Nickel field-emission microcathode: Art of fabrication, properties, and applications


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1. Introduction

At present, the application of the field-emission (FE) as a method for generation of free electrons is limited as compared to the thermionic emission widely used in modern scanning electron microscopes or various types of gas-discharge devices [1,2], because various areas of science and technology require extra-high electric field gradients \( E \geq 10^7 \) V/cm to obtain technologically significant emission currents. It is important here, that such high electric field strengths should be obtained at comparatively low voltages applied to an emitting system. Nevertheless, the field-emission has a number of extremely valuable features that can be used to construct devices with unique characteristics, e.g., emitters providing current densities of \( \sim 10^6 \) A/cm², superminiature diodes or triodes with a \( 10^{-13} \) s response time, devices for microwave electronics, light emitters [2], or flat display panels [3], etc. Modern requirements to micro- and nanostructured active elements of electronics have to a certain extent determined the development of the field-emission technology. The stated electric field strengths can be obtained at comparatively low applied voltages (namely 200–300 V) in the case when the interelectrode gap and the emitting tip diameter are small enough. According to our previous results [4], an electric field strength of \( 6 \times 10^7 \) V/cm can be obtained in the immediate vicinity of an emitting tip at an emitting tip diameter of \( \sim 35 \) nm, an 1.5-µm interelectrode distance, and applied voltage of 250 V.

In the study, a low-cost and effective method for fabrication of field-emission microcathodes by the ion-track technology was suggested and implemented. The method is suitable for mass production of devices whose geometric parameters are stable over a large area. This µEFC system shows a high current performance at only few hundred volts applied, extra-short time response, and extra-high electric field strength. In addition, the possible application areas of the µEFCs are outlined.

2. Samples and the art of manufacture

Our method is based on the ion-track technology. It is well-known [5,6] that, in order to form microscopic objects, the material (usually a polymer) should be irradiated with heavy ions having MeV energies. This procedure can generate latent tracks, i.e., regions with high density of radiation-induced defects, in the bulk of the polymer. In our case, a 10-µm Mylar [polyethylene terephthalate, \( \text{C}_6\text{H}_{10}\text{O}_4 \)] film is irradiated with 53-MeV Ar ions at a fluence of \( 6 \times 10^7 \) cm⁻². Using this track technology, we next form cone-shaped tracks within the irradiated film by etching it with KOH alkali after its preliminary exposure to ultraviolet. The height of single tracks is \( 8 \pm 0.2 \) µm. To form tip emitters, the cone-shaped tracks are filled with Ni by the standard method of electroless nickel-plating of dielectric materials [7]. The distances between the tracks on the surface of the irradiated film are distributed by the Gauss law. The average distance \( \langle a \rangle = \frac{1}{\sqrt{2\pi N}} \) is determined by \( N \) varied in the range \( 10^5–10^6 \) cm⁻². It should also be emphasized that, as follows from expression in Ref. [8]

\[
E = \frac{U}{Q} \frac{2}{\pi} \frac{c}{i} \tanh \left( \frac{\pi \cdot h}{\langle a \rangle} \right),
\]

the attenuation of the electric field strength for an ensemble of microemitters with the indicated parameters is negligible. Here, \( E \)
is the electric field strength; \( U \) is the voltage; \( h \) is the microemitter height; \( r \) is the nanotip radius; and \( d \) is the interelectrode gap. To apply a negative potential to the microemitters, the surface of the Mylar film, on which the cone bases lie, is also coated with Ni. The final stage consists in etching-off the rest of the latent tracks with KOH alkali to coaxially create \( \sim 0.7\)–\( \mu \)m apertures above the emitting nanotips. In the process, (i) the thickness of the Mylar film decreases due to surface etching and (ii) there is a distinct etching of Mylar along the microemitter surface because of the large difference between the Ni and K\(^+\) (potassium) electrode potentials. It should be noted that cavities created around the nanotips strongly enhance the electrical strength/durability of the microcathode. An empirical choice of conditions in which the latent tracks and the surface layer of the film, on which the nanotips and anode apertures are situated (“front side”), are simultaneously etched makes it possible to obtain the optimal distance between the emitting nanotips and the film surface formed during etching. The anode electrode is fabricated by evaporation of a metal onto the “front side” of the Mylar film. The principal features of this method for device fabrication are (i) use of a common polymer film for both creating an ensemble of cone-shaped microemitters with nanotips and forming the second electrode (anode) on its “front side” and (ii) possibility of a controlled variation of the interelectrode gap. Fig. 1 shows a structure fabricated using the method described. In order to observe the emitting nanotips with a scanning electron microscope (SEM), some technological parameters of this particular specimen were slightly changed. A regular working specimen has apertures \( \sim 0.7\) \( \mu \)m in diameter just above the emitting nanotips with diameters of 35–40 nm, which are situated \( \sim 1.5\) \( \mu \)m below the surface.

3. Properties and applications

We now estimate the theoretical value of the emission current density that can be obtained using Ni microemitters with nanotips. Let the work function \( \phi \) of Ni be 4.5 eV, and the electric field strength, \( 6 \times 10^7 \) V/cm (this value corresponds to an interelectrode voltage of \( \sim 250\) V for the above-stated geometric parameters of the system). In accordance with the well-known Fowler–Nordheim equation \[9\]

\[
E = \frac{2 \cdot U}{r \cdot \ln \left( \frac{3r}{2d} \right)}.
\]

the theoretical value of the emission current density is \( \sim 4.2 \times 10^9 \) A/cm\(^2\) at \( N = 6 \times 10^6 \) cm\(^{-2}\). Here, the current load of a single microemitter is several tens of \( \mu \)A. Certainly, the actual operating current may be substantially lower for several reasons, the main of which is the contamination of nanoemitter surface, resulting in an increase in the Ni work function up to \( \sim 6\) eV.

Fig. 2 shows that the electric field strength decays away from the nanotip. Namely, at a distance of 50 nm, it is more than 100 times lower, which results in that the velocity of an emitted electron is determined by the interelectrode voltage along its whole path toward the anode. At 250 V, this velocity is \( \sim 3\)% of the speed of light. Taking into account the acceleration, we can estimate the time of flight of an electron from the nanotip to the anode (\( \sim 1.5\) \( \mu \)m) to be \( \sim 2 \times 10^{-13}\) s, which is two to three orders of magnitude shorter than the switching time of p–n junction semiconductor diodes.

The dependence of the maximum electric field strength on the nanotip diameter at different interelectrode gaps (1, 2, and 3 \( \mu \)m) is demonstrated in Fig. 3. At intermediate values of the gap, the maximum strength can be found by interpolation. In addition, the inset of Fig. 3 shows how the anode aperture diameter can affect the maximum field strength. It is clearly seen that the aperture diameter noticeably affects the electric field strength in the immediate vicinity of a nanotip only at interelectrode gaps \( \leq 1\) \( \mu \)m. It can be seen in the inset that, for a 1-\( \mu \)m interelectrode gap, the maximum electric field strength decreases by \( \sim 10\)\% upon a 3-fold increase in the aperture diameter.

The results presented in Figs. 2 and 3 were obtained numerically with CP03D program. We can also estimate the value of \( E \) in the vicinity of a nanotip with a \( \sim 20\)-\% precision by using a simple analytical formula \[9\]

\[
j = 1.4 \times 10^{-6} \cdot \left( \frac{E^2}{\phi} \right) \cdot 10^{4.39/\sqrt{\phi}} \cdot 10^{-2.82 \ln^{3/2} (x)},
\]

Fig. 1. SEM image of a part of a \( \mu \)TEC slightly modified to visualize the emitting nanotips coupled with apertures on the “front side”. The inset shows a single microemitter with a radius of about 15 nm. It should be noted that the number of overlapping nearest apertures is inversely proportional to a squared aperture diameter. For the regular working specimen, this number is approximately eight times smaller than that for the structure shown in the figure.

Fig. 2. Constant-electric-field contours in the vicinity of an emitting nanotip of the \( \mu \)TEC.
The structures we fabricated open up wide opportunities both in scientific studies and in the field of specific technological innovations.

The high values of $E$ make it possible to study the Stark-effect for determining the intramolecular forces and explaining the dielectric properties of molecules and to examine the secondary electron emission caused by positively charged ions and the mobility of these ions at $10^5$–$10^6$ V/cm, etc.

Three-electrode systems in which the anode apertures act as a grid of a vacuum triode, have not been calculated and designed. However, it is most likely that the technology of such systems will not considerably complicate the fabrication processes described above. Fabrication of superminiature active elements of current control devices based on FE cathodes could inspire a renewed interest in development of vacuum integrated circuits (VICs) containing no semiconductors. This is because the advantages of VICs are widely known, namely, their ability to work in strong radiation fields, at high temperatures, etc.

In addition, the μFEC structures obtained open up new opportunities in biology, namely, they enable studies of macromolecules by surface-enhanced Raman spectroscopy [10,11].

If the examined system of μFEC structures operates in gas/air in the secondary electron emission mode, it can also serve as a source of ions. It should be noted here that the cost of all the technological processes for fabrication of the suggested structure is low. In addition, use of a polymer matrix enables production of a cathode tape for determining the intramolecular forces and explaining the dielectric properties (e.g., carbon-like materials) can be deposited.

4. Conclusion

Thus, the track technology meets the main requirements to methods for fabrication of multiple-tip FE electron sources: (i) simplicity and low cost and (ii) operation at low voltages because of the small emitting nanotip diameter of ~30–40 nm and micrometer-sized interelectrode gap, obtained with a high (±0.2 μm) precision. The main advantage of the technology is that the same polymer film is used both for creating an ensemble of cone-shaped microemitters with emitting nanotips and for making the second electrode (anode) on its surface, where the emitting nanotips are situated, with the possibility of simultaneously controlling and varying the interelectrode gap. The art of fabrication of μFECs has been to a great extent finished and is patented now. So it could be extremely important to carry out team-work profound investigations of μFECs as to extend their fundamental properties understanding and to bring them to a series of applications.

References