Magnetic properties of [100] oriented Cu-Ni superlattices

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We have fabricated Cu-Ni superlattices with exclusive [100] modulating orientation by using a dc magnetron sputtering system. The layer thicknesses of both Cu and Ni range from 5 to 125 Å. The high quality of the samples is confirmed by the intense satellite peaks in the x-ray diffraction. The spontaneous magnetization at 5 K, which is found to be inversely proportional to the Ni layer thickness, vanishes at two Ni atomic planes. A very large difference in magnetic surface anisotropy has been found between [100] and [111] textured Cu-Ni superlattices, displaying the important role of modulating orientation on the magnetic properties of superlattice.

I. INTRODUCTION

Metallic superlattices have received considerable attentions recently,[1] of which Cu-Ni superlattices represent the most extensively studied system so far, facilitated by the fact that Cu and Ni share the same crystal structure (fcc) and almost identical lattice constants. Magnetic properties of superlattice system can be tailored by varying its modulation wavelength (λ), amplitude, and orientation. However, the control of orientation is not easily achieved; for example, all previous studies[2–4] of the Cu-Ni superlattices have been limited to samples with [111] or mixed textures which are most easily realized by various methods and deposition conditions. Theoretical calculations[5–7] show that the characterizations of the Ni layer on [100] Cu are drastically different from those of the Ni layer on [111] Cu. The magnetic surface anisotropy is also expected theoretically to be very different in the two orientations.[8] Therefore, in the study of superlattices, a tight control of the modulating orientation is highly desirable.

In this work, we have successfully fabricated high-quality Cu-Ni superlattices with new [100] modulating orientation. Very different magnetic behaviors have been found and will be compared with those of the [111]-oriented system.

II. EXPERIMENT

The Cu-Ni superlattice films have been fabricated by using a sputtering system equipped with two dc magnetron guns and a rotating platform. The vacuum prior to sputtering was in the 10^{-8}-10^{-7} Torr range with a liquid-nitrogen-cooled Meisner trap in the chamber. We have chosen to fix the deposition rates of both Cu and Ni at 7 Å/s, monitored by a thin-film thickness controller. The rotating platform was installed with resistive heaters and a thermometer, and its temperature was accurately maintained by a temperature controller. A digital servo motor system controlled the speed of the platform that determined the modulation wavelength of the superlattice. A series of films with λ ranging from 5 to 250 Å have been made on single-crystal NaCl and mica substrates. A Cu buffer layer of about 150 Å was first deposited at substrate temperature of 350 °C, and then the dual deposition was carried out at 200 °C. The total film thickness was about 0.5–1 μm.

Magnetic measurements were performed by using a SQUID magnetometer with field range of 0–50 kOe.

III. STRUCTURES

The structure of the samples have been analyzed with x-ray and electron diffraction. Films deposited on mica are [111] oriented as previously obtained by others,[2–4] but those deposited on [100] air-cleaved NaCl single-crystal substrates yield *exclusively* [100]-oriented Cu-Ni superlattices. This clearly demonstrates the importance of substrate on the structure of superlattice. Figure 1 shows the x-ray diffraction patterns of a few [100]-oriented samples. The (200) and (111) diffraction peaks of bulk Cu and Ni are indicated by the arrows. Notice that the (111) peaks are completely absent. For the sample with $\lambda = 250$ Å, the central and satellite peaks are too close to be resolved, and only the envelope function can be seen. At smaller λ values, resolved satellite peaks appear. As λ is further reduced, the system gradually evolves into superlattices with a uniform d spacing, as evident from the existence of a single central peak and satellites around it (e.g., $\lambda = 34$ Å). The uniform d spacing is 1.788 Å which is the average d spacing of [200] Cu and Ni.

IV. MAGNETIC PROPERTIES

Typical magnetization curves $M(H)$ at $T = 5$ K in both the parallel ($H_{\parallel}$) and perpendicular ($H_{\perp}$) geometries are shown in Fig. 2. Magnetization with $H_{\parallel}$ can be easily saturated while a much larger field is required in the case of $H_{\perp}$. All the samples exhibit large magnetic anisotropy difference between $H_{\parallel}$ and $H_{\perp}$ indicating that the films are flat and continuous over large areas. The spontaneous magnetizations (M_s) are obtained by extrapolating $M(H)$ curves from high field (50 kOe) to zero field at temperature $T = 5$ K, eliminating any diamagnetic or paramagnetic contributions. The error of M_s determination is about 10%, resulting primarily from sample area measurement and to a lesser extent from error in thickness control and SQUID magnetometer. The values of M_s of all the samples at 5 K are plotted in Fig. 3 as a function of inverse Ni layer thickness ($1/d$). It is apparent from Fig. 4 that M_s depends linearly on $1/d$ for Ni layer thickness of 5–4100 Å. A fit to the data gives the following relation:

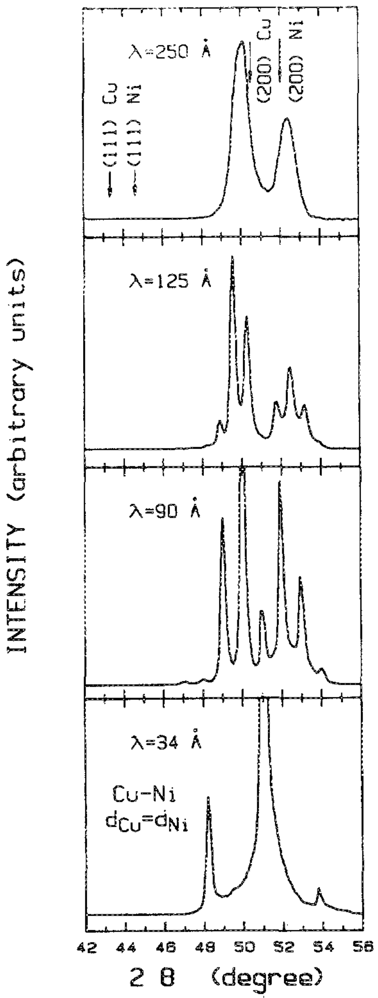

FIG. 1. θ-2θ x-ray diffraction patterns of [100] Cu-Ni superlattices.

$$M_s = M_0[1 - d_s/d],\tag{1}$$

where M_0 is the bulk magnetization and d_s ($= 3.6$ Å) is the Ni thickness at which M_s reduces to zero.

One of the most interesting problems in Cu-Ni system is whether there exist magnetically dead Ni layers at the Cu-Ni interface. A simple interpretation of Eq. (1) is that d_s/d is the fraction of the Ni planes with no magnetic moments while the rest have the bulk value. Since $d_s = 3.6$ Å is close to the thickness of two Ni atomic planes, the result implies that the first Ni atomic plane adjacent to both Cu layers is magnetically dead while the interior Ni remains ferromagnetic. Although our data can be explained by the existence of magnetic dead layer, caution has to be taken in adapting this interpretation, because the dramatic reduction in M_s may also be caused by interface diffusion. Gyorgy *et al.*[3] and Zheng *et al.*[4] have studied the magnetization of [111] Cu-Ni samples in relation to modulation amplitude which was altered by thermal annealing. They found that the M_s was reduced as the modulation amplitude decreases, and eventually it approached that of the uniform Cu-Ni alloys. In our system, the fact that relation (1) holds indicates that the interface diffusion is limited to the very first Cu-Ni interface layer, and only the Ni interface layer suffers dramatic reduction in M_s. The work by Gyorgy *et al.*[2] also observed the reduction of M_s in [111] Cu-Ni superlattices with decreasing Ni layer thickness, although the linear relation of M_s vs $1/d$ was less obvious.

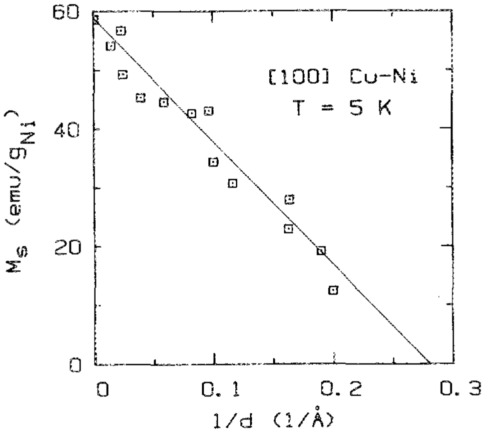

FIG. 3. Spontaneous magnetizations vs $1/d$ at $T = 5$ K.

In [111] Cu-Ni superlattice system a large magnetic surface anisotropy (MSA) has been discovered. It is expected that such MSA is sensitive to the orientation of the films. This is indeed so in our [100] system. We have studied the MSA by measuring the kink field in the $H_\perp$ magnetization curve, the field at which the magnetization reaches its satu-

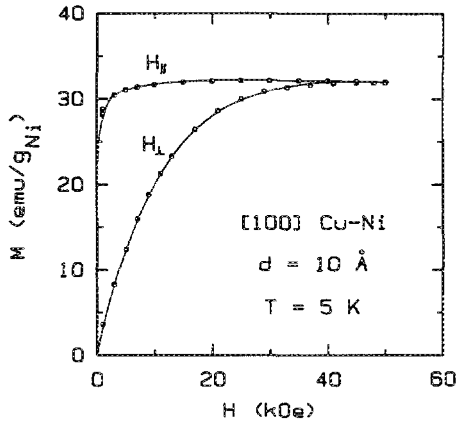

FIG. 2. Magnetization curves in parallel and perpendicular geometries of [100] Cu-Ni superlattice with $\lambda = 10$ Å at $T = 5$ K.

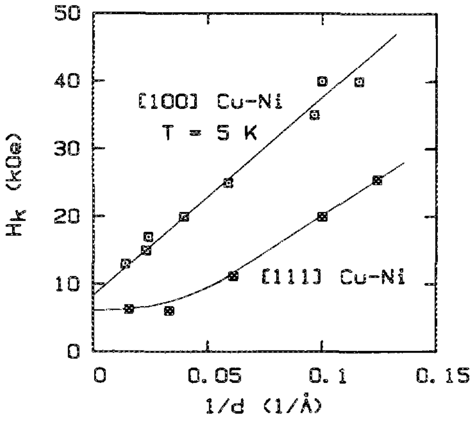

FIG. 4. Magnetic anisotropy fields vs $1/d$ at $T = 5$ K. The data of [111] Cu-Ni superlattices are from Ref. 2.

ration value. This is the same method used by others[2] to determine MSA in the [111] system. The kink field is commonly chosen to be the anisotropy field (H_k) which depends on the thickness of magnetic layer (d) according to

$$H_k = 4\pi M_s + \frac{2K_v}{M_s} + \frac{4K_s}{M_s}\frac{1}{d}, \tag{2}$$

where K_v is the bulk crystalline anisotropy constant and K_s, the surface anisotropy constant, the first term is due to the shape anisotropy. The H_k data as a function of $1/d$ are presented in Fig. 4; also included are the H_k data of the [111] Cu-Ni system.[2] The H_k of the [100] samples are much larger than those of the [111] Cu-Ni superlattices. This is a marked effect caused by the different modulating orientation.

The [100] axis of Ni is the bulk magnetic hard axis. The bulk crystalline anisotropy field is about 5 kOe at $T = 5$ K. After excluding $4\pi M_s$ and $2K_v/M_s$ in relation (5), the surface anisotropy constant K_s of [100] Cu-Ni is estimated to be 0.23 erg/cm^2. For [111] Cu-Ni superlattices K_s is about 0.12 erg/cm^2 at $T = 4.2$ K.[2,9] Therefore, the magnetic surface anisotropy of the [100] Cu-Ni interface is enhanced by a factor of 2 comparing with the [111] orientation.

V. SUMMARY AND CONCLUSIONS

High-quality Cu-Ni superlattices have been fabricated with new [100] modulation orientation. The low-temperature magnetization of the system is inversely proportional to the thickness of the Ni layer, and vanishes by extrapolation at two Ni atomic planes. This suggests the possibility of magnetic dead layers. The surface anisotropy constant K_s for [100] orientation has been determined to be 0.23 erg/cm^2, which is about twice of that in the [111] orientation.

ACKNOWLEDGMENT

This work was supported by National Science Foundation Grant No. DMR86-07150.

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