

Delta-doping of semiconductors

Preface

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C. H. Proetto

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Introduction

E. F. SCHUBERT

This book is devoted to semiconductors containing very thin, highly doped layers. Assuming that doping impurities are distributed uniformly within the two-dimensional layer, the doping profile depends on only one spatial dimension. Frequently, such doping distributions are described by the delta (δ -) function. This chapter will introduce the reader to the field of δ -doping. Section 1.1 will address the questions: What are δ -doped semiconductors? How are they fabricated? Why are they made? In Section 1.2, a historical sketch of this subject will be provided. The electronic structure of δ -doped semiconductors will be derived in Section 1.3. Finally, the implications of δ -doping on state-of-the-art microelectronic devices will be discussed in Section 1.4.

1.1 Delta doping: what is it and how is it done?

Delta doping is motivated by the need for well-defined, narrow doping profiles in semiconductors. Doping distributions with high peak concentrations and narrow distribution widths are advantageous for many device applications. The narrowest one-dimensional (1D) doping profile is achieved if doping atoms are confined to a single atomic layer in the host semiconductor. Such a situation is illustrated schematically in Fig. 1.1, which shows a semiconductor substrate, an epitaxial layer, and a dopant sheet embedded in the epitaxial layer. All impurities, shown as dark circles in the inset to Fig. 1.1, occupy substitutional lattice sites in the host semiconductor. In group-IV semiconductors, all lattice sites are identical. In III-V semiconductors, we have the distinct cation and anion lattice sites. Therefore, the doping plane shown in Fig. 1.1 may be either an anion or a cation sublattice plane.

The two parameters characterizing a δ -doping profile are the location of the dopant sheet and the density of doping atoms in the sheet. Assuming that the wafer surface is in the xy -plane of a cartesian coordinate system, that the z -coordinate is measured from the surface to the bulk, and that the dopants are located in the plane at $z = z_d$, then the doping

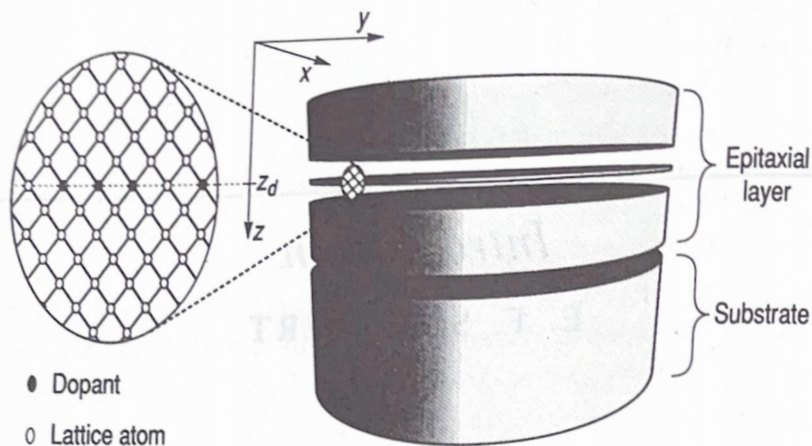


Fig. 1.1. Schematic illustration of a semiconductor substrate and an epitaxial film containing a δ -doping layer. Also shown is a schematic lattice with the impurity atoms being confined to a single atomic plane.

profile is given by

$$N(z) = N^{2D} \delta(z - z_d) \quad (1.1)$$

where the two-dimensional (2D) density, denoted by N^{2D} , is the number of doping atoms in the doping plane per cm^2 . Equation (1.1) states that the doping concentration is zero for all locations, except for $z = z_d$. Integration of Eqn. (1.1) yields $\int_{-\infty}^{+\infty} N(z) dz = N^{2D}$, that is, the 2D doping density.

The growth of δ -doped semiconductors will be discussed for different epitaxial growth techniques in Chapter 3. Here, we summarize briefly the basic procedure common to all growth techniques. Consider a semiconductor during epitaxial growth. In the *first step* of δ -doping, the epitaxial growth of the semiconductor is suspended, which can be achieved by closing the effusion cells in molecular-beam epitaxy or by valving off the semiconductor precursor flow in vapor-phase epitaxy. We assume that the non-growing semiconductor surface will be atomically flat with no atomic terrace steps on the surface. In the *second step*, the surface is exposed to either a flux of elemental doping atoms or to the flux of a doping precursor. For efficient incorporation, it is desirable that the doping atoms have a sticking probability near unity, or, for the case of a precursor, that the decomposition probability of the precursor is near unity. If the doping atoms do not re-evaporate, then they can form bonds with host semiconductor atoms. Impurity atoms are *chemisorbed* at the semiconductor surface. Ideally, all doping atoms occupy substitutional lattice sites on the semiconductor surface. In the final *third step* of δ -doping, the deposition of dopants is terminated and the epitaxial growth of the host semiconductor is resumed. In the absence of impurity redistribution effects such as diffusion, drift, and segregation, the doping atoms are then confined to one atomic layer of the semiconductor.

However, if the semiconductor surface on which the impurities are deposited is rough and contains steps or terraces, or if thermally stimulated redistribution of impurities does occur during subsequent growth, then the impurities cannot be confined to a single atomic