

Visualizing and modifying objects at the nanometer length scales

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In the closing decades of this millennium, our civilization has seen the rise in scientific and popular interest in tiny entities. We have come to accept as common place, previously unexpected and seemingly impossible effects that occur at very short length scales. We have developed new theories that are rooted in quantum mechanics and built sophisticated tools to model, investigate and fabricate small, densely-packed devices for faster and more powerful computers, for storing and retrieving massive amounts of data, for diagnosis and treatment of diseases, for generation of energy and for providing new insights into the nature of matter. We have coined the word “nanotechnology”, which has become a universal term to denote systems that are on the order of a nanometer - a billionth (10^{-9}) of a meter, comparable to interatomic spacing in solids.

The advances in nanotechnology came as a direct result of our ability to ‘observe’ individual atoms. To date, there are only two instruments that possess the extraordinary resolving power to view structures far smaller than visible light. These are the transmission electron microscope and the scanning tunneling microscope. Both use electrons as probes: the former uses electrons that are accelerated up to several thousand volts that impinge on the specimen, while the latter relies on low energy electrons (< 10 Volts) that “tunnel” between the specimen and a very sharp probe. While these instruments earned their pioneers, Ruska, Binnig and Rohrer, the Nobel prize in physics in 1986 (http://nobelprize.org/nobel_prizes/physics/laureates/1986/), it is the scanning tunneling microscope (STM) with its elegantly simple principle that allowed researchers to investigate atoms at relatively low cost on a tabletop apparatus. It is a crucial invention that spurred advances in nanotechnology.

The STM uses an atomically sharp metallic tip and is placed very close to the surface with about a 1 nanometer gap (Binnig et al. 1982). When a small bias voltage is applied between the sample and probe, some of the electrons from the sample manage to cross over to the probe and be detected as current. This process is known as ‘quantum tunneling’, which does not have an analog in classical physics. Tunneling is forbidden in the classical theory of Newtonian mechanics because it implies that an object hitting a wall can be found on the other side without damage to itself, the wall and without going above the wall. In quantum theory, this is possible because it offers the alternative description that physical objects need not be viewed exclusively as particles with well-defined edges. Instead, objects are described by probability distributions analogous to clouds that have smeared spatial extent. Thus, in bringing the probe tip close to the sample, it begins to feel the electron cloud from the atoms on the sample that extends be-

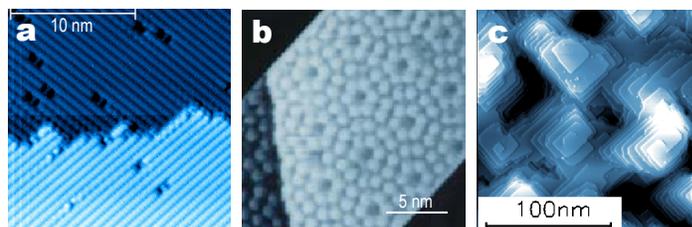


Figure 1. Atomically resolved STM images of **a.** ‘2x1’ reconstructed Si(100) with missing atoms, **b.** ‘7x7’ reconstructed Si(111) and **c.** 14 nm thick Fe(100) deposited epitaxially (lattice matched) on (100) magnesium oxide surface.

yond the gap. In other words, there is a finite probability that an electron from the sample can be found across the gap and at the location of the probe. Under this condition, a small but measurable current flow occurs into the probe tip. The sensitivity to atomic features arises since the tunneling current depends exponentially on the separation between the sample and tip. Scanning the tip across the surface at a fixed height causes the measured current to vary with the concomitant surface structure. Examples of atomically resolved images are shown in Figure 1 for two different faces of crystalline silicon: Si(100) and Si(111) (Binnig et al. 1983, Gomez 1990). Notice that the atoms are not in the same configuration as those in bulk. As happens in most surfaces, the difference in the number of nearest neighbors between the surface and the bulk causes massive rearrangement of surface atoms to lower the energy. This is the case with the so-called ‘2x1’ Si(100) and ‘7x7’ Si(111) reconstructions. Si(100) has a square lattice in the bulk. But due to the truncation of periodicity at the surface, the atoms in one direction move closer to each other which form ‘dimer’ rows that appear in the STM images. The 7x7 reconstruction is even more exotic and it involves the rearrangement of 49 atoms. Metal surfaces are a little harder to resolve atomically because their electronic probability clouds are less localized. However, the STM can still provide exquisite details on how films grow. An example is the atomically registered or epitaxial growth of Fe on the crystalline surface of MgO (Lee et al. 2006). It forms terraces resembling ziggurats of ancient Mesopotamia, where each terrace is separated by a single atomic step. Studies such as these enable VLSI (very large scale integration) researchers to understand the formation of surface crystallinity, defects and epitaxy as

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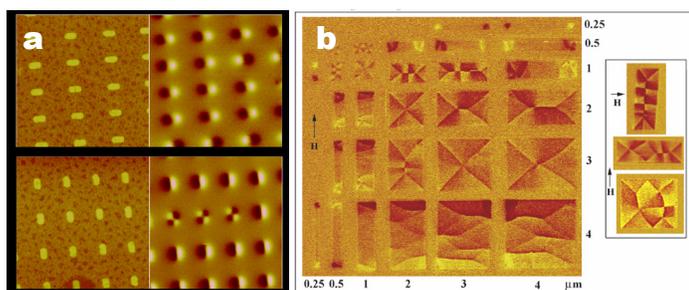


Figure 2. a. topography (left) and magnetic structure (right) of 300x100x15 nm of cobalt grown epitaxy on Si(110) surface. b. magnetic domain patterns of patterned polycrystalline NiFe alloy, showing the richness of magnetic phenomena in small structures.

increasingly smaller devices are fabricated into semiconductor chips.

From an implementation point of view, a key feature of the STM is the use of piezoelectric crystals as highly accurate probe manipulators. Crystals such as lead zirconate titanate ($\text{Pb}[\text{Zr}_x\text{Ti}_{1-x}]\text{O}_3$ $0 < x < 1$) can be formulated to elongate or contract at a rate of about 0.1 nM/V, so that probe positioners made from these can be controlled with extraordinary accuracy.

A few years after the STM, it became evident that the same technology can be used for imaging nonconducting surfaces using a method reminiscent of the bygone days of vinyl recording. In order to map the topographic features of the surface, the probe is made out of a cantilever beam with a sharp point on the free end, which is in contact with the surface. As the probe is scanned across the surface, the cantilever deflects in accordance with the surface contour (Binnig et al. 1986). The technique is called atomic force microscopy (AFM) because the deflection of the cantilever in normal operation is directly proportional to the force between the surface and the probe tip. The resolution is typically 10 nm and somewhat less than the STM. However, this is more than made up for by the versatility of the technique. Apart from the ability of the AFM to image nonconducting samples, the AFM can be used to detect any force between the tip and the sample. For example, if the cantilever is electrically charged then the force is dominated by the electrostatic field from the surface (Gomez et al. 1998). Similarly if a tiny magnet is placed at the probe tip and the sample is magnetic, then the image is magnetic in origin. The technique is called magnetic force microscopy or MFM. Figure 2 shows examples of magnetic images of nanomagnets comprised of (~100x300x25 nm) cobalt islands (Ganesan et al. 2000) and various patterns of $\text{Ni}_{80}\text{Fe}_{20}$ alloy (Gomez et al. 1999), a widely used material in magnetic technology. The bright and dark regions on the cobalt islands are locations of magnetic charges, which we often refer to as the poles of a magnet, whereas the films

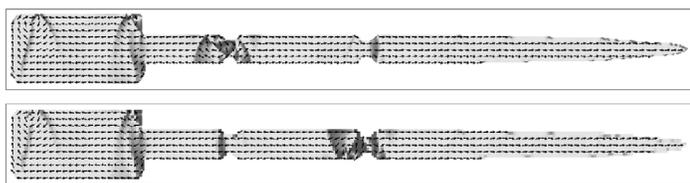


Figure 3. A test structure showing a micromagnetic model of distribution of local magnetic dipoles which are consistent with superimposed experimentally derived MFM images. The long length is 3 microns, the width of the middle segment is 100 nm and the constrictions are 50. The images show trapped domains on the left constriction (top image) and on right constriction (bottom image), respectively. This is a design concept for a magnetic random access memory element.

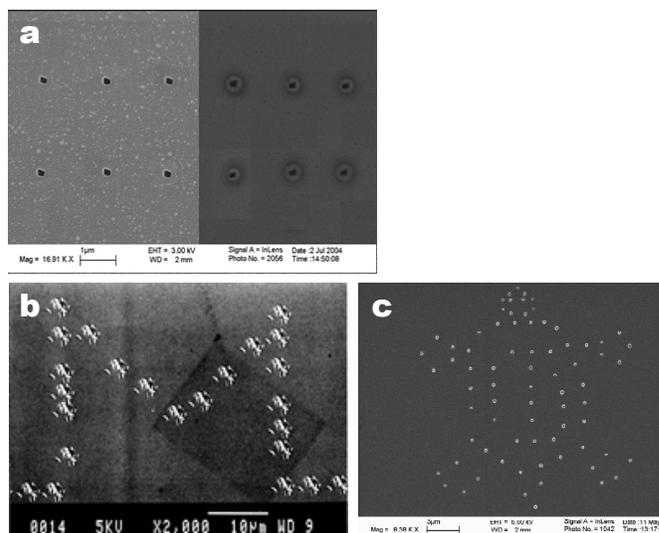


Figure 4. Scanning electron micrographs of features formed using nano-electrostatic discharge showing a. 100 nm diameter holes on 30 nm Si membrane, b and c. stamping of repeated patterns at well-defined placements. M is for University of Maryland and the testudo the turtle is its mascot.

of NiFe show interior geometric shapes known as magnetic domains. When imaging is conducted in the presence of an external magnetic field, important attributes such as switching and reversal of domains can be analyzed (Gomez 2001). Yet another example of the complex magnetic structure that occur in areas with extreme geometrical confinement such as a nanometer constriction is shown in Figure 3 along with a calculated model of distribution of the magnetic dipoles (Florez et al. 2004). This is a concept device for a new magnetic memory element. The local magnetic structures affect the flow of electrons across the device by virtue of another quantum mechanical entity, the electron spin. In addition to charge, an electron also exhibits angular momentum akin to a spinning top. It could have 'up' or 'down' spin, which is affected by local magnetic field. Thus, the magnetic images when correlated with electrical measurements provide direct knowledge of the role of the electron spin on electrical properties such as current and resistance. Electrical conduction in polarized materials, i.e. those that have preferentially more spin 'up' than spin 'down' states, exhibit extraordinary sensitivity to magnetic fields which is further amplified in nanocontacts (Chung et al. 2002). These insights on nanomagnetism allow profound understanding and control of magnetic domains that have enabled today's high density disk drives, high performance sensors, and magnetic random access memory (Florez et al. 2006).

Finally, the technology for scanned probe microscopy can also be used for surface modification. There are many creative methods that have been successfully implemented, including the patterning of polymer masks in semiconductor fabrication processes, chemical modification and writing of molecular ink using probe technology. One implementation uses the STM probe to produce tiny sparks caused either by the dielectric breakdown of the gap molecules or avalanche field emission. The idea is straightforward. Electrical energy stored in a capacitor is discharged between the probe tip and sample in a highly controlled process. By appropriately tuning the discharge parameters, the energy can be controlled to modify the surface with well-defined results. Some examples are shown in Figure 4. In the left image, 100 nm wide holes are blasted through a 30 nm silicon nitride membrane using high intensity pulses. The right image, on the other hand, was

created using low power and longer duration pulses, which formed impressions of the tip shape on the surface. The deliberate pattern (of M and a turtle) is possible because the tip controlled by piezoelectric positioners can be programmed for virtually any configuration. These structures can be useful for applications ranging from DNA sequencing, investigations of ion channels, to nanophotonics.

In conclusion, we are reminded of Richard Feynman's famous phrase that he uttered about small structures at CalTech in 1959, "There is plenty of room at the bottom." (<http://www.its.caltech.edu/~feynman/plenty.html>). Nearly 50 years later and having developed tools to visualize what is at the bottom, we are overwhelmed by its vastness. Indeed, there appears to be a whole gym down there.

References

- Binnig G, Quate CF, Gerber C. Atomic force microscope. *Phys Rev Lett* 1986; 56:930-933.
- Binnig G, Rohrer H, Gerber C, Weibel W. Tunneling through a controllable vacuum gap. *Appl Phys Lett* 1982; 40:178-180.
- Binnig G, Rohrer H, Gerber C, Weibel W. 7×7 reconstruction on Si(111) resolved in real space. *Phys Rev Lett* 1983; 50:120-123.
- Chung SH, Munoz M, Garcia N, Egelhoff WF, Gomez RD. Universal scaling of ballistic magnetoresistance in magnetic nano-contacts. *Phys Rev Lett* 2002; 89:287203-287206.
- Florez S, Dreyer M, Gomez RD. State of the art of magnetic force microscopy to investigate nanometer magnetic elements. In: Gianluca Gubbiotti, ed. *Magnetic Properties of Laterally Confined Nanometric Structures*. Kerala: Transworld Research Network, 2006:57-97.
- Florez SH, Dreyer M, Schwab K, Sanchez C, Gomez RD. Magnetoresistive effects in planar NiFe nanoconstrictions. *J Appl Phys* 2004; 95:6720-6722.
- Ganesan S, Park CM, Hattori K, Park HC, White RL, Koo H, Gomez RD. Properties of lithographically formed cobalt and cobalt alloys single crystal patterned media. *IEEE Transactions on Magnetics* 2000; 36:2987-2989.
- Gomez RD. PhD Dissertation (University of Maryland, College Park) 1990.
- Gomez RD. Recent advances in magnetic force microscopy: Quantification and in-situ field measurements. In: de Graef M, Zhu Y, eds. *Experimental Methods in the Physical Sciences*. Vol 36. San Diego: Academic Press, 2001:69-109.
- Gomez RD, Luu TV, Pak AO, Kirk KJ, Chapman JN. Domain configurations of nanostructured permalloy elements. *J Appl Phys* 1999; 85:6163-6165.
- Gomez RD, Pak AO, Anderson AJ, Burke ER, Leyendecker AJ, Mayergoyz ID. Quantification of magnetic force microscopy images using combined electrostatic and magnetostatic imaging. *J Appl Phys* 1998; 83:6226-6229.
- Lee J, Dreyer M, Krafft C, Gomez RD. Scanning tunneling microscopy/magnetic force microscopy study of ultrathin Fe film on MgO(001) in ultrahigh vacuum. *J Appl Phys* 2007; 101:09D123-1-09D123-3.