Uniaxial magnetic anisotropy of quasi-one-dimensional Fe chains on Pb/Si

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We fabricated quasi-one-dimensional Fe chains on a 4° miscut Si (111) substrate with a Pb film as a buffer layer. The magnetic properties and morphology of Fe chains were investigated by means of scanning tunneling microscope (STM) and surface magneto-optical Kerr effect (SMOKE). STM images show that Fe chains are formed by Fe random islands along the steps of the Pb film due to step decoration. SMOKE data indicate that the Fe chains exhibit in-plane uniaxial magnetic anisotropy along the step direction. The effective in-plane uniaxial anisotropy constant at room temperature was determined by means of electron spin resonance. © 2009 American Institute of Physics. [DOI: 10.1063/1.3054340]

Surface-supported quasi-one-dimensional (Q1D) magnetic nanostructures such as atomic chains, nanostripes, and nanowires have often been used as model systems to investigate one-dimensional magnetism. For this purpose, vicinal metallic substrates are commonly used.1–6 However, for transport and spintronic applications,7 it is highly desirable to grow the magnetic nanowires on Si substrates so that a natural integration with Si-based devices can be achieved. A well-known obstacle is the formation of silicides. While this issue has been somewhat addressed for the growth of magnetic thin films on Si by inserting buffer layers such as copper and iron silicide,8–12 similar approaches failed to grow Q1D ferromagnetic nanostructures on silicon substrates. The only attempt to grow Fe nanowires on Si has been made by Lin et al.13 using organometallic chemical vapor deposition and CaF2 masks on a stepped Si (111) substrate, although no ferromagnetic properties were reported.

In this letter, we report the fabrication of Q1D Fe chains on vicinal silicon substrates using atomically flat Pb films as a buffer layer. The Pb buffer layer prevents interdiffusion of Fe/Si. The Q1D Fe chains have been observed to exhibit ferromagnetic properties above 120 K with their easy magnetization axes along the chain direction for the Fe coverage larger than 1.3 ML. The in-plane uniaxial magnetic anisotropy along the step direction is confirmed by both in situ surface magneto-optical Kerr effect (SMOKE) and ex situ electron spin resonance (ESR) measurements.

The experiments were carried out in an ultrahigh vacuum (UHV) molecular beam epitaxy chamber with a base pressure of 2 × 10−10 mbar. The system is equipped with scanning tunneling microscope (STM), SMOKE, Auger electron spectroscopy (AES), and low-energy electron diffraction (LEED). The 4° miscut Si (111) substrates were prepared by well-established flashing procedures.14 The crystallographic quality and the cleanliness of the substrate were monitored by STM, LEED, and AES. First, we grow a stepped Pb film (step width of ~10 nm) on a 4° miscut Si (111) substrate to avoid Fe/Si intermixing. The Pb films with narrow steps were fabricated by evaporating Pb from a Knudsen cell onto the Si sample surface at a low temperature (LT) of ~120 K via a two-step growth method.16 Then, Fe chains were deposited on the Pb films at LT from an iron wire (99.999% purity) heated by e-beam bombardment with a deposition rate of 0.2 ML/min. Due to the lattice mismatch (ΔaFe = 2.87 Å and ΔaPb = 3.5 Å) and the vastly different surface free energy between Fe and Pb (σFe = 2.48 J/m2 and σPb = 0.5 J/m2), Fe tends to form Q1D chains along step edges of Pb films. Afterward the samples were slowly warmed to room temperature (RT) to prevent from destroying Pb film and Fe nanostructures. STM measurements were recorded at RT and SMOKE measurements were carried out at both RT and LT after STM measurements. ESR measurements were performed at 9.0 GHz using conventional modulation and lock-in detection techniques at RT. For the ex situ ESR measurements, NaCl (~14 ML) was deposited on Fe/Pb/Si (111) as a capping layer to protect samples from being oxidized.

A STM image of the stepped Pb film (27 ML) grown on the 4° miscut Si (111) substrate is displayed in Fig. 1(a). The surface morphology shows uniform narrow steps with an average terrace width of about 10 nm at this Pb coverage. The terrace width of 4° miscut Si (111) substrate is much smaller than 10 nm, and these terraces have strong internal stress in the case of this high angle miscut. This affects the surface...
topography and the width of the stepped Pb films deposited on the Si (111) substrate so that the stepped Pb films cannot be formed until the stress from the underlying substrate is relaxed at high Pb coverage (>18 ML). At the Pb coverage of 27 ML, a terrace width of 10 nm is fabricated, which corresponds to the equilibrium between the stress and terrace width of 4° miscut Si substrate.

Step decoration growth of Q1D Fe chains on Pb/Si (111) is observed at RT, as shown in the STM images for 1.3 and 1.7 ML Fe on Pb/Si (111) in Figs. 1(b) and 1(c), respectively. At the coverage of 1.3 ML, Q1D Fe chains are formed by a coalescence of Fe islands along the step edges of the Pb film. The edges of the chains are rough due to the random shape of Fe islands, resulting from a lattice mismatch and large difference in surface energy between Fe and Pb. The center to center distance of the chains is the same as the terrace width of the stepped Pb film. At a higher Fe coverage of 1.7 ML in Fig. 1(c), wider chains become much more continuous without a direct perpendicular connection between chains as indicated by the STM image. It is not like Fe stripes grown on Cu (111) substrate on which Fe atoms have a tendency to grow across the steps. The Fe islands firstly located on the Pb steps at low coverage facilitate the nucleation of Fe atoms deposited afterward along the steps, decrease the diffusion across the steps, and smoothen the edge of chains at higher coverages.

Figure 2 illustrates representative magnetic hysteresis loops at these two coverages, measured at both RT and LT. At the Fe coverage of 1.3 ML, the magnetic hysteresis loops could be only observed in the longitudinal SMOKE at LT, which indicates that at the coverage of 1.3 ML, Q1D Fe chains exhibit long range ferromagnetic order at LT, and the easy magnetization direction is parallel to the surface along the chains. We attribute this to the induced magnetic anisotropy associated with the step edges and the contribution of dipolar interaction between the Fe chains and/or islands in-

side the chain. At LT, the hysteresis loop is characterized by a small remanence, coercivity, and saturation field (~50 Oe) but at RT the hysteresis loop vanishes. With increasing coverage up to 1.7 ML, the longitudinal magnetization curves at LT become much more pronounced with a near rectangular shape, still keeping the easy magnetization direction along the chain direction. Compared to 1.3 ML, the remanence and coercivity at 1.7 ML are larger. Furthermore, at the coverage of 1.7 ML, Fe chains show a hysteresis loop indicative of the easy magnetization direction being parallel to the chains, both at LT and RT, suggesting that the blocking temperature ($T_B$) is above RT.

Besides in situ SMOKE measurements, an ex situ ESR measurement could allow us to determine the easy magnetization direction as well as the magnetic anisotropy constant. Before taking the ex situ ESR measurements, the SMOKE data have been taken in the UHV chamber to compare the signals before NaCl capping layer and after. No difference has been found. After exposure to the atmosphere, SMOKE data have been taken to check whether any magnetic property has been changed. Even one month later, the signals are still the same and stable. Figure 3(a) and 3(b) show the angular dependence of in-plane and out-of-plane ESR spectra taken at RT for the 1.7 ML Fe chains, respectively. The in-plane and out-of-plane ESR spectra both consist of two peaks (labeled by $P_1$ and $P_2$). The black circles in Figs. 3(c) and 3(d) show the angular variation of in-plane and out-of-plane resonance fields for the $P_1$ peak (the $P_2$ peak shows that resonance fields do not change with angles, which is a paramagnetic resonance peak that existed in the background spectra). This implies that the sample has uniaxial in-plane symmetry because it shows three peaks in the angular dependence in the plane of the film if cubic anisotropy of Fe is presented. Considering the SMOKE data, it is assumed that only the Zeeman energy, the in-plane uniaxial magnetic anisotropy energy, and demagnetization energy are taken into account for the free energy density of the system for 1.7 ML Fe/Pb/Si (Ref. 19 and references therein). So the in-plane and out-of-plane resonance fields $H_{res}$ can be calculated by
using the following equations derived from Landau–Lifshitz equation without damping.\textsuperscript{14,20,21} The lines obtained by fitting the experimental data with equations are also shown in Figs. 3(c) and 3(d). The in-plane uniaxial magnetic anisotropy is found to display a dominant uniaxial symmetry and its easy axis is along the chain direction, consistent with the SMOKE measurements. The parameters \(g\), \(2K_u/M_S\), and \(4\pi M_{\text{eff}}\) were estimated from the fit lines with \(g=2.03\), \(2K_u/M_S=150\) Oe, and \(4\pi M_{\text{eff}}=3.51\) kOe, which prove that the \(P_1\) peak is the ferromagnetic resonance peak. Considering the fact that each Fe three-dimensional random island inside the wire in Fig. 1(b) contains on average 6000 atoms, one would expect these Fe islands to have a magnetization close to bulk value. Taking the bulk value \(M_S=1700\) G, the overall in-plane uniaxial anisotropy constant \(K_u\) could be determined as \(1.3 \times 10^5\) erg/cm\(^3\). The ESR measurement provides additional quantitative information on the magnetization, magnetic anisotropy, and the Landé factor value for studying low dimensional magnetic nanostructures.

It is well known that an isolated 1D chain cannot exhibit long range ferromagnetic order above zero temperature unless RKKY interaction, magnetic anisotropy, or dipolar interaction exists in the system. Due to the random shape islands at the edges of the chains and the slightly varying distance between the chains for the coverages of 1.3 and 1.7 ML, the positive and negative contributions from the RKKY-type interaction mediated by the stepped Pb film are mostly canceled out. Therefore, the RKKY interaction in Fe chains is unlikely to play an essential role. Having ruled out the RKKY interaction, the 1D ferromagnetism of the Fe chains may originate from the magnetocrystalline anisotropy. As above discussed, these Fe islands could be treated to have a magnetocrystalline anisotropy close to bulk value. However, the crystallites of Fe islands and the easy magnetocrystalline anisotropy direction are arranged randomly spatially, which would not lead to an in-plane uniaxial magnetic anisotropy along the chain direction in SMOKE measurements. Therefore mainly the step-induced anisotropy and dipolar interaction result in an overall magnetic anisotropy that behaves to align the chain direction with a value of \(1.3 \times 10^5\) erg/cm\(^3\).

In summary, we fabricated Q1D Fe chains on a 4° miscut Si (111) substrate by using a stepped Pb film as buffer layer. Both SMOKE and ESR data indicate that the Fe chains exhibit in-plane uniaxial magnetic anisotropy along the step direction. The effective in-plane uniaxial anisotropy constant \(K_u=1.3 \times 10^5\) erg/cm\(^3\) at RT was determined by \textit{ex situ} ESR measurements.

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