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Field electron emission from a nanostructured tungsten surface

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Abstract. In this paper, the electron emission from a nanostructured tungsten surface was investigated. A method for measuring an extremely low current ($10^{-12} - 10^{-14}$ A) has been tested. It made possible to reduce the effect of the electric field on the sample surface and to minimize the probability of spontaneous breakdowns. For a detailed study of tungsten fuzz, a point tungsten anode (diameter 90 μm) was used. Field enhancement factor ($\beta = 2000 - 3000$) and effective emission area were calculated using the Fowler–Nordheim plots. The pre-breakdown current rise was studied. The emission current waveforms suggest the formation of several emission structures before the breakdown.

1. Introduction
In a thermonuclear reactor, the tungsten walls are subjected to the flux of high-energy helium ions. As a result, various thread-shaped nanostructures (fuzz) are formed on the surface [1]. The thickness of the nanostructures layer is about 1-50 μm, the diameter of the threads is 5-40 nm. Since the discovery of these structures, their properties have been actively studied [1-3]. The main negative property of fuzz is the increased probability of unipolar arcs formation, which leads to the rapid destruction of the reactor components [4].

To understand the mechanism of unipolar arc formation, it is necessary to study the properties of field emission from tungsten fuzz. Since at a place with a high field amplification, the probability of explosive electron emission and, consequently, the probability of a unipolar arc formation is much higher [5]. The emission properties of the nanostructured tungsten surface are being actively studied [6, 7]. Field enhancement factors ($\beta$ about 1000) were obtained. But in all works, samples with an area of 1-20 cm² were studied. It is necessary to study the uniformity of the nanostructure distribution on the surface and their influence on the breakdown process. This work is devoted to the local study of the tungsten fuzz emission properties.

2. Experimental setup and methods
A schematic of the electrode assembly is shown in figure 1. A sample with a tungsten fuzz (a disk with a diameter of 2 cm) is installed on the cathode. The heating coil allows heating the cathode up to 400°C. This is necessary to remove the absorbed gases from the sample surface. This procedure was carried out once during pumping of the vacuum chamber. The anode assembly consists of a thin tungsten anode (diameter 90 μm), a metal grid, and a phosphor screen. The grid is located at a distance...
of 4 cm from the tungsten sample. This is necessary to observe the pattern of emission centers. The distance between the anode and the cathode was 400-800 µm, which allows to work with the electric field up to 30 kV/mm. There are ballast resistors in the anode circuit to limit the breakdown and arc currents. The experiments were carried out with vacuum pressure in the range 10⁻⁸ Torr.

Two methods were used to determine the emission characteristics of the sample. Method A (figure 1) used a 3 MΩ shunt to measure µA and mA currents. During the experiment, it turned out that at a current of several µA, a breakdown of the gap occurs and it is not possible to measure the current–voltage characteristic by this technique. Later, this technique was used to study the growth of the pre-breakdown current; for this, the signal from the shunt was recorded using an oscilloscope.

The purpose of Method B (figure 1) is to measure pA currents (10⁻¹²). For this purpose, instead of a shunt, a 285 pF capacitor was used, which accumulated the charge from the emission current. After charging the capacitor (4-8 minutes), it was discharged to an oscilloscope, and the emission current was calculated from the discharge graph. In this method, it is assumed that the emission current is constant during the charging process of the capacitor, therefore, the averaged values of the emission current are obtained. Also, for simplicity of calculations, the field was calculated by the formula for a plane-parallel system $E = U/d$ ($E$ is electric field, $U$ is voltage, $d$ is distance between anode and cathode). This method allows measuring fairly small currents up to 10⁻¹⁵ A, using fairly simple equipment. The main disadvantage of this method is the long measurement time. Usually, it took up to 6 hours to measure the current–voltage curve (9 different voltage values and 5 measurements for each value, the capacitor charge is up to 8 minutes).

3. Results and discussion

The measurement results allow the field enhancing factor to be calculated using the standard Fowler-Nordheim (F–N) formula. To determine the coefficient $\beta$, the formula was used:

$$\lg \frac{i}{E^2} = -5.85 - \frac{2.82 \cdot 10^9 \phi^{3/2}}{\beta} + \frac{4.39}{E^{3/2}} + \lg \frac{S \beta}{\phi},$$

where $i$ is the emission current, $\beta$ is the field enhancing factor, $\phi$ is the work function and $S$ is the effective square of emission area.

The emission area can be derived from the F–N plot as:

$$S = \frac{\phi}{\beta^2} \cdot 10^{4.585-4.39 \phi^{3/2}},$$

Figure 1. Schematic of the experimental setup.
where $k$ is the $y$-intercept of the F–N plot.

Figure 2 shows a typical F–N plot, which consists of 7 $E$ values and 5 measurements for each value (circle is a single measurement, a triangle is averaged value). From this graph, it can be concluded that the emission is unstable and, despite the averaging of each current measurement for 8 minutes, the spread of values reaches 15%. Figures 2-5 show the emission characteristics of a tungsten fuzz. From the F–N curves, it follows that on an undamaged surface the field enhancement factor is about 2000-3500 at a distance of 400 $\mu$m and for a distance of 800 $\mu$m $\beta = 2000$-2500. With an increase in the electric field to 18 kV/mm, breakdowns began to occur with a frequency of several kilohertz. After a breakdown, $\beta$ decreased to 750-1200, and the emission area increased (figure 5). This can be explained by the destruction of the tallest emitters, but the overall fuzz structure is preserved.

**Figure 2.** The typical F–N plot. A circle is a single measurement; a triangle is averaged value, $d = 450$ $\mu$m, $\beta = 3028$, $S = 7.1 \cdot 10^{-6}$ nm$^2$.

**Figure 3.** F–N plot, $d = 800$ $\mu$m, $\beta = 2083$, $S = 1.23 \cdot 10^{-4}$ nm$^2$.

**Figure 4.** F–N plot, $d = 425$ $\mu$m, $\beta = 2898$, $S = 5.6 \cdot 10^{-6}$ nm$^2$.

**Figure 5.** F–N plot after the breakdown, $d = 425$ $\mu$m, $\beta = 950$, $S = 0.013$ nm$^2$.

Figures 6 and 7 show the pre-breakdown current rise. To measure them, the voltage values were set slightly less than the critical value and a breakdown occurred within half an hour. On the graphs, it can be seen that before the breakdown, the current increases at a non-constant rate. In figure 6, the current increases exponentially. Figure 7 shows 2 different segments of current growth. It can be assumed that, at first, an increase in the current corresponds to an increase in one emission center, after 12 $\mu$s,
another center is switched on, and the current growth increases significantly. The characteristic current rise time is on the order of several tens of microseconds.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{pre_breakdown_current1.png}
\includegraphics[width=0.4\textwidth]{pre_breakdown_current2.png}
\caption{The pre-breakdown current.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{pre_breakdown_current3.png}
\includegraphics[width=0.4\textwidth]{pre_breakdown_current4.png}
\caption{The pre-breakdown current.}
\end{figure}

The emission current can increase for two reasons: an increase in the field enhancement factor and an increase in the emission area. From formula 1 it follows that with an increase in $\beta$, the current grows exponentially, and with an increase in S, it grows closer to a linear form. The field enhancement factor can change due to surface restructuring under the action of an electric field, possibly stretching or turning of fuzzy fiber.

4. Conclusions
The field enhancement factor for tungsten with a nanostructured surface is 2000-3000. After an electrical breakdown, the $\beta$ decreases to 750-1200, but the fuzz characteristics remain the same. The emission area for intact areas is significantly less than the area of one nanofiber. This may indicate a change of work function or the presence of a large number of absorbed atoms. Formula (1) is also valid for one emission center, while there may be several hundred of them. It should be noted that the emission current is unstable in both: the millisecond and minute ranges.

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