Inhomogeneous and Open Systems: Electronic Devices

18.1 Inhomogeneous, Open Systems

The strong interest for the physics of semiconductors, and in particular for the charge transport properties of these materials, is mainly due to their use in electronic devices. The related technology has reached limits inconceivable when the adventure started, in 1948, with the invention of the transistor\(^1\) [24,416].

When we move from the study of homogeneous, theoretically infinite, bulk materials to the analysis of electronic devices, we must consider two essential points. On one side, the systems are not homogeneous, often made of parts realized with different materials. Furthermore, we are dealing with open systems, where electrons and/or holes can enter and leave the systems through contacts which connect them to external reservoirs, generally maintained at different potentials.

The general problem of electron transport in a device can be formulated as follows: find the distribution of charge density, current density, and electric potential, inside a system with given geometry of materials and doping concentrations, in the presence of a certain number of contacts, in general from two to four, kept at given potentials, through which electrons and/or holes can enter or leave the system.

The presence of regions with different concentrations of fixed (ionized dopants) and mobile charges implies that the transport equation must be solved self-consistently with the Poisson equation:

\[
\nabla \cdot (\varepsilon(r) \nabla \phi(r)) = -\rho(r)
\]

(18.1)

\(^1\) The name transistor was suggested by J.R. Pierce, as an adaptation of trans-resistance to the names of other devices, such as varistor and thermistor.
The problem of modeling an electronic device is often simplified by reducing the number of essential dimensions on the basis of some symmetry of the device. In case (a), translational symmetry is assumed along the directions $y$ and $z$ so that the quantities of interest depend only upon $x$, and the problem becomes one-dimensional; in (b), the problem is two-dimensional, assuming symmetry along $z$.

Here, $\phi(r)$ is the electric potential field, $\varepsilon(r)$ is the dielectric constant of the material, and $\rho(r)$ is the charge density given by

$$\rho(r) = e(p - n + N_D - N_A),$$

(18.2)

where $p$, $n$, $N_D$ ed $N_A$ are the concentrations of holes, electrons, ionized donors, and ionized acceptors, respectively. The boundary conditions are given by the applied potentials on the electrode boundaries, and are supposed to be given by homogeneous Neumann conditions, i.e., zero normal derivative of the potential, $\nabla V|_n = 0$, at the insulating boundaries, on the basis of the continuity of the normal component of displacement field $D$ and the higher dielectric constant of the device material with respect to the exterior.

In its general formulation, the problem is very difficult to solve and can be approached only with severe approximations and/or with numerical techniques. Often the problem is simplified by reducing the number of significant space dimensions, as illustrated in Fig. 18.1.

The problem becomes even more difficult when, with present-day technology, the linear dimensions of the device become comparable with the carrier coherence length (see below and Chap. 16), and a quantum treatment of the electron dynamics is necessary.

### 18.2 Self-Averaging Transport, Coherent Transport, and Intermediate Cases

When the physical system of interest, albeit inhomogeneous, may be decomposed in a number of relatively large homogeneous regions, within each of such regions charge carriers may encounter a large variety of different microscopic situations: they may be scattered by impurities with different impact parameters, or absorb and emit phonons of different branches with different momenta. In such a case, electrons behave in a manner similar to what they do in homogeneous materials. In each region, they sample, on average, the different possible occurrences. This situation is called *self-averaging regime*...