3. Space-Charge Spectroscopy in Semiconductors

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With 24 Figures

In this chapter we will discuss the special case of thermally stimulated trap-related phenomena in semiconductors. In particular, we will focus on the effects of trapping and emission of carriers at deep energy levels which are located in the space-charge layer of a pn junction or Schottky barrier. A space-charge layer is essentially depleted of mobile carriers and hence is very much like the bulk insulators discussed in Chap. 2. In addition, however, such layers have certain unique features which both simplify the analysis and make possible a totally different class of experimental techniques. We will discuss the various electrical measurements — capacitance, current, and voltage — which have been used to study deep levels in the space-charge layers associated with semiconductor junctions.

Much of the general groundwork for our discussion has been laid in Chap. 2, especially the rate equations which describe the dynamics of carrier capture and emission at deep energy levels. Therefore, we will begin by pointing out those aspects of thermally stimulated processes which are unique to semiconductor space-charge layers. We will then discuss the transient electrical response of semiconductor junctions containing traps, including such topics as the spatial and temporal variations of sensitivity, trap concentration profiles, and the special problems associated with large trap concentrations. Our treatment of the specific experimental techniques will be divided into two parts. First, we will discuss the so-called single-shot techniques which are the simplest and were historically the first developed. Secondly, we will examine in some detail the more recently developed synchronous-detection methods, which are generally referred to as Deep-Level Transient Spectroscopy (DLTS). The discussion of the implementation and interpretation of the various experimental techniques will be followed by a section on carrier capture measurements. This will include a discussion of the corrections to the measured activation energy which are necessary if the capture cross section or energy level are temperature dependent. Finally, we will conclude the chapter with a brief discussion of the instrumentation useful in the practical application of space-charge spectroscopy.
3.1 Unique Aspects of Thermally Stimulated Processes in Semiconductor Junction Space-Charge Layers

3.1.1 Ideal Space-Charge-Layer Properties

The existence of a space-charge layer at a pn junction or Schottky barrier is a general characteristic of semiconductors. Such a layer is necessary to create the electrostatic potential variation needed to counteract the diffusion potential of the carriers across the junction and hence equalize the Fermi level through the material, i.e., maintain thermal equilibrium. The ideal space-charge layer (i.e., without traps) for an asymmetric p+n step junction is shown in Fig. 3.1. For simplicity we will confine most of our examples in this chapter to the case of p+n junctions or Schottky barriers on n-type material (for which Fig. 3.1 is also applicable). The extension to n+p junctions is trivial; the situation for arbitrary junction profiles is usually straightforward but often tedious and beyond the scope of this chapter.

We may think of a semiconductor space-charge layer as somewhat like a variable-width insulator, typical thicknesses are in the range of about 0.1 to 10 μm. Therefore, with reverse bias voltages of 1–100 V, the maximum electric field $F_m$ in the layer is very large, typically of order $10^4$–$10^5$ V cm$^{-1}$. From a