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INFLUENCE OF ARGON-ION IRRADIATION ON FIELD EMISSION FROM POLYCRYSTALLINE CU AND LARGE-GRAIN NB SURFACES

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Abstract

In the present work, systematic investigations of the enhanced field emission from polycrystalline copper and large grain niobium surfaces before and after argon-ion irradiation with an energy of 5 keV were performed with a variation of the irradiation time. Results show that the suppression of the EFE might be achievable.

BACKGROUND

Enhanced field emission (EFE) from particulates and surface defects [1 - 3] that remain on the surface even after chemical etching and dry-ice cleaning processes is one of the main field limitations of high-voltage vacuum devices, such as normal conducting traveling-wave cavities of the Compact Linear Colider (CLIC) and high-field superconducting Nb resonators for particle accelerators. Motivated by the results of the surface smoothness of polycrystalline Cu [4], similar tests were done on both polycrystalline Cu and large-grain Nb samples, to change the morphology of the remaining defects on the surface.

In the present study, we used flat Cu and Nb samples that were fabricated like typical accelerating structures. Furthermore, the EFE before and after Ar^+ ion irradiation of the samples was studied in detail.

MEASURMENT TECHNIQUE

Experimental Setup

For the present work we have used the field emission scanning microscope (Fig. 1) with a base pressure of ca. 10^{-8} Pa [5]. A fine-focused Ar^+ ion-source IQE 12/38 (SPECS, Berlin, Germany) was mounted at an incident angle of 23° to the surface normal and used for in-situ processing of copper and niobium samples applying an ion energy of 5 keV. The EFE measurements of Ar^+-irradiated areas were performed by applying a positive voltage U to a tungsten anode with a truncated cone of 350 µm in diameter and at a surface gap d of ca. 55 µm. The resulting applied electric field E was measured as:

$$E = \frac{U}{d}, \quad (1)$$

and using the modified Fowler-Nordheim equation for a tunnelling current I [6]:

$$I = A\frac{S\beta^2E^2}{\phi t^2(y)} exp\left(-B\frac{\phi^{3/2}v(y)}{\beta E}\right), \quad (2)$$

the field enhancement factor β and the emitting area S can be obtained for a given work function ϕ. For simplicity, the following parameter were used: ϕ = 4.65 eV (Cu) and ϕ = 4 eV (Nb), v(y) = t(y) = 1, A = $154\text{x}10^4$ A eV m^2/MV^2, B = 6830 MV/(eV^2 m).

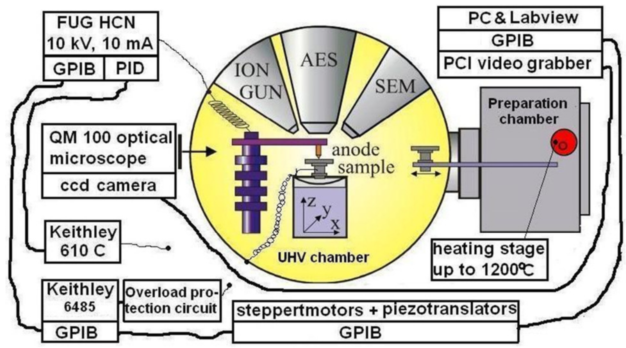

Figure 1: Schematic view of the field emission scanning microscope.

The surface morphology changes of Cu and Nb samples before and after the Ar^+ ion irradiation were characterised with an optical profilometer and atomic force microscope (FRT MicroProf®, Bergisch Gladbach, Germany) in contact mode.

Samples

Five circular polycrystalline Cu discs in diameter of 12 mm with an average roughness R_a of 35-107 nm (root-mean square roughness R_q of 55-137 nm) and two large-grain Nb discs in diameter of 28 mm with R_a = 9 nm (R_q = 12 nm) were used (Fig. 2). The discs were prepared at CERN and DESY according to the original preparation procedures for normal-conducting and superconducting cavities [1, 3].

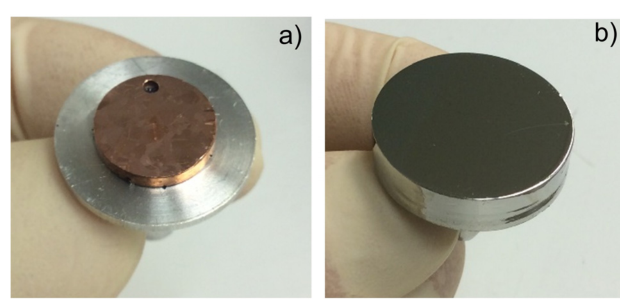

Figure 2: Images of polycrystalline Cu sample fixed on an Al holder (a), and a large-grain Nb sample (b).

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RESULTS AND DISCUSSION

Polycrystalline Copper Samples

Figure 3a show the profiles of the polycrystalline Cu surface after Ar^+ ion irradiation at 5 keV for 3, 6, 9 and 12 h. The resulting depth profiles nearly have a Gaussian shape and the average diameter of the spot size is about 0.8 mm, which corresponds to the nominal size of the ion beam. The half maximum of the depth profile was taken into account for the determination of an average sputter rate (Fig. 3b). Hence, the sputter rate could be roughly estimated to be about 6 nm/min.

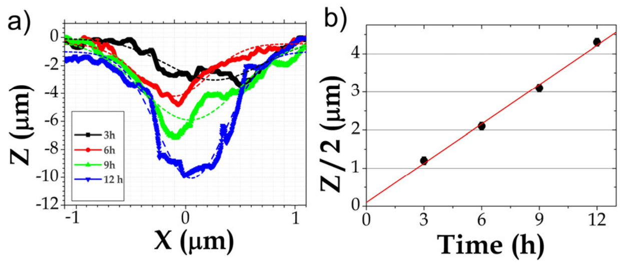

Figure 3: Depth profiles, Z, of the Cu surface along the X axis after 5 keV Ar^+ irradiation for 3-12 h with Gaussian fit curves (a) and the half maximum of the crater depth vs. time (b).

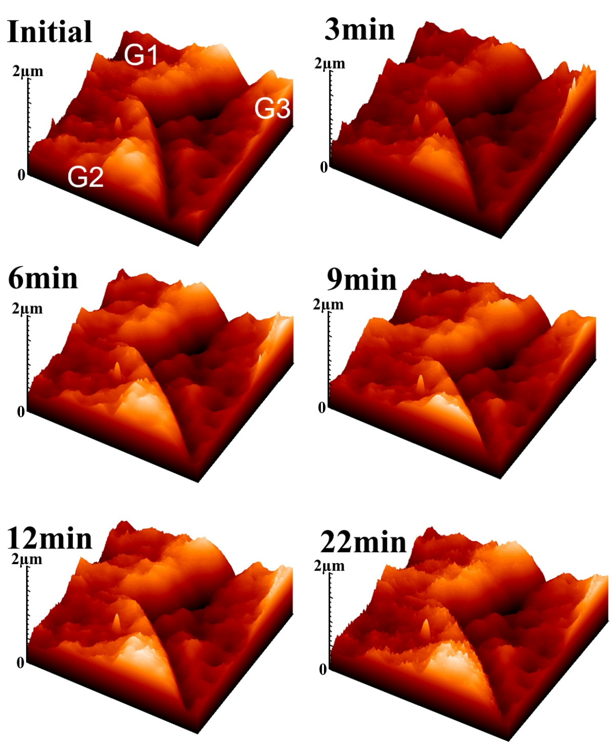

Figure 4: AFM micrographs (50x50 µm^2) of the polycrystalline Cu surface before and after 5 keV Ar^+ ion irradiation for 3, 6, 9, 12 and 22 min. Three different grains (G1-G3) are indicated.

In Fig. 4, AFM micrographs of the Cu surface before and after the Ar^+ ion irradiation at 5 keV for 3-22 min are shown. The scanning area was 50×50 µm^2 and contained three neighbouring grains (G1-G3). A formation of tip-like nanostructures was already observed after the irradiation for 3-6 min, and the height of these nanostructures increases with the time of irradiation (for G1 and G2) reaching typical heights up to 100 nm. Hardly visible changes can be seen in grain G3. This is probably due to a different sputter yield for different surface orientations of the individual grains.

Typical I-E characteristics of the Cu surface before and after the Ar^+ ion irradiation are presented in Fig. 5. Two opposite behaviors were obtained. A significant increase of the onset field from 103 MV/m to 154 MV/m for an emission current of 1 nA and a substantial reduction of the field enhancement factor β from 32 to 26 were initially observed after 6 min of Ar^+ irradiation (Fig. 5a). The measurements indicated a strong activation effect after the ion irradiation, which led to a significant decrease of onset field from 121 MV/m down to 49 MV/m for the emission current of 1 nA and an increase of the field enhancement factor β from 35 to 66 (Fig. 5b).

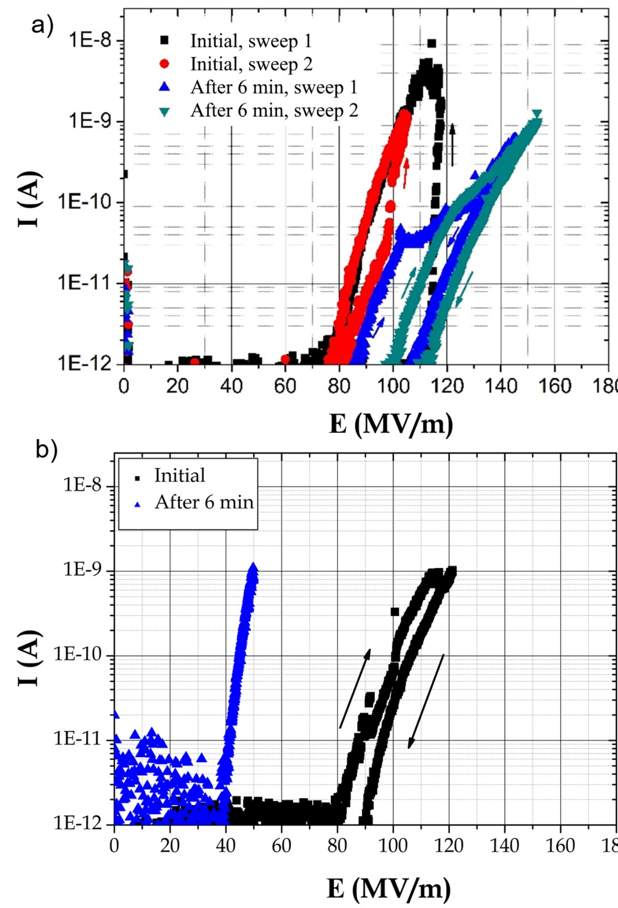

Figure 5: I-E characteristics of emitters before and after the ion irradiation: deactivation (a) and sharpening effects (b) could be observed.

Large-Grain Niobium Samples

Figure 6 shows typical AFM micrographs of Nb samples before and after the Ar^+ ion irradiation at 5 keV. Both Nb samples showed horizontal lines along the scanning direction after the Ar^+ ion irradiation. The systematically observed issue suggests that, unlike to Cu surface, the surface

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of Nb became more porous and thus rougher on the nanoscale after the ion irradiation.

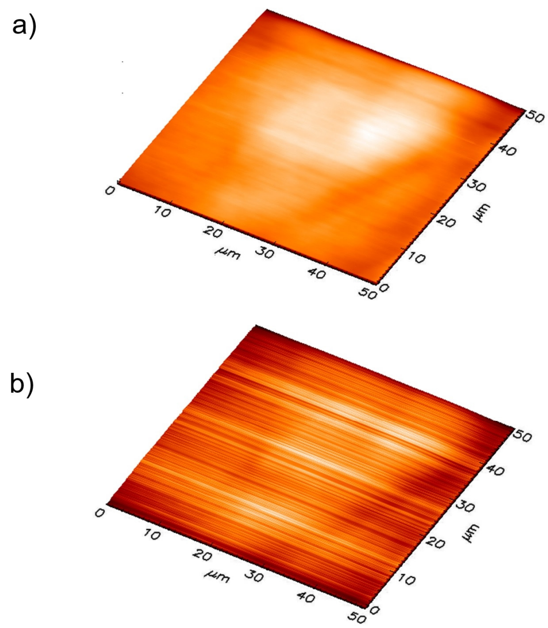

Figure 6: AFM micrographs of Nb surface at initial state (a) and after Ar^+ ion irradiation at 5 keV for 20 min (b).

Typical local field emission results of the large-grain Nb surface are shown in Fig. 7. No field emission was observed from the initial Nb surface up to 180 MV/m. However, ion irradiation for 20 min resulted in rather stable and reproducible electron field emission already at 175 MV/m for 0.2 nA current and yielded a field enhancement factor of $\beta = 19$. After an additional Ar^+ ion sputter treatment for the next 20 min, the EFE was observed at 140 MV/m for the same current value of 0.2 nA and a slightly larger field enhancement factor of about 29 that can be related to an increased roughness on the nanoscale.

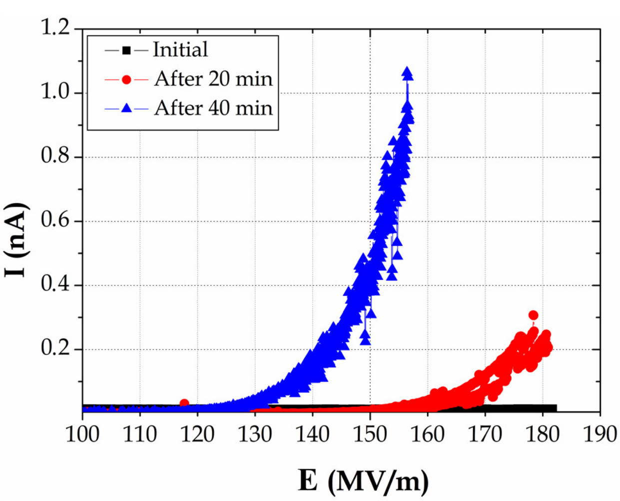

Figure 7: I-E characteristic of an emitter before and after the ion irradiation.

CONCLUSIONS AND OUTLOOK

Surface morphology changes and the EFE behavior of polycrystalline Cu and Nb surfaces were investigated after an Ar^+ ion irradiation at 5 keV for different times at an incident angle of 23° to the surface normal. The Ar^+ ion processing of the polycristalline Cu surface led to both suppression and activation of the EFE. In contrast, Ar^+ irradiation of Nb surface showed only the reduction of the onset-fields after the ion processing and the increase of the field enhancement factor. Moreover, AFM measurements of the Nb sample in contact mode hinted on a possible porosity of the upper layer. Further systematic experiments with a variation of the ion incident angle and different ion energies are ongoing.

ACKNOWLEDGMENT

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