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NONEQUILIBRIUM ELECTRON DISTRIBUTION FUNCTIONS INDUCED BY FAST IONS IN SEMICONDUCTOR PLASMA

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The results of experimental investigations of distribution functions of nonequilibrium electrons induced by H^+ and He^+ ion beams with energies 1-2,25 MeV in solid-state plasma of Ge, GaAs and CdTe semiconductors are presented. It is shown, that distribution functions have a power-law character with one power index on the whole electron energy range of 5÷100 eV being investigated; the corresponding power indices are presented. The yields of secondary electron emission induced by He^+ ions are measured.

INTRODUCTION

Universal steady-state nonequilibrium power-law particle distribution functions $f=Ap^{2s}$ (p is a momentum) are exact solutions of kinetic equations with the Boltzmann collision integral. Kats et al. firstly obtained it by means of a group symmetry approach [1]. Such distribution can be realized in solid-state plasma under certain conditions.

Entry of an additional kinetic energy into plasma of a solid gives rise to ionizations of medium atoms and production of a plenty of free electrons, which have energies above an equilibrium level [2]. In such conditions it is possible to form of electron distributions differing from equilibrium ones [3, 4]. As it has been shown in a number of theoretical and experimental investigations, under bombardment of high energy ion beams the presence of a particle (energy) flux generated in momentum space by a source (ionization) and a sink (emission of electrons) results in the formation of a steady-state nonequilibrium power-law distribution function of electrons in a solid-state plasma:

$$f(E)=\alpha I^{1/2}E^{s}, \qquad (1)$$

where α is a normalizing constant, I is a flux of particles (energy), s is a power index [4, 5]. Here E is a total energy of electrons in a solid: $E=\varphi+E_F+eU$, where φ is a work function, E_F is a Fermi level, and the energy eU is measured from a vacuum level. Power-law distributions are characterized by the presence of significant part of high energy electrons. For example, the fraction of electrons with energies higher than E_p=18,9 eV (where E_p is energy of a plasma oscillations in beryllium) in the electron distribution induced by 4,9 MeV α-particles in beryllium specimen can exceed 37 % [6].

When velocity of an incident ion v essentially exceeds velocity of each electron of target atom, elastic losses are negligible small, and inelastic losses of energy usually referred to ionization losses or stopping power, are determined by the Bethe-Bloch formula [7]:

$$-dE/dx=(4\pi Z_1^2e^4/mv^2)Z_2N\ln(2mv^2/I), \qquad (2)$$

where m is the mass of an electron, Z_1 is the charge of the incident particle, Z_2 is the charge of the substance atoms, N is density of target atoms, and I is their mean excitation potential. As appears from the formula (2), in a high energy region ionization losses decrease as v^{-2}. Entry of an additional charge into the quasi-neutral equilibrated system of solid-state plasma results in excitation of electron plasma oscillations - plasmons [8]. Thus, the energy lost by an ion moving in a solid-state plasma, can be transferred to electrons of medium in two different ways: a fraction of the ion energy goes into excitation of plasmons, and the other fraction is converted into the energy of individual electrons in collisions (in particular, in ionizing collisions with atoms) [2]. New free electrons produced have energies which significantly exceed the equilibrium level. The nonequilibrium situation realizable in such a way gives rise to considerable changing of a distribution function of free electrons [4].

It is possibly to obtain information about nonequilibrium electron distributions formed in solid-state plasma by measuring secondary effects that occur during the passage of a charged particle through a solid [6, 9].

The part of the nonequilibrium electrons produced in solid-state plasma, having the proper values and directions of momentum, can escape from the substance or, in other words, a secondary ion induced electron emission (SIEE) takes place. Process of an emission occurs in three stages:

1) production of nonequilibrium electrons;
2) transport of electrons (diffusion) to a surface of a solid and collisions;
3) overcoming potential barrier existing on a surface, and ejection into vacuum.

Since well-known Sternglass paper [10] such approach is considered to be most thorough representing the mechanisms of SIEE [11].

The integral characteristic of SIEE is coefficient of SIEE γ frequently termed in the literature as an

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electronic yield [12]. Electronic yield γ is defined as a relation of a number of secondary electrons N_e emitted to a number of incoming ions N_i:

$$\gamma = N_e/N_i\,. \qquad (3)$$

The value of electron yield essentially depends on energy of bombarding ions. Now it is considered theoretically and experimentally proved, that for light ion impact electronic yield γ is proportional to the specific ionization losses (electronic energy loss per unit path lengths) in substance dE/dx [10, 12, 13].

Considerably more informative characteristics of SIEE are energy spectra of secondary electrons. The experimental study [14-16] has shown, that energy spectra of secondary electrons have power-law character. As it has been shown in [9] studying the energy spectrum of the emitted electrons enable to find the shape of the electron distribution function in a solid.

The experimentally investigated energy distribution functions of nonequilibrium electrons in a plasma of metals have piecewise power character with different power indices for different energy intervals [5, 16, 17].

The theoretical study [3, 4, 18] and the numerical modeling analysis [19] show that, in a semiconductor plasma, the power-law distribution function corresponding to a constant energy or particle flux in momentum space can exist in the energy range $(E-E_F) > E_F$. This distribution is formed by both collisions with electrons in the energy range $(E-E_F) > E_F$ and collisions with background (equilibrium) electrons.

From the expression for the electron emission current density [3, 4, 9, 20] we can see that, in a plasma with a nonequilibrium electron distribution, the electron emission current density is anomalously high, because, the distribution function decreases very gradually in the inertial interval. The conduction characteristics of the medium are governed by the density of the current carriers, so that, in a semiconductor plasma with a nonequilibrium electron distribution, this density is very high, in contrast to the case of an exponentially decreasing equilibrium distribution function [19]. That is why, under the action of intense fluxes of fast particles, the emission and conduction properties of a semiconductor plasma can become anomalous [19].

Experimental study of nonequilibrium electron distribution functions in semiconductor plasma has not been carried out yet. Thus, in this paper we tried to restore such distributions formed in a semiconductor plasma under the bombardment of fast light ions by means of measuring energy spectra of SIEE.

EXPERIMENTAL SETUP

The investigations of distribution functions and electron yields of secondary electron emission induced by fast light ion beams were carried out on the experimental setup which schematic diagram is represented on Fig. 1.

The electrostatic ion Van de Graff accelerator, used as a source of primary particles, permitted to produce hydrogen H^+ and helium He^+ ion beams with energies from 1 up to 2,25 MeV.

A system of target replacement developed by us was dispose inside the experimental chamber. It permits reliable moving and fixation on the beam axis up to 6 targets without vacuum failure. All targets under study 1 had 10 mm diameter and were fixed in copper workholders fastened on holder 2. The ion beam, collimated by means of diaphragm system, impinged on the target and caused backward secondary electron emission from its surface. Plane of the target was perpendicular to beam axis. The diameter of the beam spot on the target was 3 mm. The ion current density was not higher, than 30 μA/cm^2. Experiments were carried out with polycrystalline targets prepared of germanium, gallium arsenide and cadmium telluride.

The chamber was pumped out with a NMD-0,4-1 magnetic-discharge pump and an NVPR-16D fore vacuum pump with a liquid nitrogen trap, developed for elimination of vacuum oil contamination of chamber constructional elements. In all experiments vacuum system has allowed to provide residual gas pressure in the chamber no more than 10^{-6} torr.

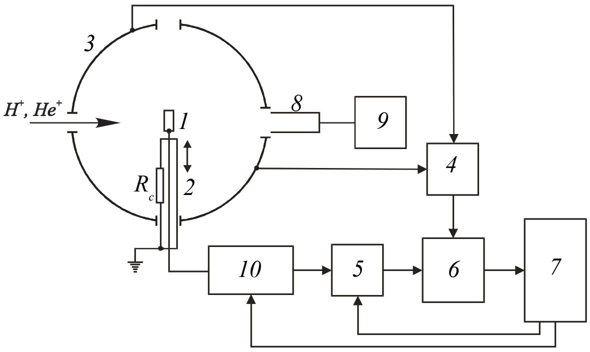

Fig. 1. Schematic diagram of the experimental setup: 1 – target; 2 - holder of a target; 3 - half-spheres; 4,5 - electrometric amplifiers; 6 - the analog-digital converter; 7 - IBM PC computer; 8 – Faraday cup, 9 - current device F303; 10 - source of sawtooth voltage

The secondary electrons emitted from the target surface, hit on the spherical collector consisting of two 100 mm radius hemispheres 3. By means of target replacement system the specimen under study was positioned between two hemispheres at center of the collector. The gap between hemispheres was 15 mm. The input window of the hemisphere was 10 mm diameter. Simultaneously with measuring collector current I_C the target current I_T was registered. The target

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current is a sum of the ion beam current I_B and a current of the secondary electrons, which have reached the collector: $I_T = |I_C| + I_B$. The measured collector current I_C and target current I_T amplified correspondingly by electrometric amplifiers 4 and 5, were fed through the analog-to-digital converter 6 to the IBM PC COMPUTER 7. In order to calibrate the measuring system a Faraday cup 8 was disposed behind the back hemisphere. It permits to carry out direct measuring of ion beam current I_{FC} when the targets are brought out of the beam. The dimensions of the Faraday cup were ∅=20 mm and l=130 mm. Its current I_{FC} was measured by means of current device F303 9. Electron yield was determined by the formula:

$$\gamma = |I_C| / (|I_C| - I_T). \qquad (4)$$

Studying energy spectrum of SIEE electrons by means of the spherical analyzer designed for a point source of emission, it is possible to find an explicit shape of the distribution function of electrons inside a solid [9]. When the electron distribution is the power-law function the derivative of emission currents on electron energy dI/dU can be represented as:

$$dI/dU = B\cdot(E_F+\varphi+eU)^{s+1}, \qquad (5)$$

where B is a constant, E_F is Fermi level, φ is work function, eU is the energy of electrons in vacuum. Hence, the dependence (5) in logarithmic scale represents straight line, which slope ratio is equal to $s+1$.

The energy distributions of secondary emission electrons were measured by means of the spherical collector in a retarding field energy analyzer mode. The retarding field was ranged from 0 to 100 V with 1 V step. The retarding electric field was produced in the space between the target 1 and two hemispheres 3. As the radius of the energy analyzer considerably exceeded target size the electrical field distribution was close to spherical one. The holder of each target 2 was a ceramic tube ∅=5 mm whose outer surfaces were covered by resistive layers. The specific resistance of layer R_c was varied nonlinearly along the tube so that the holder potential did not disturb the electrical field inside the energy analyzer. The target was in contact with one end of the resistive layer, whose another end was grounded. The retarding potential produced by the sawtooth voltage generator 10 controlled by COMPUTER 7 was applied to the target inside a ceramic tube. Thus, the current flowing along the resistive layer produced a potential distribution along the holder. The emitted secondary electrons, being moved on radial trajectories, hit the collector. When the retarding potential is applied to the target only those electrons which energy were sufficient for overcoming retarding field hit the collector. The experiment control program allowed making of 100 measurements of electron emission current for each value of the retarding potential during 7 seconds. Then the averaged value of that current was fed to the COMPUTER and memorized. As a result of that procedure the obtained dependences of the collector current on retarding voltage (5) (retarding curves) allowed to obtain the energy spectrum of SIEE electrons by differentiation of these dependences, and then restored the distribution function.

Calculation procedure of the power index s values of electron distribution functions included some operations. At the beginning the "fitting" of electron emission current and differentiation of the retarding curves were carried out. Then the linear approximation of the dI/dU dependences on a total energy of electrons inside a solid $(E_F+\varphi+eU)$ plotted in logarithmic scale was performed. According to (5), the slope ratio of the straight lines is equal to $(s+1)$.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental investigation performed has shown, that for all energies of incident H^+ and He^+ ions the electron energy distribution functions in solid-state plasma of semiconductors under study have power-law dependence. The typical double logarithmic-scale distribution function of nonequilibrium electrons induced by 1,25 MeV He^+ ions from gallium arsenide sample is presented on Fig.2. The experimental points are seen to fit well in one straight line with power index s=-2,9 in the whole vacuum electron energy interval of 5…100 eV. As a result of experimental data processing we have obtained the power index s values of electron distribution functions. The corresponding power indexes for semiconductor samples are presented in Tables 1 depending on primary ion energy.

As we have mentioned above the electron distribution functions formed in a metal plasma during the passage of fast light ions have piecewise power character with different power indices for different electron energy intervals [5, 16, 17]. At least two such energy intervals were observed.

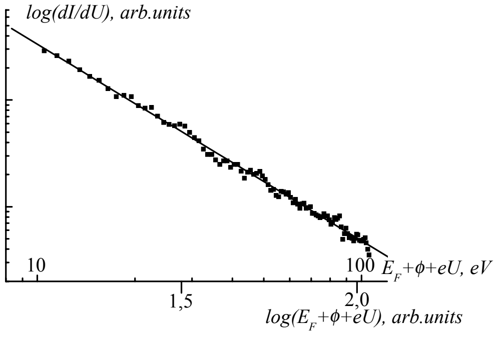

Fig.2 Typical log(dI/dU) dependence on log($E_F+\varphi+eU$) for gallium arsenide bombarded by ions He^+ with

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energy 1,25 MeV. The distribution function has one section on the whole energy interval 5…100 eV with power index s=-2,9

Table 1

Ion	Energy, MeV	Power index		
		Gallium arsenide	Germanium	Cadmium telluride
He^+	1	-	2,8	-
	1,25	2,9	2,8	-
	1,5	2,9	2,8	-
	1,75	2,6	2,7	2,9
	2	2,6	2,8	2,8
	2,26	2,7	2,8	2,9
H^+	1	3,1	2,9	3,1
	1,25	2,9	2,8	3,0
	1,5	2,8	2,9	3,0
	1,75	2,8	2,6	2,7
	2	2,7	2,6	2,7
	2,26	3,0	2,8	2,8

In our opinion, the presence of piecewise character, namely two sections on the distribution function observed for metal samples, perhaps, is connected with the action of two different mechanisms of energy transfer from the moving fast ion to the electron subsystem of the solid: plasma oscillation excitation with subsequent electron production by plasmon ionization and inelastic collisions with substance atoms, leading to direct ionization. The energy of the electron produced by the former mechanism can't exceed the plasmon energy E_P. For semiconductors the energy of plasmons, which are spread in conduction electron medium, is significantly less than ionization potential of substance atoms. In this connection, semiconductors have one power index in the whole energy interval of secondary electrons.

An electron yield is considered to be basic characteristic of secondary ion induced electron emission. In our experiments we have measured this quantity too. The results of experimental measurements of the electron yield values for He^+ ions are presented in Table 2.

Table 2

Ion	Energy, MeV	Electron yield γ		
		Gallium arsenide	Germanium	Cadmium telluride
He^+	1	-	2,4	-
	1,25	2,3	2,3	-
	1,5	2,2	2,3	-
	1,75	1,7	2,0	2,0
	2	2,1	1,9	1,9
	2,26	1,9	1,7	1,9

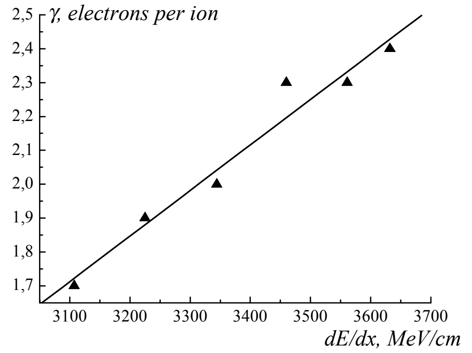

Fig.3. Electron yield from germanium sample as a function of the stopping power dE/dx for He^+ projectiles

The assumption of a proportionality between the electron yield of SIEE and the stopping power is demonstrated in Fig.3. As evident from this figure, the experimental points of electron yield dependence on the stopping power *dE/dx* for germanium and He^+ projectiles are seen to fit well in straight line.

CONCLUSIONS

As a result of the experiments performed it is shown, that the nonequilibrium electron distribution functions induced by fast hydrogen and helium ions in solid-state plasma of the semiconductors under study have power-law dependence with one power index on the whole electron energy range of 5…100 eV being investigated. Presumably, earlier observed presence of two electron energy intervals on the distribution function in metal plasma is connected with plasma oscillation mechanism in a solid. For semiconductors the energy of plasmons spreading in free electron medium, is less than ionization potential of substance atoms. Thus, semiconductors have one power index in the whole energy interval of secondary electrons. Thus, the influence of plasma oscillations in solid state plasma on formation of electron distribution functions has been demonstrated.

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