

Fabrication and uniaxial magnetic anisotropy of Co nanowires on a Pd(110) surface

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We have fabricated Co atomic chains and nanowires on a Pd(110) surface oriented along the [1-10] direction. This is possible due to high diffusion anisotropy of the Co adatom on the Pd(110) surface. The Co nanowires on Pd(110) exhibit a strong uniaxial in-plane magnetic anisotropy, in which the easy axis is along [1-10], i.e., nanowire direction. © 2005 American Institute of Physics. [DOI: 10.1063/1.1870127]

In the last decade, nanoscale magnetic materials have been widely discussed due to the current development of electronic devices and data storage media. Thus it has been a particularly attractive topic to investigate the fabrication and magnetic properties of nanoscale, even atomic scale magnetic materials, such as nanowires or nanostripes,¹⁻⁷ nanoparticles or nanodots,⁸⁻¹⁰ and nanopillars.^{11,12}

With the development of ultrahigh vacuum (UHV) and molecular beam epitaxy techniques, a rich variety of far-from-equilibrium nanostructures can be created depending on the atomic nature of the adlayer-substrate system, deposition temperature, and rates. Among them, the symmetry of the substrate is an important factor. In this respect, the Pd(110) surface is an attractive example.^{13,14} The Pd(110) surface is one of the few unreconstructed fcc(110) surfaces which consist of close-packed atomic rows along the [1-10] direction separated by deep channels.¹⁵ At not too high temperatures, preferential diffusion of incoming adatoms takes place along these channels, i.e., the [1-10] direction, resulting in the island elongation, even formation of linear one dimensional (1D) chains along the [1-10] channels.¹⁶ In fact, Röder *et al.* have obtained Cu monatomic wires on Pd(110) substrate which are oriented along the [1-10] direction.¹⁷ Thus 1D Co wire growth on Pd(110) could be expected. Moreover, theoretical studies have predicted some magnetic properties of monatomic Co wires on Pd(110), such as perpendicular magnetic anisotropy, the magnetic moment of an isolated supported wire, induced spin-polarization in the Pd atoms close to the Co wire and the magnetic interaction between adjacent wires.^{18,19}

In this letter we demonstrate that Co monatomic chains are indeed formed on a Pd(110) substrate. Moreover, the magnetic anisotropy of Co nanowires on the Pd(110) substrate shows in-plane uniaxial anisotropy.

The experiments were performed in a multichamber UHV system equipped with a molecular beam epitaxy (MBE) setup, scanning tunneling microscopy (STM), Auger electron spectroscopy (AES), low-energy electron diffraction (LEED), and *in situ* magneto-optical Kerr effect (MOKE). The base pressure is better than 5×10^{-11} mbar. The Pd(110) crystal was cleaned by cycles of Ar⁺ sputtering and subsequent annealing at 950 K. The sample was occasionally an-

nealed in an oxygen atmosphere of 1×10^{-6} mbar at 600 K to eliminate C and S contaminants on the Pd(110) surface. The cleanliness of the surface was confirmed by LEED, AES, and STM. According to STM, the average terrace width is about 15 nm. Co films were prepared by thermal deposition from a Knudsen cell. In order to suppress gas adsorption and interdiffusion of Co and Pd(110) substrate, the films were prepared at room temperature (RT), and then immediately transferred to the cooled sample stage of the MOKE chamber. STM data were recorded in constant current mode at RT.

Figures 1 and 2 display a series of STM images characterizing the growth of submonolayer Co on Pd(110) at RT. At the coverage of 0.15 ML, Co monatomic chains are formed and oriented along the [1-10] direction as shown in Fig. 1(a). At this coverage, the Co atomic chains have an average length of 6.9 nm, corresponding to 25 Co atoms arranged along [1-10]; and the average distance between Co atomic chains is 2.7–3.1 nm, corresponding to 7-8 close-packed atomic rows. A zoom-in picture of an arbitrary cho-

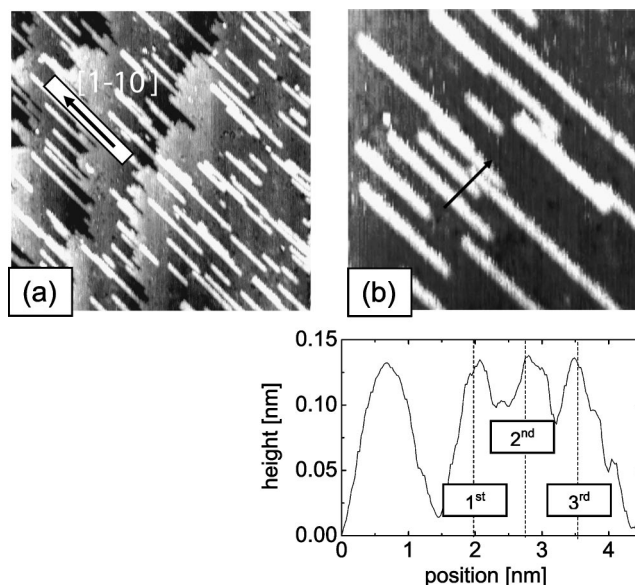


FIG. 1. (a) STM image ($50 \text{ nm} \times 50 \text{ nm}$) of 0.15 ML of Co deposited at RT on Pd(110) surface. Co atomic chains are oriented along [1-10] as it is identified by the arrow. (b) Zoom-in ($20 \text{ nm} \times 20 \text{ nm}$) of the STM image shown in (a). STM line profile is taken along the black arrow which indicates the distance between the first and third chain is 1.6 nm, and that the second chain as well as two blanks exist in between.

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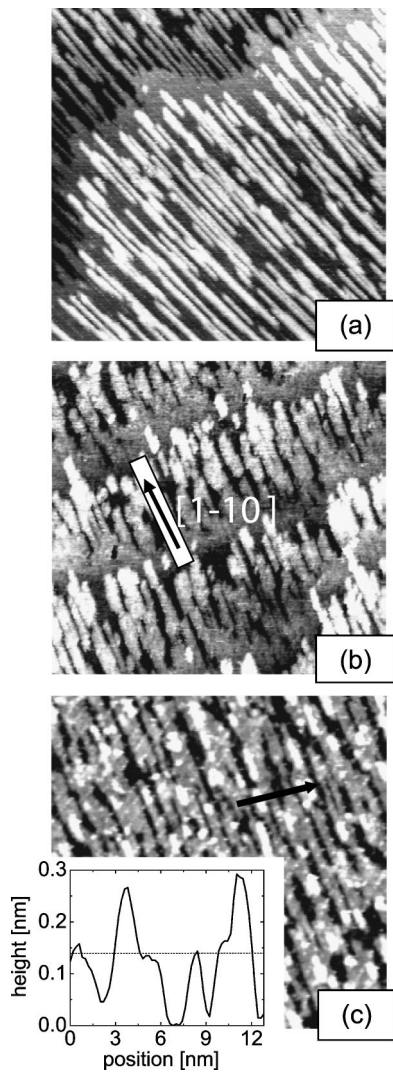


FIG. 2. STM images ($50 \text{ nm} \times 50 \text{ nm}$) at different Co coverage on Pd(110) surface: (a) 0.3 ML, (b) 0.5 ML, and (c) 0.65 ML. Both Co atomic chains [in (a)] and Co nanowires [in (b) and (c)] are oriented along $[1-10]$ as it is identified by the arrow in (b). STM line profile taken along the black arrow in (c) is shown in the inset, in which the dashed line indicates the height level of the first Co atomic layer.

sen area from the STM image of Fig. 1(a), and the line profile perpendicular to three neighboring chains, are shown in Fig. 1(b). The profile shows discrete maxima at multiples of an elementary distance $a = (0.4 \pm 0.05) \text{ nm}$. The separation distance between the peak of the first chain and the peak of the third chain is about 1.6 nm which corresponds to four multiples of the distance between two neighboring Pd atomic rows on the (110) surface. Moreover, blank spaces between the neighboring chains are visible. A blank space indicates one elementary distance though the width of a blank space is smaller than that of the chains. Within the distance of 1.6 nm between the first and the third chain, the second Co chain and two blank spaces are visible. This arrangement corresponds to four elementary distances only in the case when the width of the second chain is exactly one atom, i.e., if it is actually a monatomic chain. This means that we can measure the lateral island separation down to two elementary distances and show that the chains do not consist of double-rows of atoms.

With increasing coverage to 0.3 ML, the average distance between Co atomic chains becomes 1.6 nm, and some

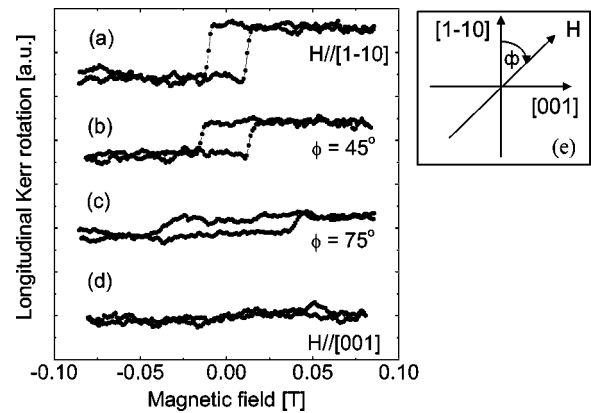


FIG. 3. Hysteresis loops of 0.5 ML Co on Pd(110) surface measured at the magnetic field applied along the $[1-10]$ direction (a), under the angle $\phi = 45^\circ$ (b), $\phi = 75^\circ$ (c), and along the $[001]$ direction (d). The loops were measured at 55 K. The orientation of magnetic field with respect to the main crystallographic directions is schematically shown in (e).

individual Co chains can span a whole terrace length [see Fig. 2(a)]. Moreover, some short Co atomic chains are aggregated to the long Co chains. At the coverage of 0.5 ML, as shown in Fig. 2(b), Co atomic chains grow up to two-dimensional nanoislands which are preferentially elongated along the $[1-10]$ direction with a width of 1.2–2.0 nm. Moreover, the STM images clearly show the role of substrate step edges as heterogeneous nucleation centers. Both Co atomic chains and nanowires easily grow outward from substrate steps though Co nanowires are not aligned along the steps. When the coverage exceeds 0.6 ML [see Fig. 2(c)], the gaps between some Co islands are filled up, and the second layer nucleation is observed on top of the first Co layer. As demonstrated by the line profile of the inset, the height of the second partially completed layer of the Co islands has almost the same height as the first layer, i.e., one Co atomic layer. Moreover, the two layers thick Co islands are also exclusively oriented along the $[1-10]$ direction. We also analyzed the structure of submonolayer Co on Pd(110) by LEED. The observed LEED patterns (not shown here) show (1×1) periodicity without additional spots indicating that the Co islands grow pseudomorphically onto the Pd(110) substrate. In addition to this, lines of diffracted intensity are observed perpendicular to the $[1-10]$ direction. This is caused by the pronounced ordering of the Co atoms only along the $[1-10]$ direction and a not well defined periodicity along the $[001]$ direction. This, according to diffraction theory, leads to one-dimensional features in the LEED patterns along the $[001]$ direction.

An important issue for the investigation of Co nanostructures on Pd(110) is their uniaxial magnetic anisotropy. Here we demonstrate that Co nanowires on Pd(110) substrate have a strong uniaxial in-plane magnetic anisotropy. Figures 3(a)–3(d) show a series of representative MOKE hysteresis loops of 0.5 ML Co on Pd(110) with the magnetic field applied along the different in-plane directions of Pd(110) surface. The magnetization is always probed along the field direction. The measurement temperature is 55 K. The square hysteresis loop with the magnetic field applied along $[1-10]$ direction displays minimum coercivity and maximum Kerr signal [see Fig. 3(a)]. When the magnetic field is applied in the sample plane under a variable angle from $[1-10]$ direction [see Figs. 3(b) and 3(c)], we found the intensities of

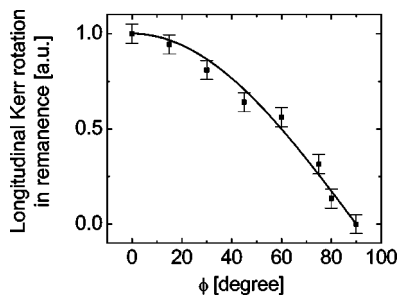


FIG. 4. Longitudinal Kerr rotation in remanence as a function of ϕ , i.e., of the direction of magnetic field with respect to $[1-10]$, normalized to the value measured along $[1-10]$. A $\cos(\phi)$ function is plotted (solid line) for comparison.

measured Kerr signals decreasing with increasing deviation angle of the magnetic field from the $[1-10]$ direction. This fact indicates that the magnetization is not saturated along the direction of the applied magnetic field, and the measured Kerr signal is due to a projection of the magnetization oriented along the easy axis (i.e., $[1-10]$) to the magnetic field direction.²⁰ Moreover, the shapes of the Kerr loops are all almost square. This indicates that magnetization direction is almost fixed within the $[1-10]$ direction. Only at higher fields the magnetization rotates towards the field direction and saturates. The magnetization component to the field direction is given by:

$$M = M_s \cos(\theta - \phi). \quad (1)$$

In this expression, M_s is the saturation magnetization, and θ and ϕ denote the angles subtended by the magnetization and field, respectively, with respect to the easy axis. The value of θ is zero in the range of magnetic field we applied [see Fig. 3(e)]. Thus the Eq. (1) can be replaced by:

$$M = M_s \cos(\phi), \quad (2)$$

where ϕ is measured with respect to the $[1-10]$ direction. When the applied magnetic field is along the $[001]$ direction, no Kerr rotation loop is observed as shown in Fig. 3(d).

Figure 4 shows the magnetization component measured in remanence along the field applied under different angles with respect to the $[1-10]$ direction. We plotted the data, and found out that M indeed follows a cosine function with the maximum when parallel to the wires. This confirms that the stripes are magnetized along the $[1-10]$ direction and only magnetization projection to the field direction is detected by MOKE.

For below 0.5 ML Co coverage, it is difficult for our MOKE setup to detect Kerr signals. This is due to the lowest temperature of 50 K that can be achieved, which is not enough for the ultrathin films of low Curie temperature (which is expected at the coverage below 0.5 ML). When the thickness of Co film exceeds 1 ML, the easy magnetization direction switches in plane to $[001]$, i.e., is perpendicular to the nanowire direction. For 0.5 ML Co coverage, the spins in Co nanowires on Pd(110) surface are confined along the nanowire direction by the shape anisotropy of the Co nanowires. It also takes place in elongated Fe islands on W(110)

surface that the shape anisotropy favors the easy magnetization direction along elongated island direction.⁴

Moreover, contradictory to some theoretical and experimental reports on the perpendicular anisotropy in the Co-Pd system,^{18,22,23} no Kerr signal is observed in polar geometry within the thickness range of 0.5–6.0 ML even at an applied magnetic field of 0.8 T. More precisely, for the Co films grown on Pd(110) at RT we do not detect any polar signal for any Co thickness when the MOKE experiment is performed immediately after the sample deposition. Only after: (1) The sample is exposed to the residual atmosphere at low temperatures a sufficiently long time, or (2) the sample is annealed, or (3) the sample is covered e.g. with Au, the polar signal is detected. The details will be published elsewhere.²¹

In conclusion, we have fabricated Co atomic chains and nanowires taking profit of the Co adatom diffusion anisotropy on Pd(110). The Co nanowires exhibit a strong uniaxial in-plane magnetic anisotropy with the easy axis along the $[1-10]$ direction, i.e., along the nanowires.

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