

SURFACE EFFECTS FOR ELECTRON CLOUD*

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Abstract

The ability of a low Secondary Electron Yield coating to mitigate detrimental electron cloud effects potentially affecting accelerators' performances has been convincingly validated. The interference of such coatings with other properties required to accelerator constructive materials (i.e. vacuum compatibility, magnetic permeability, high surface conductivity, etc.) is of great concern and has recently attracted a lot of interest and studies. For instance, the severe impedance budget constraint requires the highest conductivity in the surface layers within the skin depth (typically some μm) characteristic of the e.m. interaction. It is therefore of utmost importance to define the minimum thickness one overlayer should have in order to be an effective electron cloud mitigator and minimize its impact to surface conductivity.

To this purpose, XPS and Secondary electron spectroscopy have been simultaneously applied to the prototypical system formed by increasing coverages of amorphous Carbon (a-C) deposited on atomically clean Cu. XPS has been successfully used to qualify and quantify the a-C thickness, rendering possible a detailed coverage dependent study. A significantly thin a-C layer, of about 5 to 7 nm, is surprisingly enough to lower the secondary emission properties of the whole system below 1. This observation opens up the possibility to develop, on industrial scale, thin enough electron cloud mitigators that will not affect impedance issues.

INTRODUCTION

Electron clouds - generated in accelerator vacuum chambers by photoemission, residual-gas ionization, and secondary emission - can affect the operation and performance of hadron and lepton accelerators in a variety of ways. They can induce increases in vacuum pressure, emittance growth, beam instabilities, beam losses, beam lifetime reductions, or additional heat loads on a (cold) chamber wall [1, 2]. When electrons are accelerated by the positive passing beam in the direction perpendicular to it, they gain energy and, when finally hit the vacuum chamber, they create other secondary electrons at the accelerator walls. The number of electrons created during such occurrence is governed by a material surface property called Secondary Electron Yield (SEY). SEY is defined as the ratio between the number of emitted electrons (also called secondary electrons) to the number of incident

electrons (also called primary electrons) and is commonly denoted by δ . When the effective SEY at the chamber is larger than unity, the electron population rapidly grows with successive bunch passages. This can lead to a high electron density and hence, to Electron cloud effects (ECE). One powerful method to control and overcome such effects is to ensure a low SEY, ideally always less or just around one. Different solutions have been proposed to this end, one being to treat the surface by Laser Ablation Surface Engineering (LASE) [3, 4] or by TiZrV [5, 6] or amorphous Carbon (a-C) coating [7]. LASE surfaces have a low SEY due to their particular micro and nano-metrical grooves morphology. TiZrV is a Non-evaporable Getter (NEG) that, once activated at $\sim 180^\circ\text{C}$, not only is an extremely powerful vacuum pump, but shows a SEY typically less than 1. Also a-C has a quite low SEY thanks to its intrinsic properties connected to the sp^2 Carbon bonds typical of graphite-like materials [8–10].

All those coatings, used as ECE mitigation remedies, must necessarily be compliant to a number of stringent specifications [11]. Material conductivity, magnetic properties, vacuum, constructive compatibility, impedance issues are among the most stringent ones, suggesting a more general approach when qualifying a material to be used in accelerators. In terms of vacuum constructive compatibility, for example, NEG, LASE and a-C do behave quite differently. Activated NEG is an active pump that can ensure superb vacuum performances if sufficiently thick (more than a μm to grant some reservoir for pumped gasses). However, for space reasons, it is not always easy or possible to implement its activation and it is not yet known its ability to pump at cryogenic temperatures. LASE is certainly vacuum compatible and does not require activation. Recently, it was shown [12] that ices cryo-sorbed on its surface, desorb in a temperature interval much larger than the very sharp one observed from a flat surface. The cryogenic vacuum properties of LASE augmented effective surface are still under study.

One more intriguing example, where material constraints are challenging, relates to the surface conductivity required to build an accelerator within a given impedance budget. LASE, TiZrV and a-C have a significantly reduced surface conductivity in respect to Cu and their use may indeed have a significant impact on this issue [13, 14, 16, 17]. Impedance issues require to minimize surface resistance in the first few microns, the typical skin depth of the e.m. interaction between beam and materials. One line of research is then to try thinning the ECE mitigator coating well below the size of this skin-depth. A very thin coating, even if badly conduc-

* Work supported by INFN National committee V through the “MICA” project.

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tive, will not add any significant contribution to the machine impedance. This coating thickness reduction is indeed possible even if it may significantly affect other properties: a thinner LASE will have smaller grooves and porosity and will possibly be less effective as ECE mitigator, a very thin NEG will have a significantly reduced pumping capacity. Synergic to this research line, at the Frascati National Laboratory, we launched a detailed study to define more precisely how thin a coating should be to act as an effective ECE mitigator. We report here some preliminary data that refer to the case of a-C grown on polycrystalline atomically clean copper. The data are relative to a laboratory designed surface science experiment and, therefore, consequences on real coatings, to be performed on industrial scale, must be extrapolated with caution.

EXPERIMENTAL

The experiment was performed in the Material Science Laboratory of the INFN-LNF at Frascati (Rome, Italy), in an ultra-high vacuum system routinely used for XPS/SEY experiments. It consists of a preparation chamber and an analysis chamber, both having a base pressure of 1×10^{-10} mbar and is described in some more details in the literature [1, 8–10, 18]. Polycrystalline Cu substrate was cleaned by cycles of Ar^+ sputtering at 1.5 kV and prolonged thermal annealing at temperatures of 800-1000 K. Atomically clean Cu substrate, even if not representative of realistic carbon coatings for accelerators, was chosen to minimize spurious effects (like contaminations or electron beam induced SEY modification [10]) and be able to single out only the desired phenomenon.

Carbon was deposited by an electron beam evaporator (Tetra GmbH.) from a 99.999 purity C rod with a stable rate of ≈ 0.03 nm/min. This method, though unpractical for industrial productions, allows a very careful monitoring of thickness, especially at very low coverages, and produces well controlled and clean a-C films. During C evaporation, the background pressure was $\leq 5 \times 10^{-10}$ mbar. C layers were deposited in steps and after each evaporation XPS and SEY analysis were performed. XPS measurements were carried out by using an Omicron EA125 analyzer to reveal the photoelectrons excited by the non monochromatic radiation of an Mg K ($h\nu = 1256$ eV). SEY is measured as described in detail in Refs [1, 8–10]. SEY is, by definition, equal to $I_{out}/I_p = (I_p - I_s)/I_p$, where I_p is the current of the primary electron beam hitting the sample, I_{out} is the current of the electrons emerging from the sample and I_s is the sample current to ground, as measured by a precision amperometer. In brief I_p (some tens of nA) was measured by means of a Faraday cup positively biased, whereas I_s was determined by biasing the sample at -75 V. SEY curves as a function of the primary energy E_p are characterized by a maximum value (δ_{max}) reached at a certain energy (E_{max}). As already discussed [18], we can correctly measure SEY starting from few hundreds of meV above the sample work function. SEY measured curve drops from 1 to 0 within an E_p region whose

width (0.85 eV) is determined by the thermally broadened electron beam emitted by the thermoionic cathode. SEY measurements are only valid after this drop, which occurs at an energy related to the surface vacuum level. XPS was used to quantitatively define a-C coverage by looking at the increase of the C 1s signal and the concomitant Cu 2p decrease during deposition, which is assumed to be homogeneous. Standard practice XPS analysis procedures [20] was used to estimate, after each deposition, the carbon layer quality and thickness. This standard practice in XPS analysis is based on reasonable assumptions on the electron mean free path in a-C and in Cu [19], on a close to layer by layer growth and by assuming that the Cu core level intensities follows a Beer-Lambert law in a layer on a substrate model [20, 21].

RESULTS

The prototypical system we decided to investigate - namely a-C on atomically clean polycrystalline Cu - offered the possibility to follow XPS and SEY data as a function of deposition time. XPS analysis [21], not shown here, allows us to determine with an experimental uncertainty of approximately 30 %, the thickness, in nm, of the a-C film. XPS also confirms that the a-C film is mainly sp^2 in character and can be indeed assumed to be closer to a distorted graphite than to diamond. Once XPS allows us to define the thickness of the various a-C films deposited, we can plot the evolution of SEY versus a-C coverage.

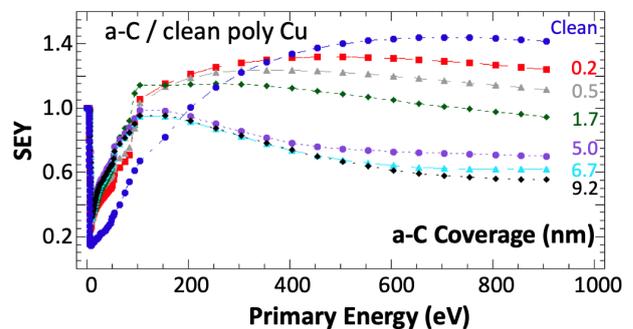


Figure 1: SEY evolution at different a-C thicknesses.

This is shown in Fig. 1, where we can observe:

- The SEY of the atomically clean polycrystalline Cu shows a δ_{max} of ~ 1.4 at around $E_{max} \sim 640$ eV consistent with literature results [1, 18, 22];
- For the initial low coverages of a-C, we notice some significant effect, specially in the very low energy part of the SEY spectrum. This confirms how this low energy range of SEY is sensitive to very small quantities of adsorbates, and even of contaminants [22] in the sub-monolayer regime;
- Increasing carbon coverages, the low energy part of the SEY spectrum does not change significantly any more, while the overall curve is severely modified in shape, δ_{max} and E_{max} ;
- δ_{max} is steadily reduced from ~ 1.4 (clean copper) to less than 1 (after ~ 6 nm of a-C);

- Also E_{max} is significantly and steadily reduced with increasing a-C thickness going from ~ 650 eV (clean copper) to ~ 100 eV after already 6 nm.
- For intermediate coverages, the δ curve can be considered as a superposition of the modified yield of the substrate and the SEY of the overlayer.

We report, in Fig. 2, δ_{max} and E_{max} versus the estimated a-C coverage. On increasing the thickness, δ_{max} goes from the value of clean Cu, to the one typically measured for graphite and a-C [8, 9]. On the other hand, E_{max} starts from the clean Cu value but ends up significantly lower than what is observed in graphite. Something similar, if not so effective, was observed for E_{max} after repeated Ar^+ sputtering cycles on otherwise crystalline Graphite, implying that E_{max} could get reduced by increasing disorder (and/or amorphization) [9].

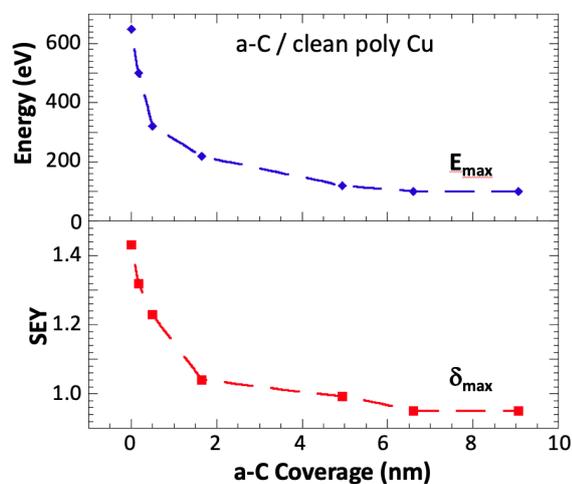


Figure 2: δ_{max} (bottom panel) and E_{max} at different a-C thicknesses. $\Delta\delta_{max}/\delta_{max} = 5\%$ and $\Delta E_{max}/E_{max} = 10\%$

For the test case studied here, SEY curve does not seem to vary after that 5 to 6.5 nm of a-C were deposited on the atomically clean Cu surface. After this coverage, SEY is dominated by the overlayer signal.

DISCUSSION

Here, we are reporting results from a prototypical system which can not be used for production both due to the use of an atomically clean Cu substrate and to the EB-PVD used to evaporate Carbon. Clearly, our results should be confirmed and extended to other systems and materials. They are still extremely challenging and call for a reexamination of the coating thickness normally used to mitigate e-cloud. Even with safety margins (up to 5 to 10 times in thickness) typical of an industrial production, it is indeed possible to have an ECE mitigator coating which only marginally affects the surface resistance within the skin depth and therefore is fully compliant with the impedance budget. Maybe, magneto-sputtering deposition technique, which is routinely used for coating accelerator pipes, is not easily controlled in the very low coverage regimes and could either been implemented /

modified or even substituted with coating techniques more apt to control the quality in the very low coverage regime. What is here clear, for the first time in this context, is that 5 to 6.5 nm of a-C coating are enough to finally reduce SEY below one. This observation would call for a technological effort to be able to reproduce and safely control such low thickness coatings on industrial scale with the aim to finally produce ECE mitigators that do not affect impedance.

CONCLUSIONS

We have studied a prototypical system formed by a thin C layer incrementally evaporated, at low rate, on a polycrystalline Cu substrate. We address the question on what is the minimal layer thickness that defines the SEY of the system as the one of the overlayer and not of the substrate. We demonstrate that, in this case, 5 to 6.5 nm are sufficient to reduce the SEY from 1.4 (copper) to ~ 1 (a-C). More data are needed to confirm this to be a general trend, valid also for different substrates, eventually with significantly higher SEY and overlayer materials. The results open up the possibility to design ECE mitigators fully compliant with impedance issues.

ACKNOWLEDGMENT

We thank for technical assistance V. Tullio, M. Pietropaoli, V. Sciarra and G. Viviani from the DAΦNE-L support group.

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