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Development of Kelvin-probe microscopy for detector characterization

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Tutorial Introduction

Abstract

An accurate measurement of surface potential is important in assessing many classes of devices. Field-effect transistors operate by precise application of spatially varying potentials. Detector devices such as avalanche photodiodes are often limited in performance by fringing electric fields that cause unwanted breakdown leading to parasitic currents. Of particular interest to us is the effect of variations in surface potential and work function on the performance of photocathodes, a critical component in low-noise UV detectors.

The purpose of this task was to develop the method of Scanning Kelvin Probe Microscopy (SKPM) as a way of imaging microscopic variations in surface potential and/or work function [1]. The measurement uses atomic force microscopy (AFM), modified to image potential in addition to measuring surface topography.

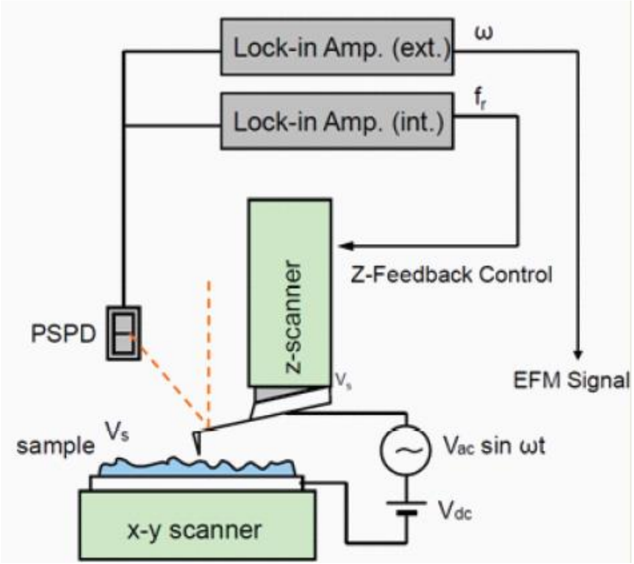

Figure 1: Schematic of scanning Kelvin probe microscopy (SKPM). An atomic force microscope is used to scan a tip across the surface. In addition to measuring conventional topography, the tip is biased (DC + AC modulation) in order to zero the electrostatic force between tip and sample. A second lock-in amplifier is used to detect the zero. In this way, surface potential can be imaged with high spatial resolution.

Problem Description

a) Ever-shrinking device dimensions now require characterization on very small scales. The particular detector application that guided this development was a UV photocathode. Unlike many solid-state devices that rely on properties of buried interfaces, photocathode performance vitally depends on surface electronic properties. Among other properties, the charge state of the emitting surface is crucial in determining emission threshold and quantum efficiency. UV photocathode emission properties depend both on electron affinity and on the degree of downward bending of the electronic bands near the surface. The magnitude of the band bending is determined by surface charge, so understanding and controlling the surface charge state is paramount.

b) SKPM is a simple, direct way to measure spatial variations of surface potential on a microscopic scale, a measurement that is difficult by other techniques. This technique will be a valuable addition to the tools at the Microdevices Laboratory, and at JPL, for assessing device parameters and performance.

c) In addition to the development of the technique for general applications using existing JPL equipment, our goal was to demonstrate its application to structures relevant for ongoing JPL detector development. But it is a technique with broad applications. We expect that the method will be valuable in assessing performance factors in a wide range of device structures.

Methodology

Non-contact AFM operates by oscillating the cantilever that carries the tip at a high frequency. When the tip nears the surface, the attractive interatomic forces begin to be felt and the oscillation frequency shifts. When imaging, the AFM electronics detect this shift and move the tip in or out to maintain constant force. Thus imaging lines are lines of constant force, and a topographic image of the surface is built by raster scanning the surface.

SKPM adds a second feedback loop to the picture. A DC voltage is applied to the tip together with an AC modulation voltage. The AC voltage is at a frequency well away from the cantilever vibration frequency so that the two frequencies do not interfere with each other. The AC voltage signal causes the electrostatic force to modulate at that same frequency via a change to the charge on tip and sample. The changing electrostatic force is detected by a change in cantilever resonance properties. As the tip scans, tip voltage is adjusted to minimize the electrostatic force; this applied voltage equals the work function difference between tip and sample. Figure 2 shows the relative alignments of tip and sample energy levels for SKPM of a metal sample surface for several different conditions.

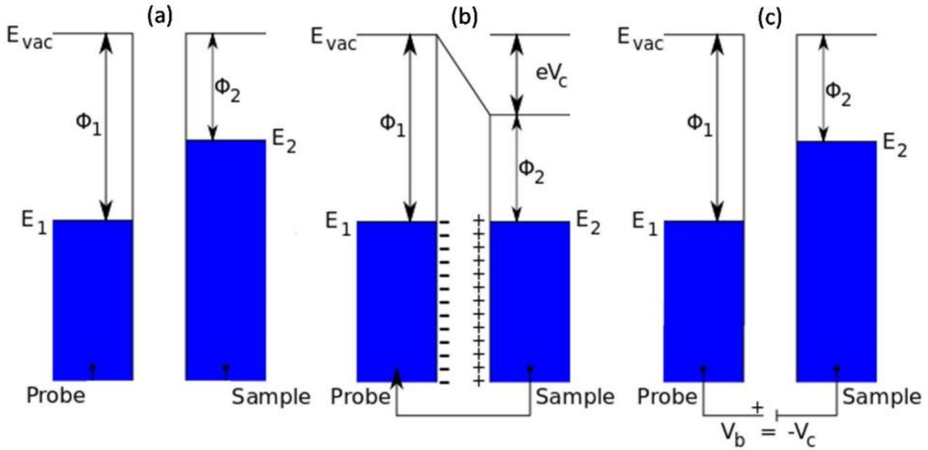

Figure 2: Band diagrams for SKPM of a metal sample. (a) When the probe tip is far from the sample, vacuum levels align but Fermi levels do not. (b) If electrical contact is made between the two, the Fermi levels align by transfer of charge, and a potential is created between tip and sample. (c) If a backing voltage is applied between tip and sample to zero the charge, the applied voltage is equal to the work function difference. SKPM measures the force due to surface charge, and can determine when surface charge has been zeroed by the backing voltage, allowing a measurement of work function difference.

Results

The goal of this task was to implement the method of SKPM as a way of imaging microscopic variations in surface potential and/or work function [1],[2].

A GaN photocathode sample was chosen to evaluate the success of this development. We have found that surfaces with faceted hillocks exhibit higher emission than smooth surfaces, suggesting that some property of the hillocks produces higher emission. One possibility is that either larger band-bending or a lower electron affinity (the semiconductor equivalent of work function) increases electron emission in certain areas associated with the hillocks.

Figure 3 shows an AFM topographic image of a hexagonal hillock, together with the corresponding SKPM potential image. It is clear that the step risers at the perimeter of the hillock have a higher positive potential than the surrounding areas, corresponding to a lower electron affinity or larger band-bending. Reproducible points of higher potential can also be observed, likely due to either surface defects or localized high doping regions. It is important to remember that there is no external bias applied to the sample; the potential variations are due to built-in potentials caused by variations in fixed surface charge.

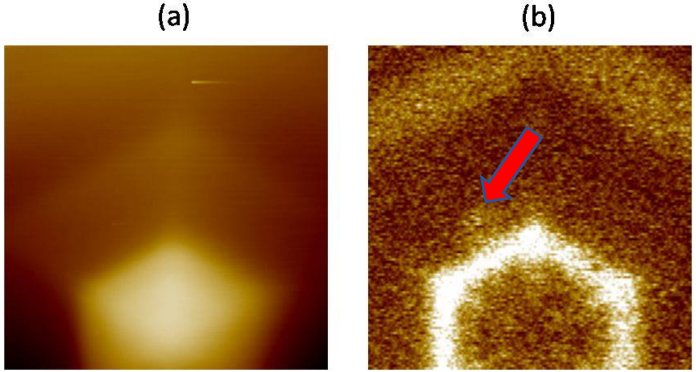

Figure 3: SKPM results for a grounded GaN sample. Images are 50 x50 microns. (a) Surface topography of a hexagonal surface hillock. (b) Potential image of the same hillock. Color scale range is about 150 mV. The bright spot indicated by the arrow is reproducible, and is likely due to a defect, dopant cluster, or surface contamination.

The technique has been demonstrated using existing MDL equipment, and can now be used to characterize functional potentials on many other device surfaces.

References

1) M. Nonnenmacher, M. P. O’Boyle, and H. K. Wickramasinghe, "Kelvin probe force microscopy,“ *Applied Physics Letters* **58**, 2921 (1991).

2) W. Melitz, J. Shena, A. C. Kummela, and S. Lee, "Kelvin probe force microscopy and its application,“ *Surface Science Reports* **66**, 1–27 (2011).

Publications

None.