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Nanoscale Imaging of Electric and Magnetic Fields by Off-axis Electron Holography

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Off-axis electron holography in the transmission electron microscope provides a unique and powerful approach to visualizing electric and magnetic fields within materials with resolutions approaching the nanometer scale [1]. The ability to image phase shifts at medium resolution opens up a wide field of interesting and important materials problems. In this work, the technique has been successfully used to quantify electrostatic and magnetic fields in and around deep-submicron transistor devices and patterned nanomagnets. An important extension of this work has involved *in situ* biassing of the samples to quantify the electrostatic potentials of active devices.

In previous electrostatic studies, we characterized a 90-nm Si CMOS transistor device and field-emitting carbon nanotubes [1]. In these cases, considerable progress was made in overcoming the challenging problems associated with sample preparation since not only must the sample be prepared for biasing so that it is neither shorted nor open but, in addition, it must conform to all the demanding requirements for holographic imaging [2]. Figure 1 illustrates an example of a biasing experiment for a 1-dimensional p-n junction [3]. Platinum electrodes for contact purposes were deposited on the surface of the sample prior to thinning the area to electron transparency. A movable electrode was then used to apply the bias voltage while the holograms were recorded. The line profiles shown in Fig. 1b indicate that the sample was successfully biased in both the forward and reverse directions. The large applied bias relative to the corresponding voltage response of the sample indicates that the sample configuration provided additional paths for current conduction. However, the sample response in the area for holography behaved as expected, including increased depletion widths and "flat-banding" at negative bias.

Magnetic flux-closure states of opposite chirality (clockwise and counter-clockwise) could possibly provide an alternative type of binary logic suitable for magnetic data storage applications. However, shrinking dimensions make it difficult to track the behavior of separate magnetic nano-elements. We have used off-axis electron holography to systematically investigate *in situ* the influence of the size and shape of individual patterned nanostructures on their magnetic properties [4]. Electron holography and Lorentz microscopy were used to study remanent states and magnetization reversal in nanopatterned Co elements in the "double pacman" and slotted ring shapes. Figure 2 shows stages in the hysteresis cycles of individual double pac-man shapes. In the case of rings and ellipses, different switching mechanisms were observed depending on the relative ring diameters and ring widths. Slotted disks and rings had very stable and well-defined remanent states, unlike complete disks and rings. Moreover, the commonly observed flux-closure pattern served to reduce markedly the magnetostatic interaction between neighboring elements. Very high packing density of such magnetic nanoelements, which is essential for future data storage use, would thus become feasible.

References

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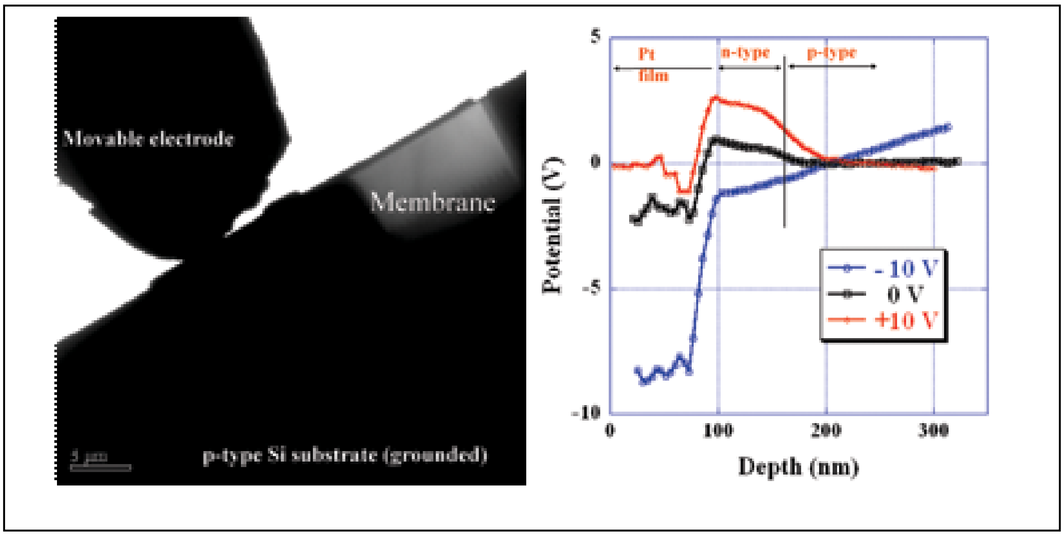

FIG. 1. - a). TEM image showing the FIB-prepared sample set-up for biasing 1-D p-n junction. The moveable electrode is in contact with a Pt layer that extends over the thin membrane from which the holograms are acquired. b) Line profiles across the p-n junction at various applied voltages.

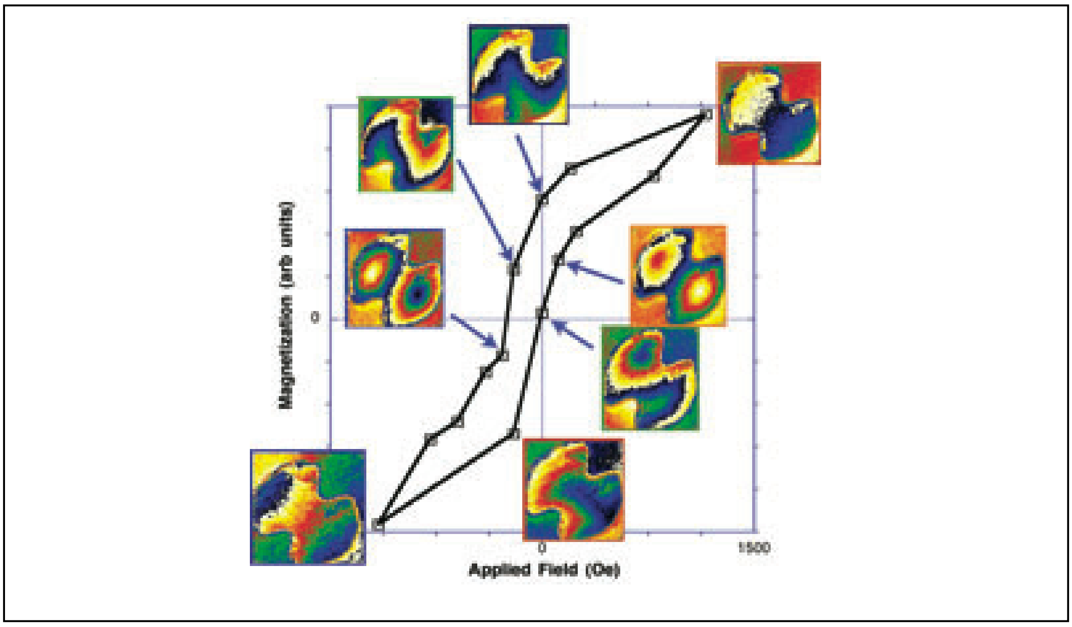

FIG. 2. Hysteresis loop derived from electron holographic phase images of a double pac-man shape. The field was applied along the diagonal of the figure. Also shown are the magnetic configurations of the element at various stages in the reversal cycle. Color contours follow the magnetic field lines.