Arc tracks on nanostructured surfaces after microbreakdowns

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Abstract. Studying of initial steps of unipolar arc ignition process is important for reduction of probability of arcing between the plasma and the wall in thermonuclear devices. Tungsten nano-fuzz surface formed by helium plasma irradiation at high fluences and temperatures is a perfect material for arc ignition. Snowflake-like craters were detected on the fuzzy surfaces after short micro-breakdowns. Such sort of craters have not been observed before on any other metallic surfaces. These specific traces are formed due to unique properties of the fuzz structure. The nano-fuzz could be easily melted and vaporized by micro-breakdown current, due to its porosity and bad thermal conductivity, and formation of low conducting metallic vapour under the cathode spot causes discharge movement to the nearest place. Thus, even low current arc can easily move and leave traces, which could be easily observed by a secondary electron microscope.

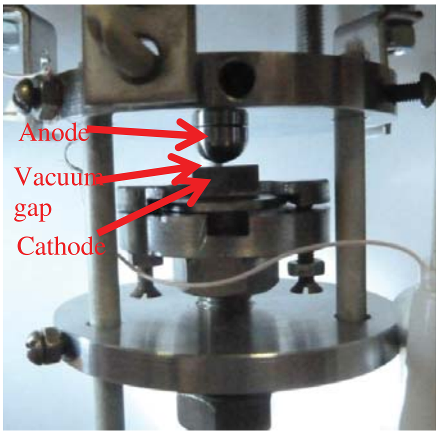
1. Introduction

Unipolar arcing is a negative phenomenon taking place between the plasma and the first wall in fusion devices with magnetic confinement. Moreover, arcing becomes more frequent with increasing the surrounding plasma density. It is well known that arcing probability is strongly dependent on properties of plasma facing materials [1]. Thin (10-30 nm) tungsten nanostructures called fuzz can be formed on tungsten surfaces after helium irradiation with fluence of ~10^{25} m^{-2} when the surface temperatures was in the range of 1000-2000 K [1]. It was shown [2] that fuzzy tungsten surfaces can demonstrate enhanced frequency of arcing in linear simulator machines, but there are only few experimental works that investigated the mechanisms of such behavior. Thus, investigation of the pre-breakdown phenomena is an important step for mitigating unipolar arcing. In this study, pre-breakdown phenomena on the fuzzy tungsten samples are investigated using vacuum diode measurements.

2. Experimental setup

Vacuum diode designed for current-voltage characteristic (CVC) measurements from fuzzy surfaces is shown in figure 1(a). This device allows comparing CVCs of different fuzzy structures grown on substrates of equal thickness without changing of the vacuum gap. The gap distance can be varied from 0.3 mm, which allows working with the electric field strength up to 40 kV/mm using voltage source up to 12.5 kV and maximum current of 2 mA. The spherical shape of the anode is for solving the problem of parallel positioning of the electrodes that is very important for small distances. The vacuum and electric schemes of the setup are shown in figure 1 (b). The operating vacuum pressure was in the range of 3-5 10^{-7} Torr for restricting secondary processes in the vacuum gap. Electrical scheme consisted of the negative high voltage source 7, nanoammeter 8 and ballast resistor 6 for limiting current at the 300 μA level in case of a breakdown, as shown in figure 1(b).

a)



b)

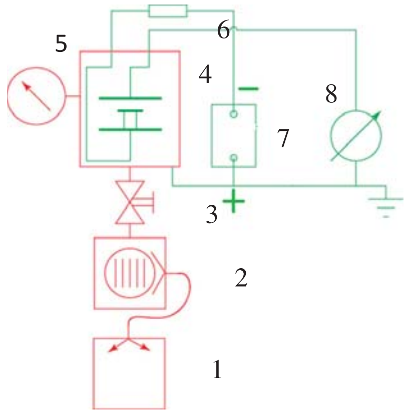


Figure 1. A photo of the vacuum diode for pre-breakdown current measurements (a) and the scheme of setup (b): 1 – rotary pump, 2 – turbomolecular pump, 3 – gate, 4 – vacuum chamber, 5 – pressure gauge, 6 – ballast 25 MOhm resistor, 7 – high voltage source, 8 – nanoammeter.

3. Results and discussion

Fuzzy samples were prepared in the NAGDIS-II device [3] with high density helium plasma, the typical density and temperature of which are, respectively, 10^{19}m^{-3} and 5 eV. Specimens were installed to the plasma and electrically biased to −100 V for reaching total fluence ~10^{25} m^{-2}. The surface temperature was raised by the bombardment of helium ions up to 1000 K. A CVC was measured in the vacuum diode just after preparation in the NAGDIS-II. Only small nanoampere currents of 25-35 kV/mm were detected and are shown on the Fowler-Nordheim plot in figure 2 (black dots).

After increasing of the field strength up to 40 kV/mm, a microbreakdown has occurred, and after this event, CVC changed: significantly higher currents up to several tens of microamperes were emitted at much lower field strength (gray dots in figure 2). The currents have not changed even after an exposure in atmosphere and the reason seems to be only modification of the surface relief during the microbreakdown.

Local field amplification factors were calculated using CVCs for two cases: before and after the breakdown. According to the equation (1) for relation between the emission current *I* and the electric field strength *E,* the local field enhancement factor β can be calculated from the slope [4].

$$\lg\left(\frac{I}{E^2}\right)=-\frac{2.818\cdot 10^9\cdot\varphi^{3/2}}{\beta}\cdot\frac{1}{E}+\frac{4.406}{\varphi^{1/2}}+\lg\left(\frac{S\cdot\beta^2}{\varphi}\right)-5.854 \quad (1)$$

In this equation φ=4.5eV is the work function for tungsten, *S* is effective emission area. Before the breakdown this factor was 110 and taking into account that β can be estimated roughly for a tip on the plane as *h*/*r* (*h* - height of the tip, *r* - radius of the tip), such value can be rather possible for some protrude nanostructures. But in the case of "after the breakdown", β was about 1300, and this value seems impossibly high for surface protrusion. These currents could not be explained by the classical field emission theory and could be due to thermofield emission from heated protrusions.

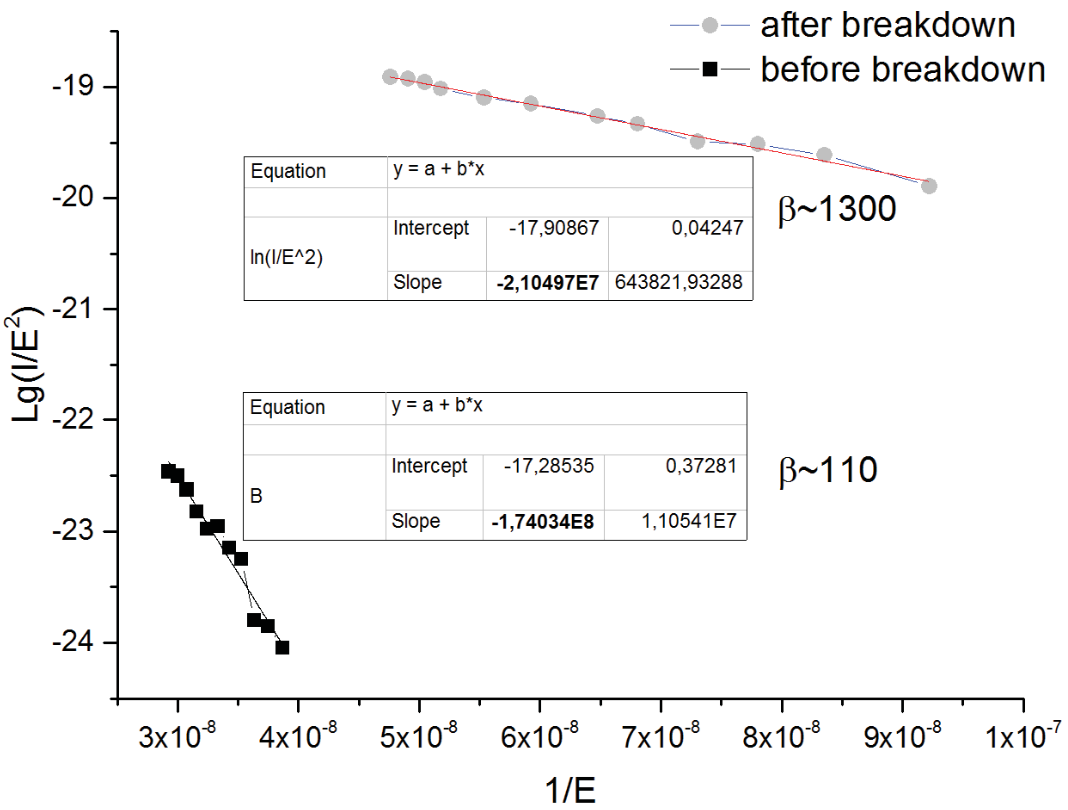


Figure 2. Current-voltage characteristic of the tungsten nanostructured sample before and after a microbreakdown.

After field emission measurement, the emission zone of the fuzz sample was observed by a scanning electron microscope (SEM). Some parameters of the breakdown are shown in table 1.

Table 1. Parameters of the microbreakdowns on tungsten and molybdenum.

Material of fuzzy structure	W	Mo
Break voltage	10 kV	12.5 kV
Current after break	163 μA	236 μA
Number of large "snowflakes"	12	55
Diameter of "snowflake"	50 μm	50 μm

The places of microbreakdown are shown in figure 3 for tungsten (a) and molybdenum (b) fuzz. The area modified by craters is about 1.5 mm^2, which is rather close to the calculated one for the used vacuum diode with the spherical anode. In this calculation the area of the cathode, which was estimated near which electric field strength, is not lower than 90% from maximum value. The breakdown region consists of two separated parts shown in figure 3, the main black crater with a lot of black dust around it and a lot of "snowflake"-like craters in some distance from the main one. The reason of separation can be due to local field reduction near the main crater during the breakdown process. Probably, the main crater is formed earlier than "snowflakes", because it is surrounded by them. The main crater looks like after explosion due to a lot of small black dust near it and this explosion can be the initiator of the breakdown.

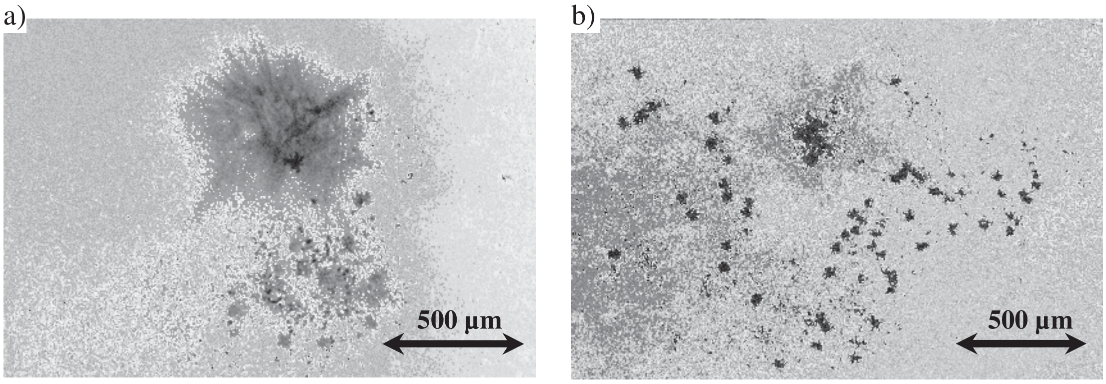


Figure 3. Places of the breakdown for tungsten (a) and molybdenum (b) fuzzy samples.

However, the presence of the main crater is not necessary for the cathode area after the breakdown. In figure 4 another breakdown place contains only "snowflakes". These structures consist of black separated dots with ~2 µm diameter – presumably they were arc spot traces, but these black points very often merge into continuous tracks. The tracks of "snowflake" usually have central symmetry. This means that arcs diverge in all directions in spite of surface scratches. The diameters of the snowflakes are usually about 50 µm, which is the same for tungsten and molybdenum and doesn't depend on the nanostructure material properties.

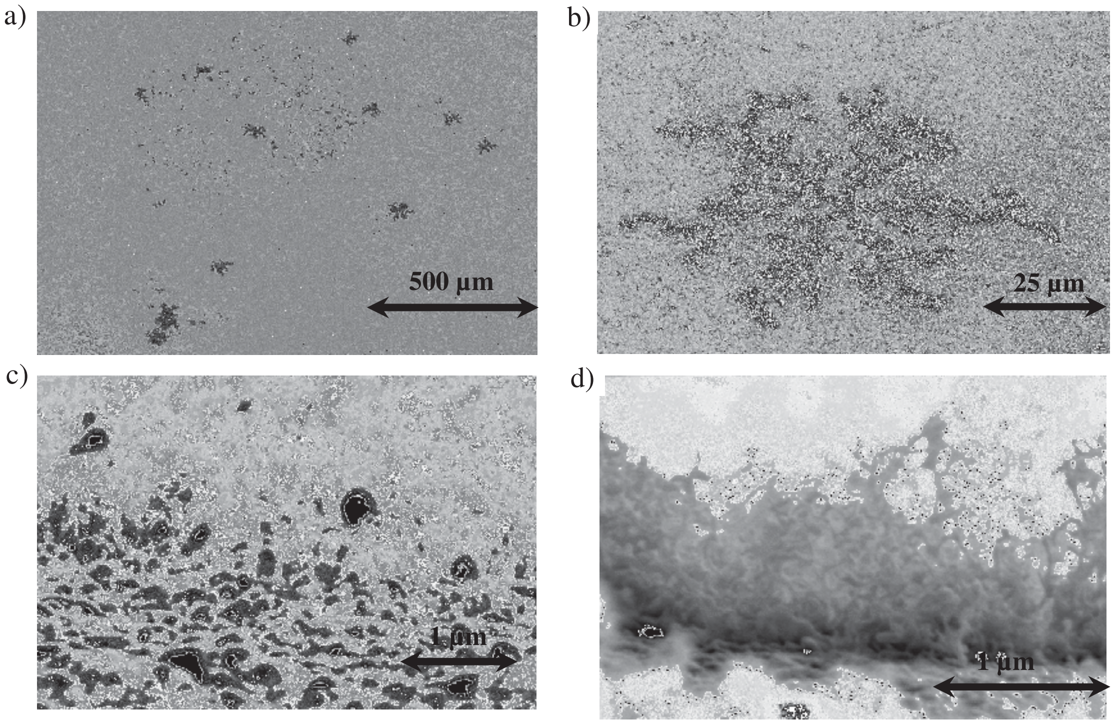


Figure 4. Photos of the "snowflakes" on the tungsten fuzz surface after a breakdown: a) and b) general view of the snowflakes, c) and d) the sliding angle view on the "snowflake" crater bottom.

The arc current is usually rather high compared with the current limit by the ballast resistor, so the capacity of the vacuum diode could be the main source of the current. The last one can be estimated about 10^{-12} F.

When the arc spot is hot enough for evaporating of liquid material of the cathode, it is usually profitable for the arc to move on to the nearest place, because of the bad conductivity of the metal vapor and lower resistant of a new cold place at all [5]. Thus, the necessary energy for evaporation of the tracks of the "snowflakes" can be comparable with the total capacitor energy. Then, the crater depth can be estimated by the order of value in equation (2). For this estimation, the density of fuzzy structure was taken 0.05 of tungsten density from [6]. Other referential parameters were taken from [7] and are shown in table 2.

$$H \cdot S \cdot 0.05\rho \cdot (c \cdot (T_{\text{melt}} - 300\text{K}) + H_{\text{melt}} + c \cdot (T_{\text{boil}} - T_{\text{melt}}) + H_{\text{boil}}) = CU^2/2 \quad (2)$$

Table 2. Number of craters and material properties of nanostructure.

Material of the fuzzy sample	Total "snowflakes" area S, µm^2	Density ρ, kg/m^3	Heat capacity c, kJ/kg·K	Melting point T_{melt}, K	Boiling point, T_{boil}, K	Heat of fusion H_{melt}, kJ/kg	Heat of vaporization H_{boil}, kJ/kg	Break-down voltage U, kV
Tungsten	10^4	19250	0.13	3700	6200	190	4200	10
Molybdenum	10^5	10280	0.25	2900	4900	390	6200	12.5

Calculation of the craters depth H by the formula (2) gives ~1 µm for tungsten fuzz and ~0.2 µm for molybdenum, which is close to the depth observed by SEM. It is interesting to note that in spite of the much higher melting point of tungsten, the amounts of energy necessary for evaporation mass unit are very close to each other due to the higher heat capacity, heat of fusion and vaporization.

For investigation of dependence between the total area of craters and the capacitive energy of the vacuum diode, a microbreakdown for 5 kV was initiated and only 4 small "snowflakes" were found on the surface after the current increase from 5 to 21 µA. The total area of the craters was ~$2 \cdot 10^3$ µm, which was 5 times less than that for 10 kV breakdown and well corresponds to the capacitive energy of vacuum diode with 5 kV voltage.

4. Conclusion

It was shown that surfaces covered by the fuzzy nanostructure can indicate traces of the breakdown and pre-breakdown phenomena that is very important for investigation of arc initiation. Such effect can be explained by ease of fuzz melting due to well thermal insulation of each nanostructure. Arcs are moving rather randomly on the surface that is well illustrated in "snowflake"-like traces. It was established that formation of the "snowflake" craters significantly increases intensity of the pre-breakdown currents. The energy source for the breakdown was a capacity of the vacuum diode: a correlation was found between the diode energy under fixed voltage and the number and the size of the craters. "Snowflake" craters formation accompanied by tungsten dust erosion is the negative outcome for a thermonuclear machine.

Acknowledgements

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