The model of thermal field emission from tungsten fuzz

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Abstract. Tungsten fuzz is a material formatted due to interaction of helium plasma with tungsten surface. This material consists of large number of thin nanostructures "growing" on the tungsten surface and having enhanced field emission properties. However, the calculation of field amplification factor from emission current-voltage characteristic gives large value which is not correlated with geometrical parameters of the nanostructures. Thermal field electron emission model that takes into account the Joule heating by emission current is presented in this work. This model predicts qualitatively similar current values corresponding to experiment and explains enhanced field amplification factor from the current-voltage characteristic.

1. Introduction

Tungsten is the main candidate for plasma facing material in the divertor zone of a fusion reactor due to high melting temperature, high thermal conductivity and low sputtering yield. However, its surface can be modified by "fuzz"–nanostructure, which can be formed in linear simulators and tokamaks under helium irradiation with fluence as high as \(-10^{25}\) m\(^{-2}\), the sample temperature in the range of 1000-2000 K and energy > 20 eV. It was shown [1] that fuzzy tungsten surfaces can demonstrate enhanced frequency of arcing in linear simulator machines, but there are only few experimental works demonstrating the reason of such behaviour. Pre-breakdown current is often an initial step of the breakdown, but the mechanism of its emission is still unclear. Field emission from nanostructure filaments could be the reason of the pre-breakdown current, but in this case field amplification factor should be very high. As soon as the nanostructure consists of huge number of helium bubbles, its resistance could be high enough for intensive local heating and transition to thermal field emission (TFE). There are a lot of works devoted to calculation of the TFE current, but less of them take into account the heating of filaments by emission current.

2. Experimental results

Field emission from the flat cathode covered by tungsten fuzz was measured in the vacuum diode in [2]. In that work significant change of the current voltage characteristics (CVC) after microbreakdown was found. These CVCs were built in Fowler-Nordheim (F-N) plot (figure 1) and field amplification factors \(\beta\) were calculated from their slopes using the engineering formula:

\[
\beta = \frac{2.818 \cdot 10^{3} \cdot \phi^{3/2}}{\text{slope}},
\]  

(1)
where $\varphi$ is work function in eV, $E$ is electric field in V/m and $I$ is emission current in A that are necessary for calculating the slope.

Photo of the fuzzy structure cross-section is shown in figure 2 and one can see a nanostructure protruding from fuzzy layer in it. The electric field strength may increase on such structure and the amplification factor $\beta$ can be roughly estimated as the height of filament divided by the radius [3]. However, there were no filaments found with $\beta$ > 100, while the factors $\beta$ obtained from CVC were 150 and 230 for the cases before and after breakdown, respectively. To explain this discrepancy one can suppose that the fuzzy nanostructure temperature could be increased due to Joule heating even by low field emission current and after that the main emission mechanism could be the TFE.

**3. Calculation model**

For the TFE current calculation formula (1) from [4] was used:

$$j(E,T,\xi) = \frac{4\pi mkTe}{h^3} \left[ \ln \left( 1 + \exp \left( -\frac{E}{kT} \right) \right) \frac{W - \xi}{kT} \right] dW + \frac{4\pi mkTe}{h^3} \int_{\psi}^{\infty} \ln \left( 1 + \exp \left( -\frac{W - \xi}{kT} \right) \right) dW,$$

where $m$ – electron mass, $T$ – temperature, $k$ – Boltzmann constant, $h$ – Plank constant, $\xi$ – Fermi energy level, $F$ – electric field strength, $W$ – part of an electron kinetic energy corresponding to normal to the surface velocity. The first term in (2) strongly depends on the electric field strength while the second one depends on the temperature. The calculation model is based on the power balance (3) between Joule heating and radiation cooling of a filament.

$$I(T,E,S) R = \sigma T^4 S_{surf} = mc\Delta T/\Delta t,$$

where $I$ is emission current, $\sigma$ - the Stefan-Boltzmann constant, $T$ - temperature, $m$ - mass, $R$ - resistance, $S_{surf}$ - surface area of a filament, $c$ - heat capacity of tungsten. Initially emission is only due to the electric field which leads to some heating. As soon as the TFE is significantly effective at $T > 700$ K and current increase rate is rather high, energy losses due to the thermal conductivity were not taken into account.
If the temperature of the emitting filament exceeds some melting level, this will reduce its field amplification factor and, as a consequence, emitting current. In [5] it was shown that the melting level for tungsten fuzz is about 1200 K and in [6] density of the fuzz was estimated to be about 5% from bulk tungsten. Time dependence of the temperature (figure 3a) and the emission current (figure 3b) were calculated for two constant electric field strengths. Electric field strength larger than some critical value was sufficient for reaching the melting point and then emission sharply decreases, while at lower electric field the temperature and the current finally reach the constant value. The critical electric field depends on geometry of each filament because of the strong dependence of the field emission on field amplification factor.

The TFE current was calculated for 3 types of nanostructures with field amplification factors 50, 70, 120 and CVCs for them are shown in figure 4. The last point for each characteristic at maximum electric field strength corresponds to nanostructure melting and stopping of the emission. This could be the reason why the measured current is unstable and has the hysteresis effect with voltage between the electrodes increasing and decreasing. The dependences in $F$-$N$ plot look linear, like a field emission current, and the $\beta$ factors calculated using formula (1) are 94, 133, and 233 respectively. Thus, the TFE could be one of the reasons leading to overestimation of $\beta$ by calculating a slope from CVC in $F$-$N$ plot.

Figure 3. Evolution of the temperature (a) and emission current (b).

Figure 4. Current-voltage characteristics simulated in the model for field amplifications factors 50, 70 and 120.
In figure 5 experimental and simulated CVCs for the tungsten fuzz are shown. Each CVC was simulated for $10^6$ nanostructures that corresponds to 1% of nanostructures on the experimental emission area. Scanning electron microscope analysis detect similar number for protrude nanostructures on the average. Simulation was made for $\beta = 50$ and the currents in order of magnitude are rather close to experimental values. Typical current spread due to current instability is shown on the experimental curve.

Figure 5. Experimental and simulated current-voltage characteristics for tungsten fuzz.

4. Conclusion
The numerical model was developed for thermal field electron emission from tungsten fuzz. Emission starts only due to electric field and then structures are heated according to the Joule law and cooled due to radiation. If the temperature reaches 1200K, then melting starts, and field amplification factor decreases, that usually stops the emission. Currents simulated using the model are comparable with experimental currents within the order of magnitude. Current-voltage characteristics in Fauler-Nordheim plot are linear as well as it should be for the field emission current. However, an attempt of calculation of the field amplification factor from the slope of them gives approximately twice overestimated value.

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