Model of electron transport in cell of a thin-film vacuum nanotriode

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Abstract. Thin-film vacuum nanotriode with cone-shaped emitters is considered. Each emitter has height 200 nm with 1 nm radius of surface curvature on the top. Current-voltage characteristics are calculated for single cylindrical triode cell (655 nm in diameter). It is shown the value of the emission current comes to microamperes, when the voltage is less than 20 V applied on the anode-emitter gap 500 nm. Anode-cathode voltage 16-20 V can generate more than 0.5 mA emission current flown to the anode when gate-cathode voltage is less than 14 V and gate diameter is 150 nm.

The modulator or extractor electrode is often used to control field emission process from cold cathodes in height-power THz applications. Although simple vacuum diode system is sufficiently to start electron emission, triode configuration with field emitter as cathode, extractor electrode as gate and distant anode as collector is more stable. This configuration (figure 1 (a)) is selected for modeling of thin-film field-emission Spindt-type cathode [1]. One can say that the whole field of vacuum electronics developed from the production technology for a thin-film field emission cathode developed by Charles Spindt et al [1]. For an instance, figure 1 (a) schematically shows a field emission triode cell based on Spindt cathode. On substrate plane there is a conic metal emitter whose tip protrudes inside a hole in the controlling electrode film acting as a gate. Height of the cone, radius of the tip and of the gate hole can vary depending on the technological process requirements. Besides, there is a remote anode that acts as an electron collector.

The function of a vacuum thin-film nanotriode and other devices of vacuum nanoelectronics is based on several mutually interacting processes:

- Base factor is appearance of an electric field within the structures.
- Some particular values of field strength at the emitter surface cause field electron emission to appear. The process of field electron emission of electrons from metal is sufficiently precisely described by the well known Fowler-Nordheim equation:

\[ j(E) = \frac{AE^2}{\delta e^2} \exp \left[ -B \frac{a^{3/2}}{E} v(y) \right] \]  

(1)

Here \( j \) stands for the emission current density, while \( A \) and \( B \) are constants connected to fundamental physical values via equations \( A = \frac{e^3}{8\pi\hbar} \), \( B = \frac{8\pi\sqrt{2m}}{3\hbar^2} \), where \( h \) is the Planck constant, \( e \) is the electron charge and, \( m \) is the rest mass of a free electron, \( t(y) \) and \( v(y) \) are elliptic Nordheim functions of...
\[
y = \sqrt{\frac{e^3}{4\pi \varepsilon_0 \Phi}} \approx \frac{11619}{0.95 - y^2}, \quad \Phi
\]

is an electric constant, \( E \) is a value of external electron field strength, \( \Phi \) is the work function of the material used as a measure of energy of bond between the electrons and the solid.

- Because of the emission, electronic gas (plasma) is formed inside the structures. It can move under the influence of applied field.
- A space charge inside the structures that appears because of that acts as a source of secondary electric field that superimposes itself onto the base field.
- Processes that occur in parallel to this are secondary electron emission, polarisation and emergence of surface charge on the insulant, ionisation of remaining gas molecules.

**Figure 1.** Scheme of the thin film vacuum field emission nanotriode cell and electron trajectories with electric force lines in the computer model.

It is well-known that the space charge created by emitted electrons over the emitter surface can have influence on field electron emission. In [2] it is shown that for objects with emitter surface curvature radius of \( 1-10 \) nm non-negligible influence of space charge (change in the field by \( 1-10 \) \% begin with current density of \( 10^{13} \) A/m, while large influence (about 50\%, i.e. for the same current density the voltage has to be increased two-fold or more relative to calculated values) appears with current density \( 10^{14} \) A/m.

On the other hand, for emission current of approx. \( 10^{-7} \) A and distance between cathode and anode of about 500 nm every electron in the interelectrode space can be regarded as not interacting with other electrons, as the time of passing of particular electrons is smaller than their average time interval between two consecutive exits into the vacuum.

Besides, the emitted electron trajectories can be roughly regarded the same as the electric field force lines. This approach is called the assumption of “zero mass”, and it is the more precise the closer the force lines of the field are to straight lines. This approach is known also as electron massless approximation and used for electrostatic simulation of vacuum emission nanoelectronics devices. In vacuum nanoelectronics due to potential character of the electric field, integral of the vector \( \mathbf{E} \) along an arbitrary force line between two conductors is equal to the difference of their potentials, i.e. it is invariant. Thus, force lines with less curvature correspond to higher electric field strength. On the other hand, because of considerable non-linearity of Fawler-Nordheim formula, greater part of emission current is formed in areas with maximum field strength. Thus electron trajectories inside the whole area of emission can be regarded the same as force lines of vector \( \mathbf{E} \).
Trajectory analysis in massless approximation is performed by introducing the current flow function, well known in hydrodynamics [3]. The model supplies current-voltage characteristics including the effects of grid leakage current and the Fowler-Nordheim equation is used to calculate cathode current density.

Figure 2. Current-voltage characteristics of the triode cell. The anode current is dotted line, the gate current – solid line.

The thin-film field emitters produced by the technology of electron-beam evaporation are naturally polycrystallic. Cathodes produced this way have the same multiple shape as all thin-film electrodes and the crystal structure of its surface may vary between samples depending on crystal orientation, shape and contents of the substance.

Consequently, physical conditions on the emission surface of cathode are often non-uniform and prone to variance because of asperities, changes in the work function (incl. due to adsorbents) etc. This leads to emission not being observed from all the surface of cathode. For Spindt cathode the real emission surface is the surface of hemisphere with a radius equal to curvature radius of the emitter tip. For example, for radius of 30 nm the emission surface is about 565 sq. nm, and for a multitude of small areas of atomic size the combined emission surface would range from 0.13 sq. nm to 0.2 sq. nm [4] (other sources mention values up to 3 sq. nm [5]).

Accordingly, a considerably smaller voltage is required for a current to appear than one would expect in case of a physically and geometrically uniform emission surface.

Accounting for such minute geometrical details would make modelling of emitters considerably more complex (there are works in that direction: [6-10]). On the other hand, even then the Fawler-Nordheim equation would still describe the Spindt cathode emission current with sufficient confidence, despite that it assumes planar geometry.

Both those facts call for using the Fawler-Nordheim model. To adapt it for our needs, we introduce the local field enchantment factor

$$\gamma(s) = \frac{E_n(s)}{E_M(s)}$$

where $E_n(s)$ is the normal component of local electric field at point $s$ of the surface, $E_M(s)$ is the value of surface electric field strength in approximation of flat geometry (i.e. without nano-protrusions and other non-uniformities).

Regarding physical conditions of the surface, we make the following assumptions:
Work function is constant throughout the entirety of cathode surface (influence of the local changes in work function on the emission current is difficult to separate from field enhancement effect).

The variable $\gamma(s)$ is replaced with an effective constant $\gamma_{\text{eff}}$:

$$
\int_S \frac{A(y(s)E_M(s))^2}{\Phi t^2(y)} \exp \left( -B \frac{\Phi^{3/2}}{\gamma(s)E_M(s)} v(y) \right) ds
= \int_S \frac{A(y_{\text{eff}}E_M(s))^2}{\Phi t^2(y)} \exp \left( -B \frac{\Phi^{3/2}}{\gamma_{\text{eff}}E_M(s)} v(y) \right) ds
$$

where $S$ is the total surface of cathode, all the other values are the same as in equation (1).

Effective values of local field enhancement factor, that can be experimentally measured by the slope of Fawler-Nordheim line for flat electrodes in vacuum usually vary from several dozens to several thousands of units.

This work is based on modeling of nanotriode with a matrix of classical Spindt cathodes produced by the MIT (USA) [11]. This nanotriode is special in that radius of curvature at the tip of a cathode is just about 1 nm, thus influence of microstructure and nanoprotrusions of emission surface in negligible, and values of $\gamma_{\text{eff}}$ must be close to one. The microtriode matrix consists of 975 emitter cells. Modeling of one cylindrical cell used the following initial parameters: distance between the gate and the anode 500 nm, height of the tip 200 nm, tip curvature radius 1 nm, diameter of gate diaphragm 150 nm, thickness of gate 40 nm, distance between the gate and the base of the cell 195 nm, radius of a cylindrical cell 655 nm, work function value $\Phi = 4.2$ eV.

Calculated integral current characteristics are presented on figure 2. In the same time, current characteristic for $\gamma_{\text{eff}}=1.15$ is the same as on the experimental line presented in [11]. The value of the emission current comes to microamperes, when the voltage is less than 20 V. In dependence of the gate and the anode voltages current of emitted electrons can flow to the gate film (figure 1 (b)) or to the anode film (figure 1 (c)). As a result we have found voltage range corresponding to switching regime of electron current between the anode and gate electrodes. A comparison with edged cylinder-shaped emitter cell [12] is next step of the study.

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