The co-evaporation technique has been used for deposition of Co-Cr layers. Deposition has been done under intermediate angle of incidence of opposing vapour streams. The layers showed a single phase hcp poly-crystalline structure. The (002) plane turned out to be tilted towards the direction of the Co source. The layers showed good perpendicular magnetic behaviour although the magnetic anisotropy axis was also inclined towards the Co-source because of the opposing angle of incidence for Co and Cr atoms, a process-induced segregation takes place which causes a relative high coercivity also at low process temperatures. A simple model for the segregation effect can explain the relation between the existence of a non-magnetic region and an increased coercivity of the Co-Cr film.

**RESULTS AND DISCUSSION**

Single crystal Si wafers were used as substrate material. The substrates were tightly mounted against a substrate plate which is heated from the backside by an infra-red heater. The monitored process temperature \( T_p \) is not the actual substrate temperature \( T_{sub} \) but the control temperature of the infra-red heater. \( T_p \) is expected to be proportionally smaller than the actual \( T_{sub} \) and was in the range 50-300°C.

From every deposition cycle, several samples were analysed, each from a different position on the substrate holder and thus showing a change in their composition and slightly in their thickness.

The magnetic properties were measured by VSM and a torque magnetometer. The structure of the layers was analysed by X-ray diffraction (Co-K\(\alpha\) and the so-called rocking curve was measured. TEM analysis was performed in order to determine crystallinity and grain size.

**ABSTRACT**

The co-evaporation technique has been used for deposition of Co-Cr layers. Deposition has been done under intermediate angle of incidence of opposing vapour streams. The layers showed a single phase hcp poly-crystalline structure. The (002) plane turned out to be tilted towards the direction of the Co source. The layers showed good perpendicular magnetic behaviour although the magnetic anisotropy axis was also inclined towards the Co-source because of the opposing angle of incidence for Co and Cr atoms, a process-induced segregation takes place which causes a relative high coercivity also at low process temperatures. A simple model for the segregation effect can explain the relation between the existence of a non-magnetic region and an increased coercivity of the Co-Cr film.
It was found that in the LP, the peak of the rocking curve was shifted over an angle \( \theta_p \) from the peak that occurred in the TP. Also a lower peak value was measured in the TP. This shift in the longitudinal plane is caused by a preferential inclination of the [001] crystal axis towards the Co-source. The shift angle at \( d=400 \text{nm} \) is \( \theta_p=1^\circ \) independent of the angle of incidence but seems to depend on the layer thickness (\( \theta_p=5-7^\circ \) for \( d<200 \text{nm} \)).

Because of the oblique incidence, we might expect a canting \( \beta \) of the columns from the perpendicular direction according to [11]:

\[
\beta = \arctan \left( \frac{1}{\tan \theta_p} \right)
\]

In our case the canting will be towards the direction of the Co source because most of the material in the layer is Co. Generally \( \beta \) is larger than the observed shift in the rocking curve. Unfortunately we have not yet performed an observation of the cross-sectional view by SEM in order to observe the actual angle of canting of the columns. However, on the basis of other experiments, we can obtain information on this canting. This will be discussed in combination with the results of our torque measurements.

Concerning the material properties of the layers, we can summarize a polycrystalline single-phase hcp structure with an orientation which is preferentially inclined through a number of degrees towards the direction of the incidence of the Co atoms.

\[ M_1 = 339 \text{ kA/m} \]
\[ H_{ci} = 60 \text{ kA/m} \]
\[ H_{c} = 24 \text{ kA/m} \]

\[ T_p = 125^\circ \text{C} \]
\[ \delta = 150 \text{ nm} \]

Fig. 3 Typical M-H loop of the Co-Cr layers

**Magnetic properties**

In Fig.3, a typical M-H loop of the deposited layers is shown. A good perpendicular magnetic behaviour is obtained. The inplane coercivity \( H_{ci} \) of the layers is 25-35 kA/m. Fig.4 shows the perpendicular coercivity \( H_{ci} \) versus saturation magnetization \( M_s \). The thickness of these samples is near 200 nm and deposition was carried out at several values of \( T_p \). At constant \( M_s \), a higher \( H_{ci} \) is observed for increasing \( T_p \), as is usually found for Co-Cr layers. A comparison is shown of \( H_{ci} \) values of Ouchi[12] for 1 \( \mu \text{m} \) sputter-deposited layers at \( T_p=200^\circ \text{C} \) and those estimated from data of Sugita[4] for 0.15 \( \mu \text{m} \) evaporated at \( T_p=160^\circ \text{C} \). It can be seen that a clear difference between the two methods exists in the high \( M_s \) region. In the former a maximum is found near \( M_s=700 \text{ kA/m} \) while in the latter this maximum occurs at lower \( M_s \) values. This will be due to the difference in energy of the vaporized atoms which is much higher in sputtering. Increasing \( T_p \) might partially compensate for the lower energy level at evaporation. However, for our co-evaporated samples, already at low \( T_p=50^\circ \text{C} \), an increased \( H_{ci} \) is observed. A correlation between this result and the existence of a "Co-rich" part in the Co-Cr layer can be found if we observe the relation between \( M_s \) and the mean Cr concentration \( C_d \) as was measured by XRF. (see fig.5).

At higher Cr contents, a deviation from the bulk \( H_{ci} \) value is measured. This deviation is more pronounced at higher \( T_p \). Already at \( T_p=50^\circ \text{C} \) a considerable volume of "Cr-rich" Co-Cr must exist. This cannot only be a segregation by ad-atom diffusion during film growth. Therefore a process-induced segregation must also exist. This will be caused by shadowing effects during deposition under the opposing intermediate oblique incidence. A good treatment of such type of problem can be found in [13] showing these effects to occur in Fe-Cr layers deposited at varying angles of incidence.

The relation between the existence of this segregated state and the occurrence of an increased coercivity of the Co-Cr layers could be explained by a model introduced by Andrä and Dannan[14]. This model is based on a grain boundary with increased Cr content which forms pinnig points for domain-wall motion at low peak concentration and a non-magnetic boundary resulting in particulate behaviour at peak concentrations higher than 25-27 at% Cr.

We tried to fit the model, using (2) for the Cr distribution in a column, to our measured relation between \( C_d \) and \( M_s \).

\[
C(d)=C_{c}(C_{d}-C_{c})e^{-(d-D)^{2}/2R^2} \quad (0<d<D) \quad (2)
\]

with \( C_{c} \) = column centre Cr concentration, \( C_{d} \) = Cr concentration at column boundary, \( D \) = column diameter, \( W \) = measure for the column boundary width.

We modified the model to a better fit to the results of Sugita[6]. We assume \( C_{c} \) to depend only on \( C_{d} \) and a constant \( S_p \), denoting the degree of segregation. Further we assume \( W/D \) to be constant for a certain \( C_{d} \), independent of the degree of segregation. This can be understood from the fact that at higher \( T_p \) generally both segregation (and thus \( W \)) but also the column size \( D \) increase. We assume \( W \) to be proportional to the potential amount of Cr that can segregate: \( C_{d} \) \( \times \) D. Thus:

\[
C_{d} = S_{p} \times C_{c} \quad (3) \quad \text{and} \quad W/D = W/D \times C_{c} \quad (4)
\]
The fitting parameter $W_0/D = 0.005$ will give a good fit with Sugita's results. We only have to change the relative peak concentration in this simple model in order to fit it to our $M_0(Go)$ curve. A reasonable agreement is obtained at $C_m = 2.5-3.5 \% C_r$, as is shown in Fig.6. It is clear in this figure that a significant deviation from the line of homogeneous distribution of Cr starts at a value $C_m=C_{crit}$ which depends on the point when the peak concentration exceeds 27 at%Cr and thus a non-magnetic boundary is introduced. In most of the cases $C_{crit}$ is near 15 at% Cr. However, also at $C_m>C_{crit}$, the segregation might exist but will not lead to an easily observable deviation from the line for bulk saturation magnitisation.

In other words, $C_{crit}$ will indicate the start of the formation of the non-magnetic boundary and thus also the change in the reversal mechanism from domain-wall pinning into particulate behaviour. In our case, $C_{crit}=12-17\%$ Cr which is also near the point where an increased $H_{ci}$ is observed (Fig.4) as could be expected from a more particulate behaviour.

Magnetic Anisotropy

In magnetic layers, deposited under oblique incidence, a magnetic anisotropy axis is found which is rotated towards the tilted columns[15]. Although our layers showed a typical magnetic behaviour of a layer with a perpendicularly orientated magnetic anisotropy, an inclined magnetic anisotropy exists. This could be detected by the torque magnetometer and using the method of Swaving e.a.[16] to calculate the anisotropy constant and the direction of the anisotropy axis.

For samples with $d > 200$ nm we found a $K_p=15 \times 10^4 J/m^2$ (with $K_p=K_{an}/2d_h$). The angle of the anisotropy axis towards the film normal $\gamma_0$ depends on the angle of incidence $\alpha$ on the sample. In Table I the results are given together with the values of the other important directions which have been found. These samples were deposited at $T_s=125^\circ C$ and $d=400$ nm.

<table>
<thead>
<tr>
<th>Substrate position</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma_0$</th>
<th>$\gamma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>21°</td>
<td>11°</td>
<td>9-11°</td>
<td>9°</td>
</tr>
<tr>
<td>II</td>
<td>26°</td>
<td>14°</td>
<td>9-11°</td>
<td>14.5°</td>
</tr>
<tr>
<td>III</td>
<td>31°</td>
<td>17°</td>
<td>9-11°</td>
<td>16°</td>
</tr>
</tbody>
</table>

It can be seen that the anisotropy direction moves or less coincides with the expected column cation. This would imply a significant contribution of shape anisotropy to the magnetic anisotropy. However, the appearance of the shift in the rocking curve also indicates a small rotation of the crystal axis towards the column direction and thus the magnetic crystal anisotropy will also be rotated although this will not completely explain the full rotation of the magnetic anisotropy axis. We planned to further investigate this.

**CONCLUSION**

The deposition by co-evaporation under intermediate oblique incidence and opposing vapour streams has some significant influences on the properties of Co-Cr layers. In our investigations we found, besides the usually found properties, some process induced effects: - a preferential inclined orientation of the single phase hcp structure towards the canted column.

- a rotation of the magnetic anisotropy axis to the canted column.

Both effects might be related to each other but the rotation of the crystal axis will not fully explain the rotation of the magnetic anisotropy axis. This might indicate that a shape anisotropy term will also occur. Notwithstanding this inclined anisotropy, the layers showed good perpendicular behaviour with high anisotropy energy. Based on the magnetic measurements we found:

- at relative low process temperature we could obtain a high $H_{ci}$ (upto 70 kA/m) in the $H_s$ range 200-500 kA/m.

This is due to a process-induced segregation caused by shadowing during deposition.

- By fitting a simple model for the Cr distribution to the measured $M(Go)$ curve, a $C_{crit}$ can be defined at which point a non-magnetic boundary between magnetic Co-Cr parts is formed. This $C_{crit}$ correlates with the increase of $H_{ci}$ vs $H_s$ thus indicating the relation between the occurrence of this non-magnetic boundary and a particular like behaviour of the magnetic reversal mechanism.

In general, these layers deposited under intermediate oblique incidence showed good perpendicular magnetic properties which might be improved by optimized geometrical design.

**ACKNOWLEDGEMENT**

This work was sponsored by the European Community and by Leybold Heraeus GmbH, Hanau, FIG.

**LITERATURE**