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Dependence of Magnetic Anisotropy in Thin Ni-Fe Films

On Heat Sink and Annealing Temperatures

by

Louis Henri Jacomme

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CHAPTER I

Design of a Magnetometer

I. 1 Historical Background and Literature

Many of the techniques used in the construction of magnetometers have been known for a long time. However it is only recently that, on the one hand, the introduction of fused silica torsion fibers has allowed the measurement of very small forces such as those resulting from the interaction of a thin Fe-Ni film with a magnetic field and that, on the other hand, the introduction of electronics has rendered the instrument automatic by making it self-balancing. Humphrey and Johnston report on the use of these technologies, and at the same time explain the evolution of the magnetometer into a truly sensitive instrument well suited for thin film research.

I. 2 Fused-Silica Suspension

A few of the advantages of fused silica are listed below:

1. Low thermal expansion coefficient. \((\alpha = 52 \times 10^{-6} \text{ } ^\circ\text{C}^{-1} \text{ compared to } 9 \times 10^{-6} \text{ } ^\circ\text{C}^{-1} \text{ for Invar, and } 10.1 \times 10^{-6} \text{ } ^\circ\text{C}^{-1} \text{ for steel.})\)

2. No hysteresis: If one defines the coefficient of thermal hysteresis for a sample of length \(l\) as \(\beta = \frac{\Delta l}{l(t_2-t_1)}\) the sample being heated from \(t_1\) to \(t_2\) and then cooled to \(t_1\), and \(\Delta l\) being the residual difference in length.

\[
\text{Then for quartz } \beta = 5 \times 10^{-9} \text{ } ^\circ\text{C}^{-1} . \quad \text{In contrast for Invar (36\%Ni + 64\%Fe) } \beta = 100 \times 10^{-9} \text{ } ^\circ\text{C}^{-1} .
\]

3. High melting point \((1200^\circ\text{C}).\)

4. Elastic properties.
If one considers a rod of section \( \Sigma \) and length \( l \) and apply a stress \( S_n \) perpendicular to \( \Sigma \) then one can write:

\[
\frac{1}{\Sigma} \frac{\Delta l}{\Delta S_n} = \frac{1}{Y} \quad (Y = \text{Young's modulus})
\]

For a fiber of 50\( \mu \)m

\[
Y = 5.2 \times 10^{11} \text{ dynes/cm}^2 \quad (2)
\]

For a fiber of 30\( \mu \)m

\[
Y = 7.1 \times 10^{11} \text{ dynes/cm}^2 \quad (3)
\]

For these numbers see H. V. Neher and Reinkober.

One is actually more interested for the present case in the tangential coefficient of elasticity which is the inverse of the rigidity modulus \( Z \).

\( l \) = length of the rod

\( r \) = radius of the rod

\( L \) = applied torque

\( \phi \) = angle of twist

\( S_t \) = tangential stress

Then

\[
\frac{1}{2l} \frac{\Delta (\phi r)}{\Delta S_t} = \frac{1}{Z} \quad \text{where} \quad S_t = \frac{L/r}{n r^2} = \frac{L}{n r^3}
\]

For a fiber of 50\( \mu \)m

\[
= 3.2 \times 10^{11} \text{ dynes/cm}^2
\]

For a fiber of 30\( \mu \)m

\[
= 3.5 \times 10^{11} \text{ dynes/cm}^2
\]

The torsion constant of the fiber can be obtained immediately.

One can write

\[
\frac{1}{Z} = \frac{1}{2l} \frac{\phi r}{L/n r^3} = \frac{n}{2l} \frac{\phi r^4}{L}
\]

Therefore

\[
k = \frac{L}{\phi} = \frac{n}{2l} Z r^4 \quad (1)
\]

For example, according to Braddock, the torsion constant of a fiber 1 cm long and 10\( \mu \)m in diameter is \( 4100 \times 10^{-5} \) dynes-cm. In contrast, the torsion constant for a fiber 1 cm long and 5\( \mu \)m in diameter is only \( 325 \times 10^{-5} \) dynes - cm. On this basis one would expect a torsion constant for a 1 cm
long, 10μ in diameter fiber of \(2^4 \times 325 \times 10^{-5}\) dynes-cm = 5200 x \(10^{-5}\) dynes-cm which differs from the experimental value of \(4100 \times 10^{-5}\) d-cm by 20%.

For a 1 cm long, 30μ diameter fiber \(k = 2.54\) dynes-cm (experimental).

Let us note also that quartz will stretch and twist before breaking more than any other known metal or alloy.

The low loss of energy due to internal friction when stresses are applied (the loss amounts to \(10^{-3}\) of that in the best metals) and the feasibility of easily producing fibers down to one micron in diameter, makes fused silica the most suitable material for the determination of small forces.

Before describing the whole quartz assembly it is desirable to have an idea of the order of magnitude of the forces involved. Typically, the anisotropy constant for a thin film is \(10^3 - 10^4\) erg/cm\(^3\). The films fabricated in this laboratory and used for research were circular, 1 cm in diameter, and varying in thickness between 400 \(\AA\) and 2000 \(\AA\). The maximum torque of a given film being KV (V=Volume), we will consider a film 100 \(\AA\) thick in order to have an idea of the torques to be detected.

In such a case, one gets approximately \(10^{-3}\) dynes-cm. Humphrey and Johnston claim a sensitivity of \(10^{-6}\) dyne-cm in their magnetometer. If one constructs a torquemeter of this sensitivity and uses a 5μ diameter, 3 cm long fiber for which \(k = \frac{325}{3} \times 10^{-5} = 10^{-3}\) dyne-cm/rad, in order to detect a \(10^{-6}\) dyne-cm torque one has to have a sensor system able to detect \(\frac{10^{-6}}{10^{-3}} = 10^{-3}\) radian, or about 3'. On the other hand, if one uses a 50μ diameter, 3 cm long fiber for which \(k = 10^{-3} \times 10^4 = 10\) dyne-cm/rad', in order to detect \(10^{-6}\) dyne-cm, one needs a sensor system that can detect
\[ \frac{10^{-6}}{10} = 10^{-7} \text{ radian} - \text{that is, an angular sensitivity } 10^4 \text{ times larger.} \]

The fused silica suspension is described in figure 1. The mirror is a part of the sensor system, which will be discussed later. The quartz suspension is gold plated to make it conductive. The section labeled torquing element, offset from the torsion axis, generates the torque necessary for balance according to the law of Biot and Savart. The necessary magnetic field is provided by permanent magnets. The torque rebalance current flows through the torsion fibers and torquing element by way of the upper and lower spring which are attached to an 0-shape frame (See fig. 2).

According to the law of Biot and Savart, the restoring torque in dynes-cm =

\[ \frac{1}{10} H_{oe} i_A dl_{cm} da_{cm} \]  

\[ \text{Taking } \quad dl = 0.45 \text{ cm}, \quad da = 1 \text{ cm} \]

\[ H = 6000 \text{ oe} \]

\[ \text{Torque} = 270 i_A \]

We saw that the maximum torque on a thin film was given as KV. Using \( K=2\times10^3 \text{ ergs/cm}^3 \) and a thickness of 5000 Å, "the maximum torque is less than \( 10^{-1} \text{ dyne-cm.} \) This means that our gold coating should be able to stand \( i_A = \frac{10^{-1}}{270} = 0.37 \text{ mA} \)

According to Humphrey, a 3μ diameter fiber, coated to 100Ω, can stand 20 mA. If one calls \( d \) the diameter of a fiber, \( t \) its coating thickness, its electrical resistance is inversely proportional to the product \( t d \). For a given voltage appearing at points A, B of fig. 2, this means that the current is proportional to \( t d \) or that since the resistance at points A, B in our magnetometer is 300 Ω, a current of \( 20 \times \frac{100}{300} = 7 \text{ mA} \) can be carried safely by
the coating. From equation (2), 7mA corresponds to a torque of 2.1 dyne-cm, which is about twenty times the torque provided by a thin film 5000 A° thick with an anisotropy constant of \( K = 2 \times 10^3 \text{ ergs/cm}^3 \). We are therefore sure the gold coating is thick enough to allow the study of at least a large class of ferromagnetic thin films. The gold coating on all rods linked to the torsion fibers provides excellent heat sinks for the heat that might be generated in the fiber coating and subsequently damage it. The springs were provided for possible thermal expansion of the quartz rods and fibers beyond the elastic limit. The sample fork can easily be loaded with a thin film and its substrate which together weighed an average of 530 mg. The quartz fiber diameter was determined from the torsion constant, which was calculated from measurements on the natural period of oscillation of the quartz assembly (See I. 5 - natural frequency of oscillation of quartz assembly) and found to be 50μ. All other dimensions given in figures 1 and 2 are drawn to scale and will therefore not be cited here.

I. 3 Permanent Magnets for restoring torque

Let the subscript \( m \) refer to the permanent ferromagnetic material (Alnico V), \( i \) to the soft iron pole pieces, and \( a \) refer to the air gap. Then, assuming no leakage, the design equations are written:

\[
H_m l_m + H_i l_i + H_a l_a = 0
\]

\[
B_{hi} A_{hi} = B_i A_i = B_a A_a = \phi
\]

Assuming \( B = \mu_0 H + M \)

and \( M = \mu_0 \chi H \)

one has \( B = \mu_0 H + \mu_0 \chi H = \mu_0 (1 + \chi) H = \mu_0 \mu H \)
then one can rewrite the design equations as:

\[ -H_m l_m = -F_m = \phi \left( \frac{l_i}{\rho_i \rho_i A_i} + \frac{l_a}{\rho_o A_a} \right) = \phi \left( R_i + R_a \right) \]

However \( \rho_i \gg 1 \) and since \( l_i \) and \( l_a \) do not differ by more than one order of magnitude, and \( A_i = A_a \), we can conclude that \( R_i \ll R_a \).

Therefore \( -F_m = \phi R_a \)

\[ -H_m l_m = B_m A_m \frac{l_a}{\rho_o A_a} \]

The slope of the load line is therefore:

\[ \frac{B_m}{H_m} = -\rho_o \frac{l_m}{l_a} \frac{A_a}{A_m} \]

In the present case

\[ \rho_o = 4 \pi \times 10^{-7} \text{ Henry/meter} \]

\[ A_a = A_m = 0.5 \text{ cm}^2 \]

\[ l_m = 6 \text{ cm} \]

\[ l_a = 0.3 \text{ cm} \]

\[ -4 \times 3.14 \times \frac{6}{3} \times \frac{5}{5} \times 10^{-7} = -2.5 \times 10^{-5} \text{ Henry/meter} \]

If we refer to the demagnetization curve for Alnico V, we see that our design has allowed us to achieve the maximum \( B_m H_m \) value.

Neglecting the magnetomotive force corresponding to the soft iron we can write:

\[ H_a^2 = -\frac{1}{\rho_o} \frac{B_m H_m V_m}{V_a} \quad (V \text{ is volume}) \]

So that if \( B_m H_m \) is maximum, \( H_a \) is also maximum.

\( (B_m H_m)_{\text{max}} = 0.94 \times 3.8 \times 10^4 \text{ MKS} = 3.6 \times 10^4 \text{ MKS} \)

\[ \frac{V_m}{V_a} = \frac{l_m}{l_a} = 20 \]

\[ H_a^2 = 57 \times 10^{10} \text{ MKS} \]

\[ H_a = 7.5 \times 10^5 \text{ MKS} = 9.5 \text{ KG} \]
However, a Hall probe measurement of the field in the gap when the magnet was not positioned around the quartz assembly gave a value of 6.8 kG. This measurement points out the importance of leakages and the influence of the demagnetizing field when the two shoe-shaped magnets, having been charged with keepers around the charging bar of magnetizing machine, had to be opened partially in order to form the magnetic circuit of figure 3. However, the magnets were made of Alnico V and occupied the largest available space so that it is unlikely that a higher field would have been obtained in the gap of .3cm.

In order to study the magnetic properties of a thin film, the sample is deposited on the sample fork and a field is applied to it. This field will interact with the current flowing in the fibers and provide a stray torque. However, since the field is always less than $10^{-3}$ times the permanent magnet field we will consider this source of error negligible.

I.4 Sensor System

The sensor system includes a light source GE 253 x (P.S. : 2.5 AC), a miniature bulb located in the focal plane of a condenser (See fig. 4). The condenser is composed of two small lenses 1 cm in diameter, focusing the light rays from the miniature bulb onto a slit. The slit, 0.1 cm in width is in the image plane of the light source. These three items constitute what we might call the light source system, which is enclosed in a housing (See fig. 4). The slit is located in the object focal plane of a lens with a focal distance of 7 cm and a diameter of 5 cm. A screw adjustment is provided in order that a parallel beam of light reflecting from the mirror, and converging after passage through the lens, focuses on the photocell.
A micrometer screw allows a lateral displacement of the photocell in order to adjust the zero of the balance. The mirror and photocell together constitute what we might call the detector system. The photocell is a T I silicon dual-element photovoltaic null indicator, Type LS 221. The maximum output from the inbalance between the sensitive elements, in the linear operating region of the photo-cell is 50 mV as stated by the manufacturer. If we assume a gain of 50 for the feedback amplifier and corrective network, we see that the input to the points A, B of figure 2 will be of 50 x 50 x 10^{-3} = 2.5^v across a resistance of 3.6^k (see section 1.15). This voltage corresponds to a current of .7 mA or a restoring torque of .19 dyne-cm, which is a very large torque compared to the torques usually encountered in thin non-magnetostrictive films. We note also that the current of .7 mA is not large enough to damage the gold coating of the fibers. The photocell is therefore well suited for the present study.

In the H&J system, a torque sensitivity of 10^{-6} dynes-cm was shown to correspond to an angular sensitivity of 10^{-3} radian. Considering an offset of the torquing element with respect to the torsion axis of .5 cm, we conclude that the lateral displacement of the torquing element is 5 x 10^{-4}cm = 5\rho. The shadow of the torquing element on the photocell will therefore be 5\rho off center.

In the system under discussion, a torque sensitivity of 10^{-6} dyne-cm corresponds to an angular sensitivity of 10^{-7} - that is, a linear displacement of the light beam on the photocell of 2 x 10^{-7} x 7 = .14\rho. (See fig. 4).

In order to prevent the sensor system from vibrating independently of the quartz suspension system, both systems were screwed together very
f tightly to the same aluminum plate.

I.5 Natural Frequency of Oscillation of the Quartz Assembly

If one considers a substrate of dimensions a, b, c, homogeneous, and such that \( a \gg c \) \( b \gg c \)

the moment of inertia with respect to an axis perpendicular to the face a b and passing through the center of gravity is given by:

\[ i = \frac{m}{12} (a^2 + b^2) \]

\( m \) is the mass of the substrate.

Assuming \( m = 0.5311 \text{ g} \)

\[ a = 0.621 \times 2.54 \text{ cm} = 1.577 \text{ cm} \]

\[ b = 0.626 \times 2.54 \text{ cm} = 1.59 \text{ cm} \]

\[ c = 0.031 \times 2.54 \text{ cm} = 0.079 \text{ cm} \]

then

\[ i = \frac{0.5311}{12} (0.621^2 + 0.626^2) \times 2.54^2 = 0.222 \text{ g-cm}^2 \]

If one lets the quartz assembly oscillate in torsion, the movement can be described by the following differential equation.

\[ I \frac{d^2 \theta}{dt^2} + k \theta = 0 \]

\( I = \) Moment of inertia of assembly.

\( k = \) Torsion constant of fibers.

We have neglected damping because of the very high Q of such a system.

The quartz was shown to lose very little energy by internal friction so that most of the energy losses are attributable to friction on the air (viscosity), which can be neglected in first approximation.
The period of such a system is:

\[ T = 2\pi \sqrt{\frac{I}{k}} \]

Suppose we leave the quartz suspension unloaded. The assembly will then oscillate with the period:

\[ T_1 = 2\pi \sqrt{\frac{I}{k}} \]

If we load the sample fork with one substrate as described above, the system will oscillate with the period:

\[ T_2 = 2\pi \sqrt{\frac{I + \frac{4n^2}{T_2^2 - T_1^2}}{k}} \]

In order to determine the periods \( T_1 \) and \( T_2 \), the output of the photocell was recorded in both cases on a strip chart recorder (Sanborn H. P).

From this we can write

\[
\begin{align*}
    k &= i \cdot \frac{4n^2}{T_2^2 - T_1^2} = \frac{m}{i_2} (a^2 + b^2) \cdot \frac{4n^2}{T_2^2 - T_1^2} \\
    I &= i \cdot \frac{T_2^2}{T_2^2 - T_1^2} = \frac{m}{i_2} (a^2 + b^2) \cdot \frac{T_2^2}{T_2^2 - T_1^2} 
\end{align*}
\]

As seen in fig. 5, we have determined \( T_2 \) experimentally for two different substrates and for the two of them put together, and \( T_1 \) for the unloaded quartz fiber.

<table>
<thead>
<tr>
<th>( T_1 ) (Sec)</th>
<th>( T_2 ) (Sec)</th>
<th>( m ) (g)</th>
<th>( k ) (cgs)</th>
<th>( I ) (cgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.8</td>
<td>1.10</td>
<td>.3440</td>
<td>9.95</td>
<td>.16</td>
</tr>
<tr>
<td></td>
<td>1.214</td>
<td>.5311</td>
<td>10.5</td>
<td>.17</td>
</tr>
<tr>
<td></td>
<td>1.45</td>
<td>.8751</td>
<td>9.90</td>
<td>.16</td>
</tr>
</tbody>
</table>

These results give us an estimate of the error to be expected. We could also evaluate an upper limit for it by writing:
\[
\begin{align*}
|\frac{d\kappa}{\kappa}| & \leq |\frac{di}{i}| + \frac{2}{T_2 - T_1} |\frac{dT_1}{T_1 T_2 - T_1}|
\end{align*}
\]

Estimate \(dT_1 = .005\), and assume that most of the error on the determination of \(i\) does not come from mass or length measurements but from an offset of the torsion axis with respect to the axis going through the center of gravity. Assuming a possible error of 1 mm of offset in positioning the substrate, \(di = \frac{1}{2} \times .5311\) (choosing the 2nd measurement to evaluate the error).

\[
\begin{align*}
di = .005, \text{ so that } & \quad \frac{di}{i} = \frac{.005}{.2} = \frac{3}{100} \\
\text{Finally } & \quad |\frac{d\kappa}{\kappa}| \leq \frac{3}{100} + \frac{2}{100} = \frac{5}{100} \\
& \quad |\frac{dI}{I}| \leq \frac{3}{100} + \frac{2}{100} + \frac{2}{100} = \frac{7}{100}
\end{align*}
\]

These estimates are well in agreement with previous measurements.

According to Braddock (4), we saw that \(k = \frac{1}{\phi} = \frac{n}{22} Z r^4\), \(k\) is the torsion constant of a fiber of length \(l\), radius \(r\). The length of the quartz fiber in the present case is \(l = 2.35\) cm. Therefore, 1 cm of the present fiber would have a torsion constant equal to \(10.5 \times 2.35 = 25\). Braddock gives the value of 2.54 per cm for a 30\(\rho\) diameter quartz fiber. Therefore, if we call \(x\) the diameter of the present fiber and assume that the modulus of rigidity \(Z\) stays constant for a fiber between 30\(\rho\) and 50\(\rho\), one gets:

\[
\left(\frac{x}{30}\right)^4 = \frac{25}{2.5} = 10
\]

\[
x = 30 \times 10^{\frac{1}{4}} = 30 \times 1.775 = 50 \rho
\]
We are therefore operating with a 50μ fiber.

Now let us comment on sensitivity versus time response. We saw that the torsion constant is the torque per radian \( k = \frac{L}{\theta} \). For a given torque, the torsion angle is larger if the torsion constant is smaller, that is if its diameter is smaller. In other words, a fiber with a smaller diameter has more sensitivity. But on the other hand, we saw that the period of free oscillation for the quartz suspension is given by \( T = 2\pi \sqrt{\frac{I}{k}} \), and we therefore anticipate that the more sensitive the quartz fiber, the longer the period of free oscillation, and the time response.

1.6 Calibration of the Torquemeter in Terms of Rebalance Current

After the torquemeter was assembled, and before it was made automatic, it was necessary to make a few preliminary measurements of torques with the operator included in the servo loop. The following operations were carried out:

- The screw adjustment on the photocell was turned until 0 output from the photocell was obtained.

- Then a small DC current from a 1.5V battery and 100k pot combination was sent through the fibers and torquing element. The current was adjusted to 50 μA. The light beam moved from 0 to A. The adjustment screw was turned until 0 output from the photocell was again obtained and the rotation angle of the screw was recorded. An angle of 108° was found. Knowing from a previous calibration that one turn (360°) of the screw corresponds
to a displacement of \( \frac{1}{40} \) of an inch or \( \frac{2.54}{40} \) cm, the displacement of the light beam was evaluated as:
\[
\frac{108}{360} \times \frac{2.54}{40} = 0.019 \text{ cm}
\]
The distance lens-photocell (fig. 4) being 7 cm, the rotation \( \theta \) of the mirror could be computed as:
\[
\theta = \frac{0.019}{7} = 0.00272 \text{ radian}
\]
\[
\theta = 0.00136 \text{ rad.}
\]
The corresponding torque is therefore:
\[
k\theta = 10.5 \times 0.00136 = 0.0143 \text{ dyne-cm.}
\]
This torque is equal to the electromagnetic restoring torque. The length of the useful torquing element is taken as 1 cm, which is the thickness of the magnet.
\[
k\theta = \frac{B(KG) \ da(cm) \ dl(cm) \ i \ (mA)}{10} = \frac{B(KG) \times 1 \times 0.45 \times 50 \times 10^{-3}}{10}
\]
\[
0.0143 = B \times 2.25 \times 10^{-3}
\]
\[
B = 6.4 \text{ kG}
\]
This value compares well with the value found experimentally in Section I. 3.
The same result would have been obtained if the quartz fiber had been loaded, an additional moment of inertia having no effect on the static behaviour of the fiber. The torque rebalance current scale factor \( K_c \) is therefore:
\[
K_c \ \text{(dyne-cm/mA)} = \frac{B(KG) \times dl \ (cm) \ da \ (cm)}{10} = 0.29
\]
As a check, the following currents were sent through the fibers and torquing element, and the corresponding rotation angles were recorded.

<table>
<thead>
<tr>
<th>Feedback Current</th>
<th>Rotation Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ( \mu \text{A} )</td>
<td>108°</td>
</tr>
<tr>
<td>200 ( \mu \text{A} )</td>
<td>440°</td>
</tr>
<tr>
<td>600 ( \mu \text{A} )</td>
<td>1320°</td>
</tr>
</tbody>
</table>
All of these measurements are in close agreement. Before tests could be made on magnetic thin films, and measurements of the anisotropy constant could be carried out, it was necessary to develop a micromanipulator well adapted to the particular dimensions and design of the torquemeter, in order to position the film and substrate on the sample fork, accurately and without the risk of breaking the quartz fiber.

I. 7 Design of a Micromanipulator

Let us call \( x \) horizontal axis and \( y \) a vertical axis. From fig. 6 we can see that between the point where we load the substrate on the substrate holder, and the point where we drop the substrate on the sample fork, we have to travel a horizontal distance of more than 12 cm. This consideration, added to the specific dimensions of the torquemeter made it impossible to find a micromanipulator unit available on the market and ready for use.

In figure 7, a sketch of the completed micromanipulator is shown.

Two microscope slides (from Brinkman Instruments) properly arranged at right angles to secure \( x \) and \( y \) movements provide fine displacements. In addition, mounting the two microscope slides on a cart which slides on two stainless steel rods provides a gross \( x \) displacement. An appropriate sample holder was also designed to allow an easy deposition of the substrate on the sample fork (fig. 6). Detailed measurements are omitted; however, figure 6 is drawn to scale.

I. 8 Design of a Cube-Coil System \((5)\)

In order to provide a region of space in the vicinity of the magnetic sample free of magnetic fields, it was necessary to build a cube coil system
already described in the literature\(^{(5)}\). In the present case, there were two sources of magnetic fields - the earth field (horizontal \(0.5\Omega_e\), vertical \(0.2\Omega_e\)) and the stray magnetic field from the permanent magnet used in the restoring torque system (horizontal \(0.5\Omega_e\))

The field at a point \((z)\) from a square coil \((N=1)\) carrying current \(I\) is:

\[
H_1(z) = \frac{2I}{nL} \left( \frac{1}{1 + \left( \frac{z}{L} \right)^2} \right) \left( \frac{1}{2 + \left( \frac{z}{L} \right)^2} \right)^{\frac{1}{2}}
\]

For \(z=L\), \(H_1(L) \approx \frac{1}{n\sqrt{3}} \frac{I}{L} = 0.184 \frac{I}{L}\)

From a pair of coils we get:

\[
2H_1(L) = \frac{2}{n\sqrt{3}} \frac{I}{L} = 0.37 \frac{I}{L}
\]

For the coils built, \(L = 0.19\ m\)

\(2H_1(L) = 1.95I\)

If one evaluates the possible error in field uniformity due to a slight displacement \(x\) around \(L\), one can calculate the variation of the field as:

\[
\frac{2}{n\sqrt{3}} \frac{I}{L} \left[ 1 + \frac{5}{3} \left( \frac{x}{L} \right)^2 \right]
\]

For \(x = 0.005\ m\)

\(L = 0.19\ m\)

Compare 1 to \(\frac{5}{3} \left( \frac{0.005}{0.19} \right)^2 = 1.1 \times 10^{-3}\)

In conclusion, this uniformity is quite sufficient for our measurements.

Each square coil was wound with 200 turns so that the contribution from each pair of coils was: \(2H_{200}(L) = 390 I\)
To obtain 1 oe, for example, or 79.6 A/m, we must provide \( \frac{79.6}{390} \) or less than 204 mA.

Each pair of coils has a resistance of 60 \( \Omega \) (AWG # 26 wire was used). The power dissipated in the extreme case of 204 mA flowing through is about 2.5 watts. We conclude that we can build three pairs of coils for the three components of magnetic field, and we actually need less than 400 mA total, from a power supply. (Kepco, voltage limited 50V, current limited 750 mA)

The circuit is shown in fig. 8. Consider the following case:

The resistance \( R \) is the resistance of 18 \( \Omega \) as seen from the base. If we assume a gain of 50, 1mA flowing through the base corresponds to 50 mA flowing through the emitter so that the 18 \( \Omega \) will correspond to \( R = .9 \) \( \Omega \). The equivalent circuit is drawn with

\[
\frac{1}{.66} = \frac{1}{2.5} + \frac{1}{.9}
\]

and

\[
V = \frac{.66}{2.2 + 2.5 + .66} \times 32 = .12 \times 32 = 3.85 V
\]

The current flowing through the transistor is therefore \( \frac{3.85}{18} = 208 \) mA.

We therefore see that by proper biasing of the transistor base we can achieve the currents we are looking for, from 0mA to approximately 260 mA.

I.9 Design of Two Crossed Helmholtz Pairs of Coils

In H & J system, the rotating field is provided by one pair of Helmholtz...
coils, rotating mechanically in circular grooves and driven by a slow motor. It was felt that such a system might bring about additional vibrations to the ones already existing and consequently create extraneous problems in restoring electronically the torque exerted by the rotating field. A different approach was attempted. The torquemeter was set on an aluminum plate 1 -1/4" in thickness, resting on concrete blocks cemented together and to the floor. The torquemeter was fastened to the table top by means of spring-loaded screws specially designed for the purpose, the verticality of the torquemeter being controlled by three micrometer screws 120° apart.

Two pairs of Helmholtz coils were designed to fit around the protective glass chamber of the torquemeter and to fit inside one another. The two pairs of Helmholtz coils were held in place by a specially designed support with adjustment screws so that the distances of the coils could be varied slightly, and fastened to the table top by means of screws. These precautions were taken in order to isolate the torquemeter from any moving part, or any source of vibrations except the unavoidable vibrations from the floor.

As is well known, the reason for using Helmholtz coils is to provide uniform fields over a region of space large enough to include the magnetic sample.
For a one turn coil of radius $R$, the field $H_x$ at point $0$ is given by:

$$H_x = \frac{I R^2}{2(R^2 + a^2)^{3/2}}$$

We consider now two coils of one turn each mounted coaxially:

$$H_x(P) = \frac{IR^2}{2} \left\{ \left[ R^2 + (a-x)^2 \right]^{3/2} + \left[ R^2 + (a+x)^2 \right]^{3/2} \right\}$$

$$H_x = \frac{IR^2}{2} \left( R^2 + a^2 \right)^{-3/2} \left\{ 2 - \frac{3}{R^2 + a^2} \left[ -1 + \frac{5a^2}{R^2 + a^2} \right] x^2 + \ldots \right\}$$

The coefficient of $x^2$ in the curly bracket will be zero for $a = \frac{R}{2}$

In this case $H_x = H_o + H_4 x^4 + \ldots$ (1st order, 3rd order terms are zero by symmetry)

$$H_o = \frac{IR^2}{2} \left( \frac{2}{R^2 + R^2/4} \right)^{3/2} = \frac{8}{\sqrt{125}} \frac{I}{R} = 0.716 \frac{I}{R}$$

If we consider a point $Q$ off axis at a distance $r$ from the axis, and a distance $x$ from center $0$ as before, we can write:

$$\text{div } \vec{H} = 0$$

$$\frac{1}{r} \frac{\partial}{\partial r} (rH_r) + \frac{\partial H_x}{\partial x} = 0$$

$$\frac{\partial H_x}{\partial x} = 4H_4 x^3$$

$$\frac{1}{r} \frac{\partial}{\partial r} (rH_r) = -4H_4 x^3$$

$$H_r = -2H_4 rx^3$$

Therefore in general $\vec{H} = (H_o + H_4 x^4 + \ldots) \hat{i} - (2H_4 r x^3 + \ldots) \hat{j}$, $\hat{i}$, $\hat{j}$, are
unit axial and radial vectors respectively.

To evaluate $H_\text{x}(\mathbf{P})$ the simplest way is to develop $H_\text{x}(\mathbf{P})$ in a Taylor Series around $x = 0$.

$$H_\text{x}(\mathbf{P}) = H_\text{x}(0) + \frac{x}{1!} H'_\text{x}(0) + \frac{x^2}{2!} H''_\text{x}(0) + \frac{x^3}{3!} H'''_\text{x}(0) + \frac{x^4}{4!} H^{iv}_\text{x}(0) + \ldots$$

Carrying out the calculation of the successive derivatives one finds:

$$H_4 = -\frac{1.65 \times I \times R^2}{R^7} = -\frac{.82 \times I}{R^5}$$

$$\mathbf{H} = \left( \frac{.716 \times I}{R} - \frac{.82 \times I \times x^4}{R^5} \right) \mathbf{i} + \frac{1.65 \times I \times x^3}{R^5} \mathbf{r} \mathbf{j}$$

Consider: $R = .13$ m

$x := .005$ m

$.716 \frac{1}{R} = 5.5$ \hspace{1cm} $.82 \times \left( \frac{5 \times 10^{-3}}{.13} \right)^4 = 1.4 \times 10^{-5}$

We clearly see that the field is quite uniform.

Let us now give a few details about the design of the Helmholtz coils.

The larger pair of coils has a radius of 13.7 cm, and a resistance of 11.52 when connected in series; the smaller pair of coils has a radius of 8.6 cm and a resistance of 7.24 when connected in series. Both pairs are wound with 250 turns of AWG #20. A calibration of the larger pair of Helmholtz coils gives 16.8 oe/amp. A calibration of the smaller pair of Helmholtz coils gives 26.75 oe/amp.

Each pair of coils is to be driven by two independent sinusoidal voltages 90° out of phase so that the resultant field will be uniformly rotating. It would be useful to have the same calibration for the two pairs of coils since we want to drive them with identical circuits, and the same output voltages.
For this reason, an additional resistance is connected in series with the smaller pair of coils:

\[ \frac{x + 7.24}{16.8} = 11.52 \]
\[ \frac{26.75}{x} = 11.11 \, \Omega \]

The resistances of the two pairs of coils were measured with a Wheatstone bridge and a rheostat was supplied \((18 \Omega, 5 \, A)\) and connected in series with the smaller pair of coils, and adjusted to \(11.11 \, \Omega\).

I.10 Comparison of Anisotropy Constant Determined with Torquemeter and Anisotropy Constant Determined with B. H. Looper Tracer.

Before making the instrument fully automatic, a few measurements were carried out on thin ferromagnetic films, their anisotropy constants calculated and compared to the B-H loop tracer. A few problems were encountered which will be recalled. It is necessary to cancel the stray fields with the cube coils adjustments. A gross adjustment with the torquemeter removed from the table top can be easily obtained with a probe. However, stray fields coming from the permanent magnet of the torque restoring system have to be cancelled. The stray field comes from the flux closure of the gap of the permanent magnet and lies along the hard direction of the film. If one saturates the film along the easy axis, the output of the photocell will read \(a_1\). If one saturates
the film in the opposite easy axis direction, the output of the photocell will read \( a_2 \). We then adjust the cube coil corresponding to the y axis so that the output of the photocell reads \( \frac{a_1 + a_2}{2} \) and then bring this reading to zero with the photocell adjustment screw for lateral displacement. At this point we are ready for measurements on thin films. A typical curve and the values recorded are shown in fig.9 for 9-5-66 #3 film 19-81 (2400 A°), with a constant rotating field of 20 oe. The necessary values of current to send in each pair of Helmholtz coils, for each angle were easily determined from the calibration of the coils (the 11.11 Ω resistance had not yet been connected to the smaller pair of coils). As the values of currents were changed by manual control of the power supplies, the torque on the film and consequently the output of the photocell varied; it was necessary to send a feedback current through the torquing element with the same type of instrumentation as described in section I-6, to bring back the output of the photocell to zero. A switch was added in order to be able to reverse the current in the fiber and torquing element.

At equilibrium we can write:

\[
KV = K_c \text{ (mA)} \max \text{ in cgs.}
\]

\[
K = K_c \frac{\text{(mA)} \max}{V}
\]

\[
V = 2400 \times 10^{-8} \times \frac{3.14 \times 1^2}{4} = 1.88 \times 10^{-5} \text{ cm}^3
\]

\[
\text{(mA)} \max = .125 \text{ mA}
\]

\[
K_c = .29
\]

\[
K = 1920 \text{ ergs/cm}^3 = 193 \text{ MKS}
\]

\[
\frac{2K}{M} = 386 \text{ MKS} = 4.85 \text{ oe}
\]
assuming \( M = 1 \) MKS or 10,000 gauss.

The measured value with the B-H loop tracer is 4.5; the difference is about 10\%, in this case.

The error on \( K \) can be accounted for in the following way:

\[
\left| \frac{dK}{K} \right| < \frac{dK_c}{K_c} + \frac{di}{i} + \frac{dV}{V} = \frac{17}{100} + \frac{2}{100} + \frac{5}{100} = \frac{24}{100}
\]

where

\[
\left| \frac{dK_c}{K_c} \right| < \frac{dk}{k} + \frac{d\theta}{\theta} + \frac{2|dl|}{l} + \frac{d|l|}{l} = \frac{5}{100} + \frac{5}{100} + \frac{5}{100} + \frac{2}{100} = \frac{17}{100}
\]

Each one of these errors, however, is an estimate.

I.11 Frequency Response of the Quartz Fiber.

In order to design a feedback amplifier unit to cancel automatically the applied torques, a frequency response analysis of the quartz suspension was first carried out. The experimental set-up and the readings are shown in figure 10. A few samples of input-output sinusoids are shown in fig. 11 for the frequencies .01 cy/sec, .05 cy/sec, .88 cy/sec, .91 cycle/sec.

We saw in section I.5 that the natural periods of oscillation of the quartz suspension were .8 sec, 1.1 sec, 1.214 sec, for respectively no substrate, substrate \( m = .3440 \) g, substrate \( m = .5331 \) g. The corresponding frequencies of oscillation are respectively 1.25 cycle/sec, .91 cycle/sec, .82 cycle/sec. Since the substrate with weight \( m = .3440 \) g is the microscope slide variety 0211 currently in use, for film fabrication, it was decided to study the frequency response of the quartz fiber with a substrate 0211 set on the sample fork. We verify on figure 12 that the resonant frequency is indeed the natural frequency of the quartz system + substrate (\( m = .3440 \) g). Because
of the high Q of the quartz suspension, it was necessary to wait some time between each frequency recording. The gain can be determined from figure 11 as well as the phase. Beyond .94 cycle/sec, however, it is difficult to give numbers for the phase because the gain drops down very rapidly to zero.

1.12 Design of a Compensating Network - Amplifier Feedback System.

From classical control theory we know that in order to make our system stable we have to compensate it so that the frequency response of the compensated network crosses the gain-1 axis with a slope of 1 (in log-log system). Note that usually gain refers to the ratio of output to input (in this case voltage output to voltage input) and no ambiguity arises because the system is assumed to be completely electrical. However, in the present case, a light beam constitutes the coupling between input voltage $V_i$ across the torquing element and $V_o$, output voltage from the photocell. The gain 1 axis is therefore somewhat arbitrary and because of this arbitrariness, and the impossibility to determine accurately gain and phase beyond .94 cy/sec, the apparent -3 slope at crossing of the 1 gain axis was not considered as indicating necessarily the order of the system (the system, actually should be of order 2). It was decided, therefore, to try to compensate the system with one lead network only, and to add additional lead networks if the first compensation was inadequate.

We saw in Section I-4 that a gain of about 50 for the feedback amplifier would be adequate. On the other hand, we have to build a lead network to stabilize the system. For these applications, Union Carbide operational
amplifiers were used. A is of the order of 40,000. The output saturating
toltage is \( \pm 10^v \), which is appropriate for the present application.
These amplifiers have very high
input impedance, low output imped-
ance and can be used in series without loading problems.

\[
\frac{E_{out}}{E_{in}} = \frac{Z_2}{Z_1}
\]

The impedance of a parallel R, C network is \( Z = \frac{R}{1 + RCS} \)

If one considers the following circuit, one can write:

\[
\frac{E_{out}}{E_{in}} = \frac{R_2}{R_1} \frac{1}{1 + R_1 C_1 S} \frac{1}{1 + R_2 C_2 S}
\]

The break frequencies are:

\[
\frac{1}{R_1 C_1} \quad \text{and} \quad \frac{1}{R_2 C_2}
\]

At low frequencies

\[
\frac{E_{out}}{E_{in}} = \frac{R_2}{R_1} \quad (s \to 0)
\]

At high frequencies

\[
\frac{E_{out}}{E_{in}} = \frac{C_1}{C_2} \quad (s \to \infty)
\]

A Bode plot would give:

\[
\log \left| \frac{E_{out}}{E_{in}} \right| = \frac{C_1}{C_2}
\]

\[
\frac{R_2}{R_1} \quad \frac{1}{R_1 C_1} \quad \frac{1}{R_2 C_2} \quad \log \omega
\]
We note that if we make \( C_2 = 0 \) \[ E_{\text{out}} = \frac{R_2}{R_1} (1 + R_1 C_1 S) \]

In this case, the Bode plot would be:

Let us choose \( R_1 = R_2 = 120^k \) (1\%) and consider the break frequency \( \frac{1}{R_1 C_1} \) to be 0.95 cycle/sec. Then \( 2 \pi f_1 = 5.97 \text{ rad/sec} \) and \( R_1 C_1 = \frac{1}{5.97} = 0.1675 \). Therefore \( C_1 = \frac{0.1675}{R_1} = \frac{0.1675}{1.2 \times 10^5} = 1.4 \times 10^{-6} = 1.4 \mu\text{F}. \)

The gain was obtained with the following design:

The resistances were actually resistance boxes so that the gain could be varied to tighten or loosen the loop.

The final design was the following:
This design proved to be satisfactory, and therefore no additional lead-networks had to be built.

1.13 Specifications and Design of Two D-C Amplifiers to Drive the Two Pairs of Helmholtz Coils.

In order to measure the anisotropy constant with the torquemeter one has to provide a uniformly rotating field that has to be large compared to the anisotropy field of the film considered. Although the anisotropy field of thin films varies over large ranges of values, one can take 5 oe as an average value in the case of non-magnetostrictive films. A rotating field of magnitude $8 \times 5 = 40$ oe to $10 \times 5 = 50$ oe can then be considered as large compared to the anisotropy field. The calibration of the large pair of Helmholtz coils gave us 16.8 oe/amp. To reach a magnitude of 50 oe, we need approximately 3 amperes, which means an input voltage of $11.52 \times 3 = 35$ volts. The heat dissipation would be of the order of 100 watts, which does not bring about excessive heat to the plastic frame of the coils. For the smaller coils, the calibration gives 26.75 oe/amp, so that in order to obtain 50 oe, only 1.87 A is necessary. However, we have added a resistance of 11.11 so that the same value of voltage to the coils would produce the same magnetic field. The problem is therefore to design two identical D.C. Amplifiers with 35 to 40 volts output. The principle of one of these D.C. amplifiers is shown in figure 13-1 and 13-2. We see that this design allows us to keep the same current requirement, but decreases by a factor of two the voltage requirement. Figure 13-3 and 13-4 show with a few more details, how the well-known amplifier techniques can be applied to
the present case. Figure 14 shows one complete amplifier unit (each D.C. amplifier has two of these units). The use of an Union Carbide amplifier block is to be noticed in the input stage. The output of the amplifier is fed back to the input, giving proper stability to the amplifier unit, which may be viewed as a big operational amplifier with gain equal to the ratio \( \frac{100}{36} = 2.75 \). Considering that the Union Carbide operational amplifier blocks saturate at \( \pm 10 \) V, we see that a maximum of 27.5 V can be obtained at the output of the amplifier unit that is 55 V across the load. Actually, for our specifications an input voltage of \( \pm 7 \) V is sufficient since it would give us 38 V across the load or 55 \( \text{oe} \) rotating field. Our calibration can therefore be taken as:

8 \( \text{oe/volt \ at \ input} \).

I. 14 Design of a Sine-Cosine Generator.

The two D.C. amplifiers have to be driven by two sine waves 90° out of phase. One way to accomplish this is to use a sine-cosine potentiometer driven by a motor (2 cy/min). In order to know the angle of rotation of the field, a linear potentiometer is driven by the same motor, the output of which is proportional to the angle of rotation. The sine and cosine potentiometers (3W, 20^k) are mounted on the same shaft. The linear, sine and cosine potentiometers use three different power suppliers in order to avoid interaction of one circuit on another. The sine and cosine power supplies can be driven manually simultaneously by a single external potentiometer so that with the motor stopped at any angle one can trace a curve torque versus magnetic field. The output impedance of the sine-cosine potentiometer can be as high as 20^k; on the other hand, the input impedance of the D.C. amplifier
is $36^k$. In order to avoid any loading problem, an impedance matching box has to be built with two operational amplifiers having a 1 Meg input impedance and gain 1; the output impedance of these operational amplifiers can be shown to be very low as already mentioned. Fig. 15 shows a diagram of the driving coil system. In order to record rotating field torque curves, one can switch on the motor and reverse it as the field reaches the easy axis angular position. In this case the $x$ axis of the recorder is proportional to the angular position of the rotating driving field, the $y$ axis being proportional to the torque. However when one wants to record the torque curves versus $H$ field for a given angular position of the $H$ field, one stops the motor at that position and increases the field by means of the voltage control pot, the output of which is recorded on the $x$ axis. The linear pot is then disconnected.

I.15 Calibration of Torquemeter in terms of Rebalance Voltage of Output Photocell.

A few words need to be said about the calibration of the torquemeter in terms of dyne-cm/mV. We saw previously in Section I.6 that the torque rebalance current scale factor is: $K_c = 0.29$ dyne-cm/mA. One milliampere through the conducting fibers correspond to $3.6 \times 10^3$ mV since a resistance of $3.3^k$ was added to the fibers and torquing element to avoid loading problems, and to reduce the rebalance current to a range of values.
compatible with the torques to be measured. A circuit breaker was also added to protect the thin conducting layer of gold of the fibers at 10 mA (we saw that 7 mA could be carried easily by the fibers coated at 300°; see Section I.2) The photocell output voltage (input to the recorder) scale factor will therefore be:

\[ K_v = \frac{0.29}{3.6 \times 10^3} = 3.8 \times 10^{-3} \text{ dyne-cm/mV} \]

We have to reconsider the possible error on \( K_v \). We have seen in I.10 that the possible error on \( K_c \) was 17%. However, the gain is determined by resistance boxes for which the resistance is known with a 5% error, to which we should add the possible error on the 3.3° resistance. We can therefore say that a possible error on \( K_v \) may be as large as 32%. In conclusion, the determination of the anisotropy constant may involve an error of 39%. As an example, consider films 11-25-67, 80-20 Ni Fe, 800 Å thick.

Recorder calibration: 2 mV/inch

Maximum torque: 2.25 inches

Volume: \( 6.28 \times 10^{-6} \text{ cm}^3 \)

\[ K \times 6.28 \times 10^{-6} = 3.8 \times 10^{-3} \times 2.25 \times 2 \]

\[ K = 2700 \text{ ergs/cm}^3 = 270 \text{ MKS} \]

The corresponding anisotropy field is:

\[ H_K = \frac{2 \times 270}{1} = 540 \text{ MKS} = 6.8 \text{ Oe} \]

However, a determination by the B-H loop tracer shows that \( H_K = 5 \text{ Oe} \), that is, a difference between the two methods of 36%. Experiments carried out on many different films showed that a reproducibility of 5% or better
could be expected from a measurement of the anisotropy constant. We will therefore adjust our value of the photocell output voltage scale factor to fit this value of 5 δe.

\[ K_v \times 4.5 = 2000 \times 6.28 \times 10^{-6} \]

since \( \frac{2K}{M} = 5 \text{ oe} = 400 \text{ MKS} \quad K = 200 \text{ MKS} = 2000 \text{ ergs/cm}^3 \)

\[ K_v = 2.8 \times 10^{-3} \text{ dynes-cm/mV} \]

I.16 Feedback System.

At this point, we can give a summary of the entire system by drawing a block diagram, indicating in detail, what pieces of hardware actually corresponds to the block in question. The diagram is shown in figure 16. Let us give one word of explanation for the origin of the input torque. Consider the following situation.

The spin system of the thin film is in constant equilibrium under the influence of the magnetic field and the anisotropy, and as will be shown in the next chapter the torque is given by \( L \):

\[ L = K \sin 2\phi = MH \sin (\alpha - \phi - \theta) \]

The quartz fiber experiences a torque \( k\theta \) and under equilibrium one can write \( k\theta = K\sin2\phi = MH\sin (\alpha - \phi - \theta) \).
I.17 Dynamic Motion.

Let us assume that we apply a field $H$ to the thin film resting on the quartz suspension, at an angle $\alpha$. There results a torque $MH \sin (\alpha - \phi)$ where $\phi$ is given by $K \sin 2\phi = MH \sin (\alpha - \phi)$. But this is at time $t = 0$ (the relaxation time of the spin system being negligible) when $\theta$ is zero. As time goes by when $\theta$ starts increasing, the total torque acting on the magnetometer is $-k\theta + MH \sin (\alpha - \theta)$ where $\phi$ is now given by $MH \sin (\alpha - \phi - \theta) = K \sin 2\phi$.

If we did not have any restoring torque, we would be able to write:

$$I \frac{d^2 \theta}{dt^2} = -k\theta + MH \sin (\alpha - \phi - \theta)$$

If we assume that the applied $H$ field is large, then $\phi \propto \alpha - \theta$ and we could write

$$I \frac{d^2 \theta}{dt^2} = -k\theta + K \sin 2(\alpha - \theta)$$

where $I$, $k$, $K$, $\alpha$ are known. If the applied torque were independent of $\theta$ the problem would be straightforward. However, the present problem, would probably require the use of a computer even if we assume that $\alpha$ is a linear function of time.

Considering the existence of a restoring torque that we can evaluate from fig. 16, for example, as:

$$T_{rest} = 1208e + 2.15 \frac{d\theta}{dt}$$

we can write the complete dynamic equation,

$$I \frac{d^2 \theta}{dt^2} = -k\theta + MH \sin (\alpha - \theta - \phi) - T_{rest}$$

$$MH \sin (\alpha - \theta - \phi) = K \sin 2\phi$$
H, α can be given any values we please and ϕ is determined by the second equation. I = 1.7, k = 10.5, M = 10^4 gauss

I. 18 Sensitivity of the Torquemeter.

Since the output voltage of the photocell is the quantity that we record, we can see that the sensitivity of the torquemeter is determined by the smallest voltage we can measure, which is limited by the noise (mostly mechanical at low frequencies). From our measurements, noise can be estimated at 0.1 mV, which corresponds to 2.8 \times 10^{-3} \times 0.1 \text{ dyne-cm or } 2.8 \times 10^{-4} \text{ dyne-cm.}

Let us note that using K=2000 ergs/cm^3, 2.8 \times 10^{-4} \text{ dyne-cm corresponds to a thickness of less than } 17 \text{ Å for a film 1 cm in diameter, that is less than five atomic layers.}

I. 19 Conclusion.

From the user's point of view, the magnetometer that was developed has the following characteristics.

1. Rotating magnetic fields up to approximately 56 oe.

2. Scale factor for the photocell output voltage of 2.8 \times 10^{-3} \text{ dyne-cm/mV, from which the anisotropy constant can be calculated in the following way:}

\[
K \times \text{(Volume)} \overset{\text{cgs}}{=} 2.8 \times 10^{-3} \times (x_{\text{mV}})
\]

3. Sensitivity limited to approximately 0.1 mV or 2.8 \times 10^{-4} \text{ dyne-cm.}

In H & J system, the film sample could be hung vertically and in this position, other magnetic characteristics could be determined such as coercive force, remanent and saturation magnetization. Although a hanger was built, no measurements were carried out on thin films in the vertical position.
CHAPTER II

Torque Measurements and the Stoner-Wohlfarth Model

II. 1 Rotation Model.

If one applies a magnetic field to a thin magnetic film, the total energy of the system can be written:

\[ W = K \sin^2 \phi - MH \cos (\alpha - \phi) \]

The equilibrium position for the magnetization, can be found by minimizing the energy.

\[ \frac{\partial W}{\partial \phi} = 2K \sin \phi \cos \phi - MH \sin (\alpha - \phi) = 0 \]
\[ K \sin 2\phi = MH \sin (\alpha - \phi) \]

The torque exerted by the magnetic field is \( |\vec{M} \times \vec{H}| = MH \sin (\alpha - \phi) \).

From the minimum energy consideration it is also \( K \sin 2 \phi \).

\[ |\vec{L}| = |\vec{M} \times \vec{H}| = MH \sin (\alpha - \phi) = K \sin 2\phi \]

The model just described is called the rotation model or Stoner Wohlfarth model.

Usually one sets \( H_k = \frac{2K}{M} \), \( \frac{H}{H_k} = h \).

Then one can write \( 2h \sin (\alpha - \phi) = \sin 2\phi = \frac{L}{K} \)

When \( \phi = 45^\circ \), \( \frac{L}{K} \) is maximum.

There are three regions of interest for this model -

\[ 0 < h < \frac{1}{2} \]
\[ \frac{L}{K} \] has the character of \( \sin \alpha \) - (no hysteresis)
\[
\frac{1}{2} < h < 1 \quad \frac{L}{K} \text{ shows hysteresis}
\]

\[
1 < h \quad \frac{L}{K} \text{ has the character of } \sin 2\alpha \text{ (no hysteresis)}
\]

In the previous treatment we assumed that the angle \( \theta \) between the easy axis after application of the magnetic field and the easy axis before application of the magnetic field has been brought back to zero by the restoring electromagnetic torque.

It is impossible to describe the torque in terms of \( \alpha \) and \( H \) by means of an explicit equation, in most cases.

Let us consider the case \( \alpha = 90^\circ \).

\[
\frac{L}{K} = \sin 2\phi = MH \cos \phi \quad \sin \phi = \frac{HM}{2K} = \frac{H}{H_k}
\]

\[
L = MH \left\{ 1 - \left( \frac{H}{H_k} \right)^2 \right\}^{1/2}
\]

From this expression we can write:

\[
\frac{1}{M} \frac{dL}{dH} = \frac{1 - 2(\frac{H}{H_k})^2}{\left[ 1 - \left( \frac{H}{H_k} \right)^2 \right]^{3/2}}
\]

In general, one cannot give an explicit equation for the torque as a function of the angle \( \alpha \). However, the torque equation can be solved with the computer:

\[
2h \sin(\alpha - \phi) = \sin 2\phi = 2 \sin \phi \cos \phi
\]

\[
h \sin \alpha \cos \phi - h \cos \alpha \sin \phi = \sin \phi \cos \phi
\]

From the theory of envelopes, we recognize that if we set:

\[
x = h \sin \alpha
\]

\[
y = h \cos \alpha
\]

the equation \( F(\phi) = x \cos \phi - y \sin \phi - \sin \phi \cos \phi = 0 \)

is the equation of a straight line whose characteristic point has for coordinates, the solution of the following two equations:
\[ F(\phi) = x \cos \phi - y \sin \phi - \sin \phi \cos \phi = 0 \]
\[ F'(\phi) = -x \sin \phi - y \cos \phi - (\cos^2 \phi - \sin^2 \phi) = 0 \]
\[ x = \sin^3 \phi \]
\[ y = -\cos^3 \phi \]

In general, through a point \((x, y)\) we can draw four tangents to the astroid, (real or imaginary).

II.2 Numerical Solution of Stoner-Wohlfarth Model.

For a computer solution, it is more advantageous to find these four solutions in a different manner however:

Let us set \( Z = \tan \frac{\phi}{2} \)

Then the torque equation becomes:
\[ x \frac{1-Z^2}{1+Z^2} - \gamma \frac{2Z}{1+Z^2} - 2Z \frac{1-Z^2}{(1+Z^2)^2} = 0 \]

which can be written as:
\[ Z^4 + \frac{2}{x} (\gamma - 1) Z^3 + \frac{2}{x} (\gamma + 1) Z - 1 = 0 \]

The problem is to find the roots of this fourth degree polynomial. The computer 7040 has a sub-program called POLRT which solves for the roots of a polynomial up to the 36th degree by the Newton-Raphson approximation method.

The torque was computed for values of \( \alpha \) spaced every 15° apart and for values of the reduced field equal to .25, .4, .5, .6, .75, 1.0, 1.5, 2.0, 4.0.

A few details for the torque curves were needed around \( \alpha = 90° \). Two other programs were written, derived from the first program by changing 3 cards in each case.
In order to get a better accuracy for the extremum of the curves -

\[ L = f(H) \] for given \( \alpha \), one can write the following:

\[ L = \text{Torque} = K \sin 2\phi = MH \sin(\alpha - \phi) \quad \alpha = C \text{st} \]

\[
\frac{dL}{dH} = K \frac{2 \cos 2\phi}{dH} \frac{d\phi}{dH} = 2MK \frac{\cos 2\phi \sin(\alpha - \phi)}{2K \cos 2\phi + MH \cos(\alpha - \phi)}
\]

If \( \alpha = \phi \) then \( H \) is infinite.

If \( \phi = \frac{\pi}{4} \) then, the maximum torque of \( K \) occurs for \( h = \frac{1}{2 \sin(\alpha - \frac{\pi}{4})} \)

Numerical values for this curve can be easily calculated.

Results for the torque curves as a function of \( \alpha \) (\( h = \text{constant} \)) are presented in figures 17 and 18. We see that in the range \( h > 1 \), only two real solutions exist. In the range \( 0.5 < h < 1 \), two or four real solutions exist and for \( h < 0.5 \), we have four real solutions. The hysteresis for \( 0.5 < h < 1 \) is shown in figure 18, A, B, C.

The question of knowing whether a mathematical solution is acceptable physically is determined by the sign of \( \frac{d^2W}{d\phi^2} \)

\[ W = K \sin^2 \phi - MH \cos(\alpha - \phi) \]

\[ \frac{dW}{d\phi} = K \sin 2\phi - MH \sin(\alpha - \phi) \]

\[ \frac{d^2W}{d\phi^2} = 2K \cos 2\phi + MH \cos(\alpha - \phi) > 0 \]

\[ \cos^2 \phi - \sin^2 \phi + h(\cos \alpha \cos \phi + \sin \alpha \sin \phi) > 0 \]

\[ x \sin \phi + y \cos \phi + \cos^2 \phi - \sin^2 \phi > 0 \]

\[ x \frac{2Z}{1+Z^2} + y \frac{1-Z^2}{1+Z^2} + \left(\frac{1-Z^2}{1+Z^2}\right)^2 - \frac{4Z^2}{(1+Z^2)^2} > 0 \]

or, \[ Z^4(1-\gamma) + 2xZ^3 - 6Z^2 + 2xZ + \gamma > 0 \]
The results for the torque curves as a function of $H$ ($\alpha = \text{const}$) are presented in figures 19 and 20. The details we mentioned previously around $\alpha = 90^\circ$, are presented in figure 21. Figure 22 gives the deviation $\alpha - \phi$ as a function of $\alpha$ for $h \gg 1$ and figure 23 is a different presentation $\phi = f(\alpha)$ for the rotation model. We note that the rotation equation can be rewritten as:

$$\cos \alpha = \cos \phi \left\{ - \frac{\sin^2 \phi}{h} + \sqrt{1 - \frac{\sin^2 2\phi}{4h^2}} \right\}$$

In parenthesis, let us notice that in the case of a bias field of magnitude $H$ and angular position $\alpha$, the torque curves for the rotation model would be obtained from the solutions of the 4th degree polynomial given previously. However, in this case:

$$x = h \sin \alpha + H_r \sin \alpha$$

$$y = h \cos \alpha + H_r \cos \alpha$$

where $H_r = \frac{H}{H_k}$. Two programs were written for the solution of this problem; one according to Bairstow's polynomial factorization method, the other one by the previously mentioned Newton-Raphson method using the available POLRT sub-program from the computer library. The same values as before were used for magnitude and angular position of the rotating field. For the bias field angular positions of $0^\circ$, $45^\circ$, $90^\circ$, $135^\circ$, $180^\circ$, were used, and magnitudes of $H_r = 0, 0.1, .25, .5, 1, 2, 4$.

Both methods give the same numerical answers. In particular for $H = 0$, both methods reproduce the answers given by the first program (rotation model without bias).
II. 3 Experimental Torque Curves vs Angle of Rotation.

Doyle, Feldtkeller, and many others have reviewed different experimental methods for determining the anisotropy field $H_k$ in ferromagnetic thin films. Doyle, in particular, gives also a method to determine both angular and magnitude dispersion in the anisotropy. In figure 24, are shown the experimental torque curves versus angle for different values of rotating field (Reminder: 1° = 8 oe).

The film is 1-23rd #2 thickness 670 A°. Therefore following Chapter I calibration:

$$K \times 670 \times 10^{-8} \times 3.14 \times \frac{3.14}{4} = 2.8 \times 10^{-3} \times 2.2$$
$$\chi = 1170 \text{ ergs/cm}^3 = 117 \text{ MKS}$$

$$\frac{2K}{M} = \frac{117 \times 2}{234} \text{ MKS} = 2.9 \text{ oe}$$

The B-H loop tracer gives $H_k = 3$ oe. The agreement is satisfactory. We notice several departures from the rotation model. In particular at high field some hysteresis is present. This is usually attributed to dispersion. At 4 oe rotating field, for example, we already have significant hysteresis losses when the rotation model does not predict any. On the other hand, as the field increases, hysteresis should start at $h = 1/2$ according to the rotation model. This prediction is not verified in most cases, although in the present case no significant departure is noticeable. As is well known, the most serious objection to the rotation model especially in the lower field range is that it ignores the existence of domain walls. However, the general features predicted by the model are found in the actual thin films.
In figure 25, the torque curves versus H field for constant values of the angular position of the field are given for the same film 1 - 23rd -1967 #2. The 90° curve shows that \( H_k = 3.2 \) oe. If we consider the value of H for which the extremum occurs, we find \( \frac{H_k}{\sqrt{2}} = 2.4 \) or \( H_k = 3.4 \) oe. The shape of the curves for various values of the angle \( \alpha \) agree fairly well with the rotation model predictions. The angular dispersion, determined from the irreversibility of the increasing and decreasing values of H curves is about 6° which is a rather large and exceptional dispersion compared with most of the films made in the laboratory. No determination of the anisotropy magnitude dispersion was carried out. In the following chapters, we will always determine the anisotropy constant from the high field torque curves. When necessary the anisotropy field will be determined from the measured anisotropy constant \( K \) and the bulk magnetization of the material such as given by Bozorth.

II. 4 Model for Non-Interacting Regions with Angular Dispersion.

The rotation model, in spite of its inherent over-simplification, has however been used as a foundation to which several types of anisotropies were added to explain features related to particular thin films. Coren and Juretschke, Cundall and King, Brukiewa and Coren have given models including angular dispersion or magnitude dispersion or both, assuming interaction or non-interaction between the regions of different anisotropies. The following discussion is an effort in the same direction.

Let us assume two regions with the same anisotropy magnitude and angular dispersion \( \varepsilon \), and no interaction between regions. Then, the energy is
\[ W = \frac{K}{2} \sin^2 \phi + \frac{K}{2} \sin^2 (\phi + \varepsilon) - MH \cos (\alpha - \phi) \]

In first approximation, assuming \( \varepsilon \) small, one obtains:

\[ W = K \sin^2 \phi + K\varepsilon \sin \phi \cos \phi - MH \cos (\alpha - \phi) \]

Minimizing the energy:

\[ \frac{dW}{d\phi} = K \sin 2\phi + K\varepsilon \cos 2\phi - MH \sin (\alpha - \phi) = 0 \]

The torque \( L \) is therefore:

\[ L = MH \sin (\alpha - \phi) = K \sin 2\phi + K\varepsilon \cos 2\phi \]

If one sets \( x = h \sin \alpha \) then \( \phi \) is the solution of the equation:

\[ F(\phi) = x \cos \phi - y \sin \phi - \frac{1}{2} \sin 2\phi - \frac{1}{2} \varepsilon \cos 2\phi = 0 \]

The characteristic point of this straight line is a solution of the two following equations:

\[ F(\phi) = x \cos \phi - y \sin \phi - \frac{1}{2} \sin 2\phi - \frac{1}{2} \varepsilon \cos 2\phi = 0 \]

\[ F'(\phi) = -x \sin \phi - y \cos \phi - \cos 2\phi + \varepsilon \sin 2\phi = 0 \]

The solution to these equations is:

\[ x = \sin^3 \phi + \frac{\varepsilon}{2} \cos \phi \left( 1 + 2 \sin^2 \phi \right) \]

\[ y = \cos^3 \phi + \frac{\varepsilon}{2} \sin \phi \left( 1 + 2 \cos^2 \phi \right) \]

Which should look like an astroid. No numerical calculations were carried out; however, it would be rather simple to construct this curve for values of the dispersion equal to 2°, 4°, ---10° for example.

To obtain the torque curves, one would start as previously from
\[ x \cos \phi - y \sin \phi - \sin \phi \cos \phi - \frac{\varepsilon}{2} (\cos^2 \phi - \sin^2 \phi) = 0 \]

and set \( \frac{\phi}{2} = z \)

One is then led to find the roots of a polynomial of fourth order:
\[
\left( x + \frac{\varepsilon}{2} \right) z^4 + 2(y-1) z^3 - 3\varepsilon z^2 + 2(y+1)z - (x-\varepsilon) = 0
\]

Numerical solutions could be obtained with a program very similar to the first program, by adding one loop to the program to take the dispersion into account.

II. 5 Model for Non-Interacting Regions with Angular and Magnitude Dispersion.

Let us assume now that we have as before no interaction between two regions of anisotropy constants \( K_1 \) and \( K_2 \) with angular dispersion \( \varepsilon \).

Then \( W_{an} = \frac{1}{2} K_1 \sin^2 \phi + \frac{1}{2} K_2 \sin^2 (\phi + \varepsilon) \)

Considering \( \sin (\phi + \varepsilon) = \sin \phi + \varepsilon \cos \phi \)

and neglecting second order terms:

\[ W_{an} = \frac{1}{2} K_1 \sin^2 \phi + \frac{1}{2} K_2 \sin^2 \phi + \varepsilon K_2 \sin \phi \cos \phi \]

We note that if \( \varepsilon = 0 \), then the problem would be trivial since we would have to assume \( K_{eq} = \frac{K_1 + K_2}{2} \).

The total energy \( W \) is therefore:

\[ W = \frac{K_1 + K_2}{2} \sin^2 \phi + \varepsilon K_2 \sin \phi \cos \phi - MH \cos (\alpha - \phi) \]

Minimizing the energy:

\[ \frac{dW}{d\phi} = \frac{K_1 + K_2}{2} \sin 2 \phi + \varepsilon K_2 \cos 2 \phi - MH \sin (\alpha - \phi) = 0 \]
The torque is therefore given by:

\[ L = MH \sin (\alpha - \phi) = \frac{1}{2} (K_1 + K_2) \sin 2 \phi + \varepsilon K_2 \cos 2 \phi \]

Now, \( \phi \) is a solution of the following equation:

\[ F(\phi) = x \cos \phi - y \sin \phi - (H_{k1} + H_{k2}) \sin \phi \cos \phi - \varepsilon H_{k2} (\cos^2 \phi - \sin^2 \phi) = 0 \]

where \( x = 2 H \sin \alpha \)

\[ y = 2 H \cos \alpha \]

The characteristic point of this straight line is given by:

\[ F'(\phi) = -x \sin \phi - y \cos \phi - (H_{k1} + H_{k2}) \cos 2 \phi + 2 \varepsilon H_{k2} \sin 2 \phi = 0 \]

After proper elimination, one gets:

\[ x = (H_{k1} + H_{k2}) \sin^3 \phi + H_{k2} \varepsilon \cos \phi (1 + 2 \sin^2 \phi) \]

\[ y = (H_{k1} + H_{k2}) \cos^3 \phi + H_{k2} \varepsilon \sin \phi (1 + 2 \cos^2 \phi) \]

One can observe the similarity of this result to the previous one.

Note however that \( x = 2 H \sin \alpha \) and \( y = 2 H \cos \alpha \).

Numerical calculations and graphical representations could again be obtained for various assumed values of \( H_{k1}, H_{k2}, \varepsilon \).

The torque curves can be computed from the following equations:

\[ L = \frac{1}{2} (K_1 + K_2) \sin 2 \phi + \varepsilon K_2 \cos 2 \phi \]

where \( \phi \) is a solution of:

\[ x \cos \phi - y \sin \phi - \frac{H_{k1} + H_{k2}}{2} \sin 2 \phi - H_{k2} \varepsilon \cos 2 \phi = 0 \]

If we set \( \tan \frac{\phi}{2} = z \), \( z \) turns out to be the zeros of a 4\(^{th}\) order polynomial:

\[ (x + H_{k2} \varepsilon) z^4 - 2(H_{k1} + H_{k2} - y) z^3 - 6H_{k2} \varepsilon z^2 + 2 (y + H_{k1} + H_{k2}) z + H_{k2} \varepsilon - x = 0 \]

Again solutions can be obtained and torque curves computed by this method. Also, we note that the previous method can be extended to any number of regions.
CHAPTER III

Experimental Results on Magnetic Anisotropy

In Ni-Fe Thin Films

III. 1  Design of a Cooling System.

The order to quench thin films at different rates, a cooling system was designed. The heat transfer rate $q_c$ from the surface of a solid to a fluid is defined as: $q_c = A h_m (t_w - t)$, where $h_m$ is the coefficient of heat transfer from surface to fluid, excluding any radiation, $A$ is the area of the surface, $t_w$ is the surface temperature of the wall, and $t$ is the bulk temperature of the fluid. The heat transfer coefficient $h_m$ depends on some physical properties of the fluid, the dimensions of the apparatus, velocity of the fluid past the surface, on whether or not the fluid is changing phase and frequently on the temperature potential $\Delta t$.

Our design specifications therefore should include - 1/ a high surface to volume ratio. 2/ a good etancheity of the cooling system since it is to be used in a vacuum system. 3/ a high thermal conductivity of the block to be cooled and a low thermal conductivity for the tubing used to carry the cooling fluid in order to avoid heat transfer to the outside when the block is heated to a high heat sink temperature.

The third requirement leads us to choose copper for the block and would lead us to choose stainless steel for the tubing if it could be bent more easily. For flexibility, copper tubing was chosen since the heat transfer was not considered important. Fig. 26 shows how the system
was assembled and soldered.

The different cooling rates were obtained by using:

1/ Natural cooling: switching off the infra-red heating element and letting the system cool at its own speed. Although the cooling rate is not a linear function of time, and is dependent upon the initial temperature, (the final temperature is taken at the room temperature) several observations have shown that the cooling rate is approximately \( 0.5^\circ \text{c/min} \) in this case.

2/ Water cooling: switching off the infra-red heating element and running tap water through the cooling system. The heat of vaporization of water being 580 Cal/g, we expect relatively fast cooling from heat sink temperature (if it is greater than 100\( ^\circ \text{c} \)) to the boiling point of water at 100\( ^\circ \text{c} \) and slower cooling from 100\( ^\circ \text{c} \) to room temperature. No recording of the cooling rate with respect to time was made. However, an average of cooling rate measurements with water gave 12\( ^\circ \text{c/min} \).

3/ Liquid nitrogen cooling: by forcing liquid nitrogen to flow through the copper tubings after switching off the infra-red heating element, one gets an overall cooling rate from heat sink temperature to room temperature, of approximately 25\( ^\circ \text{c/min} \). However, the heat of vaporization of nitrogen being 48 Cal/g, one is not absolutely sure that, in the high temperature region (> 200\( ^\circ \text{c} \)) where diffusion of atoms or rearrangement of dislocations, are more likely to occur, the cooling rate of liquid nitrogen is actually twice as large as in the case of water.

In conclusion, the previous design has allowed us to obtain values of cooling rates in the range .5\( ^\circ \text{c/min} \) to 25\( ^\circ \text{c/min} \).
III. 2 Results of Cooling-Rate Experiments.

The following experiments were designed to test the influence of the cooling rate on the anisotropy constant.

The films were evaporated in a varian vacuum system (mechanical + diffusion pump) at normal incidence from a flat rectangular tungsten boat $\frac{\alpha" \times 1"}{2}$ by sending 300 amperes through its ends. The distance between the substrates (corning 0211) and the tungsten boat being approximately 7" only four films 1 cm in diameter were made at each evaporation in order to avoid any angle of incidence effect. The melt was made of 81-19 perm-alloy wire wound in a helix shape (length of wire being 4 inches). The magnetic field applied during deposition was 36 oe. Two films were made at a thickness of 400 A° and the two remaining ones at a thickness of 800 A°.

<table>
<thead>
<tr>
<th>Film</th>
<th>Vacuum Pressure</th>
<th>Deposition Rate</th>
<th>Heat Sink Temper.</th>
<th>Cooling</th>
<th>K (cgs) Torque</th>
<th>H_k (oe)</th>
<th>H_c (oe)</th>
<th>BH Loop</th>
<th>B-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-2nd-67 #5</td>
<td>Before</td>
<td>300 Amp.</td>
<td>400°c</td>
<td>Water</td>
<td>1560</td>
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<td>5.0</td>
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<tr>
<td>#6</td>
<td>4x10^-7</td>
<td></td>
<td></td>
<td></td>
<td>1600</td>
<td>4.0</td>
<td>3.0</td>
<td>5.0</td>
<td></td>
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<tr>
<td>#8</td>
<td>During</td>
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<td></td>
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<td>5.1</td>
<td>3.0</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>#9</td>
<td>$\omega$10^-6</td>
<td></td>
<td></td>
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<td>2000</td>
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<td>3.0</td>
<td>5.0</td>
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<td>300 Amp.</td>
<td>400°c</td>
<td>Water</td>
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<td>3.0</td>
<td>4.0</td>
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<td></td>
<td></td>
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<td>35A°/Sec</td>
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<td></td>
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<td>3.0</td>
<td>5.0</td>
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<td>Film</td>
<td>Vacuum Pressure</td>
<td>Deposition Rate</td>
<td>Heat Sink Temp.</td>
<td>Cooling</td>
<td>K(cgs) Torque</td>
<td>H_k(oe) Torque</td>
<td>H_c(oe) BHloop</td>
<td>H_k(oe) BHloop</td>
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<tr>
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<td>1600</td>
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<td>3.5</td>
<td>4</td>
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</tr>
<tr>
<td>#4</td>
<td>35A/Sec</td>
<td></td>
<td></td>
<td>2040</td>
<td>5.1</td>
<td>3</td>
<td>5</td>
<td></td>
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<td></td>
<td>1960</td>
<td>4.9</td>
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<td>12-5th-67 #1</td>
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<td>300 Amp.</td>
<td>400°c</td>
<td>Natural</td>
<td>1650</td>
<td>4.1</td>
<td>3.5</td>
<td>5</td>
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<tr>
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<td>Cooling</td>
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<tr>
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<td></td>
<td>1870</td>
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<td></td>
</tr>
<tr>
<td>#5</td>
<td>~10^{-6}Torr</td>
<td></td>
<td></td>
<td>1870</td>
<td>4.7</td>
<td>2.5</td>
<td>5.5</td>
<td></td>
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</tr>
</tbody>
</table>

The films once deposited at 400°c were annealed at that temperature for one to two hours. The cleaning procedure used for the preparation of the substrates was the following:

1/ 10 minutes of ultrasonic cleaning in acetone.

2/ 10 minutes of ultrasonic cleaning in methanol.

3/ 10 minutes of ultrasonic cleaning in acetone.

If one compares the 800 A° films among themselves, or the 400 A° films among themselves, one does not observe any drastic variation in the anisotropy field. The anisotropy field was computed from the anisotropy constant by taking $M = 1.0$ MKS. Although the cooling rate must still be considered as an important parameter, it seems that one needs a much larger heat sink to reach the high values of cooling rates that would provide a true quenching of the system. However, the cooling system as designed allows
a considerable saving of time in the annealing process and will be used to make deposition at low temperatures. Also we note that the difference in $H_k$ values between the 400 A° films and the 800 A° films is probably due to the fact that the films do not have a nonmagnetostrictive composition, since as pointed out by West\textsuperscript{14} the films are probably slightly iron-rich due to the alloying of the Ni with the tungsten boat. In such a case, we can expect the stress distribution in the film to contribute slightly to the anisotropy and be dependent upon thickness.\textsuperscript{15,16} One method of minimizing these composition gradients is to avoid evaporating as the permalloy is just starting to melt, but wait until a steady homogeneous composition can be expected (20 sec. when the rate of evaporation is 35 A°Sec). No temperature higher than 400°C was tried, since the softening temperature of the substrate being around 500°C - 600°C, impurities from the substrate might have started diffusing into the thin film and influencing the anisotropy constant.\textsuperscript{16} The Curie temperature for this composition is close to 600°C according to Bozorth. Subsequent annealing of films 11-2-67 and 11-6-67 in the easy direction and applied magnetic field of 36 oe with heating rate of 5°C/min, annealing for 4 hours at 300°C and water cooling gave the same values for the anisotropy constant as may have been expected, within experimental precision.

III. 3 Results on Easy-Axis Annealing on 81-19 films Deposited at Room Temperature and Liquid Nitrogen Temperature. (Heat Sink Temperatures)
<table>
<thead>
<tr>
<th>Film</th>
<th>Vacuum Pressure</th>
<th>Deposition Rate</th>
<th>Heat Sink Annal Temp.</th>
<th>Cooling</th>
<th>Annealing Time</th>
<th>K (CGS)</th>
<th>H_{k} (oo)</th>
<th>H_{c} (oo)</th>
<th>H_{k} (oo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-9-67#1</td>
<td>Before</td>
<td>300 Amp</td>
<td>50°C</td>
<td>Water</td>
<td>4 hrs.</td>
<td>2090</td>
<td>5.3</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>#2</td>
<td>5x10^{-7}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2180</td>
<td>5.5</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>#4</td>
<td>During</td>
<td>35A/Sec</td>
<td></td>
<td></td>
<td></td>
<td>2760</td>
<td>6.9</td>
<td>1.8</td>
<td>7</td>
</tr>
<tr>
<td>#5</td>
<td>~10^{-6}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2760</td>
<td>6.9</td>
<td>2.2</td>
<td>7</td>
</tr>
<tr>
<td>11-9-67#1</td>
<td></td>
<td></td>
<td>175°C</td>
<td>Water</td>
<td>6 hrs.</td>
<td>2140</td>
<td>5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>2x10^{-7}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2220</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2320</td>
<td>5.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2670</td>
<td>6.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11-9-67#1</td>
<td></td>
<td></td>
<td>300°C</td>
<td>Water</td>
<td>6 hrs.</td>
<td>2260</td>
<td>5.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>2x10^{-7}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2180</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2500</td>
<td>6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>11-9-67#1</td>
<td></td>
<td></td>
<td>400°C</td>
<td>Water</td>
<td>5 hrs.</td>
<td>2050</td>
<td>5.2</td>
<td>5</td>
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</tr>
<tr>
<td>#2</td>
<td>3x10^{-7}</td>
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<td>2000</td>
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<td>5</td>
<td>7</td>
</tr>
<tr>
<td>#4</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>6.7</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>#5</td>
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<td></td>
<td>2760</td>
<td>6.9</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

In the previous table, N° 1, 2 films are 800° A, N° 5, 4 are 400° A thick. As shown by torquemeter measurements, the films stay uniaxial throughout the magnetic annealing treatment. However, the B-H loop data reveal that the coercive force increases in such a way that the films tend to show identical B-H loops in the easy as well as in the hard direction.
Since the opening of the hard axis loop is related to the dispersion in the films which in turn is related to grain size, we can conclude that easy direction annealing in the present case does not change appreciably the anisotropy constant (it may decrease slightly). However, it increases the coercive force, the dispersion and the grain size - all properties seemingly related to inclusions, imperfections and more generally dislocations. We note that this result does not seem too surprising since most workers in the field attribute anisotropy for this composition to an iron-pair ordering mechanism ($\sim 80\%$) which is not perturbed by a magnetic annealing well below Curie temperature. However, vacancies or imperfections can diffuse more easily and migrate to the boundaries of the grains which increase in size where they collapse, resulting in a weaker density of imperfections.

Films were deposited at liquid nitrogen temperature by circulating liquid nitrogen in the cooling system for about an hour until the substrate holder was cool enough so that liquid nitrogen at the input exhausted in liquid form at the output and by maintaining this flow for about 30 minutes.

It is not obvious that films with uniaxial anisotropy can be made in this way since one is not even sure that the metal deposit will stick well to the substrate (adhesion). On the other hand, the diffusion properties as well as the stress system, to mention only two of the most important components of uniaxial anisotropy, are -
<table>
<thead>
<tr>
<th>Film</th>
<th>Vacuum Pressure</th>
<th>Deposition Rate</th>
<th>Heatsink Anneal Temp.</th>
<th>Heating Cooling</th>
<th>Annealing Time</th>
<th>K (cgs)</th>
<th>H' (oe)</th>
<th>Hc (oe)</th>
<th>H'k(oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-15-67#1 Before</td>
<td>300 Amps</td>
<td>-196°C</td>
<td>From -196°C to -196°C</td>
<td>20 min. at</td>
<td>2100</td>
<td>5.8</td>
<td>2.8</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>1.5x10⁻⁷</td>
<td>35°/Sec</td>
<td>Room Temp 48°C/ min.</td>
<td>2100</td>
<td>5.3</td>
<td>2.2</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1780</td>
<td>4.5</td>
<td>1.8</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>4x10⁻⁷</td>
<td></td>
<td></td>
<td></td>
<td>2050</td>
<td>5.2</td>
<td>2.0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>11-15-67#1 3x10⁻⁷</td>
<td></td>
<td>300°C</td>
<td>Water 4 hrs.</td>
<td>2140</td>
<td>5.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td></td>
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<td></td>
<td></td>
<td>2230</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1780</td>
<td>4.5</td>
<td></td>
<td>Not Meas.</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2100</td>
<td>5.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11-15-67#1 3x10⁻⁷</td>
<td></td>
<td>400°C</td>
<td>Water 5 hrs.</td>
<td>2050</td>
<td>5.2</td>
<td>4.0</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2</td>
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<td></td>
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<td>1830</td>
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<td>4.0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2050</td>
<td>5.2</td>
<td>3.5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2140</td>
<td>5.4</td>
<td>3.5</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

certainly dependent on the deposition temperature. This dependence will be discussed in the next chapter. For the moment, we will take for granted the fact that one can deposit 81-19 Ni Fe films on glass substrates at -196°C and obtain uniaxial films. The observation of the B-H loops showed that the films after being first prepared had a very low dispersion (hard axis loop being a straight line). However, after the last anneal at 400°C, conclusions were reached which were similar to those reached about room temperature deposited films. It is to be noticed that all magnetic properties of thin films were measured at room temperature. Only one curve was
drawn through the experimental points, although two curves ought to have been drawn since we considered two different thicknesses of films. The previous results are summarized in figures 27, 28, 29.

III. 4 Results of Experiments on Uniaxial Anisotropy versus Heat Sink Temperature for 81-19 Ni-Fe Composition Melt.

Three evaporations made from 81-19 melt have already been reported. The heat sink temperatures were 400°c, 50°c, -196°c. Four more evaporations were made at intermediate temperatures. The annealing time at deposition temperature was four hours (although from the previous results, one is lead to believe that no annealing at all would give the same results).

<table>
<thead>
<tr>
<th>Film</th>
<th>Vacuum Pressure</th>
<th>Deposition Rate</th>
<th>Heat Sink Temp.</th>
<th>Cooling</th>
<th>Annealing Time</th>
<th>K (cgs) Torque</th>
<th>H_e (oe) Torque</th>
<th>H_u (oe) BH Loop</th>
<th>H_v (oe) BH Loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-25-67#1</td>
<td>Before</td>
<td>300 Amp.</td>
<td>150°c</td>
<td>Water</td>
<td>4 hrs.</td>
<td>2000</td>
<td>5.0</td>
<td>2.5</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>#2</td>
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<td></td>
<td></td>
<td></td>
<td>2000</td>
<td>5.0</td>
<td>2.5</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3x10^{-7}</td>
<td></td>
<td></td>
<td></td>
<td>1960</td>
<td>4.9</td>
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<td>5.5</td>
</tr>
<tr>
<td></td>
<td>#4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1960</td>
<td>4.9</td>
<td>2.1</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>#5</td>
<td></td>
<td>10^{-6}</td>
<td></td>
<td></td>
<td>1960</td>
<td>4.9</td>
<td>2.1</td>
<td>5.5</td>
</tr>
<tr>
<td>11-27-67#1</td>
<td>Before</td>
<td>300 Amp.</td>
<td>200°c</td>
<td>Water</td>
<td>4 hrs.</td>
<td>2140</td>
<td>5.4</td>
<td>3.0</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>#2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2140</td>
<td>5.4</td>
<td>2.0</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4x10^{-7}</td>
<td></td>
<td></td>
<td></td>
<td>2140</td>
<td>5.4</td>
<td>2.0</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>#4</td>
<td></td>
<td>35A^0/Sec</td>
<td></td>
<td></td>
<td>2220</td>
<td>5.6</td>
<td>1.8</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>#5</td>
<td></td>
<td>10^{-6}</td>
<td></td>
<td></td>
<td>2050</td>
<td>5.2</td>
<td>2.1</td>
<td>5.5</td>
</tr>
<tr>
<td>11228-67#1</td>
<td>Before</td>
<td>300 Amp.</td>
<td></td>
<td>Water</td>
<td>4 hrs.</td>
<td>2130</td>
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<td>1.8</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>2100</td>
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<td>1.8</td>
<td>5.5</td>
</tr>
<tr>
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<td>1960</td>
<td>4.9</td>
<td>1.6</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>#4</td>
<td></td>
<td>35A^0/Sec</td>
<td></td>
<td></td>
<td>2220</td>
<td>5.6</td>
<td>2.0</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>#5</td>
<td></td>
<td>10^{-6}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FILM</td>
<td>Vacuum Pressure</td>
<td>Deposition Rate</td>
<td>Neatsink Temp.</td>
<td>Cooling</td>
<td>Annealing Time</td>
<td>K (CGS) Torque</td>
<td>H_k (oe) Torque</td>
<td>H_x (oe)</td>
<td>H_L (oe)</td>
</tr>
<tr>
<td>-------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>---------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>12-6-67#1</td>
<td>Before 300 Amp.</td>
<td>350°c</td>
<td>Water 4 hrs.</td>
<td>1650</td>
<td>4.2</td>
<td>2.2</td>
<td>4.8</td>
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<td></td>
</tr>
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<td></td>
<td></td>
<td>1690</td>
<td>4.3</td>
<td>Nc. Meas.</td>
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<tr>
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<td>During 35A/Sec</td>
<td></td>
<td></td>
<td>1870</td>
<td>4.7</td>
<td>2.2</td>
<td>4.8</td>
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</tr>
<tr>
<td>#5</td>
<td>n 10^{-6}</td>
<td></td>
<td></td>
<td>1960</td>
<td>4.9</td>
<td>2.2</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 30 summarizes the previous results. Only the 800 A° films were considered. The interpretation of these data will be attempted in Chapter IV.

III. 5 Results of Experiments on Uniaxial anisotropy versus Heat Sink Temperature for Ni (99.9%).

Three evaporations were made with pure Nickel at the heat sink temperatures of -196°c, 20°c, 300°c. Since the rotating field of the torque-meter is limited to 56 oe, it will not be possible to measure the anisotropy constant by the usual method in the event that H_k > 56 oe.

In this case the torque curves for all H < 56 oe will show 360° symmetry and not 180° symmetry:

The torque equation can be written:

\[ L = K \sin 2\phi = MH \sin(\alpha - \phi) \]

For \( \alpha = 90° \)

\[ \sin \phi = \frac{MH}{2K} \quad \cos \phi = \left(1 - \frac{M^2 H^2}{4K^2}\right)^{1/2} \]

\[ K = \frac{M^2 H^2}{2 \left(M^2 H^2 - L^2\right)^{1/2}} \]

L is the torque per unit volume.

The nickel melt was cut in small parallepipeds \( 1 \times 1 \times 2 \text{ cm}^3 \) weighing each approximately .18 g.
The same tungsten boat and the same rate of evaporation were used. The cleaning procedure and the glass substrates (0211) were again utilized in the same fashion.

The annealing times at deposition temperatures of $20^\circ C$ and $300^\circ C$ in a magnetic field of 36 oe were of four hours. However, at $-196^\circ C$, the annealing time was reduced to a mere 20 minutes to a half hour.

<table>
<thead>
<tr>
<th>Film</th>
<th>Vacuum Pressure</th>
<th>Deposition Rate</th>
<th>Heat Sink Anneal Temp</th>
<th>Cooling</th>
<th>Annealing Time</th>
<th>K (cgs) Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-29-67#1</td>
<td>Before</td>
<td>300 Amp</td>
<td>30$^\circ C$</td>
<td>Water</td>
<td>4 hours</td>
<td>9700</td>
</tr>
<tr>
<td>#2</td>
<td>$5 \times 10^{-7}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9700</td>
</tr>
<tr>
<td>#4</td>
<td>During</td>
<td>35A$^\circ$/Sec</td>
<td></td>
<td></td>
<td></td>
<td>9800</td>
</tr>
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<td>#5</td>
<td>$\sim 10^{-6}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9750</td>
</tr>
<tr>
<td>12-1st-67#1</td>
<td>Before</td>
<td>300 Amp</td>
<td>300$^\circ C$</td>
<td>Water</td>
<td>4 hours</td>
<td>780</td>
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<tr>
<td>#2</td>
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<td></td>
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<td>980</td>
</tr>
<tr>
<td>#4</td>
<td>During</td>
<td>35A$^\circ$/Sec</td>
<td></td>
<td></td>
<td></td>
<td>450</td>
</tr>
<tr>
<td>#5</td>
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<td></td>
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<td>450</td>
</tr>
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<td>12-11th-67#1</td>
<td>Before</td>
<td>300 Amp</td>
<td>$-196^\circ C$</td>
<td>Heater</td>
<td>20 Min.</td>
<td>9800</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>$7^\circ C$/Min</td>
<td></td>
<td>9800</td>
</tr>
<tr>
<td>#4</td>
<td>During</td>
<td>35A$^\circ$/Sec</td>
<td></td>
<td></td>
<td></td>
<td>11000</td>
</tr>
<tr>
<td>#5</td>
<td>$\sim 10^{-6}$</td>
<td></td>
<td></td>
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<td>10600</td>
</tr>
</tbody>
</table>

III. 6  Results of Experiments on Uniaxial Anisotropy versus Heat Sink Temperature for 50-50 Ni-Fe.

The experimental conditions were identical to those used previously.
Three evaporations at heat sink temperatures of -196°C, 50°C, 260°C, were made. Again when the driving field limitations of the instrumentation were reached the anisotropy constant was estimated by the formula given in III.5. The 50-50 Ni Fe melt was cut from an orthonol ribbon used for transformers in 4 inches long cuts.

Fig. 31 summarizes the results obtained for Ni and Ni-Fe (50-50) for the 800°A films. (The average for the two 800 A° films made was actually drawn). In the case of Ni, or 50-50 NiFe no annealing experiments were carried out.

For Ni, one expects uniaxial anisotropy to originate primarily from magnetostriction and stresses.

For the 81-19 composition, the so-called non magnetostrictive composition, the uniaxial anisotropy seems to have its source primarily in the iron-pair ordering mechanism in the Ni lattice.

For the 50-50 NiFe composition, both magnetostriction and iron-pair ordering are present.

As reported by many workers in the field, many other sources of uniaxial anisotropy such as imperfections and impurities seem to contribute to the total uniaxial anisotropy.

<table>
<thead>
<tr>
<th>Film</th>
<th>Vacuum Pressure</th>
<th>Deposition Rate</th>
<th>Heat sink Anneal Temp.</th>
<th>Cooling</th>
<th>Annealing Time</th>
<th>K (CGS) Torque</th>
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<tr>
<td>12-7th-67#1</td>
<td>Before</td>
<td>300 Amp</td>
<td>260°C</td>
<td>Water</td>
<td>4 hours</td>
<td>25600</td>
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<tr>
<td>#2</td>
<td>$4 \times 10^{-7}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25800</td>
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<tr>
<td>#4</td>
<td>During</td>
<td>35A°/Sec</td>
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<td></td>
<td>25600</td>
</tr>
<tr>
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<td></td>
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<tr>
<td>Film</td>
<td>Vacuum Pressure</td>
<td>Deposition Rate</td>
<td>Heat sink Anneal Temp.</td>
<td>Cooling</td>
<td>Annealing Time</td>
<td>K (cgs) Torque</td>
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</tr>
<tr>
<td>12-8\textsuperscript{th} - 67#1</td>
<td>Before</td>
<td>300 Amp</td>
<td>50$^\circ$C</td>
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<td>25700</td>
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<tr>
<td>#4</td>
<td>During</td>
<td>35A\textsuperscript{0}/Sec</td>
<td></td>
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<td>25500</td>
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<tr>
<td>12-13\textsuperscript{th} - 67#1</td>
<td>Before</td>
<td>300 Amp</td>
<td>-196$^\circ$C</td>
<td>Heater</td>
<td>20 min.</td>
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CHAPTER IV

Review of Literature

It seems pertinent before discussing the results obtained experimentally to summarize briefly the existing theories or combination of them which give descriptions of the uniaxial anisotropy in thin films due to magnetic annealing. We will emphasize especially the heat sink and annealing temperature dependence.

IV. 1 Neel's Theory of Iron-Pair Ordering. 18, 19

IV. 1, A. Case of dilute solutions.

Suppose that A and B are the constituents of a solid solution and that calling $C_A$ and $C_B$ the respective concentrations of constituents A and B, we have $C_B \ll C_A$. Assume that the solid solution is treated at temperature $T_1$ (below the Curie temperature) in a magnetic field, $T_1$ being sufficiently high to make diffusion of atoms possible, for a sufficiently long time so that equilibrium is established. Assume that it is quenched to temperature $T_0$ sufficiently rapidly so that the equilibrium at $T_1$ is not modified. Assume that the temperature $T_0$ (usually room temperature) is low enough so that no change in this equilibrium is possible. Then a uniaxial anisotropy develops in the ferromagnetic material this anisotropy being certainly very weak as compared to $kT$, but detectable.

Consider the case of a polycrystalline substance, with isotropic distribution of interatomic bonds B-B.

Then the anisotropy constant per unit volume is given by:

$$C_s = \frac{nC_B^2 L^1 o L^1 N_B}{15 V kT_1} = \frac{nC_B^2 L^1 o L^1}{15 VRT_1}$$
\[ \lambda_{111} \times 10^6 = -27 c_A^2 + 134 c_A c_B + 13 c_B^2 \]
\[ \lambda_{100} \times 10^6 = -55 c_A^2 + 340 c_A c_B - 245 c_B^2 \]

One can therefore write (A = Ni, B = Fe)

\[
\begin{align*}
N_a l_{AA} &= \frac{9 V}{n N_a} \left\{ -27 c_{44} + 55 (c_{11} - c_{12}) \right\} 10^{-6} = 0.8 \times 10^8 \text{ ergs} \\
N_a l_{BB} &= \frac{9 V}{n N_a} \left\{ 13 c_{44} + 245 (c_{11} - c_{12}) \right\} 10^{-6} = 12 \times 10^8 \text{ ergs} \\
N_a l_{AB} &= \frac{9 V}{n N_a} \left\{ 134 c_{44} - 340 (c_{11} - c_{12}) \right\} 10^{-6} = -3.8 \times 10^8 \text{ ergs}
\end{align*}
\]
\[ N_1 = 2.0 \times 10^9 \text{ ergs.} \]

The temperature variation of these coupling coefficients, however, does not appear in any obvious way. Since they are linear functions of the magnetostriction constants one could assume a linear dependence from room temperature to Curie temperature. For iron the Curie temperature being 1040\(^{\circ}\)K, \((N_1 \text{Fe}_Fe)\) would decrease to zero at that temperature. For Ni, the Curie temperature being 650\(^{\circ}\)K, \((N_1 \text{NiNi})\) would decrease to zero at 650\(^{\circ}\)K.

However in the case of \((N_1 \text{Ni-Fe})\) one does not know what temperature to use.

IV.1.B. Ideal non-dilute solution.

In this case:
\[
C_s = \frac{n C_A^2 C_B^2 L_0 L_1}{15 \sqrt{V} R T_i}
\]

If one calls \(\nu = \nu_{AA} + \nu_{BB} - 2 \nu_{AB}\) the ordinary bond energies of nearest neighbours in the solution, taken two by two, the case of the ideal solution corresponds to \(\nu = 0\) according to Néel.

IV.1.C. Non-ideal, non-dilute solution.

In this case:
\[
C_s = \frac{n S L_0 L_1'}{15 \sqrt{V} R T_i}
\]

with
\[
S = \frac{4 C_A^2 C_B^2 \exp \left\{ \frac{-\nu}{k T_i} \right\}}{\sqrt{1 + x} \left( 1 + \frac{1}{\sqrt{1 + x}} \right)^2}
\]

For the Ni-Fe solid solutions \(\nu = 6 \times 10^{-10} \text{ ergs.}\)

The non ideality of the solution introduces a factor of .37 for \(C_A = 0\) or \(C_B = 0\), a factor of .68 for \(C_A = .25\) or \(C_B = .25\), a factor of .94 for \(C_A = C_B = .5\) with respect to the ideal case.

IV.2 Taniguchi's Theory of Iron Pair Ordering.\(^{23}\)

Starting from Van Vleck's formulation of crystalline anisotropy, Taniguchi derives the following equation -
\[ K = A' \frac{N n^2 C^2 B_1^2(T_0) B_1^2(T)}{kT_1} \]

\( A' \) Coefficient depending on crystal lattice.

\( n \) Concentration of B atoms assumed much smaller than 1.

\( C \) Coupling coefficient \( = C_{AA} + C_{BB} - 2C_{AB} \) at temperature \( T_1 \).

\( T_1 \) Annealing temperature.

\( T_0 \) Quenching temperature usually room temperature.

\( N \) Number of atoms per unit volume.

\( k \) Boltzmann constant

\( B_1 \) Reduced Brillouin function.

The reduced Brillouin function \( B_1(\theta) \) is related to the ordinary Brillouin function \( B(\theta) \) by the relationship -

\[ B_1(\theta) = S B(\theta) \]

\( S \) Spin quantum number of all atoms.

Plots of the Brillouin functions are available from different sources.

Also the dependence of the Curie temperature with composition of Ni-Fe can be found from several sources. In Taniguchi's paper, which followed Néel's paper, Taniguchi, comparing his formula of uniaxial anisotropy to Néel's, finds Néel's formulation advantageous in so far as Néel's derivation can be extended to non-dilute ferromagnetic solid solutions, whereas Taniguchi's derivation assumes \( n \ll 1 \). On the other hand, Taniguchi considers the temperature dependence of uniaxial anisotropy derived by Néel rather "obscure" whereas the reduced Brillouin function gives the temperature dependence of the anisotropy (except for the factor \( \frac{1}{T} \)) for Taniguchi's formulation.
IV. 3 Concluding comment.

From the user's point of view, both treatments although complex have only a limited value, when used to describe experiment. In fact some workers in the field of ferromagnetic anisotropy borrow the compositional dependence of anisotropy from Neél, and the temperature dependence of anisotropy from Taniguchi, ignoring in both cases the temperature dependence of these coupling coefficients. One would expect the coupling coefficient $L'_1$ in Neél's formula to go to zero at the Curie temperature of the alloy considered. However, the presence of the Brillouin function in Taniguchi's derivation already accounts for this fact. In the vicinity of the Curie temperature a dependence on annealing temperature of the form $T_c - T_1$ is valid as shown by Ferguson's experimental work. However, in the range of temperatures below $400^\circ$C this formulation ceases to be valid. Moreover, the temperature of annealing $T_1$ is often ill defined, since the rate of cooling cannot be made infinitely large.

We therefore have the three following possibilities.

\[ K \propto c^2 (1-c)^2 \frac{1}{T_1} \quad (\text{Neél}) \]

\[ K \propto n^2 \frac{B^2_i(T_i)}{T_i} \quad (\text{Taniguchi}) \]

(vicinity of Curie Temp.) \[ K \propto c^2 (1-c)^2 (T_c - T_1) \quad (\text{Lin. Approx.}) \]

For the determination of the proportionality constant it is often convenient to consider the value of $K$, at the non-magnetostrictive composition that is around 82% Ni, from experiment. Indeed, for this composition most workers attribute as much as 80% of the origin of uniaxial anisotropy to iron-pair ordering.
In Fig. 32, the anisotropy constant according to Taniguchi's theory is given as a function of both composition and substrate temperature \(^{27}\). The following formula has been used:

\[
K_d = 8.7 \times 10^7 \frac{n^2 B_1^2(T_i)}{T_1} \text{ ergs/cm}^3
\]

IV. 4 Magnetostrictive constraint.

Robinson\(^{28}\) showed that the uniaxial stress set at the temperature of annealing and constrained by the substrate at T' (possibly lower than T_1, deposition temperature) can contribute a uniaxial magnetic anisotropy.

\[
K_s = \frac{3}{2} \frac{\lambda_{T_0}}{\lambda_{T'}} E
\]

E = Young's modulus \(^{29}\) (1 kg/mm\(^2\) = 10\(^8\) dynes/cm\(^2\))

\(\lambda_{T_0}\) = Magnetostriction at room temperature (Bulk value\(^{32}\))

\(\lambda_{T'}\) = Magnetostriction at constraint temperature (Bulk value)

The magnetostriction is taken to decrease linearly with temperature and go to zero at Curie temperature. Bozorth and Walker\(^{30}\) give the values of the magnetostriction for different compositions at room temperature.

West\(^{31}\) showed that Robinson's calculation of the magnetostrictive contribution to the anisotropy on the basis of the average polycrystalline value of magnetostriction

\[
\lambda = \frac{3}{5} \lambda_{III} + \frac{2}{5} \lambda_{100}
\]

was not correct in principle from an energy average standpoint. His calculations lead to the following magnetostrictive anisotropy constant:

\[
K_s = \frac{9}{10} \left[ (c_{11} - c_{12}) \lambda_{100}(T_0) \lambda_{100}(T') + 3 c_{44} \lambda_{III}(T_0) \lambda_{III}(T') \right]
\]
When the iron-pair and the magnetostrictive contribution to the anistropy are added together, one obtains the total anisotropy constant.

In Fig. 33, we made the calculations for $T_0 = 20^\circ C$ and $T' = T_1 = 240^\circ C$. One sees that outside of the compositional range 65-95% Ni the differences between the West and Robinson methods start to show up. The iron-pair ordering anisotropy was arbitrarily set at 2000 ergs/cm$^3$ at 82% Ni composition for which $\lambda = \frac{3}{5} \lambda_{iii} + \frac{2}{5} \lambda_{100}$ goes to zero.

As the temperature increases, both Robinson's and West's magnetostrictive contributions will decrease because of the dependence of the magnetostriction constants on temperature.

We note that the introduction of $T'$ as a new parameter gives one more degree of freedom to the problem of magnetic anisotropy. This approach was used by Beam and Siegle$^{33}$ to fit their experimental composition curves to the so-called pair-strain model.

However, as pointed out by West$^{31}$ it is not at all certain that the constraint temperature can be uniquely related to the deposition temperature, and in fact the constraint temperature must be related to the film-substrate adhesion. For weak film-substrate adhesion the constraint temperature could be as low as room temperature. For high film-substrate adhesion it could be as high as deposition temperature or even higher due to the kinetic energy of the incident Ni-Fe beam. In this sense the activation energy and relaxation time for this model are related to the strength of the film-substrate adhesion. The cleanliness of the substrate is important as one may expect, and according to Schossberger$^{34}$ et al., the adherence is better
for higher substrate temperatures. However the bonding energies are low for good vacua (presence of $0^2$ is necessary for high adhesion: chemisorption).

An objection to the film-substrate adhesion model is the fact that the constraint may arise from grain boundary interactions. Then the annealing kinetics would be determined by grain growth and grain boundary migration.

IV. 5 Imperfection Model - Kinetics.

Studies on the kinetics of the possible contributing processes to magnetic anisotropy in thin films have been performed by Kneer & Zinn$^{35}$. They performed annealing experiments on nearly magnetostriction free 81Ni-19Fe thin films. For the recording of an isotherm they switched the field in a hard-axis direction at a certain fixed annealing temperature, and recorded the variation of $H_\perp$ inside the vacuum system with a magnetoresistance method. The film considered was evaporated under the following characteristics -

\[ P = 10^{-8} \text{ Torr}, \ 10^{-7} \text{ Torr during deposition} \quad \vdash \quad R = 4 \text{ Å/sec} \]

\[ T_{\text{depos}} = 180^\circ \text{C} \]

Thickness = 370 Å

Annealing temperatures for the recording of isotherms -

\[ 180^\circ \text{C} - 400^\circ \text{C.} \]

There are in a film several species (i) of various pairs or existing defects which with the concentration $n_1$ and the anisotropy energy $\xi_1$ contribute to the entire anisotropy of the film. Assuming a reaction of order 1 and a temperature $T$: 
\[ H_k = \sum_i H_{k_i}^{(0)} \left[ 2 \exp \left\{ -\frac{t}{\tau_i} \right\} - 1 \right] \]

\[ \tau_i = \tau_{i0} \exp \left\{ \frac{E_i}{kT} \right\} \quad \text{Arrhenius relation} \]

\[ H_{k_i} = 2n_i \varepsilon_i / M \]

\( E_i \) is the activation energy of process (i)

\( M \) Magnetization

\( t \) Time

\( \tau_i \) Relaxation time at temperature T

\( \tau_{i0} \) Relaxation time at temperature \( T = \infty \) (extrapolated)

Kneer and Zinn were able to identify four processes by a least mean square error computer fitting for the experimental isotherms carried out at various temperatures \( T \). These processes have discrete activation energies and relaxation times. However, they cannot be identified with possibly similar processes in bulk; the phenomena of formation and migration of different dislocation processes could indeed require activation energies and relaxation times that are different in thin films from bulk. The process with an activation energy of 1.5 eV and relaxation time of \( 2 \times 10^{-8} \) Sec has been assigned to the ordering of iron pairs.

Fig. 34 (a) and (b) summarizes the results.

Similar experiments were performed by Kneer and Zinn for magnetostrictive compositions of Ni-Fe films, in particular for Ni films. The conditions of evaporations were the following:

\[ P = 10^{-8} \text{ Torrs before evaporation, } 10^{-7} \text{ during.} \]

\[ R = 3^\circ \text{A/sec} \quad : \quad T_{\text{deposition}} = 205^\circ C \]

Thickness = 300 - 600 A°
For the recording of each isotherm the field is switched to the original axis brought to the desired temperature for as long a time as necessary to stabilize the magnitude of $H_k$ (See Fig. 37). In Ni films no iron-pair ordering exists; most of the anisotropy has its origin in stresses between film and substrate, and possibly in anisotropic components of stress fields due to dislocations. The results show that in contrast with 81Ni-19Fe discrete activation energies and relaxation times cannot be defined; in other words, the Arrhenius relationship does not hold. (See shaded areas of Fig. 34 (c)). Although it is only a rough approximation and not unambiguous, for purposes of comparison, the activation energies and relaxation times for permalloy films (81-19) were tentatively assigned to Ni (process 1 in permalloy lying inside of region I of Ni, process 11 in permalloy lying inside of region II of Ni, process 111 in permalloy lying inside of region III of Ni). From the temperature dependence of the anisotropy constant, Kneer and Zinn suggest that the anisotropy in Ni films can be described by West's model. However, it is assumed that macroscopic slips occur between film and substrate when the shear stress overcomes the magnetostrictive stress, which in turn implies that the temperature of constraint $T'$ does not stay the same on cooling but changes in a stepwise manner. These changes in $T'$ as they occur in time are of course dependent on many factors such as cooling rate, thermal expansion of film and substrate material, critical flow stress (which depends on impurity and dislocation density), interactions between grains, interactions between dislocations and impurities or grain boundaries, and adhesion film-substrate.
D. O. Smith et al. made a similar study, which is summarized in Fig. 35. Evaporation conditions were:

\[ R = 10 \text{ A}^0/\text{Sec} \]
\[ T = 100^\circ\text{c} \]
\[ P = 10^{-5} - 10^{-6} \text{ Torrs} \]
\[ \text{Thickness} = 350 \text{ A}^0 \]

Annealing temperatures for the recording of isotherms -
\[ 23^\circ\text{c} - 200^\circ\text{c} \]

No details are given on the annealing conditions and procedures for recording the isotherms. We have:

\[ H_k(t) + H_k(0) = \sum_j 2 H_{kj} e^{-t/\zeta_j} \]

\[ \zeta_j = \zeta_o \exp \left\{ Q_j / kT \right\} \]

\[ \sum_j H_{kj} = H_k(0) \]

The highest activation energy found by D. O. Smith and al in an analysis of isotherms is 0.48 eV. It seems difficult, therefore, to attribute a mechanism of iron pair ordering to this process. If we compare these results with Kneer and Zinn's, it seems that possible reasons for the absence of iron pair ordering in Smith's data are the lower deposition and annealing temperatures.

Further numerical results based on Kneer and Zinn's work are given in Fig. 36, 37.

IV. 6 Influence of Evaporation Conditions

From the kinetic theory of gases, the number of gas molecules striking the substrate per unit time is given by:

\[ \nu = 3.51 \times 10^{22} \frac{P_{\text{Torr}}}{\sqrt{M' T}} \text{ Molecules/cm}^2\text{ sec} \]
\[ M^1 = \text{Molecular weight of gas.} \]

\[ T = \text{Absolute temperature of gas.} \]

Assuming a sticking probability of 1 of the metal atoms to the substrate, the number of molecules of film material adhering to the substrate is given by:

\[ \lambda = 10^{-8} \times R \times \rho \times \frac{N_o}{M} \text{ Molecules/cm}^2\text{-sec.} \]

\[ R = \text{deposition rate in A}^0/\text{sec (Determined experimentally)} \]

\[ \rho = \text{film density}. \]

\[ N_o = \text{Avogadro's number} \]

\[ M = \text{molecular weight of film material} \]

The contamination can than be defined as:

\[ \chi = \frac{\nu}{\lambda} = \frac{3.51 \times 10^{22} \times P(\text{Torr})}{\sqrt{M^1T}} \times \frac{M}{10^{-8} \times R \times \rho \times N_o} \text{ Molecules/cm}^2\text{-sec.} \]

Consider the case of Ni-Fe alloys:

\[ T = 300^0\text{K} \]

\[ M^1 = 32 \text{ (oxygen). One could take } M^1 = 29 \text{ for air} \]

\[ M = 58 \text{ (average)} \]

\[ \rho = 8.5 \text{ (average)} \]

\[ N_o = 6.02 \times 10^{23} \]

\[ \nu = 3.58 \times 10^{20} P(\text{Torr}) \text{ Molecules/cm}^2\text{-sec.} \]

\[ \lambda = 8.8 \times 10^{14} R(A^0/\text{Sec}) \text{ Molecules/cm}^2\text{-sec.} \]

\[ \chi = 4.07 \times 10^7 \frac{P(\text{Torr})}{R(A^0/\text{Sec})} \text{ per cent.} \]

Numerical results are given in Fig. 38 for pressures and rates of the same order of magnitude as the ones used in the present experiments.

The evaporation source temperature essentially determines the rate at which the substance will be removed as vapour per unit area.

\[ \text{From Langmuir } \ G_{\text{q/cm}^2\text{-sec}} = 5.85 \times 10^{22} \times P_{\text{mm}} \sqrt{\frac{M}{T}} = \frac{3.51 \times 10^{22}}{6.02 \times 10^{23}} \frac{M_{\text{Porr}}}{T^{1/2}} \]
On the other hand, Fig. 39 reproduces data from Dushman for Ni and Fe. The results are so close to one another that for practical purposes, the following relationship was found to fit well the data for both Ni and Fe:

\[
\log_{10} P_{mm} = - \frac{20250}{T} + 9.45
\]
\[
\log P_{mm} = - \frac{46700}{T} + 21.8
\]

Hence
\[
P_{mm} = \exp \left\{ 21.8 - \frac{46700}{T} \right\}
\]

Taking \( M \approx 58 \) (average)

\[
G \, g/cm^2 \cdot \text{sec} = 445 \times \frac{1}{\sqrt{T(\circ K)}} \exp \left\{ 21.8 - \frac{46700}{T(\circ K)} \right\}
\]

For the charges used (permalloy wire, 4 inches long, wound in spiral) it was found that the wet area was about 3 \( cm^2 \). In general we will call it \( S_{w-Ni} \). We have to relate the rate of evaporation from the tungsten boat to the rate of deposition on the substrates. This is easily done, following the Cosine law \(^45\) and assuming sticking probability equal to unity.

Assume that \( G \, g/cm^2 \cdot \text{sec} \) evaporates from \( dS_1 \) (surface), then the amount of material passing through the solid angle \( d\omega \) is given by:

\[
dG = G dS_1 \cos \phi \frac{d\omega}{n}
\]

\[
d\omega = \sin \phi \, d\theta \, d\phi
\]

On integration one checks the validity of the cosine law.

Therefore the mass deposited per second \(^{45}\) on a surface \( dS_2 \) whose normal
is at an angle $\theta$ of the $\phi$ direction, will be:

$$dG = \frac{G}{n} \frac{dS_1}{\cos \phi} \frac{dS_2 \cos \theta}{r^2}$$

In the present situation $\phi = \theta = 0$ and $r = R_{ws}$

$$dS_1 = S_{w-Ni}$$
$$dS_2 = P$$

$$P = \frac{1}{n} \frac{S_{w-Ni}}{R_{ws}^2} G = \alpha G \quad [g/cm^2 \cdot sec]$$

If one considers that $S_{w-Ni}$ can vary between .2 cm$^2$ and 6.46 cm$^2$ and that $R_{ws}$ can vary between 11 cm and 30 cm one sees that the coefficient $\frac{S_{w-Ni}}{R_{ws}^2}$ will vary between $2.22 \times 10^{-4}$ and $5.33 \times 10^{-2}$.

The rate of deposition in thickness of film deposited will be given by:

$$R = \frac{P}{P} \quad (cm/\sec) = \frac{1}{8.5} \times 10^6 \quad P (\AA/\sec) = 1.176 \times 10^7 \alpha G \quad \AA/\sec$$

In the present case $\alpha = \frac{1}{n} x \frac{3}{(17.8)^2} \approx 3 \times 10^{-3}$

Figs. 40, 41, 42, summarize the preceding results.

It has been shown that isotropic stresses existing in thin films could not be entirely accounted for by a difference in thermal expansion between film and substrate.

$$S = E \alpha \Delta T$$

$S$ = Differential stress (dynes/cm$^2$)

$\alpha$ = Differential CTE between metal and substrate ($^0$C$^{-1}$)

$E$ = Young's modulus for metal (dynes/cm$^2$)

$\Delta T$ = Deposition temperature - Measurement temperature.

For Corning 0211 glass at a deposition temperature of 320$^0$C this would lead to $S = 5 \times 10^9$ dynes/cm$^2$. 

There exists a so-called intrinsic isotropic stress which can be compressive or tensile, larger than the previous thermal stress. These two components add up to give a total stress the magnitude of which is beyond the elastic limit of the metal. \((1-2 \times 10^9 \text{ dynes/cm}^2\) for 80-20 Ni Fe). Although some research has been done in this area, definite conclusions have not been reached as to the dependence of these stresses upon substrate temperature, composition, contamination. Freedman\(^43\) reports an increase of the isotropic stress by a factor of four when the pressure increases from \(10^{-9}\) to \(10^{-7}\). On the other hand the coercive force increases by a factor of nearly two and the anisotropy constant decreases by about 50%.

It seems therefore safe to conclude that impurities, as well as inclusions and defects contribute not only to the stresses in the film but also to the coercive force and the anisotropy.
CHAPTER V

Interpretation of Results

V.1 Introduction.

The energy supplied by the annealing magnetic field in the formation of magnetic anisotropy is quite negligible compared to kT. Actually the presence of the magnetic field is not necessary for the formation of the anisotropy, the demagnetizing fields of individual crystallites being sufficient. The larger part of the energy necessary for the diffusion processes is thermal.

V.2 Radiated Power.

Only a fraction of the source power is used in the vaporization process, as well as for radiation. Most of the power is dissipated by conduction. Let us evaluate the radiated power. According to Stefan-Boltzman law the energy radiated by a source of temperature \( \theta_w \) for a surface \( S_w \) (m²) is, assuming surroundings at 300°K.

\[
W_r = 5.67 \times 10^{-8} \times \varepsilon_w \times S_w (\theta_w^4 - T_v^4) \approx 5.67 \times 10^{-8} \varepsilon_w S_w \theta_w^4
\]

\( T_v = \text{Room temperature} = 300^\circ\text{K} \)

\( \varepsilon_w \) is the total emissivity of the tungsten boat and is a function of temperature.

<table>
<thead>
<tr>
<th>°K</th>
<th>1400</th>
<th>1500</th>
<th>1600</th>
<th>1700</th>
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<tbody>
<tr>
<td>( \varepsilon_w )</td>
<td>.175</td>
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<td>.222</td>
<td>.236</td>
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<td>.270</td>
<td>.279</td>
<td>.288</td>
<td>.296</td>
<td>.303</td>
</tr>
</tbody>
</table>
For the rate of 35 A°/sec corresponding approximately to 1980°K, we will take \( \epsilon_w = 0.263 \). For the estimation of the surface we will take into account the fact that the temperature of the tungsten boat is 1980°K only in the center region, therefore \( S_w = 2 \times \frac{1}{2} \times (2.54)^2 \times 10^{-4} \text{ m}^2 \)

\[
S_w = 6.46 \times 10^{-4} \text{ m}^2
\]

\[
\theta_w = 1980°K \quad \theta_w^4 = 1.54 \times 10^{13} \quad T_v^4 = 8.1 \times 10^9
\]

\[W_r = 149 \text{ watts}\]

V. 3 Absorbed Power.

However, 1 cm\(^2\) of the film will absorb only a fraction of this power.

\[
W_a = a_s \left( \frac{1}{R_{ws}(\text{cm})} \right)^2 \times 5.67 \times 10^{-8} \times \epsilon_w \times S_w \left( \theta_w^4 - T_v^4 \right) \text{ watts/cm}^2
\]

\(a_s\) = absorptivity of metal film being deposited = 0.15 for Ni (44)

\[
\left( \frac{1}{R_{ws}} \right)^2 = \text{view factor} = \text{solid angle from source to substrate.}
\]

\(R_{ws}\) = distance from tungsten boat to substrate holder = 7" \(\times\) 2.54 = 17.8 cm.

\(T = \text{Temperature of film} < 1000°K. \quad T^4(1000) = 10^{12} \quad \theta_w^4 = 17 \times 10^{12}\)

In the present case

\[
W_a = \frac{0.15}{(17.8)^2} \times 149 = 7 \times 10^{-2} \text{ watts/cm}^2
\]

We note that the absorptivity coefficient will depend upon the thickness of the film and its temperature.

Approximately

\[
W_a \propto a_s \frac{1}{R_{ws}(\text{cm})^2} \times 5.67 \times 10^{-8} \times \epsilon_w S_w \theta_w^4
\]
V. 4 Heat of Vaporization.

We must consider also the rate at which molecules give up most of their energy by changing phase from vapor to solid.

From physical tables:

Heat of vaporization for Ni = 100 k cal / g atom
Heat of vaporization for Fe = 87 k cal / g atom

Let us express these quantities in terms of electron-volts per atom.

Heat of vaporization for Ni = 4.33 eV/atom
Heat of vaporization for Fe = 3.76 eV/atom

An atom of iron or nickel leaving the tungsten boat at 1500°C has an additional kinetic energy of the order of kT, that is, .13 eV. In first approximation we can neglect this energy since it is an order of magnitude smaller than the heat of vaporization. Let us express again, the heat of vaporization in another unit: Heat of vaporization for Ni = \(\frac{100 \text{ k cal/g}}{58.69}\) = 1.7 k cal/g

Heat of vaporization for Fe = \(\frac{87 \text{ k cal/g}}{55.85}\) = 1.5 k cal/g

For practical purposes, we will take 1.6 k cal/g as the heat of vaporization for permalloy.

Therefore the power generated by the phase change is:

\[ W_p = 1.6 \times 10^3 \times 4.18 \times P \] watts/cm² (See chapter IV, 6)

\[ W_p = 6.7 \times 10^3 \times \alpha \times \frac{445}{\sqrt{T(\text{oK})}} \exp \left\{21.8 - \frac{46700}{T(\text{oK})}\right\} \] watts/cm²
At the temperature of $1980^\circ K$ and for the present operating point

$$W_p = 6.7 \times 10^3 \times 2.9 \times 10^{-6} = 2.0 \times 10^{-2} \text{ watts/cm}^2$$

A comparison of $W_a$ and $W_p$ in a range of temperature of interest to our present situation is given in Fig. 43.

For this graph we have used:

$$W_a = \left[a S \times 5.67 \times 10^{-8}\right] \left[\frac{S_w}{R_{ws}^2}\right] \left[\epsilon_w \theta_w^4\right]$$

Considering $a = .15$ the first parenthesis gives: $8.5 \times 10^{-9}$

The second parenthesis $\frac{S_w}{R_{ws}^2}$ will be called geometrical factor:

In the present situation we had

$$S_w = 6.46 \times 10^{-4} \text{ m}^2$$

$$R_{ws} = 17.8 \text{ cm}.$$

Let us vary $R_{ws}$ between 11 cm and 30 cm.

Let us vary $S_w$ between $.2 \times 10^{-4} \text{ m}^2$ and $6.46 \times 10^{-4} \text{ m}^2$

Then $\frac{S_w}{R_{ws}^2}$ will vary between $2.22 \times 10^{-8}$ and $5.33 \times 10^{-6}$.

If we lump together the first two parentheses and write:

$$W_a = \beta \epsilon_w \theta_w^4$$

then $\beta$ will vary for our design specifications between, $1.89 \times 10^{-16}$ and $4.53 \times 10^{-14}$.

These curves are generally applicable provided some flexibility is given to the definition of the parameters $\alpha$ and $\beta$ to include such factors as the design and material of the evaporating boat, the sticking probability of the substrates, and variation of the absorptivity of the metal film with thickness and temperature.
V.5 A Model for the Deposition Temperature of a Permalloy Film vs. Time.

Let us consider that before evaporation, the heat sink has been left at a temperature $T_0$ (°K) for a sufficiently long time so that the glass substrate (0211) can be considered to have the same temperature $T_0$. Start evaporation at $t = t_0$.

Then let us consider the time during deposition when a mass $m$ has been deposited ($m = P(t - t_0)$, assuming a 1 cm$^2$ film). At time $t$, the temperature of the film is $T$. Consider the time $t + dt$. The mass deposited is $m + dm = m + P \, dt = P(t + dt - t_0)$. The temperature is now $T + dT$.

Because of the high thermal conductivity of the metal, the temperature is assumed uniform throughout the thickness of the film.
Conservation of energy can be applied to the system represented by the mass \( m \) during time \( dt \). The energy going to the system is provided by radiation: \( W_a \, dt \), and by the phase change from vapour to solid: \( W_p \, dt \) (neglecting the kinetic energy of the beam).

Losses can be accounted for in the following way:
The heat coming from the film flows through the substrate to the copper square plate (with a hole 1 cm in diameter to give a circular shape to the film), and from the copper square plate to the aluminum substrate holder which is in contact with the heat sink by means of four screws. The thermal contact resistances are probably high because no pressure is applied against the substrate holder.

The clamping of the substrates against the heat sink would be a better solution from the heat conduction point of view. However this procedure would induce stresses in the substrate, which after deposition and removal of the films from the vacuum system, would be relieved from the substrate but induced into the metallic deposit. This might modify the anisotropy constant, by creation of anisotropic stresses, through the magnetostrictive mechanism, which can be important for compositions different of 81 Ni-19 Fe.

We will consider the following data.

\[
\begin{align*}
\text{Thermal conductivity of 0211 glass} & = 8 \times 10^{-3} \text{ watts-cm/cm}^2/\text{°C} \\
\text{Thermal conductivity of permalloy} & = .58 \\
\text{Heat capacity of 0211 glass} & = .67 \text{ Joule/g/°C} \\
\text{Heat capacity of permalloy} & = .42 \text{ Joule/g/°C}
\end{align*}
\]
Before we analyse in more detail the losses through conduction, let us review the other possible loss mechanisms.

The heat lost by convection can be approximated by:

$$E_o = \alpha \Lambda_o P_p \sqrt{\frac{273}{T_v}} (T - T_v) \text{ watts/cm}^2$$

\(\alpha\) = Accommodation coefficient for permalloy surface and air (.8 or .9)

\(\Lambda_o\) = free molecule heat conductivity at 0°C = 16 x 10^{-6} for O_2 and N_2.

\(P_p\) = pressure in microns = 10^{-3} (in present case)

\(T - T_v\) = temperature difference between film surface and ambient temperature; in all cases it is smaller than 10^3 °C.

Therefore \(E_o < 0.8 \times 16 \times 10^{-6} \times 10^{-3} \times 10^3 = 1.3 \times 10^{-5} \text{ watts/cm}^2\)

We will not consider in the following, the heat losses through convection as having a significant effect.

The heat lost by radiation does not have to be considered since we have already considered the radiation absorbed by the film from the tungsten boat. The heat lost by conduction can be approximated by assuming that Fourier's law holds (the actual three dimensional problem may be exceedingly difficult to solve analytically).

$$L_c = K (T - T_0)$$

\(K\) depending on the geometry, glass substrate, and the two thermal contact resistances.

The following energy balance relationship can therefore be written:

$$W_a dt + W_p dt - U dt + c dm (1750 - T) =$$

$$(m + dm) c dT + K (T - T_0) dt$$

The first two terms represent the energy rate going to the system. The 3rd term is the energy rate necessary in time \(dt\) for metallurgical processes to
take place at temperature higher than T that is processes such as crystallization, grain growth, migration and diffusion processes. Unfortunately one can not know about the magnitude of this term. The fourth term represents the heat brought to the mass m when the mass dm cools from the average melting point of 1750 °K to the temperature T. This term can be neglected as compared to \( W_p \frac{dt}{dt} = dm \times 1.6 \text{k cal/g} \) because \( c \approx 106 \text{ cal/g} \) and \( 1750 - T \) is of the order of \( 10^3 \) so that \( c(1750 - T) \) is approximately \( 0.106 \text{k cal/g} \).

The equation can be rewritten as:

\[
W_a + W_p - U = P e t \frac{dT}{dt} + k(T - T_0)
\]

This equation is of little practical value since we do not know, as mentioned earlier, the magnitude of \( U \) and \( K \).

V. 6 Experimental Results on the Temperature of a Film vs Time During Deposition.

An experimental approach to the problem of the determination of the temperature versus time of the film seems the most appropriate. Such curves have not been studied for the system Ni-Fe. However, in a recent paper, Belous and Wayman deposited Au and Ag films on the junctions of Au-Ni thin film thermocouples connected in series and found that the actual temperature of the film could be as high as 500 °K above the heat sink temperature. The thermocouples were 2500-3000 Å thick. The vacuum system pressure was \( 10^{-7} - 10^{-6} \text{ Torrs} \). Curves T-t are given for deposition rates of 10-100 Å/sec. Some of the results are summarized in Fig. 44.

We note that for fast rates of order 50-100 Å/sec the evaporant is
entirely melted before the temperature has reached equilibrium. (a).

For low rates $10 \, ^\circ A^0/sec$ the evaporant is still melting whereas the temperature has reached equilibrium. (b).

Let us assume that $T_1$ is the threshold temperature below which ordering processes are not appreciable, and that $t_1$ is the time at which the operator turns off the current to the evaporation boat, for the same thickness. The time interval $\Delta t$ is dependent on the two time constants of the operation. 1. The first time constant corresponds to the rising part of the $T$-$t$ curve.

If one considers the large difference in thermal conductivity between Ni-Fe and glass on one hand, and the almost equal heat capacity of Ni-Fe and glass on the other hand, one can easily conclude that the rise time is approximately the same as the deposition time. (a).

2. The fall-time is characteristic of the heat capacity of both metal film and glass, and of the contact resistances which cannot be evaluated directly.

An electrical analogue would be the following:
One expects in the case of our substrate holder design to have a large time constant for the falling part of the curve. For the 100 µ thick mica sheet clamped directly to the heat sink, Belous and Wayman give T-t curves, the falling part of which have a time constant of approximately 30 sec. For the present system, we therefore expect a falling time constant of a few minutes.

We also note from Belous and Wayman's data that for a rate of deposition of 100 A⁰/sec, the heat of vaporization and the radiation provide approximately the same rise in temperature. From Fig. 43, taking \( \alpha = 3 \times 10^{-3} \) and \( \beta = 1.73 \times 10^{-14} \) (current operating points) for the same rate of deposition of 100 A⁰/sec, one gets a contribution of \( 6 \times 10^{-2} \) watts for the heat of vaporization and \( 8.6 \times 10^{-2} \) watts for the radiation heat.

The above results show that the evaporation characteristics of the two systems are similar. The use of thin film thermocouples for the recording of the T-t curves seems to be the best engineering solution. Their lack of availability makes the reproduction of such experiments difficult to carry out.

However, several experimental studies were made in order to estimate the equilibrium radiation temperature at the location of the substrates.

First a chromel-alumel bead (gauge 20) of ordinary size was placed at the site of the substrate. A current of 300 A corresponding to normal evaporation conditions was sent through the tungsten boat. The temperature rose 100⁰C in 10 minutes. However the thermocouple junction constituted a large heat sink for the radiation area compared to a similar hypothetical experiment with a thin film thermocouple.
One could compare the ratio \( \rho = \frac{nR^2}{4nR^3} = \frac{3}{4R} = 7.5 \) \((R = .1 \text{cm})\)

for the case of a bead junction to the ratio

\[
\rho = \frac{nD^2}{\frac{4nD^2}{4} \times \tau} = \frac{1}{\tau} = 10^5 \quad (\tau = \text{thickness} = 1000 \text{Å})
\]

An improved design with a higher surface of irradiation to volume ratio was then realized with a small sheet of copper to which was silver-soldered a copper-constantan junction (30 gauge). The results are shown in Fig. 45 for the temperature rise and in Fig. 46 for the temperature cooling. The time-response is not the correct one. However, the losses through the thermocouple wires by conduction should not be less than the losses through the high thermal contact resistances in the actual situation of the thin film.

One sees that the temperature rose to 220\(^o\)c in ten minutes. Due to the rise in pressure in the vacuum system, the experiment was stopped after ten minutes. The exponential shape of the curve suggests that a plot on semi-log paper might give the asymptotic temperature versus time.

The analysis was carried out and showed that a final temperature of 450\(^o\)c provided the best fit to the experimental curve, (possible error \(\pm\) 150\(^o\)c) a temperature that we will take as an estimate for the temperature rise due to radiation. From Fig. 43, we see that for the operating 35 \(\text{Å}^0/\text{sec}\) rate of deposition, the heat due to radiation is \(7 \times 10^{-2}\) watts/cm\(^2\); the heat due to vaporization heat is \(2 \times 10^{-2}\) watts/cm\(^2\). Therefore a temperature rise of \(450 \times \frac{2}{7} = 130^o\text{c}\) is to be expected from vaporization heat only.

The total temperature rise would therefore be around 600\(^o\)c. We will discuss later what this means in terms of the characteristic ordering processes.
As the metal first deposits, the radiation is mostly transmitted through the glass and the first few layers so that the optical properties of the film play a more important role than the absorptivity of the metal in itself. In order to gain some understanding of this transient phenomenon a small\textit{\textit{th-c}} chromel-alumel (gauge 36) after being spot-welded was cemented between two substrates and placed in the substrate holder. The experimental $T-t$ curve for heating and cooling is shown in Fig. 47. Although one would expect a very low temperature rise with time due to transmission of the radiated power through the substrates, the experimental temperature rise, which is about twice smaller than for the copper sheet, shows that the cement used for this application is not quite as "transparent" as the substrates are.

V. 7 Interpretation of Experimental Results on 81-19 Permalloy Films.

One never gets exactly zero magnetostrictive films, however measurements made at liquid nitrogen temperature showed a contribution of the magnetostrictive mechanism less than 20\% in all cases. Experiments performed with non magnetostrictive composition melt are shown in Fig. 30. Films 800 A\textdegree thick were deposited from $77^0\text{K}$ to $673^0\text{K}$ heat sink temperature. The films deposited at liquid nitrogen temperature are particularly significant because they exhibited uniaxial anisotropy in the torquemeter as well as in the B-H loop tracer with a hard axis curve very close to a straight line. If one assumes that the film temperature is $77^0\text{K}$ during deposition, this result cannot be understood if one assumes that in this range of composition, anisotropy is the result of ordering processes and primarily iron-pair ordering. Lykken and Mitchell\textsuperscript{47} report that the low temperature films
they made were isotropic, when observed in a B-H loop tracer. Their films (82-18) were deposited at a rate of $17 \text{A}^0/\text{sec}$, $2 \times 10^{-9}$ Torrs, from a circular tungsten filament wound with an iron-nickel wire charge (the distance between evaporation source and substrate and the clamping of the substrates to the heat sink were not reported). Ahn reports making films at liquid nitrogen temperatures which exhibited uniaxial anisotropy. The pressure was $2 \times 10^{-6}$ Torrs; the rate of deposition, type of evaporation source, shape of the melt, the distance between source and substrate, and the clamping of the substrates to the heat sink were not reported.

In our experiments the films made at $-196^\circ$C were deposited at a rate of approximately $35 \text{A}^0/\text{sec}$, that is for a thickness of $800 \text{A}^0$, a deposition time of 24 sec. However, we saw that the relevant time, which is expected to be a few minutes, depended on the cooling rate of the substrates through the thermal contact resistances. According to Kneer and Zinn's analysis of non magnetostrictive films the relaxation time for iron pair ordering considered as the main process is 72 sec at $800^\circ$K. We saw that the films that we made at a heat sink temperature of $77^\circ$K were actually made at a temperature close to $700^\circ$K, and the results of our measurements of the anisotropy constants for films deposited at heat sink temperatures between $300^\circ$K and $600^\circ$K did not show any significant departure from the measured value of the anisotropy constant of the films made at heat sink temperature of $77^\circ$K. We must therefore conclude that all ordering processes are completed for the films deposited at $77^\circ$K heat sink temperature. Fig. 30 shows that the coercive force stays noticeably the same in the same range of temperature.
Several studies on the variation of anisotropy constant with "deposition" temperature are summarized in Figs. 46 and 47.

Prutton and Bradley\textsuperscript{41} evaporated their films from a silica crucible, and reported several curves of anisotropy versus temperature for melt compositions of 81-19, 82-18, 83-17, 84-16, 85+15. The experimental points show a considerable amount of scatter and the "curves drawn through the experimental points" are shown in Fig. 48. In their experiments, the evaporation rate was 40 A°/sec; the pressure during evaporation was $3 \times 10^{-4}$ Torrs. The distance between substrate and crucible and the clamping of the substrates to the heat sink were not reported.

Engelman and Hardwick\textsuperscript{42} give curves for the non-magnetostrictive composition at different rates of deposition. There is not an important scatter in the experimental points. The source was formed by a tungsten filament wound with a Ni-Fe wire. The vacuum during deposition was $10^{-5} - 10^{-6}$ Torrs. The distance between evaporation source and substrates and the clamping of the substrates to the heat sink were not reported. Results are given in Fig. 49.

In Fig. 30, the decrease in $H_k$ and increase in $H_c$ beyond $300^\circ$C are not clearly understood. However similar trends are noted by Engelman et al.\textsuperscript{42} and Prutton\textsuperscript{41}. One possible explanation might be found in the Néel-Taniguchi mechanism. Another explanation is the following: taking into account the rise in temperature of the film due to both phase change and radiation, the actual temperature of the film may be around $1000^\circ$C - $1100^\circ$C. The melting point of 0211 glass being approximately $1200^\circ$C it is
possible that a diffusion of impurities from the glass substrate into the metallic film may occur. A possible magnetic dilution would then lower \( H_k \), whereas many vacancies and imperfections may be filled by the incoming impurities, thereby reducing the number of nucleation centers and therefore increasing \( H_C \). Studies by Cohen\(^{50}\) on the system Ni-Fe-Cu show that such trends occur as the concentration in Cu increases.

The experiments on the cooling rate performed with the 81-19 films deposited at a heat sink temperature of 400\(^\circ\)C under the same experimental conditions showed (Fig. 27) that the heat sink has a too large heat capacity, and cannot be cooled fast enough in order to quench the films rapidly. No difference in \( H_C \) or \( H_k \) was recorded for films cooled at .5\(^\circ\)C/min or 25\(^\circ\)C/min.

The experiments on the easy axis annealing (4 hours) of films deposited at heat sink temperature of 50\(^\circ\)C are shown in Fig. 28. No change in \( H_k \) was noticed for subsequent anneals at heat sink temperatures higher than room temperature. This is not surprising in view of the fact that the actual temperature of the film at deposition was some 600\(^\circ\)C higher than room temperature, and we are therefore annealing them at a lower temperature than their actual deposition temperature. However \( H_C \) increases after a four hour anneal at 400\(^\circ\)C to the point that the film looks actually isotropic. We can find an explanation for this last observation in the imperfection model. Dislocations that do not contribute to the anisotropy migrate to grain boundaries and eventually collapse. Their number is thereby reduced; consequently the number of nucleation centers for wall motion is reduced and the coercive force \( H_C \) increases.
The same conclusions can be applied to the films 81-19 deposited at a heat sink temperature of 77°F (See Fig. 29).

V.8 Interpretation of Experimental Results on Ni Films.

In this case, the anisotropy has its origin in the magnetostrictive mechanism, as pointed out by Robinson and West in recent years. However the constraint temperature depends not only on the actual deposition temperature of the film but also on the nature of the adhesion film-substrate which should be higher at higher heat sink temperature because of the higher chemical affinity of Ni for oxygen (chemisorption). On the other hand the constraint can vary in a stepwise manner as pointed out by Kneer and Zinn as the temperature is cooled from heat sink temperature to room temperature. (Shear stress becomes more important than magnetostrictive stress, resulting in a slip). The calculation of the anisotropy constant based on West's formula leads to a value of 1550 ergs/cm³ at 240°F, as compared to the present experimental result of 900 ergs/cm³ at 300°F. The assumption of a temperature rise of the film for a few minutes makes the chemisorption adhesion mechanism easier and should contribute to a better adhesion metallic film-substrate.

For the same vacuum pressure of 10⁻⁶ Torrs the torque curves show a 360° symmetry when the heat sink temperature is 77°F or room temperature. However in spite of the temperature rise in the film, the actual temperature may not be large enough to produce an adhesion of the chemisorption type. Because of the definite limitations of the instrumentation, the anisotropy constant was estimated by the formula given in chapter III under
the assumption of the validity of the rotation model. It is possible that if
the adhesion of the substrate to the film is very weak for these heat sink
temperatures, there is no uniaxial anisotropy that can form under these
experimental conditions. Tables summarizing the many different experi-
mental observations made on Ni films deposited at heat sink temperatures
of 50°C and 300°C are reported in several books or papers, in particular
in West 31 and Prutton 27. Several observers report "unidirectional" symmetry.
The results obtained on Ni films are summarized in Fig. 31

V. 9 Interpretation of Experimental results with 50-50 (Ni-Fe).

In this case, both types of anisotropy, ordering mechanisms and mag-
netostrictive constraint, can exist. However, according to Néel-Taniguchi
theory the number of iron-pairs per unit volume is larger than in the 81-19
permalloy composition. Although it is difficult in this case to separate
magnetostrictive constraint from ordering processes, one expects that on
the basis of the temperature rise of the film at deposition, the anisotropy
constant for a heat sink temperature of 240°C will be 6000 ergs/cm³ (see
Fig. 38); that is, the ordering process is completed. However, we have
to add the contribution of the magnetostrictive constraint, so that the total
should amount to 7500 ergs/cm³. The torque curves for films made at
this heat sink temperature showed 360° symmetry, so that the anisotropy
constant was estimated as described in Chapter 3 by assuming the rotation
model to hold. This calculated value turns out to be three times larger
than the previously predicted one. For the films made at heat sink tempera-
tures of 50°C the conclusions are very similar to those formulated for the
240°C heat sink temperature deposited films. Because of the rise in temperature in the film at deposition one expects the completion of the ordering process as previously. However, the existence or magnitude of a magnetostrictive component is difficult to foresee on the basis of experimental results for Ni films.

Because of the observed 360° symmetry one can again estimate the magnitude of the anisotropy constant from the formula given in Chapter 3 on the assumption of the validity of the rotation model. Results are given in Fig. 31.

Perhaps a more significant result was obtained for films deposited at heat sink temperature of 77°C where uniaxial films were observed with the torquemeter. On the basis of the same temperature rise of the film at deposition this result would suggest that only part of the iron-pairs completed the ordering process. On the basis of Ni films made at this heat sink temperature it is possible that the magnetostrictive component is not appreciable. Results in Chapter 3 and Fig. 31.

Conclusions

The present research allowed us a better understanding of uniaxial anisotropy formation:

1. Importance of deposition rate in relation to the temperature rise in the film during deposition.

2. Importance of the design and emissive surface of the evaporation source, and the design of substrate holder (heat flow).
3. Necessity of knowing the curves $T - t$ (Temperature versus time) of the film at deposition.

4. The existence of two mechanisms of different nature: magnetostrictive constraint and iron-pair ordering.
Fig 1

Quartz assembly (gold coated)  Scale 1:1
Fig 2
Quartz assembly and support (Gold plated)

Fig 3
Permanent magnet

Torquer current

A
B

Gold plating removed

O-shape frame

Scale 1:1
Sensor system

Fig 4
June 25th 1967  
QUARTZ FIBER UNLOADED  
\[ T_1 = 0.8 \text{ sec} \]  
Speed paper: 10 mm/sec

June 26th 1967  
QUARTZ FIBER LOADED: \( m = 0.344 \text{ g} \) (substrate)  
\[ T_2 = 1.1 \text{ sec} \]

June 22nd 1967  
QUARTZ FIBER LOADED: \( m = 0.5311 \text{ g} \) (substrate)  
\[ T_2 = 1.214 \text{ sec} \]

June 25th 1967  
QUARTZ FIBER LOADED: \( m = 0.5311 + 0.344 = 0.8751 \text{ g} \) (2 substrates)  
\[ T_2 = 1.45 \text{ sec} \]
Fig 8

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Fig 9
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<th>Frequency cyc/sec</th>
<th>$V_1$ (mV)</th>
<th>$V_0$ (mV)</th>
<th>Gain</th>
<th>Phase</th>
<th>Frequency cyc/sec</th>
<th>$V_1$ (mV)</th>
<th>$V_0$ (mV)</th>
<th>Gain</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>14.7</td>
<td>30</td>
<td>2.04</td>
<td>0</td>
<td>0.02</td>
<td>5.6</td>
<td>60</td>
<td>10.7</td>
<td>0</td>
</tr>
<tr>
<td>0.05</td>
<td>14.7</td>
<td>32</td>
<td>2.2</td>
<td>0</td>
<td>0.04</td>
<td>5.6</td>
<td>78</td>
<td>13.4</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>14.7</td>
<td>34</td>
<td>2.3</td>
<td>0</td>
<td>0.06</td>
<td>5.6</td>
<td>100</td>
<td>17.8</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>14.7</td>
<td>40</td>
<td>2.7</td>
<td>0</td>
<td>0.08</td>
<td>1.14</td>
<td>32</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>0.6</td>
<td>14.7</td>
<td>52</td>
<td>3.5</td>
<td>0</td>
<td>0.09</td>
<td>1.14</td>
<td>125</td>
<td>110</td>
<td>60</td>
</tr>
<tr>
<td>0.65</td>
<td>14.7</td>
<td>56</td>
<td>3.8</td>
<td>0</td>
<td>0.091</td>
<td>1.3</td>
<td>60</td>
<td>200</td>
<td>180</td>
</tr>
<tr>
<td>0.7</td>
<td>14.7</td>
<td>68</td>
<td>4.6</td>
<td>0</td>
<td>0.092</td>
<td>1.3</td>
<td>22</td>
<td>73</td>
<td>180</td>
</tr>
<tr>
<td>0.72</td>
<td>5.6</td>
<td>32</td>
<td>5.7</td>
<td>0</td>
<td>0.094</td>
<td>1.3</td>
<td>10</td>
<td>34</td>
<td>?</td>
</tr>
<tr>
<td>0.74</td>
<td>5.6</td>
<td>34</td>
<td>6.1</td>
<td>0</td>
<td>0.098</td>
<td>4.86</td>
<td>56</td>
<td>11.5</td>
<td>?</td>
</tr>
<tr>
<td>0.76</td>
<td>5.6</td>
<td>40</td>
<td>7.1</td>
<td>0</td>
<td>1.0</td>
<td>4.86</td>
<td>70</td>
<td>14</td>
<td>?</td>
</tr>
<tr>
<td>0.78</td>
<td>5.6</td>
<td>50</td>
<td>9</td>
<td>0</td>
<td>2.0</td>
<td>4.86</td>
<td>5</td>
<td>1</td>
<td>?</td>
</tr>
<tr>
<td>0.80</td>
<td>5.6</td>
<td>55</td>
<td>9.8</td>
<td>0</td>
<td>10.0</td>
<td>4.86</td>
<td>0</td>
<td>0</td>
<td>?</td>
</tr>
</tbody>
</table>
**Fig 11**

Attenuation: 1

Paper speed: 0.25 mm/sec

Attenuation: 20

Frequency: 0.01 cycle/sec

0.05 cycle/sec

Attenuation: 1

Paper speed: 5 mm/sec

Attenuation: 5

0.88 cycle/sec

0.91 cycle/sec
Torque (normalized)
B-H loop data: \(H_{c0} = 1.8\text{oe} \quad H_{m} = 3\text{oe}\)

FilM 1-23-67 #2 : single layer : 670Å

JULY 31st 1967
Fig 26

Silver soldered

Copper fittings
Copper tubings

Copper blocks
Hole for infra-red heating lamp

Scale: 3/4
$H_k$ vs Cooling Rate

Heat sink temperature for 3 evaporations: 400°C

- 400 Å
- 800 Å
Fig 28

Films 11-97-67
■ 400 Å
○ 800 Å

Heat sink temp (°C)

Deposition 1st Anneal 2nd Anneal 3rd Anneal

Hc (Oe)

D-H Loop

Heat sink temp (°C)
Films 11-15th 67
• 400 Å
• 800 Å

Fig 29

Heat sink temperature (°C)

Deposition

1st Anneal
2nd Anneal

Heat sink temp (°C)
$H_K$ vs heat sink temperature

81-19 Ni-Fe \( \cdot \cdot \cdot 800 \, \text{Å} \)

$H_C$ vs heat sink temperature

81-19 Ni-Fe \( \cdot \cdot \cdot 800 \, \text{Å} \)
Fig. 33

Iron-pair ordering

$K_2 \times 10^{-3}$ (ergs/cm$^3$)

% Ni

40 50 60 70 80 90 100

Magnetostriuctive constraint

$K_3 \times 10^{-3}$ (ergs/cm$^3$)

% Ni

40 50 60 70 80 90 100

Total anisotropy constant

$K_{Total} \times 10^{-3}$ (ergs/cm$^3$)

% Ni

40 50 60 70 80 90 100

$T' = T_1 = 240^\circ C$  $T_0 = 20^\circ C$
Fig 35

<table>
<thead>
<tr>
<th>Temp Range</th>
<th>eV Q</th>
<th>$\zeta_0$ (sec) mean</th>
<th>$\zeta_0$ (sec) limits</th>
<th>$\alpha H_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.200</td>
<td>.18</td>
<td>$7 \times 10^{-2}$</td>
<td>$2.30 \times 10^{-2}$</td>
<td>.25</td>
</tr>
<tr>
<td>50.150</td>
<td>.34</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$.4 \times 3.5 \times 10^{-3}$</td>
<td>.20</td>
</tr>
<tr>
<td>50.200</td>
<td>.15</td>
<td>$2 \times 10^{-6}$</td>
<td>$.7 \times 5$</td>
<td>.30</td>
</tr>
<tr>
<td>23.60</td>
<td>.48</td>
<td>$6 \times 10^{-6}$</td>
<td>$.3 \times 300 \times 10^{-6}$</td>
<td>.25</td>
</tr>
<tr>
<td>150.200</td>
<td>.26</td>
<td>$3 \times 10^{-2}$</td>
<td>$0.4 \times 10^{-2}$</td>
<td>.15</td>
</tr>
<tr>
<td>Process</td>
<td>(2e^{-\frac{t}{\tau_{c_{1-1}}}})</td>
<td>(2e^{-\frac{t}{\tau_{c_{2-1}}}})</td>
<td>(2e^{-\frac{t}{\tau_{c_{3-1}}}})</td>
<td>(2e^{-\frac{t}{\tau_{c_{4-1}}}})</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Time (sec)</td>
<td>(T = 293^\circ K)</td>
<td>(T = 513^\circ K)</td>
<td>(T = 800^\circ K)</td>
<td>(T = 1000^\circ K)</td>
</tr>
<tr>
<td>1</td>
<td>.96</td>
<td>.6</td>
<td>.04</td>
<td>.38</td>
</tr>
<tr>
<td>10</td>
<td>.92</td>
<td>.78</td>
<td>.10</td>
<td>.10</td>
</tr>
<tr>
<td>30</td>
<td>.92</td>
<td>.78</td>
<td>.10</td>
<td>.10</td>
</tr>
<tr>
<td>(10^2)</td>
<td>.92</td>
<td>.78</td>
<td>.10</td>
<td>.10</td>
</tr>
<tr>
<td>(10^3)</td>
<td>.92</td>
<td>.78</td>
<td>.10</td>
<td>.10</td>
</tr>
<tr>
<td>(10^4)</td>
<td>.92</td>
<td>.78</td>
<td>.10</td>
<td>.10</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>30</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(10^2)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>(10^3)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(10^4)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
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<td>1.0</td>
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<td>1.0</td>
</tr>
<tr>
<td>30</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(10^2)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(10^3)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(10^4)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
**Fig 38**

\( \nu_0^2 \) (molecules / cm\(^2\)·sec)

<table>
<thead>
<tr>
<th>( P_0^2 ) (Torr)</th>
<th>10(^{-5})</th>
<th>10(^{-6})</th>
<th>10(^{-7})</th>
<th>10(^{-8})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_0^2 )</td>
<td>3.6 \times 10^{15}</td>
<td>3.6 \times 10^{14}</td>
<td>3.6 \times 10^{13}</td>
<td>3.6 \times 10^{12}</td>
</tr>
</tbody>
</table>

\( \lambda_{Ni-Fe} \) (molecules / cm\(^2\)·sec)

<table>
<thead>
<tr>
<th>Dep. rate (Å/sec)</th>
<th>1</th>
<th>10</th>
<th>35</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{Ni-Fe} )</td>
<td>8.8 \times 10^{14}</td>
<td>8.8 \times 10^{15}</td>
<td>3.1 \times 10^{16}</td>
<td>8.8 \times 10^{16}</td>
</tr>
</tbody>
</table>

\( K = \frac{\nu}{\lambda} \) = contamination in %

<table>
<thead>
<tr>
<th>( P_0^2 ) (Torr)</th>
<th>Deposition rate (Å/sec)</th>
<th>1</th>
<th>10</th>
<th>35</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>10(^{-5})</td>
<td>4.1 \times 10^{-1}</td>
<td>4.1 \times 10^{-1}</td>
<td>1.2 \times 10^{-1}</td>
<td>4.1 \times 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>10(^{-6})</td>
<td>4.1 \times 10^{-2}</td>
<td>4.1 \times 10^{-2}</td>
<td>1.2 \times 10^{-2}</td>
<td>4.1 \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>10(^{-7})</td>
<td>4.1 \times 10^{-3}</td>
<td>4.1 \times 10^{-3}</td>
<td>1.2 \times 10^{-3}</td>
<td>4.1 \times 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>10(^{-8})</td>
<td>4.1 \times 10^{-4}</td>
<td>4.1 \times 10^{-4}</td>
<td>1.2 \times 10^{-4}</td>
<td>4.1 \times 10^{-5}</td>
<td></td>
</tr>
</tbody>
</table>

**Fig 39**

<table>
<thead>
<tr>
<th>Fe</th>
<th>( P_\mu ) microns (Data temp range: 1092 - 1246)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10(^{-2})</td>
</tr>
<tr>
<td>t (°C)</td>
<td>1107</td>
</tr>
<tr>
<td>W (g/cm(^2)·sec)</td>
<td>1.17 \times 10^{-7}</td>
</tr>
<tr>
<td>( T_m ) = 1539 °C</td>
<td>( P_\mu ) = 30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ni</th>
<th>( P_\mu ) microns (Data temp range: 1034 - 1310)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10(^{-2})</td>
</tr>
<tr>
<td>t (°C)</td>
<td>1142</td>
</tr>
<tr>
<td>W (g/cm(^2)·sec)</td>
<td>1.19 \times 10^{-7}</td>
</tr>
<tr>
<td>( T_m ) = 1452 °C</td>
<td>( P_\mu ) = 5</td>
</tr>
</tbody>
</table>
### $\nu_0^2$ (molecules / cm$^2$.sec)

<table>
<thead>
<tr>
<th>$P_0^2$ (Torr)</th>
<th>$10^{-5}$</th>
<th>$10^{-6}$</th>
<th>$10^{-7}$</th>
<th>$10^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_0^2$</td>
<td>$3.6 \times 10^{15}$</td>
<td>$3.6 \times 10^{14}$</td>
<td>$3.6 \times 10^{13}$</td>
<td>$3.6 \times 10^{12}$</td>
</tr>
</tbody>
</table>

### $\lambda_{Ni-Fe}$ (molecules / cm$^2$.sec)

<table>
<thead>
<tr>
<th>Dep. rate (Å/sec)</th>
<th>1</th>
<th>10</th>
<th>35</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{Ni-Fe}$</td>
<td>$8.8 \times 10^{14}$</td>
<td>$8.8 \times 10^{15}$</td>
<td>$3.1 \times 10^{16}$</td>
<td>$8.8 \times 10^{16}$</td>
</tr>
</tbody>
</table>

### $K$ ($= \frac{\nu}{\lambda} = $ contamination in %)

<table>
<thead>
<tr>
<th>$P_0^2$ (Torr)</th>
<th>1</th>
<th>10</th>
<th>35</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$</td>
<td>4.1</td>
<td>$4.1 \times 10^{-1}$</td>
<td>$1.2 \times 10^{-1}$</td>
<td>$4.1 \times 10^{-2}$</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>$4.1 \times 10^{-1}$</td>
<td>$4.1 \times 10^{-2}$</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$4.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>$4.1 \times 10^{-2}$</td>
<td>$4.1 \times 10^{-3}$</td>
<td>$1.2 \times 10^{-3}$</td>
<td>$4.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$10^{-8}$</td>
<td>$4.1 \times 10^{-3}$</td>
<td>$4.1 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>$4.1 \times 10^{-5}$</td>
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</table>

### $F_e$

<table>
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<th>$P_p$ microns (Data temp range: 1092 - 1246)</th>
</tr>
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<tbody>
<tr>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>$t$ ($^\circ$C)</td>
</tr>
<tr>
<td>$W(g/cm^2$.sec)</td>
</tr>
<tr>
<td>$T_m$ = 1539 °C</td>
</tr>
</tbody>
</table>

### $Ni$

<table>
<thead>
<tr>
<th>$P_p$ microns (Data temp range: 1034 - 1310)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>$t$ ($^\circ$C)</td>
</tr>
<tr>
<td>$W(g/cm^2$.sec)</td>
</tr>
<tr>
<td>$T_m$ = 1452°C</td>
</tr>
</tbody>
</table>
Evaporation rate vs Source temperature

- Operating point A

$T \times 10^{-3} (^K)$
Fig 41

Deposition rates (g/cm²·sec) vs source temperature

P(g/cm²·sec)

10⁻⁸

10⁻⁷

10⁻⁶

10⁻⁵

10⁻⁴

10⁻³

10⁻²

α = 10⁻²

α = 10⁻³

α = 10⁻⁴

α = 10⁻⁵

T x 10⁻³ (°K)
Fig 42

Deposition rates (Å/sec) vs Source temperature

$R (\text{Å/sec})$

$R = 1.17 \times 10^7 \alpha G$

$\alpha = 10^{-2}$

$\alpha = 10^{-3}$

$\alpha = 10^{-4}$

$\alpha = 10^{-5}$

$T \times 10^{-3} \text{ (°K)}$
Fig 44

Deposition rate: 100 Å/sec

Deposition rate: 10 Å/sec

Deposition rate: 100 Å/sec
Heat sink temp: 391 °K

Dashed line: temperature increase due to radiation only.
Solid line: temperature increase due to radiation and heat of vaporization.
A: The film deposition is stopped (melt completely evaporated)
B: Filament turned off.
Radiation curve (Heating)
Current: 300 A
Copper - Constantan: Gauge 30
silver-soldered to copper plate (3/4" - 3/4" - 1/8")

Time (sec)

Temperature (°C)
Copper-constantan, Gauge 30
Silver-soldered to copper plate
(3/4" - 3/4" - 1/16")
Cooling curve
Current: 300 A
Chromel - Alumel : Gauges 36, 37, cemented between 2 substrates 0211.

Current: 300 A

Radiation and cooling curves

Time (sec)

Temperature (°C)
Fig 48

82.18 Ni-Fe

Iron-pair ordering for 80-20

Temperature (°C)

H_k (oe)

K (ergs/cm^3) x 10^3

Temperature (°C)
Particle size:
- increases with deposition temperature.
- decreases with increasing deposition rates.
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