Ultra high-level Radiation Monitoring with Thin Metal Nano-Layers

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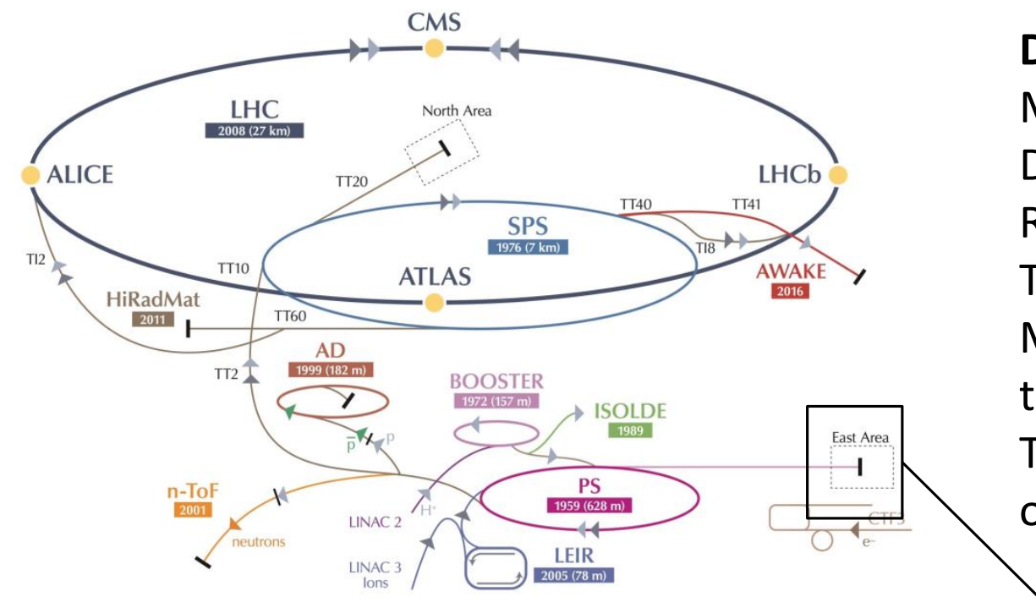
ABSTRACT

At CERN Proton Irradiation Facility (IRRAD), electronic components and systems are exposed to particle beams, in order to assess their level of radiation tolerance and reliability when operating in a radiation environment. 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

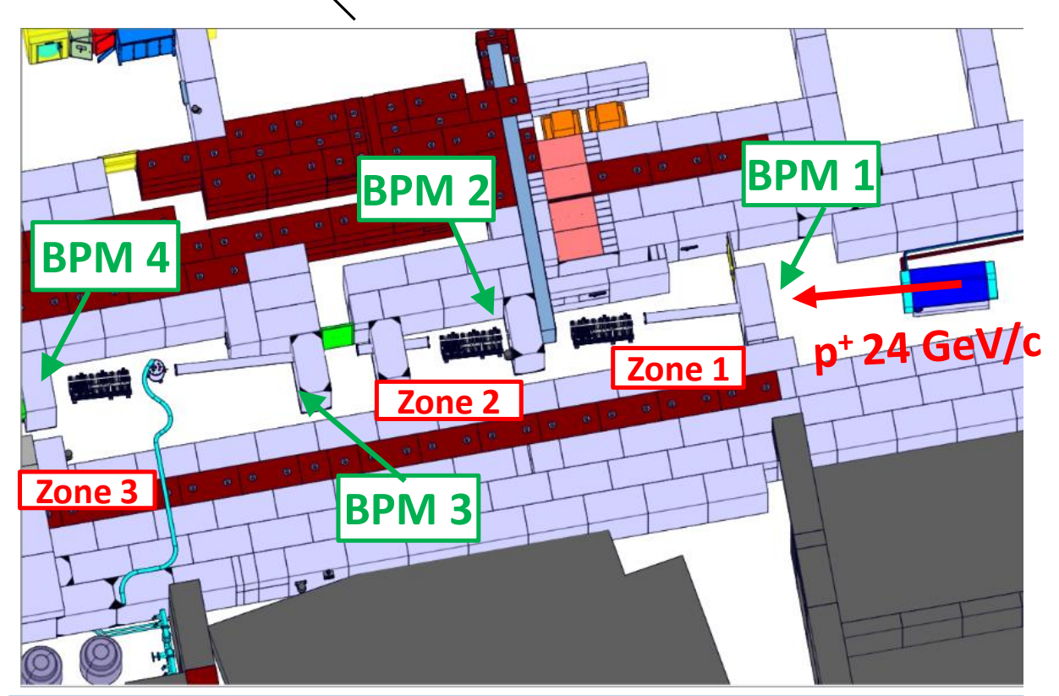


DETECTOR SPESIFICATIONS
Measurement: Beam profile
Dynamic range: 10^9 - 10^{11} p/cm^2
Resolution: 4500 um
Typical operation: Transfer Line
Momentum: 24GeV/c primary beam of the PS
Time structure: 2.4s cycles with a flat top of about 400ms (PS proton extraction)

The BPMs are installed on every irradiation system of the IRRAD facility and exposed to the beam together with the samples to be irradiated.

Standard BPMs **drawbacks**:

- **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.
- 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, when all the irradiation systems of IRRAD are positioned in beam
- 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



Location of multi-pads BPM detectors in IRRAD

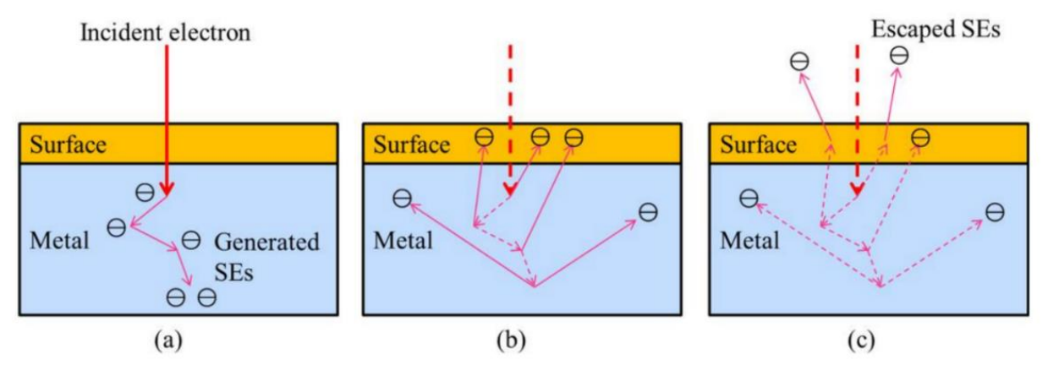
Requirements:

1. Withstand high radiation levels (~10^{18} protons per year).
2. Made of short radioactivity materials (to minimize the exposure of the operators and users).
3. Beam monitoring: permanent and real time as the data are used by the CERN Control Centre (CCC) to tune the beam extraction parameters (e.g. shape, position, charge)
4. Thin to avoid the multiple scattering and any interference with the projectile beam, but thick enough to allow easy handling.
5. Low cost, easy manufacturing

SENSING PRINCIPLE

When a charged particle beam strikes a metallic surface, two types of SE are generated:

- true SEs from interaction with surface
- Backscattered e^- (BSEs) from deeper regions



The **SEE process** consists of three steps (schema above).

a) The target metal absorbs the incident particles and the inner electrons become excited. Some of these electrons receive enough energy to be knocked out from their atoms. The most energetic electrons, or delta rays, can themselves produce secondary ionizations.

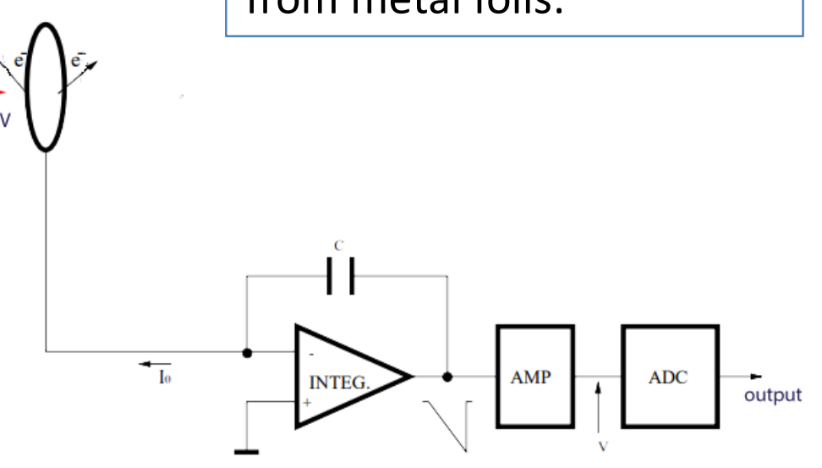
b) The secondary electrons diffuse toward the metal surface with energy loss through inelastic collisions. The probability of reaching the surface decreases with the depth at which the secondary electrons are created so, in practice, only electrons generated close to the surface can contribute to the emission (SEE is, then, a surface effect).

c) Some of the SE go over the surface potential barrier and escape.

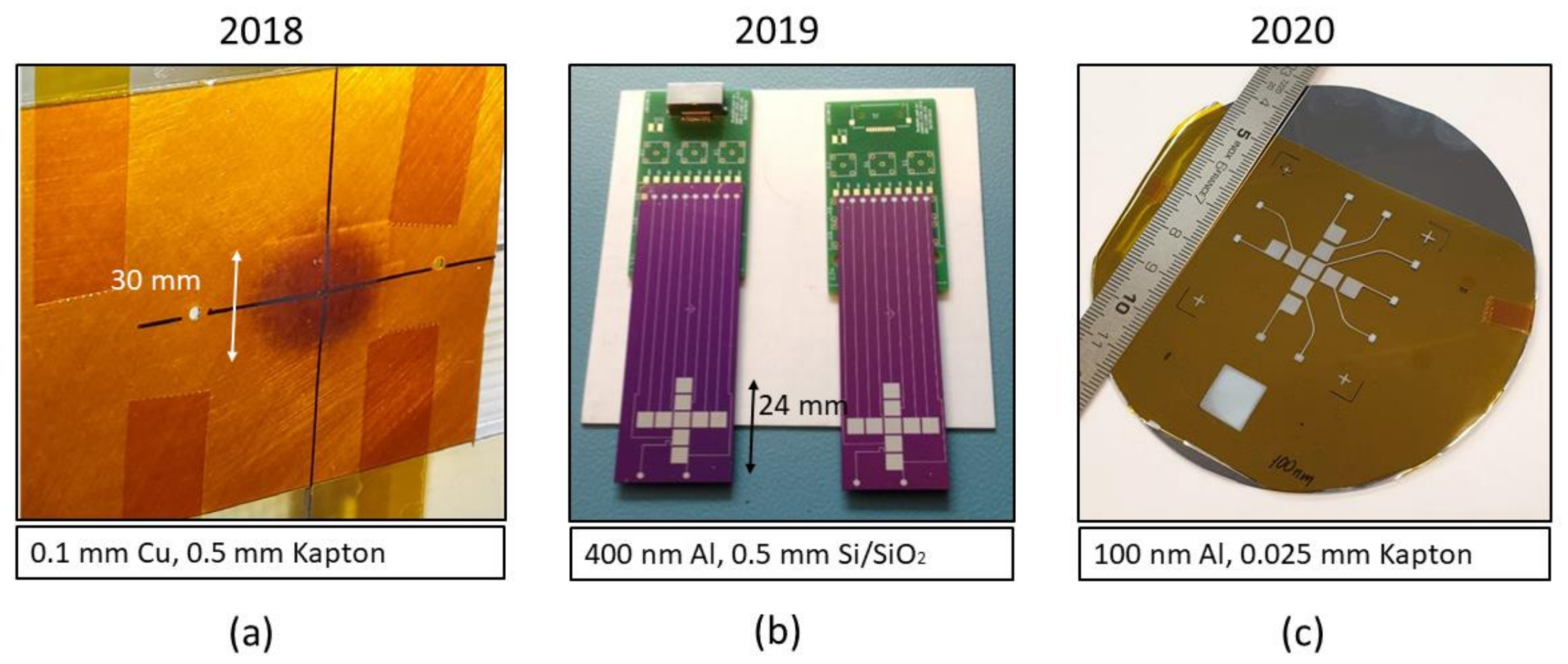
Parameters that influence SEE:

- Primary energy
- Sensing material
- Oxide/Nativre oxide
- Vacuum
- Angle

Circuit for SEs extraction from metal foils:



DESIGN AND FABRICATION



0.1 mm Cu, 0.5 mm Kapton
400 nm Al, 0.5 mm Si/SiO₂
100 nm Al, 0.025 mm Kapton

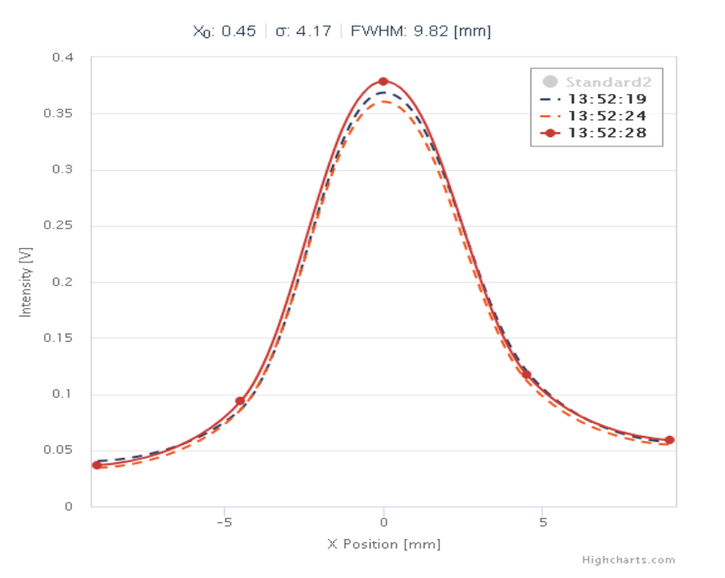
(a) (b) (c)

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.

2019

Findings from first prototypes (Si/SiO2 substrate)

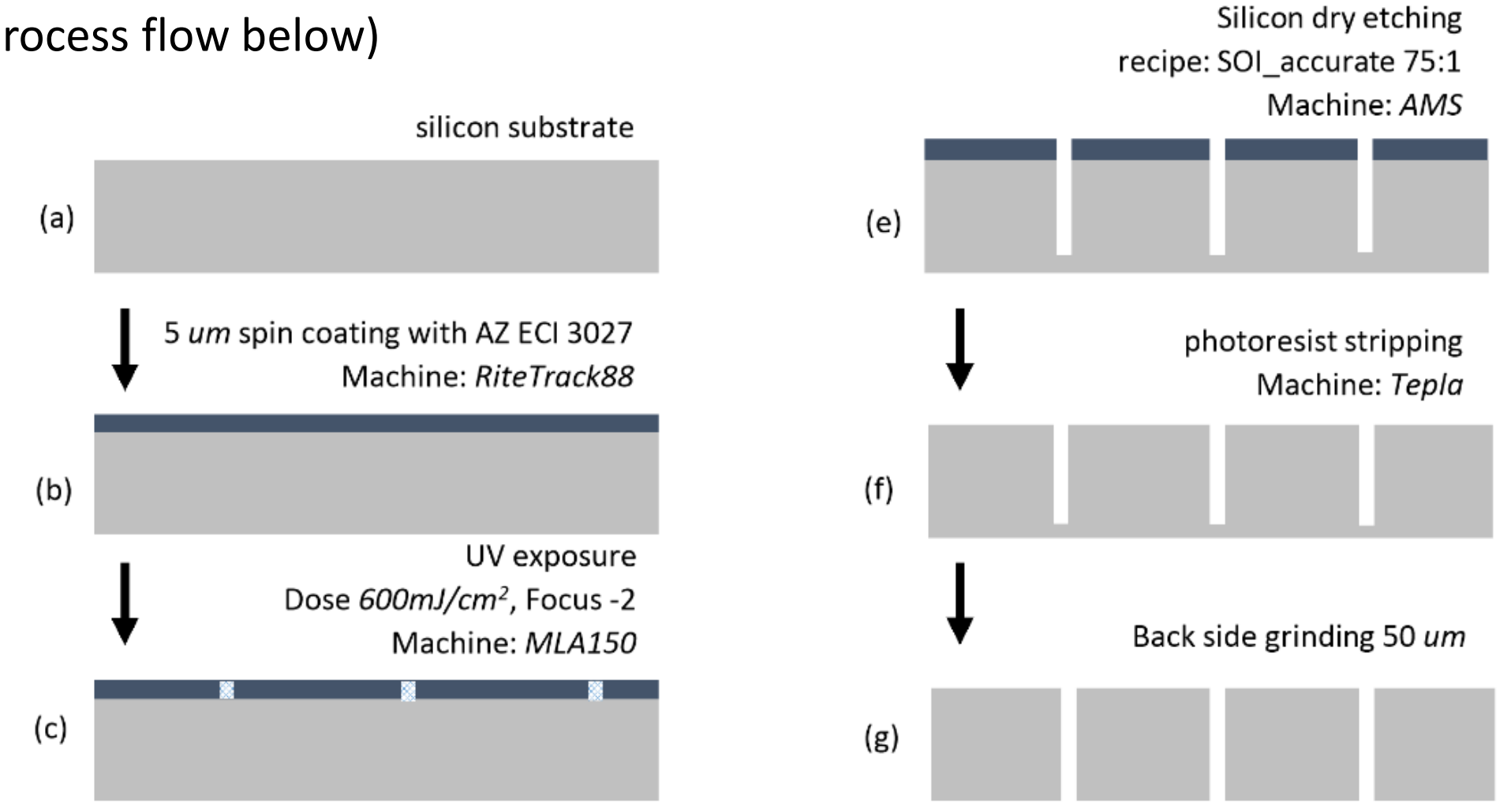
- multiple metal layers nor isolation of the sensing material influence the signal intensity.
- Suspicion of contribution from the silicon substrate to the total signal suggested to move forward and focus our research on the manufacturing on insulating substrates. Subsequent productions were therefore realized using polyimide as substrate.



Profile recorded during the experimental run of 2019 in CLEAR

2020

Development of BPMs with **shadow mask** technique (Process flow below)



(a) silicon substrate

(b) 5 *um* spin coating with AZ ECI 3027
Machine: *RiteTrack88*

(c) UV exposure
Dose *600mJ/cm²*, Focus -2
Machine: *MLA150*

(d) photoresist development
Machine: *RiteTrack88*

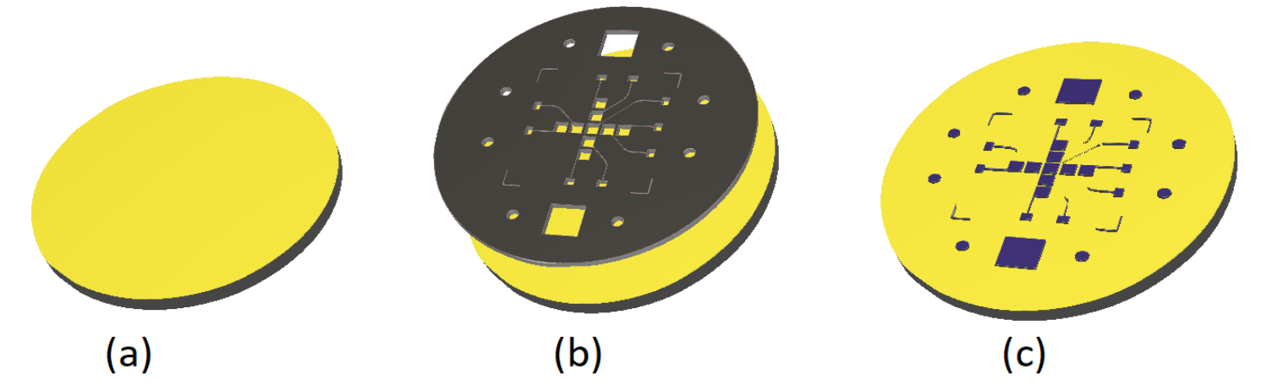
(e) Silicon dry etching
recipe: SOI_accurate 75:1
Machine: *AMS*

(f) photoresist stripping
Machine: *Tepla*

(g) Back side grinding 50 *um*

New BPM **advantages**:

- 200 times thinner (less invasive when interacting with the beam)
- present an enhanced radiation tolerance (avoids gluing)
- higher sensitivity to the beam (Al has higher SEY than copper)
- More durable



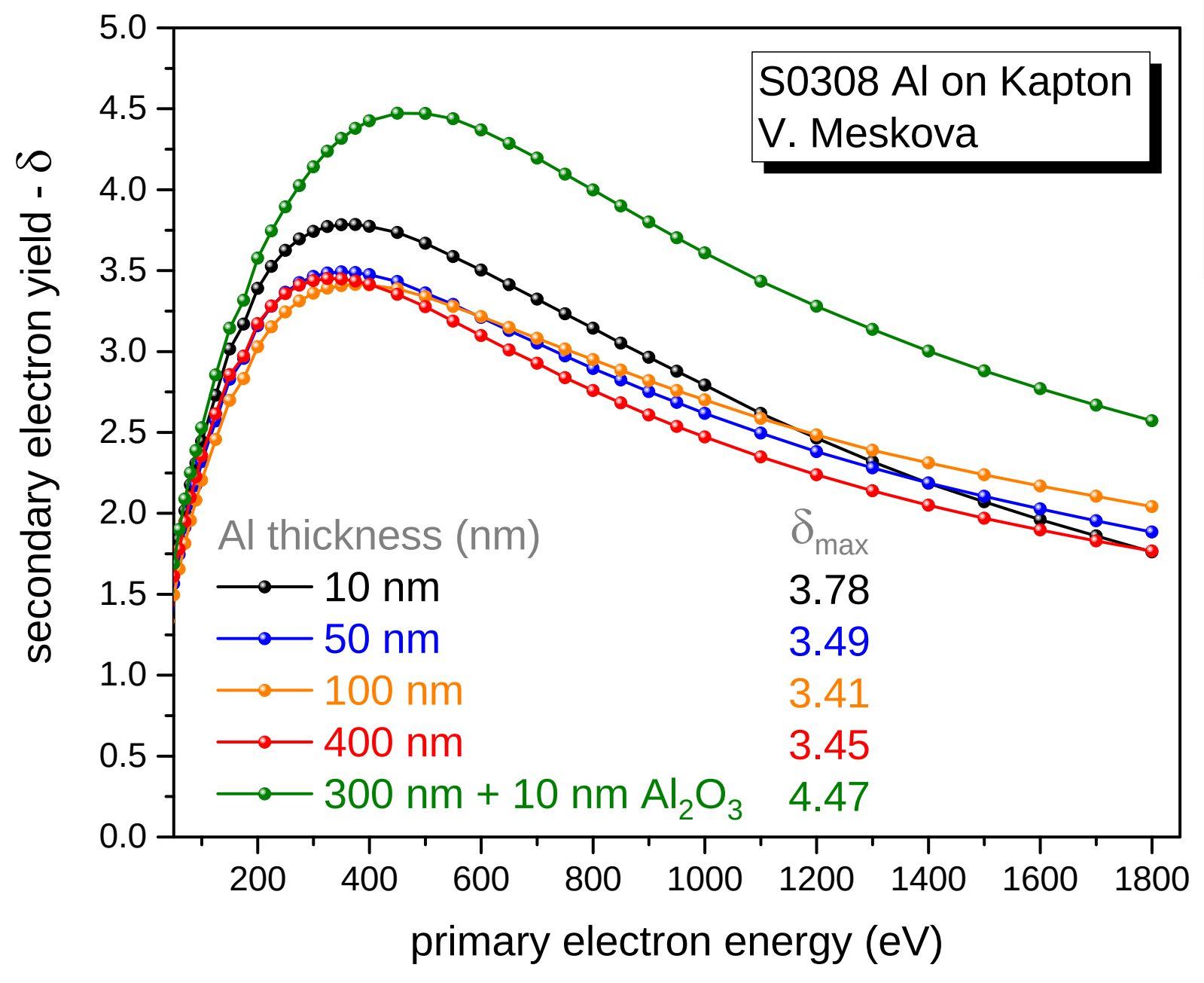
Shadow mask deposition technique. (a) Thin polyimide film on a silicon wafer support. (b) Shadow mask is put on the top on the polyimide. (c) BPM design patterned on the top on polyimide after aluminium sputtering process.

Cleanroom restrictions:

- mask fragility
- target (metal) thickness limit
- thin polyimide film manipulation
- mask fixation on the substrate
- machine power modes (burning issues)
- support size (usually wafer shaped

LABORATORY CHARACTERIZATION

SEY EVALUATION



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

Aluminum:

- availability,
- low cost
- higher SEY ($d_{max(Al)}$=3.5 vs $d_{max\ (copper)}$=2.4)

RESULTS

- SEY of Al in vacuum is **independent** of the thickness of the metal, especially at increasing primary particle energy
- Extra oxide layer **increased** the yield by 23% (vacuum) (increase the SEY, sensitivity)

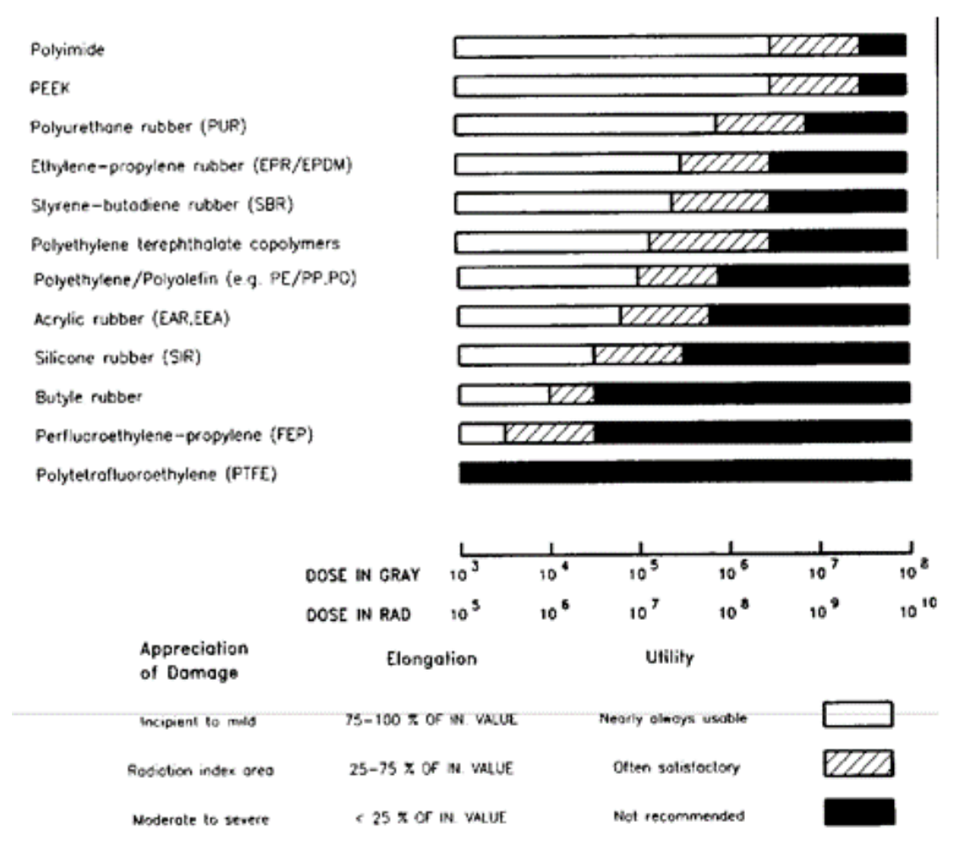
	SEY [%]
100 nm Al (Commercial tape)	3.4
10 nm Cr	2.4
400 nm Al Si 1%	3.5
800 nm Al Si 1%	3.5

SUBSTRATE EVALUATION

Polyimide (Kapton):

- thermal and chemical stability,
- low dielectric constant,
- high electrical resistivity,
- possibility of getting very thin film
- increased radiation tolerance.

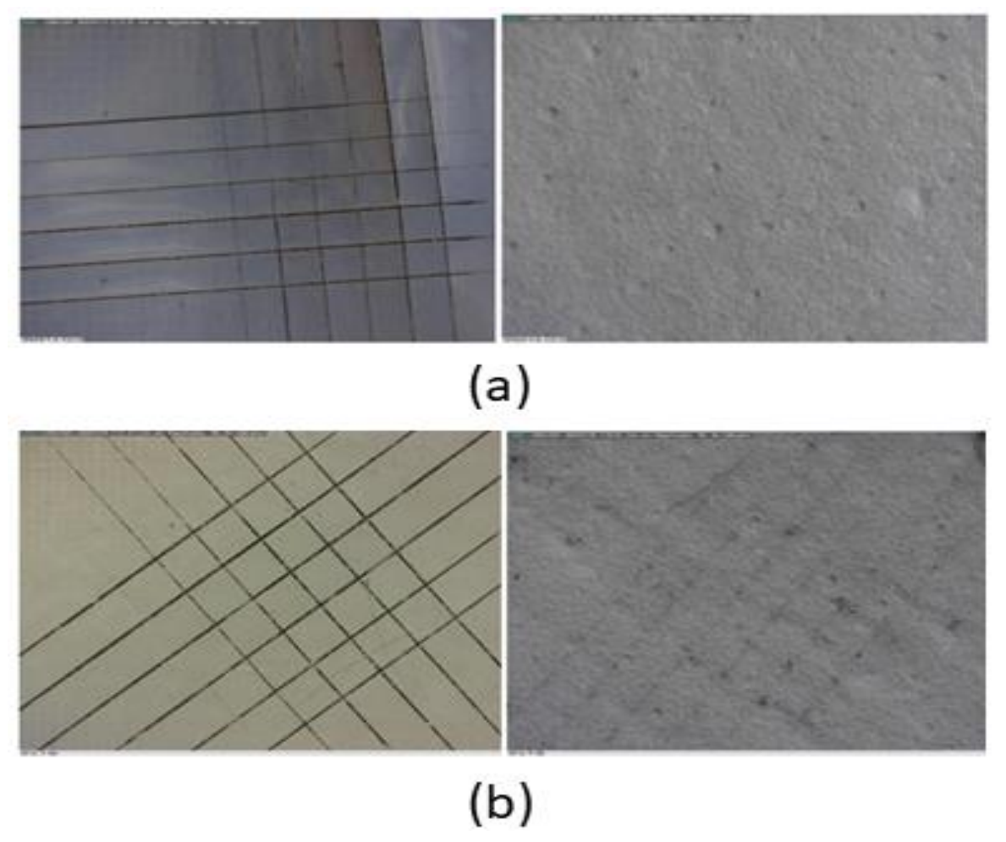
Classification of the materials according to their radiation resistance:



ADHESION EVALUATION

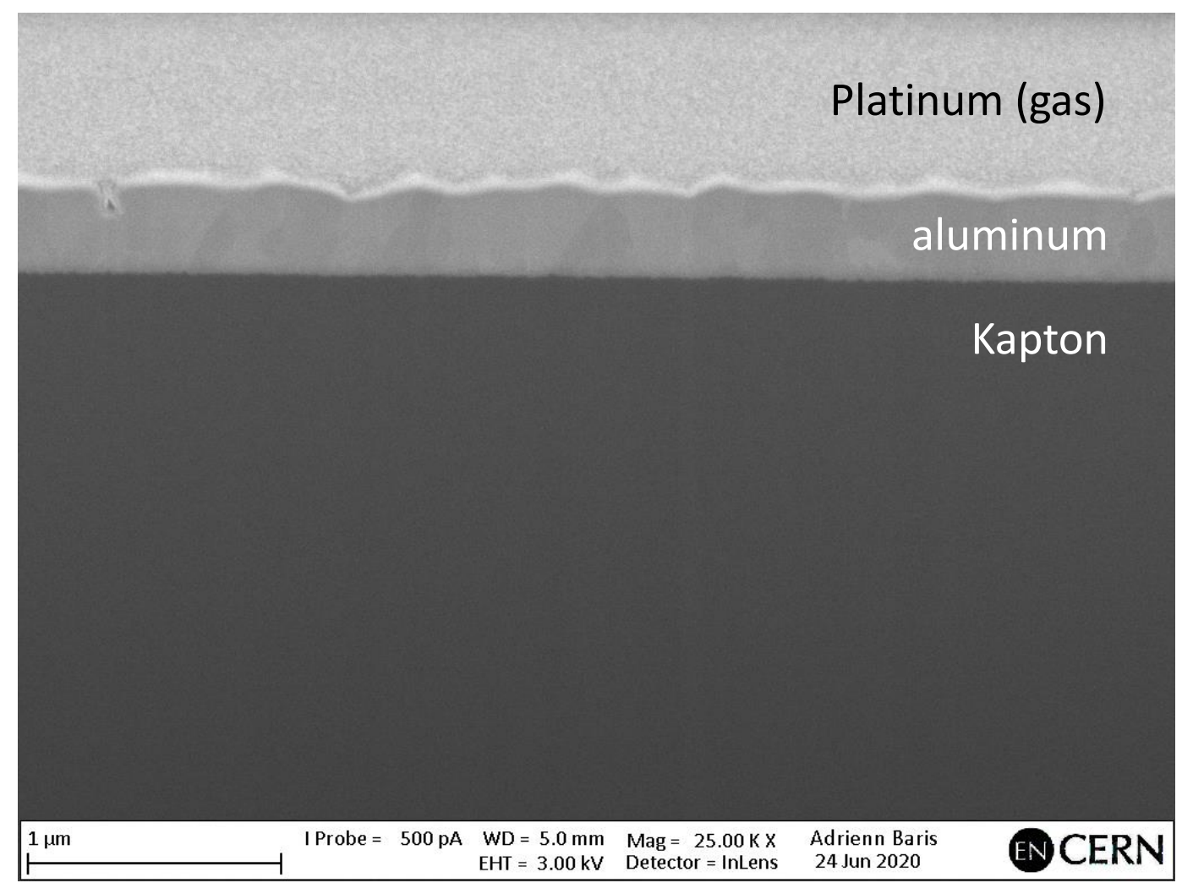
Adhesion improvement by polyimide treatment under vacuum pressure with:

- oxygen plasma
- titanium



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.

SENSING MATERIAL DEPOSITION EVALUATION



Example of Focused Ion Beam (FIB) analysis on 400 nm sample (measured 380 nm (table)).

Nominal Al thickness + Al_2O_3 [nm]	Deposition power [W]	Measured thickness [nm]
400	200	380
300 + 10	200	166 + 17
100	200	122
100	2000	80
100 (commercial)	-	88
50	200	52
10	200	49

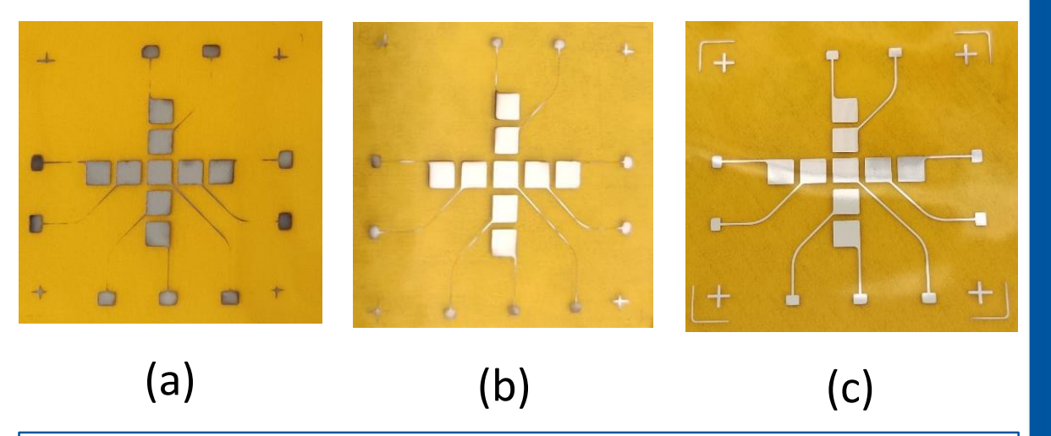
Nominal thickness: Indicated in the sputtering machine
Measured thickness: Focused Ion Beam (FIB) measurements

RESULTS

- Cross-check the Al thickness deposited by sputtering
- Analysis of the homogeneity of the deposition

REPRODUCIBILITY EVALUATION

Machine	Deposition	Dep power	No samples	Dep time
SPIDER600, cluster system	Sputtering	200 W	20 (in a row)	14 min
DP650,single chamber multi-target	Sputtering	400 W	One-by-one	16 min
EVA760, e-gun	Evaporation	200 W	8 (same time)	1h30

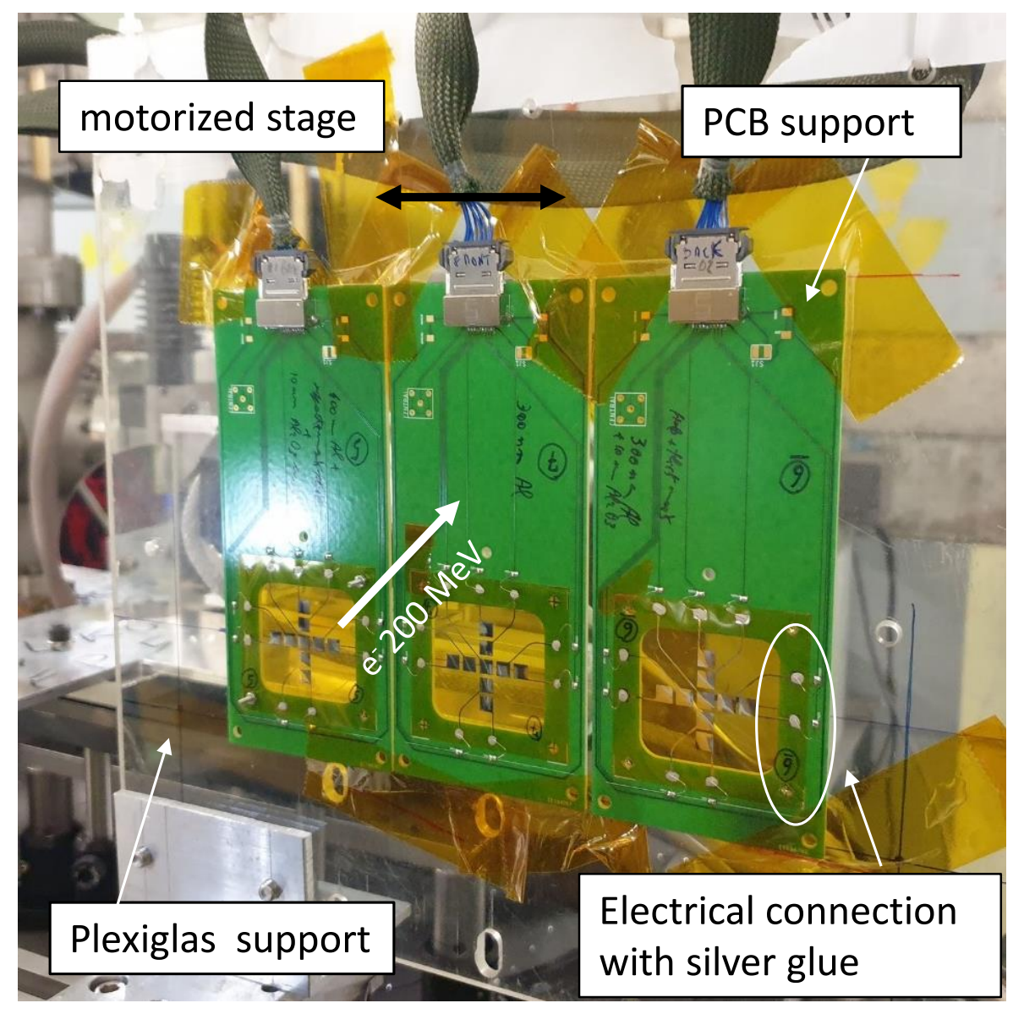


100 nm Al deposited by the three different machines. (a) SPIDER600, (b) DP650, (c) EVA760.

- Best deposition obtained by evaporation.

IRRADIATION TESTS

CERN CLEAR facility 200 MeV e beam

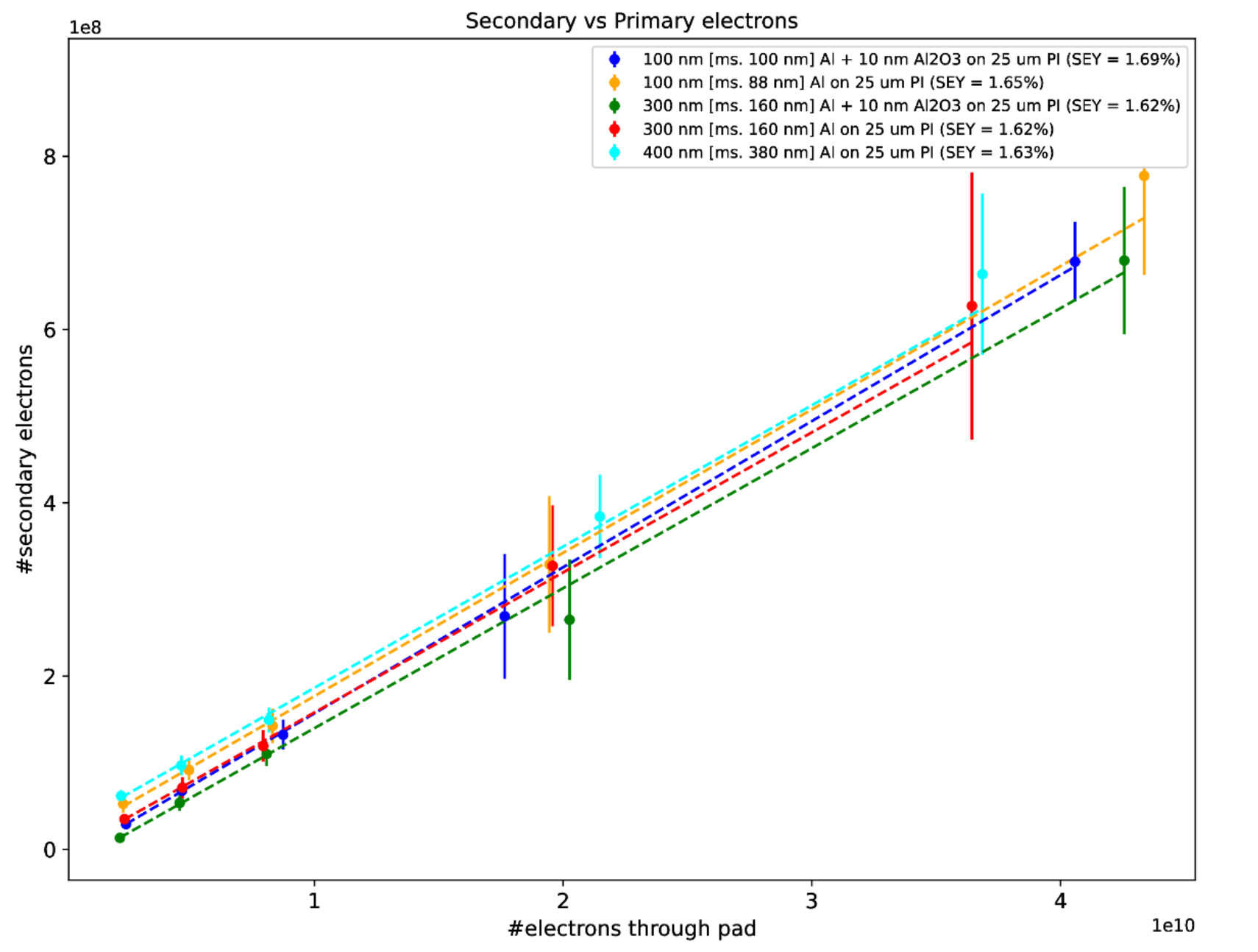


Intensity scan in THz focused beam on central pad with:
~ 0.4 nC- 6 nC

- verify the linearity of the response
- determine the SEY

RESULTS

- SEY = ~1.6% independent of Al thickness or extra oxide (100nm, 300nm, 400 nm metal, with or without Al_2O_3)
- Yield in good agreement with SEY evaluation plot (see SEY evaluation section figure for hundreds of MeV primary particle energy)
- SEY in air for copper is lower than 1 % (old devices)



Experimental SEY from different Al pads, sputtered on 25 um polyimide

SUMMARY OF THE PERFORMANCE

	2018	2019	2020
Substrate	FR4	Si/SiO_2 wafers	Kapton
Active material	Cu	Al	Al
No of sensing layers	6	2	1
Metal thickness	100 um	400 nm	100 nm
Substrate thickness	475 um	525 um	25 um
Total material budget in IRRAD	8 mm	525 um	0.5 mm
Theoretical SEY (maximum)	2.4	3.5	3.5
Measured SEY (200 MeV e^-)	<1%	1.6%	1.6%
Radiation-induced degradation	observed	not observed with electrons	not observed with electrons

CONCLUSIONS

- New fabrication technique developed (microfabrication)
- Devices more transparent (less material budget) and sensitive (higher SEY)
- Oxide coating affect SEY in vacuum but not in atmospheric air
- Evaporation is the most promising metal deposition technique

Future vision:

- Radiation hardness test in proton beam
- Radiation test in proton beam with lower energy

EP-DT
Detector Technologies

CMi EPFL Center of MicroNanoTechnology

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ATTRACT