Photoconductivity of inhomogeneous semiconducting solid solutions

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The basic characteristics of photoconductivity (PC) of semiconducting solid solutions with spatial fluctuations in composition are examined theoretically.

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All real solid solutions to one extent or another are characterized by the presence of spatial fluctuations in composition. Some properties of small-scale fluctuations, related to the static nature of the distribution of atoms at the lattice sites, are examined in Refs. 1-3. Such fluctuations have a small amplitude and affect the properties of semiconductors only at low temperatures.

However, direct experimental observations often reveal in solid solutions composition fluctuations with much larger spatial dimensions and amplitudes, apparently of a technological origin (see, for example, Refs. 4 and 5). The fact that different inhomogeneities can noticeably change the electronic structure of a semiconductor is quite obvious. However, primarily impurity-concentration fluctuations, which modulate the energy bands in a parallel (covariant, according to the terminology used by Blackmore[6]) manner,[7,8] are examined in the literature. On the other hand, composition fluctuations in a solid solution give rise, as a rule, to antiparallel (contravariant) modulation of bands (Fig. 1). We shall use photoconductivity to show that the properties of such semiconductors differ considerably both from homogeneous and inhomogeneous doped semiconductors.

Some properties of PC were discussed in Ref. 3 for solid solutions with small-scale fluctuations. We shall speak of large-scale fluctuations with characteristic dimensions L, exceeding the de Broglie wavelength and the mean free path of carriers. In such a system of random variable-band microscopic regions, the motion of the carriers can be considered to be classical.

We shall prove the general assertion that in solid solutions with such concentration fluctuations, PC will be less than in the homogeneous solution with average composition with a forbidden bandwidth $\overline{\epsilon}_g$ (of course, we are talking about light with energy $\hbar\omega > \overline{\epsilon}_g$).

Since the lifetime τ of nonequilibrium charge carriers (NCC) greatly exceeds their energy relaxation time, the NCC are distributed in the specimen in a sharply inhomogeneous manner, collecting near local minima in the width of the forbidden band ϵ_g[1)] for constant concentration of recombination centers, τ in narrow-band regions as a rule does not exceed the value (for Auger recombination, much less) in wide-band regions. For this reason, the average NCC concentration $\overline{\Delta n}$ in an inhomogeneous solid solution would be greater than in a homogeneous solution. This fact, together with the theorem,[9] according

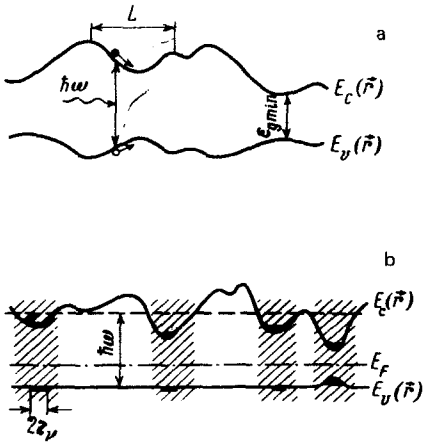

FIG. 1. Band diagram of an inhomogeneous solid solution with $L \leqslant r_s$ (a) and with $L \gg r_s$ (b). The generation regions are shaded and the regions of localization of NCC are colored black.

to which in the inhomogeneous case the conductivity (in our case, the PC $\Delta\sigma$) is less than $\overline{\Delta n}e\mu$ (μ is the mobility), proves this assertion.

We recall that inhomogeneities, modulating the bands in a parallel manner, separate the NCC spatially and increase the PC.[8] In our case, the potential pattern, instead of leading to separation, leads to localization of electrons and holes in the same regions of the specimen, which is what brings about the opposite effect on the PC. Thus, for photoelectric instruments, fluctuations in the composition of a solid solution, in contrast to impurity-concentration fluctuations, always play a negative role.

For a more specific examination of PC, we shall additionally propose that L greatly exceeds the screening length r_s as well. In addition, fluctuations in the band edges of the main carriers (for definiteness, holes) are screened and there is no potential pattern in this band with the exception of possible fluctuations, where ϵ_g is so small that the intrinsic concentration of carriers exceeds the concentration of the dopant p_0 (Fig. 1b). Photoconductivity in this case is due only to holes, since in contrast to electrons they do not have to be activated to the flow level. In spite of the absence of barriers in the valence band, nonequilibrium holes, due to local quasineutrality, are distributed just as inhomogeneously as electrons. As a result, it turns out that under illumination the hole concentration increases sharply near the local minima ϵ_g, remaining essentially unchanged in the rest of the specimen.

Let us examine some fixed minimum $\epsilon_{g\min} = \epsilon_g(r_0)$, near which the energy at the bottom of the conduction band varies according to the law $E_c(\mathbf{r}) = \beta|\mathbf{r} - \mathbf{r}_0|^2$. If ν nonequilibrium electrons are localized in it, then at $T = 0$, they occupy the region near r_0 with radius

$$r_\nu = \left[\frac{9\pi\hbar^3\nu}{4(2m\beta)^{3/2}}\right]^{1/6}. \qquad (1)$$

As already mentioned, nonequilibrium holes are also concentrated in this region.

Thus, from the point of view of electrical properties the inhomogeneous solid solution represents a matrix of conductivity $\sigma_0 = ep_0\mu_h$, in which inclusions, having conductivity $\sigma_0(p_0 + \Delta p)/p_0$ and relative volume f, arise under illumination. The conductivity of such a system according to Ref. 10 is equal to $\sigma_0[(1 + 3f\Delta p/(3p_0 + \Delta p)]$. It follows from (1) that both Δp and f are proportional to $\sqrt{\nu}$, i.e., to the square root of the light intensity I. As a result, the lx-A characteristic is linear for small I ($\ll I_c \simeq p_0^2/a\tau(m\Delta/\hbar^2)^{3/2}$, where Δ is the amplitude of the inhomogeneities) and follows a square-root dependence for $I \gg I_c$. It is evident that I_c is very small, $(m\Delta/\hbar^2)^{3/2}\, 1/p_0 \gg 1$ times less than the intensity, which creates a PC in the homogeneous specimen with the same τ equal to σ_0.

As the temperature is increased, the role of the potential pattern decreases, NCC are distributed in the specimen more uniformly, and PC increases (if τ does not drop too strongly with increasing temperature). Therefore, the temperature dependence of PC is also opposite to that which occurs in inhomogeneously doped specimens.

The spectral dependence of PC is determined, first, by the number of NCC ν, created at each separate minimum, and, second, by the number of minima satisfying the condition $\epsilon_{g\,\min} < \hbar\omega$. For direct allowed transitions, $\nu \sim \int\sqrt{\hbar\omega - \epsilon_{g\,\min} - \beta r^2}\, r^2 dr \sim (\hbar\omega - \epsilon_{g\,\min})^2$ (for one-dimensional inhomogeneities, the analogous problem was solved in Ref. 11). The second factor in the region of deep tails in the absorption coefficient α depends exponentially on ω and for this reason is decisive. In particular, for Gaussian fluctuations,

$$\Delta\sigma(\omega) \sim \alpha(\omega) \sim \exp\left[-\frac{(\bar{\epsilon}_g - \hbar\omega)^2}{2\Delta^2}\right], \tag{2}$$

In conclusion, we note that in inhomogeneous semiconductors and in those cases of parallel band modulation, when NCC are in a quasiequilibrium state, the lx-A and spectral characteristics are interrelated, since they are determined by a single parameter: the rate of generation $I, \alpha(\omega)$. In our case, there is no such interrelationship. Due to the effect of accumulation of NCC in inhomogeneous solid solutions, regions of NCC generation, which determine the characteristic $\Delta\sigma(\omega)$, are much greater than regions of NCC localization, which determine $\Delta\sigma(I)$, and which have a different dependence on the parameters of the problem. Thus, for example, as I increases with ω fixed, the former do not change, while the latter increase in the bulk.

[1)]In contrast with parallel modulation of bands, there will never be quasiequilibrium here between separate minima.

1. Zh. I. Alferov, E. L. Portnoĭ, and A. A. Rogachev, Fiz. Tekh. Poluprovodn. 2, 1194 (1968) [Sov. Phys. Semicond. 2, 1001 (1969)].
2. S. D. Baranovskiĭ and A. L. Éfros, Fiz. Tekh. Poluprovodn. 12, 2233 (1978) [Sov. Phys. Semicond. 12, 1328 (1978)].

3. A. Yu. Maslov, Fiz. Tekh. Poluprovodn. **16**, 347 (1982).
4. A. I. Vlasenko, Yu. N. Gavrilyuk, V. Z. Latuta, A. V. Lyubchenko, and E. A. Sal'kov, Pis'ma Zh. Tekh. Fiz. **5**, 1013 (1979) [Sov. Tech. Phys. Lett. **5**, 423 (1979)].
5. O. V. Pelevin, S. A. Afanas'ev, A. M. Sokolov, V. M. Khnykov, and N. I. Shmatov, Proceedings of the 5th All-Union Symposium on Semiconductors with a Narrow Forbidden Band and Semimetals, L'vov, 1980, pt. 2, p. 118.
6. J. Blackmore, Statistics of Electrons in Semiconductors [Russian translation], Mir, Moscow, 1964, p. 119.
7. B. I. Shklovskiĭ and A. L. Éfros, Élektronnye svoĭstva legirovannykh poluprovodnikov [Electronic Properties of Doped Semiconductors], Nauka, Moscow, 1979.
8. M. K. Sheinkman and A. Ya. Shik, Fiz. Tekh. Poluprovodn. **10**, 209 (1976) [Sov. Phys. Semicond. **10**, 128 (1976)].
9. A. M. Dykhne, Zh. Eksp. Teor. Fiz. **52**, 264 (1967) [Sov. Phys. JETP **25**, 170 (1967)].
10. L. D. Landau and E. M. Lifshitz, Élektrodinamika sploshnykh sred [Electrodynamics of Continuous Media], GITTL, Moscow, 1957.
11. S. N. Artemenko and A. Ya. Shul'man, Pis'ma Zh. Éksp. Teor. Fiz. **19**, 145 (1974) [JETP Lett. **19**, 89 (1974)].

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