Production of a periodic heterophase semiconductor-metal surface structure by laser illumination

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(Submitted 18 January 1988)
Zh. Eksp. Teor. Fiz. **94**, 50–60 (December 1988)

The production of a periodic structure in the form of alternate bands of metal and semiconductor on the surface of a semiconductor, by exposure to intense laser radiation, is investigated for the first time. The development of an instability in the uniform surface distribution of temperature and nonequilibrium carrier concentration in the solid semiconductor gives rise to a seed structure (with a period $d \sim \lambda$), which contains bands of metal of infinitesimal width. These bands are either semiconductor melts or nonequilibrium solid metallic states produced by the laser radiation. The subsequent evolution of the periodic structure is investigated by performing a rigorous numerical solution of the electrodynamic problem of diffraction of laser radiation by the heterophase structure. The electrodynamic perturbation theory that is normally employed to investigate surface periodic structures is not valid under these conditions. It is shown that diffraction produces a redistribution of energy between the semiconductor and metal bands on the surface. Maximum energy release occurs in the semiconducting region near the separation boundary with the metal. This gives rise to a discontinuous increase in the width of the seed metal bands up to about $0.4d$–$0.5d$ (depending on the optical parameters of the material) when the laser radiation reaches a critical intensity. This behavior has been confirmed experimentally.

When intense laser radiation is allowed to interact with a semiconductor, a periodic structure is formed on its surface. The period of this structure is determined by the wavelength of the initiating radiation.[1,2] There is a whole series of positive feedback mechanisms whereby the anomalous penetration of electromagnetic radiation into a periodic structure with a particular period (Wood anomalies) gives rise to the growth of initial perturbations with the same period. Which particular mechanism predominates depends on the particular experimental conditions. Several ways in which the periodic structure can evolve were identified in Ref. 3, depending on the energy of the incident radiation.

The most extensively investigated periodic structures are those produced when the energy input is sufficient for the uniform melting of the surface layer of the target material. Positive feedback mechanisms, and the initial linear stage of the growth of the periodic structure, have been investigated in detail.[1] Several publications devoted to the nonlinear evolution of the periodic structure under these conditions have recently appeared.[4–6] When the incident energy is below the melting threshold, the periodic structure is formed in the solid semiconducting phase.[1,7–10] The periodic structure can then be due either to the modulation of the properties of the semiconductor in the surface region on a plane separation boundary[7–10] or to corrugation of the surface.[1]

On the other hand, the intermediate stage, in which the periodic structure is formed by alternate bands of melt and solid phases, has been observed experimentally,[3,11] but has not, so far, received an adequate theoretical description because of difficulties in solving the electrodynamic problem for this type of structure. The optical parameters of the initial semiconducting phase and the metallic melt are very different, which means that perturbation theory cannot be used to calculate the field in the structure. In this paper, we investigate the intermediate stage by performing a rigorous numerical solution of the problem of diffraction of electromagnetic radiation by a heterophase periodic structure. Studies of this stage are important for the correct understanding of the theories of successive stages of formation of the periodic structure as the radiation energy increases. In a wider sense, this is also an investigation of the melting of semiconductors by coherent laser radiation.

It is shown in Refs. 8 and 9 that, under the influence of laser radiation, the homogeneous state of a semiconductor becomes unstable against the formation of a periodic distribution of electron-hole pairs of concentration $n(x)$ and temperature $T(x)$ as the incident energy is increased beyond a critical value. For normally incident laser radiation, the period of the structure is $d \sim \lambda$ and its wave vector points in the direction of the electric vector in the light wave. Local melting occurs when the temperature exceeds the melting point. Melts of typical semiconductors such as germanium, silicon, and gallium arsenide are metals. A periodic structure produced by temperature modulation will transform for particular incident radiation energy, into a periodic structure consisting of bands of metallic melt embedded in the semiconducting hosts.

The effect of laser radiation on a semiconductor does not always reduce to a simple heating of the surface layer. Experiments reported in Ref. 12 reveal the formation of a solid metallic state on the surface of indium antimonide when the latter is placed in liquid nitrogen and exposed to laser illumination. This phase transition may be due to the excitation of a sufficient quantity of nonequilibrium hole pairs.[8] During the initial stage of the process, the significant factor is the instability of the homogenous surface distribution of pair concentration. The development of this instability is accompanied by the appearance on the surface of periodically distributed bands of the solid metallic phase. Their subsequent evolution is determined by the character of the redistribution of radiation in the structure. From the point of view of electrodynamics, this structure is completely analogous to that formed as a result of local melting. To be specific, we shall consider a periodic structure formed as a result of

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local melting, bearing in mind the fact that the results will also be valid for the description of the evolution of the structure in the case of the nonthermal mechanism of the semiconductor-metal phase transition under laser illumination.

The optical parameters of metallic and semiconducting phases are significantly different, and the formation of the bands of metal on the surface produces a radical change in the conditions under which radiation penetrates the sample. It follows that, to elucidate the subsequent evolution of the structure, we must know the distribution of the radiation flux in the modified structure. We shall confine our attention to the electrodynamic problem, assuming that the character of the variation in the state of the material at a given point x on the surface can be deduced if we know the radiation flux $P(x)$ penetrating the sample at the point x.

Under typical conditions, a periodic surface structure is observed when the depth h of the melt is usually less than 0.1 μm. The change in the density of the material during melting is 10% in the case of silicon and 5% in the case of germanium. It follows that the depth of the surface variations when the bands of the alloy are formed is at most 0.01 μm and can be neglected when the electrodynamic problem is being solved, i.e., the surface of the sample can be assumed to be flat. We thus arrive at the structure illustrated in the insert in Fig. 1: bands of the alloy with permittivity ε_2 and width c lie on the surface of the semiconductor with permittivity ε_3. We wish to determine whether the width of the seed band of the alloy can be increased by redistributing the radiation within the structure.

The solution of the diffraction problem for the structure shown in Fig. 1 will be obtained by using the integral form of the exact theory of diffraction for multilayered periodic structures.[13] The assumed absence of corrugation on the surface of the sample resulted in a significant simplification of the problem and enabled us to reduce it to the solution of a single integral equation. Were it not so, we would have had to solve a set of *two* integral equations.

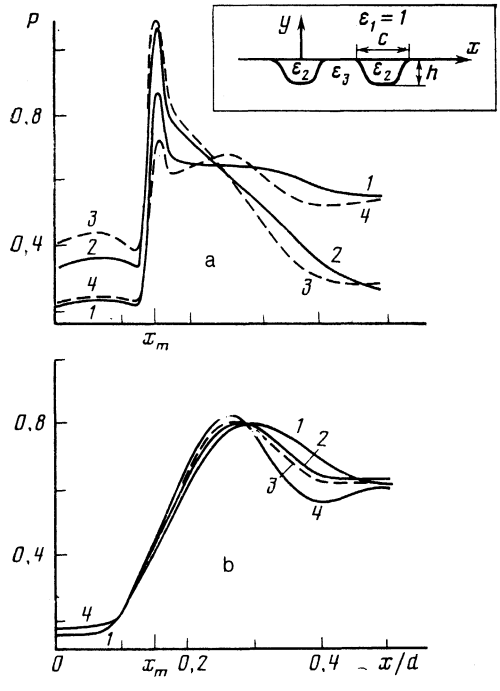

FIG. 1. Flux distribution $P(x)$ penetrating a periodic structure on the surface of germanium for $\lambda = 1.06$ μm, $c = 0.3d$, $h = 0.05\lambda$, and size of transition region $a = 0.05d$; a—TE-polarization, b—TH-polarization for the following values of d/λ: 1—0.9; 2—0.98; 3—1.00; 4—1.10. The insert shows the geometry of the structure under investigation.

Let us first briefly describe how the initial diffraction problem can be reduced to an integral equation. The necessary condition for using the integral form is that each of the layers of the structure be continuous. We shall therefore assume that the melt covers the entire surface of the sample, but its thickness h_m outside the actual bands (for $|x| > c/2$) will be assumed infinitesimal. This leads us to the following problem: there are two separation boundaries, namely, melt-vacuum at $y = 0$ and melt-solid semiconductor at $y = f(x)$, where $f(x) = f(x + d)$ and the period is $d \sim \lambda$. The integral form of the exact theory of diffraction is based on the use of Green's formula which enables us to express the field throughout space in terms of its values u_Γ and their normal derivatives du_Γ/dn on the separation boundary between the media. The integral equations for u_Γ and du_Γ/dn are obtained by evaluating the limiting values of the field obtained by using Green's formula for each of the media and allowing the point of observation to approach the separation boundary. When there is only one corrugated boundary, this procedure leads to a set of *two* integral equations. They have to be solved by numerical methods and require considerable amounts of computer storage and running time. We shall therefore use a variant of the integral formalism that enables us to reduce the problem to the solution of a single integral equation. The method essentially consists of replacing the two unknown functions u_Γ and du_Γ/dn with a combination of them. The method is based on the successive solution of auxiliary problems in which either the fields or their normal derivatives have a discontinuity across the separation boundary. The following proposition is then valid.[14]

Consider a periodic profile $y = f(x)$ that separates two half-spaces in which the electromagnetic field satisfies the same equation, namely,

$$\Delta u_j + k_j^2 u_j = 0, \tag{1}$$

and the field and its derivative along the normal n to the surface $y = f(x)$ have the following discontinuities across the surface:

$$\tau(x) = u_+(x, f(x)) - u_-(x, f(x)),$$
$$\eta(x) = \frac{du_+}{dn}(x, f(x)) - \frac{du_-}{dn}(x, f(x)). \tag{2}$$

The field throughout space can then be written in the form

$$u(x,y) = \int_0^d G^{(j)}(x-x', y-f(x'))\,\eta(x')\,[1+f'^2(x')]^{1/2}\,dx'$$
$$+ \int_0^d \frac{dG^{(j)}}{dn}(x-x', y-f(x'))\,\tau(x')\,[1+f'^2(x')]^{1/2}\,dx' \tag{3}$$

and the Green function is given by[14]

$$G^{(j)}(x,y) = \frac{1}{2id}\sum_{n=-\infty}^{\infty} \frac{1}{\beta_n^{(j)}} \exp[i\alpha_n x + i\beta_n^{(j)}\,|y|], \tag{4}$$

where

$$\alpha_n=\frac{2\pi}{\lambda}\left(\sin\theta+\frac{n\lambda}{d}\right),\quad \beta_n^{(j)}=(k_j^2-\alpha_n^2)^{1/2},\quad k_j^2=\left(\frac{2\pi}{\lambda}\right)^2\varepsilon_j,$$

and θ is the angle of incidence of the radiation.

The field above the flat surface of the sample for $y>0$ can be written in the form of the Rayleigh series ($\varepsilon_1=1$):

$$u_1(x,y)=\exp(i\lambda_0 x-i\beta_0^{(1)}y)+\sum_{n=-\infty}^{\infty}B_n^{(1)}\exp(i\alpha_n x+i\beta_n^{(1)}y), \tag{5}$$

where $B_n^{(1)}$ are the amplitudes of the diffracted radiation. We assume that the amplitude of the radiation falling on the sample is equal to unity and that the plane of incidence is the xy plane.

To find the field in the structure, we consider the following auxiliary problems. The first problem is: consider an electromagnetic field u_2 for $y<0$, which satisfies (1) at all points for $j=2$, coincides with the required field u for $y>f(x)$, and is continuous across the separation boundary $y=f(x)$. The solution of this problem can be written down using (3) with $\tau(x)=0$. The presence of the flat boundary at $y=0$ can be taken into account by adding to (3) the field reflected into the sample, which has the form of the Rayleigh series

$$\delta u_2=\sum_{n=-\infty}^{\infty}A_n^{(2)}\exp(i\alpha_n x-i\beta_n^{(2)}y). \tag{6}$$

Let $\Phi(x)$ be the discontinuity in the normal derivative du_2/dn in the first auxiliary problem. The field for $y>0$ has the form indicated by (5), and the following boundary conditions must be satisfied on the $y=0$ surface, since u_2 is identical with the true field for $y>f(x)$:

$$u_1(y=0)=u_2(y=0),\quad \frac{1}{c_1}\frac{du_1}{dy}\Big|_{y=0}=\frac{1}{c_2}\frac{du_2}{dy}\Big|_{y=0}, \tag{7}$$

where $c_j=1$ for TE radiation (electric vector $\mathbf{E}$ of the light wave perpendicular to the wave vector $\mathbf{Q}$ of the periodic structure under consideration) and $c_j=\varepsilon_j$ for the TH polarization ($\mathbf{H}\perp\mathbf{Q}$). The conditions defined by (7) enables us to express $B_n^{(1)}$ and $A_n^{(2)}$ in terms of the function $\Phi(x)$ that we have introduced. In particular,

$$B_n^{(1)}=\frac{1}{(c_1/c_2)\beta_n^{(2)}+\beta_n^{(1)}}\left\{\frac{c_1}{idc_2}\int_0^d\Phi(x)\exp[-i\alpha_n x-i\beta_n^{(2)}f(x)]\right.$$
$$\left.\times[1+f'^2(x)]^{1/2}dx-[(c_1/c_2)\beta_0^{(2)}-\beta_0^{(1)}]\delta_{n0}\right\}. \tag{8}$$

Having expressed $A_n^{(2)}$ in terms of $\Phi(x)$, we find the limiting values of the field u_2 and the derivative along the normal to $y=f(x)$ as the point of observation approaches the surface from above, i.e., as $y\to f(x)+0$. These quantities are eventually given by integrals of the function $\Phi(x)$. If we recall that the solution of the first auxiliary problem for $y>f(x)$ is identical with the required field u, and if we use the matching conditions for u across a corrugation $y=f(x)$ such as that defined by (7), we find an expression for the limiting value of the true field u in terms of $\Phi(x)$ as $y\to f(x)-0$.

We now turn to the second auxilary problem. Suppose that a field u_3 satisifies (1) at all points for $j=3$, vanishes above the corrugation, and is equal to the true field u for $y<f(x)$. Using the results of the first auxiliary problem, we can now find the expressions for $\tau_3(x)$ and $\eta_3(x)$. Substituting these expressions in (3), we obtain u_3 at all points. Next, we find the limiting value of u_3 as $y\to f(x)+0$, and equate it to zero (this is a necessary condition in the second auxiliary problem). As a result, we obtain the following integral equation for the function $\bar{\Phi}(x)\equiv\Phi(x)[1+f'^2(x)(x)]^{1/2}\exp(-i\alpha_0 x)$:

$$\int_0^d dx'\left\{\frac{G^{(2)}(x,x')}{2}+\frac{c_3}{c_2}\frac{G^{(3)}(x,x')}{2}+\int_0^d dz\left[N'^{(3)}(x,z)G^{(2)}(z,x')\right.\right.$$
$$\left.\left.+\frac{c_3}{c_2}G^{(3)}(x,z)N^{(2)}(z,x')\right]\right\}\bar{\Phi}(x')+\int_0^d dx'\left[N'^{(3)}(x,x')F_i(x')\right.$$
$$\left.+\frac{c_3}{c_2}G^{(3)}(x,x')\frac{dF_i}{dn}(x')\right]+\frac{1}{2}F_i(x)=0, \tag{9}$$

where

$$G^{(2)}(x,x')=\frac{1}{2id}\sum_{n=-\infty}^{\infty}\frac{1}{\beta_n^{(2)}}\exp\Big[inQ(x-x')$$
$$\times\left\{\exp[i\beta_n^{(2)}|f(x)-f(x')|]\right.$$
$$\left.+\frac{(c_1/c_2)\beta_n^{(2)}-\beta_n^{(1)}}{(c_1/c_2)\beta_n^{(2)}+\beta_n^{(1)}}\exp[-i\beta_n^{(2)}(f(x)+f(x'))]\right\}, \tag{10}$$

$$N^{(2)}(x,x')=\frac{1}{2d}\sum_{n=-\infty}^{\infty}\exp[inQ(x-x')]$$
$$\times\left\{\left[\operatorname{sign}(f(x)-f(x'))-\frac{\alpha_n}{\beta_n^{(2)}}f'(x)\right]\right.$$
$$\times\exp[i\beta_n^{(2)}|f(x)-f(x')|]-\left[1+\frac{\alpha_n}{\beta_n^{(2)}}f'(x)\right]$$
$$\left.\times\exp[-i\beta_n^{(2)}(f(x)+f(x'))]\right\}, \tag{11}$$

$$G^{(3)}(x,x')=\frac{1}{2id}\sum_{n=-\infty}^{\infty}\frac{1}{\beta_n^{(3)}}$$
$$\times\exp[inQ(x-x')+i\beta_n^{(3)}|f(x)-f(x')|], \tag{12}$$

$$N'^{(3)}(x,x')=\frac{1}{2d}\sum_{n=-\infty}^{\infty}\left[\operatorname{sign}(f(x)-f(x'))-\frac{\alpha_n}{\beta_n^{(3)}}f'(x')\right]$$
$$\times\exp[inQ(x-x')+i\beta_n^{(3)}|f(x)-f(x')|], \tag{13}$$

$$F_i(x)=\frac{2\beta_0^{(1)}}{(c_1/c_2)\beta_0^{(2)}+\beta_0^{(1)}}\exp[-i\beta_0^{(2)}f(x)], \tag{14}$$

$$dF_i(x)/dn=-i(\beta_0^{(2)}+\alpha_0 f'(x))F_i(x), \tag{15}$$

$$Q=2\pi/d.$$

Having solved (9), we can calculate the field diffracted by

the structure through all space. Using (5) and (8), we obtain the radiation flux distribution $P(x)$ that enters the sample over the $y=0$ surface. It is readily shown that, for both polarizations, $P(x)$ can be written in the form

$$P(x)=\frac{c}{8\pi}\operatorname{Re}[\mathbf{EH}^*]_y=-I_0\operatorname{Im}\left(u_1^*\frac{\partial u_1}{\partial y}\right)\Big|_{y=0}, \qquad (16)$$

where I_0 is the incident intensity.

In addition to $P(x)$, we shall calculate the radiation flux $P_f(x)$, crossing the currugated surface $y=f(x)$. Comparison of P with P_f for $|x|>c/2$ then enables us select the parameters of the computational scheme and, in particular, to establish the criterion of the convergence of the results as $h_m\to 0$.

Equation (9) was solved numerically, using the method described in Ref. 14. We note that the kernel of this integral equation is singular for $x\to x'$. The numerical solution of (9) and, consequently, the quantities $B_n^{(1)}$ in (8) were therefore calculated subject to a certain error. To find the flux $P(x)$, we must sum the Fourier series (5) for $y=0$ with the coefficients subject to this error. This procedure turns out to be incorrect, so that the summation was performed with stabilization according to Tikhonov.[15] The regularization parameter was chosen using the values of $p_f(x)$ for $|x|>c/2$. This enabled us to avoid fictitious oscillations on $P(x)$, due to the instability in the summation of the series, without losing, as a result of smoothing, the true singularities in the flux distribution $P(x)$. The parameters of the computational scheme for solving (9) were chosen using the convergence condition for the results.

Since the output quantity in our computations was the integral characteristic $P(x)$, and the conclusions were expected to be qualitative in character, we took $f(x)$ in the form of a simple model function. The actual results are not very sensitive to the form of $f(x)$ and are governed by parameters such as the width c and thickness h of the melt band and the size a of the transition region. Most of the calculations were performed for $f(x)$ defined as follows:

$$f(x)=\begin{cases}-h-h_p, & |x|<c/2-a,\\ -\frac{h}{2}-h_p+\frac{2h}{a}z\left[\frac{15}{16}-\frac{5}{2}\left(\frac{z}{a}\right)^2+3\left(\frac{z}{a}\right)^4\right], & \frac{c}{2}-a<|x|<\frac{c}{2},\\ -h_p, & c/2<|x|<d/2,\end{cases} \qquad (17)$$

where $z=x-(c-a)/2$.

In addition, the calculations were repeated with the transition region in (17) replaced with

$$f(x)=\frac{h}{2}\sin\frac{\pi z}{a}. \qquad (18)$$

The results obtained for these two model functions were not very different, but the advantage of (17) was the continuity of $f(x)$ and its first two derivatives, which improved the convergence of the numerical method.

We shall now confine our attention to normally incident radiation. The computation was performed for radiation with $\lambda=1.06\,\mu$m on germanium or silicon, and radiation with $\lambda=0.53\,\mu$m on silicon. The permittivities were as follows: for germanium $\varepsilon_2=-32+72i$ (Ref. 3), $\varepsilon_3=16+0.8i$ (Ref. 16), for silicon $\varepsilon_2=-16.8+21.6i$ (Ref. 17), at $\lambda=0.53\,\mu$m (Ref. 16) and $\varepsilon_2=-14.7+63i$ (Ref. 17) and $\varepsilon_3=12.25+7\cdot10^{-4}i$ (Ref. 16) at $\lambda=1.06\,\mu$m. Our problem was to calculate the flux $P(x)$ for a varying width c of the melt. The width c increases for given energy of the initiating radiation if there are regions in the semiconducting part in which the flux is higher than the flux P_s in the case of the homogeneous semiconducting surface. A thermophysical calculation has to be performed to determine the specific flux difference for which a melt is produced at a given point on the surface. We shall not do this here and will deduce that an increase in c has taken place from the mere fact that the flux has exceeded P_s.

It is well known that the modulation of the flux penetrating the corrugated surface of a homogeneous material,[1,2,5] or crossing a surface with periodic distribution of permittivity,[7,8] has a well-defined resonant character. It is therefore interesting to examine the resonance properties of the periodic structure consisting of bands of the melt. Figure 1 shows $P(x)$ for different values of the period, obtained by the above method in the case of germanium with $c=0.3\,d$ and $\lambda=1.06\,\mu$m. We note the dependence of $P(x)$ on d is different for different polarizations. Thus, for the TE polarization, the variation is monotonic as d increases, but a resonance occurs near $d\sim\lambda$ in the case of the TH polarization. For the TE polarization, and for TH well away from resonance, the flux $P(0)$ penetrating the metal is close to that penetrating the homogeneous material, $P_m=1-R_m=0.22$. On the other hand, in the semiconducting region, the value $P(d/2)$ is close to the flux penetrating the homogeneous semiconductor, i.e., $P_s=1-R=0.64$ (R_m and R_s are the reflection coefficients of the melt and solid phase, respectively). Diffraction by the structure results in redistribution of flux near the separation boundary x_m between the melt and the semiconductor (the position of this boundary is indicated in Fig. 1). The resonance near $d\sim\lambda$ in the case of the TH polarization takes the form of a substantial change in the flux $P(d/2)$ entering the semiconductor, an increase in the maximum near the separation boundary, and an increase in the flux entering the metal. These last two factors facilitate the increase in the width c of the initial band of melt. The dependence of $P(x)$ on d has a similar character for each values of c. The resonance value of d varies slightly with c. Because of this, the subsequent calculations were performed for $d=0.98\lambda$.

Before we turn to an analysis of the evolution of the periodic structure, let us consider the dependence of the shape of $P(x)$ on the parameters of the model function $f(x)$. Figure 2 shows a family of $P(x)$ curves for different h, $a=0.05d$, and $a=0.10d$ (Ge, $\lambda=1.06\,\mu$m). For $a=0.05d$ and small h, the function $P(x)$ has a characteristic form, namely, there are two flux maxima P_1 and P_2 near the separation boundary x_m when $x_m=0.15d$. As h increases, the position of P_1 shifts toward the semiconducting region, and P_2 vanishes. For $a=0.1d$, the maximum P_2 is better defined and does not vanish with increasing h, whereas P_1 lies in the

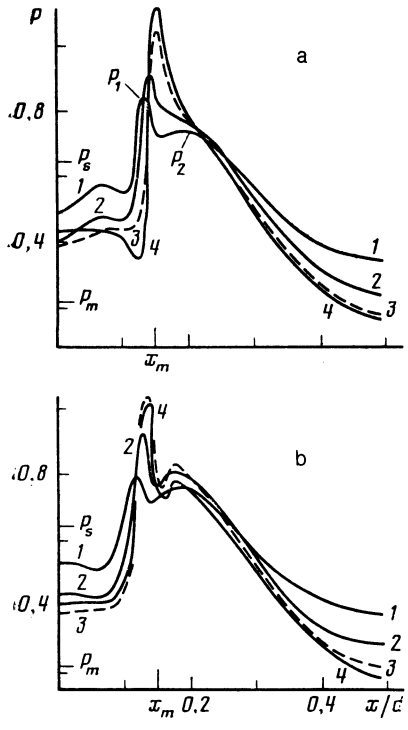

FIG. 2. Distribution $P(x)$ in germanium for $a = 0.05d$ (a) and $a = 0.1d$ (b), $d = 0.98\lambda$, and $c = 0.3d$ for the following values of h/λ: 1—0.01; 2—0.02; 3—0.04; 4—0.06.

metallic region for all h. The oscillating behavior of $P(x)$ near the separation boundaries is actually due to diffraction by an edge, so that these features are sharper as the width of the transition region a is reduced and are enhanced by an increase in h.

Despite the difference in the behavior of $P(x)$ near the boundary for different a, the curves shown in Figs. 2a and 2b have much in common. Somewhere near the boundary x_m, the flux penetrating the semiconductor is found to be higher than P_s. The coordinate x_0 of the point at which $P(x_0) = P_s$ is not very sensitive to h and has a similar value for both values of a ($x_0 = 0.26d$ for $a = 0.05d$ and $x_0 = 0.27d$ for $a = 0.1d$). The flux $P(0)$ penetrating the melt and the flux $P(d/2)$ at the center of the semiconducting region are not very dependent on a; beginning with $h = 0.02\lambda$, these values are not very dependent on h (the depth δ penetrated by light in germanium is $1.1\times10^{-2}\lambda$ for $\lambda = 1.06\ \mu$m). Since the

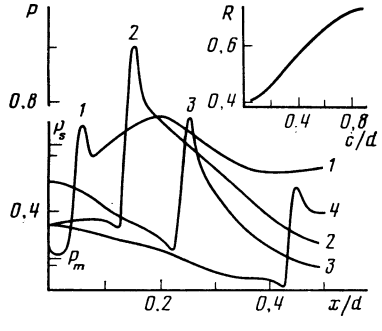

FIG. 3. The function $P(x)$ in germanium for $h = 0.05\lambda$, $d = 0.98$, and the following values of c/d: 1—0.1; 2—0.3; 3—0.5; 4—0.9. The insert shows the reflection coefficient as a function of c.

change in the state of matter at a given point x on the surface is determined not only by the local value of $P(x)$, but also by heat transfer to neighboring regions, sharp features on $P(x)$ near x_m are smoothed out. The evolution of the periodic structure is not therefore very dependent on the size a of the transition region or the thickness h of the melt. Because of this, we confined subsequent calculations to $h = 0.05\lambda$ and $a = 0.05d$.

Figure 3 shows $P(x)$ for different c in the case of germanium and $\lambda = 1.06\ \mu$m. When c is small (curve 1), there are two well-defined flux maxima P_1 and P_2. Only P_1 survives after $c = 0.2d$ has been reached, and lies in the semiconducting region at the point x_{max} in the immediate neighborhood of x_m. The value of P_1 initially increases with c, reaches a maximum at $c = 0.2d$, and then declines. The fact that the position of the flux maximum shifts toward the semiconducting region as c increases results in a positive feedback situation: an increase in the width of the metallic band leads to a shift of the flux maximum which gives rise to stronger heating of the region and, consequently, an increase in c and a further shift of x_{max}. The increase in c continues until P_1 reaches its critical value P_{crit} which is determined by P_s and the thermophysical parameters of the material. In principle, P_{crit} can be either somewhat higher or lower than P_s because of the diffusion of heat in the system.

To be specific, we shall now assume that $P_{crit} = P_s$. Figure 3 then shows that the result of the above mechanism is that the periodic structure produced by modulation of the permittivity of the solid semiconducting phase when critical intensity is exceeded undergoes a discontinuous transition to a periodic structure consisting of bands of the melt on the surface of the semiconductor with $c = c_{crit} = 0.5d$. An interesting property is that, as c varies from zero to c_{crit}, the coordinate of the point at which $P = P_s$ holds remains almost constant. An increase in c above c_{crit} leads to a reduction in P_{max} below P_{crit}, and to a reduction in the flux entering the melt in the neighborhood of x_m. This ensures that even an increase in the energy of the initiating radiation within a certain range will not lead to an increase in c above c_{crit}.

The insert in Fig. 3 shows the dependence of the reflection coefficient on the structure under consideration. The nonlinearity of $R(c)$ is relatively weak, i.e., the resultant reflection is formed by an almost additive contribution of the metallic and the semiconducting segments. The discontinuous increase in c, on the other hand, is due to diffractive redistribution of energy both between the metallic and semiconducting regions and wiithin the semiconducting region.

Figures 4 and 5 show the functions $P(x)$ for silicon at $\lambda = 1.06\ \mu$m and $\lambda = 0.53\ \mu$m. For $\lambda = 1.06\ \mu$m, the shape of the $P(x)$ curve is very similar to that for germanium (Fig. 3). The difference is that, in the case of silicon, the maximum P_2 extends up to $c = 0.4d$ and the maximum value of P_1 is reached for $c = 0.3d$. The critical value c_{crit}, on the other hand, is of the order of $0.5d$, just as in the case of germanium. For $\lambda = 0.53\ \mu$m in silicon (Fig. 5), the relationship between P_1 and P_2 is different. The position of P_1 shifts to the metallic region, and a flux maximum is observed at x_m on the boundary of the melt. Moreover, for $c = 0.1d$, the value of the flux at this point, P_{min}, is less than P_{crit}, but, on the other hand, the flux into the melt is then significantly greater than P_m. As already noted, the state of the material is determined by $P(x)$ and by the diffusion of heat from neighboring

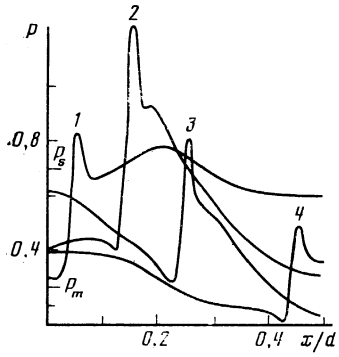

FIG. 4. Flux distribution $P(x)$ in the case of silicon illuminated by radiation with $\lambda = 1.06\,\mu$m, $a = 0.05d$, $h = 0.05\lambda$, and $d = 0.98\lambda$ for the following values of c/d: 1—0.1; 2—0.3; 3—0.5; 4—0.9.

regions. The width of the initial "fluctuation band" of the melt can therefore increase in this case. For larger values of c, on the other hand, $P_{\min}$ exceeds P_{crit}, and this definitely assures a further increase of c up to $c_{\text{crit}} = 0.4$ for which $P_2 = P_{\text{crit}}$.

An interesting feature of all these cases is that the flux penetrating the metallic regions is found to be greater than P_m because of diffractive redistribution of energy. The ratio $P(0)/P_m$ can reach 2 or more. This effect facilitates the increase in the width of the bands of melt due to the diffusion of heat from the metallic to the semiconducting regions. The increase in $P(0)$ for small c is an indication that the homogeneous state of the semiconductor may be unstable against the formation of periodically distributed bands of the melt, even without taking into account the formation of the periodic structure by the modulation of permittivity in the solid semiconducting phase.

This feature of the penetration of radiation into the above structure can lead to an interesting effect in a material in which a nonthermal transition to the metallic state is possible.[8] When the radiation intensity reaches its critical value I'_{crit} in this case, a periodic structure consisting of bands of nonequilibrium solid metallic phase begins to form on the surface. The significant point is that I'_{crit} is less that I_{crit} (necessary for the appearance of local melt regions). On the other hand, an increase in the flux into the metal, due to the diffractive redistribution of radiant energy, can lead to a

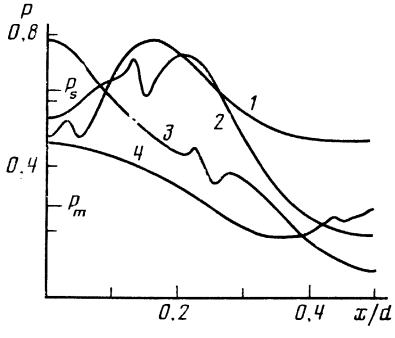

FIG. 5. The function $P(x)$ for $\lambda = 0.53\,\mu$m in the case of silicon, $h = 0.05\lambda$, $a = 0.05d$, and $d = 0.98\lambda$ for the following values of c/d: 1—0.1; 2—0.3; 3—0.5; d—0.9.

higher temperature of the metallic phase and to its thermal melting. Local regions of the melt can therefore form for radiant energy below the melting threshold. The important point is that this occurs via an intermediate nonequilibrium metallic state. This type of effect would impede the observation of nonthermal phase transitions under the influence of laser radiation. The diffractive redistribution of energy in the structure thus seems to lead to the threshold appearance of bands of the melt of finite width $c = c_{\text{crit}}$. The fact that the qualitative features of this process are not very dependent on the particular values of the permittivity of the melt enables us to use our results to explain the experiment reported in Ref. 11, where a sudden increase was observed in the fraction f_m of the melt on the surface of silicon exposed to radiation with $\lambda = 10.6\,\mu$m. Our analysis enables us to describe the first step on f_m (I) as being due to the formation of a periodic structure with $d \sim \lambda$ (the value f_m in Ref. 11 is 0.4). The subsequent steps on f_m (I) are related in Ref. 11 to the formation of a periodic structure with $d \sim 2\lambda$, 3λ, etc. Without going into the transition between the periodic structure with $d \sim \lambda$ to the periodic structure with $d \sim 2\lambda$, we shall assume that this doubling has already occurred, and will examine the evolution of the function $P(x)$ with increasing c for the structure. Calculations analogous to those discussed above then show that there is a second critical value c_{crit2} before which a band of the melt with $d \sim 2\lambda$ can appear in the periodic structure. For the materials we have discussed, $c_{\text{crit2}} = 0.7d$, which is close to the value reported in Ref. 11.

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Translated by S. Chomet