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THE HEATING AND DESTRUCTION OF THIN FILMS BY LASER RADIATION

by

M. N. Libenson

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By: M. N. Libenson

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А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yë or ë. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	A	α		Nu	N	ν	
Beta	B	β		Xi	Ξ	ξ	
Gamma	Γ	γ		Omicron	O	o	
Delta	Δ	δ		Pi	Π	π	
Epsilon	E	ε		Rho	P	ρ	
Zeta	Z	ζ		Sigma	Σ	σ	ς
Eta	H	η		Tau	T	τ	
Theta	Θ	θ		Upsilon	T	υ	
Iota	I	ι		Phi	Φ	φ	
Kappa	K	κ		Chi	X	χ	
Lambda	Λ	λ		Psi	Ψ	ψ	
Mu	M	μ		Omega	Ω	ω	

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

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THE HEATING AND DESTRUCTION OF THIN FILMS BY LASER RADIATION

M.N. Libenson (Leningrad)

The article is devoted to the theoretical analysis of the process of interaction of powerful light flow with thin films of absorbing materials. The problems examined here have a direct relation to the number of uses of laser radiation in film technology and also to the use of thin-layer coatings as mirrors of laser resonators.

A thermal model of the destruction of opaque media is assumed as a basis. According to this model, the process of the interaction of the laser radiation with the substance can be conditionally divided into several stages: 1) the transfer of energy (from the moment of absorption of radiant energy to the moment of its transition into thermal energy); 2) heating of the material to a temperature which corresponds to the beginning of the destruction; 3) destruction of the material and removal of the products of destruction; 4) cooling of the material after completion of the action. All the listed stages are characteristic also for thin films; however, in this case they have their own characteristics connected, in the first place, with the considerable effect on the optical properties of the films of the granular structure with the dependence of their properties and rate of heating of the films on their thickness and also the properties of the backing [2].

Energy transfer. Let us be limited to the analysis of the process of the interaction of the laser radiation only with films with a thickness of $h \geq 500$ Å, the properties and structure of which approach the properties and structure of the solid material. To

avoid the misunderstandings, let us point out also that the discussion is about the action on the film of the radiation of pulse lasers in the visible and near IR region at densities of the light flux of $I < 10^8$ W/cm^2, for which the thermal mechanism of destruction is correct [1].

This stage occurs differently in materials of different classes. The optical properties of metals are satisfactorily described by the model of free electrons, according to which the depth of penetration of the light wave into the metal (δ) consists of $\sim 10^{-6}$ cm. Therfore, the metallic films of the examined thickness are weakly transparent for the incident radiation: $h \gg \delta$. The powerful absorption of light leads to the absence of noticeable oscillations of coefficients of reflection and transparency of the film with an increase in its thickness, which are bound to the interference of the direct and inverse waves in the film; moreover, when $h >> \delta$ the inverse wave can be completely disregarded. In this case the law of the decay in the density of flow in the light wave in the first approximation should correspond to Bouguer's law $I(x) = I(1 - R)\exp(-ax)$, where I(x) and I are the density of the light flux at distance x from the surface of the film being irradiated and in the incident beam, respectively; R - the coefficient of light reflection from the film; $\alpha = 1/\delta$ - absorption factor.

However, the diffusion character of the scattering of free electrons on the surface of the film and also on the boundaries of grains and crystallites there changes the spatial distribution of the light flux in depth (anomalous skin effect), causing deviation from the Bouguer law; the coefficient of the light reflection from the film is simultaneously changed [3].

The absorption of light by free electrons of the film[1] leads to [illegible] heating up; then they return the absorbed energy to the grid with collisions with the phonons, and also with scattering

[1]With small thicknesses of the film, the free electrons can be completely captured by the surface energy levels; here the interaction of the radiation with the film will be determined also by the bound electrons [2].

on the surface or boundaries of the grains for the time $\tau_r \sim 10^{-11} - 10^{-10}$ s [1]. Regarding the spatial distribution of sources of heat heating the grid, it will be distinguished from the law of the weakening of the light wave in the film due to the commensurability of the mean free path of the electron in the film l' and depth of the skin layer δ. As is known [2], when $l' < h$ and $l' = l(1 - 1/4h)$, where l is the mean free path of the electron in the solid material; $l' \sim 10^{-6}$ cm. Considering that the electron gives away the excess energy to the thermal oscillations at a distance of the order of $10^2 l' \geqslant h$, it is possible to assume that the heat sources in the grid will be uniformly distributed over the thickness of the film. The process of the transfer of heat from the zone of irradiation by the unheated layers is accomplished in the metallic film by mechanisms of heat conductivity, from which just as in the massive metals, the electronic heat conductivity is the main mechanism [1].

In proportion to heating the optical characteristics of the film and, first of all, the reflectivity R are changed, which in turn changes the rate of the heating. As is shown in [3], when $h > \delta$, taking into account the anomality of the skin effect, the absorptivity of the metal A, the optical properties of which are described by the single-zone model for electrons of conductivity, is equal to

$$A = 1 - R \approx \frac{3}{4}\frac{v_0}{c_0} + \frac{e_0}{\sigma(T)}\left(\frac{N}{\pi m_0^*}\right)^{1/2} \qquad (1)$$

where v_0 is the velocity of the electron on the Fermi surface ($v_0 \sim 10^8$ cm/s); c_0 - velocity of light in a vacuum; e_0 and m_0^* - charge and effective mass of the electron; N - concentration of free electrons; $\sigma(T)$ - electrical conductivity on constant current dependent on temperature.

Thus the temperature dependence of the absorptivity is connected with the change in electrical conductivity. For films having small structural changes in the heating process, quantity A should be increased with an increase in the temperature linearly [4], since[2]

$$\frac{1}{\sigma(T)} = \frac{m_0^* \nu_{ei}'}{N_0 e_0^2} \approx \frac{m_0^* k_0}{3\hbar N_0 e_0^2} T$$

In semiconductors having at room temperature an insignificant concentration of free electrons, the absorption of light is determined mainly by the bound carriers. Here greatly absorbing the radiation at frequency ω will be only those semiconductors for which the energy of the quantum $\hbar\omega$ is greater than the width of the forbidden band E_g. For example, for Ge when $\lambda = 1\,\mu m$ ($\hbar\omega = 1.2$ eV, $E_g = 0.8$ eV) $\alpha = 10^4$ cm^{-1} [5]. Films of these materials, as a rule, possess a noticeable transmission up to thicknesses $h \sim 10{,}000$ Å, as a result of which their optical parameters (R, A and D - transparency) are the oscillating functions of thickness[3] (due to the interference of the direct and inverse waves) and to a great degree depend on the optical properties of the backing [2].

The absorption of light in the semiconductor when $\hbar\omega > E_g$ occurs, as is known, by the direct and indirect transitions of the electrons of the valence band into the zone of conductivity (internal photoeffect), which leads to the growth in concentration of the free carriers. The stationary concentration of the free electrons N_0 is determined by the density of concentration of the light flux and also by processes of bipolar diffusion and recombination of the carriers [5]. Not regarding these questions in more detail, let us indicate that when $I \sim 10^6$ W/cm^2 the quantity N_0 consists of $\sim 10^{20} - 10^{21}$ cm^{-3} and is reached during the time $\tau_m \sim 10^{-8} - 10^{-7}$ s.

With such large concentrations of free electrons the semiconductor approximates the metal with respect to its optical and electrical properties (approaches the degeneracy of the semiconductor). Thus for moments of time $t > \tau_m$ the heat release in the lattice of the semiconductor and the processes of heating

[2]The reason for that indicated is the increase, with a temperature increase, in the collision frequency of the free electrons with the phonons.

and destruction of the material caused by them should occur mainly similar to the corresponding processes in the metals (see also work [6]). What has been said is valid for the semiconductor films.

The rate of heating of the film is greatly affected by the backing, into which can be drained off the basic portion of the heat released in the film. If the film is semitransparent, and the backing is opaque, then the radiation penetrates directly into the backing and, in transferring into heat in it, can serve as an additional source of heating of the film.

Heating of the films. The transition of light energy into heat during the time considerably less than the pulse duration makes it possible to consider that simultaneously with the beginning of the action in the film and backing there is formed a volume source of heat, which repeats the time structure of the laser pulse. Thus the stage of the film's heating can be examined within the framework of the boundary value problem of thermal conductivity with the known initial and boundary conditions. Before turning to an analysis of this problem, let us note that the heating of the film by laser radiation in the mode of free generation, in spite of its short-lived nature, can be compared to the structural changes in the film and the diffusion of atoms into the backing, which here are not examined. Furthermore, besides the heating, evaporation of the material occurs, but this process is weakly marked until the partial vapor pressure becomes equal to the external pressure [7]. Such a condition corresponds to the point of the phase transition liquid (solid body) - vapor on the phase diagram (T_v).

Let us examine now the boundary value problem of heat conductivity in a one-dimensional approximation valid under the

[3] Here we are diverted from the structural features of the semiconductor films having a porous structure. This can be considered by the introduction of the effective constants n^* and κ^*.

[4] In the mode of free generation the pulse duration is $\tau \sim 10^{-4} - 10^{-3}$ s; in the mode of modulated quality $\tau \sim 10^{-7}$ s.

condition $R_0 \gg \sqrt{a_1 \tau}$, where R_0 is the dimension of the light spot on the surface of the film, τ - pulse duration, a_1 - thermal conductivity of the film. We will consider the the thermal contact of the film with the backing to be ideal and the backing itself, for simplicity, to be transparent for the laser radiation. We will disregard also the change in the optical and thermophysical parameters of the film and backing in proportion to their heating. For example, let us take that the power of the heat release in the film is constant along the section of the light spot and is not changed during the entire laser pulse. Then the system of equations of heat conductivity with the boundary and initial conditions will take the form

$$\frac{\partial T_{1,2}(x,t)}{\partial t} - a_{1,2}\frac{\partial^2 T_{1,2}(x,t)}{\partial x^2} = \frac{q_{1,2}(x)}{\rho_{1,2}c_{1,2}}$$

$$T_1(x,0) = T_2(x,0) = T_0, \quad \frac{\partial T_1}{\partial x}(0,t) = 0 \qquad (2)$$

$$T_1(h,t) = T_2(h,t), \quad k_1\frac{\partial T_1}{\partial x}(h,t) = k_2\frac{\partial T_2}{\partial x}(h,t) \quad T_2(\infty,t) = T_0$$

Subscripts 1 and 2 refer to parameters of the film and backing, respectively; coordinate x is counted off from the front surface of the film.

In the examined case $q_2(x) = 0$, a $\int_0^h q_1(x)dx = IA$, where A is the absorptivity of the film; A = I-R-D. Considering, as it was proposed above, that the heat is released uniformly over the thickness of the film, i.e., $q_1(x) = \text{const} = q_0$, for q_0 we get

$$q_0 = \frac{IA}{h}$$

To solve the boundary value problem of thermal conductivity (2), let us apply to the equation of thermal conductivity and boundary conditions the Laplace transform with respect to time [8]

$$\bar{u} = \int_0^\infty e^{-pt}u(t)dt$$

Dropping the intermediate calculations, which are produced according to the standard method, for the Laplace form of temperature of the film $\overline{T}_1(x)$ as a result we obtain

$$\overline{T}_1(x) = \frac{q_0}{\rho_1 c_1 p^2} \times$$

$$\times \left[1 - \frac{\exp(-\sqrt{p/a_1}\,x) + \exp(\sqrt{p/a_1}\,x)}{(1-\nu)\exp(-\sqrt{p/a_1}\,h) - (1+\nu)\exp(\sqrt{p/a_1}\,-h)}\right] + \frac{T_0}{p} \quad (3)$$

where p is the parameter of the transformation; $\nu = k_1\sqrt{a_2}/k_2\sqrt{a_1}$.

Completing the inverse Laplace transform (see, for example, [9]), we can find the time dependence of the surface temperature of the film (x = 0); in the given case this dependence has the form

$$T_1(0,t) - T_0 = \frac{q_0 t}{\rho_1 c_1} - \frac{\alpha q_0}{\rho_1 c_1 (1+\nu)} \sum_{l=0}^{\infty} \left(\frac{\nu-1}{\nu+1}\right)^l \left\{\left[t + \frac{h^2(2l+1)^2}{\alpha a_1}\right] \cdot \right.$$

$$\left. \cdot \operatorname{erfc} \frac{h(2l+1)}{2\sqrt{a_1 t}} - \frac{h(2l+1)\sqrt{t}}{\sqrt{\pi a_1}} \exp\left[-\frac{h^2(2l+1)^2}{4a_1 t}\right]\right\}$$

The characteristic feature of the heating of the film (or thin layer) for the extent of the larger part of the laser pulse is the fulfilment of the condition

$$h \ll \sqrt{a_1 t} \quad \text{or} \quad \gamma \ll 1 \quad (4)$$

where $\gamma = h/\sqrt{a_1 t}$, and $\sqrt{a_1 t}$ is the layer heated by means of thermal conductivity, which, as a rule, consitsts of $\sim 10^{-4}$ cm for the gigantic laser pulse and $\sim 10^{-2}$ cm for the pulse of free generation.

Here the film temperature with respect to thickness can be considered identical with an accuracy of 10% through time $t_0 \approx 10h^2/a_1$ from the beginning of the pulse. This conclusion follows directly from the expression (3) given above for $\overline{T}_1(x)$ taking condition (4) into account, which is copied from the representations, i.e., when $\sqrt{p} \ll h/\sqrt{a_1}$. It is easy to extend it to the case of the arbitrary spatial distribution of heat sources $q_1(x)$.

For metallic films with thickness $h \approx 1000$ Å $t_0 \sim 10^{-8}$ s, and for semiconductor films - $t_0 \sim 10^{-7}$ s. Consequently, for a description of the stage of heating of the film by radiation when $t > t_0$, it is sufficient to know the total quantity of heat releaseable in it per unit time, which can be expressed in terms of of the incident flux and absorptivity of the film

$$\int_0^h q_1(x)\,dx = IA$$

Then expanding in (3) when $\sqrt{p} \ll h/\sqrt{a_1}$ the exponential terms in series and being limited to the first two terms of the expansion for each series, taking into account $q_0 = IA/h$ for $\bar{T}_1(x)$, we obtain

$$\bar{T}_1(x) \approx \frac{IA\sqrt{a_2}}{p\sqrt{p}\,k_2(1 + \nu h\sqrt{p}/\sqrt{a_1})} + \frac{T_0}{p}$$

Turning to the original [9], we find the solution to the stated boundary value problem of thermal conductivity, which has the form

$$\Delta T(t) = T_1(0,t) - T_0 \approx$$

$$\approx \frac{IA\sqrt{a_2 t}}{k_2}\left\{\frac{2}{\sqrt{\pi}} + \gamma\nu\left[\exp\left(\frac{1}{\gamma^2\nu^2}\right)\operatorname{erfc}\left(\frac{1}{\gamma\nu}\right) - 1\right]\right\} \qquad (5)$$

Quantity $\gamma\upsilon$, which determines the rate of heating of the film, is in fact a ration of the volume specific heats of the film and heated layer of the backing, since $\gamma\nu = \rho_1 c_1 h / \rho_2 c_2 \sqrt{a_2 t}$.

It is obvious that when $\tau \sim 10^{-3}$ s $\gamma\nu \ll 1$, since even for the dielectric (for example, glass) backings $\sqrt{a_2\tau} \gg h$. Then, as follows from expression (5), when $t > t_0\nu^2$

$$\Delta T(t) \approx \frac{2IA\sqrt{a_2 t}}{\sqrt{\pi}k_2} \qquad (6)$$

i.e., the heating of the film with operation of the laser in the mode of free generation is determined basically by the thermal conductivity of the backing to where the heat released in the film is drained. Only the total quantity of absorbed radiation

energy depends on the optical parameters of the film.

Let us examine now the opposite particular case ($\gamma v \geqslant 1$), when the heat transfer into the backing is little. Such a condition is approximately fulfilled for the giant pulse of the laser with heating of the metallic films ($v \geqslant 10$). From inequality $\gamma v \geqslant 1$ if ensues that the boundary of the film with the backing can in this case be considered adiabatic, i.e.,

$$\Delta T(t) \approx \frac{IAt}{\rho_1 c_1 h} \tag{7}$$

It is easy to be convinced that the relation (7) is a particular case of expression (5) when $\gamma v \geqslant 1$.

Thus the heating of the film is determined by its volumetric specific heat if the thermal conductivity of the film is so great that the temperature along its thickness is rapidly equalized, and the thermal conductivity of the backing is so small that the layer heated in it during time t is less than the thickness of the film h.

By using expressions (5)-(7), it is possible to determine the threshold density of energy of the light pulse $Q_0 = I_0\tau$, at which toward the end of the pulse the film is heated to a temperature T_v, which corresponds to the beginning of destruction. The method of calculation of quantity Q_0 is discussed in work [10].

If the initial absorptivity of the film is small, then its gradual increase with an increase in temperature (see equation (1)) can greatly accelerate the heating rate. As the appropriate calculations[5] show, the heating of the film is described in this case by the expressions

$$T(t) = \left(\frac{\varkappa}{\varepsilon} + T_0\right)\exp\left(\frac{I^2\varepsilon^2 a_2 t}{k_2^2}\right)\operatorname{erfc}\left(-\frac{I\varepsilon\sqrt{a_2 t}}{k_2}\right) - \frac{\varkappa}{\varepsilon} \quad \text{when } \gamma v \leqslant 1$$

$$T(t) = \left(\frac{\varkappa}{\varepsilon} + T_0\right)\exp\left(\frac{\varepsilon I t}{h c_1 \rho_1}\right) - \frac{\varkappa}{\varepsilon} \quad \text{when } \gamma v \geqslant 1$$

[5] It is also difficult to conduct these by means of the Lapace transform with respect to time.

where $\varkappa = 3v_0/4c_0$, $\varepsilon = k_0(m_0^*)^{1/2}/3\hbar(\pi N_0)^{1/2}$, where usually $\varepsilon T_0 \gg \varkappa$. Both equations give in the limit the exponential growth of temperature with time.

The uniform and adiabatic heatings of the thin films (or thin layers) with the fulfilment of conditions $\gamma v \gg 1$, $\gamma \ll 1$ make it possible to use them as a convenient object for the study of the kinetics of the heating process of materials by laser radiation, since in this case the results of the experiment compare best of all with the calculated dependences. Actually, when $\gamma \ll 1$ in the equation of thermal conductivity we can disregard the term , which characterized the spatial effects of the equalization of the temperature. As a result this equation becomes an equation of the first order in total differentials, and it can be solved, for example, by taking into account the dependence of not only the optical but the thermophysical parameters of the material on the temperature with an arbitrary law of the distribution of heat sources within the layer and their change with time

$$\frac{dT}{dt} = \frac{A(t)}{c(T)\rho(T)h}\int_0^h q(x',t)\,dx' \qquad (8)$$

As is evident, equation (8) does not include the coefficient of thermal conuctivity of the material, which also simplifies the analysis of the heating of the thin layer. The solution to equation (8) correctly describes the process with an accuracy to moments of time $t_0' = 100h^2/a$, during which the equalization of the temperature within the layer occurs.

The thinner the layer, the greater the "resolving power" with time of the solution of equation (8). For example, if we irradiate in a vacuum (or even in air) a layer of copper 3μm thick, then $t_0' \sim 10^{-5}$ s $\ll \tau \sim 10^{-3}$ s.

Destruction of thin films. The most probable mechanism of the destruction of thin films of absorbing materials under the effect of laser radiation is evaporation.[6] [note: see page 12]

For an analysis of the stage of the process, let us write in general the law of the conservation of energy at each moment

of time

$$IA = \eta_1 v(t) + \rho_1 c_1 \frac{\partial T_1}{\partial t}\Big|_{x=0}\left[h - \int_0^t v(\tau)\,d\tau\right] + \rho_2 c_2 \int_h^\infty \frac{\partial T_2(x,t)}{\partial t}\,dx \quad (9)$$

where η_1 is the heat of evaporation of a unit of volume of substance of the film, $\eta_1 = \eta_0 + \rho_1 c_1 T_1 + \Delta H(T_1)$, where η_0 - the heat of evaporation at 0° K; $\Delta H(T_1)$ - the difference in enthapies of vapor and a solid body; v(t) - rate of movement of the evaporation boundary. Here as usual there are used those same assumptions as in the recording of expression (2). The connection of the evaporation rate with the temperature is given by equation (see [11])

$$v_b(T) = \frac{3}{2e}\frac{\mu \bar{u}^3}{RT}\exp(-\lambda_1/RT)$$

where $\bar{u}$ is the mean velocity of sound in the substance, R - gas constant, $\lambda_1 = \eta_0 \mu/\rho$, μ - molecular weight.

It is obvious that when $h \ll \sqrt{a_2 t}$ the expenditures of heat for evaporation of the film have little effect on the total heat balance, and therfore the film temperature will increase with time in the same way as with the heating without destruction (expression (6)). A stricter condition of the correctness of such an approximation is the fulfilment of the inequality

$$\eta_1 v(t) + \rho_1 c_1 \frac{\partial T_1}{\partial t}\Big|_{x=0}\left[h - \int_0^t v(\tau)\,d\tau\right] \ll \rho_2 c_2 \int_h^\infty \frac{\partial T_2(x,t)}{\partial t}\,dx$$

which is the generalization of criterion $\gamma v \ll 1$ for the case of evaporation of the film.

Then the rate of movement of the boundary of evaporation can be found as

$$v(t) = \frac{\gamma}{\sqrt{t}}\exp(-\beta/\sqrt{t}) - v_c(t)$$

where $\beta = \lambda_1 k_2 \sqrt{\pi}/2IAR\sqrt{a_2}$, $\gamma = 3\mu_1 \bar{u}_1^3 \beta / 2e\lambda_1$, v_c is the rate of condensation, which we will consider equal to zero when $T > T_v$.

As a result the thickness of the evaporated layer of the film will be[7] [note; see page 12 for this footnote]

$$x(t)=\int_0^t v_b(\tau)\,d\tau=2\gamma\beta\left[\mathrm{Ei}(-\beta/\sqrt{t})+\sqrt{t}\exp(-\beta\sqrt{t})/\beta)\right]$$

Since $T_1 \ll \lambda_1/R$, then $v \ll \bar{u}$ and $\beta\sqrt{t} \gg 1$, owing to which

$$x(t)\approx\frac{2\gamma t}{\beta}\exp\left(-\frac{\beta}{\sqrt{t}}\right)=\frac{3\mu_1\bar{u}_1^3}{e\lambda_1}t\exp\left[-\frac{\lambda_1 k_2\sqrt{\pi}}{2IAR\sqrt{a_2 t}}\right] \qquad (10)$$

Using expression (10), it is possible to determine both the time of the destruction of the film with thickness h at the assigned magnitude I and the threshold density of energy necessary for the evaporation of this film during time τ. For example, for the film Cr 1000 Å thick on a glass backing when $\tau = 10^{-3}$ s, the density of the absorbed flow $Q_I \approx 20$ J/cm^2. The maximum temperature of the surface in this case is equal to 3600°K.

If the film is irradiated by the giant pulse of the laser, then in this case the mechanism of its destruction will be the evaporation if $I < \eta_1\bar{u}_1 \sim 10^9$ W/cm^2 [1]. Disregarding the heat transfer to the backing, instead of (8) then we obtain

$$IA\approx\eta_1\frac{B}{T_1}\exp(-\lambda_1/RT_1)+\rho_1 c_1\frac{dT_1}{dt}\left[h-\int_0^t\frac{B}{T_1}\exp\left(-\frac{\lambda_1}{RT_1}\right)dt\right] \qquad (11)$$

Equation (11) describes the kinetics of the film's heating taking into account the expenditures of heat for its evaporation when $\gamma v \geqslant 1$. Usually $\eta_1 > \rho_1 c_1 \Delta T$, and therefore the simplest estimate of the number of parameters can be produced, considering that all the heat goes for the evaporation.

Then the time of the evaporation of the film $t_1 \approx h\eta_1/IA$, the threshold of destruction $I_1 \approx h\eta_1/A\tau$, and the temperature with evaporation is determined from the expression

[6] With poor adhesion of the film to the backing, for the destruction of the covering it is sufficient only to melt the film, after which under the action of forces of surface tension the separate sections of the film are coiled into small "balls" over the whole irradiated surface.

[7] More strictly it would be to consider $x(t)=\int_{t'}^{t} v(\tau)\,d\tau$, where t' is the time of heating of the film to temperature T_v. However, due

$$IA \approx \frac{\eta_1 B}{T_1} \exp(-\lambda_1/RT_1)$$

Thus for the film Cr with a thickness of 1000 Å, when $\tau = 10^{-7}$s $I_1 = 10^7$ W/cm^2, $Q_1 = 1$ J/cm^2, which according to the order of magnitude agrees with the experimental data.

Cooling after the completion of the pulse. If the heating of the film obeyed expression (6), and the destruction was absent, then the cooling of the surfacr after the completion of the pulse is described by the function

$$\Delta T(t) = \Delta T(\tau)\left\{\sqrt{\frac{t}{\tau}} - \sqrt{\frac{t-\tau}{\tau}}\right\}$$

where $\Delta T(\tau)$ is determined by equation (6).

Time t*, according to the elapse of which the temperature of the film consists of ξ - part of $\Delta T(\tau)$ - in this case is equal to $t^* \approx \tau/\xi^2$. It is evident that after the completion of the pulse , in the film for a certain time there are continued processes of possible structural conversions and diffusions of atoms into the backing, i.e., the effective time of the action is always more than the duration of the pulse. As a rule, it is sufficient to select $\xi = 0.1$ in order that the further aftereffect could be disregarded. Here $t^* = 100\tau \sim 10^{-1}$ s.

If the film were heated by a huge laser pulse, then for $t > \tau$

$$\Delta T(t) = \Delta T(\tau)\operatorname{erf}\left[\frac{h}{\sqrt{a_2(t-\tau)}}\right], \qquad t^* \approx \frac{h^2}{\pi a_2 \xi} + \tau$$

When h = 1000 Å and $a_2 = 6\cdot10^{-3}$ cm^2/s (glass) $t^* \sim \tau \sim 10^{-7}$ s, i.e., the cooling occurs very rapidly (this is connected with the small quantity of the heat stored in the film).

[7] to the smallness of quantity $v_b(T)$ when $T < T_v$ the replacement of t' by 0 in expression for x(t) is justified.

Submitted 7 September 1967

Bibliography

1. Анисимов С. И., Бонч-Бруевич А. М., Ельяшевич М. А., Имас Я. А., Навленко Н. А., Романов Г. С. Действие мощных световых потоков на металлы. Ж. техн. физ., 1966, 36, № 7, 1273.
2. Розенберг Г. В. Оптика тонкослойных покрытий. М., Физматгиз, 1958.
3. Соколов А. В. Оптические свойства металлов. М., Физматгиз, 1961.
4. Левич В. Г., Вдовин Ю. А., Мямлин В. А. Курс теоретической физики, т. II. М., Физматгиз, 1962.
5. Мосс Т. Оптические свойства полупроводников. Изд-во иностр. лит., 1961.
6. Гринберг А. А., Мехтиев Р. Ф., Рывкин С. М., Салманов В. М., Ярошецкий И. Д. Поглощение лазерного излучения и разрушение в полупроводниках. Физ. твердого тела, 1967, 9, вып. 5, 1930.
7. Робертс Дж. Теплота и термодинамика. М., Гостехтеориздат, 1950.
8. Карслоу Г., Егер Д. Теплопроводность твердых тел. «Наука», 1964.
9. Диткин В. А., Прудников А. П. Справочник по операционному исчислению. М., «Высшая школа», 1965.
10. Вейко В. П., Имас Я. А., Либенсон М. Н. О нагреве материалов излучением ОКГ. Физ. и хим. обработки матер., 1967, вып. 1, 27.
11. Лейбфрид Г. Микроскопическая теория механических и тепловых свойств кристаллов. М.—Л., Физматгиз, 1963.

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