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To cite this version:
K. Steenbeck. ON THE INFLUENCE OF ELECTROSTATIC CHARGING ON THE MAGNETIC AND OTHER PHYSICAL PROPERTIES OF THIN METALLIC FILMS. Journal de Physique Colloques, 1971, 32 (C1), pp.C1-1096-C1-1101. <10.1051/jphyscol:19711391>. <jpa-00214431>

HAL Id: jpa-00214431
https://hal.archives-ouvertes.fr/jpa-00214431
Submitted on 1 Jan 1971

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ON THE INFLUENCE OF ELECTROSTATIC CHARGING  
ON THE MAGNETIC AND OTHER PHYSICAL PROPERTIES  
OF THIN METALLIC FILMS

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Résumé. — Une charge électrostatique permettant de modifier les propriétés électriques et optiques et la supraconductivité de couches minces métalliques, on a essayé de faire varier de même l’aimantation à saturation de couches minces ferromagnétiques : la couche forme l’une des armatures d’un condensateur placé dans une balance de torsion et le couple mesuré varie suivant la tension appliquée aux bornes du condensateur. Ces variations du couple sont attribuées à des variations de l’aimantation liées à un excès ou un défaut d’électrons dans le métal. Pour une charge élémentaire la contribution au moment magnétique mesuré est de l’ordre de $1/2\mu_B$.

Abstract. — Electrical, superconducting and optical properties of thin metal films can be influenced by electrostatic charging. In the same way attempts have been made to change the saturation magnetization of ferromagnetic films, which was measured e. g. with the torque method. Using the film as one plate of a capacitor torque changes are measured for different voltages. The torque changes are assumed to be caused by magnetization changes due to an altered electron concentration of the metal. The contribution of one unit charge to the magnetic moment was estimated to ca. $1/2\mu_B$.

Several electronic qualities of metals change systematically with the ratio of the number of electrons to the number of metal atoms, commonly varied by substituting some of the atoms by others with different valence. This work reports on experiments in which the electron concentration is examined to change by electrostatic charging of thin metal films. Our main concern is the problem, wether the electrons induced at the surface of a ferromagnetic metal take part in the ferromagnetic coupling or not, and whether these electrons produce a measurable change in the magnetic moment of the sample.

I. The metal surface in the electric field. — For metals, too, an electric field penetrates through the surface to a certain depth of the metal interior thus changing the spatial distribution of the electric charge. The depth of penetration can be estimated applying Fermi-Dirac statistics for metal electrons [1]. As follows from the law of equality of the chemical potential at every point of a conductor and from the Poisson equation the charge distribution is proportional to $\exp(-x/d)$ where the coordinate $x$ is directed into the interior of the metal and $d = \sqrt{E_F/6\pi g e_0^2}$ means the screening length of the electric field ($^1$). For Ni we get $d \approx 0.5 \text{ Å}$, that means practically the whole charge is stored in the outer atomic layer of the metal sample. Calculations of the capacity of thin film condensors [2] and measurements of light reflection on metals [3] confirm this conception.

The altered charge density in the outer atomic layer means an altered probability of the position for electrons in this region. In this case we need not think of the electrons to be particles localized at the surface but they should be supposed to interact as electron gas with the interior of the metal. Thus in a negatively charged metal we can expect the spins of the added electrons to be coupled with the magnetization of the inner atom layers.

At the metal surface the electric field produces a change of the Fermi energy due to a bending of the energy bands which are more or less being filled. Leaving aside other effects let us consider the influence of this Fermi energy shift on the magnetization of the 3 d metals. Figure 1 schematically shows the structure of energy bands of bulk Ni with the corresponding positions of the Fermi levels $E_F$ for Cu and Fe. Because of exchange interaction the two bands $3d^+$ and $3d^-$

(1) $E_F$ = Fermi energy of the electrons, $g$ = density of carriers, $e_0$ = electric unit charge.

![Fig. 1. — Filling of the energy bands in Ni (schematic). The dotted lines correspond to the Fermi levels for Cu and Fe disregarding different shifts of the 3d-bands for different metals. $E =$ energy; $g =$ number of electrons per unit energy.](image-url)
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for the two spin directions (+, −) are shifted with respect to the energy axis. For Cu (11 electrons in 3 d + 4 s states) both sub bands are filled up, for Ni (10 electrons) \( E_F \) crosses the 3 d − band only, and for alloys with less than 8.5 electrons in 3 d and 4 s states (e.g. Fe-Cr) the Fermi level runs through both subbands. With decreasing number of electrons the spontaneous magnetization first increases (Ni) and then decreases (Fe-Cr). This dependence corresponds to the experimentally found behaviour of the Slater-Pauling curve [4].

Because of the overlap of the 3 d and 4 s energy bands we can assume that side by side with a filling of the conduction band also a filling of the 3 d-band will take place. In this case for Ni we expect a decrease of the magnetization because the 3 d + band is filled. For metals with unoccupied states in the two 3 d sub-bands the sign of a magnetization change \( \Delta M \) should depend on the difference of the density of states at the Fermi level \((g^+ - g^-)\). In the simplest case we can assume \( \Delta M \approx \Delta E_F (g^+ - g^-) \approx \Delta n(g^+ - g^-)/(g^+ + g^-)\), where \( \Delta E_F \) means the change of the Fermi level due to the change \( \Delta n \) of the number of electrons.

On investigating experimentally charged metal surfaces other effects can possibly be expected to outway the influence of the Fermi level displacement. Little is known about

1. structure and stoichiometry of the metal surface layers,
2. differences in the electronic band structure \( a \), at the metal surface and \( b \), in the bulk material.

For instance all experiments imply that the induced charge is in the metal and not in adjacent conducting impurity layers.

Moreover, to some extend the electrons can occupy surface states of the metal.

Noticeable quality changes of metal films can be obtained only with great electric charge densities. In order to alter the ratio of the number of stored unit charges and the number of metal atoms by \( \Delta n/N_A = 10^{-4}\) in a 100 Å thick metal film, a charge density variation of 1-2 \( \mu C/cm^2 \) is necessary. Table I gives a summary of electric charging methods used up to now for investigating thin metal films. In method 1 the amount of applicable charge density is limited by the spontaneous polarization of the ferroelectric substrate or its piezoelectric deformations. Using the electrolyte method [3] it is possible to obtain large fields at the sample surface with small applied voltages \((\approx 1 \text{ V})\) because a dipole layer is formed at the electrolyte interface. The electrolyte and the voltage have to be selected with a view to avoid chemical reactions of the metal. Also at the interface of a metal with an adjacent other solid it is possible to get a space charge layer, because of different work functions. Semiconductor films loading the metal negatively can be evaporated as well as others which take electrons from the metal. Method 5 is based on oxidation of metals at temperatures below 40 °K. In this procedure a thin oxide film of definite thickness is formed having a layer of negative oxygen ions on its surface. These ions act like a capacitor electrode and cause a strong electron depletion of the metal (e. g. Al, In, TI, Sn, Pb [25]).

**Table I**

<table>
<thead>
<tr>
<th>Method</th>
<th>Configuration</th>
<th>( \frac{\sigma}{\mu C/cm^2} )</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Capacitor</td>
<td>( f/\text{air/e} )</td>
<td>0.1</td>
<td>[5]</td>
</tr>
<tr>
<td>2. Ferroelectric</td>
<td>( f/\text{glass/e} )</td>
<td>0.1-0.7</td>
<td>[6, 7, 8, 9, 10]</td>
</tr>
<tr>
<td>substrate</td>
<td>( f/\text{BaTiO}_3/e )</td>
<td>0.03-1</td>
<td>[11, 12]</td>
</tr>
<tr>
<td>3. Blocking contact</td>
<td>( f/\text{TiC} )</td>
<td>26.4</td>
<td>[13, 14, 15]</td>
</tr>
<tr>
<td>metal/electrolyte</td>
<td>( f/\text{Te} )</td>
<td>2.5</td>
<td>[16, 17]</td>
</tr>
<tr>
<td>4. Blocking contact</td>
<td>( f/\text{KCl} )</td>
<td>200</td>
<td>[18, 19, 20, 21]</td>
</tr>
<tr>
<td>metal/solid</td>
<td>( f/\text{KOH} )</td>
<td>100</td>
<td>[22]</td>
</tr>
<tr>
<td>5. Low temperature oxidation</td>
<td>( f/\text{SnS} )</td>
<td>200</td>
<td>[23, 24, 25, 26, 27]</td>
</tr>
</tbody>
</table>

Besides the above mentioned methods gasadsorption on clean metal surfaces can also produce a charge exchange with the metal. However, in such experiments the observed effects often are due to the metal forming a chemical compound [16].

II. THE INFLUENCE OF ELECTROSTATIC CHARGING ON NON-MAGNETIC QUALITIES OF METALS. — 1. CHANGE OF ELECTRICAL CONDUCTIVITY. — Recent measurements have clearly shown, that the conductivity of thin metal films can be influenced by electrostatic charging. Table II shows typical experimental values of resistivity changes for different metal films. Not considering an influence on the carrier mobility we expect a correlation between the sign of the resistivity change and the sign of the Hall constant. So the n-type metals Au, Ag and Gd yield a decrease of the resistivity with negative charging and metals of prevailing p-type conductivity an increase in resistivity. However, this correlation was not always found [9], which indicates the importance of the carrier mobility.

**Table II**

<table>
<thead>
<tr>
<th>Metal Method</th>
<th>( \frac{N_A}{N_e} )</th>
<th>( \frac{\Delta R}{R} )</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>1</td>
<td>−2</td>
<td>[6, 7]</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>−0.5</td>
<td>[9]</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>−120</td>
<td>[13]</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>−25</td>
<td>[13]</td>
</tr>
<tr>
<td>Ag</td>
<td>1</td>
<td>0.1</td>
<td>−0.1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>−2</td>
<td>[15]</td>
</tr>
<tr>
<td>Ni</td>
<td>1</td>
<td>0.2</td>
<td>+0.1</td>
</tr>
<tr>
<td>Sn</td>
<td>1</td>
<td>0.3</td>
<td>−0.3</td>
</tr>
<tr>
<td>In</td>
<td>1</td>
<td>+1</td>
<td>[6]</td>
</tr>
<tr>
<td>Bi</td>
<td>1</td>
<td>−4</td>
<td>[6]</td>
</tr>
<tr>
<td>Sb</td>
<td>2</td>
<td>neg.</td>
<td>[13]</td>
</tr>
<tr>
<td>Gd</td>
<td>2</td>
<td>pos.</td>
<td>[13]</td>
</tr>
<tr>
<td>Ge, Te</td>
<td>2</td>
<td>neg.</td>
<td>[24]</td>
</tr>
<tr>
<td>TI</td>
<td>1</td>
<td>neg.</td>
<td>[25]</td>
</tr>
</tbody>
</table>

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As a rule a proportionality between the relative resistivity change and the variation of the electron-atom ratio was found

$$\frac{\Delta R}{R} = C \frac{\Delta n}{N_a}$$

(1)

where $C$ depends on the metal and sample preparation and is of the order $C \approx 1$.

The dependence of resistivity changes on film thickness $D$ is hard to predict because it is a function of where the induced charges are in the film as well as of the scattering mechanism. Stadler [13] has found for gold films

$$\frac{\Delta R}{R} \propto \frac{1}{D}$$

(2)

in the range $100 \text{ Å} \leq D \leq 1000 \text{ Å}$. This is also to be expected if the induced charges were distributed uniformly throughout the film, thus changing the carrier concentration without affecting the mobility. Theoretical investigations on the conductivity changes are treated in [28, 29, 6, 7, 9].

2. Change of the Hall effect. — Panchenko [10] has measured changes of the Hall constant of about $\Delta R_{H}/R_H \approx 0.5$ due to electrostatic charging of Ni thin films ($D \leq 50 \text{ Å}$). The induced electron concentration corresponded to $\Delta n/N_a = 10^{-4}$ electrons per Ni atom. In the case of Ni the Hall constant is

$$R_H \propto \sigma^{-2} (n_e \mu_e^2 - n_L \mu_L^2)$$

where $\sigma = e_0 (n_e \mu_e + n_L \mu_L)$ is the conductivity, $n_e$ and $n_L$ denote the density of electrons and holes, respectively, and $\mu_e$ and $\mu_L$ their mobilities. Panchenko interprets the effect in terms of a decrease of the electron mobility in the negatively charged film due to the charged electron scattering mechanism.

3. Change of the superconducting critical temperature. — The change of superconducting critical temperature $T_c$ of thin metal films due to electrostatic charging was first verified by Glover and Scharill [8] in 1960 and later confirmed with different charging methods (see table III). As in the case of conductivity changes the relation $\Delta T_c/T_c = C \Delta n/N_a$ was found to be valid with $C$ in the order of 1. Also, the thickness dependence $\Delta T_c/T_c \propto 1/D$ was measured [23, 25]. As long as the film thickness is smaller than the spacing between the electrons of a Cooper pair, the $T_c$ change will be the same as for a charge density evenly distributed over the total film volume. Theoretical investigations have been carried out by [31, 32, 24].

4. Change of the optical reflectivity. — The electroreflectance method, commonly used for investigating semiconductors has been applied to metals also. With this method a modulation of reflectivity due to an electric field perpendicular to the metal surface is measured for different photon energies. The charging methods 2 [13, 14] and 3 [18, 21] have been used to produce changes in reflectivity of 0.2 % for Au [14, 18, 21], 0.7-3 % for Ag [13, 18, 19, 21] and about 0.5 % for Cu [13]. The electro reflectance spectra are closely correlated with the structure in the reflectivity of each metal. For Au films [14] the essential structure in electroreflectance was found to be the same for different charging methods. These results indicate, that the induced charges in the metal are able to change the reflectivity by the same order of magnitude as the far thicker charged layers in semiconductors. This may mean, that the reflectivity mainly depends on the number of electrons/cm$^2$, not on their penetration depth.

III. On the influence of electrostatic charging on the magnetization of thin metal films. — The problem, whether the magnetic moment of a thin ferromagnetic metal layer can be influenced by electric charging has been experimentally investigated by means of the torque method [15, 33, 34], ferromagnetic resonance [35] and $rf$ susceptibility measurements [22].

1. Measurements with ferromagnetic resonance. — In 1968 Frait [35] has tried to observe magnetization changes by electrostatic charging of magnetic films. He placed thin permalloy films (78 % Ni, 200-2 000 Å) on dielectric and ferroelectric substrates on the resonance cavity wall and measured the expected shifts of ferromagnetic resonance field, applying static voltage to such condensors. By this method changes in the order of $10^{-4}$ can be detected, but there were no reproducible effects with electric field intensity up to $2 \times 10^4 \text{ V/cm}$.

2. Measurement of the $rf$ magnetic susceptibility. — Last year Ishibashi et al. [22] measured changes of the $rf$ magnetic susceptibility of Fe-Ni films electrically charged with the electrolyte method. In these experiments the variation of resonance frequency of an oscillator was determined, the inductive coil of which contained the metal sample as a core. The coil was wound around a thin glass tube holding the evaporated metal film, a KOH solution and a Pt second electrode. For different voltages at the electrode the resonant frequency was compared to that of a dummy oscillator and the beat frequency was counted. Denoting the
frequency change due to electrostatic charging with $\Delta f_e$ and that due to sample removal with $\Delta f_s$, the reported results are

<table>
<thead>
<tr>
<th>Metal</th>
<th>57FeNi</th>
<th>57Fe6Ni</th>
<th>20Fe6Ni</th>
<th>Ni</th>
<th>Pd</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta f_e/\Delta f_s$</td>
<td>10$^{-4}$</td>
<td>3.2</td>
<td>1.0</td>
<td>2.3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The authors interpret the results in terms of a shift of the Fermi level due to the added or removed electrons.

The order of magnitude of $\Delta f_e/\Delta f_s$ agrees with the change in the electron atom ratio, but there is some uncertainty as to the interpretation of the susceptibility changes.

1) Measurements are possible only with low magnetic field intensity. The susceptibility does not only depend on the saturation magnetization but is strongly influenced by changes of magnetic anisotropy, mainly of internal strains in the films with magnetostriction not equal to zero.

2) Diffusion of ions, e.g. of hydrogen from the electrolyte into the metal cannot be excluded. Such diffusion can lower the magnetization and induce strains in the metal surface layer.

3) Assuming the Fermi energy shift to be the cause of $\Delta f_e$, then we should expect the greatest effect in Ni, where only one energy sub-band has empty states. However, for Ni $\Delta f_e = 0$ was found and for the alloy richest in Ni the susceptibility increased with negative charging.

3. MEASUREMENT WITH THE TORQUE METHOD. — We have investigated thin ferromagnetic films of Ni and Fe-Cr, which were electrically charged by the ferroelectric method. For a comparison nonferromagnetic films of Au, Ag and Cu were also used.

The films were evaporated on flat discs of BaTiO$_3$ ceramic with counter-electrodes of Al. Each specimen forms a capacitor the Al electrode of which is electrically grounded and the film is connected alternately with the electrical potentials $+U$, $0$, $-U$, $0$ switched every 8.5 s. The sample is suspended in a torque meter with both film normal and magnetic field $H$ in horizontal direction (Fig. 2). In the homogeneous field $H$ a torque is exerted on the magnetic film, which depends on the shape anisotropy of the sample and the angle $\varphi$ between the film normal and the magnetic field direction. $H$ is much greater than the anisotropy field. Therefore the film is magnetically saturated and the torque $L$ is

$$\frac{1}{V} L = \left(\frac{1}{2} N M^2 + K'\right) \sin 2 \varphi$$  \(3\)

where $V$ = volume of the film, $N$ = demagnetizing factor. The effective anisotropy constant is mainly determined by the film magnetization $M$. Moreover it includes the contribution $K'$ of other superimposed uniaxial anisotropies. If these anisotropies do not depend on the sign of the electric charging ($\Delta K' = 0$) then the magnetization changes can be determined by measurements of the variations of the maximum torque $\Delta L$.

The amplitudes of the torque curves $\widehat{L}$ were measured for different states of electric charging (+, −, 0) of the magnetic film. If $\widehat{L}_l = \widehat{L}(\varphi_l)$ then the expression

$$\Delta L = 4 \sum_{\varphi_l} \left| \widehat{L}_l(-\varphi) \right| - \left| \widehat{L}_l(+\varphi) \right|$$  \(4\)

is a measure of the change of magnetization of the film by electrostatic charging (see Fig. 3). $\Delta L > 0$ means that with negative charging the magnetic moment is greater than with positive charging.

The exact relation between the magnetization change due to electric charging and $\Delta L$ depends on the model used. However, with a simple model we can estimate the order of magnitude expected for the torque $\Delta L$. Let us imply that the electric charge $\Delta q$ is distributed homogeneously in a small volume $v$ of the magnetic film and this volume acts like an independent magnetic film without coupling to the remaining part $V - v$. Then $\Delta L$ is connected with a change $\Delta m$ of the magnetic moment of this volume $v$ and we get

$$\Delta L = \Delta \left(\frac{1}{2} N M^2 v\right) = \Delta \left(\frac{1}{2} N \frac{m^2}{v}\right) = N M \Delta m.$$  \(5\)

---

Fig. 2. — Experimental arrangement for torque measurements. $T$ = torsion wire, $U$ = voltage, $S$ = metal film, $Al$ = counter electrode, $D$ = substrate (BaTiO$_3$ ceramic), $Z$ = magnetic field.

Fig. 3. — Torque curve $L(\varphi)$ (schematic) for a Ni film at the potential $+U$ and $-U$, respectively. $L$ = torque, $\varphi$ = angle between the normal of the film and the magnetic field direction, $\Delta L < 0$. Orders of magnitude : $\Delta L \approx 10^{-3}$ dyn.cm, $\widehat{L} = 1...10$ dyn.cm.
The depth of charge penetration in the film and thus the value of \( \nu \) are not important in this model. Assuming that each electron injected by electric charging contributes one Bohr magneton \( (\mu_B) \) to \( \Delta m \), then \( |\Delta m| = \mu_B \Delta q / 1.6 \times 10^{-19} \, \text{C} \), where \( \Delta q \) ist he electric charge variation. For Ni films with \( M = 485 \, \text{G} \), \( N = 4 \pi \) and \( \Delta q = 20 \, \mu\text{C} \) we get

\[
|\Delta L| = 7.0 \times 10^{-3} \, \text{dyn.cm}.
\]

In our experiments the films were evaporated at a pressure of \( \approx 10^{-5} \, \text{Torr} \) and at a substrate temperature of 160 °C on BaTiO₃ ceramic discs of 18 mm \( \varnothing \), which had been mechanically polished and heated in a vacuum at 330 °C before film evaporation. The polarization of the film substrates at the maximum voltage of \( \pm 300 \, \text{V} \) was \( \pm 4 \, \mu\text{C/cm}^2 \). The magnetic field intensity was 8.1 kOe.

Figure 4a-c shows typical results for the dependence of the torque \( \Delta L \) on the charge difference

\[
\Delta q = |C \Delta U|,
\]

where \( C = \text{capacity of the sample} \) and \( \Delta U = \text{potential difference between the negative and positive charged film} \). These curves can be explained on the assumption that the magnetic moment for Ni films decreases and for Fe-Cr films increases with increasing electron concentration. The torque \( \Delta L \) is proportional to the charge difference \( \Delta q \). For the nonferromagnetic metals Ag, Au and Cu \( \Delta L \) remains zero, indicating no magnetic effect of the induced charges in these films.

We should expect that a magnetization change in our films is a surface effect, that means \( \Delta L \) must be independent on film thickness \( D \) beyond a critical value \( D_0 \). This was confirmed by measurements of Ni films of various thickness (see Fig. 5). The value \( D_0 = 500 \, \text{Å} \) does not surprise because of microscopic surface roughness of our mechanically polished ceramic discs. Additionally we can assume that the thin metal films have an island structure.

We can compare the saturation value

\[
|\Delta L| = (4.3 \pm 0.5) \times 10^{-3} \, \text{dyn.cm}
\]

for Ni with the calculated upper limit of

\[
|\Delta L| = 7 \times 10^{-3} \, \text{dyn.cm}
\]

and find satisfying agreement. With the model used in this calculation and the measured values of \( \Delta L \) for 400 Å thick films of Ni and Fe-Cr we get the result, that the contributions of the induced charges to the magnetic moment of the films are about

- 0.6 \( \mu_B \) per added electron in Ni,
+ 0.3 \( \mu_B \) per added electron in Fe-Cr.

That means relative changes of the magnetic moment

![Graph](attachment:image.png)
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of these films in the order of \( |\Delta n/m| = 10^{-4} \) at the charge difference \( q = 20 \mu C \). Because of our simplified relation (5) between the torque \( \Delta L \) and the magnetic moment change the numerical results should not be overestimated. However, the sign and the order of magnitude of the evaluated magnetization change agree with the positions of Ni and Fe-Cr in the Slater-Pauling curve.

To measure the torque \( \Delta L \) several perturbing effects had to be eliminated.

1) In order to compensate the main part of the whole torque \( \vec{L} \) a second magnetic film not influenced by charging was fixed perpendicular to the sample in the magnetic field.

2) Electrostatic and electrodynamic torques could be completely neglected. This was examined by measurement without magnetic field and by reversing the field direction, respectively.

3) The influence of electrostrictive deformations of the ceramic substrates had to be noticed. Using a microscopic method curvatures and radial deformations of the BaTiO\(_3\) discs were found. The bending was avoided by sticking together two discs in each case. The radial electrostrictive deformations of each sample were found to be independent on the sign of the applied voltage. These deformations cause changes of the torque curve amplitude by \( \Delta L \) which for two reasons can be isolated from the torque \( \Delta L \) : First, \( \Delta L \) does not depend on the charging sign (the relation found was \( \Delta L \propto (Ag)^2 \)). Second, \( \Delta L \propto \) film thickness. By the magnetostRICTive torque \( \Delta L \) the electric polarization applicable to the Ni film specimens without distorting the measurement of \( \Delta L \) was limited to about 4 \( \mu \)C/cm\(^2\).

4. After-effects of the charged specimens required exact timing of all measurements.

In order to test whether the induced charges are in the metal film or possibly invaded surface layers of the ceramic substrate, measurements of the electrical resistivity of Ni and Ag films have been carried out for different states of electric charging [15]. Indeed, an electric field effect was detected in the same specimens also used in our magnetic measurements. The results of electrical resistivity measurements not described in detail here are shown in Table II, line 6 and 7.

Conclusion. — Following the results of the above torque measurements most probably it is possible electrostatically to affect the magnetic moment of a ferromagnetic thin metal film. The variations obtained up to now correspond to about 5 % of the magnetic moment of a Ni monolayer. However, with charge densities in the order of 100 \( \mu \)C/cm\(^2\) attainable e. g. in thin oxide layers or in electrolytic interfaces we can expect one or more atomic layers to become non-magnetic. On principle it should be possible to influence the exchange coupling between adjacent films as well as the Curie temperature of very thin magnetic films.

Further experiments must be carried out in order to measure the magnetization change quantitatively. For that purpose, e. g. a magnetic balance with strong magnetic field directed in the film plane is suitable. For a monolayer film of 1 cm\(^2\) area with the magnetization of bulk Ni and magnetic field gradient 10\(^5\) Oe/cm the force is 10\(^{-5}\) dyn. For measurements of the magnetization of magnetic thin films a balance with a sensitivity of 10\(^{-5}\) dyn was already used [36]. The advantage of this measuring method is directly to determine the magnetic moment independently of a magnetic anisotropy.

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