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Considerations on the Curie Point of Thin Nickel Layers*

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The ferromagnetic Curie point was determined for thin nickel films with thickness ranging 20Å to 1000Å by measuring the electric conductivity, the Hall effect and the three effect of magnetoresistance.

Most of the theoretical works[1,2,3] about the influence of temperature on the magnetization of ferromagnetic films hint to a fall in the Curie ferromagnetic temperature T_f when under given thicknesses ranging from 200 Å and a few Å according to the hypothesis or the crystalline networks considered. Unfortunately, there are indeed very rare results in the experiments quantitatively agreeing with these theories. In general, the experiments bring into notice a sensible fall in the Curie point of the deposits for thicknesses under about 200 Å, a fall which grows quicker as soon as the thickness becomes smaller than 100 Å. Until now, C. A. Neugebauer[4], alone, shows that the magnetization to saturation and the Curie point of thin nickel films(evaporated under a vacuum better than 10^{-9}mmHg) are indentical with these of usual nickel for thicknesses decreasing down to about 20Å; he gives no indication as to the magnetic properties of the layers of a thickness less than 20 Å.

This work aims at confronting the results of our various determinations of Curie points of nickel layers, obtained through thermal evaporation (vaccum of 10^{-6}mm Hg) and stabilized by long reheating at 420°C[5]. The phenomena studied for that purpose are the electric conductivity, the Hall effect and the three effects magnetoresistance (Fig. 1).

Results

The study of the variation of the electric resistance with the temperature led us to consider 2 characteristic points on the curve $R=f(t)$. In fact, each of these curves shows, above a certain value T_p of the temperature, a rigorously rectilinear region corresponding to paramagnetism. The ferromagnetic Curie point T_f is defined by the point of the tangent of inflexion to each curve $R=f(t)$[5,6]. We have drawn, in function of thickness, the variation of the relation T_f/θ_f (θ_f=631°K of usual nickel). The resulting curve is represented on Fig. 5. Under 200 Å, the Curie point T_f suffers a rapid fall while the resistivity is growing. Moreover the ratio of the paramagnetic Curie temperatures T_p/θ_p (θ_p=650°K for usual nickel) is seen to vary little with the thickness of the deposits.

Figs. 1 and 2 represent the Hall tension of nickel deposits as a function of the field ($0<H<24000$ Oersteds) for a certain number of

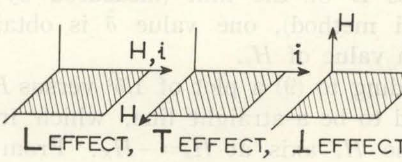

Fig. 1.

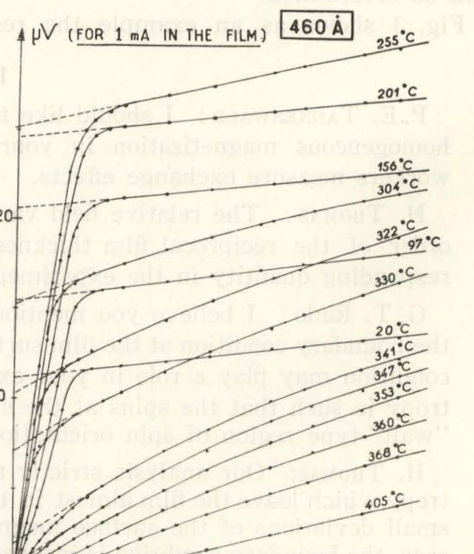

Fig. 2.

* This paper was not read at the Conference.

temperatures ranging from the ambient one and about 400°C[5,7].

It is interesting to compare these results with the networks of curves $\sigma=f(H,t)$ giving the specific magnetization as functions of the field and temperature[8]. Both phenomena considered in that manner behave very comparably. Then let us consider the isotherms superior to 200°C: the part corresponding to the rapid rising of the Hall tension (related to spontaneous magnetization) witnesses a slow decrease while the part of the curve which is hyperbolic develops itself and the slope of the line "to saturation" rises up slightly. When temperature goes on rising, the rectilinear part disappears almost completely, while the curvature lessens gradually. The values of the field that are indicated on the x-axis are the values of the applied field which do not correspond, except to saturation, with the actual induction in the deposit; now we know that the magneto-caloric phenomenon corresponds with the variation of the real magnetization. Therefore this suggests to proceed to an extrapolation of the type used by Weiss and Forrer in order to determine the temperature from which the spontaneous magnetization disappears, and consequently in order to register the Curie temperature T_f. These extrapolations as shown on Figs. 1 and 2 lead to Curie temperatures distinctly higher

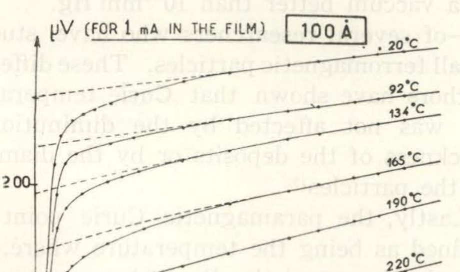

Fig. 3.

than those determined by the preceding method (Fig. 5).

The behaviour of the electric resistance of thin nickel layers, as it is the case with most magnetic materials, is revealed, when induction increases, by a diminution of the resistance when the current and the field are orthogonal; conversely, it consists in an increase of the resistance with the induction when the current and the field are parallel. However at proximity of the Curie point, and whatever the relative positions of the current and the field may be, magnetoresistance is ever revealed by a decrease of the resistance. Therefore we have availed ourselves of these properties to determine[9] the ferromagnetic temperatures of our deposits and we have measured the 3 types of magnetoresistance which correspond to the three relative positions that may assume, in relation to the layer, the current of measure and the direction of the applied field (Fig. 3).

The detailed results to which we have been led form the matter of other publications. Here we shall be concerned only with the study of phenomena in function of temperature ($0<t<400$°C) for given values of the

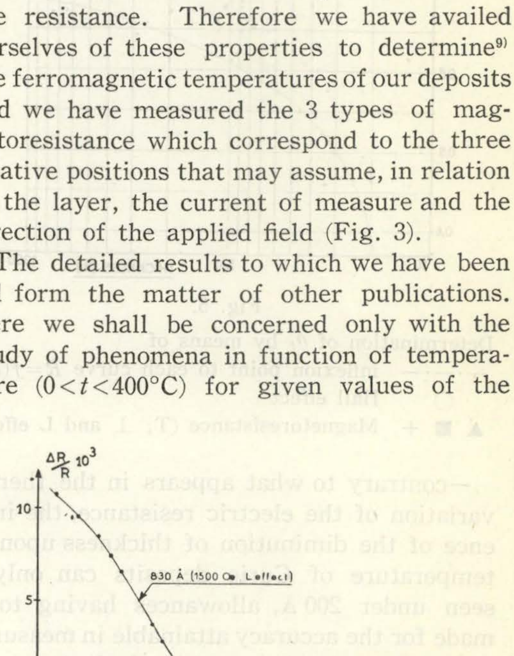

Fig. 4.

applied field. In the three cases, when temperature reaches Curie point T_f, the isotherms of magnetoresistance are deformed while the relation $\Delta R/R$ rises rapidly in absolute value. Above this temperature, $\Delta R/R$ diminishes sharply and can only be measured above 400°C. This behaviour is represented on Fig. 4 for layers different in thickness, each of them being measured in one of the relative positions previously defined.

Discussion

In Fig. 5 the different values of T_f/θ_f as a function of the thickness are represented. The confrontation of the results of the described experiments lead to the establishment of two important facts:

—generally, the relation T_f/θ_f determined from Hall phenomena or magnetoresistance are much higher than those deduced from studies on conductivity (represented by solid curve).

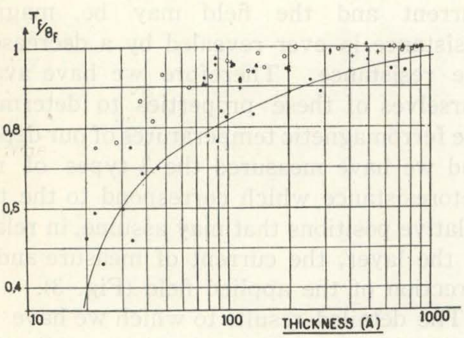

Fig. 5.
Determination of θ_t by means of
—·—·— inflexion point to each curve $R=f(t)$
○ Hall effect
▲ ■ + Magnetoresistance (T, ⊥ and L effects)

—contrary to what appears in the thermal variation of the electric resistance, the influence of the diminution of thickness upon the temperature of Curie deposits can only be seen under 200 Å, allowances having to be made for the accuracy attainable in measuring temperature in the course of these experiments.

The most accurate results are obtained by the study of the thermal variation of the magneto-electric effects: for the very acute minimum registered when passing θ_f enables to locate θ_f with the precision reached in carrying out measures of temperature. θ_f varies rather slightly for $e>100$Å whatever the direction of currents may be in relation to the field*.

To determine θ_f from the network of Hall isotherms is much more delicate. Given that accuracy with which it is possible to measure temperature, it is illusive to expect to trace very close isotherms as Weiss and Forrer[8] did about specific magnetization. Our measures have enabled us to deduce for θ_f values which are comparable to these obtained by magnetoresistance.

The variations brought to evidence in that manner between the Curie ferromagnetic temperature as determined by the study of conductivity on one hand, and by the magneto-galvanic effect on the other hand, cannot be accounted for by considerations about the experiments. It must probably be ascribed to the very choice of the inflexion point on the curve of resistivity, owing to the fact that resistivity is not a simple function of magnetization[11].

Moreover the films are obtained in a vaccum ranging about 10^{-6}mm Hg and from the evaporation of electrolytic deposits of nickel on tungsten filament. Consequently these layers contain traces of tangsten capable in spite of the precautions taken during evaporation, to lower the Curie point of the material[12]. Lastly the deposits are polycrystalline and the studied phenomena depend on an apparent magnetization necessarily inferior to the actual magnetization. These considerations appear to be confirmed by the following works:

—Neugebauer[4] dealing with the direct measuring of the magnetization of the deposits of a thickness inferior to 100 Å, obtained by the evaporation of a filament of pure nickel in a vaccum better than 10^{-9}mm Hg.

—of several researchers who have studied small ferromagnetic particles. These different authors have shown that Curie temperature T_f was not affected by the diminution of thickness of the deposits or by the diameter of the particles[13].

Lastly, the paramagnetic Curie point T_p, defined as being the temperature where:

—the characteristics $R=f(t)$ become sensibly linear[5,6]

—the Hall curves become rectilinear

—the magnetoresistance falls sharply

remains invariable when the thickness diminishes, allowances being made for the accuracy of the measure of temperature.

Therefore it seems it may be admitted that the temperature T_f as well as T_p is independent of thickness at least for thicknesses superior to 20 Å. Under that, the influence of the support and of the first layers of de-

* Similar results have been obtained by K. Kuwahara[10] in the case of longitudinal magnetoresistance.

posits becomes important and the phenomenon is perturbed.

The variations that we, as well as other experimentalists, have noticed are ascribable to the experimental techniques we had to use.

This work has been carried out in the "Laboratory of Physics for Thin Layers" of the Faculty of Science of the University of Caen. Thanks are due to Professor Colombani whose discussion and suggestions were most helpful in carring out the work.

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