1. If it is assumed [7] that $\Delta \sim 10r_d$, then the inequality $\hat{r}_0 \gg \Delta$ is satisfied for $\hat{r}_0 \geqslant 10^2$, so that $r_0/\Delta \geqslant 10$. The exception is the case of a cylindrical probe, when $\varepsilon = 1$. Here, inequality (2) should be reinforced: $\hat{r}_0 \geqslant 10^3$.

2. It is not necessary to satisfy condition (3). Equation (1) is valid for both $T_e \gg T_i$ and $T_e = T_i$. It is valid beginning with $\hat{r}_0 > 50$ in the case $\varepsilon = 0$ and beginning with $\hat{r}_0 > 10^2$ (sphere) or $\hat{r}_0 > 10^3$ (cylinder) in the case $\varepsilon = 1$.

3. Condition (4) turns out to be satisfied if $|e\varphi_0/kT_i| > 25$. Somewhat less negative potentials can be used compared to the case $\varepsilon = 1$ (Fig. 2) when $\varepsilon = 0$.

The curves in Figs. 1 and 2 make it possible to select a characteristic probe dimension and potential if the required accuracy of the determination of the concentrations is prescribed in a probe experiment using Eq. (1).

NOTATION

n_i, concentration of ions; I_i, ion current; m_i, mass of ion; T_i, ion temperature; T_e, electron temperature; k, Boltzmann constant; e, electrode charge; S, surface of probe; r_0, radius; φ_0, potential of probe; λ, mean free path; Δ, thickness of space-charge layer; r_d, Debye radius; j, current density; j_B, current density calculated by the Bohm formula.

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HEATING OF THIN FILMS BY LASER RADIATION WITH ALLOWANCE FOR THE TEMPERATURE DEPENDENCE OF THE REFLECTION COEFFICIENT

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We solve the thermophysical problem of the heating of thin metal films on semiconductor substrates by laser radiation for linear and stepwise changes of the absorptivity as a function of the surface temperature.

The laser alloying of semiconductors is a promising method of obtaining p–n junctions. Laser radiation is focused on a semiconductor substrate of gallium arsenide [1] or silicon [2, 3] covered with a film of thickness h ∿ 300-3000 Å of the alloying metal. The calculation of the diffusion of the metal into the semiconductor requires first solving the thermal problem of the heating of a two-layer system by a laser pulse.

The reflectivity of metals depends strongly on the condition of the surface (oxide film, quality of preparation, etc.). An analysis of the experimental data for a clean polished

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metal surface [4-6] shows that the reflectivity depends almost linearly on the temperature over a wide temperature range. This leads to a change of the absorbable energy flux. In [7, 8] the variation of the surface reflectivity was taken into account by a linear function of the time.

We consider the thermophysical problem of the heating of thin metal films on substrates by a square laser pulse of density q_0, W/m^2. We distinguish the thermophysical properties of the metal and substrate by subscripts 1 and 2, respectively. The thermal diffusivities are a_1 and a_2, and the thermal conductivities λ_1, λ_2. We assume that the specific heats c_1, c_2 and the densities ρ_1, ρ_2 are temperature independent. We assume ideal thermal contact between the metal film and the substrate.

The absorption coefficient of metals $\varkappa \sim 10^7 - 10^8$ m^{-1} and the strong absorption of light as given by Bouguer's law [9] show that for films of thickness $h \geqslant 500$ Å no more than 5% of the energy is directly absorbed in the substrate. For films of thickness 500 Å $\leqslant h \leqslant \sqrt{a_1 T_\mathrm{p}}$, where T_p is the pulse duration, we can neglect absorption in the substrate and assume, as shown in [10], that the heat source is uniformly distributed over the thickness of the film. In the one-dimensional approximation the equations for the temperature $T_1(x, t)$ of the metal film and $T_2(x, t)$ of the substrate have the form

$$\frac{\partial T_1}{\partial t} = a_1 \frac{\partial^2 T_1}{\partial x^2} + \begin{cases} \dfrac{q_0}{\rho_1 c_1 h}[A_1 + \beta_1 T_1(0, t)]; & t \leqslant T_\mathrm{p}, \quad (1) \\ 0; & t > T_\mathrm{p};\ 0 \leqslant x < h; \quad (2) \end{cases}$$

$$\frac{\partial T_2}{\partial t} = a_2 \frac{\partial^2 T_2}{\partial x^2};\ h \leqslant x; \tag{3}$$

$$T_1(x, 0) = T_2(x, 0) = 0;$$

$$\frac{\partial T_1(0, t)}{\partial x} = 0; \tag{4}$$

$$\lambda_1 \frac{\partial T_1(h, t)}{\partial x} = \lambda_2 \frac{\partial T_2(h, t)}{\partial x}; \tag{5}$$

$$T_1(h, t) = T_2(h, t); \tag{6}$$

$$T_{2x\to\infty} = 0, \tag{7}$$

where A_1 is the monochromatic absorptivity of the film at time $t = 0$, and β_1 is the change in the absorptivity of the film material when heated 1°K.

Using the fact that the metal film is thin, and taking the Laplace transforms of the temperatures of the film and substrate, we obtain

$$T_1(0, s) \sim \frac{q_0 A_1 \sqrt{a_2}}{\lambda_2 s(\sqrt{s} - d_1)};\ t \leqslant T_\mathrm{p}; \tag{8}$$

$$T_1(0, s) \sim \frac{A_1}{\beta_1}\exp(-sT)\left\{\frac{\exp(d_1^2 T_\mathrm{p})(1 + \operatorname{erf} d_1\sqrt{T_\mathrm{p}})}{\sqrt{s}(\sqrt{s} + d_1)} - \frac{1}{s} + \frac{d_1 \exp(sT_\mathrm{p}) \operatorname{erfc}\sqrt{sT_\mathrm{p}}}{s(\sqrt{s} + d_1)}\right\};\ t > T_\mathrm{p}; \tag{9}$$

$$d_1 = \frac{q_0 \beta_1 \sqrt{a_2}}{\lambda}; \tag{10}$$

$$\overline{T}_1(x, s) = \int_0^\infty T(x, t)\exp(-st)\,dt. \tag{11}$$

Taking the inverse transforms, we obtain for $t \leqslant T_\mathrm{p}$ the dimensionless forms

$$\theta_1(\tau) = \frac{\beta_1}{A_1} T_1(t) = \exp(\tau^2)(1 + \operatorname{erf}\tau) - 1; \tag{12}$$

$$\theta_2(\xi, \tau) = \frac{\beta_1}{A_1} T_2(x, t) = \operatorname{erfc}(\xi - \sqrt{\tau})\exp(\tau - 2\xi\sqrt{\tau}) - \operatorname{erfc}\xi, \tag{13}$$

where

$$\xi = \frac{x - h}{2\sqrt{a_2 t}}; \tag{14}$$

$$\tau = d_1\sqrt{t}. \tag{15}$$

Calculations for $t \geqslant T_p$ give

$$\theta_1(\tau) = \exp(\tau^2)(1 + \operatorname{erf}\tau_0)(1 - \operatorname{erf}\sqrt{\tau^2 - \tau_0^2}) -$$

$$- 1 + \exp(\tau^2)(\operatorname{erf}\tau - \operatorname{erf}\tau_0) + \frac{2}{\pi}\left[\operatorname{arctg}\sqrt{\frac{\tau^2 - \tau_0^2}{\tau_0^2}} - \exp(\tau^2 - \tau_0^2)\int_0^{\operatorname{arctg}\sqrt{\frac{\tau^2-\tau_0^2}{\tau_0^2}}} \exp(-\tau_0^2 \operatorname{tg}^2 U)\, dU\right], \quad (16)$$

where

$$\tau_0 = d_1 \sqrt{T_p}. \quad (17)$$

A program for evaluating such integrals by Simpson's rule is given in [11].

Experimental data on the behavior of the absorptivity of metals after reaching the melting point are reported only in [7]. Judging from the data in [7], the absorptivity of Ag jumps from 0.244 to 0.531 at $T = T_{1mp}$, and varies slowly and linearly with the temperature for $T_1 > T_{1mp}$:

$$A(T_1) = 0.53 + 0.000041(T_1 - T_{1mp}). \quad (18)$$

The temperature distribution for $t = t_1$ up to the time when T_{1mp} is reached has the form

$$T_1(t_1) = T_{1mp} \quad (19)$$

and $T_2(x, t_1) = f(x)$ is given by (13). Since the film is thin, the thermophysical characteristics of the metal do not enter Eqs. (12) and (13). This permits the following approximate formulation of the problem for $t > t_1$:

$$\frac{\partial T_2}{\partial t} = a_2 \frac{\partial^2 T_2}{\partial x^2}; \ x \geqslant h; \ t > t_1; \quad (20)$$

$$-\lambda\left(\frac{\partial T_2}{\partial x}\right)_{x=h} = \begin{cases} q_0\{A_2 + \beta_2[T_2(h, t) - T_{mp}]\}; & t < T_p, \\ 0, & t > T_p; \end{cases} \quad (21)$$

$$T_2(x, t_1) = f(x); \quad (22)$$

$$T(x \to \infty, t) = 0. \quad (23)$$

Employing Green's function for the problem on the half-line with a boundary condition of the second kind, and then taking the Laplace transform of $T_2(x, t)$ for $t < T_p$, we obtain

$$\bar{T}_2(h, s) = \frac{q_0\sqrt{a_2}(A_2 - \beta_2 T_{mp})}{\lambda_2 s(\sqrt{s} - d_2)} \exp(-st_1) +$$

$$+ \frac{A_1}{\beta_1}\left\{\frac{\exp(-st_1)}{\sqrt{s}(d_2 - \sqrt{s})} + \frac{d_1 \operatorname{erfc}\sqrt{st_1}}{\sqrt{s}(\sqrt{s} + d_1)(\sqrt{s} - d_2)} + \frac{\exp(d_1^2 t_1 - st_1)(1 + \operatorname{erf} d_1\sqrt{t_1})}{(\sqrt{s} + d_1)(\sqrt{s} - d_2)}\right\}, \quad (24)$$

where

$$d_2 = \frac{q_0 \beta_2 \sqrt{a_2}}{\lambda_2}. \quad (25)$$

The inverse transform is obtained as for (8). However, for laser alloying of semiconductors the surface temperature of the film should not be much higher than the boiling point of the metal. For such temperature gradients $\beta_2(T_{2bp} - T_{2mp}) \leqslant A_2$ for Ag. This is probably realized in practice for other metals also. Then, setting $d_2 = 0$ in (24), we obtain

$$T_2(h, t) = \begin{cases} \dfrac{2q_0\sqrt{a_2}A_2}{\lambda_2\sqrt{\pi}}\sqrt{t - t_1} + \varphi(t); & T_p > t \geqslant t_1, \\[2ex] \dfrac{2q_0\sqrt{a_2}A_2}{\lambda_2\sqrt{\pi}}(\sqrt{t - t_1} - \sqrt{t - T_p}) + \varphi(t). \end{cases} \quad (26)$$

where $\varphi(t)$ is determined from (16).

Let us consider the heating of a silver film on a silicon substrate. Values of the absorptivity of silver at various temperatures are listed in [7]. For temperatures $T_1 < T_{1mp}$ the processing of these data gives

$$A_1 + \beta_1 T_1(0, t) = 0.037 + 0.000215 T_1(0, t); \ T_1 < T_{1mp}. \quad (27)$$

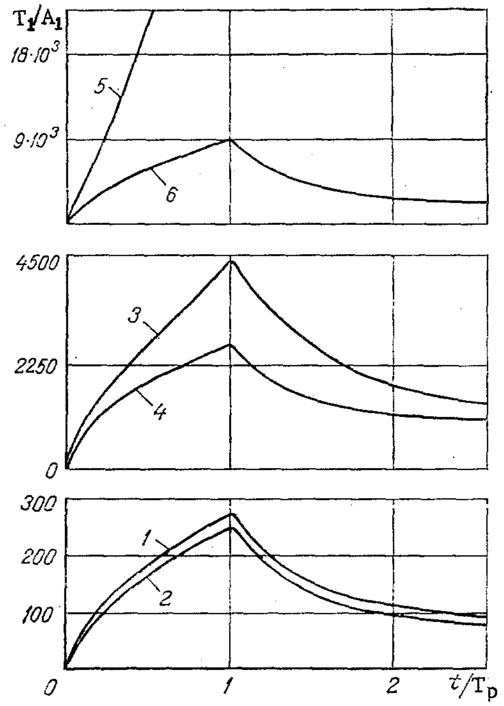

Fig. 1. Dependence of dimensionless temperature of a silver film on a silicon substrate on the dimensionless time t/T_p for a linear dependence of the absorptivity on temperature: 1) $q_0 = 10^{10}$ W/m²; 3) 10^{11}; 5) 3×10^{11}, and for a constant value of the absorptivity: 2) $q_0 = 10^{10}$ W/m²; 4) 10^{11}; 6) 3×10^{11}.

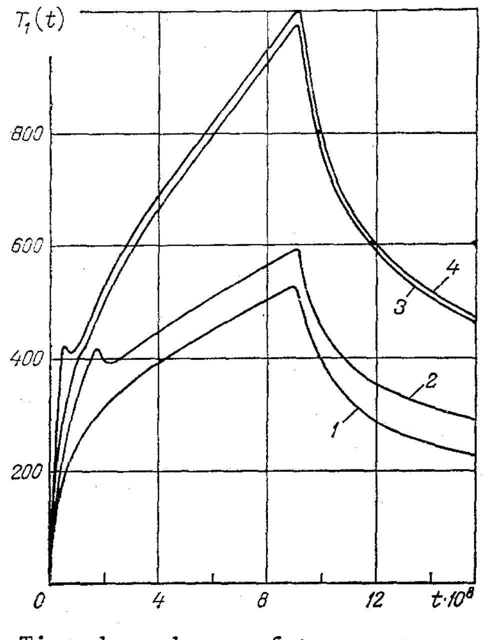

Fig. 2. Time dependence of temperature of a zinc film on gallium arsenide when irradiated with $\lambda = 0.69$-μm ruby laser radiation with $T_p = 9 \times 10^{-8}$ sec for a linear variation of the absorptivity from 0.2 to 0.1 at the melting point: 1) $q_0 = 4 \times 10^{11}$ W/m²; 3) 8×10^{11}, and for a stepwise change of the absorptivity from 0.2 to 0.1 at the melting point: 2) $q_0 = 4 \times 10^{11}$ W/m²; 4) 8×10^{11}. t is in sec.

Figure 1 shows the dimensionless temperature T_1/A_1 as a function of the time t/T_p for a pulse duration $T_p = 5 \times 10^{-8}$ sec and $q_0 = 10^{10}$ (curve 1), 10^{11} (curve 3), and 3×10^{11} (curve 5). For comparison the figure also shows the time dependence of T_1/A_1 for $\beta_1 = 0$ and the same values of q_0 (curves 2, 4, and 6, respectively). The figure shows that an increase in the flux leads to a sharp temperature increase as a result of the increase of absorptivity. Finally, for certain metals the absorptivity decreases as the temperature is increased to T_{1mp}. Thus, under the action of $\lambda = 1.06$-μm radiation the absorptivity of zinc decreases from 0.35 to 0.05. When zinc is irradiated with $\lambda = 0.69$-μm ruby laser radiation, the absorptivity decreases from 0.2 to 0.1 [12]. In this case Eqs. (12), (13), (16), and (26) with $\beta_1 = 0$ are applicable. The graphs in Fig. 2 show the time variation of the temperature of a thin Zn film on gallium arsenide when irradiated with a long pulse (T_p = 90 nsec) of $\lambda = 0.69$-μm ruby laser radiation. Curves 1 and 3 correspond to heat flux densities $q_0 = 4 \times 10^{11}$ and 8×10^{11} W/m², and were calculated for a linear variation of the reflectivity up to the melting point for $T_1 < T_{1mp}$; $A_2 = \text{const} = 0.1$.

Curves 2 and 4 correspond to a stepwise change of reflectivity from 0.8 to 0.9 for $T_1 > T_{1mp}$ and heat flux densities 4×10^{11} and 8×10^{11} W/m². For a stepwise change of reflectivity (curves 2, 4) at $T_1 = T_{1mp}$ there is a minimum of the temperature as a result of the sharp decrease of the heat flux. Unfortunately, problem (1)-(7) does not take account of the latent heat. The corresponding Stefan problem should emphasize still more clearly the presence of a minimum at $t = t_{mp}$. The relations derived permit the calculation of the film and substrate temperatures for a linear dependence of the reflectivity of the film on the temperature.

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