ISBN: 978-3-95450-222-6 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2020-TUPP37

A BEAM PROFILE MONITOR FOR HIGH ENERGY PROTON BEAMS USING MICROFABRICATION TECHNIQUES*

Wilfrid Farabolini, Antonio Gilardi, Blerina Gkotse, Alessandro Mapelli, Isidre Mateu†, Viktoria Meskova†, Giuseppe Pezzullo, Federico Ravotti, Ourania Sidiropoulou,
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Didier Bouvet, Jean-Michel Sallese
École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract

In High Energy Physics (HEP) experiments it is a common practice to expose electronic components and systems to particle beams, in order to assess their level of radiation tolerance and reliability when operating in a radiation environment. One of the facilities used for such tests is the Proton Irradiation Facility (IRRAD) at the European Organization for Nuclear Research (CERN). In order to properly control the 24 GeV/c proton beam and guarantee reliable results during the irradiation tests, Beam Profile Monitor (BPM) devices are used. The current BPMs are fabricated as standard flexible PCBs featuring a matrix of metallic sensing pads. When exposed to the beam, secondary electrons are emitted from each pad, thus generating a charge proportional to the particle flux crossing the pads. The charge is measured individually for each pad using a dedicated readout system, and so the shape, the position and the intensity of the beam are obtained. The beam profile determination with this technique requires thus the usage of non-invasive and radiation tolerant (~10^{18} p/cm^2/y) sensing elements. This study proposes a new fabrication method using microfabrication techniques in order to improve the BPMs performance while greatly reducing the device thickness, thus making them also appropriate for the monitoring of lower energy and intensity particle beams. The fabricated prototypes were tested at the CERN CLEAR facility with 200 MeV electrons.

INTRODUCTION

Beam monitoring instrumentation is essential for the IRRAD proton facility, where about a thousand samples are irradiated every year, with a total accumulated proton fluence typically exceeding 10^{18} p/cm^2. 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, have been used as Secondary Electron Emission (SEE) Beam Profile Monitors (BPMs) since several years [1]. These devices were manufactured with a standard flex-PCB technology, composed of multiple copper layers sandwiched with epoxy glue. These stacked layers were originally considered to multiply the signal, but had the drawback of making a rather thick device (~0.6 mm). Moreover, radiation-induced damage effects were observed in the sensing region of the device and, sometimes, induced its failure during operation. These effects were attributed to the epoxy not resisting the levels of radiation at which the BPMs are exposed.

This article presents a series of working prototypes based on a newly developed microfabrication process with nanometre aluminium (Al) layers on thin polymeric substrates. Compared to the old BPMs, the new prototypes are thinner (20 times the substrate, and one order of magnitude the metal), and therefore less invasive when interacting with the beam. They are expected to present an enhanced radiation tolerance thanks to the employed microfabrication technology (which avoids gluing) and have a higher sensitivity because of the usage of Aluminium (Al) as sensing material which has, intrinsically, higher secondary electron yield (SEY) than copper.

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).

STATE OF THE ART

The standard beam instrumentation for secondary beam area at CERN is 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 (left)).

Secondary Electron Emission (SEE), on which the BPMs 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 a dedicated electronics. An online web application, finally displays the current from every metallic pad resulting in two-dimensional beam profiles.

*Work supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 777222 (ATTRACT Phase-1 project).
†e-mail address: isidre.mateu@cern.ch, viktoria.meskova@cern.ch.

ISBN: 978-3-95450-222-6 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2020-TUPP37

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).

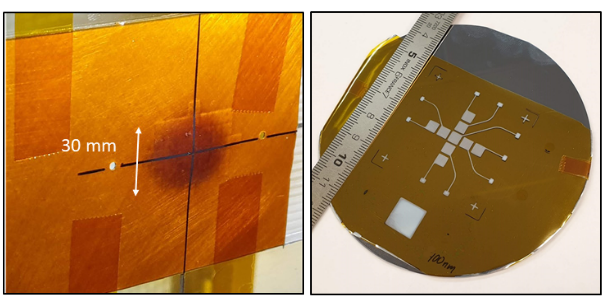

Figure 1: On the left, old BPM device, consisting of a PCB patterned with a matrix of sensing pads from copper in multiple layers. The footprint of the beam can be observed. One the right, the new BPM device, consisting of aluminium sputtered on polyimide substrate.

MICRO-BPM DESIGN & FABRICATION

Based on the experience with the old BPMs, the following requirements were identified for a new generation of devices: they should withstand the expected radiation cumulated during, at least one year of IRRAD operation, they should be made of materials that have short radioactivity, in order to minimize the exposure of the operators and users. Moreover they should 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. Relatively low cost and easy manufacturing are also desired.

Microfabrication techniques allow to meet the above mentioned requirements. Deposition of thin films down to the nanometre scale on rigid substrates can be easily achieved with standard techniques. Thus, initial production runs started in the Centre of Micro and Nano technology (CMi) of EPFL in 2018, and confirmed the perspective of microfabrication [3].

These first devices were produced on standard Si/SiO_2 wafer substrates and were 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. Suspicion of contribution from the silicon substrate to the total signal suggested to move forward and focus our research on the manufacturing on insulating substrates. Subsequent productions were therefore realized using polyimide as substrate. Polyimide (Kapton) was chosen 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 field of microfabrication related to metal deposition on polymeric substrates is still very much 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. 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.

For the microfabrication of the new devices (Fig. 1 (left)), shadow masks were produced. To engrave the substrate with the desirable pattern, aluminium was sputtered on polyimide substrate under vacuum pressure, as shown in Fig. 2. 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.

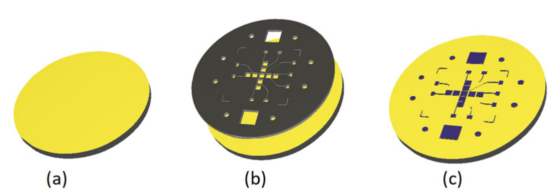

Figure 2: Shadow mask deposition technique. (a) Thin polyimide film on a silicon wafer support. (b) Shadow mask put on the top on the polyimide. (c) BPM design patterned on the top on polyimide after aluminium sputtering process.

Aluminium was chosen as sensing material because of its availability, low cost and higher SEY (δ_{max}=3.5, see Fig. 3) compared to Copper (δ_{max}=2.4 [4]). The polyimide 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.

ISBN: 978-3-95450-222-6 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2020-TUPP37

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

As mentioned in theory [5], and confirmed by a surface analysis performed at CERN (Fig. 3), 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 showed roughly the same results, especially at increasing primary particle energy, while coating the Al with an extra oxide layer (in this case 10 nm) increased the yield by 23%. 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 when the emitting surface is surrounded by air at atmospheric pressure, as shown by the experimental test at CLEAR (next section).

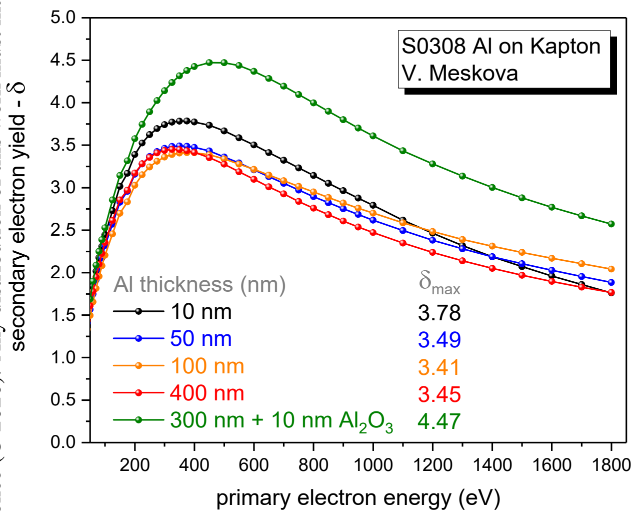

Figure 3: SEY spectra of metallized Kapton samples with different metal layer thickness. Tests were performed in a vacuum enclosure and bombardment by low energy electrons.

EXPERIMENTAL DETERMINATION OF SECONDARY ELECTRON YIELD UNDER 200 MeV ELECTRON IRRADIATION

With the objective of determining their Secondary Electron Yield (SEY), the produced devices were tested under a 200 MeV electron beam at the CERN CLEAR facility [6].

PCB frames were designed to support the BPMs during the CLEAR irradiations (Fig. 4). These frames hosted also the electrical connection between the detector and the DAQ. The connections from the BPM to the PCB were done using silver glue. Figure 4 shows the experimental setup, with three BPMs mounted on their respective PCBs, and attached to a Plexiglas support. A motorized stage was used to remotely move the support and position the different BPMs in and out the beam spot.

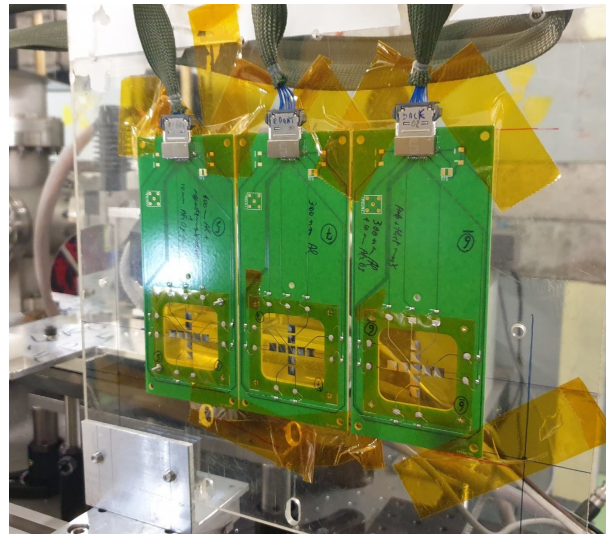

Figure 4: Experimental setup for the CLEAR irradiation tests. The BPMs were mounted on dedicated PCBs and attached to a Plexiglas support. The support, in turn, was mounted to a motorized stage which allowed positioning the devices under the beam spot.

The beam spot was focused enough to be practically fully contained in the central pad of the BPM. Beam intensity scans were performed for each of the tested BPMs in order to verify the linearity of the response and determine the SEY.

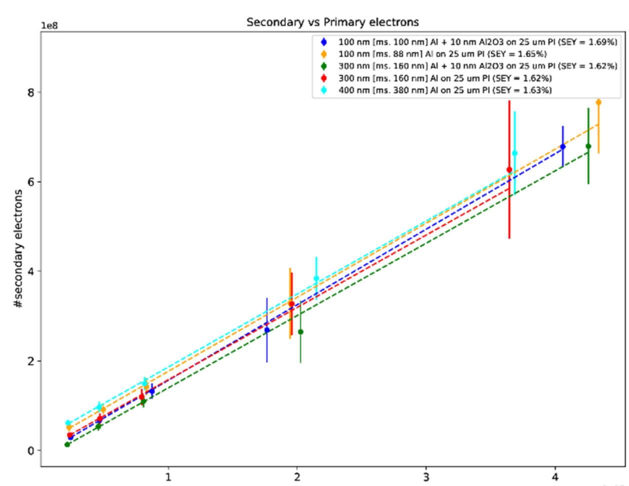

Figure 5: SEY measured for the different BPMs tested at the CLEAR facility.

Figure 5 shows the obtained results for BPMs with different aluminium layer thickness, ranging from 100 nm to 400 nm. The obtained SEY is around 1.6% in all cases, with no observed dependency on the aluminium thickness. Moreover, some of the devices featured a 10 nm Al_2O_3 layer on top of the Al layer, which did not look to have any impact on their performance.

ISBN: 978-3-95450-222-6 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2020-TUPP37

The obtained yield is in very good agreement with the values in Figure 3 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.

Table 1 summarizes the tested devices and the obtained results. The measured thickness (second column of Table 1), refers to Focused Ion Beam (FIB) measurements [7] that were done to cross-check the Al thickness deposited by sputtering and to analyse the homogeneity of the deposition (see an example in Fig. 6).

Table 1: SEY from the Aluminium Pads on 25 µm Polyimide, After Electron Irradiation at CLEAR

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

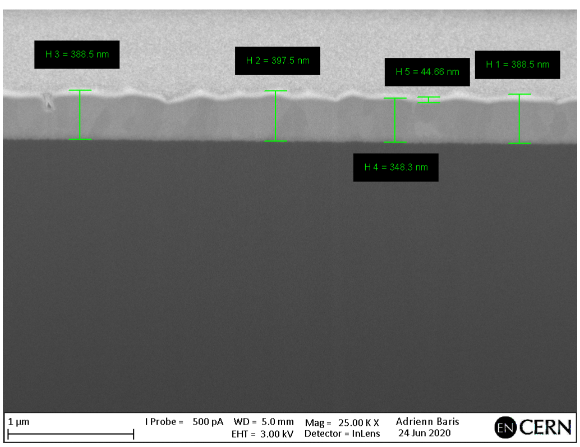

Figure 6: Focused Ion Beam (FIB) analysis on a 400 nm samples, confirming an average thickness of 380 nm.

CONCLUSION

The new devices have overall shown to work reliably 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 study, in the investigated fluence range, degradation effects were not observed. A SEY of around 1.6% was experimentally determined for all the devices, when irradiated by a 200 MeV electron beam. This represents an increase with respect to the SEY measured for the old BPMs under the same beam, which was below 1%, and is in line with the theoretical expectation of aluminium having a higher yield than copper.

These initial results, together with the intrinsic improvement in the fabrication process (see Table 2 for a performance comparison with the old devices), confirm the sputtering of thin metal films on polyimide substrate as a viable fabrication method for the next generation of BPMs in the IRRAD facility.

Table 2: Summary Table Comparing the Performance of the Old and New BPM Devices

Device Parameters	Old device (2018)	New device (2020)
Metal	Cu	Al
Metal Thickness	100 µm	100 nm
Substrate thickness	475 µm	25 µm
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

ACKNOWLEDGEMENTS

The authors wish to thank the staff of the Center of Micronanotechnology (CMi) of the École Polytechnique Fédérale de Lausanne (EPFL) for providing their assistance during the cleanroom production. In addition, we would like to express our thanks to the colleagues of the TE and EN department at CERN for the SEY and the Focused Ion Beam (FIB) measurements respectively.

REFERENCES

[1] F. Ravotti *et al.*, "The Beam Profile Monitoring System for the CERN IRRAD Proton Facility", in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16)*, Barcelona, Spain, Sep. 2016, pp. 825-828. doi:10.18429/JACoW-IBIC2016-WEPG75

[2] H. Seiler, "Secondary electron emission in the scanning electron microscope", *J. Appl. Phys.*, vol. 54, no. 11, pp R1-R18, 1983. doi:10.1063/1.332840

[3] J. Bronuzzi *et al.*, "Beam profile monitor devices using microfabricated metal thin-films", CERN, Geneva, Switzerland, AIDA-2020-NOTE-2019-003, 2019.

[4] V. Baglin *et al.*, "The Secondary Electron Yield of Technical Materials and its Variaton with Surface Treatments", in *Proc. 7th European Particle Accelerator Conf. (EPAC'00)*, Vienna, Austria, Jun. 2000, paper THXF102, pp. 217-221.

[5] L. Jiangtao *et al.*, "Secondary electron emission influenced by oxidation on the aluminum surface: the roles of the chemisorbed oxygen and the oxide layer", *Plasma Sources Sci. T.*, vol. 27, no. 4, pp. 044002, 2018. doi: 10.1088/1361-6595/aab74b

[6] D. Gamba *et al.*, "The CLEAR user facility at CERN", *Nucl. Inst. and Meth. In Phys. Res., A,* vol. 909, pp 480-583, 2018. doi: 10.1016/j.nima.2017.11.080

[7] A. Korsunsky *et al.*, "Residual stress evaluation at the micrometer scale: Analysis of the thin coating by FIB milling and digital image correlation", *Surf. Coat. Tech.*, vol. 205, pp. 2393-2403, 2010. doi:10.1016/j.surfcoat.2010.09.033