I.4 Principles of Kelvin Probe Force Microscopy

TH. GLATZEL, M.CH. LUX-STEINER, E. STRASSBURG, A. BOAG, AND Y. ROSENWAKS

In this chapter we describe and discuss Kelvin probe force microscopy (KPFM), a scanning probe microscopy technique designed to obtain laterally resolved work function images by measuring the electrostatic forces between probe and sample surface. By operating the microscope in ultrahigh vacuum, even absolute work function measurements with very high lateral and energy resolution can be realized.

The method of Kelvin probe force microscopy is introduced in the first section and the two main measuring modes are discussed in detail. The amplitude modulation technique has the advantage of requiring only small modulation voltages; however, due to long-range electrostatic forces the lateral resolution is limited. The frequency-modulation technique, on the other hand, is sensitive to the force gradient, which provides better lateral resolution, but requires a much larger sampling voltage.

The second section examines the factors affecting the sensitivity and resolution of KPFM in general, and in semiconductors measurements in particular. An efficient numerical analysis of the electrostatic interaction between the measuring AFM tip and the semiconductor surface has allowed us to derive a point spread function of the measuring tip and to reconstruct the actual surface potential from KPFM images in almost real time. Several examples of recent applications will be reviewed in our second chapter.

1 Introduction

The Kelvin probe force microscopy (KPFM) is a method for measuring the surface potential distribution with nanometer resolution. Since its introduction in 1991 by Nonenmacher et al. [1] KPFM has found many diverse applications in several fields due to the direct and quantitative measurement of the surface potential distribution. In materials research it has been used for work function mapping [1], ordering measurements in III-V compound semiconductors [2], local surface photovoltage and surface photovoltage spectroscopy [3], surface states and defects under different ambient conditions [4], domain characterization in ferroelectric materials...
measurement of organics and self-assembled monolayers [6], and many more applications. KPFM has also proved to be a very important tool for potential mapping of passive and active semiconductor devices such as \textit{pn} junctions [7], resistors and \textit{n-i-p-i} heterostructures [8], high-electron-mobility transistors (HEMT) [9,10], light-emitting diodes [11,12], solar cells [13,14], and organic and polymer-based transistors [15]. Recently several groups have reported on high-resolution measurements of low-dimensional structures such as 5-nm CdSe nanocrystals [16], and single and multi-quantum well structures [17]. Although atomic scale features in KPFM were reported five years ago [18,19], their origin is poorly understood mainly due to the long-range nature of the electrostatic forces discussed in detail in the next section. Another important aspect of local potential measurements is related to quantitative two-dimensional dopant mapping. Several groups have used KPFM for two-dimensional dopant profiling [20]; however, it was found that it is not yet the ideal tool for this purpose. The resolution of KPFM compared with scanning capacitance microscopy (SCM) [21] and scanning spreading resistance microscopy (SSRM) [22] is smaller; and with a sensitivity of a few millivolts, it is challenging to quantify doping levels in the range required by the microelectronic industry.

The KPFM method as well as the basic detection method are introduced in sections 1.1 and 1.2. The two main measuring modes used commonly in KPFM are described and discussed in sections 1.3 and 1.4. Section 2 examines the factors affecting the sensitivity and resolution of KPFM in general, and in semiconductors measurements in particular. An efficient numerical analysis of the electrostatic interaction between the measuring AFM tip and the semiconductor surface has allowed us to derive a point spread function of the measuring tip and to reconstruct the actual surface potential from Kelvin probe microscopy images in almost real time.

1.1 Kelvin Probe Force Microscopy

The contact potential difference (CPD) between two materials, for example, between an AFM tip and a sample, is defined as

\[
V_{\text{CPD}} = \frac{\Phi_{\text{sample}}}{q} - \frac{\Phi_{\text{tip}}}{q} \equiv \Delta \Phi / q, \tag{1}
\]

where $\Phi_{\text{tip}}$ and $\Phi_{\text{sample}}$ are the work functions of the tip and the sample, respectively, and $q$ is the elementary charge. Therefore, if an AFM tip and a semiconductor with different work functions are held in close proximity, an electrostatic force will developed between them, due to the potential difference $V_{\text{CPD}}$; this is schematically described in Figure 1. When the two materials are not connected their local vacuum levels are aligned but there is a difference in their Fermi levels. Upon electrical connection, the Fermi levels will align through electron current flow, as shown in Figure 1(a). The two materials (electrodes) are now charged and there is a