High Spatial Resolution Kelvin Probe Force Microscopy with Shielded Probes

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Abstract:

Kelvin probe force microscopy (KPFM) is a powerful technique to study electrical properties of materials on the nanoscale, but its spatial resolution is inherently limited by the long range of the electrostatic interaction. In this study, we mitigated these resolution limitations by electrically shielding the cantilever and the bulk of the tip. Shielded probes were created by coating conducting atomic force microscopy (AFM) probes with an insulating layer followed by a conducting layer. The tip of the probe was then exposed by focused ion beam (FIB) milling. The external metal layer formed a grounded electrical shield that extended to within two micrometers of the tip. The improvement in resolution due to shielding was analyzed using finite element electrostatic simulations.

Introduction:

KPFM was invented in 1991 at IBM by M. Nonnenmacher, M.P. O'Boyle, and H.K. Wickramasinghe as an extension of AFM that mapped sample work functions with spatial resolution of about 50 nm [1]. The Kelvin technique is non-contact and can operate in ambient conditions [2]. It has been used to study electronics, solar cells [3], biological cells [4], arrayed proteins, and deoxyribonucleic acid [2].

The basic principle of KPFM is illustrated in Figure 1. The tip of a conducting probe is brought into close proximity to the sample so that the tip and sample form a capacitor. The tip experiences a force proportional to the square of the tip-sample potential difference V_{TS}.

We electrically drove the tip at its mechanical resonance frequency while applying a DC Kelvin voltage, V_K, which we adjusted to null the oscillation and thus determine the contact potential difference between the tip and sample. We used V_K to calculate the local sample work function Φ_S as described in Figure 1. The probe scans across an area of the sample to map the work function [1].

Several studies have sought to improve the resolution of KPFM, including operating under ultrahigh vacuum with simultaneous electrostatic and topographic data collection [5], optimization of tip and cantilever geometry through both simulations and experiments [6], and modifications to probes such as nanowire tipped probes [7].

We report on our efforts to improve the technique's spatial resolution by building electrostatically shielded probes. First, we present simulation data indicating the benefits of electrostatic shielding, and second, we present the actual fabrication of shielded probes.

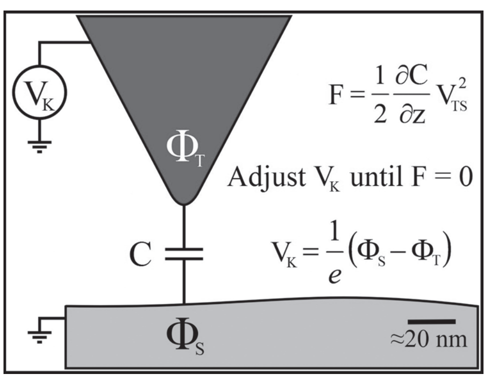

Figure 1: Schematic explanation of Kelvin probe force microscopy.

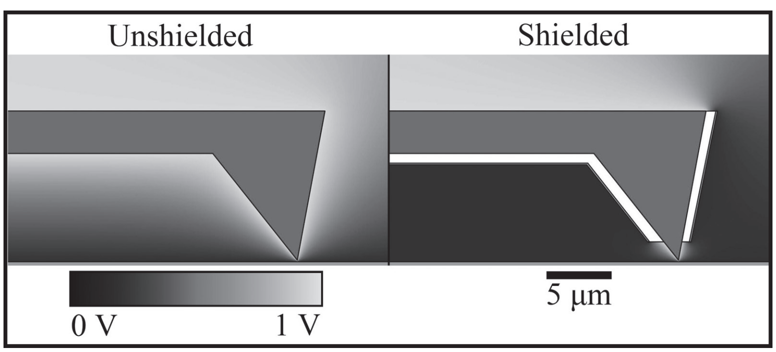

Figure 2: Two dimensional electrostatic simulations of the cross sections of unshielded and shielded probe-sample interactions.

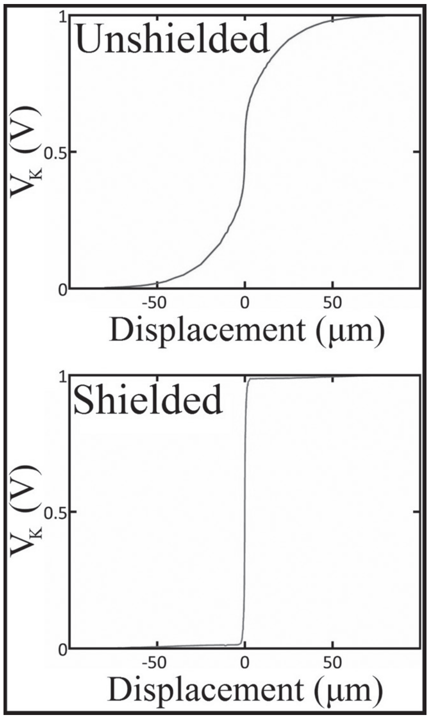

Figure 3: Results of three dimensional electrostatic simulations of probes traversing a 1 volt potential step.

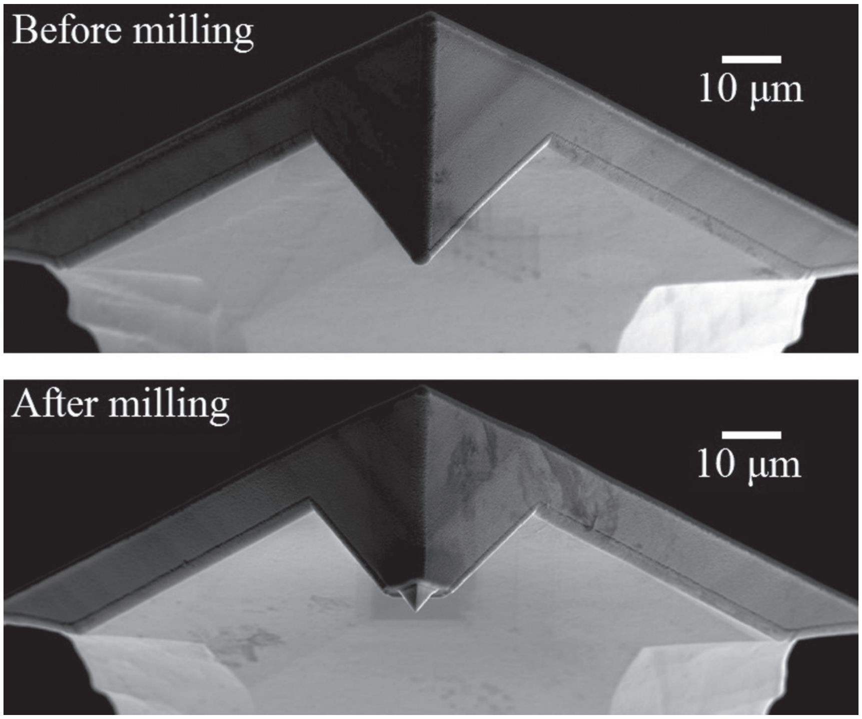

Figure 4: Scanning electron microscope images of probes before and after focused ion beam milling to expose the tip (front view).

Simulation of Shielded Probes:

We qualitatively demonstrated the benefits of shielding in Figure 2 with two dimensional (2D) electrostatic simulations. We simulated the local potential V while the probe was held at 1V and the sample was grounded. The left plot shows an unshielded probe, and the right plot shows a shielded probe with the same dimensions as those we fabricated. The potential profile of the unshielded probe exhibited a large gradient between all of the lower surfaces of the probe and the sample, indicating that the interaction area was not confined to the tip. The potential profile of the shielded probe showed that there was still interaction between the tip and sample, but it was limited to a much smaller region of the probe and sample, which will lead to improved resolution.

We quantified the resolution improvement afforded by shielding by 3D simulations of probes crossing a potential step from 0.0 volts to 1 volt. The results are plotted in Figure 3. Each probe measured a V_K that transitioned from 0.0 volts to 1 volt, but it took the unshielded probe substantially greater distances to resolve the change. The shielded probe exhibited remarkably superior performance.

Fabrication of Shielded Probes:

We started our fabrication process with commercially available conducting probes. We then coated them with approximately 1 mm of insulator using CVD. This enabled the probe and shield to be electrically disjoint. Next, we coated them with approximately 100 nm of metal, using thermal evaporation, forming the shield itself. Finally, we exposed the lower 2 mm of the probe using FIB milling. Figure 4 shows shielded probes before and after milling to expose the tip.

Conclusion:

KPFM is a very useful technique in numerous fields because of its ability to measure the local work function with high spatial resolution. We present electrostatic shielding as a viable method of further improving the spatial resolution of Kelvin probe force microscopy.

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