

# Imaging reveals working nanodevices' topology and electronic processes

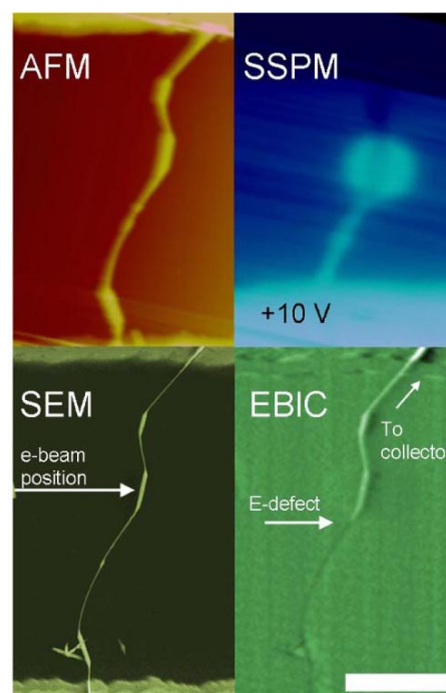
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*Modern imaging techniques can reveal the surface structure and electrical characteristics of individual metal-oxide nanowires during nanodevice operation.*

Devices based on nanowires, nanobelts, and nanotubes exhibit unique physical and chemical properties, that can be applied to optoelectronics, sensing, energy storage, catalysis, and detecting biomedical- and homeland-security threats. These components have inspired a trend: substituting pre-engineered nano-objects for the traditional active elements in microdevices.<sup>1</sup> For example, semiconducting-metal oxide nanowires—just a few microns long and with diameters on the order of a few tens of nanometers—offer relatively simple fabrication, and they are compatible with many microfabrication protocols.

As one attractive feature, nanowire-based devices include strong short-range interactions between surface processes and useful electronic and transport properties.<sup>2</sup> These features work well in chemo- and biosensors. For example, the electronic properties of nanowires depend strongly on their size (diameter), which can be used to engineer sensing behavior. Moreover, new approaches in spectroscopic and imaging techniques provide a better understanding of the operation of these devices and the mechanisms that can drive chemical and biological detection. In particular, these techniques let researchers 'watch' individual-nanowire elements in operating devices.

We fabricated three-terminal field-effect transistor (FET) devices by using individual segmented tin-oxide nanowires as the active elements.<sup>3</sup> In these nanowires, the narrower segments are particularly responsive to adsorbates. Consequently, such a device is usually referred to as a chemiresistor, because of the strong dependence of the nanowire's resistance on the gas environment. These devices are called chemFETs when a gate electrode is used. To visualize the operation of such a device, we used a number of complementary scanning-probe and electron



**Figure 1.** Various modes of imaging reveal different characteristics of a tin-oxide nanowire. Atomic-force microscopy (AFM) and scanning-electron microscopy (SEM) show the nanowire's topology. Scanning-surface potential microscopy (SSPM) and electron beam-induced current (EBIC) imaging reveal the potential distribution and electron flow along the length of the nanowire, respectively. The white bar represents 10 $\mu$ m.

microscopies. In particular, atomic-force microscopy (AFM) and scanning-electron microscopy (SEM) reveal the surface structure of a nanodevice. We used scanning-surface potential microscopy (SSPM)—a special mode of AFM—to quantitatively

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explore the potential distribution inside a working nanodevice with mesoscopic lateral resolution.<sup>4</sup> In addition, electron beam-induced current (EBIC) imaging with an SEM showed the electron/hole transport inside a nanowire. Instead of detecting the secondary-electron signal during the scan, an EBIC image is formed by collecting electron (or hole) current generated inside the nanowire by the incident-electron beam. In order to model the local electroactive defects that are often present inside nanodevices, we created one by illuminating a segment of the nanowire with a highly focused electron beam.

Figure 1 is a set of images taken during the biasing of a nanowire, which is configured as a chemFET. AFM and SEM images show the device topology, and SSPM and EBIC reveal significantly more information about the potential distribution and current flow through the nanowire. Specifically, the SSPM image shows that the electroactive defect created by the electron beam also includes the area of the neighboring oxide, which is evident as the white area in the center. This image also shows that the defect significantly modulates the potential distribution along its length of the nanowire, indicated by the sharp white-to-dark transition along its length. In fact, most of the potential drop is in the area of the defect and is due to a p-n junction, which the electron beam created in the nanowire. This result illustrates that the defect-creating technique can be used both to study and control the function of nanodevices.

Another interesting feature is the relatively broad propagation of the potential beyond the electrode. To see this, compare the white borders of the potential map—as seen in the SSPM—with the physical border of the bottom electrode—as seen in the SEM. This arises from the migration of positive charges on the surface of the gate oxide, which has to be taken into consideration when operating the device in a real-world environment. These results are complimentary to the EBIC image, which is very sensitive to discontinuities in the current flow through the nanowire. In this nanodevice, the EBIC image indicates the presence of a sharp barrier for electrons in the area of the artificial electroactive element.

Recently, we used synchrotron radiation-based spectromicroscopy to study the surface chemistry of nanodevices.<sup>5</sup> Next, we hope to use these techniques to visualize sensor performance in real time under exposure to different atmospheres.

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