Fabrication of magnetic quantum wires by step-flow growth of cobalt on copper surfaces

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One-dimensional-like Co structures 50-Å-wide and 3000-Å-long have been grown by decoration of the monoatomic steps of a Cu(111) surface and visualized with scanning tunneling microscopy. In order to achieve step-flow growth, terrace width, evaporation rate, and substrate temperature have been carefully adjusted. The choice of the (111) terrace orientation and (110) compact steps ensures a homogeneous width of the Co wires and a lateral confinement of minority-spin electrons.

Quantum confinement of electrons in less than three dimensions is a topic that has attracted sustained attention for several years. Layered semiconductor structures in which electrons are confined to two dimensions (2D) have led to new electrical and optical properties, including fundamental discoveries such as the quantum Hall effect or technological developments like the quantum well lasers. New features are expected when the electrons are further confined to one dimension (1D) of free motion in the so-called quantum wires. The transport properties of 1D systems are rather exotic: scattering is strongly reduced, since only 180° collisions are permitted, the conductance is quantized in units of $e^2/\pi h$ for wires shorter than the electron mean free path, etc. More recently, the advances in epitaxial growth of metals have led to layered metal/metal superlattices with structural perfection comparable to that of semiconductors. As a result, new magnetic properties, such as the oscillatory magnetic coupling, or related transport effects, such as the giant magnetoresistance, have been discovered. The origin of the oscillatory magnetic coupling has been traced to the existence of spin-polarized quantum well states induced by the electron confinement in 2D. In view of the many exciting predictions for 1D metallic systems (lack of Fermi level emission, Lüttinger liquid behavior, etc.), it would be very interesting to fabricate quasi-1D magnetic metals. This is, however, not an easy task. Ni lines 0.1 μm wide have been deposited on Si substrates by decomposing a metalorganic gas with the electrical field associated to the tip of a scanning tunneling microscope (STM). Electrochemical deposition onto a polycarbonate matrix containing nanometer-sized pores has produced 600-Å-thick Ni and Co nanowires perpendicular to the substrate. Laser focused atomic deposition has been used to deposit Cr lines with an average width of 650 Å and a standard deviation of 60 Å. A method to further reduce the width of the wires could involve the self-organized growth on a vicinal substrate cut a small angle away from a high symmetry direction by molecular beam epitaxy. Decoration of steps by metals at the level of many hundreds of Å is a well-known fact. The approach reported now pushes the limit to the tens of Å for magnetic metals. Here we describe the fabrication of 1D magnetic quantum wires of Co by thermal deposition onto a Co (111) substrate under ultrahigh vacuum (UHV) conditions and their visualization in situ by means of STM.

The experiments have been carried out in an UHV chamber equipped with STM, low energy electron diffraction (LEED) and Auger electron spectroscopy (AES). The Co samples have been x-ray oriented, mechanically and electrochemically polished, and cleaned in situ by cycles of sputtering and annealing. The LEED pattern was checked before transferring the sample to the STM unit. Co was evaporated from an electron-heated filament. The Co coverage was obtained from the AES spectra and cross checked with STM images and is given in units of monolayers (ML), with 1 ML = 1.77×10^15 atoms/cm².

Evaporation of atoms onto single-crystal substrates leads to several processes, such as, surface diffusion, heterogeneous and homogeneous nucleation, and further growth of the nuclei. The morphology of the film depends on the competing kinetics of the different processes. Under the appropriate growth conditions, the deposited atoms can locate themselves only at the step edges of the substrate and growth will occur by the step-flow mechanism. This requires that τs, the time that an adatom needs to diffuse to the nearest step, be much smaller than τF, the time required to deposit a monolayer. It can easily be shown that τs = L²/D, where L is the terrace width and D is the diffusivity, and τF = n/F, with n being the number of sites per surface area and F, the deposition flux. The condition τs < τF implies that the adatom diffusion length, L_D, must be larger than L for step flow to occur. The values of these parameters can be controlled experimentally. For a given adatom/substrate combination, L_D depends on the substrate temperature and the deposition rate. It can be made very large by using compact fcc (111) surfaces and low deposition rates. L can be modified by using vicinal surfaces, i.e., substrates cut at different tilt angles from the main crystallographic orientations. Thus, in principle, step-flow growth can always be achieved. Since, in order to avoid unwanted interdiffusion, the growth temperature should not be too high, it is mandatory to use substrates with reduced distances between steps. Step-flow growth on vicinal surfaces was first proposed by Petroff

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et al.\textsuperscript{12} as a method for quantum wire fabrication in semiconductors. Following this suggestion, 1D-like GaAs–GaAlAs systems with cross-sectional dimensions of 160 Å\textsuperscript{2}×20 Å\textsuperscript{2} were grown using stepped GaAs\texttextsuperscript{1}00 substrates.\textsuperscript{13}

The growth of Co on Cu\texttextsuperscript{1}111 at room temperature has been studied previously by STM.\textsuperscript{14} Triangular Co islands with double atomic height nucleate at the terraces. The island separation at the early stages of the growth reflects the average diffusion length \(L_D\) of Co adatoms on Cu\texttextsuperscript{1}111 at room temperature (RT) for a given deposition rate. \(L_D\) has been determined experimentally to be 250 Å for a deposition rate of 0.008 ML/s.\textsuperscript{15} It was already noted in that work\textsuperscript{15} that, in addition to the islands nucleated at terraces, the steps were decorated by Co islands. We set out to demonstrate that it is possible to nucleate Co exclusively at the steps by having substrates with a step–step distance smaller than the diffusion length for a given evaporation rate and temperature.

On nominally flat metal surfaces, step bunching frequently occurs. In fact, well-equilibrated, clean surfaces extensively annealed under UHV display exceptionally large terraces separated by regions, known as step bands, where many steps of monoatomic height are grouped together. The origin of this phenomenon is not known. The existence of step bands is illustrated in Fig. 1 for a nominally flat Cu\texttextsuperscript{1}111 surface, which was aligned within 0.2° of a (1\text{\textbar}1\text{\textbar}0) direction. Figure 1(a) shows a 0.3 μm×0.3 μm area. A 1500-Å-wide terrace is followed by a step band corresponding to a local inclination angle of 1.3°. The formation of these step bands has to be distinguished from the step bunching produced by the pinning of the steps by residual defects originated during excessive heating of a slightly contaminated crystal.\textsuperscript{16} In the latter case, the steps show a heavily curved, caterpillar-like shape between pinning centers, which are originated by clusters of impurities.\textsuperscript{16} The orientation of these pinned steps is not dictated by the misorientation of the crystal and, accordingly, cannot be controlled at will. On the other hand, in a step band, the steps are gently curved over distances larger than 1000 Å, but they are rather straight at distances smaller than 1000 Å as demonstrated in Fig. 1(b). On this length scale, the Cu(111) substrate is characterized by monoatomic steps aligned along the compact (1\text{\textbar}1\text{\textbar}0) directions. Within the step band, the terrace width distribution can be fitted to a Gaussian centered at 100 Å, with a standard deviation of the order of 50 Å. This means that the distance between steps in these bands is smaller than the diffusion

FIG. 1. Constant current STM images of clean Cu\texttextsuperscript{1}111; (a) 3000 Å×3000 Å and (b) 1000 Å×1000 Å.

FIG. 2. (a) STM image of 0.2 ML of Co on Cu\texttextsuperscript{1}111. Size of the image: 2000 Å×2000 Å. (b) Scan profile [along the line in (a)] showing a transversal cut across the Co wires protruding from the surface at the step edges. As a guide to the eye both the substrate steps (2 Å) and cross sections (50 Å×4 Å) of the Co wires are drawn.

FIG. 2. (a) STM image of 0.2 ML of Co on Cu\texttextsuperscript{1}111. Size of the image: 2000 Å×2000 Å. (b) Scan profile [along the line in (a)] showing a transversal cut across the Co wires protruding from the surface at the step edges. As a guide to the eye both the substrate steps (2 Å) and cross sections (50 Å×4 Å) of the Co wires are drawn.
length for Co atoms at RT; under these conditions, decoration of the steps should take place.

Figure 2 shows the results of depositing 0.2 ML of Co on Cu(111) at RT and a slow rate of 0.008 ML/s. In these conditions, the Co atoms wet uniformly the Cu steps. Continuous lines of Co decorate the steps of the substrate. As shown in Fig. 2(a); the lines are, in fact, composed of Co islands joined together forming "wires" that extend over macroscopic distances of the order of microns. The image also shows dark hexagonal holes in the Cu terraces with a depth of one atomic layer. They are the result of a spontaneous etching of the surface occurring during Co deposition. The Cu atoms removed from these vacancy islands move to the steps where their presence probably favors the nucleation of the islands forming the stripes. The Co "wires" possess almost identical widths. They are 50 Å wide and two atomic layers (4 Å) high. The fluctuations in the width along a single wire amount to 1/5 of its width. Figure 2(a) shows that in the larger terraces some Co islands have nucleated. As demonstrated in the line profile of Fig. 2(b), the wires are located mostly at the lower part of the steps, and due to their height (twice the Cu step height) they protrude from the surface. It has to be noted that recent attempts to grow Cu\(^{17}\) or Fe\(^{18}\) stripes on W (110) have yielded rather irregular lateral arrangements of wires located at the lower part of the steps with width fluctuations larger than their width. Figure 3 reproduces a large scale image of the surface array of wires after deposition of 1.3 ML of Co and proves that the growth takes place from the steps. Furthermore, it shows that the Co wires fabricated on Cu (111) do not cross each other since the steps of the original surface, driven by entropic repulsive interactions, tend to avoid each other. The wires produced in this way are not, however, equally spaced laterally, since the step-step distances in these step bands were not uniform.

Ideally, one would like to go one step further from quantum wires and grow lateral superlattices (LSL), a concept put forward in the field of growth of artificial semiconductors,\(^{12}\) which, in the case of magnetic LSL, can lead to some exciting coupling phenomena across the nonmagnetic spacer. In principle, a magnetic LSL can be constructed by using substrates with vicinal surfaces presenting straight and uniformly spaced step edges. The period of the superlattice could be varied by changing the tilt angle \(\Theta\). Work is in progress in this direction.

In summary, we have grown quantum wires of a magnetic metal on a nonmagnetic substrate by decorating the steps of the substrate. The steps present in many nominally flat surfaces can be used for this purpose. The wire dimensions in cross sections are 50 Å\(\times\)4 Å. In the wires, the electrons in the upper part of the \(s-p\) band of Co may be confined by the vacuum level (on three sides) and by the band offset (in the direction perpendicular to the surface). This implies that along the (111) direction the wave function of the minority spin \(d\) electrons of Co has no states in the substrate to connect with and is completely Bragg reflected. Compared to semiconductors with band offsets of the order of tenths of an eV, metal systems may show band offsets of several eV, giving rise to confinement at the atomic scale, since the decay constant of the evanescent wave depends on the energy distance to the band edge of the substrate. Work is in progress to characterize the electronic and magnetic properties of the Co quantum wires whose fabrication has been described here.

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