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Co nanowire arrays on *N*-terminated Cu(110) surfaces

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We demonstrate, using scanning tunneling microscopy, that the growth of Co onto Cu(110) surfaces can be dramatically altered by first terminating the Cu(110) surface with an atomic nitrogen-induced (2×3) structure. Co growth onto such surfaces results in the formation of ordered arrays of Co nanowires. These results are contrasted with Co growth on clean Cu(110) surfaces and suggest that the N termination also prevents the diffusion of Cu atoms into the Co layers.

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There is no denying the current interest in nanometer-scale structures on surfaces. Characterizing both their structure and relevant properties is taxing. Methods of structural characterization often require scanning probe techniques,[1–3] whereas characterizing electronic or magnetic properties may require photoemission[4] or optical-based techniques.[5] The experimental facilities and technical expertise rarely coincide to perform definitive complementary experiments.

Here we report the fortuitous discovery of a system that results in ordered arrays of nanometer-scale structures and that also may have significantly interesting magnetic properties. We have characterized this system with scanning tunneling microscopy (STM) and low-energy-electron diffraction (LEED) to a sufficient degree that researchers with capabilities for epitaxial growth and LEED can recreate these structures. We have found that the growth of Co onto Cu(110) surfaces can be dramatically altered by first terminating the Cu(110) surfaces with a (2×3) atomic nitrogen-induced structure. Co growth onto such surfaces results in the formation of ordered arrays of Co nanowires. These results are contrasted with Co growth on clean Cu(110) surfaces.

These experiments were performed in a conventional ultrahigh-vacuum chamber equipped with a commercial room-temperature Omicron Vakuumphysik STM and capabilities for LEED. This STM allows for the storage of up to 8 samples or tips in vacuum. The Cu surfaces used in this study were cleaned using cycles of argon-ion bombardment followed by annealing to 720 K. Atomic nitrogen-terminated surfaces were prepared by bombarding Cu(110) surfaces with 500-eV nitrogen ions followed by annealing to 600 K.[6] LEED observations afterwards showed sharp (2×3) patterns. The Co evaporator consisted of a Co plate supported by W wires and heated by a feedback-controlled electron beam. Deposition rates were determined by a quartz crystal thickness monitor. Co depositions are measured in monolayers (ML's) where 1 ML$=1.1\times10^{15}$ atoms/cm^2, the number of atoms per unit area of a Cu(110) surface. Co evaporations were performed on clean Cu surfaces at room temperature in attempts to minimize the interdiffusion of Co and Cu. To ensure a complete cooling to room temperature, the samples were brought into thermal contact with a water-cooled copper tube.

A driving force for studying these Co/Cu systems is to understand the magnetic properties of thin fcc Co films.[7] To appreciate the effect that the (2×3)N structure has on the growth of Co onto Cu(110) surfaces, one must understand Co growth on clean surfaces. This has been given brief scrutiny in a recent combined study of STM and magneto-optical Kerr effect (MOKE) showing that Co depositions resulted in three-dimensional islands that coalesced at a coverage of 1.3 ML and began displaying ferromagnetic properties only at a somewhat higher Co coverage of 4.6 ML.[8] Studies of Co growth on Cu(100) surfaces, in contrast, showed the onset of ferromagnetism at a coverage of 1.7 ML.[9]

We investigated these differences by making virtually side-by-side comparisons of Co growth on clean Cu(110) and Cu(100) surfaces. Figures 1(a) and 1(b) show the results of exposing Cu(100) and Cu(110) surfaces to the same Co flux (4×10^{14} atoms/cm^2).[10] Figure 1(a) shows small atomically flat Co islands on a Cu(100) surface. Step height measurements are consistent with the 1.8-Å step height for this surface. On the Cu(110) surface [Fig. 1(b)], one sees larger islands that are elongated in the $\langle 1\bar{1}0\rangle$ direction and are for the most part two layers thick. Line scans show that these layers are not imaged with the same interlayer spacings. The tip retracts 1.2 Å as it moves from the substrate to the first layer and then an additional 1.6 Å as it moves to the second layer. If we compute the fraction of surface area covered by the first- and second-layer growth, we obtain 0.50 and 0.33,

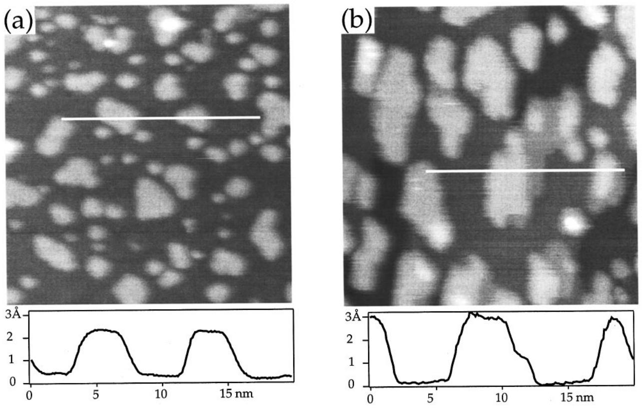

FIG. 1. Two 30×30-nm^2 STM images and associated line scans of (a) Cu(100) and (b) Cu(110) surfaces exposed to the same flux of Co atoms (4×10^{14} cm^{-2}). On Cu(100) surfaces, Co forms small single-layer islands. On Cu(110) surfaces, two-layer islands are formed with an unequal spacing between layers.

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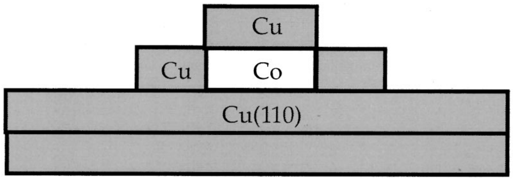

FIG. 2. Model for Co growth on Cu(110) surfaces. Cu is believed to diffuse and encapsulate the Co.

respectively. If each layer were due to Co, we would conclude that we had evaporated 0.83 ML. This is far in excess of the amount we believed was identically deposited on the surface shown in Fig. 1(a). We explain this difference by suggesting that Cu is diffusing on the surfaces to encapsulate or alloy with the Co as diagrammed in Fig. 2. Additional evidence for this comes from the observation of single-layer-deep pits appearing on the surface after Co deposition. Similar behavior has been demonstrated in a recent study of Co growth on Cu(111) surfaces.[11] Thus while Hope *et al.* have observed the coalescence of three-dimensional islands resulting from Co growth on Cu(110) surfaces,[8] we conclude that these islands contained significant fractions of Cu atoms. This most probably explains the different onsets of ferromagnetism for Co growth on Cu(110) and Cu(100) surfaces.[8,9] We note that Kief and Egelhof also expressed a belief that Co grown on Cu(110) surfaces resulted in Co-Cu agglomerates.[7]

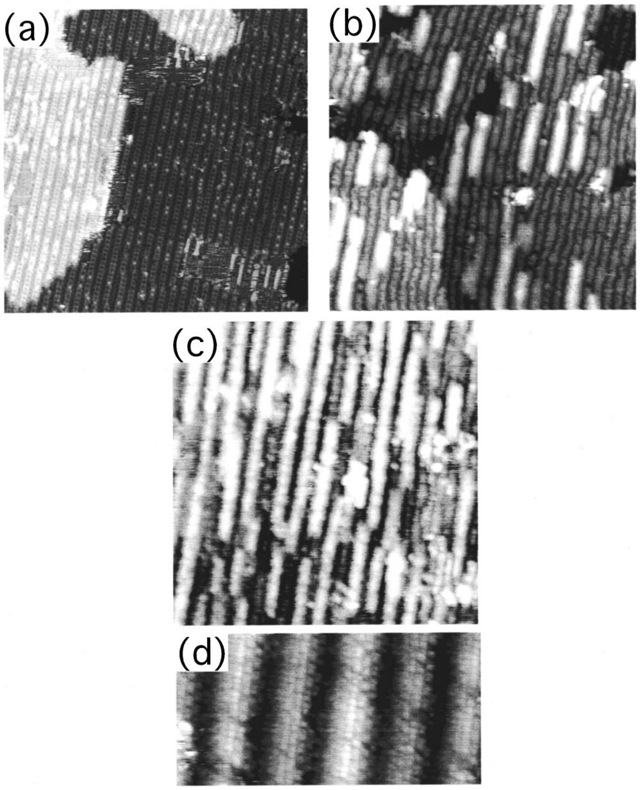

FIG. 3. Three 30×30-nm^2 STM images showing (a) Cu(110)-(2×3)N structures. (b) and (c) are results of 1 and 2 ML of Co grown on Cu(110)-(2×3)N surfaces. Co forms (b) nanowires and (c) ordered arrays of nanowires. (d) 10×5-nm^2 image showing atomic resolution on the surface of the nanowires.

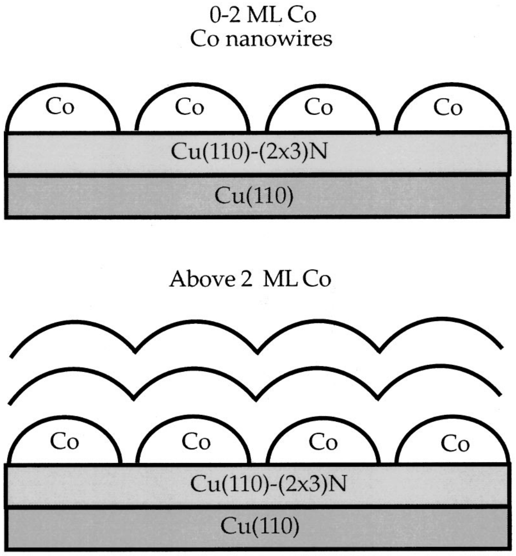

FIG. 4. Model for Co growth on Cu(110)-(2×3)N surfaces. For Co coverages between 0 and 2 ML, Co forms nanowires. Above 2 ML, layer-by-layer growth occurs on top of the nanowires.

Figure 3 shows STM images of Co growth on N-terminated Cu(110) surfaces. Figure 3(a) shows an image of a Cu(110)-(2×3)N surface. This structure is characterized by rows of features running in the $\langle 1\bar{1}0\rangle$ direction. Cu(110)-(2×3)N surfaces are sufficiently stable that they may be removed from vacuum, then reinserted, briefly degassed, and still display a (2×3) LEED pattern.[12] Figures 3(b) and 3(c) show STM images of Cu(110)-(2×3)N surfaces following Co depositions of 1 and 2 ML, respectively. Figure 3(b) shows an area of the (2×3)N structures and the appearance of narrow rod-shaped structures running along the $\langle 1\bar{1}0\rangle$ direction. As the Co coverage is increased [Fig. 3(c)], the surface appears to be covered by ordered arrays of these rod-shaped structures. The spacing between these structures is 20 Å. Significantly, LEED also shows evidence of these ordered arrays via the appearance of a (1×6) pattern coexisting with the (2×3)N pattern. The (1×6) diffraction spots are most easily observable for electron-beam energies of 12 eV. Figure 3(d) shows an image with atomic resolution on the Co nanowires. Atomic resolution images like this show individual atomic rows running along the $\langle 1\bar{1}0\rangle$ direction, with a 3.6-Å inter-row spacing and a 2.5-Å spacing between features within the rows. These spacings are consistent with the fcc(110) unit cell found on the substrate.

The following observations lead us to believe that layer-by-layer Co growth occurs on top of the nanowire arrays and that the N structures are intact underneath the Co. We have investigated Co growth up to 8 ML and still see rodlike structures similar to those shown in Fig. 3(c) with no evidence of three-dimensional growth occurring. This suggests that layer-by-layer growth is occurring. If we anneal the substrates after Co depositions much of the Co appears to ball up on the surface and the N structures can again be observed again with both STM and LEED. Similar results are obtained for Co depositions onto heated Cu(110)-(2×3)N substrates. This suggests to us that the (2×3)N structure is intact underneath the Co. Thus the (2×3)N structure may prevent the diffusion of Cu atoms into the Co layers. A proposed model for the growth of Co onto N-terminated surfaces is diagrammed in Fig. 4. We contrast this with other results, in particular, Co growth on Cu(110)-(2×1)O surfaces, where the oxygen floated to the top of the Co layers.[13]

In conclusion, we have compared the growth of Co onto clean and N-terminated Cu(110) surfaces. From comparisons of STM images of Co deposited on clean Cu(110) and Cu(100) surfaces, we suggest that Cu diffuses to encapsulate Co on the Cu(110) surface. On Cu(110)-(2×3)N surfaces, Co forms arrays of nanowires running along the $\langle 1\bar{1}0\rangle$ direction. Atomic resolution images suggest a well-ordered crystalline structure within these nanowires. We believe that the (2×3)N structures facilitate the directional growth of the Co islands and that they also inhibit the diffusion of substrate Cu. It seems reasonable to expect different magnetic properties for Co grown on the N-terminated surfaces as opposed to that grown on clean surfaces. One would expect the onset of ferromagnetism to occur at a lower coverage, and given the shapes of the Co islands one might expect these surfaces to show strong magnetic anisotropies.

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