LVII. CORRESPONDENCE

General Semiconductor Junction Relations†

By N. H. Fletcher
Division of Radiophysics, C.S.I.R.O., Sydney, Australia

[Received January 29, 1957]

Summary

General carrier density relations are derived for the case of an abrupt junction between two sections of semiconductor with arbitrary impurity contents and with an arbitrary applied bias. These relations reduce to those of Shockley at very low bias levels, but in addition take account of all types of conductivity modulation effects.

In a classic paper Shockley (1949) has treated the theory of p–n junctions in semiconductors in great detail. His treatment, however, is only valid at very small bias levels, and modifications are necessary for high forward biasses. It is the purpose of this note to derive relations valid at any bias level for a junction between two regions of arbitrary impurity content. These results necessarily agree with those of Shockley in the low level limit.

We shall assume that carrier densities are always sufficiently small that the use of Boltzmann statistics is a valid approximation. Extension of the theory to degenerate carrier distributions is simple in principle but does not give usefully simple mathematical results. We also assume that electric fields and carrier density gradients are always sufficiently small that the carriers are in quasi-equilibrium with the lattice.

Consider an abrupt junction between a semiconductor region 1 with donor density N_{D1} and acceptor density N_{A1}, and another region 2 with donor density N_{D2} and acceptor density N_{A2}. Assume further that the junction is sufficiently narrow compared with a carrier diffusion length that recombination within the junction region can be neglected.

Let n_{01}, p_{01} be equilibrium electron and hole densities in region 1 and n_{02}, p_{02} similar quantities in region 2, then we have

$$N_{A1}-N_{D1}=p_{01}-n_{01} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$p_{01}n_{01}=n_i^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where n_i is the density of holes or electrons in intrinsic material at this temperature. Similar relations hold for region 2.

We can define the ' built-in ' potential ϕ across the junction by

$$\frac{p_{01}}{p_{02}}=\frac{n_{02}}{n_{01}}=\exp\,(q\phi/kT). \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

---

† Communicated by Dr. E. G. Bowen.

Now suppose a potential V is applied across the junction in the forward direction (i.e. in such a direction that the total potential across the junction is now $\phi - V$). Let p_1 be the hole density and n_1 the electron density in region 1 just outside the junction space-charge layer, and let p_2, n_2 be similar quantities in region 2. Then from our assumptions

$$p_2 = p_1 \exp\,[q(V-\phi)/kT], \tag{4}$$

$$n_1 = n_2 \exp\,[q(V-\phi)/kT]. \tag{5}$$

The electron and hole populations are no longer in strict equilibrium with each other, but are related by the requirement of space-charge neutrality, thus

$$N_{\mathrm{A}1} - N_{\mathrm{D}1} = p_1 - n_1 \tag{6}$$

$$N_{\mathrm{A}2} - N_{\mathrm{D}2} = p_2 - n_2 \tag{7}$$

The relations (1)–(7) are sufficient to determine the carrier densities on either side of the junction for the applied voltage V. The results are

$$p_1 = [(N_{\mathrm{A}1} - N_{\mathrm{D}1}) - (N_{\mathrm{A}2} - N_{\mathrm{D}2})x]/[1-x^2], \tag{8}$$

$$n_1 = x[-(N_{\mathrm{A}2} - N_{\mathrm{D}2}) + (N_{\mathrm{A}1} - N_{\mathrm{D}1})x]/[1-x^2], \tag{9}$$

$$p_2 = x[(N_{\mathrm{A}1} - N_{\mathrm{D}1}) - (N_{\mathrm{A}2} - N_{\mathrm{D}2})x]/[1-x^2], \tag{10}$$

$$n_2 = [-(N_{\mathrm{A}2} - N_{\mathrm{D}2}) + (N_{\mathrm{A}1} - N_{\mathrm{D}1})x]/[1-x^2] \tag{11}$$

where

$$x = e \exp\,[q(V-\phi)/kT]. \tag{12}$$

These relations reduce to those of Shockley for $V \ll \phi$. When $V \rightarrow \phi$ however, all the carrier densities tend to infinity, representing the extreme of conductivity modulation. This limit cannot be approached in practice since it proves impossible to apply a voltage equal to ϕ to the junction without applying an infinite voltage to the device as a whole.

These new junction relations together with the usual equations of recombination and of current flow by drift and diffusion can be used to explain the behaviour of a wide variety of junction devices. In particular they take complete account of all conductivity modulation effects—injection, extraction and exclusion. The performance of various types of junction diodes and transistors at high current densities has been studied in this manner and the results will be published elsewhere.

The validity of the relations (8)–(12) is limited by the assumption of non-degeneracy and quasi-equilibrium. Even when these assumptions are not strictly valid, however, the relations provide a useful approximation.

REFERENCE

SHOCKLEY, W., 1949, *Bell. Syst. Tech. J.*, **28**, 435.