Magnetic Ordering and Fluctuation in One-Dimensional Fe Nanowires

Magnetism in one-dimensional (1D) systems is a classical problem but still a hot topic. Because of the simplicity and fewer parameters of the systems, this problem was treated in theoretical studies early in the 20th century. It has been proved by theories that long-range ferromagnetic order in 1D is prohibited at finite temperatures in principle. Even if all magnetic moments are initially aligned in 1D, spin flips take place owing to thermal fluctuation at finite temperatures. Accordingly, 1D spin systems are inevitably broken up into shorter magnetic domains, and total magnetization becomes nearly zero. However, ferromagnetic ground states can appear if strict one-dimensionality is broken by orbital degeneracy or quasi-1D geometry. From this point of view, we fabricate 1D Fe nanowires grown on vicinal Au surfaces and examine the magnetism in 1D by X-ray magnetic circular dichroism (XMCD).

The growth of Fe nanowires on Au(788) [1] is illustrated in Fig. 1. Fe atoms dosed on the stepped Au surface preferentially adsorb at step edges, thereby decorating them. At an Fe coverage of 0.07 ML, an array of monatomic chains is formed and the second-row growth begins. As Fe coverage is increased, 1D Fe nanowires grow in a step-flow growth mode. However, the morphology of such nanowires gradually changes depending on Fe coverage. The nanowires show periodically meandered shapes above ~0.3 ML owing to the faster growth in fcc regions than in hcp regions. Fe stripes reach adjacent ones in the fcc regions, and 2D networks are formed at around 0.6 ML.

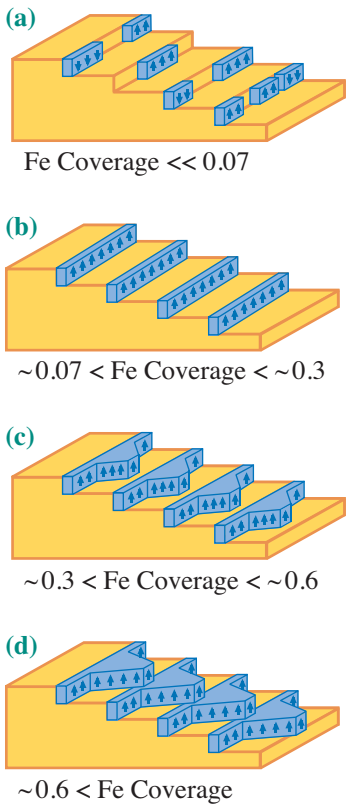

Fig. 1. Schematics of the growth manner of Fe on a Au(788) surface. **(a)** 1D fragments of Fe below 0.07 ML. **(b)** Complete formation of 1D monatomic Fe chains at 0.07 ML. **(c)** Periodically meandered quasi-1D nanowires of Fe between 0.3 ML and 0.6 ML. **(d)** 2D networks of Fe above 0.6 ML.

Figure 2(a) shows an XMCD spectrum for 1D monatomic chains of Fe (0.07 ML) [2], which was taken at **BL25SU**. Fe $L_{2,3}$ absorption edges are related to excitations from the 2*p* core level into unoccupied 3*d* valence states. The strong dichroism directly proves the existence of magnetic moments and their alignment in the external field. From the XMCD spectrum, we estimated the orbital moment to the effective spin moment ratio $m_L / m_s^{eff} = 0.26$, which is five times as large as 0.05 obtained for 2D Fe monolayers. Such an increasing in orbital magnetic moment with a decrease in coverage is mainly due to the reduction in atomic coordination.

Figure 2(b) shows the temperature dependence of magnetization at different Fe coverages. It is clear that MCD intensity decreases as temperature increases. Furthermore, we found that, as the coverage is decreased, 1D nanowires show a faster decay with *T*. Particularly, in the case of monatomic chains, magnetization rapidly drops with a slight increase in temperature. These results suggest that the orbital magnetic moment is enhanced in 1D nanowires, but that the large magnetization is rapidly suppressed with increasing temperature owing to intensive fluctuation in lower dimensions. As a result, magnetization is decreased as Fe coverage is decreased at a finite temperature of $T = 18$ K, as shown in Fig. 2(b). Presumably, cooling the samples down to a temperature low enough to suppress thermal fluctuation may yield a giant magnetization in reduced dimensionality.

Figure 3(a) shows the magnetization curves for monatomic chains. We can clearly see a phase transition from ferromagnetic to superparamagnetic. At the lowest temperature, the magnetization curve shows a hysteresis loop, where each domain is blocked in a fixed magnetization state (up or down) as a result of the freezing of thermal fluctuation. However, the curve is not a simple square like

hysteresis loop, and the remanence at the zero field is much smaller than the saturation magnetization. This implies that thermal fluctuation still seems to be not negligible in monatomic chains. As temperature increases, the coercive field disappears at the blocking temperature T_B. Above T_B, the magnetization spontaneously reverses because of thermal agitation, and typical superparamagnetic reversible S-shaped curves are observed. Furthermore, blocking temperature decreases with decreasing coverage, which is a general trend observable in low dimensionality.

Finally, we focus on magnetization reversal in Fe nanowires [3]. In the case of monatomic chains, the magnetization process is based on single spin flips, and domain boundaries can move site to site. If the growth of nanowires ideally proceeds in a step-flow growth mode, magnetization reversal behavior is independent of Fe coverage, i.e., size of nanowires. As mentioned above, however, the nanowires show the periodically meandered shapes at higher coverages. Since structural constrictions often serve as nucleation, annihilation and pinning centers for domain boundaries, magnetization reversal in quasi-1D nanowires occurs as macrospins flip to the opposite direction. Finally, the magnetization process drastically changes when the 2D networks of Fe are built up at around 0.6 ML. Superparamagnetic fluctuation is strongly suppressed, leading to a remanence-to-saturation ratio of nearly 1 [Fig. 3(b)] and the coherent rotation of the entire magnetization under the action of the external field. These results indicate that the size and overall shape of nanowires have a decisive effect on magnetic properties, such as fluctuation, domain patterns and magnetization processes.

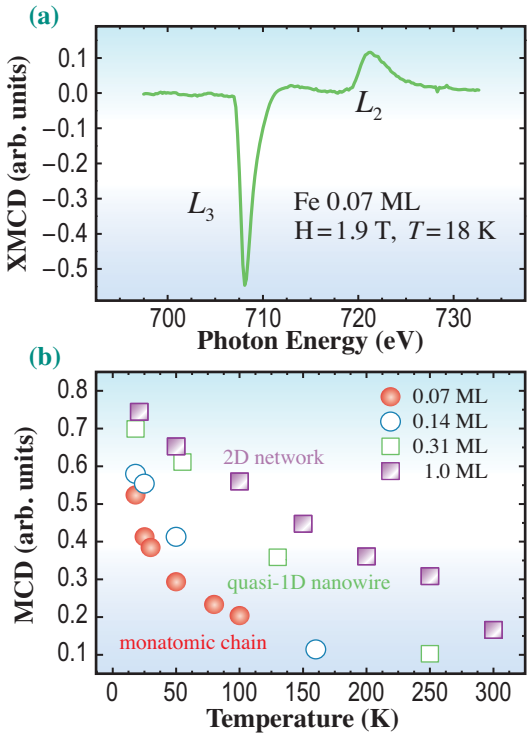

Fig. 2. **(a)** XMCD spectrum of 1D monatomic chains of Fe on Au(788). **(b)** Temperature dependence of magnetization per Fe atom of 1D nanowires on Au(788).

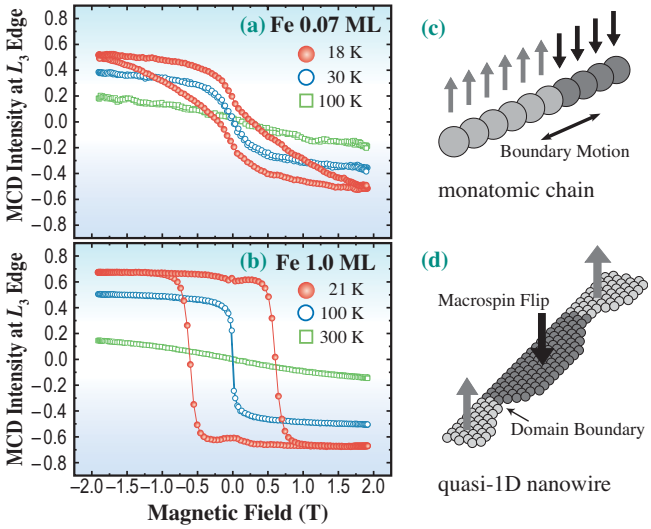

Fig. 3. Magnetization curves of **(a)** monatomic chains (0.07 ML) and **(b)** 2D monolayer (1.0 ML). Magnetic domain structures in **(c)** monatomic chains and **(d)** periodically meandered nanowires. The black and gray atoms are magnetized into and out of the surface, respectively.

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References

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