KINETICS OF NONEQUILIBRIUM ELECTRON-PHONON SYSTEM FOR SEMICONDUCTORS AND METALS IN A STRONG ELECTRIC FIELD

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Formation of non-stationary nonequilibrium distribution functions (DF) of electrons and phonons is investigated under the action of a strong pulse electric field on metal. For concreteness parameters were taken for nickel having reference temperature of 20 K. It is shown: isotropization of electron DF occurs as a result of impacts with lattice imperfections; •electron DF does not become thermodynamically equilibrium as electron-electron impacts in the given situation give essentially smaller contribution than electron-phonon collisions and collisions with a "another's" subsystem do not result to thermalization; •DF of electrons and phonons have high energy "tails" as in electron-phonon impacts the momentum is transferred with sufficiently small transfer of energy; a lot of phonons with Debye energy are being born, i.e. phonon DF is being enriched by Debye phonons.

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INTRODUCTION

In the sixtieth of the twentieth century the phenomenon of sharp reduction of resistance of metals to plastic deformation was revealed in case of excitation of their conductivity electron subsystems by either irradiation or by transmission electric current of high density $j=10^8…10^9$ A/m^2. It could not be explained by trivial thermal influence (in macroscopic display) of current therefore there was an assumption of existence of electron-dislocation interaction influencing on mechanical properties of crystals [1].

The phenomenon was offered to be named electroplastic effect (EPE). EPE mechanism was associated with the increase of disposition mobility in the neighborhood of sources and therefore with intensification of work of sources. In the purest state EPE was investigated on metal monocrystals of Zn, Cd, Sn, Pb [1]. If during deformation of samples of these materials the current pulses of magnitude $10^2…10^3$ A/mm^2 and duration of 10^{-4} are being passed through them or the samples are being irradiated by accelerated electrons if the direction of sliding the softening of the samples is revealed which is expressed by spasmodic recessions of deforming stress. Pressure oscillations are connected with jumps of plastic deformation of objects. It is established that synchronously with passage of pulses of a current and deforming stress decrease the packs of slip bands appear and also that deforming stress drop is incommensurably less in the section of quasi-elastic deformation than beyond a the yield point. These oscillations are abnormally high in the area of yield stress of the material. Deforming stress drops on the diagrams decrease when testing in a mode of stress relaxation.

Application of a pulse current has allowed to provide high density current at simultaneous exception of dominating influence of macroscopic heating by Joule heat. In case of the pulse durations of 100…200 μs, current amplitudes of 50…1000 A and frequency of pulse recurrences of $0{,}1\cdot10^4$ Hz a constant component of a current only a little exceeded 1 A and could not provide heating of a sample more than on 1…5°C. The intensity of jumps of deformation at action of pulses of the current in single crystals with slipping anisotropy has strongly pronounced orientation dependence. So in Zn the maximum of effect and the minimum of stress at which it starts to become apparent when the deformable samples are oriented for easy basal slip. These facts obviously denote the dislocation nature of EPE.

EPE has threshold character, i.e. it appears at a particular value of pulse current density which depends on a grade of the deformable crystal and temperature-speed condition. So for zinc at T=77 K it is equal to 400…500 A/mm^2.

It has been established that EPE is rather sensitive to external factors. First, the effect is amplified by action of surface-active media. For example specific crystallographic shift of amalgamated single crystals of zinc at temperature 300 K and under conditions of current pulses influence with parameters: j=600…1000 A/mm^2, frequency of recurrence of pulses of 0.1…0.5 Hz and duration of a pulse $t_p=10^{-4}$ s increases by 50…60%.

As a result of alloying the drop magnitude under active stress can grow by tens percent (up to 100%). In limits of relatively small replacement impurity content the magnitude of the effect grows linearly with concentration as it is shown in experiments with Zn, alloyed Cd from 10^{-3} up to 10^{-1} at. % (the content of other impurities did not exceed $2\cdot10^{-3}$ at. %). At the same time threshold value of stress from which the effect begins also increases when alloying. However this fact can be connected to the common increase of the critical shearing stress in alloyed crystals.

The growth of speed of test first results in weak increase of the magnitude of the effect and then in falling of it. The increase of pulse frequency lowers the common level deforming stress but also reduces the stress drop amplitude $\Delta\Pi$. The increase of duration of current pulses at constant amplitude linearly increases depth of stress drop. Last phenomenon is fixed both in stress relaxation and creep experiments. Under conditions of zinc monocrystals creep the reduction of the threshold value of duration of pulses at which EPE becomes apparent is revealed. As it was already mentioned EPE is registered beginning from some threshold amplitude of

pulses of current and then the magnitude of EPE grows linearly with the pulse amplitude. The given phenomenon is typical both for active stressing and for creep. It is necessary to note that electro-plastic effect of current can be activated also by change of the direction of current in the following pulses while the amplitude remains constant (polarity of action of current).

Prominent feature of EPE in single crystals is absence of temperature dependence in a wide interval from 77 up to 300 K. It is established at research of stress relaxation in single crystals of zinc where the jump deforming stress was measured stimulated by the first pulse of a current after the loading device stop.

The analysis of all marked laws shows that EPE cannot be reduced simply to thermal heating and should be anyhow connected with a dislocation subsystem of deformable object. More detailed research of EPE in modes of creep and stress relaxation has allowed to establish additional features of the effect [1]. It is established that the current influences during the first seconds after the loading device stop at relaxation and for electrically stimulating influences at the bottom relaxation holes change of direction of current is necessary at the same amplitude. After current switching the delay before the beginning of additional plastic deformation is observed. It testifies that the factor of a current is equivalent to occurrence of effective additional stress $\Delta\Pi$. $\Delta\Pi$ grows with the increase of Π and decreases in due course from the beginning of relaxation. Hence, it should be connected with the presence of mobile dispositions in the sample. The further experiments on EPE research in modes of creep, internal friction and stress relaxation pressure have shown that EPE is caused by the growth of effective short-range stress. At last bipolar pulses of current following without interval slow down plastic deformation and they accelerate it as it was already marked earlier if between them there is an interval of about $3 \cdot 10^{-3}$ s.

The basic laws of EPE which have been found out while deforming single crystals are observed also in experiments with polycrystalline materials. So the occurrence of spasmodic deformation is established when stretching of samples of polycrystalline zinc, cadmium, lead, indium and tin at temperature 77 K and under influence of single pulses of current of value $\sim 10^3$ A/mm^2. However the magnitude of the effect in this case was 5 times lower than in case of single crystals under corresponding conditions and did not exceed 6…8% [1]. In [1] the increase of creep speed of wire polycrystalline samples of W, Mo, Zn, and also of alloys Mo-Re, W-Re, steel etc. due to action of a constant electric current with density up to $5 \cdot 10^3$ A/mm^2 is described. It is established that logarithms of speed of creep grow linearly with the square of current density and it has allowed the authors to refuse the hypothesis of only thermal influence of current because the sample was being cooled during the experiment.

At application of current pulses while stressing (stretching) metal crystals the process of deformation turns from naturally sporadic and non-uniform into ordered discrete. The maximum of the effect is observed in the close to yield stress of samples. In case of samples alloyed by a small amount of impurity the effect grows. There is an optimum interval of speeds of deformation in which the electric current in the maximal degree lowers the resistance of metal to plastic deformation. In a wide interval of temperatures (from 80 up to 300 K) the magnitude of effect practically does not depend on temperature [2].

The similar phenomena are observed at irradiation of metal by packages of accelerated electrons pulses. Combination of influence of current and irradiation leads to intensification of effect of durability decrease of metal. Under electronic influence (current and irradiation) the probability of brittle fracture of samples at initial stages of deformation decreases and the crystals being deformed under simultaneous influence of current and irradiation are characterized by decrease of the critical cleavage stress, reduction of the factor of hardening and increase of the speed of creep [2].

It is shown, that with increase in electron energy beyond a atom knocking-out threshold (in case of zinc $E_{tr} \approx 0{,}7$ MeV) the effect of radiation hardening is imposed on radiation plasticizing of metal due to creation of additional stoppers for dispositions as dot defects and their ensembles. At increase of electron density in one pulse the effect of radiation plasticizing at first grows and then decreases. Recession of the effect is explained by influence of probable partial degeneration of electronic gas in metal on movement and interaction of dispositions [2].

It is shown that the activation volume after irradiation of metal by electrons essentially does not change and also the increase of creep speed is explained by reduction of time (increase of frequency) of the process of thermally activated overcoming of obstacles by dispositions [2].

1. MATHEMATICAL MODEL

For quantitative description of dynamics of electron-phonon system of a metal film in work [3] an important simplifying assumption about Fermi form of isotropic parts of electron distribution function with time-dependent electron temperature has been used. Though authors [3] also mention that introduction of electron temperature being equivalent to frequently used assumption about instant thermalization of electron subsystem not always can be strictly proved. So in area of very low temperatures $T_e < T^*$ (temperature $T^* \approx T_D^2 / \varepsilon_F$, T_D – Debye temperature) where electron-electron collisions dominate above the electron-phonon collisions the electron distribution function becomes thermodynamically equilibrium (Fermi-Dirac distribution function) during characteristic time periods of electron-electron interaction τ_{ee}. In usual rather pure metals $T^* \sim 1$ K and in deliberately polluted films where electron-electron interaction is being amplified because of effects of weak localization T* can be about 10 K. At temperatures of $T_e > T^*$ but $T_e < T_D$ electron thermalization in rather thick films occurs not as a consequence of direct electron-electron interaction but because of indirect interaction in form of phonon exchange. It has been shown earlier by one of the authors [3] that the electron distribution function which is close in the form to Fermi distribution function is formed also in rather thin films

(nonequilibrium phonons leave it and go to the substrate without being reabsorbed by electrons) as a result of only the process of phonon emission by "hot" electrons. In both cases a characteristic time of electron thermalization is the time electron-phonon collisions τ_{ep}.

Let's notice also that in optically thick films the uniformity of electron temperature on thickness of a film is provided by the fast leaving of electrons the area of the skin-layer and high electron heat conductivity in comparison with the phonon one [3]. Owing to additional diffusion reduction of "hot" electron density the thermalization speed of the electron subsystem essentially grows and consequently in optically thick films the approach of instant thermalization gives good agreement of the theory with experiment. In work [3] the case of small "heatings" was considered, we when considering EPE deal with very significant "heatings", therefore it is necessary for us to carry out consecutive kinetic consideration of both electron and phonon subsystems what makes the basic content of the given article.

At the kinetic description the electron behaviour submits to Boltzmann equation for electron distribution function $f(\vec{r},\vec{p},t)$ with corresponding integrals of collisions

$$\frac{\partial f}{\partial t}+\vec{\upsilon}\frac{\partial f}{\partial \vec{r}}+\frac{d\vec{p}}{dt}\cdot\frac{\partial f}{\partial \vec{p}}=I_{ee}+I_{ep}+I_{ed}, \qquad (1)$$

$$\frac{d\vec{p}}{dt}=e\left\{\vec{E}(\vec{r},t)+\left[\vec{\upsilon},\vec{B}(\vec{r},t)\right]\right\},$$

where I_{ee} is the integral of collisions of electrons with electrons, I_{ep} is the integral of collisions of electrons with phonons, I_{ed} is the integral of collisions electrons with impurities and lattice defects $\vec{\upsilon}$ is the velocity, $\vec{r}$ is the radius-vector, $\vec{p}$ is the momentum, t is the time, $\vec{E}$ is the electric field intensity, $\vec{B}$ is the magnetic induction. Further we shall consider the magnetic field absent.

Let's write down the integrals of collisions:

$$I_{ee}=\int d\vec{p}_1 d\vec{p}_2 d\vec{p}_3 w_{ee}\left(\vec{p},\vec{p}_1/\vec{p}_2,\vec{p}_3\right)\delta\left(\vec{p}+\vec{p}_1-\vec{p}_2-\vec{p}_3\right)\times$$
$$\delta(\varepsilon(\vec{p})+\varepsilon(\vec{p}_1)-\varepsilon(\vec{p}_2)-\varepsilon(\vec{p}_3))\{f(\vec{p}_2)f(\vec{p}_3)(1-f(\vec{p}))\times$$
$$\times(1-f(\vec{p}_1))-f(\vec{p})f(\vec{p}_1)(1-f(\vec{p}_2))(1-f(\vec{p}_3))\},$$
$$I_{ep}=\int d\vec{q}w(\vec{q})\{\delta\left(\varepsilon(\vec{p}+\vec{q})-\varepsilon(\vec{p})-\hbar\Omega(\vec{q})\right)\{f(\vec{p}+\vec{q})(1-$$
$$f(\vec{p}))\left[N(\vec{q})+1\right]-f(\vec{p})(1-f(\vec{p}+\vec{q}))N(\vec{q})\}+\{f(\vec{p}-\vec{q})\times$$
$$\times(1-f(\vec{p}))N(\vec{q})-f(\vec{p})(1-f(\vec{p}-\vec{q}))\left[N(\vec{q})+1\right]\}\times$$
$$\times\delta\left(\varepsilon(\vec{p}+\vec{q})-\varepsilon(\vec{p})+\hbar\Omega(\vec{q})\right)\},$$
$$I_{ed}=\int d\vec{p}'w_{ed}\left(\vec{p}'-\vec{p}\right)\{\delta\left(\varepsilon(\vec{p}')-\varepsilon(\vec{p})\right)\{f(\vec{p}')-f(\vec{p})\},$$

$\varepsilon(\vec{p})=p^2/2m$, $\vec{j}=\left\langle f\vec{\upsilon}\right\rangle$ is the density of electric current, the symbol of averaging $\langle\ \rangle$ is understood as multiplication by $2/(2\pi\hbar)^3$ and integration over $d\vec{p}$, $\hbar$ – Planck's constant, m is the electron mass, $\vec{q}$ is the phonon momentum.

The phonon distribution function also submits to the kinetic equation with integrals of collisions:

$$\frac{\partial N(\vec{q})}{\partial t}+\vec{\upsilon}_q\frac{\partial N(\vec{q})}{\partial \vec{r}}=I_{pe}+I_{pp}+I_{pd}, \qquad (2)$$

where I_{pe} is the integral of collisions of phonons with electrons, I_{pp} is the integral of collisions of phonons with phonons, I_{pd} is the integral of collisions phonons with impurities and defects of lattice, $\vec{\upsilon}_q=\hbar\partial\Omega/\partial\vec{q}$ is the phonon speed.

$$I_{pe}=\int d\vec{p}w(\vec{q})\delta\left(\varepsilon(\vec{p}+\vec{q})-\varepsilon(\vec{p})-\hbar\Omega(\vec{q})\right)\times$$
$$\times\{f(\vec{p}+\vec{q})(1-f(\vec{p}))\left[N(\vec{q})+1\right]-f(\vec{p})(1-f(\vec{p}+\vec{q}))N(\vec{q})\},$$
$$I_{pp}=-\nu_{pp}(\vec{q})\left[N(\vec{q})-N_T(\vec{q})\right],$$
$$I_{pd}=-\nu_{pd}(\vec{q})\left[N(\vec{q})-\overline{N}(\vec{q})\right],$$

where $N_T(\vec{q})=\left[\exp(\hbar\Omega/T)-1\right]^{-1}$ is the thermodynamically equilibrium phonon distribution function (Bose-Einstein's distribution function), $\overline{N}(q)=\frac{1}{4\pi}\int N(\vec{q})dO$ is the phonon distribution function averaged by angles. Taking into account that impacts of electrons with impurities, phonons and defects result in isotropization of electron distribution function we shall search it as

$$f(\vec{p},t)=f(\varepsilon(p))+\vec{f}_1(\varepsilon(p))\frac{\vec{p}}{p}. \qquad (3)$$

Taking into account that in collisions of electrons with phonons the transfer of energy is very small we shall simplify the integrals of collisions of electrons with phonons, namely we shall expand the isotropic a part of electron distribution function into series by small transfer of energy down to square-order summand:

$$f(\vec{p}\pm\vec{q})\equiv f(\varepsilon(\vec{p})\pm\hbar\Omega(q))=f(\varepsilon(p))\pm\frac{\partial f(\varepsilon(p))}{\partial\varepsilon}\hbar\Omega+$$
$$+\frac{\partial^2 f(\varepsilon(p))}{\partial\varepsilon^2}\cdot\frac{(\hbar\Omega)^2}{2}. \qquad (4)$$

Also we shall substitute this decomposition into the integrals of collisions that will allow to simplify them essentially so the integral of collisions of electrons with phonons will become

$$I_{ep}\{f(\varepsilon)\}=\sqrt{\frac{2\pi^2 m}{\varepsilon}}\frac{\partial}{\partial\varepsilon}\{\frac{\partial f}{\partial\varepsilon}\int_0^{\sqrt{8m\varepsilon}}dqw(q)q\left[N(q)+\frac{1}{2}\right]\times$$
$$\times\left(\hbar\Omega(q)\right)^2+\left[f(\varepsilon)(1-f(\varepsilon))\right]\int_0^{\sqrt{8m\varepsilon}}dqqw(q)\hbar\Omega(q)\}, \qquad (5)$$

$$I_{pe}\{N(q)\}=2\pi m^2\frac{w(q)}{q}\int_{q^2/8m}^{\infty}d\varepsilon\{\left[f(\varepsilon)(1-f(\varepsilon))\right]\times$$
$$\times[N(q)+1-f(\varepsilon)]\left[\hbar\Omega\frac{\partial f(\varepsilon)}{\partial\varepsilon}+\frac{(\hbar\Omega)^2}{2}\frac{\partial^2 f(\varepsilon)}{\partial\varepsilon^2}\right]\}. \qquad (6)$$

Taking into account a concrete kind of dependence of probability of transition $w(q)$ and also frequencies of impacts of phonons with phonons $\nu_{pp}(q)$

$w(q)=w_0 q$, $w_0=\frac{\varepsilon_{1A}^2}{2(2\pi\hbar)^3\hbar\rho s}$ and $\nu_{pp}(q)=\nu_{pp0}q^2$,

where $\nu_{pp0}=\frac{T^3 s}{a_c T_D^4 M_c}$, $\hbar\Omega(q)=sq$, ε_{1A} is a constant of deformation potential, T is the temperature of lattice, T_D is the Debye temperature, a_c is the lattice spacing, M_c is total weight of two atoms, s is the sound

speed, ρ is the substance density.

As a result of a concretization we shall obtain

$$I_{ep}\{f(\varepsilon)\}=\sqrt{\frac{2\pi^2 m}{\varepsilon}}\frac{\partial}{\partial\varepsilon}\{\frac{\partial f}{\partial\varepsilon}w_0 s^2\int_0^{\sqrt{8m\varepsilon}}dqq^4\left[N(q)+\frac{1}{2}\right]+$$

$$\left[f(\varepsilon)(1-f(\varepsilon))\right]w_0 s\int_0^{\sqrt{8m\varepsilon}}dqq^3\}, \quad (7)$$

$$I_{pe}\{N(q)\}=2\pi m^2 w_0\int_{q^2/8m}^{\infty}d\varepsilon\{\left[f(\varepsilon)(1-f(\varepsilon))\right]+[N(q)+1-$$

$$-f(\varepsilon)]\left[sq\frac{\partial f(\varepsilon)}{\partial\varepsilon}+\frac{(sq)^2}{2}\frac{\partial^2 f(\varepsilon)}{\partial\varepsilon^2}\right]\}, \quad (8)$$

$$I_{pp}=-\nu_{pp0}q\left[N(\vec{q})-N_T(\vec{q})\right], \quad (9)$$

$$I_{ed}\left\{\vec{f}_1(\varepsilon)\frac{\vec{p}}{p}\right\}=-\nu_{ed}\vec{f}_1(\varepsilon)\frac{\vec{p}}{p}, \quad (10)$$

$$I_{ep}\left\{\vec{f}_1(\varepsilon)\frac{\vec{p}}{p}\right\}=-\nu(\varepsilon)\vec{f}_1\frac{\vec{p}}{p}, \quad (11)$$

where $\nu(\varepsilon)=\frac{\pi w_0}{\sqrt{m\varepsilon^3}}\int_0^{\sqrt{8m\varepsilon}}dqq^3\left[N(q)+\frac{1}{2}\right]$, ν_{ed} is the frequency of collisions of electrons with impurities and lattice defects which in the case considered (low temperatures) determine the isotropization of the electron distribution function

$$\frac{\partial\vec{f}_1}{\partial t}\frac{\vec{p}}{p}-e\vec{E}\upsilon\frac{\partial f(\varepsilon)}{\partial\varepsilon}\frac{\vec{p}}{p}=-\nu_{ed}\vec{f}_1(\varepsilon)\frac{\vec{p}}{p}. \quad (12)$$

Considering the anisotropic additive to electron distribution function $\vec{f}_1$ as stationary and neglecting spatial dispersion we obtain final system of two equations for isotropic distribution functions of electrons $f(\varepsilon)$ and acoustic phonons $N(q)$ which is to be solved:

$$\frac{\partial f}{\partial t}-\frac{2e^2}{3m\nu_{ed}}E^2\cdot\frac{1}{\varepsilon^{1/2}}\frac{\partial}{\partial\varepsilon}\left[\varepsilon^{3/2}\frac{\partial f}{\partial\varepsilon}\right]=$$

$$=\sqrt{\frac{2\pi^2 m}{\varepsilon}}\frac{\partial}{\partial\varepsilon}\{\frac{\partial f}{\partial\varepsilon}w_0 s^2\int_0^{\sqrt{8m\varepsilon}}dqq^4\left[N(q)+\frac{1}{2}\right]+$$

$$+\left[f(\varepsilon)(1-f(\varepsilon))\right]w_0 s\int_0^{\sqrt{8m\varepsilon}}dqq^3\}+I_{ee},$$

$$\frac{\partial N(q)}{\partial t}=I_{pp}+I_{pd}+w_0 2\pi m^2\int_{q^2/8m}^{\infty}d\varepsilon\{f(\varepsilon)(1-f(\varepsilon))+$$

$$+\left[N(q)+1-f(\varepsilon)\right]\left[sq\frac{\partial f(\varepsilon)}{\partial\varepsilon}+\frac{(sq)^2}{2}\frac{\partial^2 f(\varepsilon)}{\partial\varepsilon^2}\right]\}. \quad (13)$$

Both electron $f(\varepsilon)$ and phonon $N(q)$ distribution functions are dimensionless values which satisfy such normalization conditions

$$\frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_0^{\infty}\varepsilon^{1/2}f(\varepsilon)d\varepsilon=n, \quad (14)$$

where n is the electron density in the valence band (for metals it is also the conduction band as it is filled only in part).

$$\frac{1}{2\pi^2}\left(\frac{1}{\hbar^3}\right)\int_0^{q_D}q^2N(q)dq<\infty. \quad (15)$$

Where q_D is Debye phonon momentum which is determined from the equality

$$k_B T_D=sq_D,$$

where $k_B=1.38\cdot10^{-16}$ erg/K is the Boltzmann constant, s is the sound speed, T_D is the Debye temperature.

Particularly further all quantities are taken for nickel (for which it is possible to compare calculations with the experimental results [4] s =5 10^5 cm/s, T_D = =375 K, whence the maximal phonon momentum will be 10^{19} g cm/s, the electron density in the valence band n =2.5·10^{22} cm^{-3}, the density of nickel $\rho=8.9$ g cm^{-3}, the lattice spacing (distance between the neighbouring atoms) $a=2.5\cdot10^{-8}$ cm.

In the state of thermodynamic equilibrium the electron distribution function $f(\varepsilon)$ is the Fermi-Dirac function

$$f(\varepsilon)=\left[\exp\left(\frac{\varepsilon-\varepsilon_F}{k_B T_e}\right)+1\right]^{-1}, \quad (16)$$

where ε_F =5 10^{-12} erg, T_e is the temperature of electron component (in experiments it was equal to 20 and 80 K) and initially was equal to lattice (phonon) temperature (before applying of the electric field E =0.08 CGSE (24 V/cm)). By the residual resistance of nickel ρ_{cur} =1.25·10^{-6} Ohm cm, we find the frequency of electron collisions with impurity and lattice defects ν_{ed} =7.5·10^{12} s^{-1}. For convenience of the further research and numerical modelling of the system of equations for electron and phonon distribution functions (13) we shall introduce dimensionless variables: momenta of electrons and phonons divided by $(2mk_B T_e)^{1/2}$, thus energies of electrons ε and phonons $\varepsilon_{ph}=sq$ will be divided by $k_B T_e$, time we shall measure in characteristic times of electron-phonon impacts $\tau_{ep0}=\frac{(2\pi\hbar)^3\hbar\rho}{\pi m^3 s\varepsilon_{1A}^2}=10^{-7}$ s. Then the system of equations becomes:

$$\frac{\partial f}{\partial\widetilde{t}}-\Delta\widetilde{\varepsilon}\cdot\frac{4}{\widetilde{\varepsilon}^{1/2}}\frac{\partial}{\partial\widetilde{\varepsilon}}\left[\widetilde{\varepsilon}^{3/2}\frac{\partial f}{\partial\widetilde{\varepsilon}}\right]=\frac{\beta\partial}{\widetilde{\varepsilon}^{1/2}\partial\widetilde{\varepsilon}}\{\frac{\partial f}{\partial\widetilde{\varepsilon}}\int_0^{4\sqrt{\alpha\widetilde{\varepsilon}}}d\widetilde{\varepsilon}_{ph}\widetilde{\varepsilon}_{ph}^4\times$$

$$\left[N(\widetilde{\varepsilon}_{ph})+\frac{1}{2}\right]+\left[f(\widetilde{\varepsilon})(1-f(\widetilde{\varepsilon}))\right]2\sqrt{\alpha}\int_0^{4\sqrt{\alpha\widetilde{\varepsilon}}}d\widetilde{\varepsilon}_{ph}\widetilde{\varepsilon}_{ph}^3\}, \quad (17)$$

$$\frac{\partial N(\widetilde{\varepsilon}_{ph})}{\partial\widetilde{t}}=\gamma\int_{\frac{\widetilde{\varepsilon}_{ph}^2}{16\alpha}}^{\infty}d\widetilde{\varepsilon}\{\left[f(\widetilde{\varepsilon})(1-f(\widetilde{\varepsilon}))\right]+[N(\widetilde{\varepsilon}_{ph})+$$

$$+1-f(\widetilde{\varepsilon})]\left[2\alpha^{1/2}\widetilde{\varepsilon}_{ph}\frac{\partial f(\widetilde{\varepsilon})}{\partial\widetilde{\varepsilon}}+\widetilde{\varepsilon}_{ph}^2\frac{\partial^2 f(\widetilde{\varepsilon})}{\partial\widetilde{\varepsilon}^2}\right]\} \quad (18)$$

where $\widetilde{t}=\frac{t}{\tau_{ep0}}$, $\widetilde{\varepsilon}=\frac{\varepsilon}{k_B T_e}=\frac{p^2}{2mk_B T_e}$, $\widetilde{p}=\frac{p}{\sqrt{2mk_B T_e}}$,

$\widetilde{q}=\frac{q}{\sqrt{2mk_B T_e}}$, $\alpha=\frac{ms^2}{2k_B T_e}$, $\Delta\widetilde{\varepsilon}=\frac{e^2E^2\tau_{ep0}}{6m\nu_{ed}k_B T_e}$,

$\beta^{-1}=8\cdot(\alpha)^{5/2}$, $\widetilde{\varepsilon}_{ph}=\frac{sq}{k_B T_e}$, $\gamma^{-1}=2\alpha$.

Let's copy system of the equations (17)-(18) with integration over momenta

$$\frac{\partial f(\tilde{p})}{\partial \tilde{t}} - \Delta\tilde{\varepsilon}\frac{1}{\tilde{p}^2}\frac{\partial}{\partial \tilde{p}}\left[\tilde{p}^2\frac{\partial f(\tilde{p})}{\partial \tilde{p}}\right] = \frac{1}{\tilde{p}^2}\frac{\partial}{\partial \tilde{p}}\{\frac{\partial f(\tilde{p})}{\tilde{p}\partial\tilde{p}}\int_0^{2\tilde{p}} d\tilde{q}\tilde{q}^2 \times$$

$$\times\left[N(\tilde{q})+\frac{1}{2}\right]+\left[f(\tilde{p})(1-f(\tilde{p}))\right]\frac{1}{\sqrt{\alpha}}\int_0^{2\tilde{p}} d\tilde{q}\tilde{q}^3\}, \qquad (19)$$

$$\frac{\partial N(\tilde{q})}{\partial \tilde{t}} = \int_{\tilde{q}/2}^{\infty} d\tilde{p}\tilde{p}\{\frac{1}{\alpha}\left[f(\tilde{p})(1-f(\tilde{p}))\right]+[N(\tilde{q})+1-$$

$$-f(\tilde{p})]\left[\frac{1}{\sqrt{\alpha}}\tilde{q}\frac{\partial f(\tilde{p})}{\tilde{p}\partial\tilde{p}}+\tilde{q}^2\frac{\partial}{2\tilde{p}\partial\tilde{p}}\frac{\partial f(\tilde{p})}{\tilde{p}\partial\tilde{p}}\right]\}, \qquad (20)$$

where $0 < 2\tilde{p} \le 85$, $\Delta\tilde{\varepsilon} = 0.3$, $0 < \tilde{\varepsilon} \le 1800$, $0 < \tilde{\varepsilon}_{ph} \le 18$, $0 < \tilde{q} \le \tilde{q}_D = 42.5$, $\alpha = 0.045$.

Integration of the resulted system of equations was carried out with the help of completely conservative difference schemes. Conservatism of the scheme is the obligatory requirement as it provides absence of accumulation of mistakes in calculations on long time intervals (see, for example, [5]). It is essential to satisfy several conversation laws. In this case the satisfaction of energy and particles conversation laws if needed.

2. RESULTS OF NUMERICAL MODELING AND THEIR DISCUSSION

As a result of the numerical calculations carried out non-stationary distribution functions of electrons $f(\tilde{p})$ and phonons $N(\tilde{q})$ of momenta have been found. On fig. 1 the dependence of distribution function of electrons on the dimensionless momentum in various time moments is shown. The leftmost curve corresponds to a thermodynamically equilibrium distribution function (16) which is taken as initial at the solution of equation system (19), (20).

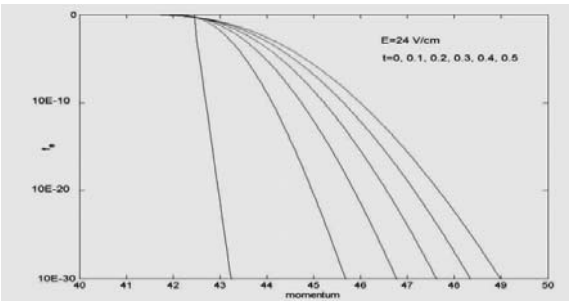

*Fig. 1. Dependence of electron distribution function f in various moments of time (*t=0; 0.1; 0.2; 0.3; 0.4) *on the dimensionless momentum, curves are located from the left – to the right accordingly*

One can see from Fig. 1 (curves with increase of time interval displace from the left – to the right) that in time the electron distribution function differs from thermodynamically equilibrium more significantly getting high-energy "tail".

Thus it is established that energy received from external electric field as a result of electron-phonon collisions partially (a small part because of quasielastic electron-phonon collisions) is transferred from the electron subsystem to the phonon subsystem and most part it is being spent not on establishment of thermodynamically equilibrium electron distribution function (as it is frequently supposed (see [1 - 4])) but on formation of intensive high-energy "tails" of the electron distribution function.

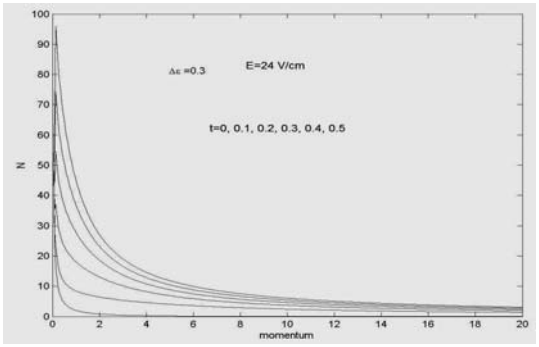

Fig. 2. Dependence of the phonon distribution function in various dimensionless time moments (t =0; 0.1; 0.2; 0.3; 0.4; 0.5) on the dimensionless momentum for the electric field E=24 V/cm. Curves are located from below - upwards accordingly

Such cardinal change of the electron distribution function results in formation of phonon distribution function that is very strongly enriched by phonons with the energy close to the Debye energy (see, Fig. 2 and Fig. 3) in contrast to work [4] in which the phonon distribution function in this area of momentum practically corresponds to Bose-Einstein function but with the temperature corresponding to temperature of the electron subsystem.

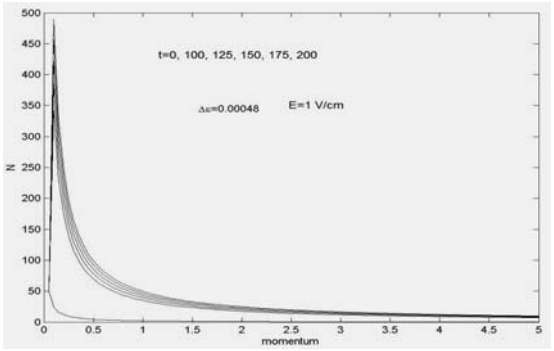

Fig. 3. Dependence of phonon distribution functions in various dimensionless time moments (t =0; 10; 15) on the dimensionless momentum for small intensity of electric field E=1 V/cm. Curves are located from below - upwards accordingly

As if has been shown by our numerical modelling the "temperature" (to speak more precisely average electron energy because the obtained electron distribution function strongly differs from thermodynamically equilibrium) electron distribution function changes insignificantly, i.e. thermalization of the energy received from electric field does not occur but high-energy "tails" which lead to such cardinal to change of phonon distribution functions are formed.

Further we shall carry out comparison of dependences of the product of phonon distribution functions on the dimensionless momentum cubed for thermodynamically equilibrium situation (Bose-Einstein's function (at the moment of time *t*=0) Fig. 4) and phonon distribution functions in various time moments after the beginning of the electric field action (Fig. 5)

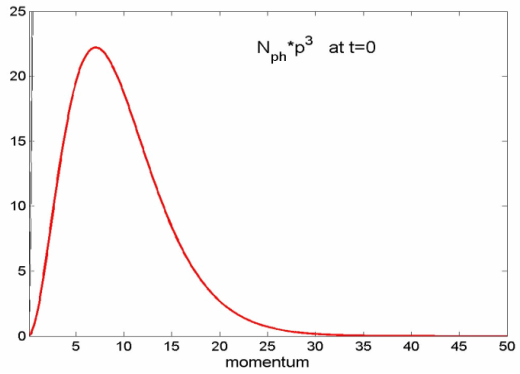

Fig. 4. Dependence of the product the thermodynamically equilibrium phonon distribution function (Bose-Einstein's functions (at the dimensionless time moment t =0)) on cube of the dimensionless momentum vs the dimensionless momentum

Apparently from Fig. 5 the phonon distribution functions in due course have more and more powerful high energy "tails" as at electron-phonon impacts the momentum is transferred by enough small transfer of energy; much phonons with Debye energy is born i.e. phonon DF is enriched by the Debye phonons.

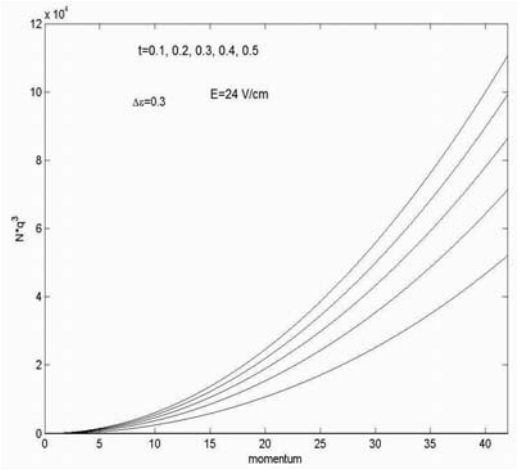

Fig. 5. Dependence of the product of the phonon distribution function (in the dimensionless time moments t =0.1; 0.2; 0.3; 0.4) on cube of the momentum vs the dimensionless momentum. Curves are located from below - upwards accordingly

As $\tau_{ep}^{-1} = \frac{\pi m^3 s \varepsilon_{1A}^2}{(2\pi\hbar)^3 \hbar \rho} = 10^7 c^{-1}$, $\tau_{ep} = 10^{-7} c$ is electron-phonon interaction time on which the system of the connected equations for electron and phonon distribution functions are normalized.

The neglect during the calculation by electron-electron impacts will be fair on times on which the energy received by the electron subsystem from electric field would not exceed the initial energy. Therefore we shall find the time τ for which the energy received by unit of volume from electric field with intensity of $E = 24$ V/cm, will heat up sample with specific resistance ρ_{curr} =1.25·10^{-6} Ohm cm on $\Delta T = T_e$ =20 K, i.e. will double its reference temperature

$$\frac{E^2}{\rho_{curr}} \tau = c\rho \Delta T_e ,$$

$$\frac{\tau}{\tau_{ep}} = \frac{c\rho\rho_{curr}\Delta T}{E^2 \tau_{ep}} = \frac{25\cdot 10^{-3} 8.9 \cdot 1{,}25 \cdot 10^{-6} \cdot 20}{(24)^2 \cdot 1 \cdot 10^{-7}} = 0.1 .$$

The increase of energy received by unit of volume of a sample from electric field for this time will make

$$\frac{E^2}{\rho_{curr}} \tau = c\rho \Delta T_e = 4.5 \text{ J/cm}^3.$$

Full energy which will be contained in unit of volume of the sample by the moment τ, appears equal

$$c(40K)\rho 2T_e = 38\cdot 10^{-3} 8.9 \cdot 40 = 13.6 \text{ J/cm}^3.$$

Energy which is contained in unit of volume of the sample in its phonon subsystem we find from expression

$$\frac{4\pi s}{(2\pi\hbar)^3} (2mk_B T_e)^2 \int_0^{\tilde{q}_D} \tilde{q}^3 d\tilde{q} N(\tilde{q}) = 6\cdot 10^2 \int_0^{\tilde{q}_D} \tilde{q}^3 d\tilde{q} N(\tilde{q}) =$$

$$= 18\cdot 10^7 \text{ erg/cm}^3 = 18 \text{ J/cm}^3.$$

The integral is found from the schedule rice 5 for the moment of time 0.1.

In papers [6, 7] a detailed analysis of influence of such abnormal behaviour is carried out by study of electron-phonon systems in a strong electric field on behaviour of samples under mechanical load that allows to explain abnormal electro-plastic properties of metals and semiconductors observable in experimental researches.

CONCLUSIONS

Formation of non-stationary non equilibrium distribution functions of electrons and phonons is investigated at action on metal of a strong pulse electric field. For concreteness parameters are taken for nickel having reference temperature of 20 K. It is shown: isotropization of electron DF occurs as a result of impacts with imperfections of lattice; •electron DF does not become thermodynamically equilibrium as electron-electron impacts in the given situation give essentially smaller contribution than electron-phonon collisions and collisions with "another's" subsystem do not result in thermalization; •Distribution functions of electrons and phonons have high energy "tails" as in electron-phonon impacts the momentum is transferred at enough small transfer of energy; much phonons with Debye energy are born i.e. phonon DF is enriched by Debye phonons.

Such behaviour of electron-phonon system in strong electric field allows to explain abnormal electro-plastic properties of metals and semiconductors observable in experimental researches (in more detail see [6, 7]).

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КИНЕТИКА НЕРАВНОВЕСНОЙ ЭЛЕКТРОН-ФОНОННОЙ СИСТЕМЫ ДЛЯ ПОЛУПРОВОДНИКОВ И МЕТАЛЛОВ В СИЛЬНОМ ЭЛЕКТРИЧЕСКОМ ПОЛЕ

В.И. Карась, И.Ф. Потапенко, А.М. Власенко

Исследовано формирование нестационарных неравновесных функций распределения (ФР) электронов и фононов под действием сильного импульсного электрического поля на металл. Для конкретности были взяты параметры для никеля, имеющего начальную температуру 20 K. Показано, что: •изотропизация электронной ФР обусловлена столкновениями с дефектами решетки; •электронная ФР не становится термодинамически равновесной, так как электрон-электронные столкновения в данной ситуации дают существенно меньший вклад, чем электрон-фононные соударения, а столкновения с «другой» подсистемой не приводят к термализации; •ФР электронов и фононов имеют высокоэнергетичные «хвосты», так как в электрон-фононных столкновениях передается импульс с достаточно малой передачей энергии; •рождается много фононов с дебаевской энергией, т.е. фононная ФР обогащена дебаевскими фононами.

КІНЕТИКА НЕРІВНОВАЖНОЇ ЕЛЕКТРОН-ФОНОННОЇ СИСТЕМИ ДЛЯ НАПІВПРОВІДНИКІВ І МЕТАЛІВ У СИЛЬНОМУ ЕЛЕКТРИЧНОМУ ПОЛІ

В.І. Карась, І.Ф. Потапенко, А.М. Власенко

Досліджено формування нестаціонарних нерівноважних функцій розподілу (ФР) електронів та фононів під дією сильного імпульсного електричного поля на метал. Для конкретності були взяті параметри для нікелю, що має спочатку температуру 20 K. Показано, що: •ізотропізація електронної ФР обумовлена зіткненнями з дефектами решітки; •електронна ФР не стає термодинамічно рівноважною, тому що електрон-електронні зіткнення в такій ситуації дають суттєво менший внесок, ніж електрон-фононні зіткнення, а зіткнення з «іншою» підсистемою не приводять до термалізації; •ФР електронів та фононів мають високоенергетичні «хвости», тому що в електрон-фононних зіткненнях передається імпульс з досить малою передачею енергії; •народжується багато фононів з дебаєвською енергією, тобто фононна ФР збагачена дебаєвськими фононами.