EMISSION CHARACTERISTICS OF SEMICONDUCTOR QUANTUM CATHODES

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Structures with a quantized band spectrum demonstrate important peculiarities of optical, electric, catalytic, and other characteristics. They are also promising for the investigation of emission effects. A special attention is attracted by semiconductor structures with a many-valley band spectrum, where the quantization provides the emission from “shallow” satellite bands with a relatively low work function. The electron population of these bands in low-strength electric fields is facilitated by a decrease of the distance of these bands from the main one, the pattern of the energy distribution of electron states, and a more effective heating of free electrons due to the dimensional quantization. In addition, the energy of the main conduction band gradually rises to the vacuum level, from where the field emission starts even at low fields, as well as the monochromatic emission from quantum cathodes. The work presents the results of the theoretical analysis and experimental investigations of the electron field (so-called cold) emission from semiconductor quantum cathodes.

1. Introduction

Quantum cathodes (QC) represent emissive structures that use the quantum-dimensional effect for electron emission [1–6]. They are promising for the intensification of emission, generation of microwave (THz) oscillations, and formation of vacuum transistors-amplifiers, as well as for the study of band and kinetic phenomena [1–5].

A special attention is paid to insufficiently studied high-energy-gap semiconductors characterized by relatively low concentrations of free carriers (i.e., a nondegenerate statistics is realized) unlike common Fowler–Nordheim (FN) emitters with “metallized” degenerate electron gas. Thus, it was necessary to generalize the cold emission theory and to test it by the example of a high-energy-gap semiconductor GaN.

2. Theoretical Analysis

The most characteristic properties of QCs are caused by the peculiarities of the electron band spectrum of quantum structures and the specific features of the energy band distribution of free carriers (electrons) in the initial state and a state excited by the electric field. The other specific features are electron heating and surface-barrier tunneling. Let us consider sequentially these four factors that determine the process of QC cold emission.

Figure 1 presents a typical form of the band structure of a high-energy-gap semiconductor GaN – for its bulk (solid curves). After the dimensional quantization, the widening of the forbidden band in a QC automatically results in a decrease of the work function [1]. As one can see from the figure, it is supposed not only for the main band but also for satellite ones (though not so abruptly due to a larger effective mass of charge carriers in the latter).

Figure 2 shows the calculated dependences of the edges of the main and satellite quantized bands (for one-, two-, and zero-dimensional structures), as well as the energy distance between these bands, on the geometrical size of quantized systems based on a high-energy-gap semiconductor GaN (E_g= 3.3 eV) [2].

The field emission currents from the main and satellite bands are calculated according to the following

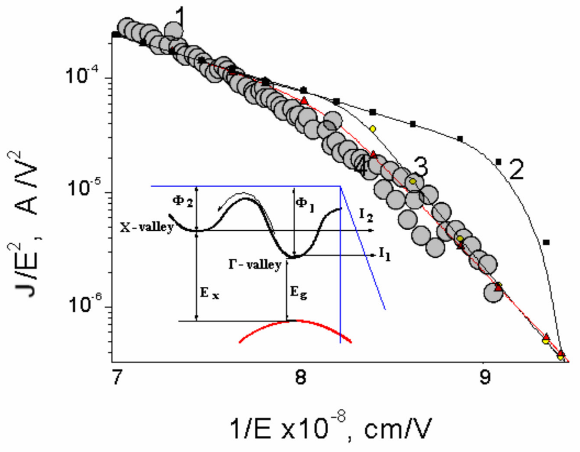


Fig. 1. Current-voltage characteristics of the field emission (in the FN coordinates): *1* – experiment, *2–4* – calculated curves for various intervalley distances: 0.5 eV (2), 0.7 eV (3), 0.8 eV (4). Inset: schematic band structure of a two-valley semiconductor

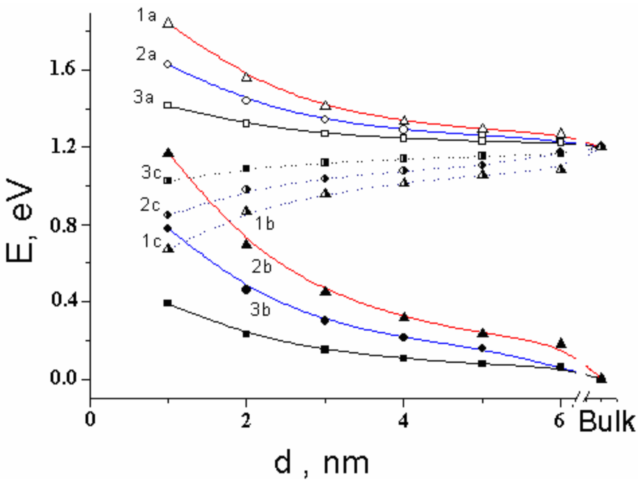


Fig. 2. Calculated variations (due to the quantum-dimensional effect) of the main and satellite valleys and the intervalley distance: $1a$–$1c$ – 0D case, $2a$–$2c$ – 1D case, $3a$–$3c$ – 2D case

general relations:

$$I_{C1}(F) = A_1 \int\limits_{E_{C1}}^{E_{C2}} n_1(F,E)\, \upsilon_{D1}(F,E)\, D(F,E)\, dE, \qquad (1)$$

$$\mathrm{I}_{C2}(F) = A_2 \int\limits_{E_{C2}}^{\infty} n_2(F,E)\, V_{D2}(F,E)\, D(F,E)\, dE, \qquad (2)$$

where E_{C1}, E_{C2} denote the energy positions of the edges of the main and satellite bands, respectively, $n_{1,2}(F,E)$ are the concentrations of free electrons in the given bands, D is the coefficient of tunneling through a vacuum barrier, υ_D is the drift velocity, F is the electric field, and E is the electron energy in the corresponding bands.

The calculation of $n(F,E)$ for QCs includes obtaining the Boltzmann dependence of the occupancy of states with electrons $f(E)$ and the corresponding distribution of electron states of the bands $N(E)$. First of all, it is worth noting a fundamental distinction of the QC band spectrum and the energy distribution of nondegenerate electrons over bands, from which the emission takes place (Fig. 3). The energy distribution in the case of a bulk cathode is rather smooth, whereas it is peak-shaped in the case of a one-dimensional QC:

$$n_{3D} = N_{3D} f(E) = \frac{\sqrt{2} m^{3/2}}{\pi^2 \hbar^3} \frac{\sqrt{E}}{1 + \ell^{\frac{E-E_F}{kT}}}, \qquad (3)$$

$$n_{1D} = N_{1D} f(E) = \frac{m^{1/2}}{\sqrt{2\pi\hbar d^2}} \frac{(E - E_{QF})^{-1/2}}{1 + \ell^{\frac{E-E_P}{kT}}}, \qquad (4)$$

where E is the energy of free electrons.

For the classic field emission, the electron gas is degenerate, the distribution function $f \approx \ln\left(1 - e^{\cdot \frac{-E+F}{kT}}\right)$ is weakly varying and close to unity, while the electron heating is practically absent. Thus, the electron concentration does not change even in maximal fields.

A completely another situation is realized for the nondegenerate distribution (Maxwell–Boltzmann distribution) typical of semiconductors. Receiving a directed momentum $p = m^* \overrightarrow{\upsilon_D} = \frac{\hbar}{k}$, the electron gas can be heated up to hundreds of millivolts and higher with the shift of the electron energy distribution. Let us use the approximations of inelastic collision and effective temperature of the electron gas T_e as a separate system quasi-isolated from the lattice:

$$E_k = \frac{p^2(F)}{2m} = \frac{3}{2} k T_e(F) \qquad (5)$$

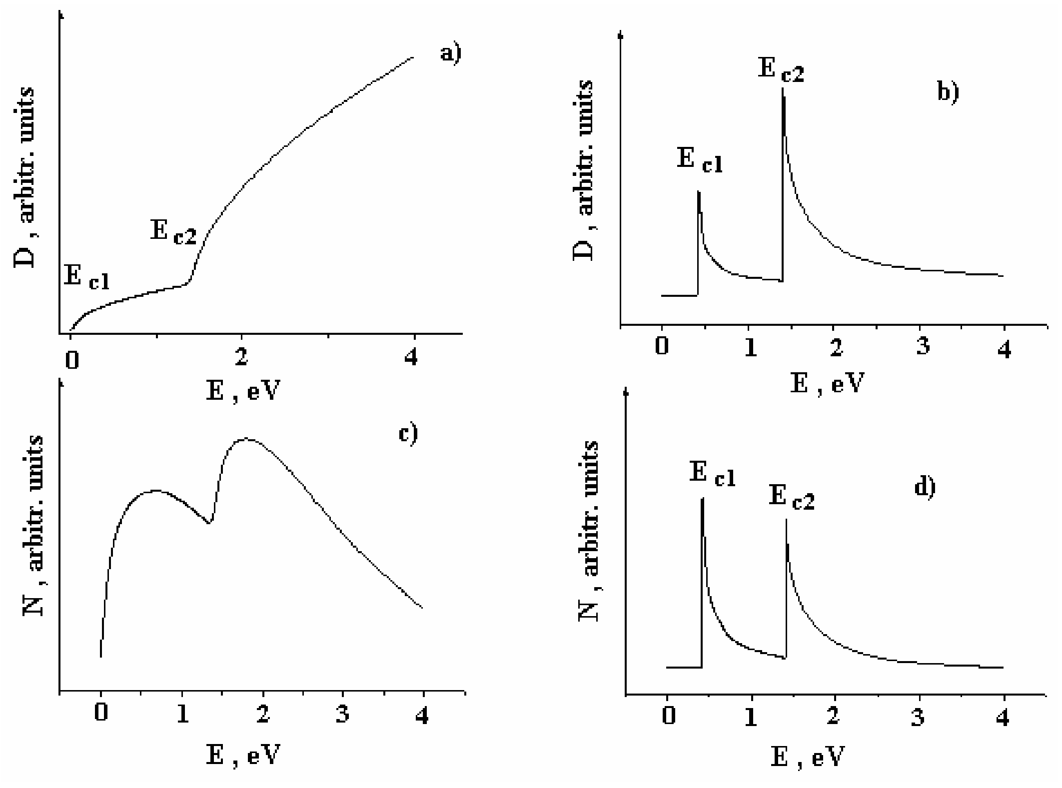
$$f(p) = C \exp\left[\frac{-(p-p_0)^2}{2m^* k T_2(F)}\right] = C \exp \frac{-E}{kT_e(F)}, \qquad (6)$$

where $E = (p - p_0)^2 / 2m^*$ is the kinetic energy of free electrons.

Under such conditions, the redistribution of electrons between the main and the satellite bands becomes possible. The redistribution is calculated in the assumption that the additional energy of heated electrons is still insufficient to induce the field ionization, i.e. the generation of free electrons from the valence band. Thus, the impact ionization is still absent, and the lattice temperature is invariable. That is, the following neutrality equation is fulfilled:

$$n_{10} + n_{20} = n_{1E}(E) + n_{2E}(E) \cong \text{const.} \qquad (7)$$

Figures 4 and 5 demonstrate the dependences of the emission current and the redistribution of free carriers depending on the electric field for bulk and quantized (1D) GaN cathodes [7]. For the sake of comparison, we present the similar dependence for a GaAs semiconductor with a small energy gap width (E_i = 1.35 eV). This material is typical of obtaining the Gunn effect, where the interband redistribution of carriers already takes place at relatively low fields $F \sim 3{\cdot}10^3$ V/cm. As one can see from Fig. 5, almost all free electrons pass to the satellite X-zone separated from the main one only by $\Delta E_v \approx 0.34$ eV. At the same time, the value of ΔE_v for a bulk GaN is much larger: $\Delta E_v \cong 1.5 \pm 0.3$ eV (according to different theoretical calculations [2]). That is why, in the "bulk" 3D case, only $\approx 60\%$ carriers can pass from the upper band to the



bulk

1D

Fig. 3. Density of states (*a,b*) and carriers (*c,d*) as functions of the band energy for the main and satellite GaN valleys in the 3D (*a,c*) and 1D (quantum-dimensional effect) (*b,d*) cases. All curves are calculated for an electric field of 5×10^5 V/cm

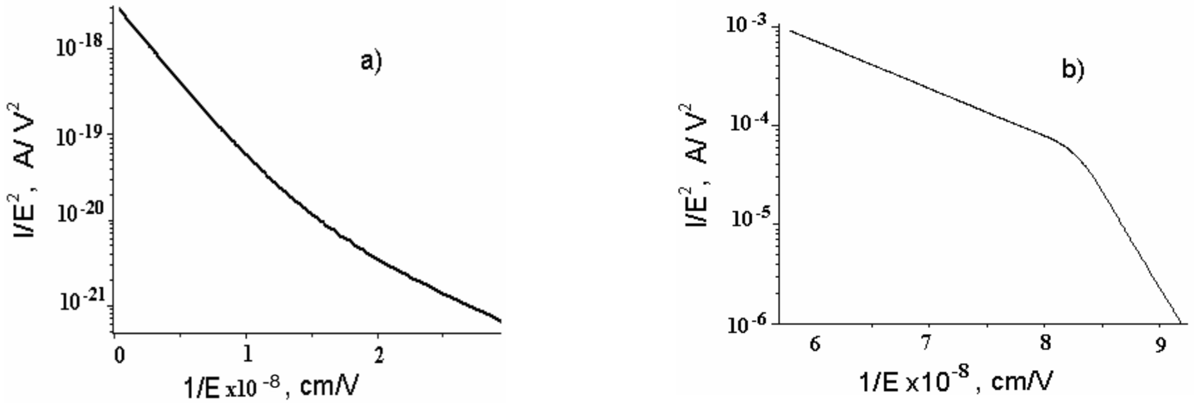


Fig. 4. Field emission currents for a bulk semiconductor (*a*) and a 1D GaN nanostructured surface (*b*). The different slopes are caused by the difference in the state densities of a bulk and nanotextured many-valley semiconductor

satellite one; moreover, this occurs at fields higher than those in the case of GaAs by two orders of magnitude [$\sim$(2–3)$\cdot10^5$ V/cm]. However, the redistribution for QCs reaches much larger magnitudes, namely up to $\sim$90%, moreover the redistribution stops in lower ($\sim$ by a factor of 2) fields. The reason for the difference consists in a much (approximately twofold) lower value of $\Delta E_v \sim$ 0.6 eV for nanostructured QCs. An abrupt behavior of

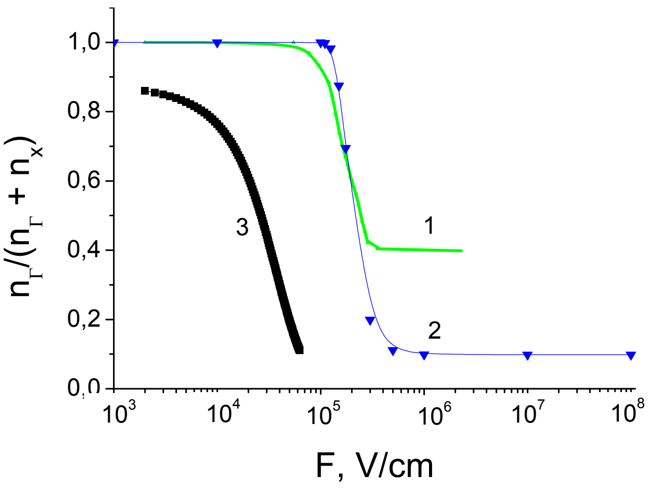


Fig. 5. Photostimulated emission from a gallium nitride surface: comparison of experiment and theory

the transient dependence $n(F)$ for QCs is caused by the δ-like form of the dependence of the state density $n_{1D}(E)$ in contrast to the smooth (dome-shaped) dependence $n_{3D}(E)$ for the bulk case (Fig. 3).

When calculating $n(E)$, we used the theoretical dependence of the drift velocity $\upsilon_D(F)$ that increases linearly up to the fields $F \sim 10^5$ V/cm and becomes almost saturated at $F \geq 2 \cdot 10^5$ V/cm (amounting to $\sim 2 \cdot 10^7$ cm/eV). In the case of the further increase of F, a slight (up to twofold) decrease is observed due to the partial transition of carriers to the satellite band, for which the effective mass m_{2c} is higher by a factor of 2–3 [1, 2].

The dependence of the tunneling coefficient on the applied electric field F is calculated in the approximation of triangular barrier with regard for the polarization forces $F_3 \sim 1/4(X+X_0)^2$ (the latter becomes significant only in the maximal fields where D is close to $\sim (0.5 \div 1)L$) [1]:

$$D\left(F,E\right) = C\exp\left\{-\frac{4}{6\hbar F}\left(2m^*\left(\Phi - E\right)^3\right)^{1/2}\right\},$$

where Φ is the work function that coincides with the surface barrier of a vacuum cathode in the case of field emission. In the classical case of the field emission described by the FN relation [1], all the other multipliers in the expression for the field current depend weakly on the field as compared to the tunneling mechanism, where D represents an exponential function of Φ and F:

$$I_e/F^2 = \sum C_{vi}\exp\left(-B\Phi_n^{3/2}\beta/F\right).$$

Here, the quantity $\beta \approx 3 + h/r$ is the coefficient of geometrical amplification of the electric field for a field pointed cathode with height h and apex radius r.

In the case of QCs, the dependences of the field current on the applied field $I(F)$ become more complicated. In the general form, they can be obtained only by means of numerical integration. However, due to the quasi-delta-shaped dependence of the electron state distribution in some important cases and in QCs, the dependences have a form close to the FN one. Moreover, the transient region appears to be even more abrupt than that in the case of the classical FN dependence, Fig. 1.

The peculiarities of the state distribution in the band spectrum, as well as those of the intervalley redistribution of carriers in the field, also result in the qualitative difference of the FN dependence for the emission of a two-valley quantum cathode. Namely, in the case of a nonquantized cathode at moderate fields F, one usually expects the FN dependence in the form of two straight lines with a downward bending (increase of the slope of the line at large fields F); whereas a broken line with an upward bending is predicted for quantum cathodes. Such a character of the FN dependences in GaN means the expected change of the slope of the FN straight lines for the transition from the emission from the lower band to the upper one with a lower work function in the case of repopulation of the latter due to the heating of the electron gas under the action of an applied electric field. A decrease of the slope can be also caused by the screening of the applied field by surface states [8], whose influence becomes inessential with application of modern technology.

In the bulk (3D) case of GaN cathodes, the current from the lower valley at low fields F is too small to be fixed. That is why under real conditions, the emission measurements start from the current from the satellite band already at moderate fields. At the highest fields F, the current from this band saturates. It is caused by the disappearance of the barrier that remains significant for the main (lower) band, where there still exists a sufficient number of carriers in the case of a bulk cathode (Fig. 5), though their concentration already does not depend on the applied field. This case imitates the classical FN dependence though with other pre-exponential multipliers and the work function corresponding to the lower quantized valley (straight line with a large slope). In transient fields, there takes place a superposition of the currents of the upper and lower valleys. Thus, in the general case, the dependence $I(F)$ has a form of a broken line consisting of three regions. In the case of QCs, the number of carriers in the lower valley remains too small (≤10%) to provide an essential current even at the highest fields. That is why a broken line including two regions with the upward bending at large fields is realized in this case, which is illustrated by Fig. 1.

3. Experimental Data

The results of experimental investigations of the field emission for common and quantum cathodes for various semiconductors (Si, Ge, Ga, GaN, InSb) were described, in particular, in [1–7].

Figures 1 and 2 present the experimental data for QCs with GaN nanoapexes obtained by means of the selective electrochemical etching [5, 7]. Unlike metal cathodes (where one expects a straight line on the FN scale), the considered ones are characterized by the presence of two (or sometimes three) straight lines with an abrupt break. From the slope of these lines, one can obtain the values of the vacuum barriers (work function) for the main ($\Phi_1 \cong 3$ eV) and satellite bands ($\Phi_2 \sim 2.5$ eV), as well as the interband distance $\Delta E_v \sim 0.6 \pm 0.1$ eV. The theoretical dependences were obtained for various interband distances ΔE_v, illustrating a high sensitivity of the current curves to the variation of ΔE_v. With increase in ΔE_v, the influence of the emission from the lower band grows, but the current itself falls so that the current becomes negligibly small even at high fields.

For bulk cathodes obtained from a microstructured strongly doped surface, a dependence in the form of three rectilinear regions with slopes close to the predicted ones was rather often observed. Moreover, the medium line corresponded to $\Delta E_v \sim 1 \pm 0.2$ eV – the intervalley distance for the bulk of GaN, whereas the two extreme ones had the same slope that corresponded to the work function of the main valley.

It is worth noting that the field emission currents for commensurable fields in the case of QCs were noticeably larger than those for bulk cathodes, which is predicted due to a decrease of the work function for both the main and satellite valleys of QCs.

Thus, the field emission method is easy-to-use for the investigation of some fundamental band characteristics of semiconductors, in particular for their nanostructured modification, for which other techniques are developed insufficiently.

In conclusion, we present the data on photostimulated emission, where the repopulation of valleys occurs by means of the excitation of electrons by light quanta rather than under the action of a heating electric field.

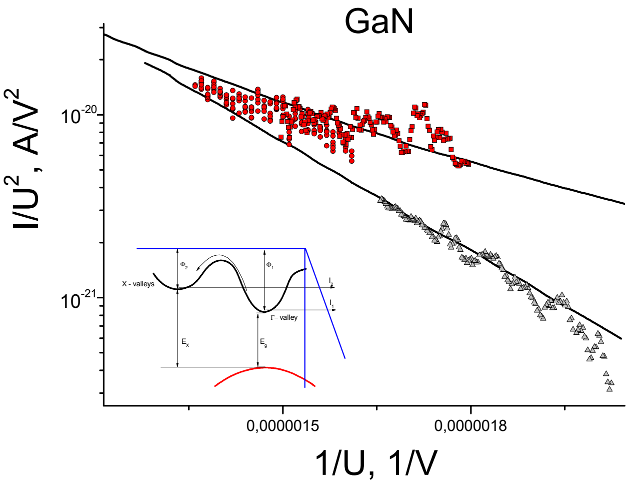


Fig. 6. Emission dependences for microstructurized GaN cathodes on illumination (upper line) and in dark (lower line)

The peculiarity of this effect consists in the fact that, for the field emission from point cathodes, one observes the cold emission in the case of the illumination with a quantum energy lower than the energy gap width (Fig. 6). The presented data concern a microporous GaN surface, where $E_g \geq 3$ eV for the main band, whereas the energy of quanta of a light-emitting diode $E_q \sim 3$ eV. The illumination increased the field emission current by a factor of 2–5, and the slope of the FN dependence decreased by a factor of ~ 1.5. The latter testifies to the fact that the current is additionally caused by the excitation from the satellite band rather than from the main one; it lies lower than the main valley by ~ 1 eV, which agrees with theoretical estimates of the position of the upper valley $E_{v2} \sim (4.3 - 4.5)$ eV.

Conclusions

Quantum cathodes are characterized by a number of useful properties. Namely, they provide an increase of the cold emission currents, and, in the case of many-valley semiconductors, they cause a change of the slope of the FN dependence that acquires the form of a broken line. The properties of nanodimensional semiconductor cathodes are determined by the dimensionally quantized band structure, quasi-delta-shaped state density spectrum, nondegenerate statistics for free charge carriers, peculiarities of the heating of free electrons in different valleys, as well as by the processes of tunneling through a vacuum barrier. Taking into account these factors, one can describe the basic properties of quantum cathodes. The comparison with experiment by the example of the many-valley high-energy-gap semiconductor GaN insufficiently investigated earlier allowed us to determine its band characteristics and to predict monochromatic electron emission from quantum cathodes.

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ЕМІСІЙНІ ХАРАКТЕРИСТИКИ НАПІВПРОВІДНИКОВИХ КВАНТОВИХ КАТОДІВ

В.Г. Литовченко

Резюме

Структури з квантованим зонним спектром демонструють важливі особливості оптичних, електричних, каталітичних та інших базових характеристик. Вони є перспективними також для дослідження емісійних ефектів. Особливу увагу привертають напівпровідникові структури з багатодолинним зонним спектром, в яких завдяки квантуванню стає можливим емісія з "мілких" сателітних зон, які мають відносно малу роботу виходу. Заселенню електронами цих зон вже у відносно невеликих електричних полях сприяє зменшення відстані цих зон відносно основної, характер енергорозподілу електронних станів, а також ефективніший розігрів вільних електронів завдяки розмірному квантуванню. Крім того, відбувається поступове підняття до рівня вакууму енергії основної зони провідності, звідки починається польова емісія вже при невисоких полях, а також монохроматичність емісії з квантових катодів. Наведено результати теоретичного аналізу та експериментальних досліджень електронної польової (так званої холодної) емісії з напівпровідникових квантових катодів.