Magnetic thin film deposition with pulsed magnetron sputtering: deposition rate and film thickness distribution

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Abstract. The goal of conducted study was an experimental determining the relations between technological parameters of magnetron sputtering process on deposition rate ($R$) and thickness uniformity of magnetic thin films. Planar Ni\textsubscript{79}Fe\textsubscript{16}Mo\textsubscript{5} target with a diameter of 100 mm was sputtered in argon (Ar) atmosphere. Deposition rate was measured in a function of gas pressure, target power and target-substrate distance. The highest value of $R$\textasciitilde280 nm·min\textsuperscript{-1}. The obtained results in deposition rate of magnetic film were compared to deposition rate of cooper (Cu), aluminum (Al), titanium (Ti) and titanium oxide (TiO\textsubscript{x}) and the deposition rate of Ni-Fe alloy were higher that Al and Ti. The film thickness distribution was measured for radial distance from the target centre ranging up to 60 mm and target-substrate distance ranging form 70 to 115 mm. Among others it was stated that for the larger value of target-substrate distance the larger uniform of film thickness are obtained.

1. Introduction

Magnetron sputtering is one of well-developed method for thin film fabrication but its extensive use in industrial application depends on the ability of obtaining high quality films with high value of deposition rate on a large deposition area. In case of large deposition are, the film uniformity play a major role and generally for different sputtering systems and different sputtering conditions, the characteristics of the sputtered atoms and the thickness profile are different. Therefore, the manifestation of the relationship between the film uniformity and the deposition parameters is required.

In magnetron technique there is a number of ways to apply the voltage to the cathode depending on the nature of the discharge: AC, DC, Pulse DC, radio frequency etc. Pulsed power operating in mid-frequency range (20-300 kHz) is a relatively new method [1-3]. The goal of this type has been mainly improving the stability of reactive processes, however, currently begins to be increasingly used in high-performance non-reactive processes. Pulsed powering almost completely suppresses the arcing and makes the process more stable, even while maintaining high power densities and the values of obtained deposition rates are even approx. 500 nm·min\textsuperscript{-1} for reactive processes [4, 5] and approx. 5000 nm·min\textsuperscript{-1} for neutral processes [6, 7].
In this article the dependence between the process parameters and the value of deposition rate and thickness profile of magnetic thin film is described. One limitation of magnetron sputtering techniques is the limited ability for using ferromagnetic targets. The main problem is that the magnetic nature of the target material interferes with the magnetic field generated by the magnetron resulting in reducing the efficiency of the process and bad film homogeneity. The iron-nickel alloy (called Superpermalloy) was used as a target. The choice of this material was dictated by its soft magnetic properties ($\mu >> 1$) and wide applications, especially in modern technology. The obtained results in deposition rate were compared to deposition rate of cooper (Cu), aluminum (Al), titanium (Ti) and titanium oxide (TiO$_x$) thin films.

2. Experimental

The investigation was performed in a vacuum system (0.14 m$^3$) equipped with rotary and turbomolecular pumps. The final pressure of the deposition chamber was about 6·10$^{-4}$ Pa.

The deposition rate ($R$) was measured as a function of technological parameters of magnetron sputtering process, by using the SQM-160 quartz crystal monitor. Thickness profile was examined by means of atomic force microscope (AFM), by measuring the high difference between the surface of the substrate and thin film surfaces (Figure 1). In this case magnetic thin films were deposited on the Corning glass (20×20 mm) and the shutter was used to shield the glass plate from deposition, while the sputtering parameters were set and the target was conditioned.

In all cases Ni-Fe alloy thin films were obtained by using Ni$_{79}$Fe$_{16}$Mo$_5$ target with 100 mm in diameter and 1 mm thick. The cathode was sputtered in pure argon (99.999 %Ar) atmosphere at pressures ($p_Ar$) ranged from 0.4 to 5.0 Pa. Magnetron target was powered by DPS Power Supply (medium frequency power supply) unit [4] with target power ($P$) up to 2000 W. The target-substrate distance ($d_{T-S}$) was changed from 70 to 115 cm. The film thickness distribution was measured for radial distance ($a$) from the target centre ranging from 0 (the magnetron centre) to 60 mm.

To compare the deposition rate of NiFe alloy film with others deposited materials the Cu (99,999 %Cu), Al (99,999 %Al) and Ti (99,999 %Ti) targets with 100 mm in diameter and 3 mm thick were used. All targets were sputtered in the same condition as Ni$_{79}$Fe$_{16}$Mo$_5$. The Ti target was in addition sputtered in pure oxygen (99.999 %O$_2$) atmosphere.

Figure 1. The AFM image of magnetic thin film cross-section (a) and result of measuring its high (b).
3. Results and discussion

3.1. Deposition rate

3.1.1. Gas pressure effect
Deposition rate of thin magnetic film in dependence on gas pressure is shown in figure 2. The results are referred to the experiment carried out in the pressure ranged from 0.4 Pa to 5.0 Pa and target-substrate distance $d_{T-S}=70$ and 115 mm. The applied target power $P$ were changed in the range from 400 to 2000 W. Based on the characteristics it can be seen that for pressures between 0.4 and 1.0 Pa, increase in pressure only cause a slight change in the deposition rate. At pressures above 1.0 Pa, increase in pressure results in decrease in the deposition rate. This, of course, is as would be expected. As the sputtered particles travel between the target and the substrate, they collide with the gas atoms and are scattered. This process can be characterized by the mean free path $\lambda$ that is related among others to the gas pressure. As mentioned in many studies, increasing pressure increases gas scattering, and hence, decrease the probability of a sputtered atom depositing on the substrate [8-11]. This effect is particularly significant at pressures higher than 1.0 Pa [12, 13].

The obtained results showed that the values of $R$ at target-substrate distance $d_{T-S}=115$ mm are similar but almost twice as small as at $d_{T-S}=70$ mm. It is reasonable to assume that the bigger the target-substrate distance, the thinner thin films are obtained.

![Figure 2](image)

**Figure 2.** Deposition rate $R$ of Ni-Fe alloy thin film in dependence on the argon pressure $p_{Ar}$ in target-substrate distances $d_{T-S}=70$ mm (a) and $d_{T-S}=115$ mm (b).

3.1.2. Target power effect
Figure 3 shows the Ni-Fe alloy thin film deposition rate at several sputtering process parameters. As expected, an increase in target power results in an increase in the deposition rate.

In our study the target power increase was generated by the increase of filling of the sputtering pulse. It causes increase in an effective sputtering time. Finally increase in sputtering time causes: i) the increase in the sputtered particle flux density and ii) pressure reduction in the region near the magnetron cathode, due to energy dissipation from sputter-ejected atoms within the gas. In the second case it causes a certain rarefaction of discharge gas near the target and consequent increase of the...
mean free path of sputtered atoms. In the examined range of $P$ the $R$ changed linearly with the applied power.

In comparison to other thin film materials, the obtained results in deposition rate for magnetic film are even higher than for aluminum and titanium (Figure 4). As can be seen the highest values of the deposition rates obtained for copper (Cu). The lowest deposition rate was measured for titanium oxide, but it is understandable that effectiveness of reactive processes is lower than nonreactive, due to the target surface oxidation. For $P=2000$ W, the $R$ values are as follows: $R_{\text{Cu}} \approx 290$ nm·min$^{-1}$, $R_{\text{Ni-Fe}} \approx 140$ nm·min$^{-1}$, $R_{\text{Al}} \approx 45$ nm·min$^{-1}$ and $R_{\text{TiO}_x} \approx 5$ nm·min$^{-1}$. The resulting dependence $R=f(P)$, in the measured target power range are linear.

### 3.2. Film thickness distribution

In figure 5, the Ni-Fe alloy film thickness distribution, plotted against radial distance $a$ from the magnetron center for several values of the target-substrate distance and target power. The obtained results showed that in the studied range of $d_{T,S}$ and $a$, the thicknesses of prepared film decrease with its...
increasing, but for the larger target-substrate distance the larger uniform of film thickness were obtained. Generally, the sputtering gas pressure also affects the film thickness distribution although, in our case, the effect is not very obvious. Further study is still required to clarify these effects.

The thickness decreasing in a function of $a$ was confirm by other studies. As can be read, the thickness distribution of thin film depends not only on the process parameters but is also conditioned by a magnetron construction (magnetron geometry and its magnetic field) [14-17].

**Figure 5.** Thickness profile of Ni-Fe alloy thin films measured for different target power $P$ and substrate-distance of 70 mm (a), 85 mm (b), 100 mm (c) and 115 mm (d). Argon pressure $p_{Ar}=1.0$ Pa (left side) and 2.0 Pa (right side).
4. Conclusions
The influence of magnetron process parameter on deposition rate $R$ and thickness profile of magnetic thin film, by sputtering Ni$_{79}$Fe$_{16}$Mo$_5$ target, has been presented. The obtained results can be summarized as follows:

(i) In case of gas pressure effect: above 1.0 Pa, deposition rate are inversely proportional to pressure. Up to the 1.0 Pa the values of deposition rate are almost on the same level.

(ii) The variation of Ni-Fe ally deposition rate with target power, at the range 400-2000 W gives evidence of a linear dependence of $R$ with $P$.

(iii) The highest value of $R \approx 280$ nm·min$^{-1}$ obtained for $P=2000$ W and $d_{T,S}=70$ mm. Our further work revealed that the values of deposition rate of Ni-Fe alloy thin film is higher than Al and Ti.

(iv) One of the factor which influence the film thickness uniformity is the variation of the target-substrate distance. Another is the gas pressure. In our investigation for larger $d_{T,S}$ the more uniform films were obtained. In case of $p_{Ar}$ on thickness profile the further study are required.

5. References
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