Absorption of a femtosecond laser pulse by metals and the possibility of determining effective electron – electron collision frequencies

V.A. Isakov, A.P. Kanavin, S.A. Uryupin

Abstract. **A method is proposed for describing absorption of an electron-heating femtosecond laser pulse that interacts with a metal under conditions of high-frequency skin effect. It is shown that the effective frequencies of electron – electron collisions accompanied by umklapp processes can be determined by measuring the absorption or reflection coefficients of a femtosecond pulse.**

Keywords*: absorption coefficient, electron – electron collisions, umklapp processes.*

The optical and kinetic properties of metals in a state close to thermodynamic equilibrium have been studied in detail (see, for example, [1 – 3]). For most of the normal metals in a broad temperature range, these properties are determined to a considerable extent by electron – phonon collisions characterised by effective collision frequencies v_{ep} exceeding the electron – electron collision frequencies v_{ee}. A different situation takes place when the metal interacts with a high-power femtosecond laser pulse [4 – 6]. Electrons absorbing a laser pulse are rapidly heated to a temperature much higher than the temperature of the lattice which remains comparatively cold during the action of the pulse; in other words, the characteristic time of energy transfer from electrons to the lattice is longer than, or of the order of, several picoseconds. Because of heating of electrons, the effective electron – electron collision frequency v_{ee} increases proportionally to T^2 [7, 8], while the electron – phonon collision frequency v_{ep}, which depends on the lattice temperature T_{lat}, remains almost unchanged. At the electron temperatures exceeding 2000 – 3000 K, conditions are realised under which $v_{ee} \gg v_{ep}$. The absorption of the laser pulse energy and heat removal from the skin layer are mainly determined by the electron – electron collisions, including those accompanied by the umklapp processes.

The high electron – electron collision rates allow us to use the concept of electron temperature for describing optical and kinetic phenomena in a metal, starting from times of the order of a few femtoseconds. A quantitative description of these processes involves a consideration of the real spatial structure of the field in the metal and the electron temperature nonuniformity. In this paper, we use such an approach for describing the interaction of an electron-heating femtosecond pulse with a metal under conditions of high-frequency skin effect. This description is based on the equation for temperature of electrons taking into account their heating in the skin layer due to electron – phonon and electron – electron collisions accompanied by umklapp processes, and cooling due to removal of heat from the skin layer. The thermal flux density also depends on the frequency of collisions of electrons with phonons and with one another, but these frequencies differ from those determining the field absorption.

Following [8], we assume that there are two electron — electron collision frequencies distinguished by independent parameters a and b. These frequencies are $v_a = a(k_B T)^2 \times (\hbar \varepsilon_F)^{-1}$, which determines by the absorption coefficient, and $v_\lambda = b(k_B T)^2/\hbar \varepsilon_F$, which is associated with the thermal flux. Here, k_B is the Boltzmann constant, $\hbar$ is the Plank's constant, and ε_F is the Fermi energy. The absorption coefficient is determined from the integral relation taking into account the inhomogeneity of the field and the electron temperature, which distinguishes our approach from the popular Drude model. We shall obtain below the numerical solution of the temperature equation and derive simple asymptotic expressions describing the time evolution of the electron temperature and the absorption coefficient. It will be shown how the parameters a and b can be determined by measuring the absorption coefficient at various stages of the action of a femtosecond pulse.

By using such an approach for describing the optical properties of a metal with hot electrons, we have analysed the experimental data [9] (see also [10]) on the time evolution of the coefficient of reflection of a femtosecond test pulse from a gold target whose electrons are heated by the main femtosecond pulse. A comparison of the experimental data obtained in [9] and the numerical results leads to values of the parameters a and b for gold, i.e., to the effective electron – electron collision frequencies. The simplicity of the approach used for describing the optical properties of a metal under conditions of high-frequency skin effect and the simplicity of the experimental technique used in [9] make it possible to determine the frequencies of electron – electron collisions (including those accompanied by the umklapp processes) without cumbersome calculations assuming the consideration of the real band structure of the metal.

Consider the interaction of a laser pulse with a metal occupying the half-space $z > 0$. We assume that the pulse is

V.A. Isakov, A.P. Kanavin, S.A. Uryupin P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: kanavin@sci.lebedev.ru

incident normally on the metal boundary and its electric field is

$$E(z,t) = E_0 \exp\left[-\frac{1}{2t_p^2}\left(t-\frac{z}{c}\right)^2\right]\sin\left[\omega\left(t-\frac{z}{c}\right)\right], \quad (1)$$

where E_0 is a vector with components $(E_0, 0, 0)$; t_p is the pulse duration; ω is the frequency; and c is the velocity of light.

During interaction of laser radiation with a metal in the visible frequency range, the conditions of high-frequency skin effect are easily realised when the characteristic radiation frequency ω exceeds the effective frequency v_a' of electron–phonon and electron–electron collisions, and the distance v_F/ω propagated by electrons during the field variation period is smaller than the skin depth $d = c/\omega_{pl}$:

$$\omega \gg v_a', \quad \frac{v_F}{\omega} \ll \frac{c}{\omega_{pl}}, \quad (2)$$

where v_F is the Fermi velocity; $\omega_{pl} = (4\pi N e^2/m)^{1/2}$ is the plasma frequency; and e, m, and N are the electron charge, mass and number density, respectively. By neglecting the effect of rare collisions and taking into account (1), we obtain the approximate expression for the field in the skin layer under condition (2):

$$E(z,t) = E(z)\exp\left(-\frac{t^2}{2t_p^2}\right)\cos\omega t, \quad (3)$$

where the field vector $E(z)$ has the components $[E(z), 0, 0]$, and

$$E(z) = 2\frac{\omega}{\omega_{pl}}E_0\exp\left(-\frac{z}{d}\right). \quad (4)$$

Expressions (3) and (4) are written in the approximation $\omega t_p \gg 1$ and neglect small difference of the field phase shift from $\pi/2$ in the metal.

Fields of type (3) and (4) are absorbed in the skin layer due to electron–phonon and electron–electron collisions. The field dissipation caused by the Landau damping is usually insignificant and will be neglected. By neglecting the variation in the effective collision frequency v_a' over a period $2\pi/\omega$, we find that the mean power absorbed over a period at the point z is

$$\frac{1}{8\pi}\frac{\omega_{pl}^2}{\omega^2}v_a'(z,t)E^2(z)\exp\left(-\frac{t^2}{t_p^2}\right)$$

$$\equiv \frac{4}{c}I(t)v_a'(z,t)\exp\left(-\frac{2z}{d}\right), \quad (5)$$

where $I(t) = (c/8\pi)E_0^2\exp(-t^2/t_p^2)$ is the radiation flux density that varies slowly during the time $2\pi/\omega$. By integrating expression (5) with respect to the coordinate z, we find the absorbed power and, dividing it by $I(t)$, obtain the absorption coefficient

$$A(t) = \frac{4}{c}\int_0^\infty dz\, v_a'(z,t)\exp\left(-\frac{2z}{d}\right), \quad (6)$$

which varies with time upon a variation of the effective electron collision frequency. The contribution to v_a' comes from electron–phonon ($v_{ep,opt}$) and electron–electron (v_a) collisions, i.e., $v_a' = v_{ep,opt} + v_a$. Contribution to the absorption comes from electron–electron collisions accompanied by the umklapp processes. At the electron temperatures $k_B T \ll \varepsilon_F$, the frequency v_a can be written in the form [8]

$$v_a = a\frac{\varepsilon_F}{\hbar}\left(\frac{k_B T}{\varepsilon_F}\right)^2. \quad (7)$$

This relation neglects the dependence of v_a on frequency ω [11]. Such an approximation is justified because at low temperatures, when $\hbar\omega \gg 2\pi k_B T$, the frequency $v_a[1+(\hbar\omega/2\pi k_B T)^2]$ modified in the optical frequency range in accordance with [11] does not exceed $v_{ep,opt} \sim k_B T_{lat}/\hbar$ if the lattice temperature T_{lat} is higher than, or of the order of, the Debye temperature. The theoretical calculation of the coefficient a is complicated due to the necessity of taking into account the real band structure of the metal (see, for example, [3, 7, 12, 13]). However, another approach is also possible when a is obtained from the measurement of the absorption coefficient of the femtosecond laser pulse that heats the electrons. Such a possibility arises when electrons are heated over a period smaller than the characteristic time of energy transfer from the electrons to the lattice, which is of the order of a few picoseconds for typical metals. If electrons are heated to a temperature higher than T_a at which $v_a(T_a) \simeq v_{ep,opt}$, or to a temperature $T_a \simeq (\varepsilon_F/k_B)(\hbar v_{ep,opt}/a\varepsilon_F)^{1/2} \gg T_{lat}$, their effective collision frequency v_a' will be mainly determined by the electron–electron collisions. At such high temperatures, the absorption coefficient A is caused by the electron–electron collisions accompanied by the umklapp processes, and its magnitude depends on the unknown coefficient a, thus making it possible to determine the value of the latter. In order to demonstrate such a possibility, let us consider the heating of electrons in the skin layer.

The temperature evolution of electrons in a metal is described by the equation

$$C\frac{\partial T}{\partial t} = \frac{4}{c}I(t)v_a'\exp\left(-\frac{2z}{d}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right), \quad (8)$$

where $C = \pi^2 N k_B^2 T/2\varepsilon_F$ is the specific heat and $\lambda = C v_F^2/3v_\lambda'$ is the thermal conductivity of electrons depending on the collision frequency $v_\lambda' = v_{ep,\lambda} + v_\lambda$. The frequencies $v_{ep,\lambda}$ and v_λ differ numerically from the electron–phonon ($v_{ep,opt}$) and electron–electron (v_a) collision frequencies that determine the absorption coefficient. Like v_a, the frequency v_λ is given by

$$v_\lambda = b\frac{\varepsilon_F}{\hbar}\left(\frac{k_B T}{\varepsilon_F}\right)^2, \quad (9)$$

where the numerical coefficient $b \neq a$.

The first term on the right-hand side of Eqn (8) describes the heating of electrons due to laser radiation energy absorption in the skin layer, while the second term accounts for heat transport to the bulk of the metal. This equation is written under the assumption that the mean free path v_F/v_λ' is smaller than the characteristic scale of temperature inhomogeneity. Note that the use of the concept of temperature, and hence Eqn (8), for describing electron heating is justified if the characteristic time of temperature variation is large in comparison with the reciprocal frequency of

electron–electron collisions. It should be emphasised that the electron–electron collision frequency is manifested in the optical properties of metals only if it exceeds the electron–phonon collision frequency which, for example, is higher than, or of the order of, 10^{14} s^{-1} for gold. This means that for pulses of duration longer than 10 fs, the contribution of non-thermalised electrons to the absorption coefficient is strongly suppressed.

It was mentioned above that the effect of electron–electron collisions on the absorption coefficient is manifested only when the electrons in the skin layer manage to get heated to a temperature exceeding T_a during the action of the laser pulse. Such a possibility can be realised for a high radiation flux density I for which the electron heating exceeds their cooling due to the removal of heat from the skin layer. Taking this into account, we will henceforth assume that

$$\frac{k_{\mathrm{B}}T}{\varepsilon_{\mathrm{F}}} > \frac{8I}{cN\varepsilon_{\mathrm{F}}} > \frac{\pi^2}{3v_a'v_\lambda'}\left(\frac{v_{\mathrm{F}}\omega_{\mathrm{pl}}}{c}\right)^2\left(\frac{k_{\mathrm{B}}T}{\varepsilon_{\mathrm{F}}}\right)^2, \quad T > T^*, \quad (10)$$

where $I = I(t = 0)$, and the electron temperature exceeds $T^* = \min(T_a, T_b)$ [T_b is the temperature at which $v_b(T_b) \simeq v_{\mathrm{ep},\lambda}$]. The left inequality in (10) provides the smallness of $mv_E^2 = e^2E^2(z)/m\omega^2$, the electron oscillation energy in the field E, in comparison with the thermal energy $k_{\mathrm{B}}T$ of the electrons. Note that as the electrons are heated, the region of compatibility of the left and right inequalities in (10) becomes larger owing to an increase in the value of the ratio $k_{\mathrm{B}}T/\varepsilon_{\mathrm{F}}$.

The right inequality in (10) allows us to neglect heat transport in Eqn (8). In this case, we arrive at the following approximate relation from (8):

$$\frac{v_a(T) + v_{\mathrm{ep,opt}}}{v_a(T_0) + v_{\mathrm{ep,opt}}}$$

$$= \exp\left\{\frac{8aIt_{\mathrm{p}}}{\pi\sqrt{\pi}\hbar cN}\left[1 + \mathrm{erf}\left(\frac{t}{t_{\mathrm{p}}}\right)\right]\exp\left(-\frac{2z}{d}\right)\right\}, \quad (11)$$

where $T_0 = T(t = -\infty)$ is the electron temperature before the action of the laser pulse, and $\mathrm{erf}(x) = (2/\sqrt{\pi})\int_0^x \mathrm{d}t \times \exp(-t^2)$ is the error function. Relation (11) holds for $k_{\mathrm{B}}T < \varepsilon_{\mathrm{F}}$, which imposes additional constraints on the laser pulse duration. Taking (11) into account, we obtain the absorption coefficient from (6):

$$\frac{A(t)}{A(t = -\infty)} = \frac{\pi\sqrt{\pi}\,\hbar cN}{8aIt_{\mathrm{p}}}\left[1 + \mathrm{erf}\left(\frac{t}{t_{\mathrm{p}}}\right)\right]^{-1}$$

$$\times\left\{\exp\left[\frac{8aIt_{\mathrm{p}}}{\pi\sqrt{\pi}\hbar cN}\left(1 + \mathrm{erf}\left(\frac{t}{t_{\mathrm{p}}}\right)\right)\right] - 1\right\}, \quad (12)$$

where

$$A(t = -\infty) = \frac{2}{\omega_{\mathrm{pl}}}[v_a(T_0) + v_{\mathrm{ep,opt}}] \quad (13)$$

is the initial absorption coefficient. Expression (12) describes the absorption coefficient under conditions of high-frequency skin effect, when $\omega > v_a'$ [see formula (2)]. The last equality imposes restrictions on the absorption coefficient which must not exceed $2\omega/\omega_{\mathrm{pl}}$ in the range of applicability of this approach. The highest value of $A(t)$ is attained for $t \geqslant t_{\mathrm{p}}$:

$$A(t \geqslant t_{\mathrm{p}}) \simeq A(t = -\infty)\frac{1}{\alpha}(\mathrm{e}^\alpha - 1) < \frac{2\omega}{\omega_{\mathrm{pl}}}, \quad (14)$$

where $\alpha = 16aIt_{\mathrm{p}}/(\pi\sqrt{\pi}\hbar cN)$. According to (14), a noticeable increase in the absorption coefficient due to electron heating occurs for $\alpha > 1$. For $\mathrm{e}^\alpha \gg 1$, the ratio $A(t \geqslant t_{\mathrm{p}}) \times A^{-1}(t = -\infty)$ defines the parameter α in accordance with the formula

$$\alpha \simeq \ln\left[\frac{A(t \geqslant t_{\mathrm{p}})}{A(t = -\infty)}\ln\left(\frac{A(t \geqslant t_{\mathrm{p}})}{A(t = -\infty)}\right)\right]. \quad (15)$$

Since the laser pulse parameters I and t_{p}, as well as the electron number density N are known, coefficient a can be determined easily by measuring experimentally the ratio of the absorption coefficients before and immediately after the action of the pulse.

Over the time of effective action of the laser pulse, i.e., in the interval $-t_{\mathrm{p}} < t < t_{\mathrm{p}}$, heat is removed from the skin layer. However, in view of the right inequality in (10), such a heat removal does not significantly affect the electron temperature in the skin layer and hence the absorption coefficient. During the action of the laser pulse, the amount of heat released per unit area of the metal surface, i.e.,

$$Q = \int_{-\infty}^{\infty} \mathrm{d}t I(t)A(t)$$

$$= It_{\mathrm{p}}A(t = -\infty)\frac{\sqrt{\pi}}{\alpha}\int_0^\alpha \frac{\mathrm{d}x}{x}(\mathrm{e}^x - 1), \quad (16)$$

is mainly concentrated in the skin layer. For $t > t_{\mathrm{p}}$, the flux density in the pulse decreases exponentially and the evolution of the electron temperature is determined to a large extent by the removal of heat from the skin layer to the bulk of the metal. The variation in the electron temperature is described by Eqn (8) in which the heat release in the skin layer can be approximately neglected for $t > t_{\mathrm{p}}$. The skin depth d is relatively small, and after the passage of a certain amount of time ($\sim 3v_\lambda'd^2/v_{\mathrm{F}}^2$) the size of the heated region is found to exceed d. For such time intervals, it is natural to seek the self-similar solution of approximate equation (8) which does not contain the first term in the right-hand side. The self-similar solution corresponding to the absence of the heat flux on the metal surface has the form

$$v_\lambda' = v_\lambda + v_{\mathrm{ep},\lambda} \simeq v_b = \frac{1}{t}\left[D + \frac{3}{2}\left(\frac{z}{v_{\mathrm{F}}t}\right)^2\right]^{-1}, \quad (17)$$

where the parameter D is determined from the relation

$$\frac{1}{2}\int_0^\infty \mathrm{d}z CT = Q. \quad (18)$$

It follows from Eqns (17) and (18) that

$$D = \frac{\pi^6}{384}\left(\frac{\hbar v_{\mathrm{F}}N}{Q}\right)^2, \quad (19)$$

where Q is described by expression (16). A dependence of type (17) takes place for $T > T_b$ and describes the evolution of the electron temperature in the heated region of the metal. The size z_{h} of the heated region of the metal

increases proportionally to the time at a typical rate $\sqrt{D}v_F$: $z_h \sim \sqrt{D}v_F t$ [14]. The electron temperature at the metal surface decreases inversely proportional to $\sqrt{t}$:

$$\frac{k_B T(z=0,t)}{\varepsilon_F} = \frac{Q}{\hbar v_F N \pi^3}\left(\frac{384\hbar}{bt\varepsilon_F}\right)^{1/2}. \tag{20}$$

Under conditions of the applicability of the self-similar solution (17), the typical scale of the temperature inhomogeneity is much larger than the skin-depth d. Therefore, the electron temperature in the skin layer decreases weakly and its magnitude is described approximately by expression (20). A weak variation of T inside a skin layer of thickness d allows us to present the absorption coefficient (6) in the form

$$A(t > t_p) \simeq \frac{2v_a'(z=0,t)}{\omega_{pl}}$$

$$= \frac{2}{\omega_{pl}}\left\{v_{ep,opt} + a\,\frac{\varepsilon_F}{\hbar}\left[\frac{k_B T(z=0,t)}{\varepsilon_F}\right]^2\right\}$$

$$\simeq A(t=-\infty) + \frac{a}{b}\left(\frac{Q}{\hbar v_F N}\right)^2 \frac{768}{\pi^6 \omega_{pl} t}. \tag{21}$$

According to (21), the absorption coefficient is mainly determined by the electron–electron collisions with umklapp processes in the time interval $t_p < t < t_h$, where

$$t_h = \frac{a}{b}\left(\frac{Q}{\hbar v_F N}\right)^2 \frac{384}{\pi^6 v_{ep,opt}}, \tag{22}$$

and decreases inversely proportional to time. One can see from the last term in (21) that the rate of decrease of $A(t)$ depends on the ratio a/b. It follows from this that the experimentally observed dependence $A(t > t_p) \propto t^{-1}$ can be used to determine the numerical value of the ratio a/b, since the remaining parameters appearing in (21) can be determined independently.

It follows from what has been stated above that the absorption coefficient increases sharply for $t \lesssim t_p$ [see formula (12)] and after attaining its peak at $t \gtrsim t_p$, decreases inversely proportional to $1/t$ in the interval $t_p < t < t_h$, attaining its original value $A(t=-\infty)$ for $t > t_h$, where t_h is assumed to be small in comparison with t_{lat}, the time of energy transfer from the electrons to the lattice. For $t_h > t_{lat}$, a dependence of the type $A(t) \propto 1/t$ is observed up to $t < t_{lat}$. Experimental investigation of such a behaviour of the absorption coefficient leads to numerical values of the factors a and b which determine the effective collision frequencies appearing both in the absorption coefficient and the heat flux.

For $t \gtrsim t_{lat}$, the right-hand side of Eqn (8) should be supplemented with a term [15, 16]

$$G(T - T_{lat}), \tag{23}$$

taking into account the energy transfer from electrons to the lattice, the parameter G characterising the connection of electrons with the lattice. For example, $G = 3.5 \times 10^{10}$ W cm^{-3} K^{-1} for gold [17]. A term of type (23) is usually significant for time periods of the order of a few picoseconds or more. If this term is taken into consideration in formula (8), it becomes possible to describe the

evolution of the electron temperature and the absorption coefficient for time periods $t \gtrsim t_{lat}$. Thus the analysis of the evolution of the absorption coefficient for $t \gtrsim t_{lat}$ makes it possible to determine experimentally the value of the parameter G.

At present, some experiments have been reported [9, 10] in which the reflection coefficient has been measured for a femtosecond test pulse interacting with a metal after the passage of time Δt following the action of the main femtosecond pulse that heats the electrons. The above approach for describing the evolution of the absorption coefficient can be used for comparison with the experimental data presented in [9]. The authors of [9] have presented relative variations of the reflection coefficient of time-averaged action of a test pulse

$$\frac{\Delta R(\Delta t)}{|\Delta R(\Delta t)|_{max}} = \frac{R(\Delta t) - R(-\infty)}{|R(\Delta t) - R(-\infty)|_{max}}$$

$$= \frac{A(-\infty) - A(\Delta t)}{|A(-\infty) - A(\Delta t)|_{max}}, \tag{24}$$

where the relation $R = 1 - A$ between the reflection coefficient R and absorption coefficient A has been used, and the notation

$$A(\Delta t) = \left[\int_{-\infty}^{\infty} dt I_{test}(t - \Delta t)A(t)\right]\left[\int_{-\infty}^{\infty} dt I_{test}(t)\right]^{-1} \tag{25}$$

has been introduced, where $I_{test}(t)$ is the energy flux density in a test pulse. The subscript max in Eqn (24) indicates the highest magnitude of the corresponding quantity. Squares in Fig. 1 indicate the values of the function $\Delta R(\Delta t) \times |\Delta R(\Delta t)|_{max}^{-1}$ (24) obtained experimentally in [9]. These values were obtained by studying the reflection of a weak 110 fs titanium–sapphire laser test pulse from a plane gold target heated by the main pulse of duration 110 fs with an energy flux density $I = 1.3 \times 10^{12}$ W cm^{-2}. Note that the role of band transitions in the absorption of such a laser radiation by a gold target need not be taken into consideration since the band transition edge in this case lies in the region $\Delta \approx 2.5$ eV [18], which is higher than the radiation energy quantum $\hbar\omega \approx 1.5$ eV. For such durations and flux densities of the titanium–sapphire laser pulse, the energy transport to the phonon subsystem is insignificant.
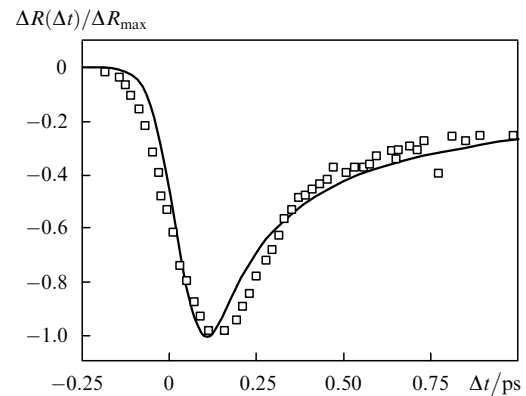
Figure 1. Relative variation of the coefficient of reflection (24) of a test pulse from a gold target. Squares correspond to the results obtained in [9]; the solid curve corresponds to calculations.

The solid curve in Fig. 1 was obtained by solving numerically Eqn (8) and calculating the absorption coefficient (6) and relative variation in the reflection coefficient (24). Calculations were made for a gold target with $\varepsilon_F = 5.5$ eV, $N = 5.9 \times 10^{22}$ cm^{-3}, and $\omega_{pl} = 1.4 \times 10^{16}$ s^{-1}, and for the main pulse parameters borrowed from [9]. The shape of the theoretical curve depends on the effective electron collision frequencies v_a' and v_λ'. At $T_{lat} \approx 300$ K, the parameters for gold are $v_{ep,opt} = 0.93 \times 10^{14}$ s^{-1} [19] and $v_{ep,\lambda} = 3.6 \times 10^{13}$ s^{-1} [20]. The contributions v_a and v_λ to v_a' and v_λ' from electron–electron collisions depend on the coefficients a and b and on the electron temperature. For moderate values of a and b and a rapid electron heating, these contributions become dominant. In this case, v_a' and v_λ' are close to v_a and v_λ and vary in proportion to a and b respectively. By varying the values of a and b, the theoretical curve $\Delta R(\Delta t)|\Delta R(\Delta t)|_{max}^{-1}$ and the experimental data [9] can be matched with each other. A rather good matching of the experimental and theoretical data in Fig. 1 was obtained for $a \simeq 1$ and $b \simeq 2$.

An analysis of the experimental data obtained in [9] shows that this approach can be used for determining the effective collision frequencies of nonequilibrium electrons by measuring the reflection coefficient. However, it should be emphasised that the precision of evaluating a and b from the experimental data obtained in [9] is comparatively low and sensitive to the pulse shape. The precision can be enhanced by lowering the test pulse duration and the error in measuring the reflection coefficient. Modern experiments make it possible to lower the pulse duration to a few femtoseconds (see, for example [21]), and to increase the accuracy of optical measurements.

References

1. Ginzburg V.L., Silin V.P. *Zh. Eksp. Teor. Fiz.*, **29**, 64 (1955).
2. Lifshits I.M., Azbel' M.Ya., Kaganov M.I. *Electron Theory of Metals* (New York: Consultants Bureau, 1973; Moscow: Nauka, 1971).
3. Gantmakher V.F., Levinson I.B. *Scattering of Charge Carriers in Metals and Semiconductors* (Amsterdam: North-Holland, 1987; Moscow: Nauka, 1984).
4. Lugovskoy A.V., Bray I. *Phys. Rev. B*, **60** (5), 3279 (1999).
5. Fisher D., Fraenkel M., Henis Z., Moshe E., Eliezer S. *Phys. Rev. E*, **65**, 016409 (2001).
6. Yoneda H., Morikami H., Ueda K., More R.M. *Phys. Rev. Lett.*, **91** (7), 075004 (2003).
7. Landau L.D., Pomeranchuk I.Ya. *Zh. Eksp. Teor. Fiz.*, **7**, 379 (1937).
8. Abrikosov A.A. *Osnovy teorii metallov* (Fundamentals of the Theory of Metals) (Moscow: Nauka, 1987).
9. Guo C., Rodrigues G., Taylor A.J. *Phys. Rev. Lett.*, **86** (8), 1638 (2001).
10. Guo C., Taylor A.J. *Phys. Rev. B*, **62** (18), R 11921 (2000).
11. Gurzhi R.N. *Zh. Eksp. Teor. Fiz.*, **35**, 965 (1958).
12. Ziman J. *Electrons and Phonons* (Oxford University Press, 1960; Moscow: Inostrannaya literatura, 1962).
13. Lawrence W.E. *Phys. Rev. B*, **13**, 5316 (1976).
14. Kanavin A.P., Smetanin I.V., Isakov V.A., Afanasiev Yu.V., Chichkov B.N., Wellegehausen B., Nolte S., Momma C., Tunnermann A. *Phys. Rev. B*, **57**, 14698 (1998).
15. Kaganov M.I., Lifshits I.M., Tanatarov L.V. *Zh. Eksp. Teor. Fiz.*, **31**, 2232 (1957).
16. Anisimov S.I., Kopeliovich B.L., Perelman T.L. *Zh. Eksp. Teor. Fiz.*, **66**, 776 (1974).
17. Groeneveld R.H., Sprik R., Lagendij K.A. *Phys. Rev. B*, **45**, 5079 (1992).
18. Theye M.-L. *Phys. Rev. B*, **2**, 3060 (1970).
19. Jonson P.B., Christy R.W. *Phys. Rev. B*, **6**, 4370 (1972).
20. Grigoriev I.S., Meilikhov E.Z. (Eds) *Fizicheskie velichini. Spravochnik* (Handbook of Physical Quantities) (Moscow: Energoatomizdat, 1991).
21. Schenkel B., Biegert J., Keller U., Vozzi C., Nisoli M., Sansone G., Stagira S., Silvestri S.De, Svelto O. *Opt. Lett.*, **28**, 1987 (2003).