 ©2016 Kvantovaya Elektronika and Turpion Ltd

DOI: 10.1070/QEL15971

Transmittance jump in a thin aluminium layer during laser ablation

N.E. Bykovsky, S.M. Pershin, A.A. Samokhin, Yu.V. Senatsky

Abstract. **A jump in the transmittance (from ~0.1 % to ~50 % for ~1 ns) of an optical gate on a Mylar film (a thin aluminium layer on a Lavsan substrate) irradiated by nanosecond (10^{-7}–10^{-8} s) pulses of a neodymium laser with an intensity up to 0.1 GW cm^{-2} has been recorded. The mechanism of a fast (10^{-10}–10^{-11} s) increase in the transmittance of the aluminium layer upon its overheating (without boiling) to the metal–insulator phase-transition temperature is discussed.**

Keywords: *neodymium laser, optical gate, aluminium film, metal–insulator transition, transparency wave.*

1. Introduction

One of the first available optical gates used to *Q*-switch the laser cavity, to decouple cascades in laser amplifiers (or a laser system from a target) and to carry out some other experiments was a thin metal layer evaporated by laser radiation [1–8]. Despite the advantages of a gate based on an evaporated metal layer (simple technology and low cost), it was a single-action device, which could not regain the initial low transmittance after actuation. Hence, this gate was soon replaced with electrooptic gates and bleaching dyes in laser setups. At the same time, experimental data on the functioning of a gate based on a metal layer are of interest for studies of the interaction of laser radiation with metals, which have been performed since the beginning of the 1960s [9–20].

In 1944, Zeldovich and Landau published a paper 'On the relation between the liquid and the gaseous states of metals' [21], where they pointed to the possibility of the metal–insulator transition for an expanded metal at subcritical temperatures. Later this suggestion was considered when discussing a sharp (by several orders of magnitude) decrease in the electrical conductivity of mercury upon stationary heating [22]. It was noted [23] that localised electron states should be expected to arise when the metal density becomes sufficiently low. The current interruptions in conductors, observed in experiments with 'exploding fine wires' (up to the instant of evaporation and plasma formation) upon pulsed heating, were most likely caused by the metal–insulator phase transition [24, 25].

N.E. Bykovsky, Yu.V. Senatsky P.N. Lebedev Physis Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: senatsky@sci.lebedev.ru;
S.M. Pershin, A.A. Samokhin A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia

Received 17 November 2015; revision received 18 December 2015
Kvantovaya Elektronika **46** (2) 128–132 (2016)
Translated by Yu.P. Sin'kov

After the development of lasers capable of vaporising metals and forming a plasma on their surface, one could expect the metal–insulator phase transition induced by laser irradiation to be experimentally observed. Bonch-Bruevich et al. [9] found that focusing a neodymium laser beam onto metal (copper, aluminium, etc.) samples led to a change in their reflectance during the laser pulse. However, when interpreting this effect, the mechanism of the metal–insulator phase transition was not taken into consideration. Later on, the concept of the metal–insulator transition was repeatedly considered when performing theoretical analysis of laser ablation and explaining results of numerous experiments on the interaction of laser radiation with metal targets.

Batanov et al. [10] suggested that, when a bulk metal target is heated by a laser beam with an intensity of 10^7–10^8 W cm^{-2}, the metal–insulator transition should be accompanied by a new peculiar physical phenomenon: propagation of a transparency wave in the melt. In this interaction regime, the metal does not undergo boiling, despite the fact that the liquid metal becomes overheated to the metal–insulator phase-transition temperature T_{mi} during the laser pulse [10]. In accordance with this mechanism, the laser energy transmitted through the melt is spent on heating the solid metal under the melt layer on the bottom of the melt crater and deepening the latter. Having taken the mechanism of transparency wave into account, Batanov et al. [10] explained the anomalous decrease in the reflectance of a metal surface during the laser pulse that was experimentally observed in [9]. A similar experiment was performed later in [12] and explained taking into account the existence of a transparency wave at a metal–insulator phase transition.

The experiments [15, 17, 18] on the interaction of nanosecond laser pulses with metals and alloys also provided data indicative of the formation of a transparency wave in the radiation–target interaction zone. An indirect confirmation of the occurrence of a transparency wave prior to boiling of a metal target subjected to nanosecond pulsed laser heating was the observation of the emission of melt droplets from the crater along the generatrix of a cone with a vertex on the crater bottom [15], as well as selective evaporation of melt components with concentrations differing significantly from azeotropic and enrichment of vapour with volatile components [17, 18].

An increase in transparency of thin metal layers subjected to pulsed laser radiation was first observed in experiments with metal films and foils [1–8]. In these experiments, two different mechanisms of the increase in metal transparency were considered: simple evaporation of a metal layer [1, 3, 5, 6] and the occurrence of the metal–insulator transition with propagation of a transparency wave in the evaporated metal [4, 7, 8].

Here, we analyse the results of the experiments [2, 4, 8] on irradiation of a Mylar film (~0.05-μm Al layer on a Lavsan substrate) by nanosecond (10^{-7}– 10^{-8} s) neodymium laser pulses, where an increase in the transmittance of the Al layer by two to three orders of magnitude for a time $\tau_t \approx 1$ ns (transmittance jump) was revealed. The mechanism of the fast (10^{-10}–10^{-11} s) increase in transparency in this metal gate with allowance for the overheating of liquid metal (without boiling) to the metal–insulator phase-transition temperature is discussed. An analysis of these experiments showed that the transmittance jump in the Al layer, which was observed in [4], is apparently the first direct experimental evidence for implementing the metal–insulator phase transition under laser irradiation.

2. Experimental results

Within the research aimed at developing a high-power laser oscillator [2], a gate based on an Al layer was used for the first time in a neodymium glass laser system with a peak power of ~1 GW to decouple a rotating-prism Q-switched master oscillator from amplifier cascades and to sharpen the leading edge of amplified pulse. A schematic of the system is presented in Fig. 1a. Active elements (rods) ∅30 × 600 mm in size, made of KGSS-7 glass (Lytkarino Optical Glass Plant), positioned in GOS-300 laser heads (LOMO, St. Petersburg), were applied in the oscillator and two-cascade amplifier. The rod end faces were cut at a small angle (1.5°–2°) to the rod axis. A plane-parallel plate made of K-8 glass was used as an output mirror in the oscillator. The gate (Mylar film) consisted of a ~0.05-μm-thick Al layer deposited on a Lavsan tape with a width of 5 cm and thickness of ~20 μm; the tape was rewound by a special device after destruction of the Al coating by a laser shot. The initial transmittance K_0 of the Mylar film for a weak signal at the laser wavelength $\lambda \approx 1.06$ μm did not exceed 0.1%; hence, the oscillator was decoupled from the amplifier.

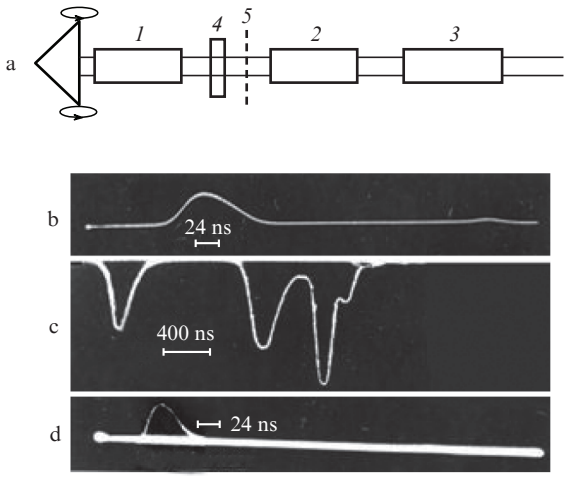

Figure 1. (a) Schematic of a rotating-prism Q-switched oscillator and a two-cascade amplifier based on KGSS-7 glass rods, in GOS-300 laser heads, with a light beam diameter of 30 mm: (*1*, *2*, *3*) rods ∅30 × 600 mm in size; (*4*) output oscillator mirror; (*5*) Mylar film with Al coating. (b–d) Oscillograms of pulses (b) at the oscillator output, (c) at the amplifier output in the absence of the Mylar film, and (d) at the output of the amplifier with a film gate.

Pulses at the outputs of the oscillator and amplifier were recorded by a FEK-09 photocell connected to a C1-14 oscilloscope (oscillograms in Figs 1b and 1d) and by an FEU-15B photoelectron multiplier connected to a DESO-1 oscilloscope (oscillogram in Fig. 1c). In the absence of the Mylar film, the oscillator and amplifier rods were optically coupled and formed in fact a unified oscillator, which generated (in the Q-switched regime) several pulses with a width of 150–200 ns and an energy up to 80 J (Fig. 1c). With a film located at the oscillator output, a single pulse with a width of ~80 ns (Fig. 1b) and energy up to 10 J was formed in a 30-mm beam, which was directed (without focusing) to the film and then to the amplifier. After the film absorbed the initial part of the pulse (with a power density of 10^7– 10^8 W cm^{-2}), the Al layer was evaporated, and the rest of the pulse arrived at the amplifier. Under these conditions, one would expect sharpening of the leading edge and a decrease in the pulse width by the time spent on heating the Al layer to evaporation. An oscillogram of a pulse with a width of ~50 ns and shortened leading edge (~10 ns) at the amplifier output is shown in Fig. 1d. The pulse energy was 60 J, the beam divergence was about 3×10^{-3} rad, and the power exceeded 1 GW [2]; this set of parameters was an achievement for neodymium lasers at that time (1965).

An additional experiment was carried out to estimate the operating speed of the film gate (Fig. 2) [4, 8]. A Kerr-cell Q-switched laser beam (pulse width ~20 ns, energy up to 1 J, power density up to 10^8 W cm^{-2} [26]) was directed (without focusing) to the gate (Fig. 2a). Two rods made of KGSS-7 glass, with a size of ∅10 × 120 mm and flat parallel end faces, were used in this laser. A cavity ~1 m long was formed by a mirror with a dielectric coating (having a reflectance of

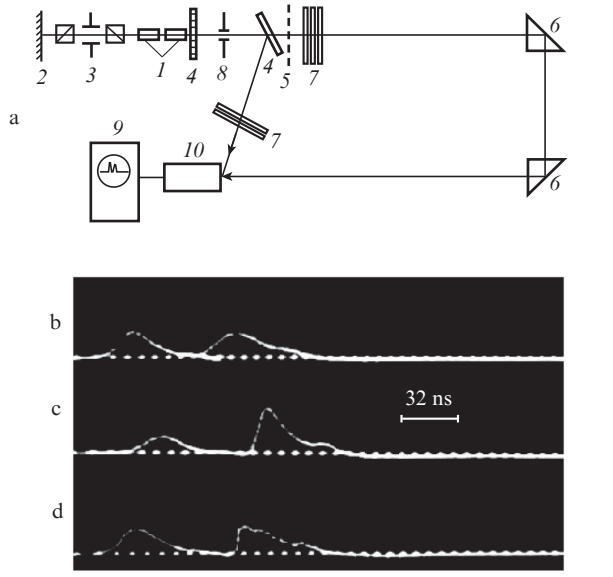

Figure 2. (a) Schematic of the experiment on formation of pulses by a Q-switched oscillator with an optical gate based on a metallised Mylar film: (*1*) KGSS-7 glass rods ∅10 × 120 mm in size; (*2*) highly reflecting mirror; (*3*) Kerr cell; (*4*) K-8 glass plate; (*5*) Al-film gate; (*6*) prisms; (*7*) light filters; (*8*) diaphragm; (*9*) C1-14 oscilloscope; (*10*) FEK-09 photocell. (b–d) Oscillograms of pulses before the gate (on the left) and after passage through the gate and along a ~23-m path (on the right) for an Al layer exposed to (b) a non-diaphragmed beam and (c, d) a beam transmitted through diaphragms (c) 5 and (d) 1.5 mm in diameter.

~100% at the wavelength $\lambda \approx 1.06$ μm) and a plane-parallel glass plate (a rod end face was also used as an output mirror).

It was found that, at a pulse energy density $\varepsilon < \varepsilon_{th} \approx 0.4$ J cm^{-2}, the Al layer was not evaporated (the ε_{th} value corresponded to the Al layer evaporation threshold). At $\varepsilon < \varepsilon_{th}$, the entire pulse passed through the film was attenuated by a factor of ~10^3. To eliminate only the weak initial portion of a Q-switched oscillator pulse and select its main part, one must deal with $\varepsilon > \varepsilon_{th}$. Under these conditions, if the energy density in the initial part of the pulse does not reach the threshold, the film delays this part of the pulse. With an increase in the pulse intensity, the inequality $\varepsilon > \varepsilon_{th}$ was satisfied, the gate became transparent, and the main part of the pulse passed through the gate with small loss. At $\varepsilon > \varepsilon_{th}$, the Al layer was removed from the film in the irradiated area. The Lavsan base transmittance K_{lav} for a laser beam with an intensity up to 10^{10} W cm^{-2} was about 90%. The integral (i.e., for the entire time of laser pulse) transmittance K_{int} of the film gate with increased transparency was ~50% [4]. At $\varepsilon > \varepsilon_{th}$, the Al film was vaporised both by the total (without a limiting diaphragm) oscillator beam with a diameter of about 10 mm and by the central part of the beam, cut by a diaphragm (5 or 1.5 mm in diameter) installed beyond the cavity.

The pulses at the input and (after the optical delay line on a path of ~23 m) output of the film gate were recorded using a FEK-09 photocell and a C1-14 oscilloscope. A comparison of the pulse oscillograms before and after the gate shows that a significant decrease in the width of the pulse leading edge is observed for only the beams cut by a diaphragm (Figs 2c, 2d). Irradiation of the film by a beam without a diaphragm barely changed the pulse leading edge after the gate (Fig. 2b). At the same time, the use of a diaphragm with a diameter of 5 mm reduced the leading edge of the transmitted pulse to ~5 ns (Fig. 2c), whereas in the case of the 1.5-mm diaphragm the leading edge was diminished to ~1 ns [4, 8]. The jump in the transmittance for the Mylar film gate was $K_{int}/K_0 = 10^2 - 10^3$.

3. Discussion

The results of shaping pulses by a film gate in the experiments performed according to the schemes in Figs 1 and 2 [2, 4, 8] can be explained by the spatial and temporal structure of laser beams, which is due to the nonuniform (over the active-element cross section) development of lasing in Q-switched lasers. In the experiment within the scheme in Fig. 2, where the Mylar film was irradiated by a beam without a diaphragm, the spatial and temporal structure of the pulse led to a spread in transparency formation instants in the film throughout its cross section. Under these conditions, the pulse leading edge did not shorten (Fig. 2b). On the contrary, when the film was exposed to radiation coming from only a small region of the active medium (i.e., when a diaphragm was used), the spread in the transparency formation instants over the film cross section decreased, and one could observe leading edge sharpening and pulse shortening (Figs 2c, 2d). The leading edge width for the 1.5-mm diaphragm (~1 ns) corresponded to the time resolution of channel detection, which gives grounds to expect even larger shortening of the pulse leading edge by a film gate.

The data of the experiment performed according to the scheme in Fig. 2 also suggest that specifically the nonuniform spatial and temporal distribution of intensity in the 30-mm beam in the laser system based on (∅30 × 600)-mm active elements (Fig. 1) did not make it possible to observe high transparency formation rates in the gate. Apparently, for the same reason, a fast increase in transparency was not revealed in other experiments with Al films [5, 6], where pulses transmitted through a film had leading edge widths up to 10 ns.

Thus, an optical gate composed of an aluminium layer ~0.05 μm thick on a Lavsan tape (Mylar) provided decoupling in an oscillator–amplifier laser system and sharpening of the leading edge of pulses transmitted through a gate in the experiments [2, 4, 8]. The result obtained (a decrease in the leading edge width to ~1 ns) revealed also that the evaporating metal layer becomes transparent at a high rate (likely, for a time shorter than 1 ns). When discussing the transmittance jump for an Al film in [4], it was indicated that a "possible mechanism of fast increase in transparency is the 'decollectivisation' of conduction electrons in the expanding heated metal layer, i.e., metal–insulator transition". However, the physical nature of the anomalously fast increase in transparency was not completely explained.

Recently, many experimental and theoretical studies have been devoted to the interaction of nanosecond laser pulses with metals (including aluminium targets) [13–20]. A theoretical analysis of the stationary evaporation from the surface of a bulk metal target for radiation intensities up to 10^8 W cm^{-2} in the presence of the metal–insulator transition [14] showed that this regime can be implemented only in a relatively narrow intensity range. An increase in radiation intensity may lead to explosive (bulk) boiling of the superheated metastable phase and formation of plasma, as it was confirmed by experiments and calculations for bulk targets and films [13–20].

As was shown in [4–8], Al films irradiated by nanosecond laser pulses become transparent in a limited range of laser intensities (10^7–10^8 W cm^{-2}). In the experiment corresponding to Fig. 2, the transparency-formation energy density $\varepsilon_{th} \approx 0.4$ J cm^{-2} for an Al layer with a thickness $h \approx 0.05$ μm irradiated by a pulse with a width of ~20 ns corresponds to a beam intensity of ~2×10^7 W cm^{-2} [4, 8]. If the thermal diffusivity of aluminium is known ($k = 0.1$ cm^2 s^{-1}) [6], one can estimate the film heating time: $h^2/k \approx 250$ ps. Thus, the heating can be considered uniform and occurring simultaneously throughout the entire film volume during the pulse.

Let us estimate the temperature to which an Al film with a thickness $h \approx 0.05$ μm can be heated as a result of the absorption of radiation with $\varepsilon = 0.2\varepsilon_{th} \approx 0.08$ J cm^{-2} (80% reflection is taken into account) for a film fragment 5 mm in diameter (fragment area $S \approx 0.2$ cm^2 and volume $V \approx 10^{-6}$ cm^3). The aluminium mass m in this fragment (aluminium density $\rho = 2.7$ g cm^{-3}) is ~2.7×10^{-6} g. For the aluminium specific heat $c = 940$ J kg^{-1} K^{-1} [16], we find the temperature to which the film is heated by radiation with $\varepsilon = 0.2\varepsilon_{th}$ to be $T_h \approx 6500$ K. The critical temperature for aluminum is $T_c \approx 7400$ K [27], and the metal–insulator transition temperature is $T_{mi} \approx 0.8T_c$ [16]. Thus, the estimate shows that the Al layer with a thickness $h \approx 0.05$ μm, irradiated by a laser pulse with an energy density $\varepsilon_{th} \approx 0.4$ J cm^{-2} in the experiment [4, 8], could be heated to the metal–insulator transition temperature. The metal density decreases upon heating, and, in principle, the metal–insulator transition may occur in the condensed phase at a temperature $T_{mi} < T_c$, a circumstance that was pointed to in [21].

In the case under consideration (Al layer), an insignificant expansion of metal leads most likely to an intermediate nonstationary state with distorted interatomic bonds in the Al lattice (because of their misorientation) in the first stage. In this state, conduction electrons are localised on atoms or atomic clusters, and the Al layer becomes transparent. Due to this,

the layer reflectance decreases, and the laser beam intensity penetrating the Al film increases. As a result, the film transparency is maintained by the residual absorption of radiation in the film and the expansion of the heated Al layer.

The increase in the transparency of Al coatings with initial transmittances ranging from 0.05% to 2%, irradiated by 30-ns Nd laser pulses, was observed in [5] at $\varepsilon = 0.1-1.2$ J cm^{-2}. Apparently, it was also related to the metal–insulator transition in the expanding metal layer, although this mechanism of transparency formation was not considered in [5]. The threshold (for transparency occurrence) laser pulse energy density was found to increase with an increase in the coating thickness in [5]. The range of coating transparency formation was limited: the integral transmittance $K_{int}(\varepsilon)$ first increased with an increase in ε and then decreased (at $\varepsilon > 1.5$ J cm^{-2}) [5].

Based on this behaviour of the dependence $K_{int}(\varepsilon)$ in [5] and the detection of transmittance jump in [4], one can suggest that the Al layer becomes transparent in the following way. When the energy density reaches the threshold (for transparency formation in an Al layer with an initial thickness h_1) value ε_{th1}, the increase in temperature and decrease in aluminium density in the layer lead to the formation of particles (clusters of Al atoms)*. Small clusters with dielectric properties (in which electrons are localised) arise, which are responsible for the transmittance jump in Al coating.

Larger clusters of Al atoms retain metal properties. These (metal) clusters are responsible for the laser radiation absorption. With an increase in the laser pulse energy density ($\varepsilon > \varepsilon_{th1}$), the number of small dielectric clusters increases, and coefficient $K_{int}(\varepsilon)$ increases, providing a transmittance jump in the Al coating. When passing through the boundary of the transparency formation range ($\varepsilon > 1.5$ J cm^{-2}), an increase in radiation intensity causes ionisation of Al atoms, due to which the transmittance of the forming plasma layer decreases.

The characteristic time τ_t of the transmittance jump, observed in an Al film with $h \approx 0.05$ μm [4, 8], can be estimated on the assumption that the front of the transparency caused by the metal–insulator transition propagates in the film jointly with its expansion at a velocity v. The film free expansion velocity v under the experimental conditions of [4, 8] should not exceed the speed of sound in metallic aluminium ($v < v_{Al} \approx 5 \times 10^5$ cm s^{-1}); therefore, the transmittance jump time can be estimated as $\tau_t = 10^{-10}-10^{-11}$ s. The high transparency formation rate made it possible to form a leading edge with a width (~1 ns) limited by only the time resolution of the detection channel for a Nd laser pulse transmitted through a Mylar film (Fig. 2d) [4, 8]. It was noted that the high rate of transparency formation in a film gate irradiated by nanosecond laser pulses in the experiments [5, 6] was 'obscured' by the spatial and temporal structure of radiation in the laser beam irradiating the film.

The observed stepwise increase in the Al film transparency can be compared with the dynamics of transparency formation as a result of metal evaporation from the surface at a successive decrease in the film thickness. The time necessary to completely evaporate and thus make transparent an Al film with $h \approx 0.05$ μm in this regime can be estimated as follows. Let us assume that a film fragment 5 mm in diameter is already heated (under the experimental conditions of [4, 8]) by the radiation of the laser pulse leading edge to the boiling temperature and continues to absorb radiation with a power density of 2×10^7 W cm^{-2}. Energy of 4 mJ is supplied to a fragment with an area of 0.2 cm^2 for 1 ns. With allowance for the film reflection, the absorbed energy is only 0.8 mJ. The latent evaporation heat of aluminium is $L_b \approx 10^4$ J g^{-1} [16]. The energy necessary to evaporate aluminium from the film fragment is $Q_b = mL_b \approx 27$ mJ; to accumulate it, the film must be irradiated for ~33 ns. Therefore, the time necessary to evaporate successively (layer-by-layer) an Al coating ~0.05 μm thick at a laser beam intensity of 2×10^7 W cm^{-2} exceeds the experimentally found time of transparency formation in the film by a factor of more than 30. This fact suggests that the observed stepwise increase in the film transparency is due to the metal–insulator transition in the expanding Al coating rather than its evaporation.

The experimental data of [2, 4–6, 8] indicate that an Al film, after absorbing the energy of the leading edge of a laser pulse with a width of 20–80 ns and passing from the initial metallic state to the new phase (metal–insulator transition), retains a rather high optical quality for several tens of nanoseconds. Indeed, Al films could be used in laser systems [2, 4–6, 8] as optical gates for collimated laser beams. The transmittances (per pulse) K_{int} for the Al films that were made transparent by nanosecond pulses turned out to be 40%–80% [5] and ~50% [2, 4, 8]. The formation of laser beams with energies up to 60 J in the oscillator–amplifier system with an Al film gate (Fig. 1) [2, 4, 8] indicates the absence of high scattering loss in the film for laser pulses with a width of ~50 ns passing through it. Apparently, the state of explosive boiling of the film material with loss of optical homogeneity was not implemented in the experiments [2, 4, 8].

For the laser scheme presented in Fig. 2, the width of pulses with a cut leading edge, transmitted through a film with $h \approx 0.05$ μm at $K_{int} \approx 50\%$ and along a path of ~23 m and then recorded by a photodetector, is ~30 ns (at the pulse base level). After this time, the thickness of the Al layer expanding with a velocity $v < v_{Al}$ does not exceed 150 μm. Thus, the above-reported experimental data and their analysis make it possible to relate the transmittance jump (from ~0.1% to ~50% for ~1 ns) in a thin Al film irradiated by nanosecond laser pulses [4, 8] to the metal–insulator phase transition in the aluminium layer overheated by laser radiation without metal boiling. One can also suggest the existence of transparency ('fed' by laser radiation) in the Al film gate for several tens of nanoseconds; this state is provided by the thin expanding aluminium layer with optical characteristics allowing laser beam transport without significant distortions.

4. Conclusions

The experimental data on the ablation of Al films by neodymium laser pulses with a width of 20–80 ns and intensity of 10^7-10^8 W cm^{-2} and the results of their analysis suggest that the transparency of optical gates based on thin Al films irradiated by nanosecond pulses in [2, 4–6, 8] may be due to the metal–insulator phase transition of the superheated liquid metal in the subcritical temperature range. However, the transparency of irradiated Al films was considered in [5, 6] as a result of evaporation of the film material. The relationship between the transparency formation in an Al film exposed to pulsed laser radiation and the metal–insulator transition was considered for the first time in [4]. The transmittance jump in an Al layer that was recorded in [4] (from ~0.1% to ~50% for ~1 ns) became, apparently, the first direct experimental

*The formation of clusters with sizes beginning with 1 nm from atoms of a copper target heated to a temperature of ~4000 K under pulsed electron-beam impact was considered in [28].

evidence for the metal–insulator transition under laser irradiation.

Note that the results obtained even in the 1960s are of interest for today's research in this field [2, 4, 8], because they yield additional information about the interaction between laser radiation with intensities of 10^7–10^8 W cm^{-2} and metals in the near-critical temperature range. Currently, in view of the development of picosecond and femtosecond lasers and the progress in laser fusion, much attention is paid to experiments on the interaction of laser radiation of high (above 10^{13} W cm^{-2}) intensities with different materials (including metal films and foils) [29–31]. At the same time, the physical pattern of the interaction between radiation of moderate intensities (10^7–10^8 W cm^{-2}) and metals, with allowance for possible metal–insulator phase transition, has been studied insufficiently.

To gain a deeper insight into the dynamics of a stepwise increase in the transparency of a metal film under laser irradiation with intensities of 10^7–10^8 W cm^{-2}, we believe it expedient to use ultrashort laser pulses for diagnostics of a medium during transformation of its optical and physical parameters. An example of high-speed optical diagnostics of transient (transparent) states of materials (semiconductors, metals) subjected to ablation by femtosecond laser pulses with the formation of layered thin-film structures on the surface of targets (before the plasma formation threshold) was reported in [29], where interference effects caused by these structures were observed.

Acknowledgements. This work was supported in part by the Russian Foundation for Basic Research (Grant Nos 13-02-01129 and 14-02-00748).

References

1. Grant D. *Proc. IEEE*, **51**, 604 (1963).
2. Basov N.G., Ambartsumyan R.V., Borovich B.L., Zuev V.S., Kryukov P.G., Letokhov V.S., Morozov V.M., Oraevskii A.N., Senatskii Yu.V., Stoilov Yu.Yu., Shcheglov V.A. *Report on Research on Project '1B'* (Moscow: FIAN, 1966).
3. Asmus J.F. *Appl. Opt*., **8**, 1252 (1969).
4. Senatskii Yu.V. *Cand. Diss.* (Moscow: FIAN, 1970).
5. Vanyukov M.P., Isaenko V.I., Pashinin P.P., Serebryakov V.A., Sizov V.N., Starikov A.D. *Kvantovaya Elektron*., (1), 35 (1971) [*Sov. J. Quantum Electron*., **1** (1), 23 (1971)].
6. Askar'yan G.A., Tarasova N.M. *Pis'ma Zh. Eksp. Teor. Fiz*., **18**, 8 (1973).
7. Dymshits Yu.I. *Pis'ma Zh. Tekh. Fiz*., **2**, 751 (1976).
8. Zuev V.S., Senatskii Yu.V. *Preprint No. 1* (Moscow: FIAN, 2015); *Kr. Soobshch. Fiz*., (4), 16 (2015).
9. Bonch-Bruevich A.M., Imas Ya.A., Romanov G.S., Libenson M.N., Mal'tsev L.N. *Zh. Tekh. Fiz*., **38**, 851 (1968).
10. Batanov V.A., Bunkin F.V., Prokhorov A.M., Fedorov V.B. *Zh. Eksp. Teor. Fiz*., **63**, 586 (1972).
11. Bonch-Bruevich A.M., Potapov S.E. *Pis'ma Zh. Tekh. Fiz*., **1**, 353 (1975).
12. Zavecz T.E., Saifi M.A., Noits M. *Appl. Phys. Lett*., **26**, 165 (1975).
13. Yoo J.H., Jeong S.H., Mao X.L., Greif R., Russo R.E. *Appl. Phys. Lett*., **76**, 783 (2000).
14. Andreev S.N., Mazhukin V.I., Nikiforova N.M., Samokhin A.A. *Kvantovaya Elektron*., **33**, 771 (2003) [*Quantum Electron*., **33**, 771 (2003)].
15. Fishburn J.M., Withford M.J., Coutts D.W., Piper J.A. *Appl. Opt*., **43**, 6473 (2004).
16. Porneala C., Willis D.A. *Int. J. Heat Mass Transfer*, **49**, 1928 (2006).
17. Pershin S.M., Colao F., Spizzichino V. *Laser Phys*., **16**, 455 (2006).
18. Pershin S.M., Lednev V.N., Bogatkin D.D., Labutin T.A., Bunkin A.F. *Kvantovaya Elektron*., **42**, 605 (2012) [*Quantum Electron*., **42**, 605 (2012)].
19. Mazhukin V.I., Samokhin A.A., Demin M.M., Shapranov A.V. *Kvantovaya Elektron*., **44**, 283 (2014) [*Quantum Electron*., **44**, 283 (2014)].
20. Mazhukin V.I., Samokhin A.A., Shapranov A.V., Demin M.M. *Mater. Res. Express*, **2**, 016402 (2015).
21. Zel'dovich Ya.B., Landau L.D. *Zh. Eksp. Teor. Fiz*., **14**, 32 (1944).
22. Kikoin I.K., Senchenkov A.P. *Fiz. Met. Metalloved*., **24**, 843 (1967).
23. Mott N.F. *Metal–Insulator Transitions* (London: Taylor & Fransis, 1974).
24. Rukhadze A.A. *Vzryvayushchiesya provolochki* (Exploding Fine Wires) (Moscow: Inostr. Lit., 1959).
25. Bartnik A., Ivanenkov G.V., Karpinski L., Mingaleev A.R., Pikuz S.A., Romanova V.M., Stepnevski V., Shelkovenko T.A., Yakh K. *Kvantovaya Elektron*., **21**, 181 (1994) [*Quantum Electron*., **24**, 169 (1994)].
26. Basov N.G., Zuev V.S., Senatskii Yu.V. *Pis'ma Zh. Eksp. Teor. Fiz*., **2**, 57 (1965).
27. Khomkin A.L., Shumikhin A.S. *Zh. Eksp. Teor. Fiz*., **148**, 597 (2015).
28. Volkov N.B., Fen'ko E.L., Yalovets A.P. *Zh. Tekh. Fiz*., **80**, 1 (2010).
29. Sokolowski-Tinten K., Bialkowski J., Cavalleri A., von der Linde D., Oparin A., Meyer-ter-Vehn J., Anisimov S.I. *Phys. Rev. Lett*., **81**, 224 (1998).
30. Lebo I.G., Tishkin V.F. *Issledovanie gidrodinamicheskoi neustoichivosti v zadachakh lazernogo termoyadernogo sinteza* (Hydrodynamic Instability in Laser Fusion Problems) (Moscow: Fizmatlit, 2006).
31. Ionin A.A., Kudryashov S.I., Makarov S.V., Seleznev L.V., Sinitsyn D.V. *Appl. Phys. A*, **117**, 1757 (2014).