Nanoscale ripple formation in Co/Si(100) thin films with Ar$^+$ beam etching.

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Abstract. We have investigated the formation of nanoscale ripples on etched Co/Si(100) films with Ar$^+$ beam in grazing incidence. Topography and dimensions of those nanoscale patterns were characterized by means of atomic force microscopy. Polycrystalline cobalt thin films were deposited by d.c. magnetron sputtering onto Si(100) wafers and, later transferred in situ to a process chamber for the production of ripples. Their average width, $w_d$, and separation between them, i.e. their periodicity $\Lambda$, were found to monotonously increase first with the etching time and, finally, reach saturation values for long irradiation times (around 30 min). The same Ar$^+$ beam etching applied on thicker Co films resulted in much wider and higher ripples, providing a more defined nanostructure for ulterior uniaxial magnetic anisotropy measurements. These changes in the ripple dimensions on increasing the Co film thickness are discussed in terms of the surface roughness in the as-deposited film.

1. Introduction
In the last decade, a great interest has focused on different experimental techniques for nanostructuring the morphology of thin films. Amongst them, the ion beam etching has revealed itself as a promising tool for tailoring metallic films up to nanoscale range [1]. For grazing incidence, that technique has been reported to form defined ripples in both semiconducting [2, 3] and metallic surfaces [1, 4]. That periodic array of quasunidimensional and parallel wires provides a unique scenario for fundamental research, e.g. magnetic anisotropy, magnetization reversal, conductance in quantum dots, or nanotechnology applications, e.g. magnetic recording.

Here, we have centered in the Ar$^+$ beam etching of Co thin films to form ripples under different experimental conditions. According to that motivation, the aim of this work has been, on one hand, to investigate the influence of some parameters involved in the growing of Co-ripples and, on the other hand, to optimize that periodic nanostructure for future applications.

2. Sample preparation and measurement techniques
Polycrystalline cobalt thin films were deposited by d.c. magnetron sputtering onto commercially available polished Si(100) wafers. The base pressure in the deposition chamber was $4 \cdot 10^{-8}$ mbar.
The films were deposited in argon $8 \times 10^{-3}$ mbar pressure range with a discharge power of 30W, corresponding to a growth rate of 0.25 nm/sec. The film thickness was obtained with ex situ x-ray reflectometry.

Right after deposition, the samples were transferred within vacuum to a process chamber for ion beam sputtering. The ion beam was provided by a commercial 3 cm Kaufman ion gun. The samples were irradiated with 1.2 keV Ar$^+$ ions at an incidence angle of 80° with respect to the substrate normal, that produced aligned ripples parallel to the ion beam direction. At these conditions the ion current density was about 0.1 mA/cm$^2$ and the estimated etching rate, 0.04 nm/s. Exposure time varies from a few minutes to an hour. The characterization of the topography and dimensions of those nanoscale patterns was accomplished by means of ex situ atomic force microscopy (AFM) at room temperature.

3. Results and discussion

3.1. Etching time dependence

For patterned Co(600Å) thin films, figure 1 shows the evolution of ripples dimensions with the etching time, ranging from 0 to 30 min. With the mentioned experimental conditions, short irradiation times (~5 min) are already able to form those nanostructures with small $w_d$ and $\Lambda$ values. Upon increasing the exposure time, both magnitudes increase monotonously. Finally, in the measured range the results plotted in fig. 1 seem to reach saturation values for long etching times (over 30 min.) This would correspond to a nanostructure of wide and well separated ripples with an average periodicity of 70 nm. Additionally, the ripple height in all Co(600Å) samples was found to be independent of exposure time and around 1.5 nm. Further erosions confirmed that saturation regime in the dimensions of ripples, in spite of their irregular distribution over the film once the substrate was reached.

![Figure 1](image.png)

**Figure 1.** Dependence of $w_d$ (left) and $\Lambda$ (right) of induced ripples on the A$^+$ beam etching time. Lines are guides to the eye.

Topographic characterization of selected samples in the nanostructured series of Co(600Å) thin films can be seen in the figure 2. For low Ar-beam irradiation times, figure 2 shows narrow and small induced ripples on the Co film, corresponding to the first stages of sculpting. On the other hand, large etching times (~30 min.) lead to the formation on the Co film of a regular and nanoscale pattern, consisting of wide and well separated ripples. These results are in accordance to previous works reporting the formation of ripples on metallic surfaces [4, 5, 6, 7].
3.2. Co film thickness dependence

For both fundamental and technical applications mentioned in the introductory section, magnetic ripples with large height and separation between them are particularly convenient[4]. Such quasilinear nanosystems would be dominated by dipolar interactions, and consequently, offer a strong uniaxial magnetic anisotropy, $K_u$. This led us to obtain further insight in improving those characteristics and meet the above requirements in our induced Co ripples. As investigated previously [8], surface rugosity is determinant to decrease the shape anisotropy of magnetic thin films, $K_{eff}$. Upon increasing their thickness, the in-plane demagnetizing effect of the fields created at the edges of terraces becomes more relevant in lowering $K_{eff}$. Thus, that enhanced number of surface structural defects could be characteristic of thick Co films. For our interest, those defects would behave, first, as favorable regions for the later Ar$^+$ beam etching, and secondly, as pinning centers to block an eventual slipping of the ripples over the Co surface. Therefore, induced ripples with optimized dimensions and large $K_u$ would arise after etching the as-deposited Co films of greater nominal thicknesses.

![Figure 2. AFM image (2µm x 2µm scans): phase contrast of an irradiated Co(600Å) film during 5 min (left) and 23 min (right).](image)

![Figure 3. (a) Left: dependence of surface roughness and rms value on the Co film thickness. (b) Right: AFM image of an as-deposited Co(3800Å), 2µm x 2µm scan.](image)

Accordingly, we have grown a series of Co films with different thicknesses (up to 3800Å) and estimated their surface roughness from the corresponding AFM scans. The obtained data for their surface roughness and rms value are shown in the figure 3(a). As expected, both magnitudes increase monotonously upon growing thicker Co films. An AFM image of a Co(3800Å) thin film has been also included in fig. 3(b) where clear evidences of a very rough Co surface can be found.
To examine the effect of Co thickness in the ripples, we have later etched a Co(2850 Å) thin film during 30 min, keeping the same for other experimental conditions. The AFM image corresponding to that sample can be seen in figure 4(a). Now, the nanostructured pattern consists of wider and more spaced ripples, whose average width $w_d$ and periodicity are 90 and 70 nm, respectively (see the height profile in fig. 4). Additionally, their relative height can be estimated as $\sim 10$ nm, being almost 10 times higher than ripples sculpted on the Co(600 Å) thin films. This enhancement of ripples dimensions seem to be in agreement with our previous speculations.

![AFM image of an Ar$^+$ beam etched Co(2850 Å) film, 2 μm x 2 μm scan.](image1)

![Selected height profile along the blue line shown in the AFM image](image2)

Figure 4. (a) Left: AFM image of an Ar$^+$ beam etched Co(2850 Å) film, 2 μm x 2 μm scan. (b) Right: selected height profile along the blue line shown in the AFM image

4. Summary

According to the discussed results in this paper, Ar$^+$ beam etching has turned to be an effective technique to pattern Co thin films in order to obtain nanoscale ripples. For Co(600 Å) films, both width $w_d$ and periodicity $\Lambda$ characteristics of the induced ripples monotonously increase on extending the etching time. This behaviour tends to some saturation regime, then appearing those ripple dimensions to be independent of the erosion length. Even in the case of large irradiation processes, Co ripples show small average width and height values, 40 nm and 1.5 nm, respectively.

We have investigated the surface roughness with the thickness of the as-deposited Co film. After analyzing their AFM images, rugosity and surface defects number increase with thicker Co films. Finally, we have applied the same etching process on these thick Co films and wider and higher ripples have been obtained ($w_d \sim 90$ and height $\sim 10$ nm). In our opinion, this enlargement in the ripple dimensions would be due to the higher effectiveness of the Ar$^+$ beam etching on a Co surface with a larger number of structural defects. This approach, intended to improve the quality of the nanoscale pattern, enables us to safely face magnetic anisotropy measurements on those ripples.

References

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