CÁTODO DE EMISSÃO DE CAMPO MULTIPONTO COMO GERADOR DE OSCILAÇÕES DE ALTA FREQUÊNCIA

MULTI-POINTED FIELD-EMISSION CATHODE AS A GENERATOR OF HIGH-FREQUENCY OSCILLATIONS

МНОГООСТРИЙНЫЙ ПОЛЕВОЙ КАТОД КАК ИСТОЧНИК ВЫСОКОЧАСТОТНЫХ КОЛЕБАНИЙ

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Received 31 August 2020; received in revised form 16 September 2020; accepted 28 October 2020

RESUMO

Os cátodos de emissão de campo de semicondutores ganharam grande popularidade na moderna rádio-eletrônica e ótica eletrônica devido à alta potência de geração do feixe de elétrons no campo elétrico externo em temperaturas próximas às ambiente. No entanto, sua ampla aplicação é restringida pela alta dependência da corrente de emissão de elétrons com o valor do campo aplicado e parâmetros geométricos do cátodo. O objetivo deste estudo foi examinar o efeito dos processos de ressonância na amplificação da emissão de campo do cátodo semiconductor multiponto. A modelagem do comportamento do tunelamento ressonante de elétrons de semicondutores para o vácuo foi simulada resolvendo a equação de Schrodinger unidimensional e a amplificação devido a processos ressonantes foi estimada. Os resultados da modelagem mostraram que conforme o campo elétrico aumenta, as condições de ressonância mudam para níveis de energia baixos. Com o aumento da largura da barreira para o elétron dentro do corpo sólido, as condições de ressonância mudam para energias mais altas. Foi estabelecido que em semicondutores unidimensionais com elétrons de largura de baixa condutividade, a energia ressonante coincide com o nível de Fermi. Essas propriedades do cátodo são ideais para amplificar a corrente de emissão e reduzir as falhas de dispositivos eletrônicos de vácuo baseados em cátodos de campo semicondutores. A técnica proposta pode ser utilizada para estudar as regularidades de amplificação de emissão devido a processos ressonantes em cátodos semicondutores multiponto com estrutura multicamadas e com pontas metálicas.

Palavras-chave: *emissão de campo, equações de Fowler-Nordheim, oscilações de corrente, cátodo de campo, amplificação de campo geométrico.*

ABSTRACT

Semiconductor field-emission cathodes have gained considerable popularity in modern radio electronics and electronic optics due to the high-power generation of the electron beam in the external electric field at temperatures close to the room ones. However, their wide application is restricted by the high dependence of the electron emission current on the value of the applied field and geometrical parameters of the cathode. This study aimed to examine the effect of resonance processes on amplifying the field emission of the multi-pointed semiconductor cathode. Modeling the behavior of resonant tunneling of electrons from semiconductors to vacuum was simulated by solving the one-dimensional Schrodinger's equation, and the amplification due to resonant processes was estimated. The modeling results showed that as the electric field increases, the resonance conditions shift towards low energy levels. With the increase in the width of the barrier for the electron inside the solid body, the resonance conditions shift towards higher energies. It has been established that in one-dimensional semiconductors with electrons of low conductivity width, the resonant energy coincides with the Fermi level. These cathode properties are optimal for amplifying the emission current and reducing failures of vacuum

electronic devices based on semiconductive field cathodes. The proposed technique can be used to study the regularities of emission amplification due to resonant processes in multipoint semiconductor cathodes with multilayered structure and with metal tips.

Keywords: field emission, Fowler-Nordheim equations, resonant processes, semiconductive cathode

АННОТАЦИЯ

Полупроводниковые полевые катоды пользуются большой популярностью в современной радиоэлектронике и электронной оптике благодаря высокой мощности генерации электронного пучка во внешнем электрическом поле при температурах близких к комнатной. Однако их широкое использование ограничено большой зависимостью эмиссионного тока электронном от величины приложенного поля и геометрических параметров катода. Целью данного исследования являлось изучить влияние резонансных процессов на усиление полевой эмиссии многоострийного полупроводникового катода. Моделирование поведения резонансного туннелирования электронов из полупроводника в вакуум осуществлялось путем решения одномерного уравнения Шредингера и оценивалось усиление, обусловленное резонансными процессами. Результаты моделирования показали, что по мере увеличения величины электрического поля резонансные состояния смещаются в сторону низких уровней энергии. С увеличением ширины барьера для электрона внутри твердого тела наблюдается смещение резонансных состояний в сторону больших энергий. Установлено, что в одномерных полупроводниках с электронами малой полуширины проводимости резонансная энергия совпадает с уровнем Ферми. Данные свойства катода являются оптимальными для усиления эмиссионного тока и меньших сбоев в работе вакуумноэлектронных приборов на базе полупроводниковых полевых катодов. Предложенная методика может быть использована для изучения закономерностей усиления эмиссии за счет резонансных процессов в многоострийных полупроводниковых катодах с многослойной структурой и с металлическими наконечниками.

Ключевые слова: автоэлектронная эмиссия, уравнения Фаулера-Нордгейма, резонансные процессы, полупроводниковый катод

1. INTRODUCTION:

The history of vacuum electronics began with vacuum tubes used in electron microscopes, radio frequency power amplifiers, and thermionic energy conversion devices such as X-ray and microwave vacuum electronic devices (Eichmeier and Thumm, 2008; Parker *et al.*, 2002). In the past, vacuum tubes could only be manufactured in relatively large sizes. Furthermore, they were energy-intensive because electron beam generation from metals required the use of thermionic electron emitters at temperatures over 1000 °C to overcome the work function of the material (Machin, 1950) (Figure 1a).

Other disadvantages of thermionic emission include the broad energy spectrum of emitted electrons and material degradation due to the high operating temperature. One of the solutions to the above challenges was creating small electron sources based on the already known "cold" emission effect. The cold field electron emission, which was first described by Fowler and Nordheim, is suitable for low-temperature emission regimes (Fowler and Nordheim, 1928). In cold or field emission (FE), electrons are emitted from the surface of a metal or semiconductor under the influence of a strong

electric field (Figure 1b). This is called the quantum mechanical tunneling effect. In these conditions, field emission properties such as high current density and narrow energy spectrum are achieved using a high electric field (up to 110 V/cm) (Radauscher *et al.*, 2016; Yamamoto, 2005). Other advantages of cold cathodes are small size, stable emission over time, and high-frequency operability. In one of the first works on miniature vacuum field emission devices (Shoulders, 1961; Spindt, 1968), the authors suggest that electron emission sources that are below micron size are practically insensitive to heating in a broad temperature range (up to 1000 °C), unaffected by ionizing radiation, and with long lifetime, because a nonlinear function relates current and voltage characteristics of the field emission device, a small change in voltage can result in the exponential growth of emission current (Utsumi, 1991; Harris *et al.*, 2015). Due to the above advantages, cold cathodes have a wide range of applications such as in flat field emission displays (FEDs), miniature microwave and X-ray emitters, parallel electron beam microscopy, high-power accelerators, and more (Bachmann *et al.*, 2015; Garven and Parker, 2020). Often, field-emission cathodes are made of monocrystalline silicon and shaped into needle-like or pyramid-like tips (Egorov and Sheshin, 2017) (Figure 2).

In spite of their unique and desired properties, FE devices have a few drawbacks that hinder their wide-scale application, such as their ultra-high vacuum requirement ($10^{-5} - 10^{-9}$ Torr) and instability of the field emission current during the long-term and short-term emission operations (Swanson and Schwind, 2009). Another limitation is that CFE sources can experience a significant emission current decay (70–90% of the initial value) within the first hours of use, increasing energy consumption needed for heating to high temperatures. Studies on FE cathodes over the past decades focused on the use of tungsten nanowires (Chen and Yang, 2017), carbon nanotubes, and coatings (Jiang *et al.*, 2011), have found many limitations. For example, tungsten nanowires are only suitable for emission under the vacuum of less than 10^{-10} Torr since operation at higher vacuum pressure can be accompanied by significant current fluctuations (Yeong and Thong, 2006).

Recent studies (Liem and Choy, 2013) of various tip coatings have shown that nanoscale graphene coatings have several advantages over other types of coatings. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, has excellent thermal, mechanical, and electrical properties (Ang *et al.*, 2017; Balandin *et al.*, 2008). It can be used to create nanotip coatings to localize and enhance the applied electric field. This was the case of metallic and semiconducting nanotips (Huang *et al.*, 2016), which were coated with graphene-based thin films. However, none of the above methods is suitable for the electron device applications because the deposition of graphene creates multiple emission sites on the cathode plane (Santandrea *et al.*, 2011), rather than a single virtual source point at the gun exit. Various attempts to overlay an ultrathin (~ 1 nm) graphene flake onto a blunted tungsten probe (Tsai *et al.*, 2012) or a graphene ring (Shao *et al.*, 2016) have also failed because coatings of this thick were found to be can easily detachable. The consequences of such damage to the coating are malfunctions and poor radiation control.

It is essential to study field emission specifics from nanostructured and composite cathodes to employ the nano-sized cold cathodes. These aspects are usually less pronounced in most reviews today and share relatively little attention, and may have some potential for significant technological progress. The methodological structure of such a comparative review is important for convenient and useful reading. Still, this task involves working with the huge diversity and complexity of the field of study.

This work presents the theoretical modeling of multi-tip cathode architecture and microwave oscillation patterns. For this, electron emission devices obtained by nanostructuring surfaces were discussed. The study focuses on theories describing the qualitatively new operational characteristics of multi-line field cathodes.

Therefore, this study aimed at establishing patterns and mechanisms to amplify field emission of semiconductor cathodes through resonant processes. For this purpose, the behavior of resonant tunneling of electrons is simulated using the theory of field emission. The effect of emission current gain due to resonant processes was estimated by solving the one-dimensional Schrodinger's equation for electrons tunneling from semiconductor to vacuum.

2. MATERIALS AND METHODS:

2.1. Field emission theory

Basic equations from the theory of field emission are applied to simulate resonance tunneling processes by electron from the surface of the semiconductor cathode.

Field emission refers to the emission of electrons from a solid surface into vacuum by tunneling through a surface potential barrier under the influence of an electrostatic field. The emission current density obtained by field emission depends on the intensity of electric field F and the work function Φ . Figure 1b shows that the effective work function Φ_{eff} for FE is dependent upon the strength of the electric field, and the emission current variation is determined by the field dependence of the barrier shape. For FE to occur, the electric field must be at $\sim 10^9$ V/m, and to create such strong fields, cathodes must have a cone shape or a tip shape (Figure 2), with a radius of less than a micron (Shoulders, 1961). The strong electric field concentrated at the tip of the emitter will thus marrow the potential barrier at the metal-vacuum interface to several nanometers. The result is a higher probability of tunneling.

Electron field emission is usually described by the Fowler-Nordheim equation (FNE) (Fowler and Nordheim, 1928). The general theory of field emission from semiconductors was described in fairly early publications (Morgulis, 1947; Stratton, 1964). It is based on statistics of degenerate carriers and takes into account different masses of electrons in a semiconductor and in vacuum. In addition, quantum-mechanical tunneling processes are an important mechanism for the transfer of current through thin barriers that are

present in metal-semiconductor transitions on highly doped semiconductors. According to the classical theory of field emission, the system is simplified to a one-dimensional structure along the direction of the external electric field. The emission tip is modeled as a semi-infinite quantum well with a work function Φ , and a linear potential approximates the applied electric field F . The FNE equation for the emission current density J would be:

$$J = A \frac{(\beta F)^2}{\Phi} \exp \left(-B \frac{\Phi^{3/2}}{\beta F} \right) \quad (\text{Eq. 1})$$

where: A and B are constants equal to $1.54 \cdot 10^{-6} \text{ AeV/V}^2$ and $6.83 \cdot 10^7 \text{ V/eV}^{2/3}\text{m}$, respectively; β is the field enhancement factor, which is the ratio between the local and the applied field. Normally, the local field potential exceeds the value of the applied field. Therefore, the field enhancement factor β can range between hundreds and thousands.

The equation (1) shows that the dependence of the emitted current on the local electric field and the work function is exponential-like. Thus, variation of the shape or surrounding of the emitter has a strong impact on the emitted current. The equation (1) can be re-arranged as follows:

$$\ln \left(\frac{J}{F^2} \right) = \ln \left(A \frac{\beta^2}{\Phi} \right) - B \frac{\Phi^{3/2}}{\beta F} \quad (\text{Eq. 2})$$

The plot of the equation (2) as a function of $1/F$ is called the F-N plot. Here, the field enhancement factor β can be calculated from the slope of the F-N plot if the work function of the emitter is already known (Fursey, 2007). The top of the triangular barrier used in our semiconductor-vacuum interface model was lowered by the electric polarization, as expected for the devices under study.

2.2. Emitters: architecture and properties

According to equation (2), the emission current density J depends on two factors: work function Φ and field enhancement factor β . Therefore, the emission current density at a low electric field will be high if the emitter exhibits a low work function or a high enhancement factor. Since the work function depends upon the intrinsic electronic properties and the surface state of the emitter, materials were chosen to create a tip or a

coating normally exhibit a lower work function. However, the lower work function is not the main factor of higher current density because not all materials have high stability and durability (Biswas, 2018). Therefore, another way to improve J is to increase β . The field enhancement factor represents amplification of the electric field at the emitter surface, determined by the geometrical shape of the emitter. The local electric field at the emitter surface can be defined as:

$$F_{loc} = \beta F \quad (\text{Eq. 3})$$

Based on the equation above, it can be noted that when the field enhancement factor β is higher, the enhancement over the local field is stronger. The value of field enhancement factor β depends upon the geometric parameters of the emitter, such as height (h) and radius of the curvature on its tip (r), as shown in:

$$\beta \propto \frac{h}{r} \quad (\text{Eq. 4})$$

Thus, the higher and the sharper the emitting center, the higher the value of the field enhancement factor. It should also be noted that the above expression (4) does not include a screening effect introduced by nearby emitters, which reduces the field enhancement factor. Therefore, it is only suitable for single emitters.

Devices using field emission and having a nanostructured cathode surface can usually be described as having a vacuum/specific material interface. The cathode material is deformed on a nanometer scale. Tunnel emission of electrons from flat surfaces can be created only in very high electric fields (or at high applied voltages), even if the cathode material is a metal. On the other hand, the creation of large fields in large volumes greatly increases the possibility of device failure due to electrical discharges. For this reason, the creation of localized deposits with a high degree of recovery is naturally preferable. This local field enhancement is most often achieved by the concentration of the radiation region in the very sharp tips of the cathodes/emitting surfaces.

The first cathodes proposed by Spindt (1968) were points with radii in the range of several tens of nanometers, etched from solid material using photolithography technologies to obtain a nanostructured surface (Figure 2). However, this development was quickly followed

by many developments: a wide variety of materials for field emission were investigated and many methods of nanostructuring of surfaces appeared. As a first obvious step, many research groups initially investigated field emission from silicon tips. This was a natural question, since the possibility of integrating field emission devices into existing silicon-based microelectronic technologies was a very attractive concept (Kleps *et al.*, 2009) further enhance the local extraction field, processes designed to convert a flat silicon surface into a porous material were performed by electrochemical etching. The obtained nanoresonators were localized near the surface and separated by nanometer-sized amorphous silicon fibrils, which became excellent field emission sites (Lee *et al.*, 2018).

In the present work, multipoint structures like multiblade silicon cathode in Figure 2 will be used to model resonance processes. The density of the homogeneous structure on the 0.5 mm diameter surface section was 200-300 points.

2.3. Tunneling probability

The probability of electron tunneling from a semiconductor to a vacuum from a stationary - time-independent Schrödinger equation is derived as:

$$-\frac{\hbar^2}{2m_e} \times \frac{d^2\Psi}{dx^2} + V(x)\Psi = E\Psi \quad (\text{Eq. 5})$$

Which can be rewritten as

$$\frac{d^2\Psi}{dx^2} = \frac{2m_e(V-E)}{\hbar^2} \Psi, \quad (\text{Eq. 6})$$

where $\hbar$ is the Planck constant, Ψ is the wave function, m_e is the effective electron mass, $V(x)$ is the potential relief on the path of the electron, E is the electron energy and x is the coordinate along which tunneling occurs (direction from the solid to the vacuum).

Assuming that the potential relief changes quite smoothly, i.e. it can be written the condition: $V(x) - E$ varies slightly on the interval $x+dx$, this is the so-called WKB-approximation (Wentzel – Kramers – Brillouin), the second equation can be represented as:

$$\Psi(x + dx) = \Psi(x) \times e^{-kdx}, \quad (\text{Eq. 7})$$

$$\text{where } k = \frac{\sqrt{2m_e[V(x)-E]}}{\hbar}$$

The minus sign is chosen because it is assumed that the particles move from left to right. For a slowly changing potential, the amplitude of the wave function at $x = L$ can be related to the wave function at $x = 0$ using the following equation:

$$\Psi(L) = \Psi(0)e^{\left(-\int_0^L \sqrt{2m_e[V(x)-E]}/\hbar dx\right)}, \quad (\text{Eq. 8})$$

where L is the classical turning point and the outer boundary of the barrier, which is the last point where the electron is inside the barrier potential. Equation 8 also relates to the WKB approximation. The general case assumes that the triangular barrier is a good approximation to describe the semiconductor-vacuum interface. The tunneling probability Ξ can be calculated in the case of approaching a triangular barrier using the following equation:

$$\Xi = [\Psi(L)\Psi^*(L)/\Psi(0)\Psi^*(0)] = e^{-\left\{2\int_0^L \left(\frac{\sqrt{2m_e}}{\hbar}\right) \sqrt{q\chi_0\left[1-\left(\frac{x}{L}\right)^2}\right] dx\right\}}, \quad (\text{Eq. 9})$$

where χ_0 is the height of the barrier at the cathode-vacuum interface. The parameter Ξ can be estimated as a function of the electric field F :

$$\Xi_{\Delta}(F, E) = C \times e^{\left[\left(-\frac{4}{3}\hbar F\right) \times \sqrt{2m_e(\chi_0-E)^3}\right]}, \quad (\text{Eq. 10})$$

where Ξ_{Δ} is the probability of tunneling through the triangular barrier. The tunneling current can be represented as the electron velocity product and the probability of tunneling and the density of available electrons. The latter can be represented as the product of the density of states and electron distribution (Fermi statistics). The electron velocity referred to here may be somewhat different from the usually determined volume drift velocity due to the effect of scattering on the barrier. However, it is hypothesized that the barrier does not significantly violate the field dependence of the drift velocity, which in any case is a much weaker function compared to another factor. The velocity corresponds to the average velocity of carriers approaching the barrier. The current density is equal to the density of available electrons to the barrier, multiplied by the probability of tunneling and the drift velocity. So, the following expression for the density of the tunneling current can be written as:

$$J_C(F) = A_C \int_{E_C}^{\infty} N(F, E) \times \Xi_{\Delta}(F, E) \times V_D(F, E) dE, \quad (\text{Eq. 11})$$

Therefore, the tunneling current shows an exponential dependence of degree 3/2 on the barrier height if all other factors N , V_D , and A_C are constant or slightly different. In the well-developed Fowler-Nordheim approximation, the tunnel current has exactly this dependence:

$$J_{FN}(F) = C_{FN} \times \frac{F^2}{\varphi} e^{-B\varphi^{3/2}/F} \quad (\text{Eq. 12})$$

Therefore, the tunneling current shows an exponential dependence on 3/2 of the power of the barrier height if all other factors N , V_D , and A_C are constant or slightly different. In this approximation, the concentration of charge carriers depends on many quantities:

$$N_{3D}(F, E) = \frac{\sqrt{2}m_e^{3/2}}{\pi^2\hbar^3} \times \frac{\sqrt{E}}{1+e^{\frac{E-\mu}{kT_e(F)}}} \quad (\text{Eq. 13})$$

This quantity describes the density of charge carriers for a bulk semiconductor, but moreover, in the case of a sufficiently thin semiconductor tip, a quantum-dimensional constraint should be expected. In this case the one-dimensional density of states will have a dramatic effect on the form of the function of the number density of carriers:

$$N_{1D}(F, E) = \frac{m_e^{1/2}}{\sqrt{2}\pi\hbar d^2} \times \frac{1}{1+e^{\frac{E-\mu}{kT_e(F)}}} \times \sum \frac{1}{\sqrt{E-E_{ql}}} \quad (\text{Eq. 14})$$

2.4. Analysis conditions

The motion of electrons to the surface of a silicon pole with Fermi energy of 1.12 eV and 4.60-4.85 eV output is considered. The applied field F changes in the range from 0.1 V / nm to 5 V / nm. The cathode temperature is 300K. The energy of the electrons ranged from 0 to 12 eV in increments of 0.0012 eV. The width of the energy barrier varied from 1 to 5 nm. Calculations and graphs of dependence were performed through the software package in MathLab.

3. RESULTS AND DISCUSSION:

The results of modeling different

resonance states under variable conditions of the energy barrier width for the electron and the value of the applied field for multipoint silicone cathodes showed that both resonance and non-resonance effects influence the amplification of the emission current.

Figure 3 shows a diagram of dependence between tunneling probability and factors, such as variation in the applied electric field F (on the left) and energy barrier width L (on the right). As can be seen in Figure 3, the tunneling probability of electrons with $L=1$ nm increases with the applied field. Also, there is a clear resonance curve peaking. The observed shift of resonance towards lower energies with increasing F is typical for band bending in quantum tunnel systems. At the applied field of 1 V/nm, the probability of tunneling increased when the L decreased, and the resonance shifted towards higher energies. This can be explained as follows. The tunneling probability of electrons approaching the cathode surface increases due to a decrease in the potential barrier height.

The latter is the main result of this work and the axial meaning of the proposal. In the case of a one-dimensional semiconductor and a one-dimensional carrier spectrum, the shape of this spectrum is very different from the wide spectrum typical of a bulk semiconductor and will show an extremely small half-width. This has interesting consequences, see Figure 4. Having a small half-width, the electrons tunneled into the vacuum will have approximately the same speed. It means they will react uniformly to control influences and the anode will also be reached uniformly. This means high quality factor, low stray currents and a low level of distortion in the operation of vacuum-electronic devices based on such field cathodes.

However, due to the integrated contribution to the emission current from several electronic states (which is typical for multi-band semiconductors), the increase in current near the resonances is usually rougher, but should also be high enough and sharp so that it can be attributed to such (Filip *et al.*, 2016; She *et al.*, 2004). There are situations where facilities designed to detect the effects of resonant field emission do not show relevant salient features (Gu *et al.*, 2012; Sarker *et al.*, 2014). In most cases, the absence of resonance behavior in the current-voltage diagrams is associated with the loss of coherence of the electron wave function when crossing the region with a high probability of scattering by defects (including free interlayer boundaries). Although experimentally quite difficult to investigate, the emission of resonant current

through an electron field from the so-called “quantum cathodes” has long been of particular interest because of its high potential for use. For example, the areas of negative conductivity of the current–voltage characteristics near resonances can allow the vibrational behavior of the field emission structure (Mukherjee and Paul, 2018).

Theoretical approaches are mainly based on the solution of the one-electron Schrödinger equation with intrinsic constraints of the envelope of the electron wave function at various interfaces, modeled as finite discontinuities in potential energy, which allows one to calculate the electron transfer coefficient (Tan *et al.*, 2016). To calculate the field emission current, the old statistical/kinetic argument is used (Murphy and Good, 1956): the contributions of all states in the substrate are taken into account using the so-called power function, weighted by the probability of transmission for each state. The feed function from the volume includes the statistical distribution of electrons (which are usually assumed in local thermodynamic equilibrium). This is a general outline that allows for many improvements. For example, when it comes to the emission of an electron field from silicon through a thin layer of diamond-like carbon, one can take into account defects in this layer, modeling them as randomly located delta potentials between which there is tunnel transport under the applied field (Xu and Huq, 2005). Without obtaining a large resonant signature, the result of this coherent model is an oscillatory current – voltage characteristic with qualitative similarity to many experimental results. No less interesting is the study of the effect of two or more layers deposited on a base substrate (Chang and Pao, 2019; Wang *et al.*, 2005).

If the uppermost layer is conductive, it represents a potential well between the previous layer and the vacuum barrier. It is interesting how the possible accumulation of electrons in this well can affect the radiation (Wang *et al.*, 2017), because the accumulated space charge changes the profile of potential energy. Therefore, to obtain the emission current in this case, a self-consistent approach of the coupled Schrödinger and Poisson equations is necessary. Besides, the very electronic structure of the substrate can also significantly affect the radiation current obtained from quantum cathodes. A thorough analysis of this aspect can explain the specific behavior of such emitters. For example, sudden changes in the slope of the current-voltage characteristics in the Fowler–Nordheim representation and the effect of substrate illumination on the field emission current (Nahhas, 2018).

It is also worth adding that no matter how promising the phenomenon of resonant tunneling through an electric field from quantum cathodes is, it should be recognized that this phenomenon can rarely be identified in its pure form in practice. When a complex emitting structure has a potential well in front of the vacuum barrier, the accumulation of electrons in this region is inevitable. Therefore, an additional type of electron transfer into vacuum should always be taken into account. This is the so-called sequential tunneling mechanism, which, unlike resonant tunneling, is necessarily inelastic and occurs in two or more “steps”. The electron breaks from one potential well to another, and as a result, to vacuum. Both resonant and sequential transfer processes must occur simultaneously from the same batch of incoming electrons from the bulk substrate. One interesting question will concern the relative share of these two mechanisms in the same field emission process. It is equally important to know the relationship (if any) between these two different processes. To answer these questions, a simple type of quantum cathode has recently been reviewed (Filip and Wong, 2016).

The individual contributions of the resonant and sequential tunneling processes to the total radiation current are estimated (Huttner *et al.*, 2017). It was assumed that the electrons undergoing sequential transfer are among those that deviate from resonance states due to various inelastic interactions within different material layers. Besides, accumulating in the structure, these electrons cause changes in the potential energy profile, directly affecting the local energy spectrum and, therefore, the resonant transfer. Thanks to this basic hypothesis, the two transfer mechanisms are closely intertwined. Both of them are directly affected by the constraints imposed by the quantum constraint in the narrow potential wells of the structure (Karlewski *et al.*, 2016). As a result, on separate volt-ampere diagrams of both current components, features can be related both to the conditions of transverse confinement and the balance of the electron flow through different layers.

4. CONCLUSIONS:

This paper applied a one-dimensional field emission model to estimate the impact of resonance processes on the probability of tunneling electrons from the surface of a semiconductor cathode with a multipoint structure. It has been shown that the emission current is amplified at a small width of the energy barrier due to resonance and non-resonance effects. In

contrast, the resonance process prevailed at increasing the external field. Such amplification is achieved through the local emission current density. It has been established that at the shift of resonance energies, the maximum increase of emission current density is reached at the coincidence of values of resonance energy with Fermi energy of semiconductor cathode. The current emission gain can be adjusted by resonance effects when calculating the design and material selection parameters for multipoint field cathodes. In the future, the proposed technique can be used to optimize the field emission current by matching the resonance processes for multipoint semiconductor cathodes with multilayer structures and metal tips.

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Figure 1. Schematic diagram showing how electrons overcome potential barriers in the metal-vacuum system via thermionic (a) and cold field electron (b) emission. Designations: x represents distance from the metal surface; $-e^2/4x$ is the potential barrier; Φ is the work function; $-eFx$ is the electric field potential with intensity F ; $e^2/4x - eFx$ is the potential barrier in an external field with an effective work function (Φ_{eff}).

Figure 2. SEM images of multitip and multiblade silicon field-emission cathodes

Figure 3. A schematic representation of dependence between tunneling probability and conduction electron energy relative to the Fermi energy level (E_F). The figure on the left shows dependence data for electrons, which are energy barrier width $L = 1$ nm, at varying applied fields. The figure on the right shows dependence data for electrons with varying energy barrier width at $F = 1$ V/nm.

Figure 4. Type of energy distribution of the density of current carriers in the emitted current in the case of a one-dimensional cathode experiencing a quantum-size constraint.