NEXT GENERATION OF SRF-GUNS: LOW SECONDARY ELECTRON YIELD BASED ON A THIN FILM APPROACH

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Abstract

Multipacting is a common issue in the context of cathode units of superconducting radiofrequency photoinjectors (SRF-guns) utilized in linear accelerators under resonant conditions. In this study, Titanium Nitride (TiN) and Carbon thin films have been prepared by DC and RF magnetron sputtering in a Nitrogen and Argon plasma discharge, respectively. Films featuring a thickness of about 600 nm were produced under various deposition conditions on substrates such as Copper, Molybdenum, and Silicon. Materials characterization was carried out utilizing SEM, Raman and FTIR spectroscopy, XRD and AFM. In order to evaluate the secondary electron yield (SEY) a new device is introduced, which is capable of quasi in-situ measurements. The latter is realized by connecting the coating-, the SEY- and a contamination chamber into one setup allowing sample transfer under UHV conditions. Even after an exposure to air, carbon shows SEY values down to 0.69. These values, however, turn out to be quite sensitive with respect to the actual surface morphology. Clean TiN surfaces, on the other hand, displayed SEY values as low as 1.4. In this case the SEY value is strongly affected by potential surface contamination.

INTRODUCTION

In electron or particle accelerators, which are for instance operated at CERN or Helmholz-Zentrum Dresden-Rossendorf (HZDR), undesirable electron clouds arise which limit the accelerator operation. This phenomenon of multipacting frequently occurs at the cathode unit of superconducting radiofrequency photoinjectors (SRF guns) in linear accelerators under resonant conditions. Electrons, for example caused by field emission at the surface of a RF component, get accelerated by the RF-field and trigger an avalanche of secondary electrons which limits the beam lifetime and causes power loss. To suppress such multipacting and to prevent a deterioration of accelerator performance, a material with a correspondingly low secondary electron yield is required.

Surfaces of metal typically feature a SEY value of 1.3, whereas contaminations like air exposure usually lead to much higher SEY values up to 2.4. Consequently, a material is required that, in spite of air exposure, shows a stable SEY value below one. In this context carbon is a promising candidate which does not require bake-out and is robust against air exposure. It was demonstrated that carbon films prepared by magnetron sputtering deposition

potentially fulfill these requirement [1,2]. Another promising coating candidate is TiN which also offers very low SEY values on the order of one and which can easily be deposit using RF-Magnetron-Sputtering [3]. Based on this work the goal of this paper is the preparation and analysis of these coating systems in particular, the influence of process parameters on the film properties and structure with reference to the SEY. To improve the adhesion of carbon films, especially on copper substrates, the applying of intermediate layers is also investigated.

EXPERIMENTAL

The films were deposited on polished Copper-plates with a diameter of 2.5cm using a CC800 PVD coating system by CemeCon (Figure 1). Prior to deposition the samples were cleaned with ethanol and distilled water to avoid contamination. High purity Krypton (99.999%) and Argon (99.999%) were used as inert sputtering gases. The carbon source was setup by two 99.9% pure graphite targets with a dimension of 40 cm x 15 cm. This setup allows for the coating of large samples such as a complete SRF-cathode. For film deposition, a target power of 3500 W was used at each graphite target leading to a power density of 5.8 W/cm². The deposition pressure varied between 500 mPa and 850 mPa depending on the gas flow ratio. Due to a rotation of the sample holder there was no constant distance between targets and sample. However, the minimum distance was 3 cm. The samples were deposit at temperatures between 60 and 630 °C, respectively, which were measured at the heating source itself. During the whole process the sample holder was biased with a medium-frequency voltage of 80 V (240 kHz). With this setting, film thicknesses of 600 nm were achieved.
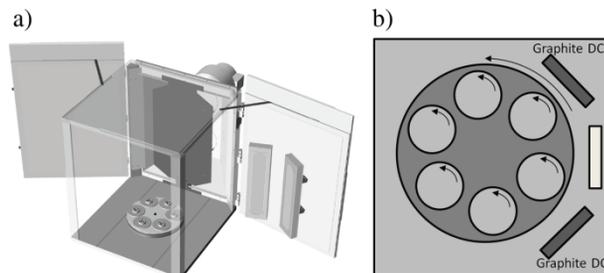
Figure 1: a) Scheme of the CC800-PVD coating system a) opened view from the side, b) closed view from the top with rotating substrate table and Graphite-DC-cathodes.

Titanium-Nitride films were produced using a different setup. The whole system is shown in Figure 2. To replace the samples, without venting the whole chamber, a load

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lock (A) is used. Transferring the sample via a manipulator into the deposition chamber (B) the samples can be coated and transferred to analysis. At a rf-generator power of 300W and a pressure of around $6 \cdot 10^{-3}$ mbar, TiN films were deposited with a variation in Argon/Nitrogen concentration at temperatures in the range of 309 to 376 °C. Here, a deposition time of one hour resulted in films featuring a thickness of 400 to 600 nm. By changing the target from a 99.99% pure Titanium target to a 99.99% pure Carbon target the setup could be utilized to produce Carbon films. These Carbon films were deposited at a pressure of $4.5 \cdot 10^{-3}$ mbar and a power of 300 W. The deposition temperature varied between 42 and 615 °C. As the deposition chamber is connected to the SEY-chamber (C) it is possible to characterize the films directly after deposition without any air exposure. An additional contamination chamber (D) is equally connected to the SEY-chamber to specifically investigate the effect of potential impurities.
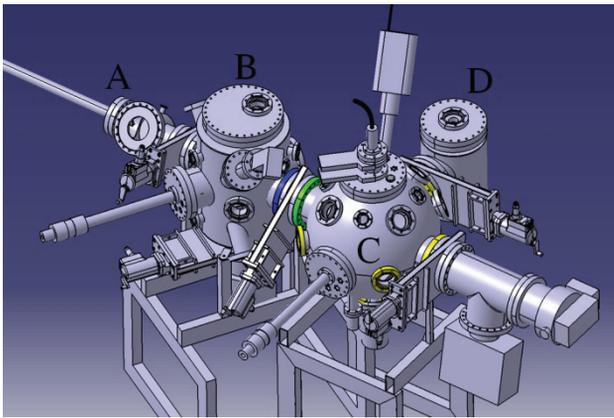
Figure 2: Scheme of coating and measuring system. A: load-lock, B: coating-chamber, C: SEY-chamber and D: contamination-chamber.

The main coating parameters of the individual samples are summarized in Table 1 including the deposition method, RF or DC magnetron sputtering, the deposition temperature, the used power and the pressure.

Table 1: Main Deposition Parameters

Sample	Method	T [°C]	Power [W]	Pressure [10^{-3} mbar]
26	RF	58	300	4.5
TiN	RF	311	300	5.5
106	DC	610	3500	8.3
112	DC	605	5000	8.2
122	DC	609	3500	8.1
123	DC	60	3500	7.9

The film thickness was measured, based on the corresponding cross-section observed for coated reference

silica wafers, by means of scanning electron microscopy (SEM, ZEISS Ultra-55). Additionally surface and morphological analysis were carried out by SEM as well as atomic force microscopy (AFM, XE-100; PSIA), respectively. Structural and chemical analysis were carried out by means of Raman- (LabRAM HR Evolution) and Fourier transform infrared spectroscopy (FTIR Nicolet-6700; Thermo-Fischer).

The SEY measurements were performed using a KIMBALL PHYSICA INC. electron gun, a µ metal electron cylinder as collector and a conducted sample holder. A schematic illustration of this setup is shown in Figure 3. The collector was positively biased with +45 V to collect secondary electrons, while at the same time the sample-holder was negatively biased with -14 V to avoid detection of slow electrons and to accelerate exiting electrons. The electrons detected with the collector lead to the collector-current I_C which represents the generated secondary electrons. The current at the sample-holder I_S, results from the difference of the incoming electrons (the current of the primary electrons I_P), and the exiting electrons I_C.

$$I_S = I_P - I_C$$

The currents were measured via two KETHLEY current amplifiers. Calculating the ratio between the produced (I_C) and incoming ($I_C + I_S$) electrons, one can directly access the corresponding SEY(δ).

$$\delta = \frac{I_C}{I_C + I_S}$$

The base pressure during SEY measurements was $1 \cdot 10^{-9}$ mbar. All reported SEY measurements were carried out at normal angle of incidence. The primary electron (PE) energy was varied between 50-1110 eV in 20 eV steps. This approach yields SEY values as a function of PE energy.
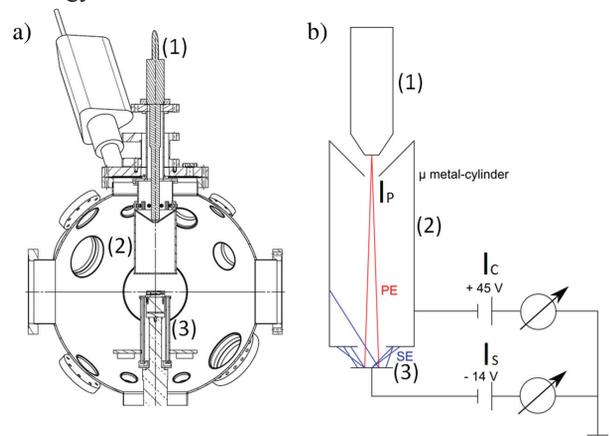
Figure 3: SEY setup consisting of (1) e-gun, (2) collector and (3) sample-holder a) technical drawing of SEY-chamber b) electrical connections and measured current.

RESULTS AND DISCUSSION

Carbon Films

The measured SEY-curves of different Carbon films are shown in Figure 4. The maximum SEY belongs to

sample 123 with a value of 1.26, using the lowest deposition temperature at DC-sputtering. All other samples have a SEY below one down to 0.69 for sample 112, where the maximum target-power of 5000 W was used. To improve the adhesion of the Carbon-films on Copper, for sample 122 and 123, an additional sublayer of Titanium was used. The results show, that the SEY is nearly independent of the substrate comparing the samples 106 and 122.
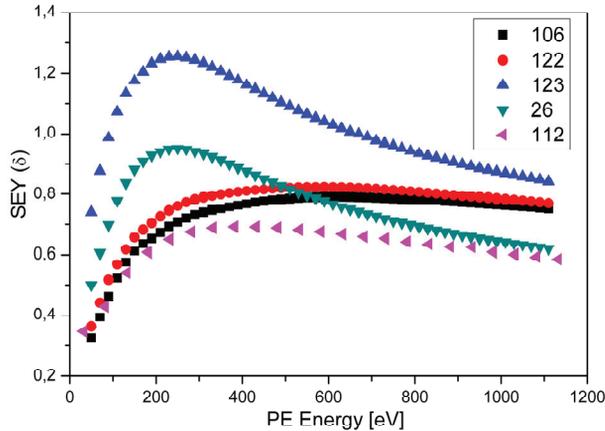
Figure 4: SEY measurement for different Carbon samples as a function of primary electron energy.

The sample deposited using the rf-magnetron sputtering (26) shows the same shape in the SEY-curve like films produced at low temperature in DC-magnetron sputtering. This commonality is reflected in the structure of the films. Furthermore, it can be observed that the coating temperature during DC-sputtering is decisive for the properties of the generated layer, which is directly connected to the SEY.

SEM and AFM images verify the different structural behavior. The samples deposit at very high temperature show a highly textured surface presented in Figure 5.
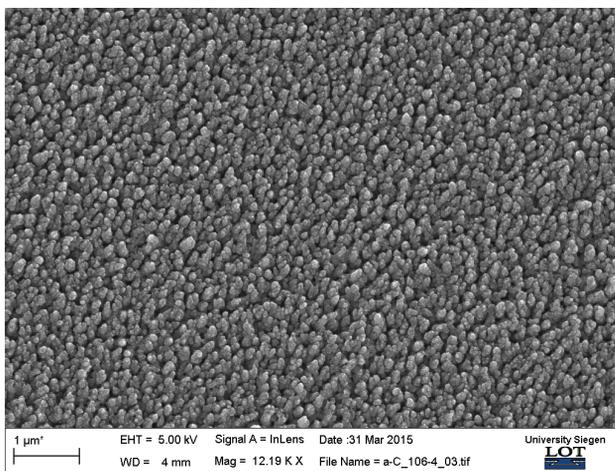
Figure 5: SEM-image (Sample 106) of the highly structured surface of carbon films deposited at 610°C.

The surface demonstrates a well-structured pattern of some kind of carbon rods wherein the cross-section

verified the same. A cross-section of a sample with an additional titanium layer, also produced at high deposition temperature, is shown in Figure 6.

The measurements conclude that the rough surface and the structure of the surface lead to such small SEY values. In comparison to the films deposited at very high temperature, the films produced at low temperature just as the films prepared with rf-sputtering show a very smooth surface and no texturing. A cross-section of such film is shown exemplary in Figure 7. On Titanium coated silicon wafer a very smooth and dense carbon film is formed.
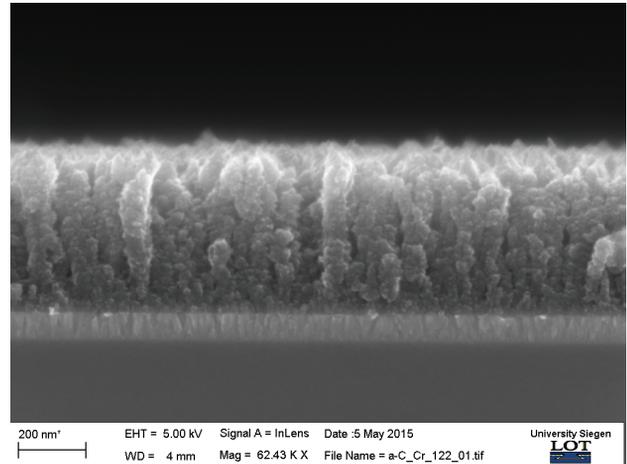
Figure 6: Cross-section SEM-image (Sample 122) of Carbon film on a titanium-coated Silicon-wafer deposited at 610 °C.
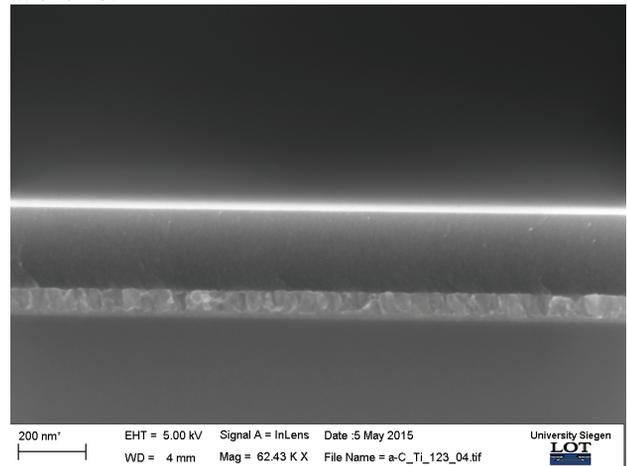
Figure 7: Cross-section SEM-image (Sample 123) of Carbon film on a Titanium-coated Silicon-wafer deposited at 60 °C.

The roughness of the different samples was measured to verify the SEM results and to determine the influence regarding the SEY. Using AFM an rms-roughness value of 1.5 nm was determined for Carbon films deposit at low temperature. For high temperature rms-values of around 11nm were calculated. AFM images of the Carbon films produced on a sublayer of Titanium at a) 610 °C and b) at 60 °C are shown in Figure 8. It can be observed, that the average roughness of samples prepared at high temperature is much higher than these made at low

temperature. The influence of the roughness on the SEY can be explained as follows. If the roughness is very high, resulting secondary electrons are prevented to leave the surface due to collisions with surface asperity. This fact, as compared to smooth surfaces, leads to a lower SEY.
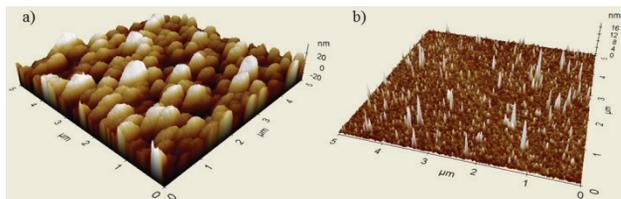
Figure 8: AFM-images of Carbon films prepared at a) high and b) low deposition temperature.

Raman spectroscopy measurements confirm the assumption that the samples prepared by rf-magnetron sputtering and the films produced at low temperature by DC-sputtering differ from the films prepared at high temperature. In Figure 9 the raman-spectra are presented for the different carbon films.
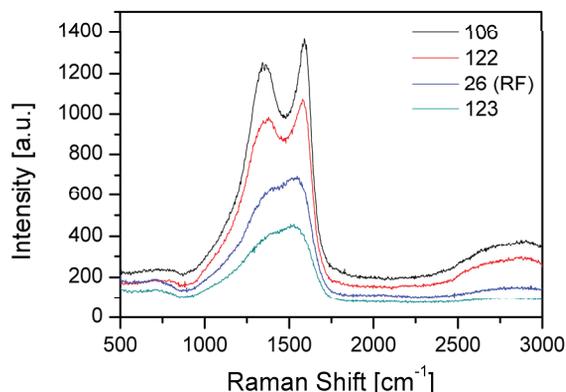
Figure 9: Raman-spectroscopy measurement of different Carbon films with amorphous (123;26) and graphite like structure (106;122).

From the spectra it can be concluded that the rf-films and the films of low temperature show amorphous structure, the other samples, however show graphitic structure verified by the two clearly separated peaks in the raman-spectra.

TiN-films and the Effect of Contamination

TiN-films produced via rf-magnetron sputtering and stored after deposition in a plastic box were measured after an ultrasonic cleaning with ethanol and distilled water. SEY-Measurements of samples without ultrasonic cleaning show SEY-values higher than 2.5 due to contamination. The SEY-curves of TiN after ultrasonic cleaning, after conditioning process and after Argon-plasma cleaning are illustrated in Figure 10. For comparison a carbon film direct after deposition and after an ultrasonic cleaning is also plotted. It can be observed that an ultrasonic cleaning process leads to a contamination of the surface. For Carbon films the SEY

increases from 1.03 to 1.76. The TiN films where not measured directly after deposition. After Argon-sputter cleaning the SEY can be reduced from 1.94 to 1.06. A conditioning process for the ultrasonic cleaned samples can reduce the value to 1.87 but only the sputter cleaning can remove the contamination. The measurements show that the SEY is significantly dependent on the contamination. Every contamination on the surface leads to a very high SEY.
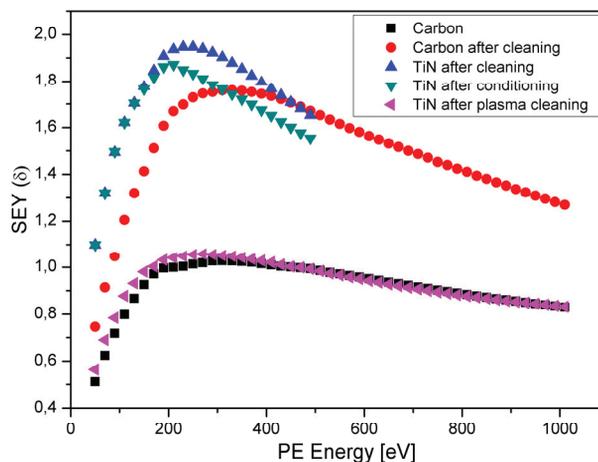
Figure 10: SEY-measurements for TiN and Carbon and the effect of cleaning processes.

Different coating parameters for TiN-films show several differences in Nitrogen content which was examined via FTIR spectroscopy and also structural variation which was checked with XRD. However, it has been found that the film-parameters have a negligible effect on the SEY. The SEY-measurement for different TiN samples after argon cleaning varies only between 1.01 and 1.06.

CONCLUSION

The investigations of Carbon and TiN films revealed, that the secondary electron yield is very sensitive to the existing surface. Contamination of any kind, even by ultrasonic cleaning processes, lead to a high SEY of around 1.7. Sputter cleaning processes which remove all kinds of contamination is promising to get a low SEY close to one for TiN films. A significantly smaller SEY below one can be achieved for Carbon films using DC-magnetron sputtering. For high deposition temperature of nearly 600 °C Carbon films can be produced with a SEY down to 0.69. The SEY-value is directly connected to the surface morphology and structure. SEM and AFM images show, that a highly textured rough film leads to smaller SEY values. In this regard, Raman spectroscopy verifies the structural changes.

ACKNOWLEDGMENT

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