δ-DOPING LAYERS. THE SHAPING OF BARRIER POTENTIALS BY PLANAR DOPING

F. Koch and A. Zrenner
Physik-Department E 16
Technische Universität München
D-8046 Garching, Fed. Republic of Germany

ABSTRACT

Electronic potential barriers, in the interior of a semiconductor, at metal-semiconductor interfaces, as well as at heterostructure interfaces, can be made and shaped using dopant impurities. The dipole layers created by doping involve the spatially separated ionized donors, acceptors and their respective, mobile screening charges. We consider the δ-function doping layer, which is a sheet of impurities introduced during epitaxial growth in a single atomic layer. For such 2D doping the mobile charge screening the ions is contained in subbands with binding lengths determined by the quantum-mechanical motion of the effective mass carriers. As a result the δ-doping dipole has a length intermediate between that of the interfacial atomic layer and a typical depletion layer. We discuss the technology of growing such δ-layers, the electronic properties of the layer and their role in shaping potential barriers.

1. INTRODUCTION

Doping a semiconductor in order to achieve specific electronic functions is a standard and straightforward step in the making of devices. One can create p-n junctions or make ohmic contacts by properly designed doping strategy. For Schottky barriers the lowering induced by the image effect is a subject to be found in the textbooks together with the necessary formulas and tables /1/. Even Capasso's DID (doping interface dipole), proposed as an instrument for tuning heterostructure band-offsets /2/, is thoroughly classical in the sense of textbook electrostatics. We have taken the liberty in Fig. 1 to include it in the classical doping strategies for the making and breaking of electronic potential barriers in a semiconductor. Nevertheless DID highlights the capabilities of modern crystal growth, the deliberate and controlled layer-by-layer growth techniques that allow the introduction of dopants with atomic-plane precision.

The traditional tools of impurity engineering are based on diffusion, implantation-anneal sequences, and incorporation during bulk crystal growth. These methods result in the random, statistical placement of the donors and acceptors with a depth resolution of not much better than \( \sim 0.1 \) µm. By contrast, in the brave new world of planar, layer-by-layer
epitaxial growth techniques, impurities can be introduced at will with near atomic-layer precision /3/. Confinement of the impurity ions in a layer whose width is much less than a Bohr radius, has dramatic consequences for the arrangement of the compensating mobile charge. In such so-called δ-function doping layers the effective mass carriers occupy distinct quantum-mechanical subbands. Their quantum properties were first recognized in Ref. /4/ and have since been explored in a number of publications.

Fig. 1. Classical doping strategies employed in the making, breaking, and shaping of barrier potentials in a semiconductor. The p-n junction and ohmic contact are well known examples. Barrier adjustment of the Schottky contact is based on shaping the tip of the potential maximum to change image and tunneling effects.

In the context of the workshop theme of metal-semiconductor and heterostructure interfaces, we aim here to explore how the quantum aspects of layer doping enter in the consideration of barrier tuning. The distinctive quantum characteristics of the δ-layer become apparent in the listing and comparison in Fig. 2 of the different dipoles contributing to the potential barrier. In planar electrostatics potential variations are linked to dipole layers. In that sense the metal work function, the semiconductor electron affinity, and the heterostructure band-offset can be understood in terms of the interfacial atomic dipole layer. This microscopic dipole consists of each of the $10^{15}$ atoms per cm$^2$ each displacing a charge of order $e$ by a length of order 1 Å. The resulting potential barrier height is of order 1 eV. On the other extreme of the scale of lengths is the macroscopic distribution of charges in the depletion zone of a p-n junction. In this case in Fig. 2, some $10^{11}$ charges per cm$^2$ are separated by a length of order $10^4$ Å to make up a macroscopic dipole layer. The rise in the potential occurs on a much larger scale. Its magnitude, however, is again $\sim$ 1 eV. In the same sense, the semiconductor depletion layer of the Schottky barrier forms a