

INGREDIENTS FOR THE UNDERSTANDING AND THE SIMULATION OF MULTIPACTING

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Abstract

The resonant multiplication of electrons in accelerator is known to degrade the performance of devices where appropriate conditions are fulfilled between, the oscillating electrical field, the dimensions of the vessel and the ability of the surface to multiply electrons. This latter property is described by the secondary electron yield (S.E.Y.). Although the S.E.Y. of most pure materials are known since the beginning of this century, they are of little use for the understanding of the multipacting in accelerators which are constructed using technical metals such as stainless steel. For these reasons a dedicated instrument was developed in the former ISR vacuum group to measure the S.E.Y. of the most common compounds encountered in accelerators. The measurement method and the results obtained for various materials will be presented for different realistic surface preparations. Results concerning the energy distribution of the emitted electron will also be shown as well as recent measurements made in an experimental beam line in EPA.

1 INTRODUCTION

The electron multiplication on surfaces exposed to an oscillating electromagnetic field causes the phenomenon of multipacting, which can degrade significantly the performance of particle accelerators. Such phenomena have been described in many accelerators, especially in accelerating cavities and more recently in the SPS where measurable pressure increases have been observed during the circulation of LHC type proton beams. In this case the electric field generated by the passing bunches can accelerate electrons which at their impact with the vacuum chamber create secondary electrons and stimulate neutral molecules desorption. Among other parameters, the multiplication of the incident electrons depend on the secondary electron yield (S.E.Y.) of the bombarded surface which has been measured for most pure metals before 1940¹²³⁴. However these data are not applicable to the real environment of accelerators built out of technical materials e.g. stainless steel, aluminum alloys or copper covered with their natural oxide and contaminants. In this contribution we will present the experimental set up and the procedure used to study the S.E.Y of technical materials then show some measurement results concerning these. Lastly, possible methods used to limit the secondary electron yields will be addressed and their effectiveness discussed in the context of a possible use in an accelerator.

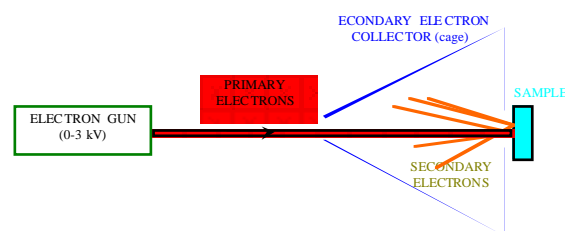


Figure 1
The experimental set-up

2 THE EXPERIMENTAL SET UP AND PROCEDURE

The measurement principle consists in recording simultaneously the current at a sample and at a secondary collector called cage while bombarding the sample by primary electrons with an energy variable between 60 and 3000 eV. A scheme of the set up is shown on Figure 1 and a top view of the system on Figure 2.

The measurement assembly is mounted in a bakeable, all metal U.H.V. system pumped by a 260 l/s turbomolecular pump and equipped with calibrated Bayard Alpert gauge and residual gas analyser. A leak valve is used to feed various gases in the system in order to modify the studied surface using ion bombardment. The samples (maximum 13) are mounted on a rotatable sample holder.

A very important feature for the measurement of the secondary electron yield is to control carefully the electron dose needed for a measurement. It will be shown



Figure 2
The experimental system

later in this paper that the S.E.Y. is strongly dependent on the dose of primary electrons. For this reason the measurements are made using short pulses (typically 30 ms) of low primary electron current (some nano amperes). Under these conditions, the total dose of electrons needed to measure the S.E.Y. between 60 and 3000 eV is less than 10 nC/mm^2 .

3 THE ORIGIN OF THE DIFFERENCE BETWEEN PURE METALS AND TECHNICAL SURFACES

The difference between pure metals and technical surfaces

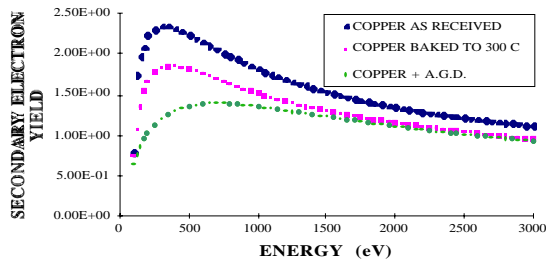


Figure 3:
The S.E.Y. of copper as a function of the surface treatment

is illustrated in the Figure 3 which shows the variation of the S.E.Y. measured for a copper sample in the as received state and after two different in situ treatments: a 300 °C bake-out and an argon glow discharge. In this latter case the S.E.Y. of the pure material is obtained: maximum yield 1.3 at 600 eV primary energy. The highest yield is obtained for the as received sample (greater than 2). A 300 °C bake out decreases this value to 1.8.

The S.E.Y. of various technical materials is shown on Figure 4 in the as received state: Aluminum alloys have

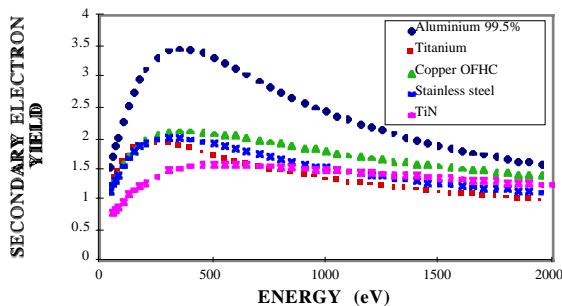


Figure 4:
The S.E.Y. of various as received technical materials

the greatest S.E.Y. (greater than 3). For primary energies lower than 300 eV, copper, stainless steel and titanium are equivalent. A titanium nitride layer⁵ has a

significantly lower S.E.Y. for primary energies lower than 600 eV

The origin of the S.E.Y. discrepancy between pure materials and technical materials is due to the presence of a surface layer (oxide and contaminants) which can be removed by an argon ion bombardment. Furthermore, the S.E.Y. of as received samples is significantly reduced by baking these materials under vacuum (e.g. to 300°C), a process leading mainly to the removal of the water vapor adsorbed on their surface.

The two following experiments illustrate the effect of the oxide layer and of the adsorbed water on the S.E.Y. :

The influence of the natural oxide layer is shown

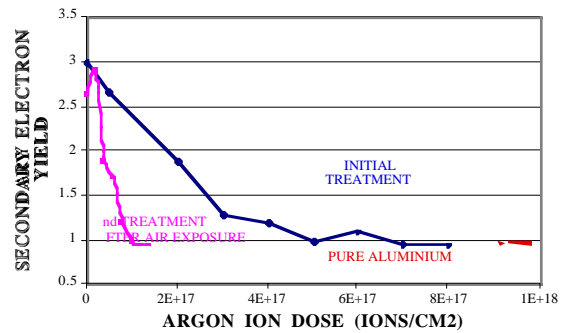


Figure 5:
The S.E.Y. of aluminum alloy 6061 as a function of the argon ion dose

on the Figure 5, displaying the evolution of the S.E.Y. of an aluminum alloy (6061) as a function of the dose of argon ions impinging on its surface. Starting at an initial value of 3, at 300 eV, the S.E.Y. decreases with increasing bombardment close to the value obtained for pure aluminum: 0.95. The dose of argon ions ($3.5 \cdot 10^{17} \text{ ions/cm}^2$) needed to reach this value is equivalent to the sputtering of a 30 nm thick oxide layer, a value close to

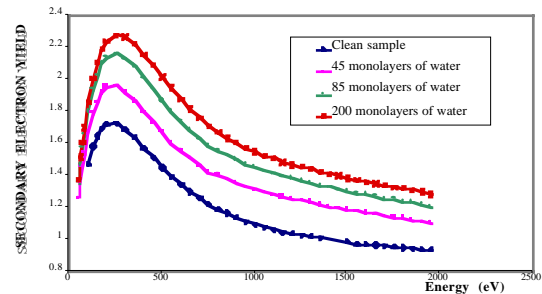


Figure 6:
The S.E.Y. of copper covered with condensed water

the one obtained for a similar layer by Auger analysis⁶. If the sample is reexposed to air after this treatment, the S.E.Y. is increased to a value higher than 2.5 which is subsequently decreased to the bulk value after the

sputtering of a layer equivalent to a 6 nm thick aluminum oxide.

The S.E.Y. of water condensed at liquid nitrogen temperature on a baked copper surface has been measured for various water thicknesses. In Figure 6 the variation of the S.E.Y. with the primary electron energy is plotted for

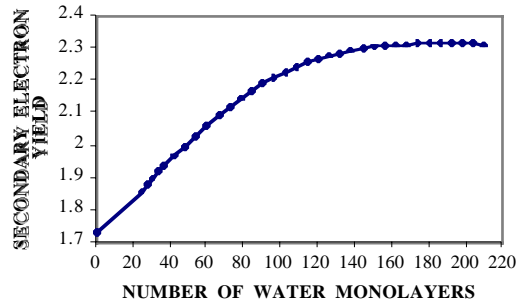


Figure 7:
Variation of the maximum S.E.Y. with the condensed water coverage

a clean sample and for coverages corresponding to 45, 85 and 200 monolayers of condensed water. The evolution of the maximum yield is shown in Figure 7 as a function of the number of water monolayers. The S.E.Y. saturates at 2.3 for water thickness greater than 160 monolayers. This value is close to the value measured for unbaked metals as copper, stainless steel and niobium.

4 METHODS TO DECREASE THE SECONDARY ELECTRON YIELD

The preceding measurements have shown the strong influence of an air exposure on the S.E.Y. of technical materials. For example the argon ion glow discharge treatment can reduce drastically the S.E.Y. of aluminum but the effect is almost completely lost after an air exposure. In the case of accelerator components or vacuum chambers, it is almost excluded to treat the surfaces in situ with the possible exception of bake-out. Hence the efficiency of all attempts to decrease the S.E.Y. by modifying the surface composition is limited by the subsequent exposure to air and water vapor unavoidable during installation. Another possible way to lower the S.E.Y. is to change the surface roughness. This causes indirectly a reduction of the emissivity of the surface as the solid angle for electrons to escape without further interaction with the vacuum chamber can be significantly decreased. A third type of process will be described in the later

4.1 Changing the surface composition

The argon ion glow discharge treatment is a powerful way to modify surfaces by ion bombardment which has been already applied to the 2 km vacuum system of the former ISR. By changing the gas used during this treatment, it is possible to produce various surface layers lowering permanently the S.E.Y. even after an exposure to air.

This is illustrated on the Figure 8 showing in the case of niobium the maximum S.E.Y. after various glow discharge treatments using argon (A.G.D.), argon 10% oxygen (A+O₂ G.D.), nitrogen (N₂G.D.). If most of the beneficial effect of the discharge is lost after an A.G.D., a significant improvement subsists after a 24 hours exposure to air after A+O₂ G.D. or after N₂G.D.. In these both cases, the final yield after exposure to air is close to

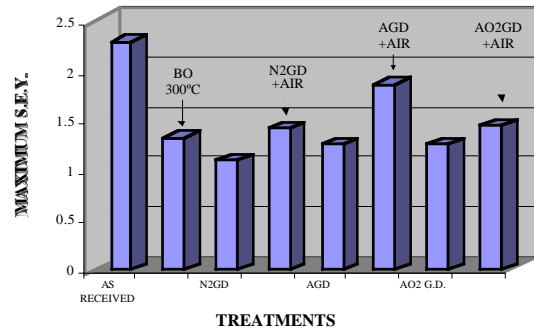


Figure 8:
Niobium maximum S.E.Y. after various surface treatments

1.4, a value which is also obtained after an in situ bake-out to 300 °C.

In the case of copper, the curves giving the evolution of the S.E.Y. with various treatments are given on the Figure 9. The permanent reduction of the S.E.Y. obtained after an N₂G.D. is also visible. A mild in situ bake out to 100°C restores most of the effect of the in-situ treatment when the system has been exposed for 24 hours to air.

Titanium nitride is known⁷ to produce a reduction of the secondary electron which depends largely on the deposition condition of the films. Figure 11 shows the S.E.Y. of TiN coatings from various sources showing a large scatter in the maximum yields (between 2.5 and 1.5). The best layer⁵ has a maximum yield significantly

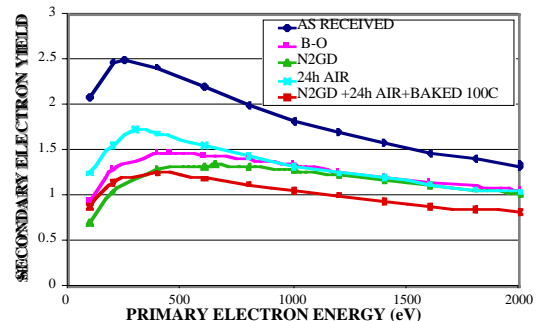


Figure 9:
S.E.Y. of copper after various surface treatments

lower than the S.E.Y. of any metal in the as received state. After a subsequent 150°C bake out, the maximum yield is close to 1.4, a higher temperature bake out (300 °C) lowers the yield to 1.2.

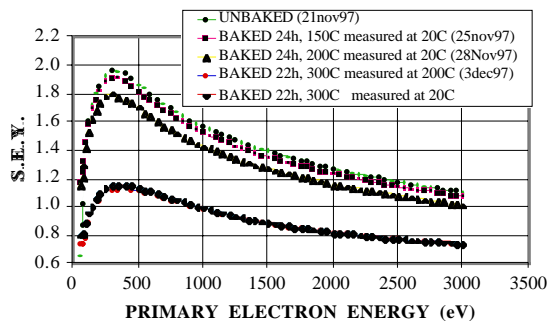


Figure 10:
S.E.Y. of a TiZr getter as a function of the activation temperature

The activation of a getter layer is another way to eliminate the oxide layer. On the Figure 10 the variation of the S.E.Y. of a Ti Zr getter layer⁸ is plotted as a function of the baking temperature. A marked decrease of the S.E.Y. is visible when the layer is heated above its activation temperature. After a 300 °C bake out, the highest yield is less than 1.2.

4.2 Changing the surface roughness

As explained above, the creation of a layer with increased roughness can permanently decrease the S.E.Y. This modification can be produced either by a chemical reaction with the substrate or by the deposition of a strongly dendritic layer.

The first approach was applied to the case of copper⁹. An in situ bake out to 350°C at atmospheric pressure for 5 minutes followed by a 6 hours vacuum bake-out creates a surface with a low S.E.Y. (1.05) as shown on the Figure 11. That treatment causes an increase of surface roughness Figure 12 measured by the BET method¹⁰ from 1.4 (as received state) to 6.5 (after air bake).

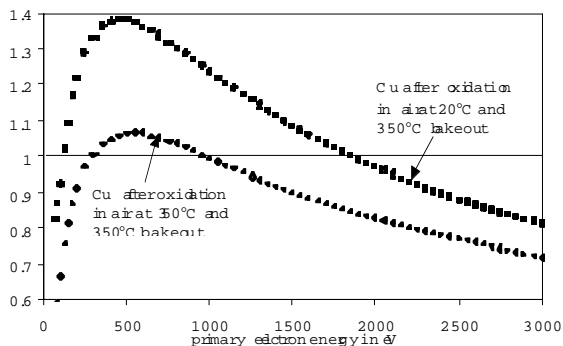
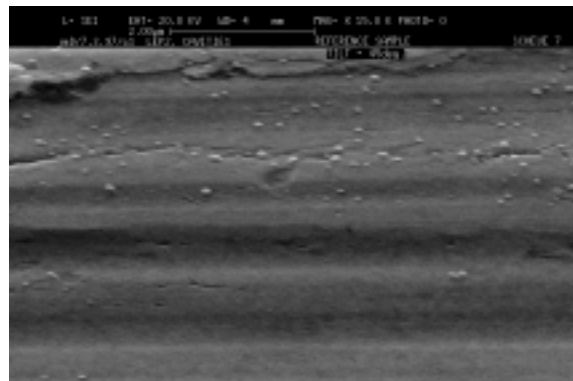
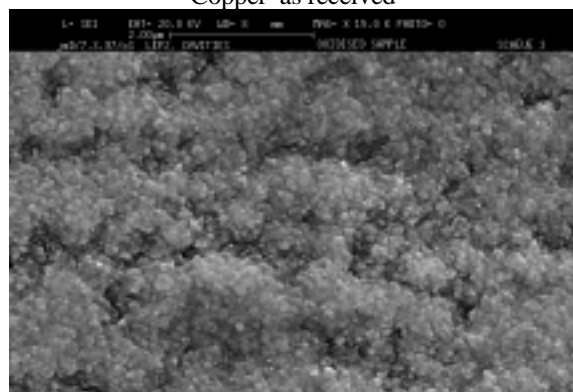


Figure 11 :
SEY of copper after 24 hours 350°C bakeout compared to the SEY of copper after 5 minutes exposure at 350°C and 6 hours bakeout at 350°C under vacuum

The creation of a strongly dendritic surface on a small copper sample, as shown on the Figure *(13) produces a surface with a S.E.Y lower than 1 even after



Copper as received



Copper after air bake

Figure 12:
A copper surface before and after air-baking

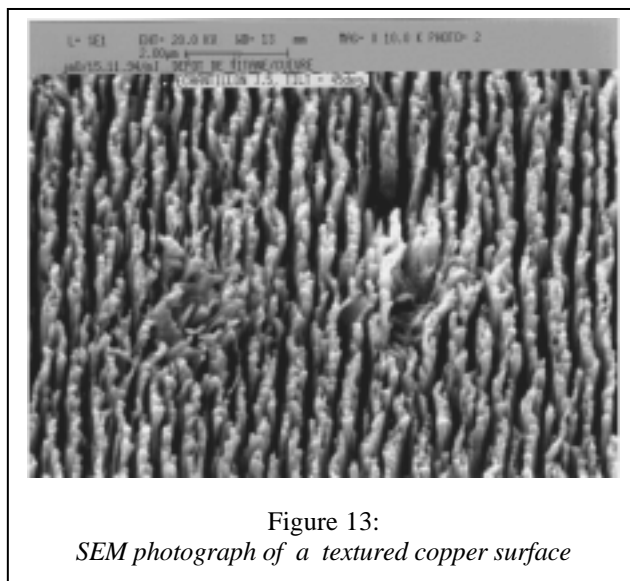


Figure 13:
SEM photograph of a textured copper surface

air exposure. Similar results have been published by A.N.Curren , K.A. Jensen and R.F. Roman¹¹

These methods seem able to produce surfaces with very low secondary electron yields (lower than 1) but difficult to apply to large surfaces such as those involved in an accelerator.

4.3 The “dose” effect

When a surface is exposed to an electron beam, its S.E.Y. decreases¹². In Figure 14 the variation of the S.E.Y. is plotted as a function of the electron dose for two energies of the primary electrons : 100 and 500 eV. In both cases the S.E.Y. decreases for doses larger than 10^{-6} C/mm² and stabilizes for doses greater than 2×10^{-3}

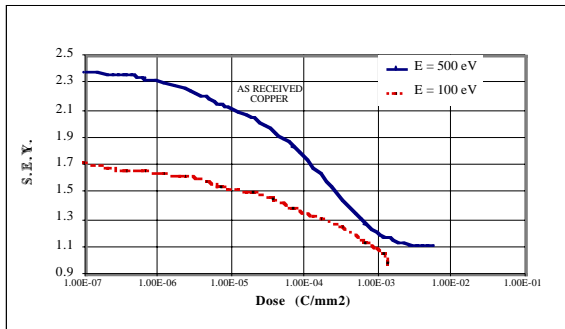


Figure 14:
Variation of the S.E.Y. of as received copper with the electron dose

C/mm² at a value close to unity. This effect is permanent when the surface is not kept under a moderate vacuum (unbaked system $p = 1 \times 10^{-5}$ Pa) as it appears on the Figure

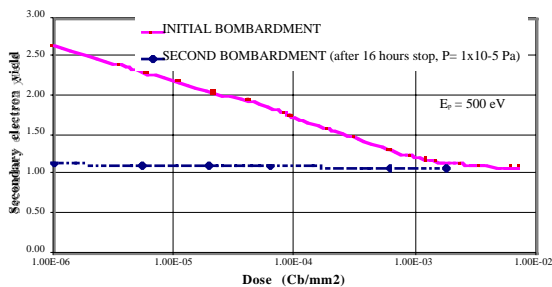


Figure 15
Variation of the S.E.Y. of copper during 2 consecutive bombardments

*(15) where the dotted line indicates a constant low secondary electron yield for a subsequent electron bombardment made with the same dose. This dose effect decreases the S.E.Y. for all energies as can be seen on the Figure 16 displaying the yield as a function of the primary electron energy before and after a bombardment with a dose of 1×10^{-3} C/mm².

Although not completely understood and difficult to investigate, as the electron doses involved are too small for the usual analysis techniques, this effect has been used

since very long time in accelerators and is called : processing!

As this effect could be a remedy for the electron cloud effect in the LHC, it has been studied in EPA,

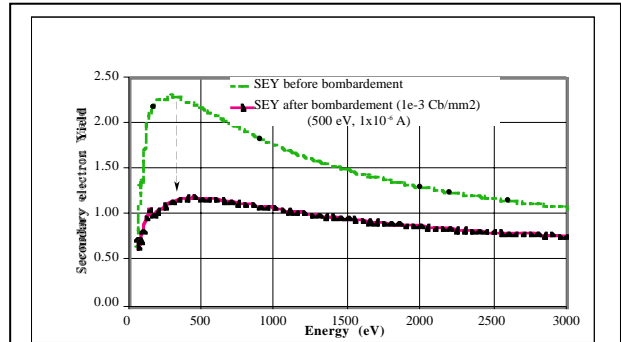


Figure 16
S.E.Y. of copper as a function of the electron energy before and after electron bombardment (10^{-3} C/mm²)

using a remotely controllable system as shown in figure 2 to measure the secondary electron yield of a copper sample. The synchrotron light radiated by the EPA electron beam (194 eV critical energy) travels along a tangential photon beam line. The sample is mounted at

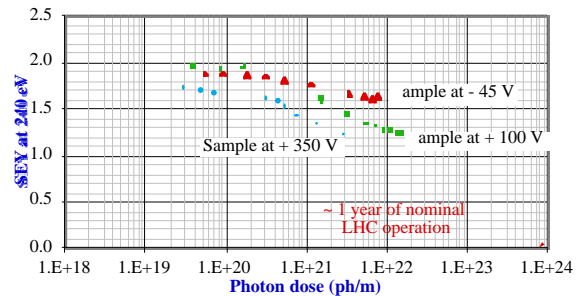


Figure 17
The S.E.Y. measured at 240 eV against the photon dose

90 ° from the plane of the synchrotron light and thus is not exposed to direct photons. Three dose experiments

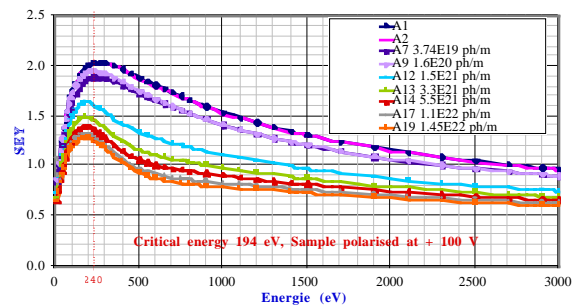


Figure 18:
Variation of the S.E.Y. versus energy curve as a function of the photon dose

were carried out, using different bias applied to the sample: -45 V (i.e. the sample was only conditioned by diffused photons), +100 V and +350 V (i.e. the sample was bombarded by photoelectrons with approximately 100 eV and 350 eV energy). The variation of the S.E.Y. measured at 240 eV is given in the Figure 17 as a function of the primary photon dose. When the sample is positively biased, the curves are very similar to those obtained in the laboratory and saturate at a value close to 1.2. When the sample is only bombarded by diffused photons, the effect is less pronounced and seems to saturate for a S.E.Y. of 1.6. Figure 18 the S.E.Y. as a function of the primary electron energy evolves during the experiment : the maximum of the curve is shifted towards lower energies which corresponds to a reduction of the secondary electron escape depth.

4.4 Summary

To summarize the efficiency of various methods for the reduction of the S.E.Y., the Figure 19 gives the S.E.Y. obtained after treatments applied ex-situ, a subsequent exposure to air and no in-situ bake out. The surfaces

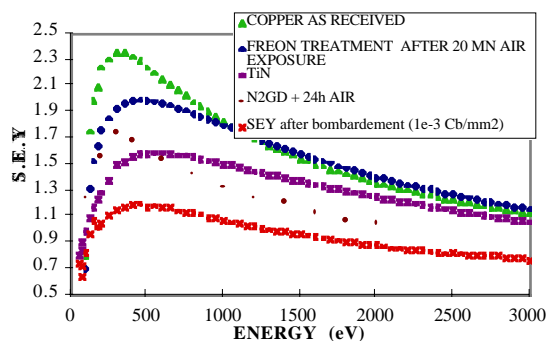


Figure 19:

The secondary electron yield of copper after various treatments and exposure to air

considered are : as received after chemical cleaning, freon processing, nitrogen glow discharge treatment, coating with titanium nitride⁵ and for comparison after an in situ electron bombardment with $1 \times 10^{-3} \text{ C/mm}^2$. The electron bombardment gives the lowest yield, for primary electrons with less than 500 eV, followed by the TiN layer, the nitrogen glow discharge treatment and the freon treatment.

5 CONCLUSIONS

The secondary electron emission is a surface dependant phenomenon, more influenced, for technical metals, by the surface preparation than by the material itself. Insulating layers (e.g. oxides as well as adsorbed water) significantly enhance the emissivity of surfaces. Various surface treatments involving (e.g. ion bombardment) or coatings (e.g. titanium nitride) can reduce the S.E.Y. although a subsequent air exposure reduces notably their efficiency. The dose effect (conditioning) is a well established and powerful method to circumvent the problems related with electron multiplication.

Nevertheless, this method can only be applied under two conditions:

-A significant dose should be applicable to the surface to reach a dose close to 10^{-3} C/mm^2 within a reasonable time.

-The electron multiplication should be mastered in order to avoid an uncontrolled runaway of the process and possible damages.

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