Possibility of focusing and self-focusing of light beams in a semiconductor by varying the electron component of its dielectric constant

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We consider theoretically new mechanisms of focusing and self-focusing in semiconductors under conditions of temperature quenching of the conductivity. The effects considered can be used in a number of problems of optoelectronics, such as for a rapid spatial displacement of light beams, for variable focusing, and for other purposes.

The self-focusing of light beams (see the reviews[1–3]) are presently actively investigated both in liquids and in solids such as quartz, ruby, glasses, and ferroelectrics (see, e.g., [1–4]). The possibility of self-focusing of light as a result of the heating of a medium by a transmitted light wave was indicated in[5,6]. Practically no such investigations were performed until recently in semiconductors, with the exception of the experiments in[7,8], where the mechanisms of self-focusing and defocusing remained unclear to the very end.

We consider in this paper new mechanisms of self-focusing and defocusing in semiconductors; these mechanisms are connected with a change of the electron component of the dielectric constant in the field of a strong light wave and are due to temperature quenching or enhancement of the conductivity.[9,10] Under the condition of temperature quenching of the conductivity,[9–13] relatively small changes in the temperature (by 20–30°) lead to an appreciable change (by 5–6 orders of magnitude) in the concentration of the nonequilibrium Ne carriers in the bands, which in turn changes the electron component of the dielectric constant.

The expression for the dielectric constant, with account taken of the heating of the medium, can be represented in the form

$$\mathcal{E} = \mathcal{E}_{\mathrm{lat}} + \mathcal{E}_{\mathrm{el}} + \frac{\partial \mathcal{E}_{\mathrm{el}}}{\partial T}\,\delta T \tag{1}$$

where $\mathcal{E}_{\mathrm{lat}}$ and $\mathcal{E}_{\mathrm{el}}$ are the lattice and electron components of the dielectric constant. The electron component of the dielectric constant can be represented for the nondegenerate case, in the form[9]

$$\mathcal{E}_{\mathrm{el}}(N_e, \omega, T) = \frac{4e^2(2m^*E_v)^{1/2}}{\pi\hbar E_g} - \frac{2e^2[2m^*(E_g-\hbar\omega)]^{1/2}}{\hbar E_g} - \frac{4\pi e^2 N_e}{m_c\omega^2}$$
$$- \frac{4\pi e^2\hbar^2}{m_e T E_g}\left(\frac{m_c}{m^*}\right)^{3/2} N_e G(\xi), \quad G(\xi) = 1 - \pi^{1/2}\xi[1-\Phi(\xi)]\exp\xi^2,$$
$$\xi = \left[\frac{m_c}{m^*}\left(\frac{E_g-\hbar\omega}{T}\right)\right]^{1/2} \tag{2}$$

Here Φ is the probability integral, E_g and E_v are the widths of the forbidden and valence bands, m_c, m^*, and m_e are the effective, reduced, and proper electron masses, respectively, with $E_g(T) = E_g^0 - \alpha T$, where α is the coefficient of the temperature shift.

From the general expression (2) we can easily obtain the change $\delta\mathcal{E}_{\mathrm{el}} = (\partial\mathcal{E}/\partial T)\,\delta T$ under the conditions of temperature quenching $\{$i.e., $N_e = N_0[1 + A\exp(-\epsilon_q/T)]^{-1}\}$.[11] We can analogously take into account also the case of thermally stimulated conductivity, when the change of the concentration of the nonequilibrium carriers with changing temperature is given by $N_e(T) = N_0[1 + B\exp(-\epsilon_t/T)]$[12] ($\epsilon_t$ is the energy of the depth of the traps and is reckoned from the bottom of the conductivity band).

We consider now the following cases, which are physically of greatest interest:

1. $A\exp(-\epsilon_q/T) \gg 1$, i.e., the conductivity has become quenched in the crystal by heating. In this case the inequality $\xi \ll 1$ can take place, i.e., the frequency of the light signal is close enough to the absorption edge, and then

$$\delta\mathcal{E}_{\mathrm{el}} = -\frac{e^2(2m^*T)^{1/2}a\omega}{E_g^{\circ 2}\,\xi T}\left[1 - \frac{2\pi^{3/2}}{(2m^*T)^{1/2}}\frac{E_g^\circ}{m_e}\frac{\hbar^2 N_0(E_g^\circ-\hbar\omega)}{\omega a T^2 A\exp\left(-\frac{\epsilon_\Gamma}{T}\right)}\right] \tag{3}$$

or $\xi \gg 1$, when the frequency of the light signal is far enough from the fundamental absorption edge and

$$\delta\mathcal{E}_{\mathrm{el}} = +\frac{e^2(2m^*T)^{1/2}\xi a}{\hbar E_g^{\circ 2}}\left[1 - \frac{4}{\pi\xi}\left(\frac{E_v}{T}\right)^{1/2} - \frac{4\pi\hbar^3 E_g^\circ N_0\,\epsilon_\Gamma}{\xi^3(2m^*T)^{1/2}a\,m_e T^3 A\exp\left(-\frac{\epsilon_\Gamma}{T}\right)}\right]\delta T. \tag{4}$$

2. $A\exp(-\epsilon_q/T) \ll 1$—the case when the released heat is insufficient to produce temperature quenching, and then

$$\delta\mathcal{E}_{\mathrm{el}} = -\frac{e^2(2m^*T)^{1/2}a\omega}{\xi E_g^{\circ 2}T}\left[1 - \frac{2\pi^{3/2}E_g^\circ\hbar^2 N_0(E_g^\circ-\hbar\omega)}{(2m^*T)^{1/2}\omega a T^2 m_e}\right]\delta T, \qquad \xi \ll 1, \tag{5}$$

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$$\delta\mathcal{E}_{\mathrm{el}} = +\frac{e^2(2m^*T)^{1/2}\xi a}{\hbar E_g^{\circ 2}}\left[1-\frac{4}{\pi\xi}\left(\frac{E_v}{T}\right)^{1/2} - \frac{4\pi\hbar^3 E_g^{\circ} N_0 \epsilon_\Gamma A \exp\left(-\frac{\epsilon_\Gamma}{T}\right)}{\xi^3(2m^*T)^{1/2} a m_e T^3}\right]\delta T, \quad \xi >> 1. \tag{6}$$

As seen from (3)—(6), $\delta\mathscr{E}_{\mathrm{el}}$ is particularly sensitive to the passage of a signal with a frequency close to the fundamental absorption edge, where the term responsible for the interband transitions increases sharply (see[9,10] for details). It is important to note that the change $\delta\mathscr{E}_{\mathrm{el}}$ can occur both as a result of the appearance of nonequilibrium carriers in the bands, and as a result of a nonuniform distribution of the temperature over the crystal. Obviously, both possibilities can be due, in final analysis, to the absorption of light, namely either direct interband absorption or two-photon absorption (when $\hbar\omega < E_g < 2\hbar\omega$) in the case of a sufficiently intense incident flux. It follows from (3)—(6) that, depending on the choice of the values of the parameters that enter in $\delta\mathscr{E}_{\mathrm{el}}$, it is possible to make one term or the other predominant in $\delta\mathscr{E}_{\mathrm{el}}$, with the appropriate sign, i.e., the interaction between the nonlinear medium and the passing light signal can lead either to effective focusing of the light or to defocusing. It is important to emphasize that in our case it is possible to have focusing proper by a thermal lens, when the required concentration N_e is produced in the crystal under the influence of an external source, and self-focusing (self-defocusing) when a sufficiently intense light beam of frequency close to the absorption edge produces for itself in the crystal the required concentration N_e, and consequently also the redistribution of $\delta\mathscr{E}_{\mathrm{el}}$.

If the change Δa of the beam radius over the crystal length d is small in comparison with the initial radius, $\Delta a \approx d\theta \ll a$, then $\theta \approx (\partial n/\partial r)\, d$ and the aftereffect of the self-refraction becomes manifest mainly outside the crystal (the so-called external self-focusing or defocusing). In this case the focal distance is $F \approx a/\theta$. If the nonlinear refraction is very strong and changes significantly the dimensions of the beam, then $\theta_{\mathrm{nl}} \sim \delta n^{1/2} = \mathscr{E}^{1/4}\delta\mathscr{E}^{1/2}/2$, and in the case of focusing the focus is produced in the medium itself at the so-called Kelly length $L_K \approx a/(\theta_{\mathrm{nl}} - \theta_D) \approx a\delta n^{-1/2}$ for $\theta_{\mathrm{nl}} \gg \theta_D$.

For the sufficiently well investigated semiconducting compounds CdS and CdSe, at values $N_e = 10^{17}$ cm^{-3} and $E_g - \hbar\omega \approx 5\times10^{-2}$ eV, we obtain for example from (6) that $\delta\mathscr{E}_{\mathrm{el}} \approx -3\times10^{-3}$, and the quantities indicated above take on the values $\theta \sim 10^{-3}$, $F \approx 10$ cm, $\theta_{\mathrm{nl}} \sim 3\times10^{-2}$, and $L_K \approx 0.2$ cm.

The characteristic time τ during which the distribution $\delta\mathscr{E}_{\mathrm{el}}$ is produced is determined by the dynamics of the generation of the electron-hole paired by the light and by the values of the characteristic times required for the redistribution of the nonequilibrium carriers in the bands, and can be quite short, $\tau \sim 10^{-6}$—10^{-8} sec.[9] The effects considered here can therefore be used in a number of optoelectronics problems, such as for rapid spatial motion of light beams, for variable focusing, etc.

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