High resolution field emission scanning electron microscopy

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In conventional scanning electron microscopy (SEM) the lateral resolution is limited by the electron beam diameter impinging on the specimen surface and interaction volume [1] of the electron collisions. This limit is also critical for the subsequent analysis of the resultant electrons, e.g. spin polarization (SEMPA), electron energy loss spectroscopy (EELS), and Auger electron spectroscopy (AES) [2]. The close proximity between the probe and sample surface of a scanning tunneling microscope (STM) operating in field emission (FE) mode provides a means of overcoming this limit.

In this work, we present a simple “near field emission scanning electron microscope” (NFESEM) capable of imaging conducting surfaces with high spatial resolution. This microscope is also refined to overcome the problems associated with the prior art, while introducing a means of comparative surface imaging using both the variations in electron intensity and the FE current. Variable current imaging generated by an STM operated in constant height (CH) mode has often been used to produce high resolution images of the surface [3]. Moreover, STM FE mode operation was also used for mapping the FE sites on surfaces [4]. It is our intention to employ such well-known imaging techniques as a comparison to our electron intensity images, which are the product of the primary beam of field-emitted electrons from an STM tip.

We report on the first topographic electron intensity image of terraces and mono-atomic steps on a single crystal substrate, not yet attained with a remote electron gun in conventional SEM. In addition the simultaneously recorded FE current surface mapping, limited only by the incident beam girth, closely resembles the topography of the electron intensity. This indicates that the maximum resolution, in accordance with the tip-sample geometry, has been reached. High spatial resolution was achieved by adhering to established theoretical models relating to the beam width of field-emitted electrons from a sharp tungsten (W) -tip [5-7], which was shown to mainly depend on the emitter radius and the tip-sample separation gap. Complimentary STM imaging, directly following NFESEM measurements, is feasible and can easily be performed. We assert that additional analysis of the secondary electrons will also exhibit a comparable resolution.

Subsequent STM imaging of the W(110) surface in constant current (CC) mode confirm sharp step edges with single atom height. The line scan in Figure 1 establishes STM-like resolution for the W(310)-orientation tip, trumping theoretical predictions; however the imaging parameters of the NFESEM and the STM differ. In the case of the STM the resolution depends on the electron tunneling probability of the overlapping wave functions through the vacuum barrier. FE-generated images exhibit a vertical resolution restricted only by the detection of the minimal current caused by deviations in tip-sample spacing. In addition there are geometrical parameters limiting the lateral resolution; thus the spatial resolution dependence is directly proportional to both current deviations and the tip-sample geometry. Our observation is well within J. Saenz’s atomic vertical resolution for the near-

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field emission regime [6]. We note that the FE current and electron intensity mapping are not always exactly the same in NFESEM. Electron intensity images show more detail with higher resolution than FE current imaging. This implies that the SE yield is more sensitive to additional parameters, which may be the local work function, specimen curvature, primary beam energy, and detector sensitivity. Moreover we have studied the current-voltage (I-V) characteristics of FE from curved surfaces. These I-V measurements enable us to determine microscopic properties of the tip including the effective emission radius, the surface field, and the effective solid angle of emission [8].

1. This is a material property associated with the beam energy and diameter, which can be three orders of magnitude larger for typical SEM operation (i.e., several KeV). It however decreases dramatically with lower primary beam energy; hence it is sufficiently small for our purpose, see I.Müllerova, and L. Frank, *Modern Research and Educational Topics in Microscopy* (Formatex, Badajoz, 2007) **2** (2007) p795.
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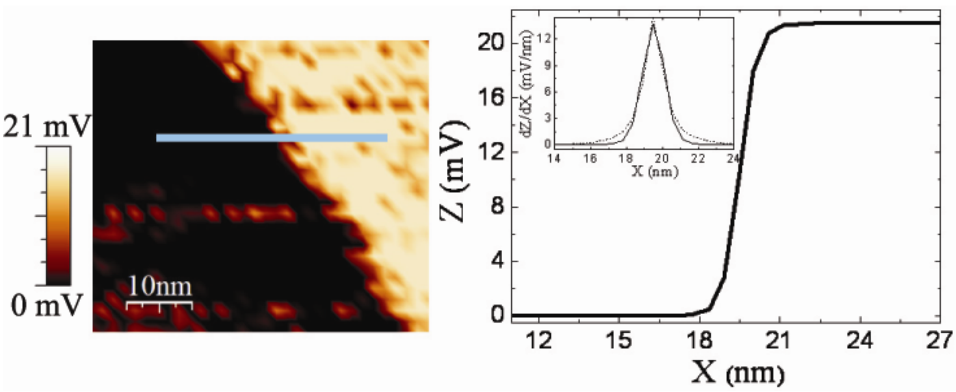

Figure 1. This NFESEM micrograph of a W(110) step-edge on the left shows a line scan, indicated by the blue line located in the center of the image, used to calculate the lateral resolution. The measured profile of the step-edge on the right, where the z-component is given by the signal increase on the detector, is differentiated in the inset. A Gaussian fit (--) yields a lateral resolution of 1.5 nm.

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