so far (3, 7, 8). More than 300 are now available in the high latitude and altitude regions of Eurasia and North America (9, 10). The quality of these (6–10) should enable the long instrumental records to be held back for meaningful long-term verification. Studies like those of Mann *et al.* (3) and others (7–9) are just a start. It is far, far better work that all paleoclimatologists need to do, better than they have ever done; it is far, far better reconstructions that are needed by the climate community.

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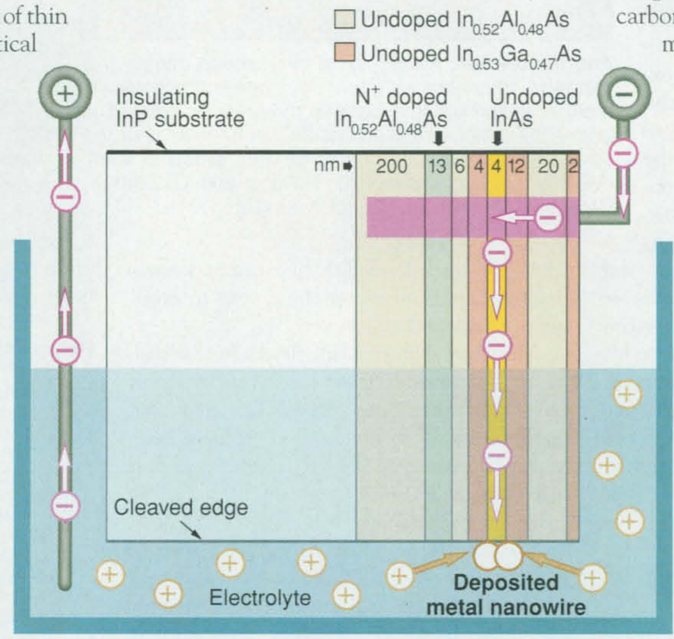
APPLIED PHYSICS

Nanowires: Small Is Beautiful

Gerhard Fasol

The fabrication of optical fibers and of thin metallic wires is among the most critical basic technologies. For example, the ability to fabricate thin metallic interconnects with favorable properties is an important factor limiting the progress of ultra-large–scale integrated circuits. And magnetic nanostructures are likely to replace today's unstructured magnetic media in the future. Over the last several years, several important new methods to fabricate metallic and magnetic nanowires have been invented. In one case, carbon and other kinds of nanotubes have been filled with metal (1), whereas in another approach, the cleaved edge of a molecular beam expitaxy (MBE)–grown 4-nm quantum well was used as a template to deposit a metal nanowire by electroplating (2). In this latter method, the atomic precision of MBE growth of semiconductors can be exploited for novel metallic and magnetic nanostructures. A completely different tack was taken recently, in which DNA molecules were used as a template to grow 100-nm-wide metal wires (3). These methods allow the fabrication of extremely thin wires with unprecedently large aspect ratio and are likely to find a range of applications. A further related area is that of short, contriction-like metallic nanowires (4, 5). The focus of this research is quantization and enhanced stability at particular thickness.



Thinner and thinner. Ultrathin metallic and magnetic nanowires can be fabricated by electrodeposition onto the cleaved edge of a semiconductor wafer onto which extremely thin layers have been grown by MBE. With this method it is possible to convert the atomic precision of MBE growth of semiconductor layers to the fabrication of metallic nanowires. [Adapted from (2)]

Carbon nanotubes (6) with lengths on the order of micrometers are produced by the discharge between two graphite electrodes. The widths of carbon nanotubes range from more than 100 Å for the case of multiwall tubes to less than 10 Å in single wall tubes. Carbon nanotubes can be filled with metals (1) and ideal one-dimensional metals (that is, strings of single atoms) can thus be fabricated. These might show new metallic phases, new electron-phonon interaction mechanisms, new superconducting pairing mechanisms, and new magnetic properties such as spontaneous magnetization (7), and therefore are currently an exciting field of research.

The electronic properties and the dynamics of filling carbon nanotubes with metals are complex. In general, there is a strong electronic interaction between host carbon nanotube and filling metal. In many cases, the carbon nanotubes end up being filled with metallic carbides. Incorporation is often found to be similar to that in graphitic intercalation compounds (8), especially in the case of alkali metal intercalation.

To reduce the complications of interactions between host nanotubes and filling metal, it has been proposed recently to fill boron nitride nanotubes (9, 10) with metal atoms. Calculations (11) show that boron nitride nanotubes should behave like ideal noninteracting hosts for metal atoms inside, unlike carbon nanotubes, which show strong charge transfer and hybridization effects. The reasons are that boron nitride is a stable insulator with a bandgap E_g around 5.5 eV, and is much less polarizable than metals and semimetals. Boron nitride nanotubes also show interesting structural variations. Recently, it has also been demonstrated that instead of being filled with metals, carbon nanotubes can be chemically converted into nanorods of other materials: Han *et al.* (12) produced 14.9-nm-diameter GaN nanorods by reacting gaseous metal oxide (MO) with carbon nanotubes in an ammonia atmosphere. This interesting reaction is expressed as:

$$MO + C(nanotube) + NH_3 \rightarrow MN(nanorod) + H_2O + CO + H_2 \quad (1)$$

Nanowires produced by filling nanotubes, however, are usually obtained in un-

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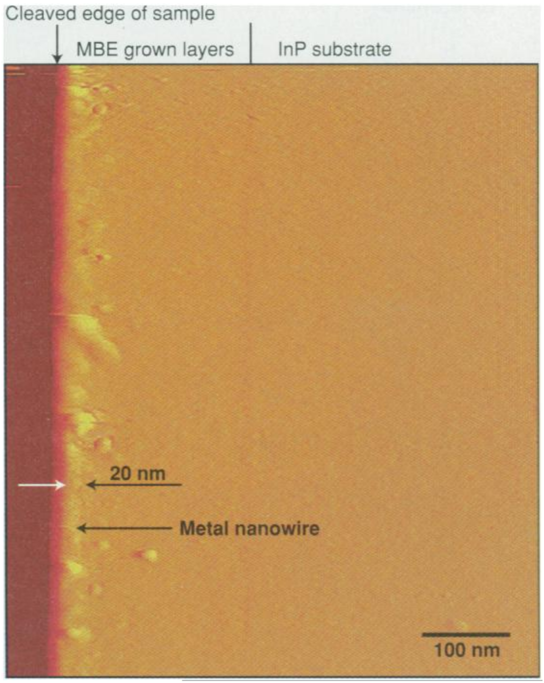

The nano edge. Atomic force microscope image of a nanowire fabricated with the selective electrodeposition method shown schematically on the previous page. The permalloy metal wire is about 20 nm in width, but the same method should work also down to widths of 4 nm. (MBE growth courtesy of M. Holland and C. Stanley, Glasgow University). [Adapted from (2)]

controlled aggregates. It is difficult, and very laborious to place such nanowires in precisely controlled locations, such as would be needed in micro-superconducting quantum interference devices (SQUIDs) for magnetic measurements. My group recently tackled this problem with a selective electroplating method (*2*), which is accessible to more conventional semiconductor fabrication techniques, as shown schematically in the figure on the previous page. A series of InGaAs and InAlAs layers is grown by MBE onto an undoped InP substrate. The particular conduction band and valence band lineup in this modulation-doped structure causes electrons to drop from the heavily doped 13-nm-thick InAlAs layer into a 4-nm InAs layer, which therefore becomes conducting. At the cleaved edge of the wafer, the 4-nm-thick InAs-conducting quantum well acts as a 4-nm thin line-source of electrons. Because deposition of metal ions from the electrolyte requires the neutralization of metal ions by electrons, selective deposition can take place only at the 4-nm exposed thin line-shaped edge of the modulation-doped InAs layer, where electrons are available. InAs is chosen because the Fermi level of InAs is pinned in the conduction band, so that the insulating surface depletion layer common in GaAs and other III-V materials is avoided, and electrons can freely flow from the InAs layer into the electrolyte. The MBE-grown 4-nm InAs layer, therefore, acts as a template for nanowire growth by selective electrodeposition (see figure on this page). As an electrolyte we have chosen a citrate-complexed nickel-iron solution that leads to deposition of a permalloy wire. However, a variety of other materials should also be possible. This method greatly expands the known methods for the controlled fabrication of metallic and magnetic nanowires.

Before this template method became available, the established way (*13*) to fabricate metallic nanowires was to shoot damage trails into plastic or other materials such as mica with high-energy particles, etch the damage trails, and then fill the damage trails with metal. After dissolving the plastic in a solvent this method leaves a pile of short nanowires on the bottom of a beaker. Many investigations of nanomagnetism published in the last few years still used this almost 30-year-old method.

In addition to their potential use as interconnects or in future magnetic storage, the fundamental physical properties of nanowires also attract many investigators. The effects of lateral quantization (causing conductance quantization) and of weak and strong localization on electrical conductivity are well known to be important in nanowires, and their intensive study is still very popular, although to my knowledge there are no known practical applications of these very interesting fundamental effects yet.

Magnetic storage is one field where metallic nanostructures may have practical use (*14*). Magnetic storage density has made dramatic progress from about 1 MBit/square-inch (0.16 Mbit/cm^2) in the 1980s and may reach about 50 GBit/square-inch (7.8 Gbit/cm^2)(*15*) in the year 2002. Today's magnetic media consist of many tiny polycrystalline grains with a random distribution of magnetization directions. Other than this, present magnetic media are initially unstructured: the position and shape of data bits are determined by the writing process. Signal-to-noise considerations demand that there be at least 1000 polycrystalline grains per bit. Increasing the storage density cannot be achieved by reducing the number of grains per bit, but a reduction of the size of individual grains would be necessary. However, as the grain size decreases, the energy needed to switch the magnetization decreases as well, and when it becomes smaller than the thermal energy, thermal fluctuations will randomly flip the magnetization. This thermal instability is called "superparamagnetism" (*16*) and is generally believed to present a fundamental limit for today's magnetic storage paradigm.

The use of patterned magnetic media and magnetic nanostructures offers the possibility to increase magnetic storage density by a factor of around 100 beyond the superparamagnetic limit. A particularly attractive option is to store each bit in an individual single-domain magnetic nanostructure, as opposed to a conglomerate of about 1000 as is done today.

Seminal investigations (*17*) of needle-shaped magnetic nanostructures with widths in the 100- to 300-nm range show that the switching fields strongly depend on the width of bar-shaped magnetic nanostructures, are almost independent of the length, and depend strongly on the shape of the ends of the nanobars (*17*). The nanobars for these studies were produced by electron beam lithography, which is clearly unsuitable for fabricating low-cost magnetic memories. Similar studies of magnetization properties may soon be done on nanostructures with widths in the nanometer range [that is, about 1/100 the width of the e-beam–produced structures of (*17*)] fabricated with the new low-cost fabrication methods for even thinner magnetic nanostructures, such as the methods discussed above.

In view of these results, the fabrication of metallic and magnetic nanowires and other nanostructures presents interesting challenges and may turn out to be crucial for the future development of high density magnetic storage and for other applications such as interconnecting quantum devices.

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