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Transport in Relaxation Semiconductors

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The Van Roosbroeck model for the exhaustion of majority carriers by the injection of minority carriers is shown to lead to an inconsistency in the requirement of the continuity of the current. The assumed exhaustion of majority carriers by this mechanism has therefore to be ruled out.

Analyzing the carrier transport in semiconductors and insulators, Van Roosbroeck and Casey[1,2] came to the conclusion that the carrier flow may be of two principally different types according to whether the dielectric relaxation time is shorter or longer than the lifetime of the injected minority carriers. If the dielectric relaxation time is shorter than the lifetime, then the space charge of the injected minority carriers is rapidly neutralized, and an increase in conductivity is observed. If, however, the neutralization of the space charge cannot be achieved before recombination takes place, the authors claim that the majority-carrier density decreases until net zero recombination with local thermal equilibrium is established. This regime of the carrier transport was called the relaxation case. It is indeed an attractive and provocative idea that upon adding minority carriers to a semiconductor the majority-carrier density should decrease substantially. Since at first sight the idea seems to be of general validity and based on firm physical principles, it seems to us worthwhile to point out that the model of Van Roosbroeck and Casey contains an inconsistency, and that a decrease of majority carriers due to recombinative space-charge injection has to be ruled out.[3]

For the sake of argument let us assume that we have an n-type semiconductor of length L, one contact to the semiconductor being an electron-, the other a hole-injecting contact. For application of a forward bias, the model of recombinative space-charge injection claims that the injection of minority holes reduces the electron concentration in the bulk within a depth d starting from the hole-injecting contact. Beyond the distance d is a transition region, and beyond that the region L-d' which retains its original electron density. Hence, the situation shown in Fig. 1 arises: Region d is of low conductivity and contains a positive space charge, whereas region L-d' is neutral and relatively highly conducting. In order to have equal current flow in region d and L-d', the electric field has to be lower in L-d' than in d. Therefore, the transition region d'-d must be negatively charged. The presence of negative charge has two consequences: On the one hand, it must increase the electron concentration and, therefore, the conductivity in the transition region relative to L-d'. On the other hand, it must also increase the electric field in the transition region relative to L-d'. These two consequences lead to violation of the law of current continuity which requires the electric field to decrease when

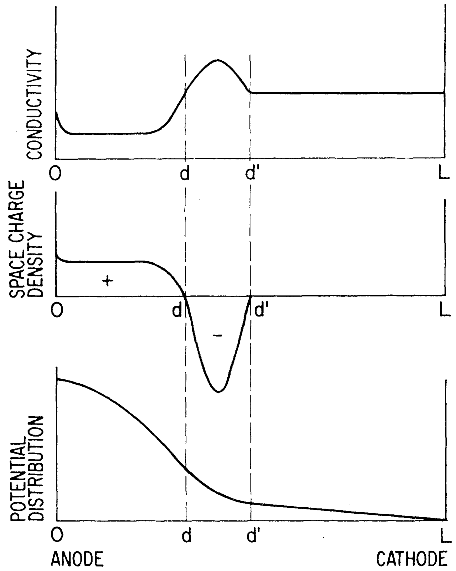

FIG. 1. Conductivity, space charge, and potential distribution in a long relaxation-case n-type semiconductor under forward bias. The distance origin is taken at the hole-injecting contact, from where the electron-depletion region expands into the bulk of the material. This configuration is unstable as shown in the text.

the carrier density increases. Therefore, we have to conclude that this configuration is not stable, and a region depleted of majority carriers cannot form under conditions of recombinative space-charge injection. The argument presented is independent of whether the negative space charge is accommodated in a small transition region, or whether it would spread over the entire region L-d'. Also, the presence of traps adds further detail to the argument but does not alter it. Finally, the inclusion of diffusion reinforces, but is not essential to, the argument.

The physics underlying the violation of the continuity equation is clear: If injected holes tend to decrease the electron concentration by recombination within a region d, the density of electrons outside d will be higher, and consequently a prerequisite for a *field-dominated* injection of electrons into d is fulfilled, namely, that a reservoir of electrons exists. Therefore, the relaxation of the positive space charge in d is no longer governed by the dielectric relaxation time $\tau_D = \epsilon\epsilon_0/\sigma$ (where ϵ is the dielectric constant, ϵ_0 is the permittivity, and σ is the conductivity), but by the much shorter transit time of the electrons through d. The injection of electrons, of course, will counteract the decrease in electron concentration and tend to restore their original density.

We would like to acknowledge stimulating discussions with M. A. Lampert and F. Stöckmann without, of course, committing them to the support of this particular argument.

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Optical Investigation of π Bands in Graphite

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We report detailed measurements of thermoreflectance spectra of graphite in the 0.5–9-eV region. The observed structures are correlated with π interband transitions on the basis of existing energy-band calculations.

A large amount of experimental data on graphite[1] has been collected in recent years. However, their interpretation in terms of the energy-band structure has not been fully successful. In fact, although some success has been achieved in relating the observed physical properties to the characteristics of the overlapping π bands near the Fermi surface, discrepancies exist in attrib-