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Novel Effects and Instabilities in Stationary Vacuum Diode Systems with Vertical Temperature Gradient

V.K.Solonovich, V.R.Sobol, L.V.Kukharenko, O.N.Mazurenko

† : *Institute of Physics of Solid and Semiconductors,*
Academy of Science of Belarus,
P. Brovky St., 17, 220072, Minsk, Belarus

Recently there has been a rise of interest in studying of physical phenomena occurring in vacuum diode systems, those in thermal scanning tunneling microscopes [1], diodes with a microspacing between the electrodes varying from 10 to 10^5 $\mathring{A}$ and the temperature gradient $10 - 10^5\ K/\mathring{A}$ in particular [2].

The objective of this paper is to model physical actions between electrodes in our diode systems as well as to investigate experimentally nonequilibrium processes of electrons flow, their instabilities included.

1. Stability and instability conditions for diode system

We consider here the simpliest diode system where the electrodes are separated by a vacuum spacing z_0 (Fig.1) with the constant potential ϕ_0.

Let us assume that at the beginning there is a stationary regime of the system with the field on the emitter E_0 and distribution functions of the emittered electrons $f_1(V_1)$ and $f_2(V_2)$ ($V_1 > 0$, $V_2 > 0$). The external or intrinsic voltage source with some delay time τ maintains constant the potential difference ϕ_0. For time $\tau_1 < \tau$ and $\tau_2 < \tau$ the stationary regime transforms into another non-stationary regime with E'_c at constant $f_1(V_1)$ and $f_2(V_2)$. In this case the potential on the collector ϕ_c will differ from ϕ_0. To restore the former potential difference the creation of a compensating electrical field $E_{d_1} = (\phi_0 - \phi_{c_1})/z_0$ or $E_{d_2} = (\phi_0 - \phi_{c_2})/z_0$ is required which, together with the emitter field, reduces the fluctuation E_0 at $\phi_E > 0$ and increases it at $\phi_E < 0$. Accordingly, the initial stationary regime will be either stable or unstable relative to the variations of E_0 with time $\tau_1 < \tau$ or $\tau_2 < \tau$.

It was shown [3,4] that the criterion for instability is satisfying the condition

$$\pi v_0/\omega_0 = z_0, \tag{1}$$

where $\omega_0 = \sqrt{4\pi e^2 n_0/m}$ is the Langmuir electron frequency. With the Debye radius decreasing further at the points $n\pi v_0/\omega_0 = z_0$ $(n = 2, 3 \ldots)$ the regime transforms from unstable into stable state alternatevely.

Later on will attempt to generalize the instability criteria for the stationary regime of the diode device with a microspacing with distribution functions of electrons from the emitter $f_1(V_1)$ and $f_2(V_2)$.

For this model (Fig.1) it is assumed that the electrons with the initial velocities V_{01} and $V_(02)$, and densities n_{01} and n_{02}, respectively, are emitting from the semi-infinite plane-parallel emitter with the coordinate $z = 0$ along the z-axis. The systems of equations describing the emitted electrons in vacuum are as follows

$$n_1 V_1 = n_{01} V_{01} \quad mV_1^2/2 = mV_{01}^2/2 - e\phi_1 \quad d^2\phi_1/dz^2 = -4\pi n_1 \tag{2}$$

$$n_2 V_2 = n_{02} V_{02} \quad mV_1^2/2 = mV_{02}^2/2 - e\phi_2 \qquad d^2\phi_1/dz^2 = -4\pi n_2 \tag{3}$$

Further solution of these systems is reduced to the integral of the type

$$(d\phi/dz)^2 = 8\pi emn_0 V_0^2 \sqrt{(1 - 2e\phi/mV_0^2)} + C, \tag{4}$$

which in the dimentionless variables is rewritten in the form

$$(d\phi'/dz')^2 = \sqrt{1 - \phi'} + C; \quad C_0 = E_0^{*2} - 1; \quad E_0^* = (d\phi'/dz') \tag{5}$$

with boundary condition $\phi'(z' = 0) = 0$, where $\phi' = 2e\phi/mV_0^2$; $z' = ez\sqrt{32\pi n_0 m^{-1}} V_0^{-1}$. Integration of (5) leads to the solution of the systems (3) as a function $\phi'_1(z')$ and $\phi'_2(z')$ which are illustrated in Fig.2 (a and b).

As seen from Fig.2 at $E_0 < 0$ the electron fluxes with distribution function $f_1(V_1)$ and $f_2(V_2)$ are stable at any collector positions. Also stable are the regimes when all the electrons are reflected. For $0 < E_0 < E_{crit}$ the regimes can be either stable everywhere or stable only to the envelope curve (Fig.2). When two extrema are present on the potential envelope the regimes could be both stable and unstable. In order to tackle the stability problem in this case one needs to calculate $d\phi_c/dE_0$ at the known $f_1(V_1)$ and $f_2(V_2)$, z'_1 and z'_2 in each particular case. If there are no particles reflecting near the first potential extremum (Fig.2) the regimes becomes unstable between the first and the other extremum.

The estimates reveal that with the Langmuir electron frequency ranging from 10^{12} – 10^{11} Hz at density $n_0 = 10^{18}$ cm the value z_0 varies from 1 - 10 μm.

However, electromagnetic fluctuations on the electrodes can affect greatly the systems stability with these spacings between the electrodes present, which we previously neglected, as well as bring about basically new physical effects.

2. The force and electric fields in vacuum diode system induced by temperature gradient

The ideas of force or ponderomotive interaction between two solid bodies at a distance of $10 - 10^5$ $\mathring{A}$ and having different temperature [5] lay the foundation of these simpliest models. In such model the interactions are presented as a sum of its components: dispersion or Van-der-Waals, Coulomb (elecrtostatic) and the force, arising from the electrical charge transport of either of thermoemission or tunneling origin. The calculation of the dispersion force was carried out using the Lifshitz-Pitaevskii theory and the Coulomb force in terms of the Hohenberg-Lang-Kohn theory [5]. In the classic representation the dispersion forces, in particular the Kazimir ones, cause attraction of solids when the effect of the electromagnetic interaction delay becomes substantial. In this case the dispersion forces are caused by electromagnetic fluctuations (fluctuations of thermal radiation of larger amplitude, in particular). This effect, in terms of quantum field theory, arises from changes of zero energy oscillations spectrum of vacuum density with limited quantization volume as well as from reduction to zero of the tangent component of electric field on the interacting surfaces. The calculation of these forces was made either in the frame of classical approximation or using the Klein-Phok equation in the theory of strings [7]. The influence of temperature on the Van-der-Waals forces, the Kazimir ones, in particular, were taken into account through temperature dependence of dielectric constant and by derivative of free energy with respect to temperature. The solution of the Klein-Phok equation for the string was aimed at finding an avarage two dimensional energy-pulse tensor. When the boundaries are semi-permeable the quantum field vacuum possesses some negative energy and non-zero local oscillations with wide spectra dependent on boundary conditions. The latter predetermines the vacuum polarization. It is shown [7] that the high temperature gradient of the order of $20\ K/\ \mathring{A}$ observed between closely placed solids leads to vacuum polarization in its longwave range

To calculate the Coulomb component of ponderomotive interaction force, according to the theory of electron density functional, the knowleage of the surface energy of solids is required. The functional for the chosen model was represented as a sum of functionals of electrostatic energy, kinetic and exchange-correlation energies with regard for the first gradient corrections, positive background discretion energy and the Madelung energy. Trial functions of electron density distribution at the solid-vacuum interface were selected in the form of the modernized Smolukhovskii-Smith functions linearly dependent on temperature. The surface energy calculation data are described in detail in [5,6].

The forces, caused by the electror charge transfer were calculated from the surface energy changes of the surfaces under consideration brought about by the difference of their chemical potentials and dipole moments.

Thus, knowing the surface energy and its corrections as a function of temperature and the band gap between the interacting solids surfaces it is easy to determine the ponderomotive force by the derivative with respect to the distance coordinate. In turn, the findings obtained on the ponderomotive forces with high temperature gradient present between the solids can provide information about the intrinsic electric field value. The calculations reveal that its value reaches $10^6 - 10^5\ V/m$ at the band gap of $1 - 10\ mm$. As follows from the above the intrinsic electrical field, arising e to temperature gradient and fluctuations of electromagnetic field of small and large amplitude, can affect noticeably the electrical potential distribution in the vacuum diode spacing.

3. The distortion of the thermoelectron distribution function of the LaB (100) emitter of the vacuum diode with microspacing

Usually the investigations of the emitted thermoelectrons energy distribution of the electrode materials are carried out either by Shelton's method or by energy analyzer of the hyperboloid mirror type [8] where external electric and magnetic fields are used. In most cases the function $n(E)$ has the Maxwellian form. However, it has been shown that the function $n(E)$ is either distorted [8,9], or displaced, with its maximum being in relatively high-energy region, or it is a more complicated non-Maxwellian form [10].

The CVC's anomalies of the diode arrangement with $W(111)$ and $LaB_6(100)$ electrodes and the interelectrode spacing $d_{ee} = 10 - 100$ mm were also found [2], though in the locking voltage range V of $-0,1 - 0$ V in this case the influence of the bulk electron charge is negligible. Latter on this will be borne out by a good fit of the measured values of work function of the emitter by using Shelton's method and the load curves method [6]. The function $n(E)$ was determined by differentiation of the CVC's of the diode on the computer. The characteristics of the electrodes under investigation and the measurement conditions have been described in detail elsewhere [2].

The distribution function of the thermoelectrons $n(E)$ *vs* the emitter temperature T is shown in Fig.3. As seen from Fig.3 $n(E)$ has the Maxwellian form through the second (non-equilibrium) peak appeares in the tail of the function $n(E)$ at $T = 1523$ K. This peak is especially noticeable at $T = 1873$ K, where its maximum lies at $0,8$ eV. With the emitter temperature rising at $T > 1573$ K (Fig.3) the first (equilibrium) and the second (non-equilibrium) peaks are shifted to a relatively high-energy region. The absence of the second peak at $T < 1573$ K testified only of the Maxwellian distribution of the thermoelectrons. This fact is also corroborated by the derivative $dn(E)/dT$ (Fig.4) which represents essentially thermoelectron spectrum. The splitting up of $dn(E)/dT$ into two maxima is observed at $T > 1523$ K. The intensity of the first maximum increases noticeably and shifts from $0,18$ to $0,40$ eV at $T = 1573 - 1873$ K. The intensity of the second maximum is not changed practically, but it shifts to higher energy region from $0,65$ to $0,90$ eV too in the same emitter temperature range.

On the one hand, the appearance of the non-equilibrium peak on the distribution function $n(E)$ (Fig.3) at some critical temperature is apparently connected with the lanthanum concentration on the emitting surface due to its diffusion from the bulk. The film system obtained forms the stream of the thermoelectrons with the same $n(E)$. This is confirmed by the violation of the ratio **B/La** in the near surface range of the emitter and by the break on the temperature dependence of the work function $\phi_e(T_e)$ at $T = 1573\ K$ [2].

On the other hand, in investigating thermal emission in the diode arrangement with a narrow vacuum emitter-collector spacing d_{ec} the influence of the ponderomotive effect on $n(E)$ can not be excluded. In particular, as shown in [5,6,7], the ponderomotive forces at the interelectrode spacing $d = 1 - 10\ \mu m$ appearing due to the electrostatic and the electromagnetic interaction between the electrodes reach the value of $0,3 - 0,05\ Din \cdot cm^{-2}$. This is equivalent to creating an intrinsic field $E^0 \sim 10^5 - 10^4\ V \cdot cm$, which is sufficient for elimination of the negative influence of the bulk electron charge and stimulation of the electrons displacement from the occupied surface states of the emitter to vacant surface states of the collector. Thus, the intrinsic field E^0 favoures the appearance of the non-equilibrium peak on $n(E)$ (Fig.3).

It should be noted, that when increasing the interelectrode spacing d_{ec} the intensity of the second (non-equilibrium) peak $n(E)$ decreases, for example at $T = 1573\ K$ this peak vanishes practicaly at $d = 200\ \mu m$ (Fig.5). Similar effects observed for the diode arrangement with $LaB_6(110)$ electrodes, but with essentially langer spacing.

The appearance of the second (non-equilibrium) peak on the $n(E)$ is found for the $\mathbf{LaB_6}$ (110) emitter.

Thus, the distribution function of the emitted thermoelectrons $n(E)$ and the thermoelectron spectrum $dn(E)/dE$ as well as their features could be determined providing the bulk electron charge in the vacuum diode arrangement is negligible, which could be achieved via reduction of the interelectrode spacing up to, for instance, $10\ \mu m$.

Additional experimental evidence for the absence of the electron charge effectin interelectrode spacing of vacuum diode is given in the work of [10]. This paper reports on the investigation of the vacuum spacing width effect on IV characteristics of such a diode. Fig.6 gives the experimental results testifying to the deviation of the Child-Lengmuir law in the vacuum diode with microspacing for different electrodes.

Conclusions

The main results obtained can be summarized as follows:

- the stability and instability boundaries of nonlinear stationary oscillations of potential in electron flux with two temperature function of thermoelectrons distribution in diode arrangement with microspacing are demonstrated;

- the appearance of a nonequilibrium peak of thermoelectrons on the equilibrium Maxwellian function of distribution over energies at critical temperature thus indicating the possibility of creating of high temperature thermoemission spectroscopy of solids is revealed;

- the physical mechanisms of the appearance of the nonequilibrium peak on the function of thermoelectrons distribution consisting in electrons displacement from the occupied surface states of the emitter to the vacant surface states of the collector as well as ponderomotive interaction of these diode surfaces are partially elucidated.

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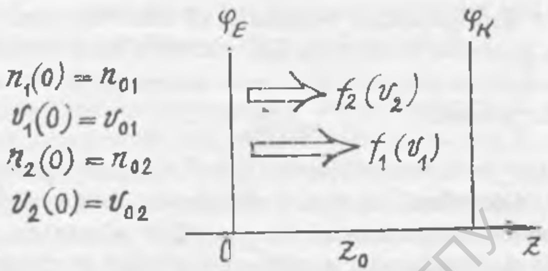

Fig.1. The schematic image of the diode system.

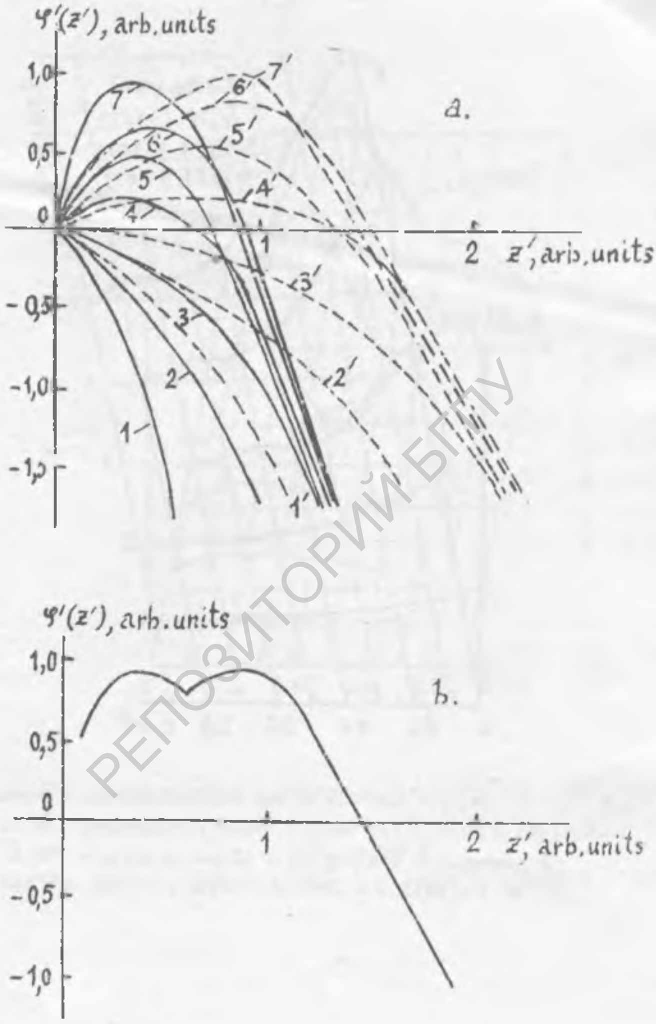

Fig.2. a. Distribution of potentials ϕ'_1 and ϕ'_2 vs parameters z'_1 and z'_2 at different electric fields E_0

b. Envelope curve of distribution functions of potentials ϕ'_1 and ϕ'_2.

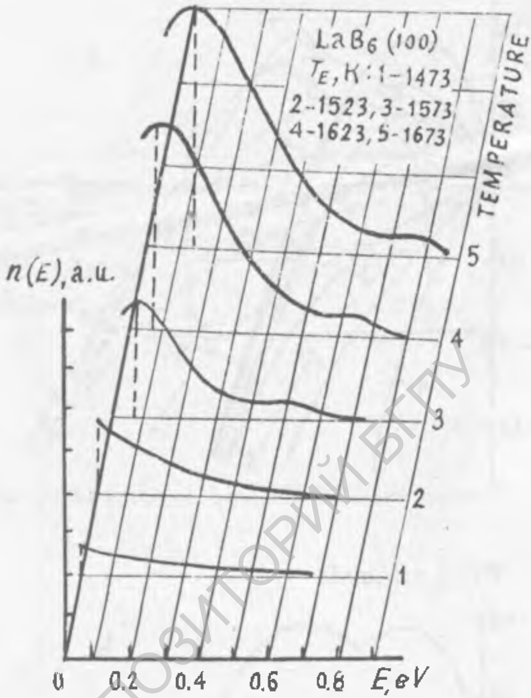

Fig.3. The distribution function of the emitted thermoelectrons from the $LaB_6(100)$ surface in the vacuum diode arrengement with a narrow interelectrode spacing $d_{ec} = 10\ \mu m$ at $\Delta T_{ec} = 300\ K$.
T_e, K; 1 – 1473; 2 – 1523; 3 – 1573; 4 – 1623; 5 – 1673.

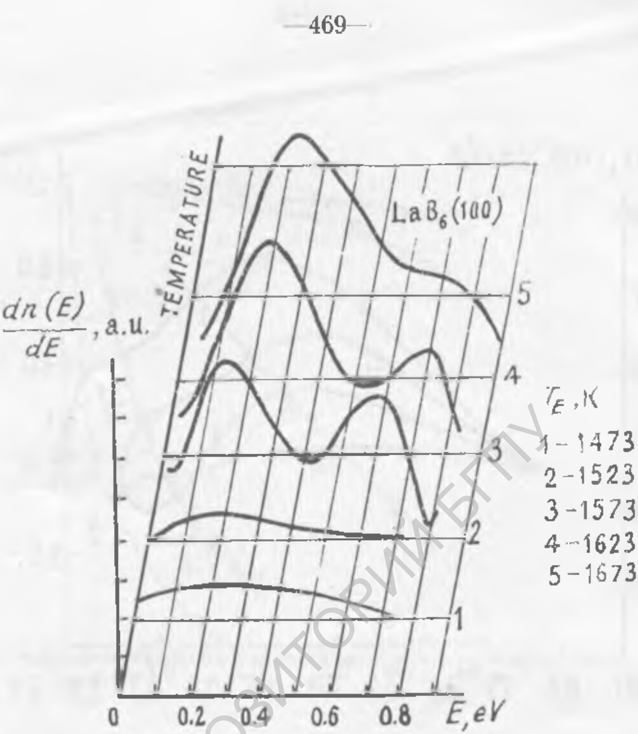

Fig.4. The thermoelectron spectrum of the $LaB_6(100)$ in the vacuum diode arrangement with a narrow interelectrode spacing $d_{ec} = 10\ \mu m$ at $\Delta T_{ec} = 300\ K$.

T_e, K; 1 — 1473; 2 — 1523; 3 — 1573; 4 — 1623; 5 — 1673.

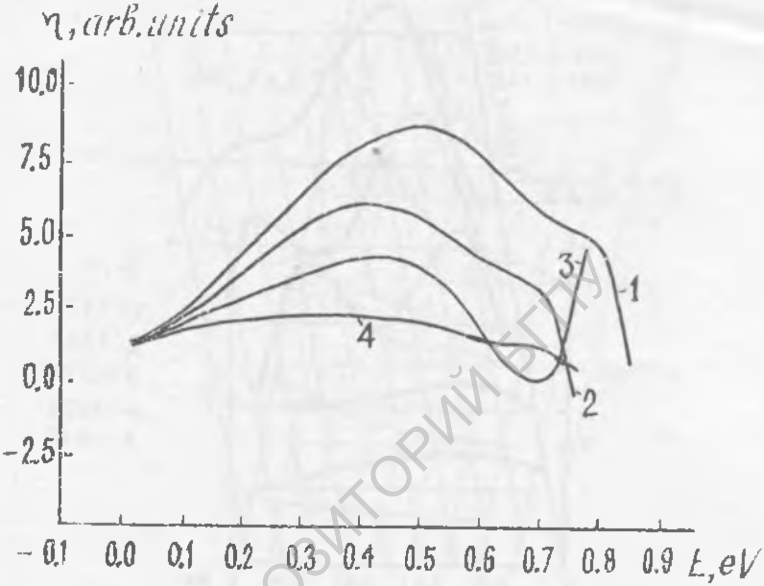

Fig.5. Ratio of vacuum diode *IVC* amplitudes with microspacing $\eta = I_{exp}/I_{cal}$ at $U = const$ *vs* the vacuum spacing width z_0; z_0, μm: 1 — 12; 2 — 50; 3 — 109; 4 — 200.

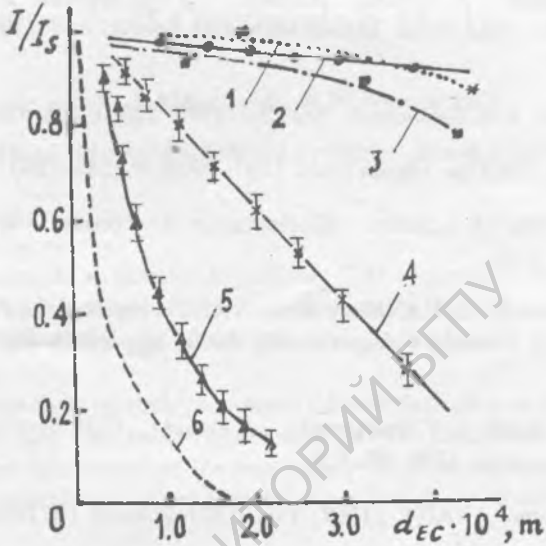

Fig.6. Ratio I/I_s of load current to saturation current *vs* the interelectrode spacing of vacuum diode [11].

1. $W - Ni - LaB_6$ at $T = 1323\ K$, $T = 1223\ K$;

2. $W(111)$ at $T = 1973\ K$, $T = 1573\ K$;

3. $Si(111)$ at $T = 1723\ K$, $T = 1673\ K$;

4. W at $T = 1773\ K$, $T = 1723\ K$;

5. $LaB_6(100)$ at $T = 1523\ K$, $T = 1223\ K$;

6. the calculation based on the Child-Lengmuir law for the $LaB_6(100)$ electrodes.

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