

INTERACTION OF LASER RADIATION WITH MATTER

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Thermal emission of electrons under irradiation of a gold target by a femtosecond laser pulse

S.G. Bezhanov, A.P. Kanavin, S.A. Uryupin

Abstract. **We study the effect of *d*-electrons on heating of a gold target upon absorption of a femtosecond laser pulse as well as on subsequent thermal emission of hot electrons. It is shown that neglecting the effect of *d*-electrons leads to a significant overestimation of the number of the emitted electrons. It is found that the approximate description of the heating field in the skin layer without the inhomogeneity of the dielectric constant taken into account does not cause a significant change in the maximum temperature of the electrons at the metal surface, and has virtually no effect on the process of thermal emission.**

Keywords: *femtosecond pulse, thermal emission of electrons, nonuniform heating, d-electrons.*

1. Introduction

Interest in the study of electron emission from a metal is associated with the problem of generation of high-density electron beams that can be used to solve important applied problems. The reason for the emission of electrons from the metal under the action of laser pulses can be multiphoton ionisation, thermionic emission, or the simultaneous manifestation of these mechanisms. It is known when the pulse duration is ~100 fs or shorter, the thermal emission dominates even at a flux density of laser radiation over 10^9–10^{10} W cm^{-2} [1]. Often, when considering thermionic emission, use is made of the Richardson–Dushman formula for j_T – the flux density of emitted electrons – obtained in the approximation when the electron temperature is considered uniform and not changing in time [2, 3]. The influence of the electron temperature gradient, which arises, in particular, during the heating of the metal due to absorption of a femtosecond laser pulse, on the value of j_T is described in [4]. According to [4], for electron temperatures less than the corresponding Fermi energy ε_F and the work function $e\phi$, the effect of nonuniformity of the temperature T on the value of j_T is defined by the parameter

$$\Lambda \sim \sqrt{2}\,(l_T/L)(e\phi/k_B T)\sqrt{(\varepsilon_F + e\phi)/k_B T}\,,$$

where k_B is the Boltzmann constant; e is the electron charge; l_T is the electron mean free path with energy $k_B T$; L is the scale of the temperature nonuniformity. Under certain conditions, this parameter is not always small. The temperature of electrons varies with time as well. However, because the electrons are emitted from the surface layer whose thickness is less than the mean free path, and for a time shorter than the inverse collision frequency, the authors [5–8], using the Richardson–Dushman formula, assumed that by the temperature T is meant its current value on the metal surface. In this case, the main emission occurs for a limited period of time when the electron temperature is close to its maximum value.

Not all electrons emitted from the metal reach the detector. Due to the formation of a near-surface space charge, a part of slower electrons is localised for a relatively long time at the surface and prevents thermal emission. The number of electrons N_{esc}, capable of escaping the space charge field, is found in [5]. According to [5], in the case of thermal emission under the action of a femtosecond laser pulse, a significant deviation from the Richardson–Dushman law occurs when $N_{esc}e^2/R_f \sim k_B T$ (R_f is the radius of the focal spot). With such a large number of N_{esc} their number is proportional to the size of the focal spot and to the maximum temperature of the electrons at the surface. At the same time, N_{esc} is logarithmically weakly dependent on the characteristic width of the time interval in which the temperature is close to its maximal value. It follows from the conclusions of work [5] that, considering the thermionic emission upon absorption of a femtosecond pulse, more emphasis should be placed on the correct calculation of the maximum temperature of the electrons at the metal surface: $T_{max} = \max[T(z = 0, t)]$.

The main objective of this work – calculation of T_{max}, and then N_{esc} – is achieved through the consistent description of the structure of the heating field created by a femtosecond laser pulse in the metal, and through the numerical solution of a coupled system of equations for the temperature of the electrons T and lattice T_{lat}. Use of the concept of temperature to describe the heating of electrons is productive if the temperature varies over time greater than the inverse electron–electron collision frequency. In typical experiments, the electrons are heated to a temperature of ~1 eV, at which the time of their thermalisation is on the order of several femtoseconds. Therefore, the consideration given below is commonly used in studying the effect of pulses that are not shorter than 10 fs. The heating field in the skin layer is found, as before [9, 10], using a small ratio of the collision frequency to the carrier frequency of the laser pulse with an inhomogeneous dielectric constant of the metal slowly varying in time taken into account. This approach to the description of the field has allowed us to obtain an expression for the absorption coefficient A and, consequently, for the rate of electron heating, differing from that used in [5–8]. The authors of these papers

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derive an expression for A by using heuristic arguments, based on the Fresnel formulas to be applied at the interface between homogeneous media.

The equations for T and $T_{\rm lat}$ are solved numerically to described the effect of a femtosecond pulse on a target made of gold. In this case, as in [6] (see also [8]), these equations take into account the effect of d-electrons on the electron heat capacity $C_{\rm e}$, chemical potential μ and parameter G, which characterises the energy exchange between the electrons and the lattice. Simple interpolation formulas for $C_{\rm e}$, μ and G are obtained using the data of [11] devoted to studying the effect of d-electrons on these parameters in the electron temperature range of ~1 eV. The dependence of $N_{\rm esc}$ on the flux density of the heating pulse is found.

2. Field in a metal

Consider the interaction of a femtosecond laser pulse with a metal occupying the half-space $z > 0$. We assume that the pulse propagates along the z axis, and the field strength in it is $\boldsymbol{E}_{\rm i}(z, t) = (E_{\rm i}(z, t), 0, 0)$:

$$E_{\rm i}(z,t) = \frac{1}{2}E_0\Big(t-\frac{z}{c}\Big)\exp(-{\rm i}\omega t + {\rm i}kz) + {\rm c.c.}, \tag{1}$$

where ω is the carrier frequency; $k = \omega/c$ is the wave number; c is the speed of light; the amplitude $E_0(t - z/c)$ for time $\sim 1/\omega$ and at a distance $\sim 1/k$ varies slightly. The field strength of the reflected pulse is written in the form $\boldsymbol{E}_{\rm r}(z, t) = (E_{\rm r}(z, t), 0, 0)$:

$$E_{\rm r}(z,t) = \frac{1}{2}RE_0\Big(t+\frac{z}{c}\Big)\exp(-{\rm i}\omega t - {\rm i}kz) + {\rm c.c.}, \tag{2}$$

where R is the complex reflection coefficient. The electric field in the metal has the form

$$\boldsymbol{E}_{\rm m}(z,t) = (E_{\rm m}(z,t),0,0),$$
$$E_{\rm m}(z,t) = \frac{1}{2}E(z,t)\exp(-{\rm i}\omega t) + {\rm c.c.}, \tag{3}$$

where $E(z, t)$ slightly changes during the time $\sim 1/\omega$. Then, in accordance with Maxwell's equations for $E(z, t)$ we have

$$\frac{\partial^2}{\partial z^2}E(z,t) + k^2\varepsilon(z,t)E(z,t) = 0, \tag{4}$$

where the dielectric constant $\varepsilon(z, t)$ depends on the coordinates and time through the corresponding dependences of the effective electron collision frequency $\nu(z, t)$. Considering the conditions under which the frequency ω is much greater than $\nu(z, t)$, for $\varepsilon(z, t)$ we use the expression

$$\varepsilon(z,t) = \varepsilon' + {\rm i}\varepsilon''(z,t), \tag{5}$$

where $\varepsilon' = \varepsilon_0'(\omega) - \omega_{\rm p}^2/\omega^2 < 0$; $\varepsilon_0''(z, t) = \varepsilon_0''(\omega) + \omega_{\rm p}^2\nu(z, t)/\omega^3$; $\varepsilon_0(\omega) = \varepsilon_0'(\omega) + {\rm i}\varepsilon_0''(\omega)$ is the contribution to the dielectric constant from the bound electrons and the lattice; $\omega_{\rm p}$ is the electron plasma frequency. In pure normal metals, the frequency $\nu(z, t)$ can be represented as a sum of the frequencies of electron–phonon [$\nu_{\rm ep}(z, t)$] and electron–electron [$\nu_{\rm ee}(z, t)$] collisions:

$$\nu(z,t) = \nu_{\rm ep}(z,t) + \nu_{\rm ee}(z,t), \tag{6}$$

$$\nu_{\rm ep}(z,t) = \nu_{\rm ep}(T_0)\frac{T_{\rm lat}(z,t)}{T_0}, \tag{7}$$

$$\nu_{\rm ee}(z,t) = a\frac{k_{\rm B}^2T^2(z,t)}{\hbar\varepsilon_{\rm F}}. \tag{8}$$

Equation (7) approximates the frequency of collisions between electrons and phonons at lattice temperatures $T_{\rm lat}(z, t)$, lower than the melting temperature but higher than the Debye temperature, $T_{\rm lat}(z, t) > T_0$; $\nu_{\rm ep}(T_0)$ is the collision frequency before the action of a heating femtosecond pulse. In formula (8) $\hbar$ is Planck's constant; $T = T(z, t)$ is the electron temperature, which is considered smaller than $\varepsilon_{\rm F}/k_{\rm B}$; the constant a depends on the type of the band structure of the metal. Equation (8) describes the scattering of electrons by taking into account umklapp processes, and it neglects an additive contribution of the form $\sim \hbar\omega^2/(4\pi^2\varepsilon_{\rm F})$ [12], which is independent of temperature $T(z, t)$. For a given frequency ω this leads to a slight change in the initial value of the collision frequency, which is mainly determined by $\nu_{\rm ep}(T_0)$, if the frequency ω refers to the visible frequency range, and T_0 is the room temperature.

Equation (4) must be supplemented by boundary conditions. Taking into account the continuity of the electric and magnetic fields at the surface $z = 0$ and assuming that deep inside the metal the field is equal to zero, we have two boundary conditions:

$$\Big[-\frac{\rm i}{k}\frac{\partial}{\partial z}E(z,t) + E(z,t)\Big]\Big|_{z=0} = 2E_0(t),\ E(z\to\infty,t) = 0. \tag{9}$$

Following paper [9], we seek the solution to equation (4) in the form

$$E(z,t) = \Big[\sum_{n=0}^{\infty}E_n(z,t)\Big]\exp\Big[{\rm i}\sum_{n=0}^{\infty}\psi_n(z,t)\Big],$$

where the subscript n corresponds to the nth order of the perturbation theory in the parameter $\nu(z, t)/\omega$. Then, up to terms linear in $\nu(z, t)/\omega$, from (4) and (9) we find

$$E(z,t) \simeq -E_0(t)\frac{2kd}{\sqrt{1+k^2d^2}} \times\Big[1-\frac{\langle\varepsilon''(t)\rangle k^3d^3}{2(1+k^2d^2)}\Big]\exp\Big[-\frac{z}{d}+{\rm i}\psi(z,t)\Big], \tag{10}$$

$$\psi(z,t) \simeq \pi - \arctan\Big(\frac{1}{kd}\Big) + \frac{1}{2}k^2d^2 \times\Big\{\frac{1}{2}\Big[\frac{1-k^2d^2}{1+k^2d^2}+\exp\Big(\frac{2z}{d}\Big)\Big]\langle\varepsilon''(t)\rangle + \frac{1}{d}\int_0^z{\rm d}z'\Big[1-\exp\Big(\frac{2}{d}(z-z')\Big)\Big]\varepsilon''(z',t)\Big\}, \tag{11}$$

where $d = (k\sqrt{-\varepsilon'})^{-1}$ is the characteristic depth of penetration of the field into the metal;

$$\langle\varepsilon''(t)\rangle = \frac{2}{d}\int_0^{\infty}\varepsilon''(z',t)\exp\Big(-\frac{2z'}{d}\Big){\rm d}z' \tag{12}$$

is the averaged imaginary part of the dielectric constant.

In the same approximation in $\nu(z, t)/\omega$, as defined by $R = |R|\exp(i\phi)$ and $A = 1-|R|^2$, for the absorption coefficient A and the phase shift ϕ of the reflected pulse, we have

$$A(t) \simeq \frac{2k^3d^3}{1+k^2d^2}\langle\varepsilon''(t)\rangle, \tag{13}$$

$$\phi \simeq \pi + \arctan\left(\frac{2kd}{1-k^2d^2}\right). \tag{14}$$

3. Heating of the electrons and the lattice

Absorption of electromagnetic field energy in the skin layer leads to heating of the electrons and the lattice. The basis for describing the evolution of the electron temperature is given by the equation

$$C_e(z,t)\frac{\partial}{\partial t}T(z,t) = \frac{\omega}{8\pi}\varepsilon''(z,t)\,|E(z,t)|^2$$

$$+\frac{\partial}{\partial z}\left[\lambda(z,t)\frac{\partial}{\partial z}T(z,t)\right] - G(z,t)[T(z,t) - T_{lat}(z,t)], \tag{15}$$

where $C_e = C_e(z, t)$ is the specific heat of electrons; $\lambda(z, t)$ is the coefficient of thermal conductivity; $G = G(z, t)$ is the parameter describing the energy exchange between the electrons and the lattice. In accordance with (10) the power absorbed by electrons has the form

$$\frac{\omega}{8\pi}\varepsilon''(z,t)\,|E(z,t)|^2$$

$$\simeq \frac{\omega}{2\pi}E_0^2(t)\frac{k^2d^2}{1+k^2d^2}\varepsilon''(z,t)\exp\left(-\frac{2z}{d}\right). \tag{16}$$

Integrating expression (16) over the thickness of the metal, we derive the absorption coefficient of the form (13)

$$\frac{\omega}{8\pi}\int_0^\infty dz\varepsilon''(z,t)\,|E(z,t)|^2 = A(t)I(t), \tag{17}$$

where $I(t) = cE_0^2(t)/8\pi$ is the flux density of the laser pulse.

Equation (15) is used below to describe the heating of electrons in the interaction of a femtosecond pulse with a gold target. Usually, considering the specific heat of electrons, a relatively simple expression $C_e(z,t) \simeq \pi^2 N k_B^2 T(z,t)/2\varepsilon_F$ is used, where N is the conduction electron density. However, it is known that for gold at temperatures of ~1 eV, d-electrons, which have a high density of states, make a significant contribution to $C_e(z, t)$. Below, in considering hot electrons we will use heat capacity calculated in [11]. For convenience of calculations, we approximate the curve $C_e(z, t)$, shown in Fig. 4c from paper [11], by the function

$$C_e(z,t) = CT(z,t)\{1 + 3.37[10^{-4}T(z,t)]$$

$$- 1.28[10^{-4}T(z,t)]^2\}, \tag{18}$$

where $C \simeq 5.25\times10^2$ erg cm^{-3} K^{-2}, and the temperature $T(z, t)$ is measured in kelvins. The plot of function (18) is shown in Fig. 1.

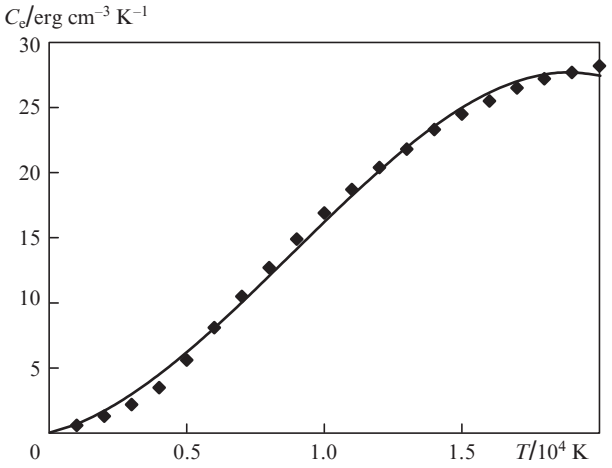

Figure 1. Dependence of the electron heat capacity C_e on the temperature T for gold. The solid curve corresponds to formula (18), points – to the data of Fig. 4c from [11].

The thermal conductivity coefficient $\lambda(z, t)$ is related to the specific heat by the expression

$$\lambda(z,t) = \frac{v_F^2}{3\nu_\lambda(z,t)}C_e(z,t), \tag{19}$$

where v_F is the Fermi velocity, and $\nu_\lambda(z, t)$ is the effective electron collision frequency, which differs from $\nu(z, t)$ (6) by the numerical values of $\nu_{ep\lambda}(T_0) \neq \nu_{ep}(T_0)$ and $b \neq a$:

$$\nu_\lambda(z,t) = \nu_{ep\lambda}(z,t) + \nu_{ee\lambda}(z,t),$$

$$\nu_{ep\lambda}(z,t) = \nu_{ep\lambda}(T_0)\frac{T_{lat}(z,t)}{T_0}, \tag{20}$$

$$\nu_{ee\lambda}(z,t) = b\frac{k_B^2T^2(z,t)}{\hbar\varepsilon_F}.$$

In equation (15) the function $G(z, t)$ depends on temperature. Processing the data of Fig. 4d from paper [11], obtained for gold, we can express $G(z, t)$ in the form

$$G(z,t) = G\{1 + 5[10^{-4}T(z,t)]^2 - 0.79[10^{-4}T(z,t)]^4\}, \tag{21}$$

where $G = 2.7\times10^8$ erg s^{-1} K^{-1} cm^{-3}. The accuracy of formula (21) is slightly lower than that of formula (18). The latter, however, does not lead to any significant change of the quantities $T(z, t)$ and $T_{lat}(z, t)$ for times less than a few hundreds of femtoseconds and at temperatures of less than 2 eV. In this case, the evolution of the lattice temperature is described by the equation

$$C_{lat}\frac{\partial}{\partial t}T_{lat}(z,t) = G(z,t)[T(z,t) - T_{lat}(z,t)], \tag{22}$$

where $C_{lat} \simeq 3k_BN_a$ is the specific heat of the lattice; N_a is the density of lattice atoms.

Below we discuss the solutions to equations (15), (22) under the assumption that before the action of a laser pulse, the temperatures of the electron and the lattice are the same,

$$T(z, t\to-\infty) = T_{lat}(z, t\to-\infty) = T_0. \tag{23}$$

In addition to the initial conditions (23), equation (15) must be supplemented by two boundary conditions. One of them corresponds to a given value of the temperature inside the metal,

$$T(z \to \infty, t) = T_0, \tag{24}$$

and the second follows from the continuity of heat flux on the surface of the metal, i.e., at $z = 0$. Electrons are emitted from the surface $z = 0$, which is accompanied by the removal of heat. However, in the range of temperatures and flux densities of laser radiation, the heat flux caused by thermal emission of electrons is small [7], and the second boundary condition can be written as

$$\lambda(z,t)\frac{\partial}{\partial z}T(z,t)\Big|_{z=0} \simeq 0. \tag{25}$$

As already noted, to describe the emission of electrons it is necessary to know the evolution of their temperature on the metal surface. To this end, we consider the numerical solution to equations (15), (20) when a femtosecond pulse of a Cr:forsterite laser with a carrier frequency $\omega \simeq 1.5\times10^{15}\ \mathrm{s}^{-1}$ irradiates a target made of gold. We assume that the flux density varies according to the law $I(t) = I_0\exp(-t^2/t_p^2)$, where the time t_p characterises the pulse duration $\tau = 2\sqrt{\ln 2}\,t_p = 100$ fs. The maximum flux density in the calculations varied from 5×10^{11} to $4\times10^{12}\ \mathrm{W\ cm^{-2}}$. For gold at a temperature $T_0 = 300$ K we used the following collision frequencies of electrons with phonons: $\nu_{ep}(T_0) = 9.3\times10^{13}\ \mathrm{s}^{-1}$ [13] and $\nu_{ep\lambda}(T_0) = 3.7\times10^{13}\ \mathrm{s}^{-1}$ [14]. The plasma frequency is $\omega_p = 1.37\times10^{16}\ \mathrm{s}^{-1}$, which corresponds to $N \simeq 5.9\times10^{22}\ \mathrm{cm}^{-3}$, $\varepsilon_F = 5.5$ eV and $v_F = 1.4\times10^8\ \mathrm{cm\ s}^{-1}$. The parameters a and b, known with a low degree of accuracy, are taken equal to 1 and 2, respectively (cf. the data of [15]). Finally, in accordance with the experimental data [13], the quantities $\varepsilon_0'(\omega)$ and $\varepsilon_0''(\omega)$ corresponding to the frequency $\omega \simeq 1.5\times10^{15}\ \mathrm{s}^{-1}$ are equal to 11 and 1.2.

The solid curve in Fig. 2 shows the dependence of the maximum temperature T_{max} of the electrons at the gold target surface on the maximum flux density I_0. The dependence $T_{max}(I_0)$ (dashed curve) is obtained by neglecting the contribution of d-electrons to the heat capacity, i.e., in the calculations we used the approximation $C_e(z,t) \simeq \pi^2 N k_B^2 T(z,t)/2\varepsilon_F$ [cf. (18)]. According to Fig. 2 in almost the entire range of considered values of I_0, neglecting the influence of d-electrons leads to a significant overestimation of T_{max}. The dotted curve shows the dependence $T_{max}(I_0)$, obtained by using of the heat source of the form [cf. (16)] in equation (15)

$$\frac{\omega}{8\pi}\varepsilon''(z=0,t)\,|E(z,t)|^2, \tag{26}$$

which leads to the Fresnel formula for the absorption coefficient. Although the neglect of the inhomogeneity, $\varepsilon''(z, t)$, in the skin layer leads to a noticeable error in the absorption coefficient [9, 10], the value of T_{max}, obtained by using the source (26), is close to that derived in a more exact calculation (Fig. 2).

The dependence of the lattice temperature at the surface at the instant of the pulse switching off ($t = 3t_p$) on I_0 is shown in Fig. 3. Due to the significant effect of d-electrons on the value of the function $G(z, t)$ (21), the lattice is heated more strongly than in the case of $G(z,t) = G$ and $C_e(z,t) \simeq \pi^2 N k_B^2 T(z,t)/2\varepsilon_F$ (dashed curve in Fig. 3). The influence of inhomogeneity $\varepsilon''(z, t)$ is small, as is evident from a comparison of solid and dotted curves. Note that in the whole range of the considered I_0, the temperature T_{lat} at the instant $t = 3t_p$ is much smaller than the melting temperature of gold $T_{melt} = 1336$ K.

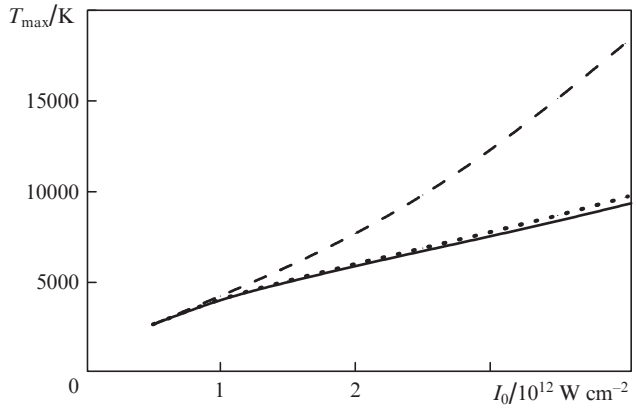

Figure 2. Dependences of the maximum temperature T_{max} of the electrons at the target surface on the maximum flux density I_0 (solid line); the dashed curve is the calculation, without the effect of d-electrons taken into account; the dotted curve – without taking into account changes in $\varepsilon''(z, t)$ in the skin layer.

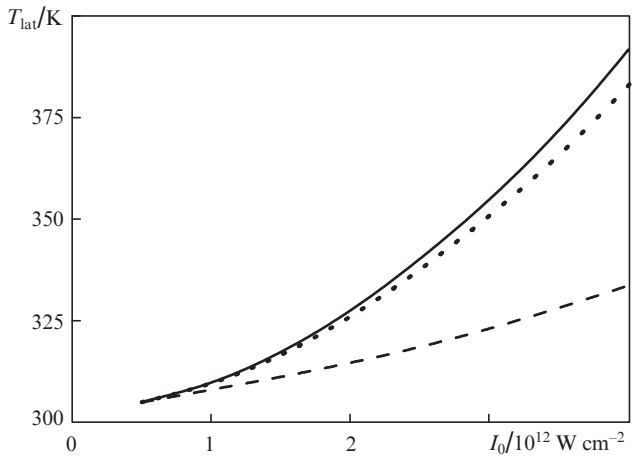

Figure 3. Dependences of the lattice temperature T_{lat} at the target surface on I_0 at the instant of the pulse switching on ($t = 3t_p$). The dashed curve is the calculation, without the effect of d-electrons on $C_e(z, t)$ and $G(z, t)$ taken into account; the dotted curve – without taking into account changes in $\varepsilon''(z, t)$ in the skin layer.

4. Thermal emission of electrons

At the energy flux densities of a laser pulse heating a gold target being considered, the thermal emission leads to the formation of a relatively large space charge of electrons above the surface of the target. The resulting difference in the potentials complicates the electron emission from the metal, which shows up in a change in the properties of thermal emission. At electron temperatures of ~1 eV and focal spot radii of ~100 μm, the Richardson–Dushman formula gives a higher value of the flux density of emitted electrons. To describe the ther-

mal emission in these conditions, the authors of paper [5] proposed the formula

$$N_{\rm esc} = \frac{k_{\rm B}T_{\max}}{ge^2}R_{\rm f} \times \ln\left\{1 + \frac{ge^2}{2\pi\hbar^3}m\tau_{\max}R_{\rm f}k_{\rm B}T_{\max}\exp\left[-\frac{\varepsilon_{\rm F} - \mu(T_{\max}) + e\phi}{k_{\rm B}T_{\max}}\right]\right\}, \quad (27)$$

which gives the number of emitted electrons, $N_{\rm esc}$, with the account for the influence of the space charge on the process of thermionic emission. In (27) $g \sim 1$ is a geometric factor; $\tau_{\max}$ is the characteristic time during which the electron temperature is close to $T_{\max}$. For example, if the near-surface charge has a disk shape, then $g = 16/3\pi$; for a sphere $g = 6/5$ [5]. Accuracy of setting $\tau_{\max}$ is even smaller. Typically, the time $\tau_{\max}$ exceeds by several times the typical pulse duration τ. However, when $k_{\rm B}T_{\max} \gtrsim N_{\rm esc}e^2/R_{\rm f}$, the inaccuracy of setting g and $\tau_{\max}$ leads to logarithmically small errors in $N_{\rm esc}$. Equation (27) includes the chemical potential μ, depending on $T_{\max}$. In calculations the function $\mu(T)$ was approximated by the formula

$$\mu \equiv \mu(z,t) \equiv \mu[T(z,t)] = \varepsilon_{\rm F}\left\{1 + 0.074\left[10^{-4}T(z,t)\right]^2\right\}, \quad (28)$$

taking into account the effect of d-electrons. Figure 4 illustrates the proximity of the interpolation formula (28) to the data of Fig. 4b from paper [11].

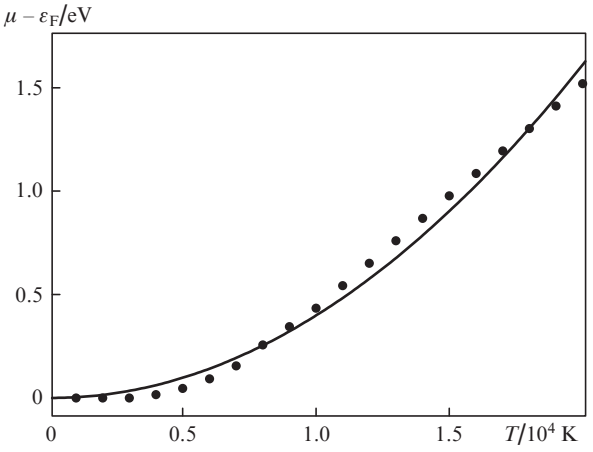

Figure 4. Dependence of the chemical potential μ on the electron temperature T for gold. The solid curve is calculated by formula (28), the dots correspond to the data of Fig. 4b from paper [11].

Using the data on the heating of electrons, given in Section 3, we consider the dependence of the number of the emitted electrons $N_{\rm esc}$ (27) on the maximum flux density I_0. We restrict ourselves to consideration of the conditions when the parameter Λ (see Introduction) is sufficiently small. The dependence of $\lg N_{\rm esc}(I_0)$ is shown in Fig. 5 by the solid curve. The dashed curve corresponds to the calculation without taking into account the influence of d-electrons on the heat capacity $C_{\rm e}(z, t)$, chemical potential $\mu(z, t)$ and function $G(z, t)$. Note that due to the contribution of d-electron, the effect of $\mu(z, t)$ and $G(z, t)$ variations on the subsequent calculation of $N_{\rm esc}$ is substantially less than the corresponding effect caused by changes in $C_{\rm e}(z, t)$. According to Fig. 5 the neglect of d-electrons can lead to an overestimation of $N_{\rm esc}$ almost by an order of magnitude. The dots in Fig. 5 present the calculations of $N_{\rm esc}$ for $T_{\max}$, calculated without taking into account the inhomogeneity of the dielectric constant at the scales of the skin layer. A very slight difference between the dotted and the solid curve is the result of proximity to the corresponding curves for $T_{\max}$ in Fig. 2. The latter is not surprising, since the effect of inhomogeneity on $T_{\max} = \max[T(z = 0, t)]$ in the framework of the approximations made manifests itself only through the removal of heat from the skin layer, which does not lead to a substantial decrease in $T_{\max}$, achieved within ~100 fs. However, the dependence of $N_{\rm esc}$ on $T_{\max}$ at the metal surface can raise the question of the need for a more detailed analysis of the influence of the quasi-stationary electric field in the vicinity of $z = 0$ on the process of thermal emission. The influence of such a field is possible both due to the temperature gradient [4] and due to the formation of a space charge at the metal surface. Analysis of the effect of a quasi-stationary field on $N_{\rm esc}$ is the subject of future consideration, involving a new formulation of the problem for calculating the field in the surface layer.

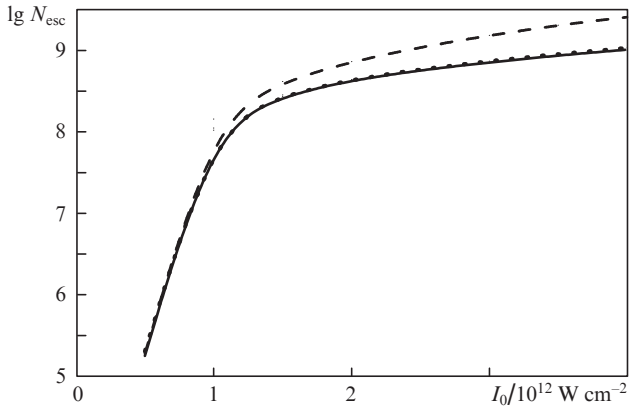

Figure 5. Dependence of the number of emitted electrons, $N_{\rm esc}$, on I_0 (solid line); the dashed curve is the calculation, without the effect of d-electrons taken into account; the dotted curve – without taking into account the inhomogeneity of the imaginary part of the dielectric constant.

5. Conclusions

We have given a quantitative description of the heating of a gold target by a femtosecond laser pulse and have analysed the influence of heating on the thermal emission of electrons. Under conditions when the electrons are heated up to a temperature of ~1 eV, we have demonstrated the important role of d-electrons both during the heating of the target and during the subsequent thermal emission. The effect of d-electrons manifests itself through the change of such physical characteristics as the specific heat of the electrons, chemical potential and parameter characterising the energy transfer from electrons to the lattice. Changing these values leads to changes in laws of evolution of the electron temperature at the target surface, which has a strong influence on the process of thermal emission. On the other hand, a detailed description (used in this paper) of the spatial distribution of the heating field has not resulted in significant changes in the number of emit-

ted electrons. This conclusion stems from the fact that in order to determine the number of emitted electrons, it is important to know the temperature of the electrons at the target surface, which during the action of the femtosecond pulse will vary slightly due to heat transfer in the skin layer. In general, we note that although the role of *d*-electrons has been established and the weak influence of the nonuniform electron heating have been obtained for a target made of gold, the results obtained are quite versatile and should be valid for targets made of other metals.

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References

1. Anisimov S.I., Kapeliovich B.L., Perelman T.L. *Zh. Eksp. Teor. Fiz.*, **66**, 776 (1974) [*Sov. Phys. JETP*, **39**, 375 1974].
2. Richardson O.W. *Phil. Magazine*, **23**, 594 (1912).
3. Dushman S. *Phys. Rev.*, **21**, 623 (1923).
4. Bowers H.C., Wolga G.J. *J. Appl. Phys*., **5**, 2024 (1966).
5. Riffe D.M., Wang X.Y., Downer M.C., Fisher D.L., Tajima T., Erskine J.L., More R.M. *J. Opt. Soc. Am. B*, **10**, 1424 (1993).
6. Wang X.Y., Riffe D.M., Lee Y.-S., Downer M.C. *Phys. Rev. B*, **50**, 8016 (1994).
7. Balasubramni T., Kim S.H., Jeong S.H. *Appl. Surface Sci*., **255**, 9601 (2009).
8. Du G., Yang Q., Chen F., Si J., Hou X. *Appl. Surface Sci*., **257**, 9177 (2011).
9. Kanavin A.P., Mischik K.N., Uryupin S.A. *J. Rus. Laser Res.*, **29**, 123 (2008).
10. Bezhanov S.G., Kanavin A.P., Uryupin S.A. *J. Rus. Laser Res*., **31**, 554 (2010).
11. Lin Zh., Zhigilei L.V., Celli V. *Phys. Rev. B*, **77**, 075113 (2008).
12. Gurzhi R.N. *Zh. Eksp. Teor. Fiz*., 35, 965 (1958) [*Sov. Phys. JETP*, **8**, 674 (1959)].
13. Johnson P.B., Christy R.W. *Phys. Rev.B*, **6**, 4370 (1972).
14. Prokhorov A.M. (Ed.) *Fizicheskaya entsiklopediya* (Encyclopedia of Physics) (Moscow: Sov. Entsiklopedia, 1990).
15. Isakov V.A., Kanavin A.P., Uryupin S.A. *Kvantovaya Elektron.*, **36**, 928 (2006) [*Quantum Electronics*, **36**, 928 (2006)].