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METHOD FOR CALCULATING EMISSION PARAMETERS

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This study proposes a method for calculating the field emission parameters using two linear regions of Fowler-Nordheim plots. The method allows to get the values of the work function, field enhancement factor and area efficiency of emission. Based on this method, an analysis of the emission properties of titanium nitride synthesized using reactive Arc-PVD was carried out. The calculated work function values are in good agreement with the values reported in other studies. The obtained relationships between the field enhancement factor and area efficiency of emission for materials with the same composition can be explained by the features of the surface morphology.

INTRODUCTION

Transition metal nitrides are promising field emission materials due to their low work function, high melting point, as well as high thermal and electrical conductivity. Reactive vacuum arc deposition has become a widely used method for their fabrication.

Measurements of field emission characteristics are most often carried out in a diode configuration using setups designed and manufactured directly in research laboratories. The analysis of data obtained on such setups is in most cases based on the Fowler-Nordheim (FN) theory; however, a generally accepted methodology for determining emission parameters does not currently exist.

The dependence of emission current I on the applied voltage U for large-area field emitters in a parallel-plate diode configuration is described by the elementary FN equation:

$$I = a\frac{\alpha A}{\varphi}\left(\frac{\beta U}{d}\right)^2 exp\left[-b\varphi^{\frac{3}{2}}\frac{d}{\beta U}\right], \qquad (1)$$

where U is the voltage between the anode and cathode (V); d is the anode – cathode distance (m); A is the macroscopic emission area (m²); $a = 1.541434\cdot10^{-6}$ A·eV·V^{-2} and $b = 6.830890\cdot10^{9}$ eV·V$^{3/2}$·V·m are the universal Fowler-Nordheim constants; φ is the work function of the cathode material (eV); β is the field enhancement factor; α is the area efficiency of emission.

Current-voltage characteristics (CVCs) of field emitters, when plotted in FN coordinates $ln\left(\frac{I}{U^2}\right) = f\left(\frac{1}{U}\right)$, either entirely or in specific regions, can be approximated by straight lines. This is considered as evidence of the quantum-mechanical tunneling process, in accordance with the laws of field electron emission [2]. The parameters of the FN plot allow determination of such characteristics of field emitters as the work function, field enhancement factor, and area efficiency of emission.

Most often, the field enhancement factor is estimated from the slope of the FN plot and the electron work function. In this case, reference values of the work function are usually used [4–8]. The disadvantage of such an approach is the inability to determine the actual work function of the studied material. This is particularly important for new materials, for which no reference values are available.

In some studies [9], the electron work function is estimated from the slope of the FN plot under the assumption of a flat emission surface, i.e., with a field enhancement factor of β = 1. The values obtained in this way are underestimated by one to two orders of magnitude and therefore significantly deviate from real values.

A more reasonable approach to determining the parameters of field emitters was proposed in works [2, 3]. In this method, the work function is determined by comparing the slopes of the CVC plots in FN coordinates for the studied material and a reference material with a known work function. Determination of emitter characteristics is carried out in three stages. According to the methodology described in [3], a plot of ln(I/U²) versus 1000/U is constructed. If the current is measured in amperes and the voltage in volts, the slope of such a plot is expressed in units of ln(A/V²)·V/1000, and the intercept in units of ln(A/V²).

At the first stage, the effective work function φ is calculated from the ratio of the slopes of the CVC plots in FN coordinates for the studied material and the reference material:

$$\varphi = \varphi_{ref}\left(\frac{S}{S_{ref}}\right)^{\frac{2}{3}}, \qquad (2)$$

where φ_{ref} is the work function of the reference material (eV); S is the slope for the studied material; S_{ref} is the slope for the reference material.

At the second stage, the field enhancement factor is calculated from the slope of the FN plot and the obtained value of the electron work function:

$$\beta = \frac{-b\varphi^{\frac{3}{2}}d}{1000\,S}, \qquad (3)$$

where d is the distance between the electrodes (m); φ is the work function (eV); S is the slope of the FN plot for the studied material.

At the third stage, the area efficiency of emission is calculated using the formula:

$$\alpha = \frac{\varphi d^2 exp(Y_0)}{a\beta^2 A}, \qquad (4)$$

where d is the distance between the electrodes (m); φ is

the work function (eV); Y_0 is the intercept of the FN plot for the studied material; β is the field enhancement factor; A is the macroscopic emission area (m²); a = $1.541434 \cdot 10^{-6}$ is the FN constant.

In [3], calculations using the described methodology showed the same value of the field enhancement factor for coatings of different compositions deposited on arrays of silicon nanoemitters. The authors explained the constant value of the enhancement factor by identical tip heights and sharpness of the emitters, regardless of the coating composition.

However, if one substitutes the work function value obtained from formula (2) into formula (3), taking into account that the slope S appears in both formulas, then after mathematical transformations the following expression is obtained:

$$\beta = \frac{-b\varphi_{ref}^{\frac{3}{2}} d}{1000\, S_{ref}}. \quad (5)$$

Analysis of expression (5) shows that the calculated value of the field enhancement factor depends exclusively on the parameters of the reference material and is constant for the materials being compared. More generally, it can be concluded that in this methodology the work function is calculated under the assumption of equal field enhancement factors for both the studied material and the reference material.

MATERIALS AND METHODS

Experimental coatings were deposited on flat samples with a diameter of 28 mm by reactive vacuum arc deposition in a Bulat-6 facility onto a molybdenum sublayer. Molybdenum was used as the reference material for determining the work function. The tabulated value of the molybdenum work function was taken as 4.3 eV [1].

For measuring the current–voltage characteristics, a custom-built setup manufactured by SEOTEK LLC (Sumy, Ukraine) was employed. The core of the setup is a stainless-steel high-vacuum capsule with an outer diameter of 116 mm and a height of 92 mm. The heating system provides degassing of the capsule up to 250 °C.

The vacuum system ensures a base pressure down to $1 \cdot 10^{-8}$ Torr and consists of a fore-vacuum pump with a pumping speed of 95 l/s, a turbomolecular pump with a pumping speed of 59 l/s, a pressure gauge with a measurement range from atmospheric pressure to 10^{-7} Pa, and a valve system. The sample holder is designed for round specimens with a diameter of 28 mm and thickness of 1…2 mm. The anode is made of polished stainless steel with a diameter of 8 mm. Mechanical adjustment of the anode – cathode spacing is possible in the range from 0.1 to 1 mm. The high-voltage power supply provides a voltage range of 0.1…10 kV at a maximum current of 5 mA. The current resolution is 10 nA. Control of the power supply, recording of the emission current, and management of the pumping system are carried out via a personal computer.

The emission characteristics were measured at an interelectrode spacing of 200 μm. At this spacing and at the maximum anode voltage of 10 kV, the electric field strength reached 50 V/μm, corresponding to the dielectric strength of the vacuum gap.

Prior to measurements, the samples required conditioning by combined exposure to temperature and electric field. To remove adsorbed gases, the measurement chamber with mounted samples was heated to 100 °C for 3 h under vacuum at a residual gas pressure not exceeding 10^{-6} Torr. Afterwards, the chamber was cooled to room temperature, and an electric field was applied to the sample. The field strength was gradually increased until electrical breakdown occurred. After breakdown, the voltage was removed and the next cycle of increasing the field strength was initiated. This procedure was repeated until a field strength of at least 20 V/μm was achieved without breakdown. The emission current appeared after one or several breakdowns of the interelectrode gap.

The total emission current from the entire emitting surface was measured by varying the electrode voltage. The emission current density was calculated by dividing the measured current by the total anode area, which was 0.5 cm². The electric field strength values were obtained by dividing the anode voltage by the anode–cathode distance. For each sample, four measurements were carried out, and an averaged current–voltage characteristic (CVC) was determined.

From the obtained values of current density as a function of electric field strength, the following parameters were determined: the turn-on field Eon at a current density of 0.4 μA/cm², the threshold field Eth at a current density of 4 μA/cm², and the maximum current density Jmax at a field of 20 V/μm. Based on the parameters of the FN plots, values of the work function, field enhancement factor, and area efficiency of emission were calculated.

RESULTS AND DISCUSSION

The current–voltage characteristics obtained for samples with a titanium nitride emission layer are shown in Fig. 1. The CVC numbers correspond to the sample numbers in Tables 1 and 2. In the FN plots constructed over the entire investigated range of electric field strengths, a characteristic bend is observed, separating the initial region I and the final region II, both of which are well approximated by straight lines. It should be noted that in the case of a zero-shift in the current measurement circuit, an additional nearly horizontal region may appear in the FN plot (inset in Fig. 2).

In our study, the calculation of emission parameters was based on the assumptions that both regions of the CVC can be described by the FN law, the work function remains constant in both regions, and the difference in slopes of the two regions is determined by different field enhancement factors. The work function was determined from the parameters of the linear region of the CVC at low electric field strengths (see Table 1), while the field enhancement factor and area efficiency of emission were determined from the parameters of the linear region at high field strengths (see Table 2). This approach combines the advantages and eliminates the disadvantages of the method based on comparison with a reference sample and the method relying on a known

work function. On the one hand, comparison with a reference sample enables calculation of the work function even for materials without reference data; on the other hand, when calculating β in the region with a different slope, expression (5) is invalid. Thus, the obtained value of the field enhancement factor corresponds to the studied material rather than the reference.

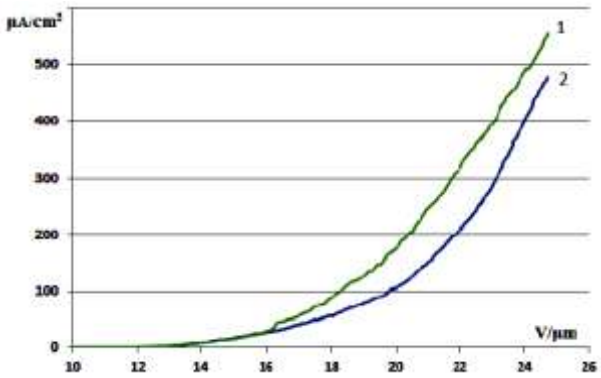

Fig. 1. CVC in linear coordinates

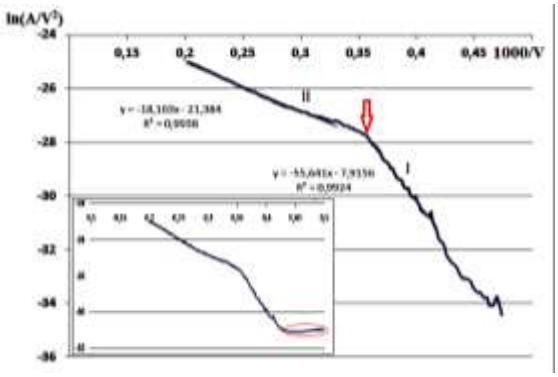

Fig. 2. CVC in FN coordinates

From the measured values of emission current I and voltage U, the parameters 1000/U and ln(I/U²) were calculated, which are necessary for constructing the FN plot. The initial linear region was approximated by a straight line. For the studied materials, this region extended from the noise level up to about 5 μA/cm². The work function was calculated from the slope values using formula (2). Samples with molybdenum coating were used as the reference material. The initial linear region of the molybdenum cathode CVC was shorter, extending only up to 1.75 μA/cm².

Next, the final linear region was approximated by a straight line. In our case, this was done using 100 data points preceding the maximum value. From the obtained slope and intercept values, the field enhancement factor was calculated by formula (3) and the area efficiency of emission by formula (4).

The obtained values of the work function, field enhancement factor, and area efficiency of emission were substituted into equation (1), which was then used to calculate the emission current and compare it with the experimentally measured current. The discrepancy between the calculated and experimental values did not exceed 4%.

Table 1

Calculation of work function

No.	Material	Slope	Intercept	φ, eV
1	TiN	-49.1	-10.5	3.49
2	TiN	-52.963	-9.43	3.67
3	Mo	-66.962	-0.863	4.30

Table 2

Calculation of parameters in the region of high electric fields

No.	Material	Slope	Intercept	Eon, V/μm	Jmax, μA/cm²	φ, eV	β	α	Jmax, calc., μA/cm²	Error Jmax, %
1	TiN	-15.863	-21.974	11.4	166	3.49	562	1.64E-12	160.96	-3.03
2	TiN	-21.387	-21.052	11.2	99.5	3.67	449	6.78E-12	99.93	0.43

The values of the work function calculated by this method for samples of similar composition are close to each other and, in this case, differ by less than 0.2 eV, which is due to the similar slopes of the FN plots in the low-field region. In contrast, when calculating φ, β, and α from the FN plot parameters exclusively in the high-field region (see Table 2), the calculated values of the work function for materials of similar composition exhibit much larger deviations, caused by the greater variation of the slope in this region.

The obtained values of the work function for the studied materials are close to those reported in other studies. According to reference data [1], the work function of titanium nitride lies within the range 2.92…4.09 eV.

For emitters based on identical materials, a decrease in area efficiency of emission with increasing field enhancement factor is observed. This can be attributed to differences in surface morphology: a higher field enhancement factor and, consequently, a smaller emission area are expected in the presence of sharper morphological structures on the surface.

The turn-on field and the maximum emission current density do not exhibit a direct dependence on the work function. This is consistent with the data reported in [10], where the correlations between the emission parameters of different materials were analyzed, and it was concluded that there is no clear dependence of the turn-on field or maximum current density on the work function without considering other factors. Surface

inhomogeneities and the dimensional ratios of elementary emitters may have a dominant influence compared to the work function.

Fig. 3 shows the emission current density versus electric field strength, plotted from the experimental data (dashed line) and from calculations using the elementary FN equation (1) with the φ, β, and α values determined by the proposed method (solid line). Noticeable deviations between these two curves are observed only in the initial region, which illustrates the practical applicability of the proposed method for calculating emission parameters.

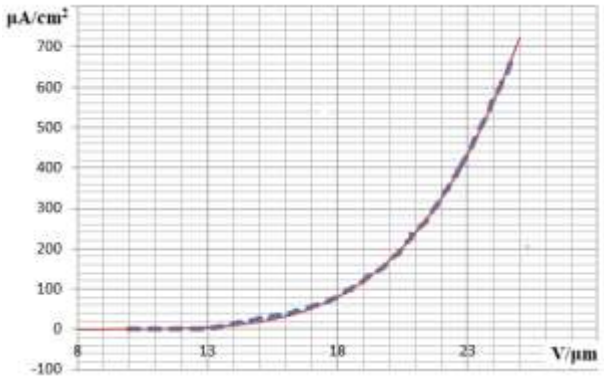

Fig. 3. CVC: experimental (dashed line) and calculated (solid line)

CONCLUSIONS

The proposed method for determining field emission characteristics based on two linear regions of the FN plot allows one to obtain such parameters as the work function, the field enhancement factor, and the area efficiency of emission.

The calculated values of the work function for titanium nitride are in good agreement with values reported in other studies. The observed correlations between the field enhancement factor and the area efficiency of emission for materials of similar composition can be explained by peculiarities of the surface morphology.

The deviations of current–voltage characteristics of transition-metal nitride emitters from the Fowler–Nordheim law require further investigation.

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МЕТОД РОЗРАХУНКУ ЕМІСІЙНИХ ПАРАМЕТРІВ

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Запропоновано метод розрахунку автоемісійних параметрів за двома лінійними ділянками графіка вольт-амперної характеристики, побудованого в координатах Фаулера-Нордгейма. Метод дозволяє отримати значення таких параметрів, як робота виходу, коефіцієнт підсилення поля та площинна ефективність емісії. На основі запропонованого методу проведено аналіз емісійних властивостей зразків із нітриду титану, синтезованого з використанням технології реактивного вакуумно-дугового осадження. Розраховані значення роботи виходу добре узгоджуються із значеннями, наведеними в інших дослідженнях. Отримані співвідношення між коефіцієнтом підсилення поля та площинною ефективністю емісії для матеріалів з однотипним складом можуть бути пояснені особливостями морфології поверхні.