Theory of anomalous behavior of charge-transport characteristics in amorphous materials

V. I. Arkhipov and A. I. Rudenko

Moscow Engineering Physics Institute
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Recent experimental results on the anomalous charge transfer in amorphous semiconductors are explained from the point of view of a theory of nonequilibrium carrier drift controlled by transitions between local levels.

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An anomalous behavior of charge-transfer characteristics was observed recently in a large number of amorphous materials, particularly in a-Se [1], As_2Se_3 [2], a-Si [3]. The anomalous behavior was observed in experiments aimed at determining the time of flight of the carriers. Consider a high-resistance plate of thickness L on which a voltage $V=EL$ is maintained. At the instant $t=0$, carriers with surface density σ are injected near one of the contacts at $x=0$. The carriers are drawn into the sample and generate a transient current $j(t)$. In the course of their transport, the carriers are trapped on levels lying in the forbidden band, with possible subsequent ejection back to the conduction band.

In the case of normal behavior, the $j(t)$ curves exhibit a "plateau" corresponding to establishment of thermal equilibrium between the conduction band and the traps. The carriers form a Gaussian packet that moves with a velocity determined by the trapping-controlled drift mobility μ_*. The arrival of the packet to the opposite contact $(x=L)$ produces an abrupt decrease of the current. This instant corresponds to the time of flight t_*, which is connected with μ_* by the relation $\mu_*=L/E\,t_*$, with μ_* independent of L. At $t>t_*$ and with normal behavior of the current $j(t)$, an exponential "tail" is observed and describes the departure of the carriers that have remained after the passage of the main part of the packet.

In the case of the anomalous behavior, neither a plateau nor an exponential tail is ever observed. The main features of the anomalous behavior consist in the following (see [4]). 1. The $j(t)$ curves plotted in a doubly logarithmic scale at different L and E can be reduced, by a shift of the axes, to a universal curve ("scaling"). 2. The $j(t)$ curves have two characteristic decreasing sections: initial $j(t)\sim t^{-(1-\alpha)}$ and final $j(t)\sim t^{-(1+\alpha)}$ with $\alpha\approx 1/2$. 3. Transition from one section to the other occurs at a certain value t_* which is treated as the time of flight. The time t_* has a "superlinear" dependence on the thickness $t_* \sim L^{1/\alpha}$, which is interpreted as a dependence of the drift mobility $\mu_* = L/E\,t_*$ on the thickness $\mu_* \sim L^{1-(1/\alpha)} \sim L^{-1}$. A stochastic model of the anomalous transport was proposed in [4]. According to this model the sample is represented as a "sieve" of cells, and the motion of the carriers is represented as a sequence of "jumps" from cell to cell with a given jump probability function $\psi(t)$. However, the choice of $\psi(t)$ remains problematic. The stochastic model does not employ at all the concepts of band structure, and the question of the character of the energy distribution of the traps and of the carrier transitions remains outside the scope of this model. In [5,6] it was suggested that anomalous behavior can occur if the drift is controlled by carrier trapping by local levels distributed in the forbidden band in a sufficiently broad energy interval. It was assumed in [5,6], however, that the carrier can execute transitions only between each of a group of localized levels and the conduction band. While this model accounts for some features of the anomalous behavior, it does not result in full agreement with experiment in a wide temporal interval, nor does it explain all the features of the anomalous behavior. It is shown in the present paper that it is precisely the allowance for transitions between localized levels (which were disregarded completely in [5,6], which accounts for all the features of the anomalous behavior. We consider the kinetics of carriers that are trapped in the course of their drift and execute transitions from one level to another, with the return of the carrier to the conduction band possible. We take into account transitions between two neighboring levels. The distribution of the levels in energy is assumed to be deep enough and close to uniform, and the number of levels is assumed large. The problem is described by the equations

$$\partial p_0(x,t)/\partial t + \mu_0 E\,\partial p_0(x,t)/\partial x = -(1/\tau)\,p_0(x,t) + (\theta/\tau)\,p_1(x,t),$$

$$\partial p_i(x,t)/\partial t = -[(1+\theta)/\tau]\,p_i(x,t) + (1/\tau)\,p_{i-1}(x,t) + (\theta/\tau)\,p_{i+1}(x,t),$$

$$p_0(x,0) = \sigma\delta(x), \quad p_i(x,0) = 0, \quad (i = 1,2,\ldots), \quad j(t) = (e\mu_0 E/L)\int_0^L dx\,p_0(x,t).$$

Here p_0 is the density of the free carriers, p_i is the carrier density on the *i-th* local level, μ_0 is the free-carrier mobility, $(1/\tau)$ and (θ/τ) determine the probabilities of the transitions between two neighboring levels, and e is the charge of the carrier. The solution of the problem is of the form

$$p_0(x,t) = \sigma\exp(-x/\mu_0 E\tau)\{\delta(\mu_0 Et - x) + [\sqrt{\theta}\,x/\mu_0 E\tau\sqrt{\mu_0 Et(\mu_0 Et - x)}]$$
$$\exp[-(1+\theta)(\mu_0 Et - x)/\mu_0 E\tau]\,I_1[\sqrt{4\theta\mu_0 Et(\mu_0 Et - x)}/\mu_0 E\tau]\},$$
$$x \leqslant \mu_0 Et$$

where I_1 are Bessel functions. At $x > \mu_0 Et$ we have $p_0(x,t) = 0$. In the cases realized in practice, θ is close to unity ($\theta \approx 1$), and τ is small $\tau \ll L/\mu_0 E$, so that the solution takes a simpler form

$$p_0(x, t) = \sigma(1/2\sqrt{\pi})(1/\mu_0^2 E^2)\tau^{-1/2} t^{-3/2} x \exp(-x^2/4\mu_0^2 E^2 \tau t), \quad t \gg \tau$$

$$j(t) = e\mu_0(\sigma/L)E(1/\sqrt{\pi})\tau^{1/2} t^{-1/2}[1 - \exp(-L^2/4\mu_0^2 E^2 \tau t)], \quad t \gg \tau,$$

$$j(t) \approx (1/\sqrt{\pi}) e\mu_0(\sigma/L)E\tau^{1/2} t^{-1/2}, \quad t < (L^2/4\mu_0^2 E^2 \tau),$$

$$j(t) \approx (1/\sqrt{\pi})\, e\mu_0(\sigma/L)E(L^2/4\mu_0^2 E^2 \tau^{1/2}) t^{-3/2}, \quad t > (L^2/4\mu_0^2 E^2 \tau).$$

The obtained theoretical characteristics have all the features of the anomalous transport. [1–4] The "time of flight" t_*, which determines the transition from the section $j \sim t^{-1/2}$ to the section $j \sim t^{-3/2}$, is of the form $t_* = L^2/4\mu_0^2 E^2 \tau$. This leads to the following dependence of the drift mobility on the field and thickness: $\mu_* = 4\mu_0^2 E\tau/L$. We note that the shape obtained in this model for the packet $p_0(x,t)$ is far from Gaussian.

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[1]G. Pfister, Phys. Rev. Lett. **36**, 271 (1976).
[2]G. Pfister and H. Scher, Phys. Rev. B **15**, 2062 (1977).
[3]D. Allan, P. G. Le Comber, and W. E. Spear, Proc. Seventh Intern. Conf. on Amorphous and Liquid Semiconductors, ed. by W. E. Spear, Edinburgh, 1977, p. 323.
[4]H. Scher and E. W. Montroll, Phys. Rev. B **12**, 2455 (1975).
[5]V. I. Arkhipov and A. I. Rudenko, Phys. Lett. A **61**, 55 (1977).
[6]F. W. Schmidlin, Phys. Rev. B **16**, 2362 (1977).