Distribution of nonequilibrium carriers and photoconductivity in inhomogeneous semiconductors

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The spatial distribution of nonequilibrium carriers in semiconductors with large-scale inhomogeneities is analyzed. In several cases the photoconductivity of such objects is described by a universal expression which contains only the curvature of the potential of the inhomogeneities and is independent of the carrier lifetime and mobility.

A central problem in the theory of nonequilibrium phenomena, including photoconductivity and luminescence, in inhomogeneous semiconductors is that of finding the distribution of nonequilibrium carriers, $n(\mathbf{r})$, in the potential field of the inhomogeneities, $V(\mathbf{r})$. To reach an understanding of the basic qualitative behavior, we first consider the very simple model problem in which V is a one-dimensional periodic function with an amplitude $\Delta/2$ and a period $2L$, and the recombination time τ and the mobility μ of the carriers do not depend on the coordinates. If the inhomogeneities are large in scale, i.e., if L exceeds the de Broglie wavelength and the carrier mean free path, then near extrema x_i, where $V(x) = \pm(\Delta/2) \mp 2\Delta(x - x_i/L)^2$, the continuity equation for determining $n(x)$ is

$$\nu''_{\pm} \mp \beta\zeta\nu'_{\pm} - (1 \pm \beta)\nu_{\pm} = -1\,, \tag{1}$$

where $\nu = n/G\tau$, $\zeta = (x - x_i)/L_D$, $\beta = 4(\Delta/T)(L_D^2/L^2)$, G is the generation rate, which is also independent of the coordinates, and $L_D = \sqrt{\mu T\tau/e}$ is the diffusion length. The solutions ν_+ and ν_- are to be joined at $x = x_i \pm (L/2)$.

Analysis of the results found here shows that three types of distributions of the nonequilibrium density may prevail, depending on the relative amplitude Δ/T and the relative period L/L_D of the inhomogeneities (Fig. 1a):

A) $\Delta \lesssim T$ or $\beta \lesssim 1$; the carriers are not redistributed, and we have $n = G\tau = \mathrm{const}(x)$.

B) $\sqrt{(\Delta/T)}\exp(-\Delta/T) \gtrsim (1/\beta)$; the distribution is a quasiequilibrium distribution, and we have $n(x) \sim \exp[-V(x)/T]$.

C) $\sqrt{(\Delta/T)}\exp(-\Delta/T) \ll (1/\beta) \ll 1$. In this case the carriers are distributed in a quasiequilibrium manner only near the minima of V. Near the maxima, the density is determined by the balance between the generation rate and the rate of removal by diffusion and drift (by virtue of the condition $\beta \gg 1$, recombination plays an insignificant role here). We thus find

$$n \simeq \frac{G\tau}{\beta} = \frac{eL^2}{4\Delta\mu} G = \mathrm{const}(x) \ll G\tau \tag{2}$$

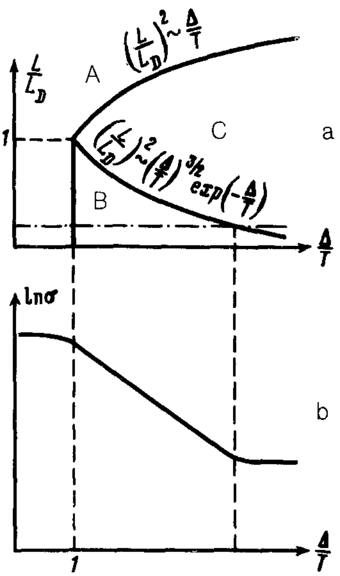

FIG. 1. a—Regions in which the three types of distributions of the nonequilibrium density prevail in inhomogeneous semiconductors; b—schematic temperature dependence of the photoconductivity.

Let us examine this last result in more detail. It holds in the case in which the homogeneities have a large amplitude, which is the most interesting case. It follows from (2) that the specific conductivity of the regions near a maximum is

$$\sigma = \frac{e^2L^2}{4\Delta}G = \frac{e^2G}{|V''(x_{max})|}, \tag{3}$$

where V'' is the second derivative of $V(x)$ at the point of the maximum. We see that the result is of a universal nature—independent of the height of the maximum, of the carrier mobility, and of the carrier lifetime [as long as the condition for the distribution C) holds, of course]. Our original assumption that τ and μ are constant is thus not a very critical assumption.

Since the density of nonequilibrium carriers near the maxima of V is substantially lower than near the minima, expression (3) evidently gives a correct estimate of the photoconductivity of a system which is inhomogeneous in one dimension. This assertion applies to not only periodic but also random potentials $V(x)$ if the scatter $V''(x_{\max})$ is not too large. Furthermore, expression (3) remains in force in a system containing inhomogeneities with two distinct size scales. It can be assumed that the carriers move in the large-scale potential, and the small-scale "ripple" renormalizes the effective values of τ and μ, which do not appear in the final expression.

In a three-dimensional potential $V(\mathbf{r})$, the photoconductivity is determined not by the maxima but by the saddle points, near which we have $V(\mathbf{r}) \simeq V_0 + \alpha_1x^2 + \alpha_2y^2 - \alpha_3z^2$ $(\alpha_i > 0)$. Under condition C), the continuity equation has an extremely complicated solution near a saddle point. However, the quantity $\int n(\mathbf{r})dxdy$, which determines the total current through the saddle point, is described by an equation analogous to (1) and is approximately equal to $(eG/2\alpha_3\mu)L^2$ (the factor L^2 represents the area from which carriers are collected to the given saddle point). When an average is taken over the sample, we thus find our previous estimate of the photoconductivity (3).

We now consider the temperature dependence of the photoconductivity of a randomly inhomogeneous sample with $L \ll L_D$. Equivalently, we are considering the motion along the dot-dashed line on the "phase diagram" in Fig. 1a. Under the condition $\Delta \lesssim T$ we have $\sigma \simeq G\tau e\mu$. As the temperature is lowered, we go into region B), in which we have $\sigma \sim \exp(\zeta - E_c)/T$ (ζ is the Fermi quasilevel, and E_c is the percolation level in the random potential). As soon as the quasiequilibrium density at some saddle point reaches the value in (2) in the course of the cooling, this density "freezes" at this value [there is a transition from case B) to case C)]. When this event occurs at the energy E_c, the photoconductivity takes on the temperature-independent value in (3). The overall temperature dependence of the photoconductivity corresponds to Fig. 1b.

Nonequilibrium carriers of only one sign have been considered here. If the condition $\beta \gg 1$ also holds for the carriers of the other sign, then $n(\mathbf{r})$ will always be a quasiequilibrium distribution, as was shown in Ref. 1. This result does not contradict the arguments above. To see this, we note that in this other case, because of the separation of carriers, we will have $\tau \sim \exp(\Delta/T)$, and the condition for case C), $\sqrt{(\Delta/T)} \exp(-\Delta/T) \ll 1/\beta$, will never be satisfied. If the situation described by (3) is to hold for the nonequilibrium carriers, there must be no effective separation of electrons and holes. This requirement determines the objects to which our theory applies. Among these objects are (1) semiconductors with sharply different mobilities or lifetimes for the electrons and holes ($\beta_n \gg 1$, $\beta_p \lesssim 1$, or vice versa), (2) extrinsic photoconductors with partially compensated levels, (3) heavy holes in a potential $V(\mathbf{r})$, which is tunneling-transparent for light electrons, (4) minority carriers in heavily doped semiconductors, and (5) solid solutions with composition fluctuations caused by an antiparallel modulation of the bands (here, under the condition $L > \Gamma_s$, where Γ_s is the screening length, we could be dealing with minority carriers, since the band of majority carriers is not modulated[2]).

The case of solid solutions has some further distinguishing features, because the width of the band gap and thus the carrier generation rate vary over space in synchronism with $V(\mathbf{r})$. For optical generation, the nature of the distribution $n(\mathbf{r})$ depends on the light frequency ω. In particular, in case C), if the condition $\hbar\omega < \epsilon_g(E_c)$ [$\epsilon_g(E_c)$ is the width of the band gap at points where the bottom of the conduction band has an energy E_c], then the carriers are not generated at the saddle points which determine the photoconductivity, the density decreases exponentially there, and we have

$$\sigma \sim \exp\left[\frac{\hbar\omega - \epsilon_g(E_c)}{T}\right].$$

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