PERSPECTIVES: APPLIED PHYSICS

Mirrors for Electrons

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Microelectronic devices are becoming ever smaller at a breathtaking rate. For example, the density of the bits of information that can be stored on a magnetic disk has increased by a factor of a million since the first appearance of hard disks in the late 1950s. Silicon devices have experienced a similar growth rate, with their bit density doubling every 2 to 3 years. And research in the field is way ahead of the curve. The key to reducing the dimensions of such devices is precise control over electronic properties on a nanometer scale. On page 1709, Paggel *et al.* (*1*) are pushing the frontier all the way to the atomic limit. They have fabricated miniature electron interferometers containing atomically smooth mirrors spaced by a few atom layers. Exploiting the fact that electrons bouncing back and forth between two interfaces build up standing waves, often labeled as quantum well states (see figure), Paggel *et al.* measure the electron wavelength in their samples with very high accuracy. And they are not the only ones pursuing this line of investigation. In a recent paper, Kawakami *et al.* (*2*) used the same principles, but in addition to varying the thickness of the samples, they placed an extra atom layer inside their sample for probing the spatial variation of the wave function.

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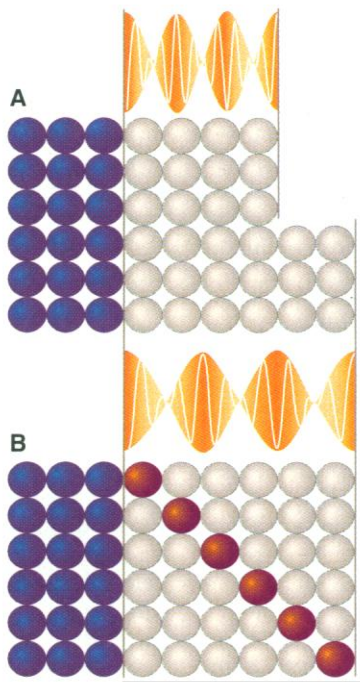
The basis of these studies is that electron waves are strongly modified in small structures. At an interface with either another material or a vacuum, the fast-oscillating wave of a free electron becomes modulated by an envelope wave function with longer wavelength (*3*, *4*). Solid state physicists are now setting out to generate tailored envelope wave functions in structures, such as multilayers, wires, and boxes. Paggel *et al.* and Kawakami *et al.* point the way to such precise control over electronic properties.

The electron mirrors were produced by preparing an atomically smooth metal surface and then evaporating atoms of another metal onto the surface, one layer at a time. Paggel *et al.* start with fine iron whiskers as substrates, which can be grown more perfectly than larger crystals. They add silver layers and thereby form two reflective interfaces, one between iron and silver, the other between silver and vacuum. With each additional layer, the length of the electron cavity between the mirrors increases by a well-defined atomic spacing. The electron wave is confined by the interfaces, and therefore its wavelength has to stretch out synchronously with the mirror spacing. That, in turn, changes the energy of the electrons that resonate. For a free electron, the energy E is related to the wavelength λ by the de Broglie relation $E = h^2/2m\lambda^2$ (h = Planck's constant, m = mass of the electron). This relation becomes more complicated in a solid, where it controls most of the electronic properties. Paggel *et al.* manage to deposit their silver layers so smoothly that they can observe the change in energy as each atomic layer is deposited, all the way up to more than 40 layers. Instead of averaging over several atomic layers, as in previous experiments, they are going to a more precise, digital measurement.

Kawakami *et al.* put an extra twist on this experiment by inserting an atomic layer of nickel that samples the wave function at regular intervals across the overlayer. By mapping out the wave function experimentally, they are bringing a mathematical construction of quantum mechanics into the real world.



Trapped in a cavity. Standing electron waves between atomic-scale electron mirrors. **(A)** The wavelength of the envelope function (orange) changes with the length of the cavity between the mirrors (*1*). **(B)** An inserted layer of atoms (red) serves as a probe of the envelope wave function (*2*).

In both experiments the use of synchrotron radiation enabled the detection of the electrons inside the cavity. Highly monochromatic, ultraviolet light was used to eject the electrons from the solid, which were then detected by an electron spectrometer. Paggel *et al.* used the Synchrotron Radiation Center (SRC) in Madison, Wisconsin, Kawakami *et al.* the Advanced Light Source (ALS) in Berkeley, California. The sharp focus that can be achieved with synchrotron radiation enabled Paggel *et al.* to utilize tiny, but perfect whiskers and for Kawakami *et al.* to scan across sophisticated double-wedge structures. Thus, precise fabrication and sensitive measurement techniques had to come together to make their studies possible.

Will such miniature electron optics ever show up on our desk tops? In fact, they may be there already. The most advanced hard disk drives on the market use the effect of "giant magnetoresistance" (GMR) in a "spin valve" for sensing the magnetic field of the stored bits (*4*, *5*). The core of a spin valve looks very much like one of the electron cavities discussed here, consisting of two magnetic layers as electron reflectors, separated by a noble metal spacer. The GMR effect is largely based on a spin-dependent reflectivity of electrons at the interfaces. It is even possible to add a magnetic monolayer as spin-reflective coating for enhancing the GMR effect (*6*). A monolayer of strongly magnetic atoms is sufficient.

It has been shown that standing electron waves in cavities are connected with a variety of other interesting phenomena, such as oscillations in the magnetic coupling (*3*, *4*) and in the spin-polarization (*7*). The two reports discussed here provide direct insights into the wave functions that drive these phenomena. They also achieve a new level of precision in fabricating cavities for electrons, which will help producing more advanced magnetoelectronic devices (*5*).

References and Notes

1. J. J. Paggel, T. C. Miller, T.-C. Chiang, *Science* **283**, 1709 (1999).
2. R. K. Kawakami *et al.*, *Nature*, in press.
3. J. E. Ortega and F. J. Himpsel, *Phys. Rev. Lett.* **69**, 844 (1992).
4. For a review, see: F. J. Himpsel, J. E. Ortega, G. J. Mankey, R. F. Willis, *Advan. Phys.* **47**, 511 (1998).
5. A series of articles on magnetoelectronics was published in *Phys. Today* **48**, 24–63 (April 1995).
6. S. S. P. Parkin, *Phys. Rev. Lett.* **71**, 1641 (1993).
7. K. Garrison, Y. Chang, P. D. Johnson, *ibid.*, p. 2801; C. Carbone, E. Vescovo, O. Rader, W. Gudat, W. Eberhardt, *ibid.*, p. 2805.

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