

Russian Academy of Sciences
Joint Institute for High Temperatures RAS
Institute of Problems of Chemical Physics RAS
Kabardino-Balkarian State University

Physics of Extreme States of Matter — 2013

Moscow, 2013

Physics of Extreme States of Matter — 2013

Edited by academician Fortov V. E., Karamurзов B. S., Efremov V. P., Khishchenko K. V., Sultanov V. G., Levashov P. R., Andreev N. E., Kanel G. I., Iosilevskiy I. L., Milyavskiy V. V., Mintsev V. B., Petrov O. F., Savintsev A. P., Shpatakovskaya G. V.

This compendium is devoted to investigations in the fields of physics of high energy densities and thermal physics of extreme states of matter. Interaction of intense laser, x-ray and microwave radiation, powerful particle beams with matter, techniques of intense energy fluxes generation, experimental methods of diagnostics of ultra-fast processes, physics of shock and detonation waves, different models and results of theoretical calculations of equations of state for materials at high pressures and temperatures, low-temperature plasma physics, issues of physics and power engineering, as well as technology projects are considered. The majority of the works has been presented at the XXVIII International Conference on Interaction of Intense Energy Fluxes with Matter (March 1–6, 2013, Elbrus, Kabardino-Balkaria, Russia). The edition is intended for specialists in physical and technical problems of power engineering.

ISBN 978-5-94691-533-5

© Joint Institute for High Temperatures of the Russian Academy of Sciences,
Moscow, 2013

CONTENTS

CHAPTER 1. POWER INTERACTION WITH MATTER

<i>Abrosimov S.A., Bazhulin A.P., Voronov V.V., Krasnyuk I.K., Pashinin P.P., Semenov A.Yu., Stuchebryukhov I.A., Khishchenko K.V.</i> New experimental data on spallation phenomena of matter in a region of negative pressures created by means of 70-picosecond laser pulse	6
<i>Krasnyuk I.K., Pashinin P.P., Semenov A.Yu., Stuchebryukhov I.A., Khishchenko K.V.</i> Application of a laser interferometer and applicability of an acoustic approach in studying shock-wave spallation phenomena	9
<i>Aliverdiev A.A., Amirova A.A., Batani D., Dezulian R., Khan M., Pant H.C.</i> About intense laser driven shock propagation in structured target	12
<i>Charakhch'yan A.A., Gryn' V.I., Khishchenko K.V.</i> Plane thermonuclear burn waves interacting with rigid wall	14
<i>Veysman M.E., Andreev N.E., Cros B.</i> Laser and wakefield dynamics in capillary waveguides under nonsymmetrical coupling conditions	18
<i>Baranov V.E., Andreev N.E., Mora P.</i> Modelling of the laser wakefield electron acceleration to multi-GeV energies	21
<i>Orlov N.Yu., Denisov O.B., Vergunova G.A., Rosmej O.N.</i> Theoretical and experimental studies of radiative and gas dynamic properties of substances at intense interaction of energy fluxes with matter	23
<i>Kostenko O.F., Andreev N.E., Chefonov O.V., Ovchinnikov A.V., Rosmej O.N., Schoenlein A., Wiechula J.</i> Characteristic X-rays generation in silver foils by relativistic laser-produced hot electrons	26
<i>Kostenko O.F., Ovchinnikov A.V., Chefonov O.V., Romashevskiy S.A., Andreev N.E., Agranat M.B.</i> Investigation of characteristic X-rays and hot electron temperature in the interaction of s-polarized femtosecond laser pulses with nanostructured foils	27
<i>Timofeev I.S., Burdonsky I.N., Golsov A.Y., Makarov K.N., Leonov A.G., Yufa V.N.</i> The interaction of high-power laser emission with multicomponent polycrystalline rocks	31
<i>Petrov Y.V., Inogamov N.A., Migdal K.P.</i> Kinetic coefficients of metals ablated under the action of femtosecond laser pulses	33
<i>Savintsev A.P., Gavasheli Yu.O.</i> Radiation resistance of sodium chloride for short laser pulses	36
<i>Gavasheli D.Sh., Savintsev A.P., Gavasheli Yu.O.</i> Modeling of laser destruction of disordered porous media	37
<i>Semenok D.V.</i> Oxidative catalysis in the laser-induced deposition of copper	39
<i>Gatskevich E.I., Ivlev G.D., Prakopyev S.L., Zaikov V.A., Gaiduk P.I.</i> Simulation of laser-induced phase transformations in heterostructures with SiGe layer	43
<i>Ivlev G.D., Gatskevich E.I., Malevich V.L., Malashkevich G.E., Shimko A.N., Freik D.M., Nykyruy L.I., Yavorski Ya.S.</i> Reflectivity dynamics of PbTe irradiated by nanosecond laser pulses	46
<i>Mkrtychev O.V., Shemanin V.G.</i> Moment method in laser ablation thermal model	47
<i>Efremov V.P., Frolov A.A., Dianov E.M., Bufetov I.A., Fortov V.E.</i> Observation of detonation regime of laser induced damage in silica-based optical fibers	49
<i>Assovskiy I.G., Kozynda V.V., Tur I.V.</i> On interaction of short laser pulse with a heterogeneous energetic material	52
<i>Bykov Y.A., Smirnov V.P., Grabovsky E.V., Gribov A.N., Oleinik G.M.</i> The development of mobile testing facility based on voltage impulse generator for tasks solution related to lightning protection	53
<i>Mayer P.N., Mayer A.E.</i> Instability and fragmentation of ablated layer at high-current electron beam irradiation of metals	55

CHAPTER 2. SHOCK WAVES. DETONATION. COMBUSTION

<i>Zubareva A.N., Kolesnikov S.A., Utkin A.V.</i> Experimental investigation of structure of compression wave in cerium at pressures up to 6 GPa	59
<i>Khokhlov V.A., Inogamov N.A., Zhakhovskiy V.V., Anisimov S.I.</i> Elastic-plastic phenomena in shock waves caused by short laser pulses. Comparison of hydrodynamic and molecular dynamics simulations	61
<i>Bayandin Yu.V., Savelieva N.V., Savinykh A.S., Naimark O.B.</i> Numerical simulation of shock wave loading of metals and ceramic	64
<i>Mayer A.E., Borodin E.N., Mayer P.N.</i> Numerical simulation of plastic flow localization in metals at high strain rate simple shear and at shock compression	66
<i>Borodin E.N., Mayer A.E.</i> Abnormal Hall-Petch relation in ultrafine grained copper and aluminum at extremely high strain rates	69
<i>Spitsin D.D., Zikova T.S., Vorobiev A.A., Komarov I.S., Chichaeva O.V., Trunilin I.B.</i> Development of two-stage electro-thermal way to accelerate solid bodies	72

<i>Khamzin T.I., Lenkevich D.A., Bivol G.Y., Kotelnikov A.L., Bazhenova T.V., Mirova O.A.</i> Effect of the cavity behind the destroyed barrier to weaken the shock wave	74
<i>Ten K.A., Prueel E.R., Lukyanchikov L.A., Tolochko B.P., Shmakov A.N., Zhulanov V.V., Shehtman L.I., Aminov Yu.A., Muzyrya A.K., Kostitsyn O.V., Smirnov E.B.</i> Diffraction studies of TATB	76
<i>Badretdinova L.Kh., Ten K.A., Prueel E.R., Lukyanchikov L.A., Tolochko B.P., Sharafutdinov M.R., Shmakov A.N., Muzyrya A.K., Kostitsyn O.V., Smirnov E.B., Kuper K.E.</i> Structure of condensed heterogeneous explosives	79
<i>Yankovskiy B.D., Milyavskiy V.V., Anan'ev S.Yu.</i> About applicability limits of empirical ratios for a velocity of nonideal detonation of RDX	84
<i>Soloviev A.M., Yankovskiy B.D., Milyavskiy V.V., Deribas A.A., Valuev A.V., Drozdov A.A., Morozov A.E.</i> Explosive compaction of the mixture of Ni-Al powders in cylindrical ampoules	87
<i>Ivanov M.F., Kiverin A.D.</i> Mechanism of hydrodynamical perturbations evolution in the flow under the moving piston	90
<i>Kiverin A.D., Ivanov M.F., Liberman M.A.</i> Mechanisms of chemical reaction wave ignition by transient energy source	94
<i>Ivanov M.F., Kiverin A.D., Liberman M.A., Yakovenko I.S.</i> Role of spatial factor on flame acceleration and deflagration-to-detonation transition in rectangular channel	98
<i>Ivanov M.F., Kiverin A.D., Smygalina A.E., Zaichenko V.M.</i> Combustion regimes of hydrogen-based mixtures in gas-fueled reciprocating engines	101
<i>Drakon A.V., Kiverin A.D.</i> Shock wave attenuation due to the endothermic decomposition of CCl ₄ admixture	104
<i>Doroshko M.V., Khramtsov P.P., Penyazkov O.G.</i> Investigation of boundary layer behind the shock wave front	106
<i>Gavrenkov S.A., Gvozdeva L.G.</i> On various types of reflection of shock waves as a function of the adiabatic indexes	109
<i>Golub V.V., [Baklanov D.I.], Ivanov K.V., Golovastov S.V., Kotelnikov A.L.</i> Prechamber influence on deflagration-to-detonation transition in channels of subcritical diameter	112
<i>Korobov A.E., Golovastov S.V., Gnatyuk J.I.</i> Investigation of influence of ejector on gas flow at pulse detonation engine	115
<i>Bocharnikov V.M., Golovastov S.V., Golub V.V.</i> On usage of gas detonation in thin tubes for needleless injections	118
<i>Krivokorytov M.S., Golub V.V., Volodin V.V.</i> The bifurcation phenomenon of gas micro jet under acoustic influence	120
<i>Golovastov S.V., Bocharnikov V.M., Mikushkin A.Yu.</i> Influence of methane additives on diffusive self-ignition of hydrogen	121
<i>Konyukhov A.V., Likhachev A.P.</i> Ambiguous representation and splitting of relativistic shock waves	123
<i>Konyukhov A.V.</i> On shocks in the high energy relativistic jets: numerical simulation	126

CHAPTER 3. EQUATIONS OF STATE FOR MATTER

<i>Shpatakovskaya G.V.</i> Shell effects in free ions characters	130
<i>Filinov V.S., Ivanov Yu.B., Bonitz M., Fortov V.E., Levashov P.R.</i> Kinetic properties of quark-gluon plasma by Wigner dynamics	132
<i>Iosilevskiy I.L.</i> Enthalpic and entropic phase transitions in high energy density nuclear matter	136
<i>Borovikov D.S., Iosilevskiy I.L.</i> Binodal layer in isentropically expanding slab target with van der Waals equation of state	140
<i>Zilevich A.I., Iosilevskiy I.L.</i> Validity of semiempirical rules for gas-liquid phase boundaries in simplified Coulomb models and real compounds	144
<i>Khomkin A.L., Shumikhin A.S.</i> Equations of state, composition, conductivity of dense vapors plasmas of various metals	147
<i>Mamchuev M.O.</i> Equation of state of rare-gas crystals	150
<i>Vorontsov A.G., Kuts D.A.</i> State of liquid at high temperatures	151
<i>Nakhushev A.M., Nakhusheva V.A.</i> On an algorithm for calculating the concentration distribution of absorbing molecules along the laser beam	154
<i>Rusin S.P.</i> Temperature determination of opaque heated body via spectral maximum of thermal radiation	157
<i>Khattatov T.A., Tkachenko S.I., Romanova V.M., Mingaleev A.R., Shelkovenko T.A., Pikuz S.A.</i> Nanosecond explosion of tungsten wire in open air	159

CHAPTER 4. PHYSICS OF LOW TEMPERATURE PLASMA

<i>Mintsev V.B., Fortov V.E.</i> On quantum bound of shear viscosity of strongly coupled plasma	162
-----------------------------------------------------------------------------------------------------------	-----

<i>Zaporozhets Yu.B., Mintsev V.B., Gryaznov V.K., Fortov V.E., Reinholz H., Röpke G.</i> S- and p-polarized reflectivities of strongly correlated dense xenon plasma	163
<i>Bystryi R.G., Morozov I.V.</i> Study of electron dynamics in ionized nanosized metallic clusters	165
<i>Derbenev I.N., Filippov A.V.</i> Screening of dust particle charge in nonequilibrium plasmas within the ambipolar approach	168
<i>Chernukha O.A., Chepelev V.M., Petrov O.F.</i> Electron beam dusty plasma and super high charging particles	171
<i>Filippov A.V., Pal A.F., Ryabinkin A.O., Serov A.O.</i> Growth of particles from sputtered metal in an RF magnetron discharge-plasma trap	175
<i>Antipov S.N., Vasiliev M.M., Petrov O.F.</i> Self-oscillations, crystallization and diffusion in cryogenic dusty plasma experiments	179
<i>Zobnin A., Usachev A., Petrov O., Fortov V., Pustyl'nik M., Thoma M., Fink M., Albrecht S., Deysenroth C., Rau C., Mitic S., Penka D., Morfill G.</i> An effect of dusty cloud on the discharge plasma glow	181
<i>Prudnikov P.I., Andryushin I.I., Zherebtsov V.A., Meshakin V.I., Rykov V.A., Vladimirov V.I., Deputatova L.V.</i> Possibilities of using electrodes of a various form for stabilization of dust plasma structures	182
<i>Andryushin I.I., Vladimirov V.I., Deputatova L.V., Zherebtsov V.A., Meshakin V.I., Prudnikov P.I., Rykov V.A.</i> Non-self-maintained discharge in inert gas for investigating of nuclear-induced dusty plasms	183
<i>Lapitskiy D.S.</i> Coulomb system of charged dust particles confinement by linear Paul trap	185
<i>Budnik A.P., Deputatova L.V., Fortov V.E., Sipachev A.V., Vladimirov V.I.</i> The theoretical model for the generation of laser radiation in neutron irradiated gas environments containing uranium nanoparticles	189
<i>Bogomaz A.A., Pinchuk M.E., Budin A.V., Leks A.G., Pozubenkov A.A., Rutberg Ph.G.</i> Investigation of oscillations in high-current discharges at superhigh pressure	193
<i>Egorov O.G.</i> Generator of powerful nanosecond pulses on the basis of an inductive storage of energy and dynamic two-stage DC interrupter	196
<i>Polushkin E.A., Kovalchuk A.V., Shapoval S.Yu.</i> ECR plasma in a pulsed mode	199
<i>Khramtsov P.P., Penyazkov O.G., Grishchenko V.M., Chernik M.Yu., Vasetskij V.A.</i> Shadowgraph photometric method application for electron density diagnostics in colliding counter-flows of compressed plasma	201
<i>Khramtsov P.P., Penyazkov O.G., Evmenchikov N.L., Grishchenko V.M., Chernik M.Yu.</i> Flash lamp for Toeppler photometric measurements based on a pulsed spark discharge in argon	204
<i>Klementyeva I.B., Teplyakov I.O., Guseva A.A.</i> Investigation of hydrodynamics and heat transfer in current-carrying fluids in electromagnetic fields	205
<i>Amirov R.Kh., Vorona N.A., Gavrikov A.V., Zhabin S.N., Lizyakin G.D., Polistchook V.P., Samoylov I.S., Smirnov V.P., Usmanov R.A., Yartsev I.M.</i> The stationary vacuum arc as plasma source for technology of ion separation	206
AUTHOR INDEX	209
ABBREVIATIONS	211

Conclusion. In connection with the problem of laser simulation of impact processes, we note that in our case, ablation pressure on the andesite target was $\sim 4 \cdot 10^6$ atm at $I \sim 10^{13}$ W/cm². A typical resulting pressure in case of micrometeorite impact (mass 10^{-13} g) is of the order of $E/[(4/3)\pi d_m^2] \sim \rho_m V^2$ [6]. It follows that these experiments could simulate a collision with velocities around 13 km/s.

1. Guskov S. Y., Borodzyuk S. *et al.* // Quantum Elec-

tronics. 2004. V. 34. No. 11. P. 989.

2. Kozłowski E. A. Mountain Encyclopedia M.: Soviet Encyclopedia, 1991 [in Russian].
3. Burdonsky I. N., Leonov A. G., Timofeev I. S. *et al.* // Investigated in Russia. 2012. V. 42. P. 574.
4. Mora P. // Phys. Fluids. 1982. V. 25. P. 1051.
5. Zel'dovich B., Raiser Y. P. // Physics of shock waves and high-temperature hydrodynamic phenomena. M.: Science, 1968 [in Russian].
6. Stanyukovich K. P. // Unsteady motion of a continuous medium. M.: Science, 1971 [in Russian].

KINETIC COEFFICIENTS OF METALS ABLATED UNDER THE ACTION OF FEMTOSECOND LASER PULSES

*Petrov Y. V.,^{*1} Inogamov N. A.,¹ Migdal K. P.²*

¹ITP RAS, Chernogolovka, ²VNIIA, Moscow, Russia

^{*}uvp49@mail.ru

Kinetic coefficients of metals in two-temperature state arising under the action of femtosecond laser pulses are calculated in dependence on electron temperature. Among metals, used as targets for the investigation of their ablation under the action of laser irradiation, simple, with s- and p-electrons, as well as noble and transition metals with laser-excited d-electrons are considered.

Keywords: femtosecond laser ablation, kinetic coefficients

Introduction. Dynamics of ablation of metals under the action of ultrashort laser pulses essentially depends upon their transport properties such as electron thermal conductivity and energy exchange between electrons and ions. At the early stage of laser pulse-metal target interaction the metal state can be characterized by electron and ion temperatures, which differ to a great extent from one another, and by the minor change of a target volume. Electron kinetic characteristics of a metal define the depth of the surface layer of a metal target heated by the laser pulse. This heated layer is produced by the electron heat propagation and heat transmission from electrons to ions resulting in the equalization of electron and ion temperatures. Because of its high temperature, target surface layer has a high pressure giving rise to the onset of ablation. We have calculated electron heat conductivity coefficient and electron-phonon coupling factor, governing the electron-ion energy relaxation. Among metals used as the targets, when laser ablation is investigated, we consider metals with different electron energy bands: simple metals with only s- and p- electrons excited under the action of laser irradiation and also rare and transition metals with laser-excited d-electrons.

Electron-ion scattering frequencies. According to the two-temperature approach, we suggest that phonons (in the Debye approximation) are described by their partition function in dependence of their momentum \mathbf{q} as $N(\mathbf{q}) = [e^{\hbar\omega_{\mathbf{q}}/k_B T_i} - 1]^{-1}$ with the ion temperature T_i different from the electron temperature T_e . Electron temperature T_e define Fermi partition function of s-, p- electrons (commonly called by s-electrons) and d-electrons with the dispersion laws

$$\varepsilon(\mathbf{p}) = \varepsilon_s + p^2/2m_s, \quad \varepsilon(\mathbf{p}') = \varepsilon_1 + p'^2/2m_d. \quad (1)$$

and effective masses m_s and m_d . d-electron energy lies within the d-band width $\varepsilon_1 \leq \varepsilon(\mathbf{p}') \leq \varepsilon_2$. Parabolic dispersion law for s- and d-electrons approximates

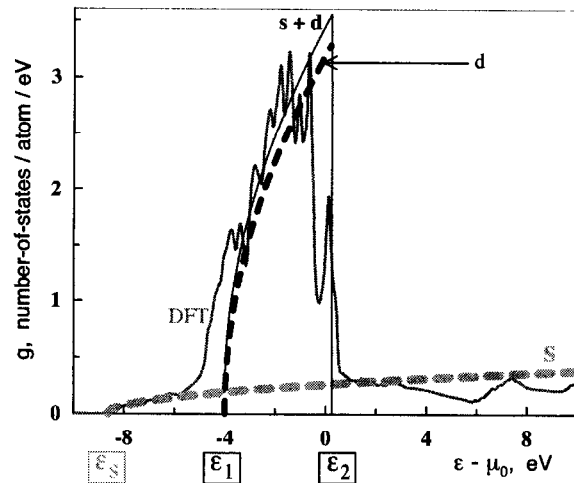


Figure 1. Ni density of state, obtained by the density functional method and parabolic approximation of the density of state of s- and d-electrons.

more real energy spectra and electron density of state which we obtained for metals under consideration by the density functional method [1]. Results of density functional theory application and parabolic approach for the density of state of Ni are presented in Fig.1.

Ion temperature T_i in our calculation lies within the interval from the Debye temperature θ to the temperature value T_* of the order of several melting temperature T_m . In single temperature (1T) case ($T_e = T_i = T$), when $\theta < T < T_*$, electron heat conductivity coefficient $\kappa_{1T} = \kappa(T)$ is defined by the electron-ion scattering (e-e collisions give negligible contribution under these conditions).

In Fig.2 experimental data on dependence of the resistivity of some noble and transition metals on the temperature in single temperature case is shown. These experimental data are obtained in modern mea-

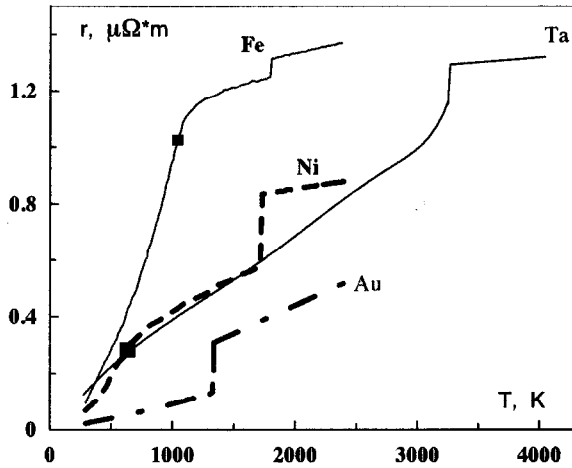


Figure 2. Dependence $r(T)$ of the resistivity of some noble and transition metals on the temperature in the single temperature case.

measurements of resistivity of thin wires, heated by the electric current pulse [2]. Experiments of this kind allows to reach the temperature values much more than the melting temperature. In solid state of pure metals above the Debye temperature resistivity r increases proportionally to T increase because of the phonon number growth. In magnetic metals (Ni, Fe in Fig. 2) linear rise of resistivity lasts up to Curie temperature (squares in Fig.2). For the iron this linear on T dependence takes place at large resistivity values, comparable with the limit metallic resistivity $r_{m,m} \sim m_e v_F / n_s e^2 a \sim \hbar a / e^2 \sim 1 \mu\Omega \cdot m$; here the collision frequency ν has its maximum value of the order of v_F / a , where v_F is the Fermi velocity, a is the lattice constant.

We take into account the change of the slope of $r(T)$ curves after the melting and their approach the maximum metallic values by writing the resistivity via its linear approximation $r_s = a + bT$ before melting and this limit metallic resistivity $r_{m,m}$ as the interpolation expression $r(T_i) = (r_s^{-2} + r_{m,m}^{-2})^{-1/2}$. The resistivity obtained by this means define the effective electron-ion collision frequency as a function of the ion temperature from the Drude relation:

$$\nu_{si} = \frac{n_s(T_e) e^2 r(T_i)}{m_s}. \quad (2)$$

Here $n_s(T_e)$ is the concentration of s-electrons, depending upon the electron temperature because of the excitation of d-electrons into the s-band.

s-s and s-d electron-electron scattering. Effective frequency of s-electron collisions with other electrons ν_{se} in metals with d-electrons can be written as $\nu_{se} = \nu_{ss} + \nu_{sd}$, with consequently s-s collision frequency ν_{ss} and s-d collision frequency ν_{sd} . Influence of s-s electron scattering onto the electron heat conductivity of simple metals was considered in [3]. Additional effective frequency of scattering of s-electrons on d-electrons is now calculated by the following manner. First we calculate the depending upon the s-electron momentum \mathbf{p} its collision frequency $\nu_{sd}(\mathbf{p})$. It can be

written as

$$\nu_{sd}(\mathbf{p}) = \frac{2\pi}{\hbar} \int \frac{u^2(q) d^3q}{(2\pi\hbar)^3} \int \frac{2d^3p'}{(2\pi\hbar)^3} S \delta. \quad (3)$$

Here s-electron having the momentum \mathbf{p} interacts with d-electron having the momentum \mathbf{p}' . \mathbf{q} is a transferred momentum. Function

$$\delta = \delta[\varepsilon(\mathbf{p}) + \varepsilon'(\mathbf{p}') - \varepsilon(\mathbf{p} + \mathbf{q}) - \varepsilon'(\mathbf{p}' - \mathbf{q})],$$

stands for the energy conservation. Statistical factor S in (3) has the form

$$S(\mathbf{p}, \mathbf{p}', \mathbf{q}) = f_d(\mathbf{p}') [1 - f_s(\mathbf{p} + \mathbf{q})] [1 - f_d(\mathbf{p}' - \mathbf{q})] + f_s(\mathbf{p} + \mathbf{q}) f_d(\mathbf{p}' - \mathbf{q}) [1 - f_d(\mathbf{p}')],$$

where f_s and f_d are Fermi distribution functions of s- and d-electrons with the chemical potential μ . Equation (3) includes a Fourier transform $u(q)$ of electron-electron screened Coulomb interaction $u(r) = e^2 \exp(-r/\lambda)/r$, where $\lambda(T_e)$ is the screening length in Thomas-Fermi approximation [4, 5]. Frequency $\nu_{sd}(\mathbf{p})$ obtained from (3) is then used to calculate the heat conduction coefficient $\kappa_{sd}(T_e)$, due to the s-d scattering. Within the τ -approach

$$\kappa_{sd} = \int (\varepsilon - \mu) (-f'_s) \left(\mu' + \frac{\varepsilon - \mu}{T_e} \right) \frac{v_s^2(p)}{\nu_{sd}(p)} \frac{p^2 dp}{3\pi^2 \hbar^3}, \quad (4)$$

where $f'_s = \partial f_s(\varepsilon) / \partial \varepsilon$, $\mu' = \partial \mu / \partial T_e$, $v_s(p)$ is the velocity of s-electron. Sixfold integration in (3) is reduced to double integration in $q = |\mathbf{q}|$, $p' = |\mathbf{p}'|$ - plane. Taking it into account, expression (4) can be written as a threefold integral over p' , q and p . Effective frequencies $\nu_{sd}(T_e)$ then can be defined as those to give the same value of the heat conductivity coefficient κ_{sd} from the Drude formula: $\nu_{sd} = C_s v_s^2 / 3\kappa_{sd}$. Analogously effective s-s collision frequency $\nu_{ss} = C_s v_s^2 / 3\kappa_{ss}$.

Effective s-electron collision frequencies $\nu_{se}(T_e) = \nu_{ss} + \nu_{sd}$ for some simple, noble and transition metals are presented in Fig. 3. As it can be seen, at electron temperatures T_e under consideration s-e contribution exceeds that one from s-i scattering only at ion temperatures T_i less than ~ 1 kK. Depending upon electron and ion temperatures electron heat conductivity coefficient $\kappa(T_e, T_i)$, taking into account s-i, s-s and s-d scattering, is shown in Fig. 4 for T_i to be a room temperature. Fig. 5 illustrates dependence on the electron temperature of the heat conductivity coefficient of nickel at different values of ion temperature T_i .

The rate of electron-ion heat transfer. The energy transferred from electrons to ions in the unit volume in the unit time can be written as [6]

$$\dot{E} = \int \hbar \omega_{\mathbf{q}} \dot{N}_{\mathbf{q}} V d\mathbf{q} / (2\pi\hbar)^3 = \alpha(T_e) (T_e - T_i). \quad (5)$$

Expression (5) defines the electron-phonon coupling factor α . The quantity

$$\dot{N}_{\mathbf{q}} = 2 \int \Phi W_{\mathbf{q}} \delta(\varepsilon_{\mathbf{p}-\mathbf{q}} + \hbar\omega_{\mathbf{q}} - \varepsilon_{\mathbf{p}}) d\mathbf{p} / (2\pi\hbar)^3$$

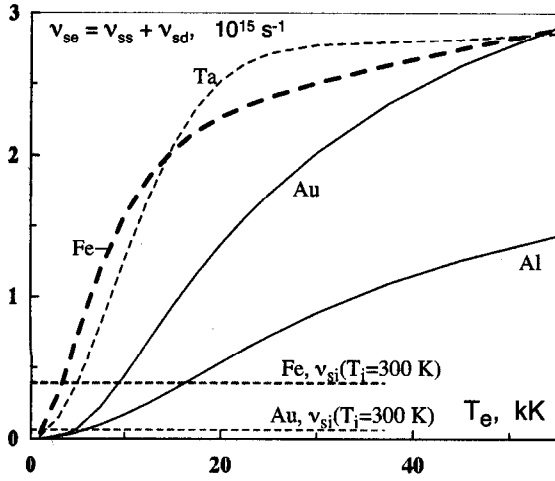


Figure 3. Effective collision frequency of s-electrons with other electrons in some simple, noble and transition metals. Horizontal lines stand for the electron-ion collision frequencies of Au and Fe at the ion temperature $T_i = 300$ K.

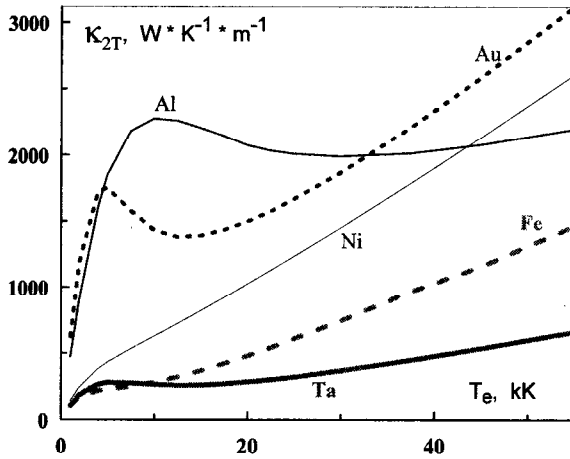


Figure 4. s-electron heat conductivity coefficient $\kappa(T_e, T_i)$ for simple (Al), noble (Au) and transition (Ni, Fe, Ta) metals. Ion temperature $T_i = 300$ K.

in equation (5) is a rate of change of longitudinal phonons with momentum \mathbf{q} and energy $\hbar\omega_{\mathbf{q}}$ concentration $N_{\mathbf{q}}(t)$.

$$\Phi = (1 - f_{\mathbf{p}-\mathbf{q}})f_{\mathbf{p}} + N(\mathbf{q})[(1 - f_{\mathbf{p}-\mathbf{q}})f_{\mathbf{p}} - (1 - f_{\mathbf{p}})f_{\mathbf{p}-\mathbf{q}}]$$

is the statistical factor with Fermi $f_{\mathbf{p}}$ and Bose $N(\mathbf{q})$ distribution functions. Phonon frequencies are taken in the Debye approach: $\omega_{\mathbf{q}} = c_s |\mathbf{q}|/\hbar$. Probability for the electron in the metal to change the momentum from \mathbf{p} to $\mathbf{p} - \mathbf{q}$ in a unit time under the interaction with longitudinal phonons is

$$W_{\mathbf{q}} \delta(\varepsilon_{\mathbf{p}-\mathbf{q}} + \hbar\omega_{\mathbf{q}} - \varepsilon_{\mathbf{p}})$$

with

$$W_{\mathbf{q}} = \pi\omega_{\mathbf{q}}/(\rho V c_s^2) \cdot n_{at}^2 U^2(\mathbf{q})$$

Here $U(\mathbf{q}) = 4\pi e^2 \hbar^2 Z_i / (q^2 \epsilon(\mathbf{q}))$, and $\epsilon(\mathbf{q})$ is the dielectric permeability in the Lindhard approach [4, 5],

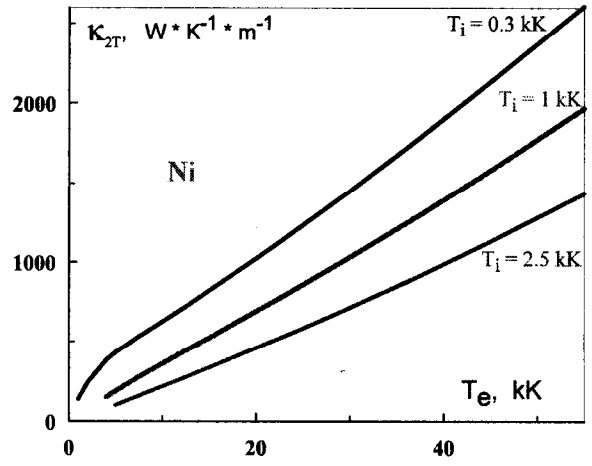


Figure 5. s-electron heat conductivity coefficient $\kappa(T_e, T_i)$ of nickel. Ion temperatures in kK above the curves correspond both to solid and liquid states.

Z_i is the effective charge of ion, n_{at} - concentration of atoms, ρ - mass density. Total electron-phonon coupling factor in (5) is a sum of separate s- and d-electron factors α_s and α_d : $\alpha = \alpha_s + \alpha_d$. For the case of α_s the effective ion charge $Z_i = n_s(T_e)/n_{at}$, and in α_d case $Z_i = Z_s(T_e) + Z_d(T_e) = \text{const}$. Electron-phonon coupling factor α_d can be written as

$$\alpha_d = \frac{m_d^2}{4\pi^3 \hbar^7} \frac{k_B^2 T_e}{\rho c_s} \times \int_0^{q_D} dq \cdot q^2 U^2(\mathbf{q}) \ln \frac{e_1 + e_2}{e_1 + 1} \Big|_{\varepsilon=a}^{\varepsilon=b}, \quad (6)$$

with

$$e_1 = \exp \frac{\varepsilon - \mu - \hbar\omega_{\mathbf{q}}}{k_B T_e}, \quad e_2 = \exp \left(-\frac{\hbar\omega_{\mathbf{q}}}{k_B T_e} \right),$$

$$a = \varepsilon_1 + \frac{1}{2m_d} \left(\frac{q}{2} + m_d c_s \right)^2, \quad b = \varepsilon_1 + \frac{p_d^2}{2m_d},$$

q_D is the Debye momentum. Electron-phonon coupling factor α_s is expressed by the formula, similar to (6). At temperatures exceeding the Debye temperature α depends only on the electron temperature but not the ion temperature. As a function of electron temperature it is shown in Fig. 6 for aluminum (simple metal) and gold (noble metal). Curves Au₁ and Au_{0.6} differ by the value of the effective mass of s-electrons (1 and 0.6 a.u. correspondently). Curve Au_{corr} is obtained by the multiplying Au_{0.6} by the factor reducing α to the experimental value [7-9] at the room temperature.

Analogously electron-phonon coupling factor for transition metals (nickel, iron and tantalum) as a function of electron temperature is presented in Fig. 7.

Fig. 6 demonstrates the significant increase of electron-phonon coupling factor with electron temperature growth in gold, similar to the results of the works [10, 11]. Of partial electron-phonon coupling factors α_s and α_d in this noble metal α_d dominantly contributes to the total α at electron temperatures greater than 5 kK.

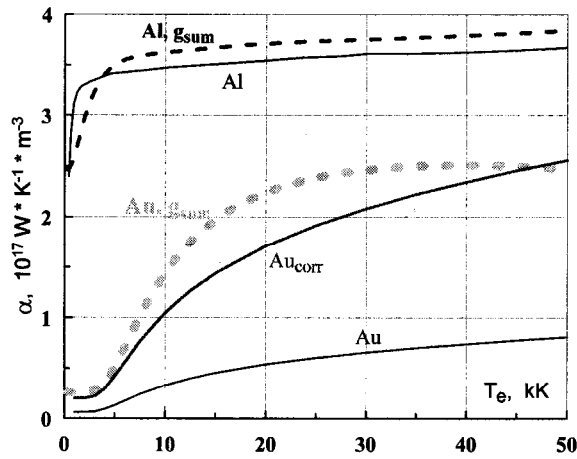


Figure 6. Electron-phonon coupling factor $\alpha(T_e)$ of Al and Au in dependence on the electron temperature. Comparison is made with the work [11] data (marked by g_{sum}).

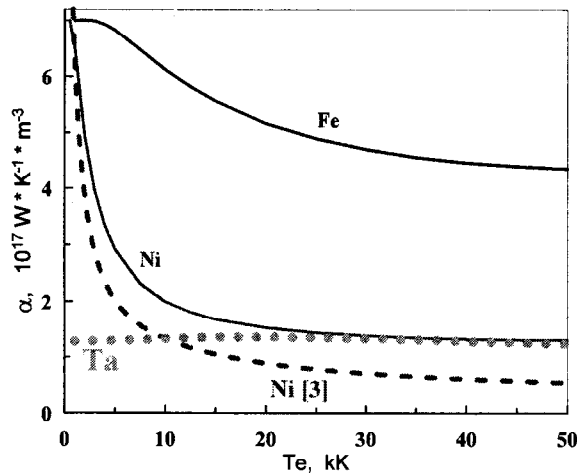


Figure 7. Electron-phonon coupling factor of transition metals (Ni, Fe and Ta) in dependence on the electron temperature. The curve Ni[3] is taken from the work[11].

In the case of transition metals α_d gives the main

RADIATION RESISTANCE OF SODIUM CHLORIDE FOR SHORT LASER PULSES

Savintsev A.P., Gavasheli Yu.O.*

KBSU, Nalchik, Russia

**pnr@kbsu.ru*

In this paper, drawing on the data calculated the radiation resistance of sodium chloride in the range of the laser pulse duration of 1 ps–50 fs. It was found that for $\tau = 200$ fs critical field strength in sodium chloride and other inorganic optically transparent material is practically the same.

Keywords: Radiation resistance, sodium chloride, laser pulse duration.

Radiation resistance of optically transparent solids numerically characterized radiation damage threshold (voltage breakdown): critical flux density of optical radiation, from which the volume or on the surface of irreversible changes occur as a result of anomalous absorption of the light flux.

For transparent solids is a certain dependence of the breakdown threshold and, consequently, the radiation

contribution into the full electron-phonon coupling factor at all electron temperatures T_e . Different transition metals differ with respect to the position of Fermi level within the d-band. Three typical cases can be observed: a) Fermi level is slightly (several percents of d-band width) lower than the upper edge of d-band; b) difference between Fermi level and the upper edge of d-band has the moderate value of the order of ten percents of d-band width; c) Fermi level is essentially lies within the d-band. Band structure of Ni belongs to the case a). Here we can see a drastic decrease of $\alpha(T_e)$ coefficient at $k_B T_e > \varepsilon_2$. In the case b) (it is presented by Fe) the $\alpha(T_e)$ decrease with electron temperature increase has a smooth fall character. And in the last case, when the Fermi level lies within the d-band (Ta), $\alpha(T_e)$ function is approximately constant.

Acknowledgments. The authors are grateful to RFBR grant 11-08-01116-a and RAS Presidium Program “Matter at high energy density” for the financial support.

1. Yu.V. Petrov, N.A. Inogamov, K.P. Migdal, *Pis'ma v ZhETF* **97**(1), 24 (2013).
2. G. Pottlacher, *High Temperature Thermophysical Properties of 22 Pure Metals*, Keiper (2010).
3. N.A. Inogamov, Yu.V. Petrov, *JETP*, **110**(3), 446–468 (2010).
4. J.M. Ziman, *Principles of the Theory of Solids*, Cambridge, The University Press (1972).
5. W.A. Harrison, *Solid State Theory*, McGraw-Hill, New York, London, Toronto (1970).
6. M.I. Kaganov, I.M. Lifshitz, L.V. Tanatarov, *ZhETF* **31**, 232 (1956).
7. Weigang Ma, Haidong Wang, Xing Zhang, Wei Wang, *Int. J. Thermophys.* DOI 10.1007/s10765-011-1063-2
8. P.M. Norris, J.L. Hostetler, A.N. Smith, D.M. Czajkowsky, P.M. Norris, *Appl. Opt.* **38**, 3614 (1999).
9. W.G. Ma, H.D. Wang, X. Zhang, W. Wang, *J. Appl. Phys.* **108**, 064308 (2010).
10. X.Y. Wang, D.M. Riffe, Y.-S. Lee, M.C. Downer, *Phys. Rev. B* **50**(11), 8016 (1994).
11. Zh. Lin, L.V. Zhigilei, V. Celli, *Phys. Rev. B* **77**, 075133 (2008).

resistance of the duration of short laser pulses. The experiments showed that, as a rule, with decreasing pulse radiation resistance increases. Study of the nature of this dependence helps to understand the mechanisms and patterns of breakdown.

This paper was given the task to calculate the values of radiation resistance of sodium chloride in the femtosecond laser pulse duration range.