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RADIATION ELECTRONICS

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Article is review of works on nonequilibrium electron distribution function formation at a presence of sources and sinks in momentum space. The analitical investigations and numerical simulation of the nonlineat collision integrals of Boltzmann and Landau-Fokker-Planck has been considered. The experimental study results of nonequilibrium electron distribution function formation in solid plasma at its irradiation by electromagnetic radiation or charged particles flows have been implemented. New type of radioisotope source of current based on others physical princeples was proposed.

1. INTRODUCTION

At present, the development of high-power particle and radiation sources is stimulating great interest in the properties of nonequilibrium systems. The presence of sources and sinks in momentum space can lead to the formation of nonequilibrium particle distribution functions with power-law tails even in spatially uniform systems. The inapplicability of the local equilibrium approximation to such situations is related to the presence of particle flows in phase space. In the second section of this paper, the asymptotic properties of such nonequilibrium states are studied, their relation to the nonextensive Tsallis' thermodynamics is established, and the dependence of the nonextensivity parameter on the intensity of the particle flow in phase space (i.e., on the intensities of sources and sinks) is determined. The third section is devoted to numerical simulations of the formation of a steady-state nonequilibrium dist-ribution of particles with a long-range repulsion potential. The collisional dynamics of such a system is studied using spatially uniform nonlinear Landau and Fokker–Planck collision integrals, which are model representations of the Boltzmann collision integral. In numerical simulations, completely conservative difference schemes are used. In the fourth section, we consider the conduction and emission properties of a semiconductor plasma irradiated with intense particle or laser beams. In the fifth section, the formation of nonequilibrium electron distribution functions (EDFs) in the plasmas of semiconductors and of a Sb/CS cathode is studied experimentally. To study these functions, the method of the secondary electron emission induced by fast low- Z ions was employed. The formed EDFs are measured, the coefficients of the secondary ion-induced electron emission are determined, and their relationship to the source power in the ion's track is found.

2. STEADY NONEQUILIBRIUM STATES OF SYSTEMS WITH STATIONARY PARTICLE FLOWS IN PHASE SPACE

Quasi-steady nonequilibrium states of particle systems can be studied by solving kinetic equations with allowance for sources and sinks. Power-law particle energy distributions were first predicted theoretically in [1–4] and then observed experimentally in [5, 6]. In [1, 2], it was shown using a similarity transformation that the kinetic Boltzmann equation for a spatially uniform system has exact stationary power-law solutions. In [3, 4], it was shown by directly calculating the Boltzmann and Landau collision integrals in kinetic equations that the power-law distributions of the form $f = AE^{-s}$ (where s is an exponent and A is a constant, are stationary solutions for which particle (or energy) fluxes in phase space are nonzero constants. These particle states are similar to turbulent Kolmogorov spectra of waves and depend only on the integral characteristics of the source and sink [4]. In particular, nonequilibrium spatially uniform systems with a component obeying a power-law distribution include electron subsystems of semiconductors exposed to radiation with a photon energy on the order of the width of the forbidden zone [7] or electron subsystems in metals that undergo ionization caused by particles propagating in them [5]. In [1–4], the exponent s of power-law solutions to the kinetic Boltzmann equation depended only on the degree of homogeneity of the particle interaction potential. In those papers, both the dispersion properties of a plasma with a power-law electron distribution and the ionization equilibrium in such nonequilibrium steady states were studied. In [8, 9], it was shown that plasma oscillations with a linear dispersion can exist in a plasma with two components of the distribution function, equilibrium and nonequilibrium. These plasma oscillations could be of importance for many interactions in semiconductor plasma, in particular, for the plasmon mechanism of superconductivity [10]. As was mentioned above, steady-state nonequilibrium distributions (SND) of particles in phase space play the same role in spatially uniform systems as Maxwellian distributions in Gibbs' thermodynamics. The presence of such great deviations from the exponential dependence should significantly change the thermodynamic properties of a system. Note that, over the last fifteen years, great progress has been achieved in the thermodynamics of strongly nonequilibrium systems; the results obtained indicate the existence of non-Gibbs (power-law) distributions in such systems.

So far, we have considered the formation of an SND with sources and sinks localized in momentum space. It should be noted that one often has to deal with systems in which both the source and the sink are nonlocalized.

In particular, wake ionization is a source that is not localized in momentum (energy) space. Moreover, the source intensity is often insufficient to provide a universal nonequilibrium distribution throughout the interval between the source and sink (see [11, 12]). In these cases, it is necessary to resort to numerical simulations.

3. NUMERICAL SIMULATIONS OF THE FORMATION OF STEADY-STATE NONEQUILIBRIUM PARTICLE DISTRIBUTIONS

A specific feature of systems of particles interacting via the Coulomb potential is that the scattering cross section increases without bound as the momentum transferred tends to zero. For gaseous and semiconductor plasmas with a large Coulomb logarithm ($\ln\Lambda$ = 10…15), one can restrict oneself to the expansion of the integrand in the collision integral in small momenta transferred (a diffusion approximation) and to represent the collision integral in the Landau or Fokker–Planck form [13, 14], which are model representations of the Boltzmann collision integral. In this model [15–17], the moments of the exact and model collision integrals coincide up to the third-order tensor moment and the forth-order scalar moment. Conservation laws for energy and the number of particles, as well as the Boltzmann *H* theorem, are valid. The model collision integral provides a correct representation of the equations for the twenty-moment Grad approximation. Finally, the exact solution to the Landau equation for Maxwellian molecules (β = 4) is the exact solution to the Boltzmann equation. Below, we will consider long range potentials ($U \propto r^{-\beta}$, with $1 \le \beta \le 4$), where r is the distance between the interacting particles), for which a local nonequilibrium particle distribution can form (see [3]). Note that the dynamics of particles interacting via the Coulomb repulsion potential (β = 1) can be considered using kinetic equations in either the Landau or Fokker–Planck form.

3.1. FORMULATION OF THE PROBLEM

In the case of an isotropic distribution function $f(\upsilon,t)$, the Landau collision integral is

$$\frac{\partial f}{\partial t} = \frac{\Gamma}{\upsilon^2}\frac{\partial}{\partial \upsilon}\left\{\frac{1}{\upsilon}\int_0^\infty dwQ\cdot\left[wf(w)\frac{\partial f(\upsilon)}{\partial \upsilon} - \upsilon f(\upsilon)\frac{\partial f(w)}{\partial w}\right]\right\};$$

$$Q = \frac{a\cdot(\upsilon + w)^{\eta+4} + b\cdot|\upsilon - w|^{\eta+4}}{(\eta+2)\cdot(\eta+6)},\ \eta = (\beta - 4)/\beta;\ (1)$$

$$0 \le \upsilon, w < \infty,\ t \ge 0,\ a = \left|\upsilon w - \left(\upsilon^2 + w^2\right)\right|;$$

$$b = \left|\upsilon w + \left(\upsilon^2 + w^2\right)\right|,\ \Gamma = 4\pi e^4 \ln\Lambda\ /\ m,$$

where the symmetric kernel $Q(\upsilon, w) = Q(w, \upsilon)$ in the case of Coulomb potential has the form $Q(\upsilon, w) = -2/3w^3$ for $w \le \upsilon$ and $Q(\upsilon, w) = -2/3\upsilon^3$ for $w \ge \upsilon$. The equilibrium solution to Eq. (1) is a Maxwellian distribution function

$$f_{Maxw} = n\frac{4}{\sqrt{\pi}}\upsilon_T^{-3}\exp\left(-\frac{3\upsilon^2}{2V_T^2}\right),\ V_T = \sqrt{\frac{3k_BT}{m}},$$

where n is the electron density, k_B is the Boltzmann constant, m is the electron mass, and T is temperature. If there are no sinks (so-urces), then the number of particles and the system energy do not vary over time: The distribution function $f(\upsilon,t)$ is bounded at $\upsilon = 0$ and quite rapidly decreases as $t \to \infty$. Below, we use dimensionless variables: the velocity in units of the thermal velocity V_T and time in units of the electron–electron relaxation time τ_{ee}, which is $\tau_{ee} = V_T^3 m^2/\left(ne^4\ln\Lambda\right)$ (where e is charge of electron) in the case of Coulomb interaction. The function $f(\upsilon,t)$ is normalized so that $n = 4\pi$, the total energy $E_{tot} = (2\pi m)^{-1}$; consequently, in Eq. (1), the constant Γ is equal to unity.

We consider the formation of a steady-state nonequilibrium solution in the presence of particle or energy flows in velocity space using the above modified versions of the Landau-Fokker–Planck collision integral in form (1). In this case, the right-hand side of the kinetic equation is added with the terms accounting for the presence of a particle (energy) source S_+ (sink $-S_-$).

The source (sink) function was modeled by an exponential function with a variable width in momentum

$S_\pm \sim I_\pm \exp\left\{-\alpha_1(\upsilon - \upsilon_\pm)^2\right\}$; a δ - function in the form $S_\pm \sim I_\pm\delta(\upsilon - \upsilon_\pm)/\upsilon^2$;

$$S_\pm \sim I_\pm\frac{\delta(\upsilon - \upsilon_\pm)}{\upsilon^2}f(\upsilon_\pm, t) \qquad (2)$$

The flow direction is determined by the positions of υ_+ and υ_-. Either a Maxwellian distribution or δ - function was used as an initial distribution. In simulations, we employed a fully conservative implicit difference scheme [15–17], for which discrete analogues of conservation laws hold true and which allow one to perform long-run calculations without error accumulation. An infinite velocity interval was replaced with the maximum interval $(10...14)\cdot V_T$, in which the distribution function was set at zero. The initial distribution $\delta(\upsilon - \upsilon_0)$ was approximated in the following way: the δ - function was set at zero for all of the velocities except for one point (usually, $\upsilon_0 = 1$).

Since the problem of relaxation is a kind of test, we first consider the Cauchy problem for the initial distribution $f^0(\upsilon) = \delta(\upsilon - 1)/\upsilon^2$. In our calculations, we used the kinetic equation with either Landau collision integral in form (1) or the Fokker–Planck one, respectively. When $S_\pm = 0$, these equations are analytically equivalent and, in the limit $t \to \infty$, lead to a Maxwellian distribution f_{Maxw}. Let us now discuss the results of numerical simulations.

3.2. DISCUSSION OF THE SIMULATION RESULTS

In [15], the formation of a nonequilibrium distribution function was numerically simulated for the kinetic equation with either the Landau or Fokker–Planck collision integral in the presence of energy and particle flows in momentum space that were sustained by a source and a sink. For this purpose, the right-hand side of kinetic equations (1) was supplemented with various types of sources S_+ and sinks S_-. First, solutions were obtained for the case where the positions of a source and a sink in momentum space were matched with the direction of a flow sustained by collisions. Note that analytic consideration of equations for the case of a localized source and sink gives a correct flow direction, namely, from high to low velocities [3]. It was shown in [15] that, within the interval between the source and sink, an SND (of the Kolmogorov kind) of particles is established with time. This distribution corresponds to the presence of an energy flow in momentum space, whereas beyond this interval, the distribution function is thermodynamically equilibrium.When using the Landau equation, the particle distribution relaxes to an SND by more than one order of magnitude faster than when the Fokker–Planck equation is used. As was noted above, the positions of the source and sink and the direction of flow in momentum space should be matched with one another. To make sure once again that this requirement is important, we performed calculations with the interchanged positions of the source and sink in energy space. It turned out that variations in the flow intensity by several orders of magnitude did not influence the equilibrium particle distribution when the source and sink positions were not matched with the flow direction [15]. It was shown that the behavior of the SND in most of the interval between the source and sink does not depend on the degree of the source (sink) localization; this indicates the local (universal) character of the solution. It is found also that, for low intensities of the source I_+ (sink I_-), a universal nonequilibrium distribution is formed in the velocity range $\upsilon \le \upsilon_+$. This is due to (i) a decrease in the cross section for Coulomb scattering with increasing velocity ($\sim \upsilon^{-3}$) and (ii) the ever-present flow of energy and particles (due to Coulomb diffusion) toward the region of the main ("background") equilibrium distribution. Consequently, as the source (sink) intensity increases, a universal nonequilibrium particle distribution is formed that occupies a progressively larger space between the source and sink. Such behavior is related to a decrease in the fraction of the flow transferred to the background plasma. It is worth noting that the increase in intensity is accompanied by an increase in the magnitude of the nonequilibrium distribution function in proportion to the flux magnitude [3].

Let us examine the form of the distribution function for power-law interaction potentials with the exponents $1 \le \beta \le 4$. Note that $\beta = 1$ corresponds to the Coulomb interaction potential, $\beta = 2$ corresponds to dipole interaction, and $\beta = 4$ describes the interaction of so-called Maxwellian molecules. It was shown in paper [15] that, for all these β values, the exponents of the formed nonequilibrium power-law distribution functions are close to one another, which agrees with the results of [3]. The magnitude of the nonequilibrium part of distribution function decreases with increasing β. These results are in qualitative agreement with the above analytic predictions.

4. FORMATION OF THE EDF IN THE INTERACTION OF RADIATION AND PARTICLE BEAMS WITH SOLID-STATE PLASMA

In this section, we consider the conduction and emission properties of a semiconductor plasma irradiated with intense particle or laser beams. A comparison of the characteristic times of ionization and relaxation shows that, in the case at hand, the steady-state EDF should be determined mainly by electron–electron collisions [3]. Hence, it can be obtained from the condition that the Boltzmann collision integral (for a semiconductor plasma, the Landau or Fokker–Planck collision integral) be zero.

It follows from the analysis (see [4]) that, for a semiconductor plasma in the energy range $E - E_F > E_F$, a power-law distribution with a nonzero flux of energy or particles in momentum space can be established. This distribution is formed due both to collisions with electrons whose energy is in the range $E - E_F > E_F$ and background (equilibrium) electrons. It was shown in [4] that a nonequilibrium electron distribution is close to a universal distribution if the intensity of the flow produced by the source and sink in momentum space is sufficiently high. Let us consider, as an example, the irradiation of a solid-state plasma with a beam of fast ions (with velocities higher than the velocities of atomic electrons) [18] or high-power electromagnetic radiation with the frequency ω satisfying the condition $\hbar\omega > k_B T$ [19]. In both these cases, a great number of high-energy electrons arise that, in accordance with the above consideration, form a nonequilibrium steady-state EDF [3]. When the distribution function is nonequilibrium, the emission current density is anomalously high since the distribution function decreases very slowly over the inertial interval.

The plasma conductivity is determined by the density of current carriers. In the case of a nonequilibrium EDF, the carrier density in semiconductor plasma is very high in comparison to the case of an exponentially decreasing equilibrium EDF. Therefore, when a semiconductor plasma is irradiated with intense radiation or particle beams, an anomaly in the emission and conduction properties of plasma should be observed. elastic losses are negligibly small, whereas the inelastic energy losses, which are usually called ionization loss, are described by the Bethe–Bloch formula (see for example

[20]). It follows from this formula that, at high energies, the ionization loss decreases as $\sim v^{-2}$. The introduction of an extra charge in a quasineutral equilibrium solid-state plasma leads to the displacement of free electrons with respect to their equilibrium positions and to the excitation of plasma eigenmodes (plasmons) [21-23]. Thus, the energy lost by an ion due to its deceleration is transferred to the target's electrons in two ways: a certain fraction of the energy is spent on the excitation of plasmons, while the rest energy is transferred to individual electrons in collisions (in particular, in collisions with atoms, which then become ionized) [20-23]. Such a nonequilibrium external action significantly changes the distribution function of free electrons [4]. A fraction of the nonequilibrium electrons that have proper magnitudes and momentum directions can escape from the target; i.e., these electrons can take part in the process of secondary ion-induced electron emission (SIEE). The emission proceeds in three stages: (i) origin of nonequilibrium electrons, (ii) their collisions and motion (diffusion) toward the surface of a solid, and (iii) overcoming the potential barrier by these electrons and their escape into vacuum. Such an approach is believed to most comprehensively account for the SIEE features and has been widely used since the Sternglass study [24] (see also [25,26]). Indeed, such an anomaly was observed, e.g., in [18, 19]. Supplying additional kinetic energy to a solid-state plasma results in the ionization of atoms and the production of a rather large number of free electrons with energies higher than the equilibrium (thermal) energy [20]. Under these conditions, nonequilibrium distributions of free electrons can form [3, 4]. It was shown in a series of theoretical and experimental studies that, when a solid-state plasma is irradiated with fast ion beams, a steady-state nonequilibrium power-law EDF

$$f(E) = \alpha I^{1/2} E^{-s} \tag{3}$$

is formed in the plasma due to the presence of a particle (energy) flow produced by a source (ionization) and a sink (electron emission) in momentum space. In Eq. (3), α is the normalizing factor, I is the particle (energy) flux, s is an exponent [4, 5], and E is the total electron energy in a solid ($E = \varphi + E_F + eU$, where φ is the work function and eU is the energy relative to the electron energy in vacuum). Power-law distributions are characterized by a rather large fraction of high energy electrons. For example, when a Be sample is irradiated with 4.9-MeV α - particles, the fraction of electrons with energies higher than E_p = 18.9 eV (where E_p is the energy of plasma eigenmodes in beryllium) can exceed 37% [21]. An integral characteristic of SIEE is the SIEE coefficient Δ_e, often called the electron yield (see [27]). The electron yield Δ_e is defined as the ratio of the num-ber of knocked-out secondary electrons N_e to the num-ber of incident ions N_i. The SIEE coefficient depends substantially on the energy of incident ions. It has been shown both theoretically and experimentally that, for low-Z ions, the electron yield Δ_e is proportional to the average specific ionization loss of ion energy in matter, dE/dx [24, 27, 28]. A much more informative characteristic of SIEE is the electron energy distribution. It has been shown experimentally that the energy spectra of secondary electrons are of power-law character [6, 29, 30]. When studying electron emission from some metals, it was shown that the distribution functions of the electrons knocked out by low-Z ions are piecewise power-law functions with different exponents s for different energy ranges [5, 6, 31]. As was shown in [32], emissivity variations accompanying the irradiation of a sample with intense charged particle beams can be efficiently used to create new energy sources. One such source is a secondary emission radioisotope current source [33] that converts the energy of α - particles into electrical energy using the nonequilibrium properties of the electron distributions. Since the efficiency of this source is proportional to the difference between the electron yields of the employed emitter materials (Δ_{e2} - Δ_{e1}) [33], it is necessary to use an emitter with the maximum possible Δ_{e2} value to increase the source efficiency. At present, the available literature data on the emission properties of materials irradiated with fast ion beams mainly refer to metals. Note that no data are available in the literature on the efficient electron emitters widely used in the photoemission and electronic techniques. Among the most widely used efficient emitters of secondary electrons are emitters based on Sb/Cs compounds. Due to the large coefficients of secondary electron emission (SEE) and photoemission (this is usually related to the low potential barrier at the boundary between the sample surface and vacuum), such compounds have been widely used in manufacturing the photocathodes and dynodes in photomultipliers and other devices [34]. To illustrate, the SEE coefficient σ_e for Sb/Cs compounds is 3–4 at low energies of primary 0.25 MeV. The cathode used as a target was a Sb/Cs layer deposited on a massive nickel substrate. The layer thickness was less than the mean free path of the incident ions in Sb/Cs. A 10-mm-diameter target fixed in a copper mount was installed on a movable holder. The ion beam collimated by a system of diaphragms was incident onto the target and caused SIEE from its surface. The target plane was normal to the beam axis. The beam diameter on the target surface was 3 mm, and the ion current density was no higher than 30 μA/cm^2. The chamber was evacuated with an NMD-0.4-1 magnetic-discharge pump and an NVPR-16D backing pump with a liquid nitrogen trap. In all our electrons ($Ee \sim$ 100 eV) and reaches its maximum value of = 8…10 at Ee = 500...600 eV [34]. Such large SEE coefficients are presumably explained not only by the low work function for this material but also the formation of a power-law nonequilibrium distribution function.

5. EXPERIMENT

This section is devoted to our experimental studies aimed at revealing the main features of the EDFs formed during the irradiation of a Sb/Cs cathode and certain semiconductors with a beam of fast low-Z ions.

5.1. EXPERIMENTAL SETUP

An electrostatic Van de Graaf generator used as a so-urce of primary particles provided beams of H^+ or He^+ ions. Energy spectra of SIEE electrons were measured for H^+ beams with ion energies from 1.00 to 2.25 MeV and He^+ beams with ion energies from 1.75 to 2.25 MeV. The ion energy was varied with a step of 0.25 MeV. The cathode used as a target was a Sb/Cs layer deposited on a massive nickel substrate. The layer thickness was less than the mean free path of the incident ions in Sb/Cs. A 10-mm-diameter target fixed in a copper mount was installed on a movable holder. The ion beam collimated by a system of diaphragms was incident onto the target and caused SIEE from its surface. The target plane was normal to the beam axis. The beam diameter on the target surface was 3 mm, and the ion current density was no higher than 30 μA/cm^2 . The chamber was evacuated with an NMD- 0.4-1 magnetic-discharge pump and an NVPR-16D backing pump with a liquid nitrogen trap. In all our experiments, the residual gas pressure in the vacuum chamber was no higher than 10^{-6} torr. The electrons emitted from the target surface were intercepted by a spherical collector consisting of two 100-mm-radius hemispheres. The target and the holder were set inside the collector. The gap between the hemispheres was 15 mm. The diameter of the entrance window of the hemisphere was 10 mm. Besides the collector current, we also measured the target current I_t, which was the sum of the beam ion current I_b and the current of the secondary electrons that reached the collector: $I_t = |I_C| + I_b$. The measured I_C and I_t currents amplified by electrometric amplifiers were applied to a PC through an analog-to-digital converter . To calibrate the measurement system, a Faraday cup was set behind the rear hemisphere. The Faraday cup allowed us to directly measure the ion beam current I_{Fc} when the target was removed from the beam path. The diameter and length of the Faraday cup were 20 and 130 mm, respectively. The current from the Faraday cup I_{Fc} was measured with an F303 current meter. The SIEE coefficient was determined by the formula

$$\Delta_e = |I_C| / (I_T - |I_C|). \tag{4}$$

By measuring the energy spectrum of SIEE electrons with a spherical analyzer and assuming that emission is produced by a point source, one can reconstruct the EDF inside the target [21]. When the EDF is powerlaw function (3), the derivative of the emission current with respect to the electron energy, $dI / d(eU)$, can be written as

$$\frac{dI}{d(eU)} = B(E_F + \varphi + eU)^{-s+1}, \tag{5}$$

where B is a constant. Hence, on a logarithmic scale, dependence (5) is a straight line with a slope equal to $-s$ + 1. The energy distributions of the secondary emission electrons were measured with a spherical collector operating in the energy-analyzer regime with a retarding field varied in the range 0...100 V with a step of 1 V.

The retarding electric potential was applied between the target and two hemispheres. Since the radius of the energy analyzer significantly exceeded the target size, the field distribution was close to spherical. A 5-mm-diameter ceramic tube with an outer surface covered with a resistive layer served as a target holder. The specific resistance of the layer *Rc* was varied nonlinearly along the tube so that the holder potential did not disturb the field inside the energy analyzer. One end of the resistive layer was in contact with the target, whereas its other end was grounded. The retarding potential was applied to the target from a saw-tooth generator controlled by a PC. Thus, the current flowing along the resistive layer produced the needed potential distribution along the holder. In experiments, the secondary electrons moved along radial trajectories and reached the collector. When the retarding voltage was applied to the target, only the electrons whose energy was high enough to get through the retarding field reached the collector. The computer software for controlling the experiment allowed the gathering of a 7-s-long time sample consisting of 100 measurements of the electron emission current for each value of the retarding field. These 100 experimental points were then averaged, and the resultant value of the electron current was stored in the PC memory. By differentiating the measured dependence of the collector current on the retarding voltage (the so-called retarding curves), one can deduce the energy spectrum of SIEE electrons and then reconstruct the EDF. The exponents *s* of power-law EDFs wereevaluated as follows. First, the time samples of the elec

tron emission current were processed and the delay curves were differentiated. Then, the dependences of $dI / d(eU)$ on the total electron energy $E_F + \varphi + eU$ in the compound under study, plotted on a logarithmic scale, were approximated by straight lines. According to formula (5), the slopes of these straight lines are equal to $-s$ + 1.

5.2. EXPERIMENTAL RESULTS AND DISCUSSION

The measurements of the energy spectrum of SIEE electrons show that, over the entire ion energy range under study, the nonequilibrium EDF formed in the plasma of a Sb/Cs cathode is a power-law function. A typical nonequilibrium EDF obtained for a sample bombarded with 1.75-MeV He^+ ions is shown in Fig. 1.

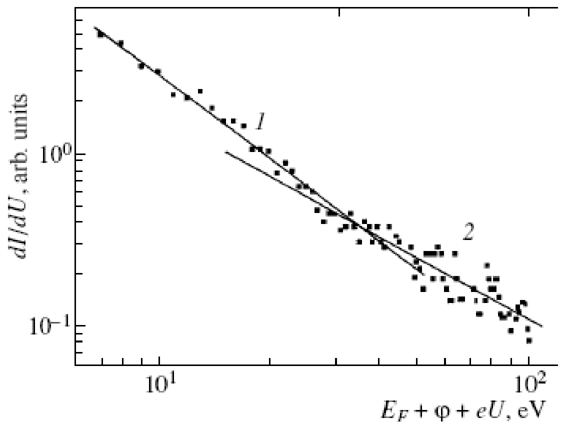

Fig. 1. Typical nonequilibrium EDF obtained for a Sb/Cs sample bombarded with 1.75-MeV He^{+} ions

The experimental points are quite well fit by two straight lines corresponding to two different exponents, s_1 and s_2, in the energy ranges of 5...30 eV and 30...100 eV, respectively. These exponents for the two parts of the EDF in the above energy ranges measured as functions of the energy of the incident H^{+} and He^{+} ions. In our opinion, the exponent of a power-law distribution function of secondary electrons could depend on the energy (specific ionization loss) of fast ions. It seems that it is the specific ionization loss that determines the intensity of the source of extra particles in momentum space. It was shown in [4, 35] that, under certain conditions, the exponent is independent of the structure of the source and sink. In this case, it can be said to be a universal power-law distribution function with an exponent equal to –5/4 [35]. In our previous experiments with a He^{+} beam and thin metal films, in which the exponents *s* were measured, it was shown that the absolute value of the exponent s_1 of a powerlaw distribution function in the first energy range corresponding to slow electrons (E < 35 eV) decreases with increasing specific ionization loss of ions in a substance [31]. In [30], it was pointed out that the fraction of fast electron increases with increasing energy of the incident ions. It is shown that the exponents s_1 for different incident ions and, accordingly, different specific ionization losses in a Sb/Cs sample differ insignificantly, although, for protons, the exponent increases with ion energy and decreases with specific ionization loss. No such dependence was observed for helium ions. It should be noted that variations in the exponent do not exceed 10%; to deduce the exact dependence of the exponent on the energy loss requires additional study. Fig. 2 shows the dependence of the electron yield Δ_e on the energy of the incident H^{+} and He^{+} ions for a Sb/Cs cathode.

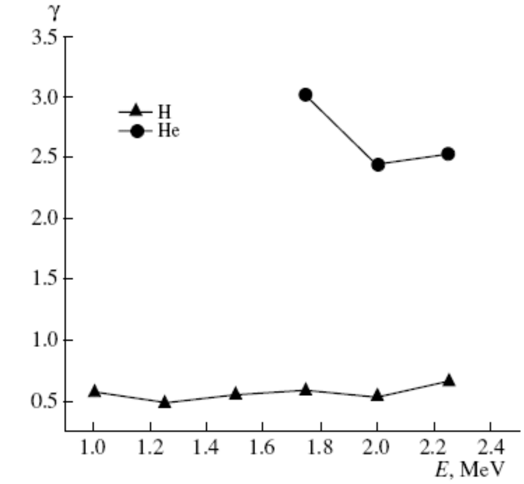

Fig. 2. Dependence of the electron yield Δ_e on the energy of the incident H^{+} and He^{+} ions

It can be seen that, for the Sb/Cs compound under study, the electron yield © exceeds that for some metals [35]. The reason could be as follows. As was mentioned above, a fraction of the nonequilibrium electrons produced in a solid-state plasma under bombardment with a beam of fast charged particles diffuse toward the surface and escape into vacuum. Electron emission proceeds from the surface layer, whose thickness is much less than the depth to which the ions penetrate into the target and is determined by the features of the electron motion toward the surface. In metals, the generated electrons, while diffusing toward the surface, interact mainly with conduction electrons. This interaction may proceed via pair collisions and collective effects—the excitation of plasmons. Due to the large density of conduction electrons in metals, the probability of electron–electron interactions and, accordingly, the effective escape depth of secondary electrons are small. In semiconductors, the density of conduction electrons is low; hence, the escape depth of secondary electrons can be quite large. Since Sb/Cs compounds possess semiconductor properties [34], the escape depth of nonequilibrium electrons can be larger than in metals. The higher (compared to metals) value of the SIEE coefficient can be, to a certain extent, explained by this factor. Sb/Cs compounds have low work functions [36]. The relatively low potential barrier at the boundary between such a compound and vacuum may lead to an increase in the fraction of nonequilibrium electrons leaving the solid. The work function determines the cutoff energy for the nonequilibrium power-law EDF formed in a solid-state plasma. Since the exponent within the first energy interval is fairly high and [6, 29–31]), even a slight decrease in the work function leads to a significant increase in the SIEE coefficient. Our experiments have shown that, for all of the energies of H^{+} and He^{+} ions, the EDFs formed in a semiconductor plasma are power-law functions. Fig. 3

shows (on a double logarithmic scale) a typical nonequilibrium EDF formed in a GaAs sample bombarded with 1.25-MeV He^{+} ions.

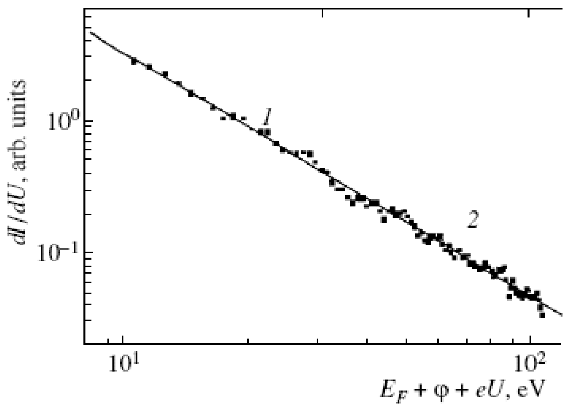

Fig. 3. Typical nonequilibrium EDF formed in a GaAs sample bombarded with 1.25-MeV He^+ ions

The experimental points can be well fit by a single straight line corresponding to the exponent s = 2.9 throughout the entire range of electron energies in vacuum (5…100 eV). It was shown in our early experiments [12] that the EDFs formed in metal plasmas are piecewise powerlaw functions with different exponents in different energy ranges. At least two such ranges were revealed. In our opinion, the piecewise power-law shape of the EDFs in experiments with metals, namely, the presence of two characteristic energy ranges, could be related to two different mechanisms for energy transfer from a fast incident ion to the electron subsystem of a solid. These mechanisms are (i) the excitation of collective plasma oscillations with a subsequent ionization in the electric field of these oscillations and (ii) inelastic collisions, resulting in the direct ionization of atoms. The energy of the electrons produced due to ionization via plasma oscillations cannot exceed the plasmon energy E_p in a substance. In semiconductors, the energy of plasmons related to conduction electrons is much lower than the ionization potential of atoms. For this reason, the distribution function in a semiconductor plasma is characterized by one power-law segment throughout the entire electron energy range under study. The measurements of the energy spectrum of SIEE electrons have shown that, for all of the ion energies under study, the nonequilibrium EDFs formed in plasma are power-law in character. As was mentioned above, the main integral characteristic of SIEE is the electron yield Δ_e. It is shown that in germanium the measured values of Δ_e plotted versus the ionization loss dE/dx for He^+ ions are well fitted by a straight line; i.e., these quantities are indeed proportional to one another.

6. APPLICATIONS

The solution of a lot of scientific and engineering tasks requires use of autonomous source of the power supplies of various devices. Those sources must satisfy the such requirements: long service life; reliability; big specific energy capacity; compact; ecology; explosion-proof. Most commonly used are the chemical elements of a feeds using as a primary source an energy of chemical reactions. Historically such elements were first and, for today most developed by the engineers. However, it is necessary to notice, that they have a rather insignificant specific power capacity hardly exceeding 0,1 KW× hour/kg. Most perfect of them are lithium batteries but they are very explosive.

6.1. THERMAL AND NONTHERMAL RADIOISOTOPE CONVERTERS

A much higher power capacity and term of work have the radioisotope sources of the power supplies, i.e. devices,in which an energy of radioactive decay converts in electrical one. The radioisotope sources of electricity have a general characteristics significantly better than analogous ones of chemical batteries. They are more preferable for the all-round utilization.

Now there is a significant amount of radioisotope sources of an electricity based on various physical principles. They are divided on two large classes:

- thermal radioisotope converters;
- nonthermal.

Nonthermal radioisotope converters manufacture an electrical energy without application of a thermal cycle. The sources with immediate gathering of electrical charges (atomic batteries) are most commonly used among such sources of a current. In these batteries the electrical potency is elected at the expense of gathering on a collector particles, which isotope emitted. A collector and emitter in similar devices are isolated of electric from each other by vacuum gap or dielectric. Such converter is a source of a current. Its voltage is determined by a resistance of loading. A residual of potentials between the anode and cathode can be equal to an energy of particles. The large interior resistance of a source, connecting with loading causes reduction of voltage and, hence, increase of the part of the charged particles energy, which goes to heat of a collector. In outcome efficiency of the source is essentially reduced. It is possible to specify some characteristic demerits reducing service life of such source:

- necessity to have an additional source of voltage for suppression of a second electronic emission from a collector;
- the presence of δ-electrons in the α-particles stream reduces a transferable current essentially.

Moreover, the high working voltage (about hundreds kilovolt) of atomic batteries requires application of insulators and vacuum conditions of very high level and hampers use of these devices.

The devices using a contact residual of potentials between the cathode and the anode are ones of varieties of atomic batteries. The space between the anode and the cathode is filled by gas, which is ionized by a radiation of a radioisotope. The created charged particles are accumulated on the cathode and the anode. Those materials have various work function. The residual of potentials, in this case, depends on work function of used electrode materials and has magnitude about one volt. First of all, the low efficiency of such device is due to a small cross-section of gas atom ionization by the char-ged particles. Insignificant increasing of efficiency is possible by use of a mixture of radioactive and rare gases at pressure some atmospheres. However, the increased pressure in atomic battery, filled by high toxic gas, creates hazard for the maintenence personnel and equipment.

One of modes of transformation of an β-particles energy in electrical power is the generation of an electrical current in a semiconductor mesh due to formation of electron-hole pairs and their separation in p-n junction area. The characteristic value of a current Is in this process is determined as:

$$I_s = eRl = mI_\beta ,$$

where R is factor of generation of a charge; l - diffusion length; m - factor of multiplication of a current; I_β - current of a β-radiation. The maximum value of voltage can be received from the following expression:

$$V = \frac{k_B T}{e} \ln\left(\frac{I_s}{I_0} + 1\right),$$

where I_0 is inverse current of saturation. From these expressions it is visible, that the characteristic value of voltage on one semiconductor mesh is compared with kT/e, i.e. rather small magnitude (less than one volt). The weak place of such sources is p-n junction destroying under attack of a hard radiation. A long irradiation of p-n junction by the β-particles causes the production of radiation damages. If the life time of p-n junction in the usual elements (transistors, chips etc.) makes up some tens thousand hours, the life time of p-n junction in the β-particles irradiation conditions will be significantly less.

The most developed thermal converters are the radioisotope thermoelectric sources of the electric power. In these devices the nuclear decay energy heats one thermoelectric junction, whilst, another one is at temperature of a refrigerator. The potential difference beetwen thermoelectric junctions is arisen through thermoelectric effect. The modern thermoelectric converters are made from semiconductor materials which have transformation coefficient significantly more than metals.

There are many various designs of thermoelectric converters. The constructions of these devices have thermocouples, which consist of some semiconductor layers divided by insulators. It is necessary to notice, that in conditions of high temperatures (about 1000 K) and hard radiation insulation materials quickly will be failed, causing the electrical break-downs and leakage . However, the basic reason restricting service life of such converter is the formation of many radiation damages in the semiconductor and ,consequence, modification of the basic characteristics of the materials.

In thermoemission devices the transformation of the nuclear particles energy in electrical one occurs through thermoemission, which take place under heating of the cathode by particles emitting from radioisotope. During this, thermoemission current is an exponential function of the ratio of the work function of the cathode material to its temperature and, therefore, the application as high temperatures as materials with small work function causes the increase of the efficiency of the converter. The basic difficulty in using of these devices is destructive influence of temperatures about 1000...2000 K at materials. Sometimes, cathode-anode space is filled by gas, mostly by caesium (Cs), in order to reduce the work function of the emitter. The presence of caesium steams causes the formation of cathode film and reduction of the work function (up to 1,81 eV, see for example, [6]). At the same time, the constant presence of caesium reduces service life of such sources essentially and creates problems of making operation safety available to maintenance personnel.

6.2. RADIOISOTOPE SECONDARY EMMISION SOURCE OF CURRENT

A new type of radioisotope source of current based on others physical principles was proposed in [37]. It is well known that passing of fast ions through substance initiates ionization of medium atoms. The some amount of electrons break loose from atoms in result of ion actions. It may passed to vacuum if it have suitable value and direction of momentum, i.e. secondary electron emission induced by ions takes place. It was shown earlier that in such situation it was possible to form steady-state nonequlibrium electrons distribution with power dependence of electrons energy. Based on the studies the results, we proposed the radioisotope source of the secondary-emission current [37]. The source consists of a radioisotope layer placed inside a vacuum container. Metallic emitters are positioned on each side of the layer. The emitter thickness is less than the mean path of the charged particle emitted by the radioisotope in the emitter material. Each emitter consists of alternating layers of two different metals with different secondary-emission coefficients. The layers are electrically isolated by vacuum gaps. A high efficiency of the radioisotope current source of this type is determined by the fact that the secondary electrons are produced along the entire path of the charged particle in the metal; i.e., the charged particle energy is directly transformed into electron energy; the amount and average energy of these electrons are much above those for the thermal electron emission.

It was stated previously that the use of heavy particles in electric-current sources leads to a high efficiency of production of secondary electrons due to negligibly small scattering of these particles (i.e., they move along almost straight trajectories). The secondary-electron distribution function is nonequilibrium; the average energy of the emitted secondary electrons exceeds 10 eV. The source efficiency increases as a result of an increase in the secondary emission under the action of δ-electrons. As a result, such a current source has high energetic parameters that are proportional to the number of the emitter layers.

Since the total thickness of the emitter does not exceed the mean path of the charged particle emitted by a radioisotope, the number of layers and, consequently, the emitter efficiency can be increased only by making each layer thinner. However, as the layer thickness decreases, the construction loses the rigidity. This can break the electric insulation between layers. For example, if the layers are bent, the vacuum gaps between them become narrower.

We have also proposed the secondary-emission current source with thinner emitter layers and, at the same time, with a sufficiently high rigidity of the emitter. This problem is solved by developing a radioisotope source of the secondary-emission current in which a radioisotope and emitter with a thickness less than the mean path of the charged particle emitted by the radioisotope are placed inside the hermetically sealed case. The emitter consists of alternating electrically insulated layers made of two different materials with different coefficients of secondary electron emission. Dielectric grids are located between the emitter layers; the grids serve to insulate the layers electrically from each other and to improve the rigidity of the emitter construction. The thickness of the dielectric grid is larger than the thickness of the emitter layers. To obtain a better effect, the dielectric grid must be deposited directly on one of the emitter layer. One of the version uses the ceramic grid, and the other one uses the plastic grid.

In order to improve the efficiency of the proposed current source, one of the alternating emitter layers can be made of a metal, and the other one of the semiconductor material with a secondary-emission coefficient exceeding that of the metal layer. It is desirable to made the semiconductor layer from silicon or gallium arsenide. The energetic parameters of the proposed source can be considerably improved by placing an additional radioisotope inside the source case, so that the emitter would be between the additional and the main radioisotopes, and the flows of particles emitted from radioisotopes be directed in opposite directions. By using all the technical solutions presented above, it is possible to create a radioisotope source of the secondary-emission current with a substantially better energetic parameters and smaller mass and sizes.

The new type of radioisotope source of current were suggested on the basis of carried out investigations [38-40]. Our source has considerably more specific energy capacity than existing ones. Use of this source is most advantageously there where it is necessary to apply devices working without human intervention for a long time. Above all, our source can be used very perspective in such branches as: medicine and space researches. This source can be very useful in the long space flights, especially on the automatic station. The employment of our source for the cardiastimulator supply is more preferable than thermal radioisotope one. Our battery can maintain it for a long time of operating and has not high work temperatures as thermoelectric and thermionic radioisotope sources. The wide perspectives are open for using it for design of artificial heart because this source almost satisfies all present requirements. It is necessary to note, other possibilities for using of our source. It can be used as electricity source for devices in hard accessible places (navigation buoys, magnitometric station etc.). Moreover, it is advantageous to use our source in the system of protection and obtaining of information.

7. CONCLUSIONS

In this paper, we have shown that the presence of sources and sinks in a spatially uniform system leads to the formation of SNDs with power-law tails. Numerical simulations of the formation of SNDs show that, for particles with Coulomb interaction, an SND is formed between the source and sink. Starting from a certain intensity of the source (sink), the powerlaw distribution function has the same exponent; i.e., it is universal. A radical change in the EEDF under nonequilibrium conditions leads to an anomalous increase in the conductivity and emissivity of the substance. The experimental data on the EEDFs formed in the solid-state plasma of a Sb/Cs cathode irradiated with a beam of fast low-Z ions are presented. In all of the experiments with H^+ and He^+ ions, the nonequilibrium EEDFs in the energy range from 5 to 100 eV are found to have a piecewise power-law shape with different exponents in the energy ranges of 5...30 and 30...100 eV. The power exponents are expected to depend on the energy (specific ionization loss) of fast ions, and this was indeed observed for protons in the former energy range. The experimental studies of the formation of nonequilibrium electron distributions in a semiconductor plasma exposed to ion beams have shown that EEDFs have power-law asymptotes with one exponent. This is related to the low energy of the plasma oscillations carried by the conduction electrons.

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РАДИАЦИОННАЯ ЭЛЕКТРОНИКА

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Обзор работ по формированию неравновесных функций распределения электронов при наличии источника и стока в импульсном пространстве. Рассмотрены как аналитические исследования, так и численное моделирование нелинейных интегралов столкновений Больцмана и Ландау-Фоккера–Планка. Приведены результаты экспериментальных исследований формирования неравновесных функций распределения электронов в твердотельной плазме при облучении ее потоками электромагнитного излучения или заряженных частиц. Описан оригинальный вторично–эмиссионный радиоизотопный источник тока, основанный на неравновесных распределениях электронов.

РАДІАЦІЙНА ЕЛЕКТРОНІКА

В.І. Карась

Огляд робіт по формуванню нерівноважних функцій розподілу електронів дії джерела та стоку у імпульсному просторі. Розглянуті як аналітичні дослідження, так і чисельне моделювання нелінійних інтегралів зіткнень Больцмана та Ландау-Фоккера–Планка. Наведені результати експериментальних досліджень формування нерівноважних функцій розподілу електронів у твердотільній плазмі при її опромінюванні потоками електромагнітного випромінювання або заряджених частинок. Описане оригінальне вторинно–емісійне радіоізотопне джерело струму, основане на нерівноважних розподілах електронів.