Al oxide (right). (c) Aluminum sputtered on polyimide substrate.

Suspicion of contribution from the silicon substrate to the total signal and difficulties in determination of the beam intensity passing through the pads of these, yet, thick devices suggested to move forward and focus our research on the manufacturing on insulating substrates. This included new studies about the quality of the adhesion between the sensing and the supporting material, the effects of oxide to the SEY, the homogeneity of the metal deposition and the electrical connections.

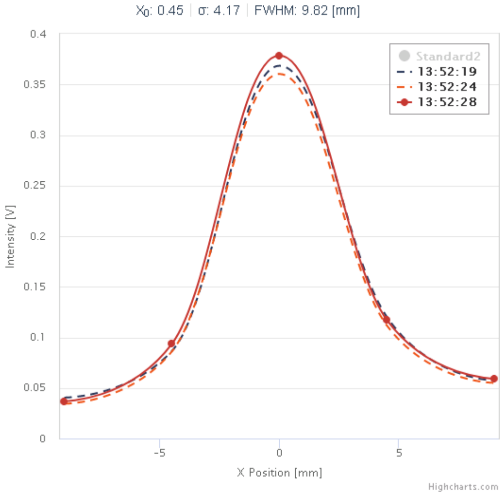


Fig. 2. Profile recorded during the experimental run of 2019 in CLEAR.

The knowledge acquired in the above fields, combined with a number of validation tests, highlighted improvements that were implemented in the final version of the device (Fig. 1(c)).

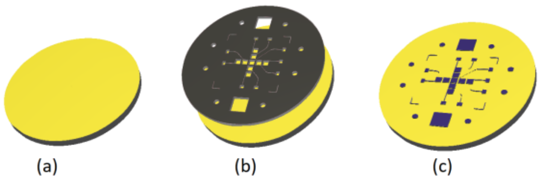


Fig. 3. Shadow mask deposition technique. (a) Thin polyimide film on a silicon wafer support. (b) Shadow mask put on the top on the polyimide. (c) BPM design patterned on the top on polyimide after aluminum sputtering process.

For microfabrication of the new devices (Fig. 1(c)), shadow masks were produced. To engrave the substrate with the desirable pattern, aluminum was sputtered on polyimide substrate under vacuum pressure, as shown in Fig. 3. Restrictions related to the cleanroom production such as mask fragility, target (metal) thickness limit, thin polyimide film manipulation, mask fixation on the substrate, machine power modes (burning issues) and support size (usually wafer shaped), emerged and have been solved by optimizing subsequent production runs.

Aluminum was chosen as sensing material because of its availability, low cost and higher SEY (δ_{max}=3.5, see Fig. 5) compared to Copper (δ_{max}=2.4 [5]). Polyimide (Kapton) was chosen as a substrate because of its thermal and chemical stability, low dielectric constant, high electrical resistivity, possibility of getting very thin films and most important increased radiation tolerance. The substrate was treated with oxygen plasma and titanium under vacuum pressure before the metal deposition, in order to improve the adhesion properties between the two materials, as experimentally tested (see Fig. 4).

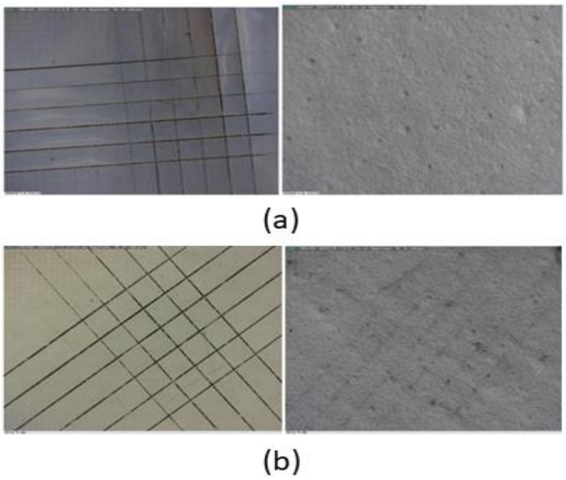


Fig. 4. Al on polyimide, after patterning with the crosshatch cutter on the right; on the left is the back-side of the peeled tape (a) Deposition of O_2 plasma-Ti-Al on 25 um polyimide foil. (b) Deposition of Ti-Al on 180 um polyimide foil.

As mentioned in theory [6], and confirmed by the surface analysis performed at CERN (Fig. 5), the SEY of Al in vacuum is rather independent of the thickness of the metal. Layers 10 nm, 50 nm, 100 nm and 400 nm thick show roughly the same results, especially at increasing primary particle energy, while coating the Al with an extra oxide layer (in this case 10 nm) increases the yield by 23 % as shown in Fig. 5.

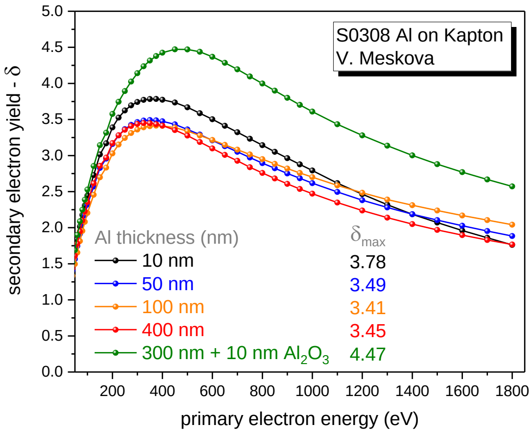


Fig. 5. SEY spectra of metallized Kapton samples.

This effect observed in vacuum could be used as a method to easily increase the SEY and hence, the sensitivity of the BPM devices to particle beams. Unfortunately, this finding was proven not to be valid while the emitting surface is surrounded by air at atmospheric pressure after the experimental test at CLEAR. Fig. 6 shows the results from the irradiation of the samples listed in Tab. 1. Independently from the thickness of the metal, or the extra oxide layer, the measured SEY is of 1.6 %. This yield is in very good agreement with the values of Fig. 5 when extrapolating them to hundreds of MeV primary particle energy. Irradiation of old standard BPMs in the same conditions at CLEAR, resulted in an experimental SEY in air for copper lower than 1 % proving the increased sensitivity of the new devices.

Expected Al thickness [nm]	Measured Al thickness [nm]	Extra Al_2O_3 [nm]	SEY [%]
100	100	10	1.69
100	88	-	1.65
300	160	10	1.62
300	160	-	1.62
400	380	-	1.63

Tab. 1. SEY from the aluminum pads on 25 um polyimide, after electron irradiation at CLEAR.

The measured thickness (second column of Tab. 1), refers to the Focused Ion Beam (FIB) measurements [7] that was done to cross-check the Al thickness deposited by sputtering and to analyse the homogeneity of the deposition (see ex. in Fig. 7). As the sputtering time for very thin layers is very short, the 10 nm was found to be inhomogeneous and thus not investigated in the following study.

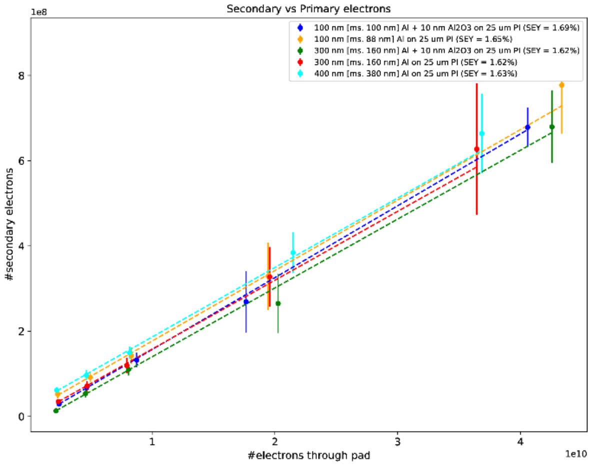


Fig. 6. Experimental SEY from different Al pads, sputtered on 25 um polyimide (see details in Tab. 1).

In order to evolve towards a fully engendered devices, PCB frames were designed to support the thin BPMs during the CLEAR irradiations (Fig. 8). These frames are also hosting the electrical connection between the detector and the DAQ. The connections were performed by testing wire-bonding technique combined with silver glue.

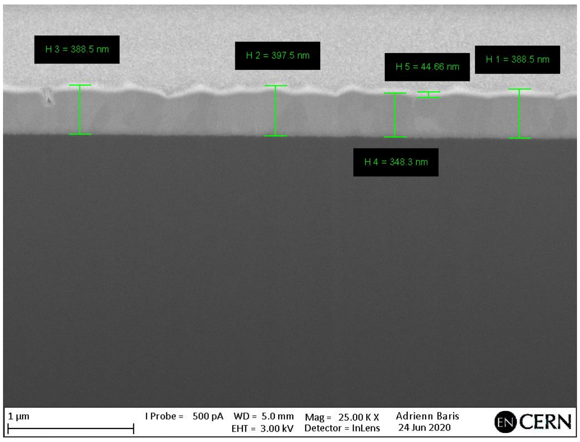


Fig. 7. Focused Ion Beam (FIB) analysis on a 400 nm samples, confirming an average thickness of 380 nm.

As the Kapton substrate is too thin for the wire to be attached directly, and thus guarantee a reliable connection, the final attachment was made on a drop of silver glue. In view of a larger scale production, the composition of the connecting pads needs to be improved for direct wire bonding.

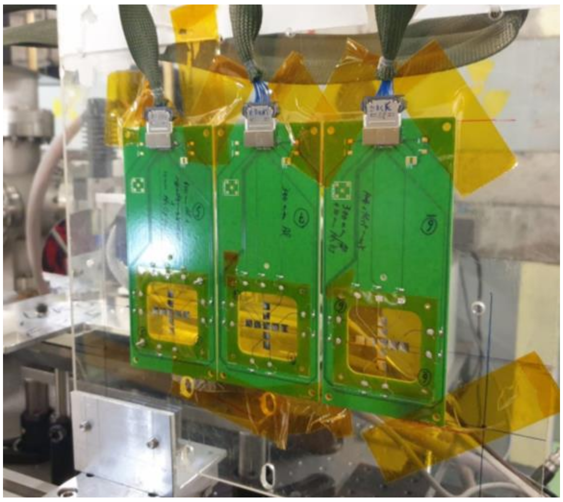


Fig. 8. New BPMs mounted on the PCB support in CLEAR facility, ready for irradiation test.

The new devices have overall shown to reliably work and feature improved parameters related to their thickness (material budget) and SEY (sensitivity). Although extensive radiation tolerance tests were not possible in the scope of this project, in the investigated fluence range, degradation effects were not observed. These initial results, together with the intrinsic improvement in the fabrication process, makes us confident that this goal has been also achieved during this project and it could be soon confirmed by dedicated experimental tests.

Device Parameters	Old device (2018)	New device (2020)
Metal	Cu	Al
Metal Thickness	100 um	100 nm
Substrate thickness	475 um	25 um
Total material budget in IRRAD	8 mm	0.5 mm
Theoretical SEY (maximum)	2.4	3.5
Measured SEY (200 MeV e^-)	<1%	1.6%
Radiation-induced degradation	observed	not observed with electrons

Tab. 2. Summary table comparing the performance of the old and new BPM devices.

FUTURE PROJECT VISION

Along with the validation of their radiation hardness, future development on the BPMs include:

- enhancement of adhesion properties between the sensing metal and the substrate;
- improvement of electrical connection between the sensor and the PCB support;
- development of more durable shadow masks for deposition of the sensing material and extension of the fabrication to larger scale devices. Today, the overall size of the BPMs is restricted to the 100-mm-diameter wafers.

About the operation, testing of the device in a proton beam is pending. Moreover, validation with lower intensity beams is foreseen since the thickness achieved with the current prototypes promises a large range of working intensities and applications.

4.1. Technology Scaling

The main step required for upgrading the existing BPM device is the standardization of the microfabrication process on flexible polymeric substrates. This include metal deposition technique enhancement (test other tools and recipes), as well as, custom-made substrate formula development.
Another line for scaling this technology is the optimization of the DAQ system (more compact, remotely controllable, user friendly, etc.) as the existent one fits the CERN IRRAD infrastructure only. Future improvements shall also include the development of a more reliable electrical interconnection technology between PCB support and the sensor.

4.2. Project Synergies and Outreach

To scale up this product at industrial level, a micro technology partner with state-of-the-art and accurate metal and polymer processing equipment is needed. Secondly, a software partner to improve the DAQ system and build an optimized User Interface (UI) would be probably necessary for a series production. Finally, a partnership with irradiation facilities to calibrate the sensors for a wide range of intensities and particles would be also advisable.

A possible collaboration could be established with the partner ATTARCT-funded project RaDFOS [6], which is developing a device for dosimetry measurements, also based on a nanotechnology process. The combination of this dosimeter with the particle intensity measurements provided by the BPMs, could supply the customers with an integrated and complete system, providing two critical and complementary measurements at the same time.

4.3. Technology application and demonstration cases

The BPM technology find value for science, industry and society. Primarily, BPM devices can be used not only by IRRAD, but also by other worldwide radiation test facilities of any kind and in a wide beam intensity range. Other applications of these monitors, is in medicine as advanced tools for hadron therapy beam calibration, in industry for sterilization processes or material modification studies as well as in the nuclear field.

4.4. Technology commercialization

To achieve commercialization level, first contact are the irradiation facilities potentially interested in the product (some have already shown interest). A list of possible interested facilities can be found in this database setup by the same team working on this project: www.cern.ch/irradiation-facilities.

Second level contact is to discuss specific requirements (the device can be adapted in size, shape, etc. depending on the measurement to perform and on facility-specific integration requirements) directly with the interested facilities and for their specific applications.

4.5. Envisioned risks

No technological risks are envisaged about the BPMs, as they already satisfy most of the expected requirements. Main upgrading risk is the lack of proper industrial partner for the fabrication or collaboration with proper irradiation facilities to confirm the BPM's features and durability. In this case, a solution could be to strengthen the partnership with academia.

4.6. Liaison with Student Teams and Socio-Economic Study

The ATTARCT project NanoRadMet has been strongly driven by the contribution of a master student. The knowledge of the community of the potentially interested facilities (see database cited before) can provide valuable inputs for a future socio-economic study.

5. ACKNOWLEDGEMENT

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