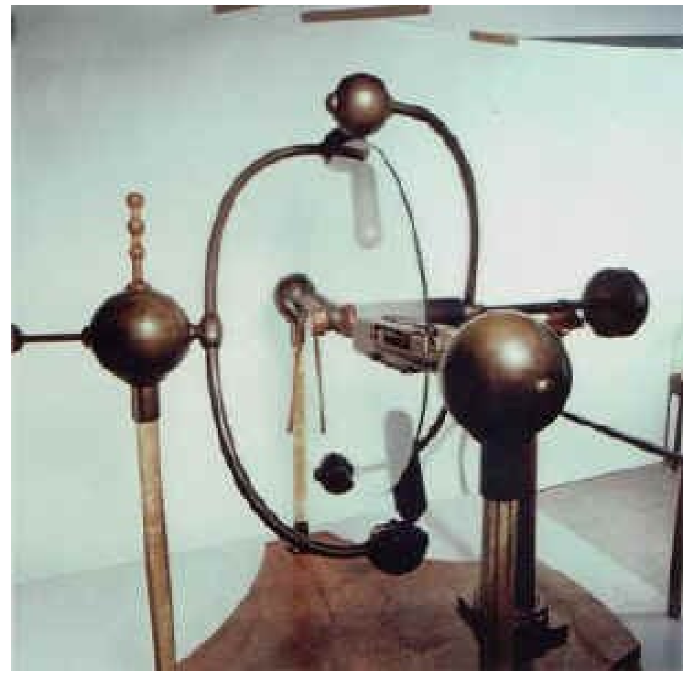
From Ohm's Law to the Nobel Prize

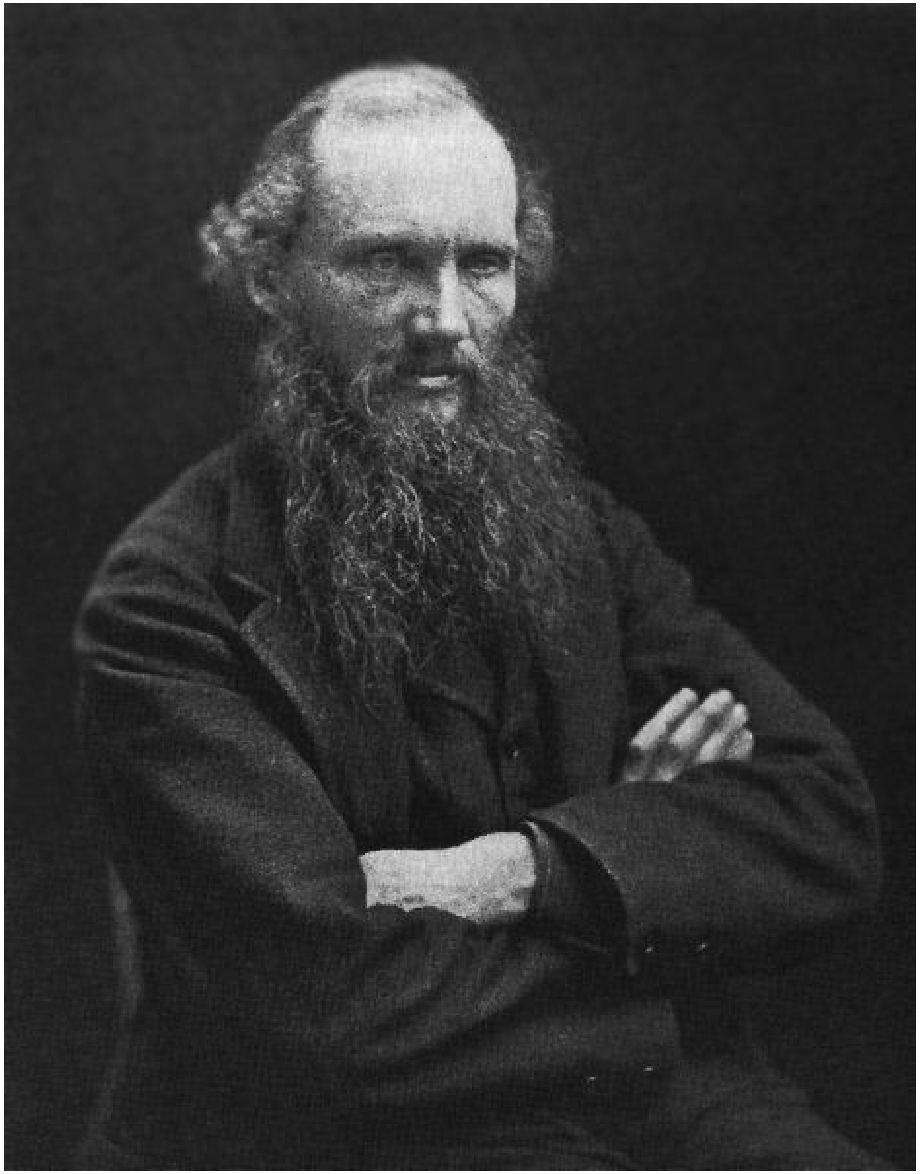
historical perspectives and historic
discoveries

Ohm's Law 1827

Georg Simon Ohm 1787-1854



Unfortunately, when Ohm published his finding in 1827, his ideas were dismissed by his colleagues. Ohm was forced to resign from his high-school teaching position and he lived in poverty and shame until he accepted a position at Nüremberg in 1833 and although this gave him the title of professor, it was still not the university post for which he had strived all his life.



William Thomson
(Lord Kelvin of Largs)

1824-1907
Professor of Physics,
Univ Glasgow 1846-99
(53 years)

FRS 1851
Knighted 1866
Peer 1892

XIX. "On the Electro-dynamic Qualities of Metals:—Effects of Magnetization on the Electric Conductivity of Nickel and of Iron." By Professor W. THOMSON, F.R.S. Received June 18, 1857.

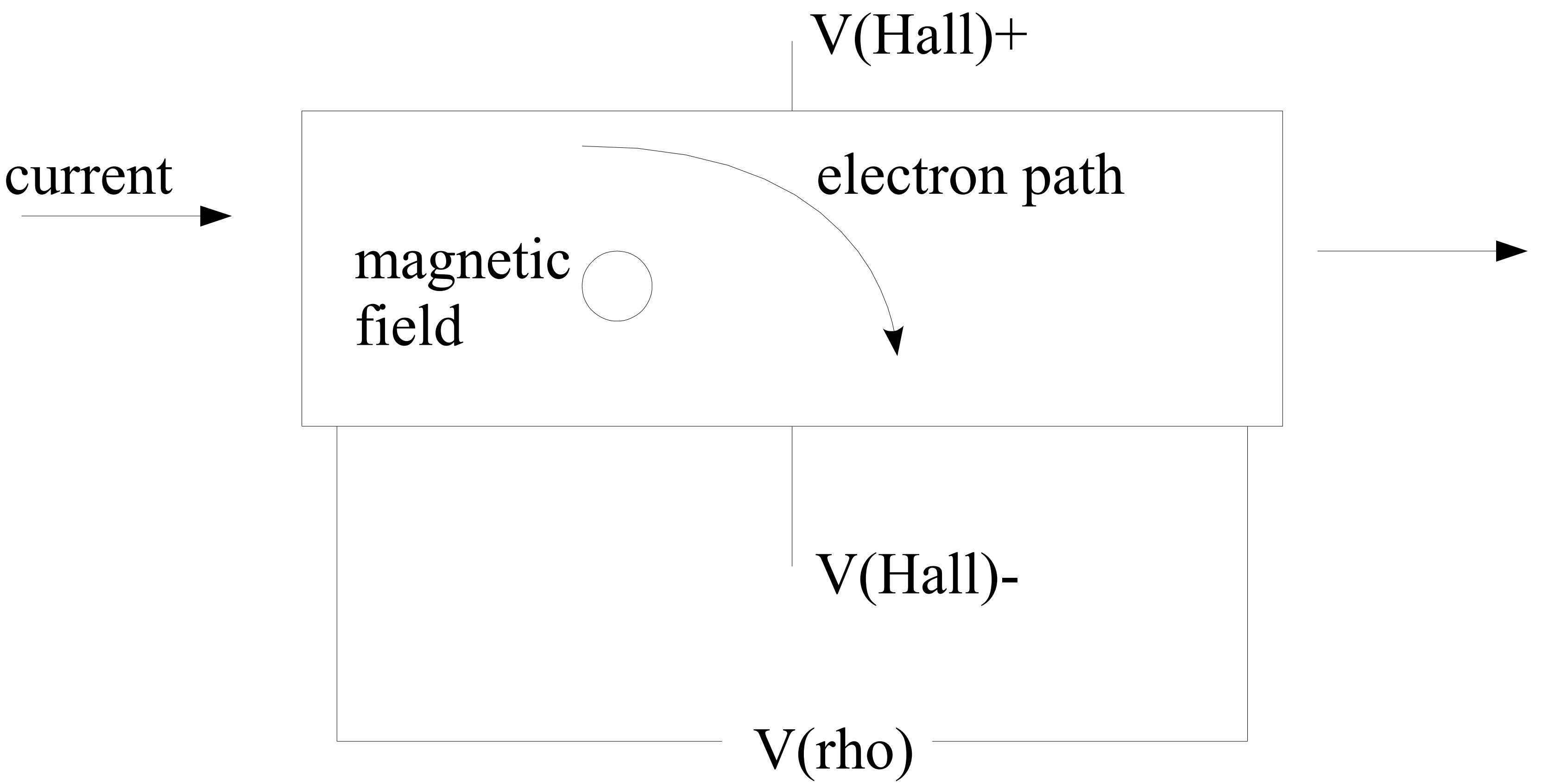
I have already communicated to the Royal Society a description of experiments by which I found that iron, when subjected to magnetic force, acquires an increase of resistance to the conduction of electricity along, and a diminution of resistance to the conduction of electricity across, the lines of magnetization*. By experiments more recently made, I have ascertained that the electric conductivity of nickel is similarly influenced by magnetism, but to a greater degree, and with a curious difference from iron in the relative magnitudes of the transverse and longitudinal effects.

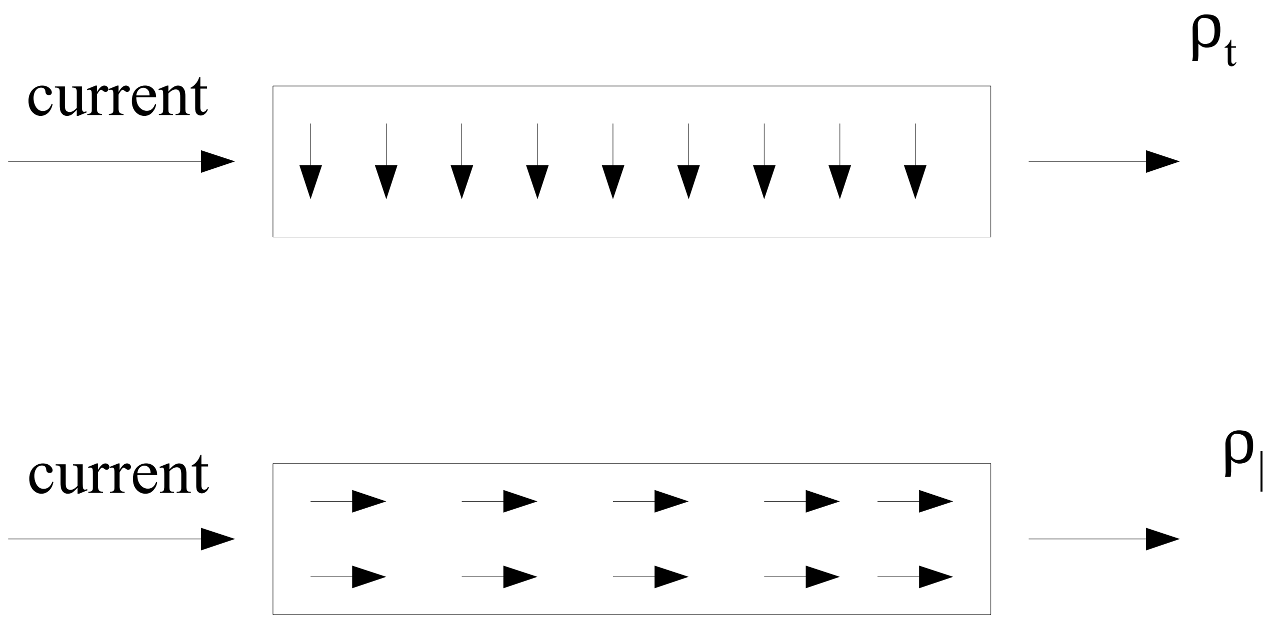
In these experiments the effect of transverse magnetization was first tested on a little rectangular piece of nickel 1·2 inch long, ·52 of an inch broad, and ·12 thick, being the "keeper" of the nickel horse-shoe (§ 143) belonging to the Industrial Museum of Edinburgh, and put at my disposal for experimental purposes through the kindness of Dr. George Wilson. Exactly the method described in § 175 of my previous communication referred to above, was followed, and the result, readily found on the first trial, was as stated.

The effect of longitudinal magnetization on nickel was first found with some difficulty, by an arrangement with the horse-shoe itself, and magnetizing helix (§ 143), the former furnished with suitable electrodes for a powerful current through itself, and the system treated in all respects (including cooling by streams of cold water) as described in § 156, for a correspondiug experiment on iron. The

* See Phil. Trans. Bakerian Lecture, "On the Electro-dynamic Qualities of Metals," Feb. 27, 1856, § 146 of Part 4 and Part 5. In the present communication that paper will be referred to simply by the sectional (§) numbers.

Ordinary magnetoresistance, Hall effect





$$\Delta\rho/\langle\rho\rangle = (\rho_{\|} - \rho_t)/\langle\rho\rangle$$

Anisotropic Magneto-Resistance (AMR)
William Thomson 1857

Fe at room temperature $\Delta\rho/\langle\rho\rangle \sim 2\%$

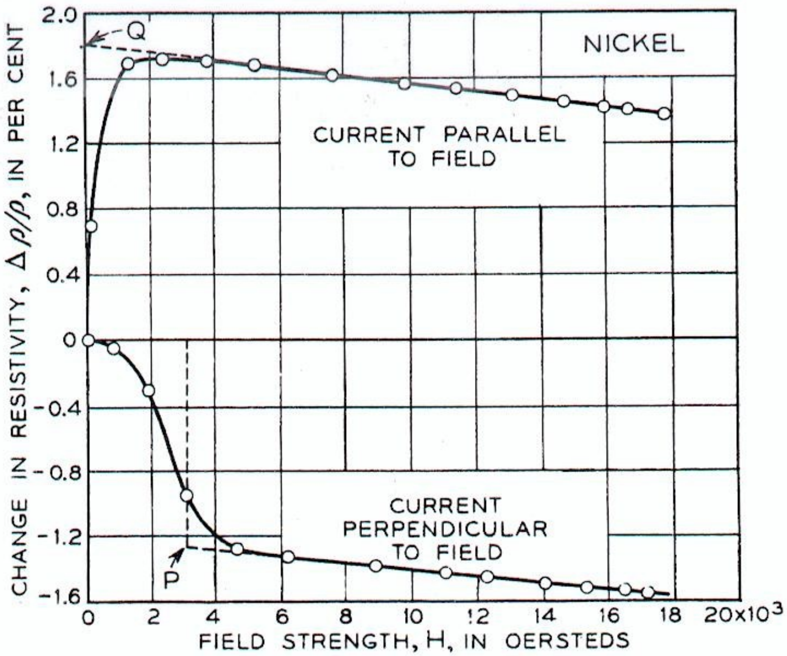


FIG. 16–7. Change of resistance of nickel in longitudinal and in transverse fields [32E1].

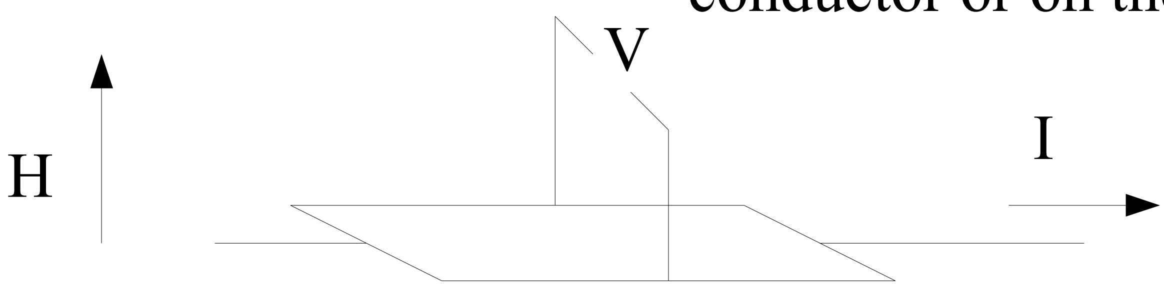
Measurement made in 1932. Ni at room temperature

Smit (1954) realized that the resistivity anisotropy is a spin orbit effect, due to fact that scattering with change of spin through terms $(L^+S^-)2$ is anisotropic. But he could not explain why the different alloys gave effects of very different strengths.

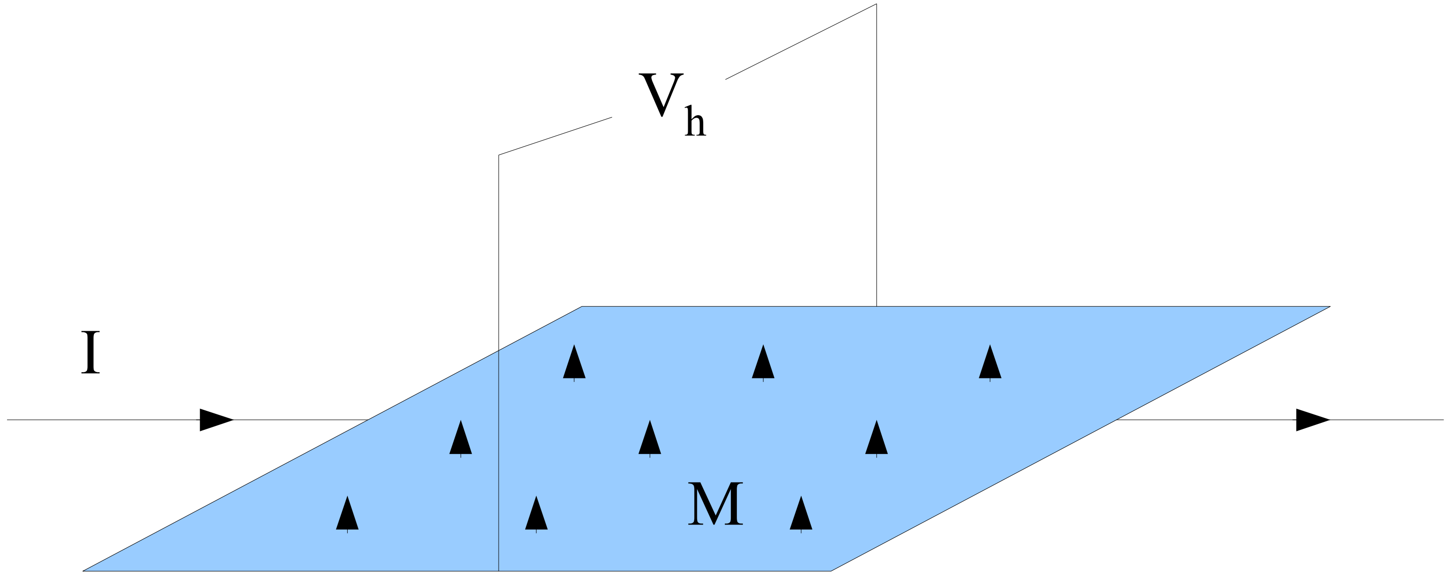
The resistivity of magnetic metals has always been of great technological importance. From 1912 on transformer plates made of magnetically soft **Fe**Si replaced pure Fe plates. As the alloy has a much higher electrical resistance, the eddy current losses in transformer cores were significantly reduced.

Edwin Herbert Hall
1855-1938
PhD at Johns Hopkins U
(with Rowland)
1879 Hall effect
1881 Hall effect Fe
Professor Harvard 1895-1921

Does the magnetic field push on the conductor or on the current ?



Anomalous Hall effect



$$V_h = R_s I M$$

On a New Action of the Magnet on Electric Currents.

BY E. H. HALL, *Fellow of the Johns Hopkins University.*

SOMETIME during the last University year, while I was reading Maxwell's Electricity and Magnetism in connection with Professor Rowland's lectures, my attention was particularly attracted by the following passage in Vol. II, p. 144:

"It must be carefully remembered, that the mechanical force which urges a conductor carrying a current across the lines of magnetic force, acts, not on the electric current, but on the conductor which carries it. If the conductor be a rotating disk or a fluid it will move in obedience to this force, and this motion may or may not be accompanied with a change of position of the electric current which it carries. But if the current itself be free to choose any path through a fixed solid conductor or a network of wires, then, when a constant magnetic force is made to act on the system, the path of the current through the conductors is not permanently altered, but after certain transient phenomena, called induction currents, have subsided, the distribution of the current will be found to be the same as if no magnetic force were in action. The only force which acts on electric currents is electromotive force, which must be distinguished from the mechanical force which is the subject of this chapter."

This statement seemed to me to be contrary to the most natural supposition in the case considered, taking into account the fact that a wire not bearing a current is in general not affected by a magnet and that a wire bearing a current is affected exactly in proportion to the strength of the current, while the size and, in general, the material of the wire are matters of indifference. Moreover in explaining the phenomena of statical electricity it is customary to say that charged bodies are attracted toward each other or the contrary solely by the attraction or repulsion of the charges for each other.

Soon after reading the above statement in Maxwell I read an article by Prof. Edlund, entitled "*Unipolar Induction*" (Phil. Mag., Oct., 1878, or Annales de Chemie et de Physique, Jan., 1879), in which the author evi-

Alpheus W. Smith
Phys.Rev. 1910

8,000 c.g.s. units for saturation; at the latter about 1,000 c.g.s. units. For all temperatures not greater than 355° C. the slopes of the curves beyond saturation is nearly the same, although their slopes before saturation are quite different. The magnitude of the effect at the temperature of liquid air before saturation is about one twenty-third of its magnitude under the same conditions at 300° C. and the magnitude at 410° is about one ninth of that at 300° C. For fields of equal intensity the Hall electromotive force at 355° is

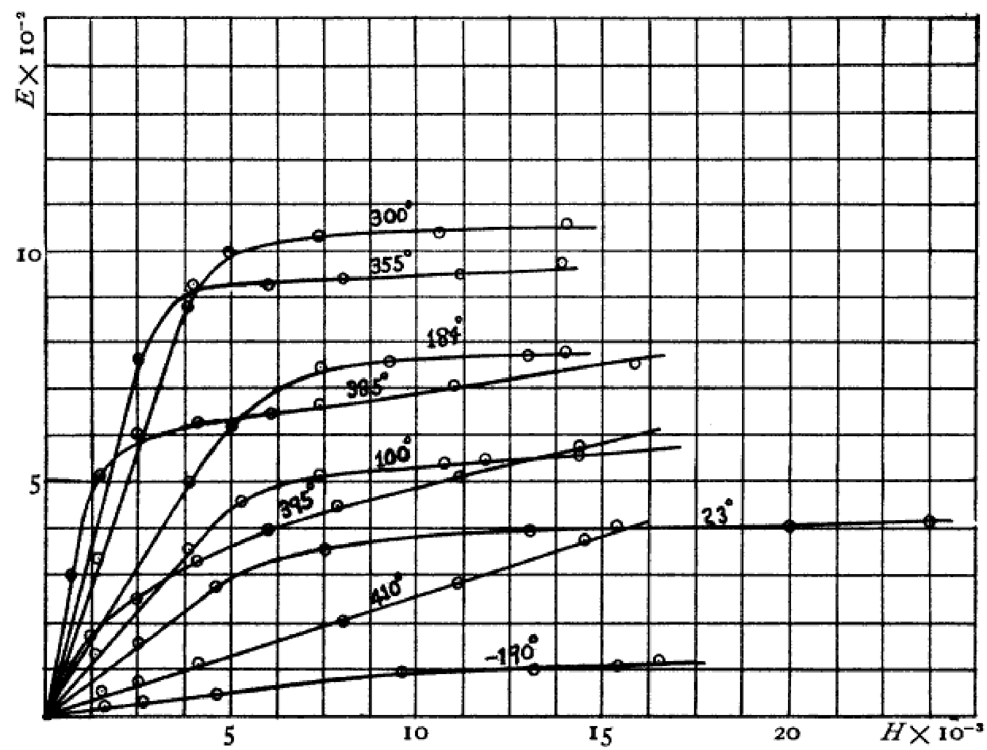


Fig. 13. Nickel.

greater than that at 300° until the field has the value of approx-

In the discussion of the reasons for the reversal of the Hall effect in iron and its failure to be always proportional to the magnetic field J. J. Thomson[2] has pointed out that in addition to the effect of the magnetic force on the electrons, while they are moving over their free paths, one must take into account the magnetic force which acts on the electrons when collisions between electrons and molecules occur. Thomson states this possible explanation of the reversed effect in iron as follows: "Imagine a body whose molecules are little magnets. Then if the body is placed in a magnetic field so that the lines of force are vertical and downwards, the molecules will arrange them-

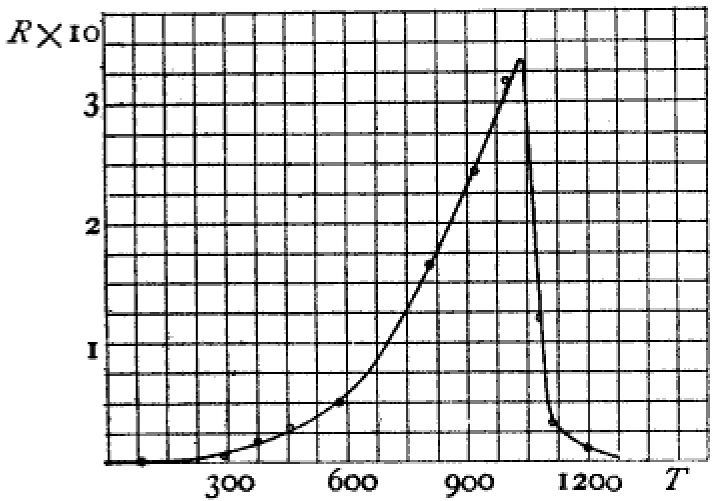


Fig. 21. Kahlbaum iron.

[1] Ibid., pp. 189–199.

[2] Corpuscular Theory of Matter, p. 70.

A.W. Smith : “according to a suggestion made by J.J. Thomson (Congres international de physique, Paris 1900) the Hall effect in iron may be explained by supposing that the field actually acting on the free electrons is not only the impressed external field but **also the field due to the orbital motion of the electrons in the metal**.”

Smith was the first to separate ordinary and extraordinary Hall terms for ferromagnetic metals (1910):

$$V_H \sim R_0 B + R_s M$$

Sir Joseph John Thomson
1856-1940
Cavendish Professor 1884-1918
discovered the electron 1897
Nobel prize 1906
(his son G.P. Thomson : Nobel prize 1937)

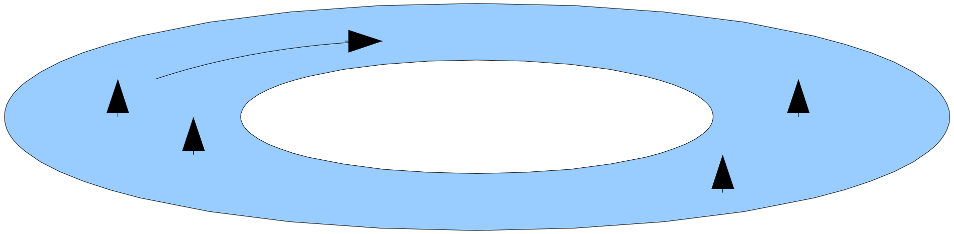
Theoretical interpretation of the extraordinary ("anomalous") Hall effect :

Karplus +Luttinger 1954 predicted a spin-orbit band term leading to a

scattering independent Hall current J_H.

As no total current can flow in the standard geometry there must be a conventional counter-current. $J_H = \lambda E$, $E = \rho J$, $V_H = \rho J_H$

$R_s \sim \lambda \rho^2$ with λ depending on the change of the spin-orbit strength with the momentum **k** of the electron which is a band effect.



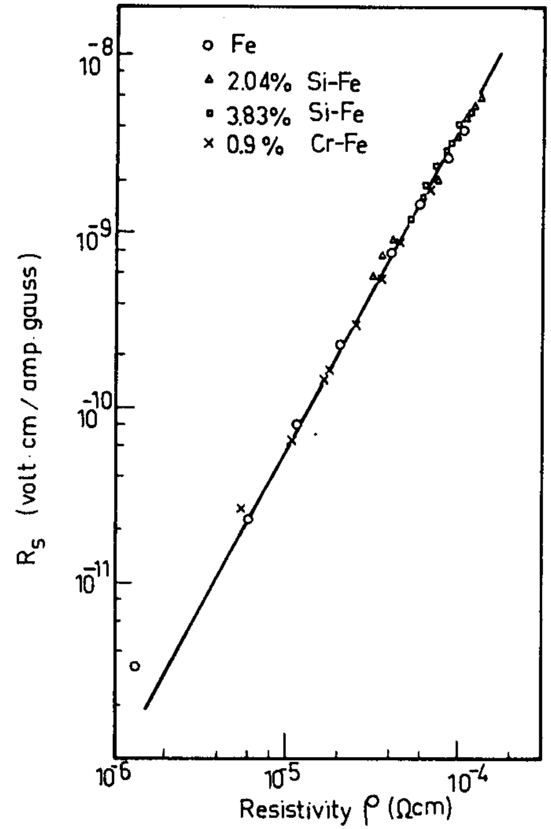


Fig. 18. Log–log plot of R_5 against ρ for Fe and some Fe alloys above nitrogen temperature (after Okamoto et al. 1962).

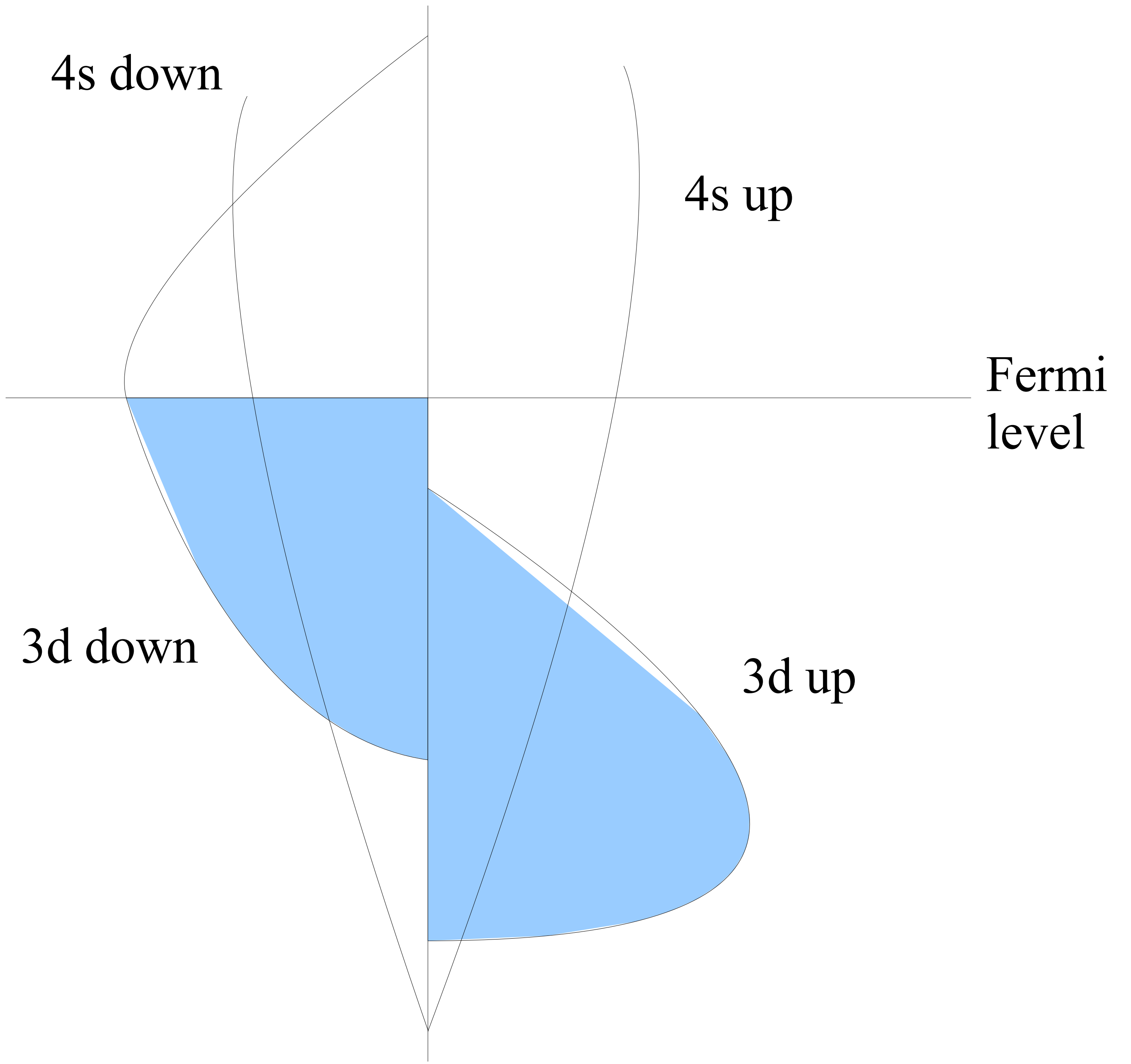
High resistivity AHE, dominated by the Karplus-Luttinger dissipationless Hall current effect, $R_s \sim \lambda\rho^2$

The **Nernst-Ettingshausen effect** is the thermoelectric analogue of the Hall effect. $\mathbf{V}(\mathrm{NE})_z \sim Q_{NE}[(\mathbf{\Delta T})_x \times \mathbf{B}_y]$

There is an extraordinary NE effect (Kondorskii ~1958)

$V_{NE} \sim [Q_0 B + Q_S M]\Delta T$

Sir Nevill F. Mott
1905-1996
(parents met working in J.J. Thomson’s lab).
After work with Bohr, Born, Bragg,...
Professor in Bristol 1933-54
Cavendish professor Cambridge1954-1971
Nobel prize 1977 (conduction in glasses)
His last PRL was published posthumously



4s down
4s up
Fermi
level
3d down
3d up

Mott (1936) : transition metals have a heavy d-band and a conducting s-band. For Ni, d-band present at the Fermi surface only for spin-down.

So for Ni :

"At low temperatures conduction electrons with spins parallel to the direction of the magnetization cannot make transitions to the d-band since the spin-up d-band is full. Thus these electrons would have much longer mean free paths than those with the opposite spin."

and again in Ni

"…..the scattering by spin disorder is not the main effect"

Mott interpreted the drop in resistivity ρ(T) near Tc in pure Ni on this model, which turns out to be incorrect.

He interpreted ρ(T) near Tc for Fe as due to spin disorder, which is in fact the correct explanation for both Fe and Ni.

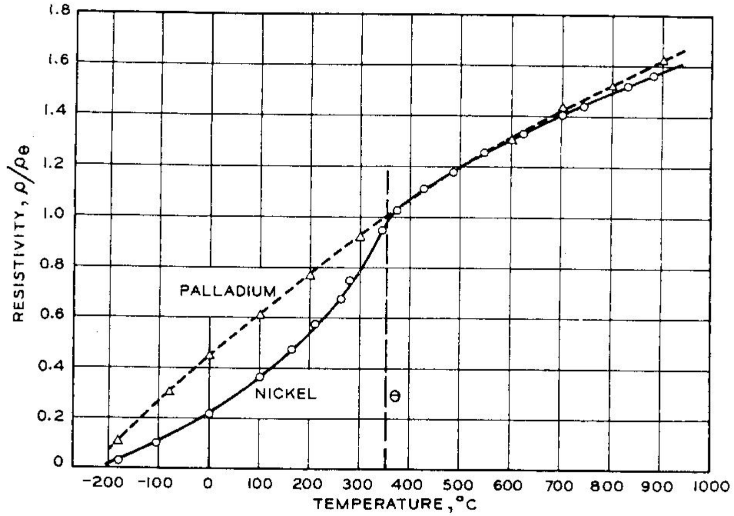
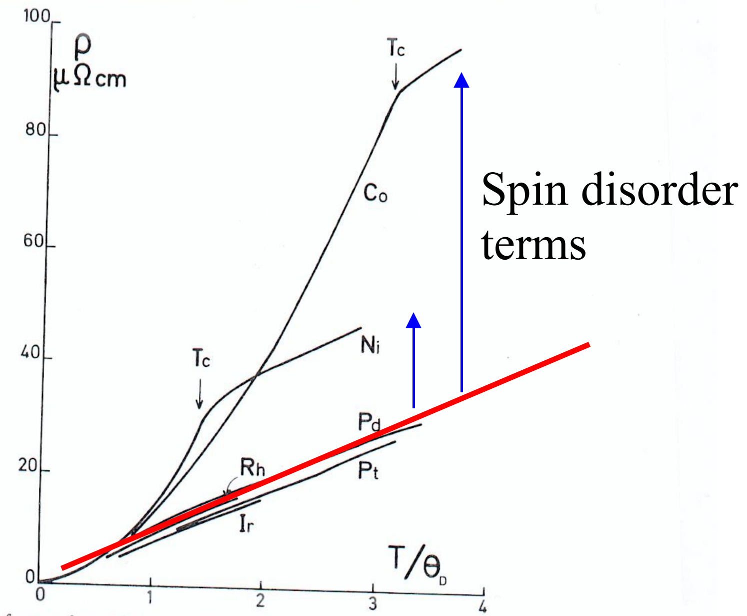
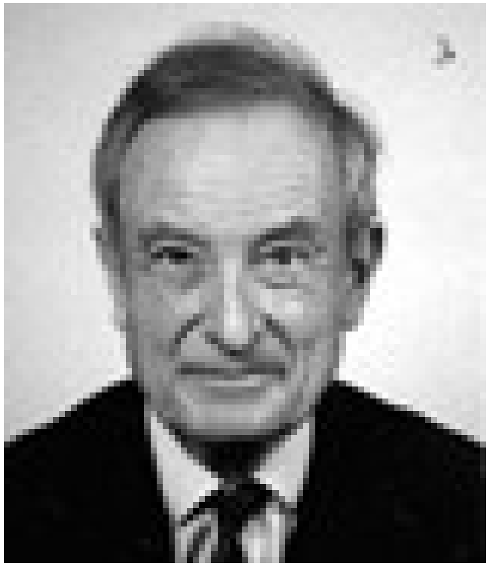


FIG. 16–24. The low resistivity of a magnetic material below the Curie point.



Resistivity of several transition metals as a function of T/θ_D. θ_D is the Debye temperature.

Mott's argument for ρ(T) near Tc was based on the image on the left where an experimentalist had arbitrarily **normalized together ρ(T) for Ni and for Pd at Tc(Ni).** The correct picture is in fact on the right where the Debeye temperatures are used for normalization. Ni like Co and Fe has an extra spin disorder scattering near and above Tc.



Jacques Friedel

Theory of alloys, d virtual bound state,...

Friedel school (1957 onwards) underlined the importance of screening at individual impurities (VBS) as against the rigid band model for alloys.

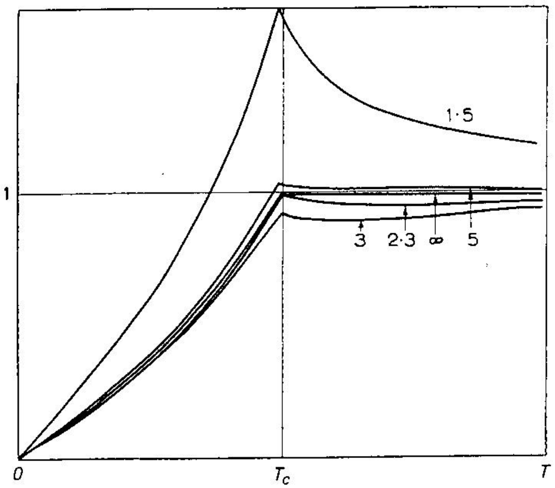
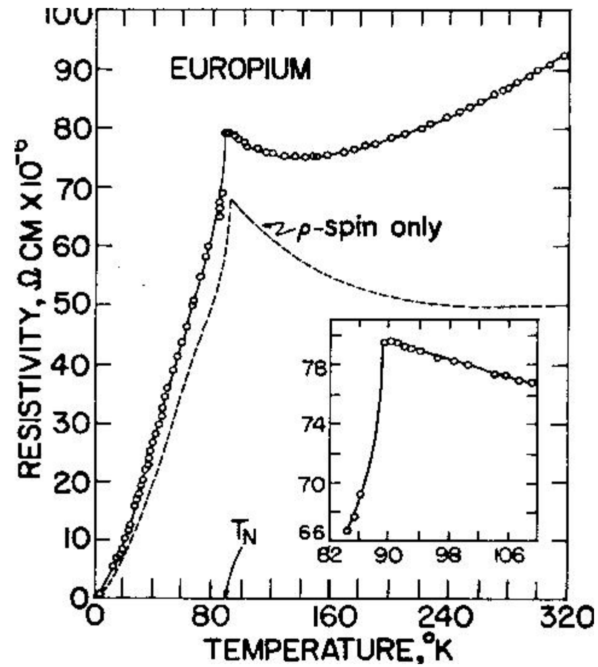
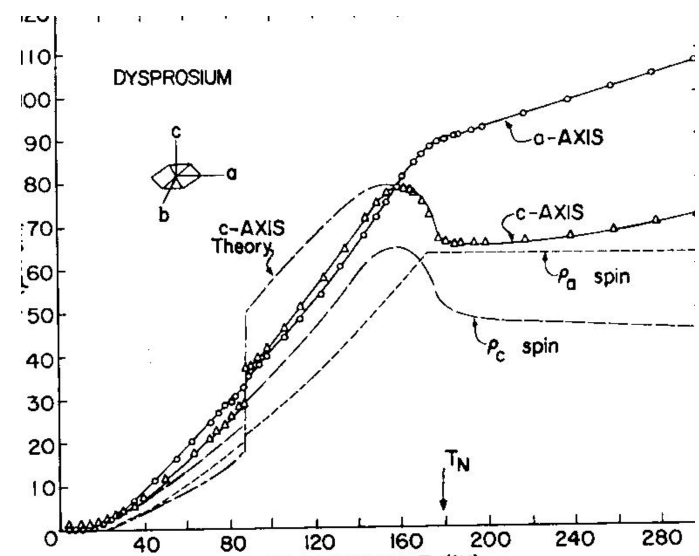


FIG. 3. Effet de l'ordre à courte distance sur la résistivité d'un ferromagnétique. Approximation élastique; traitement de champ moléculaire; spin classique. Les courbes ont été tracées pour quelques valeurs du paramètre k_0d (marquées sur le graphique).





Theoretical curves for the resistivity of ferromagnets including short range order effects (de Gennes and Friedel 1957). Experimental **ρ**(T) for Eu.

Experimental curves for **ρ**(T) along different axes in Dy.

Explained by "superzone" boundaries (Elliott and Wedgewood)

T. Kasuya (1956), K. Yoshida (1957), de Gennes + Friedel (1957)

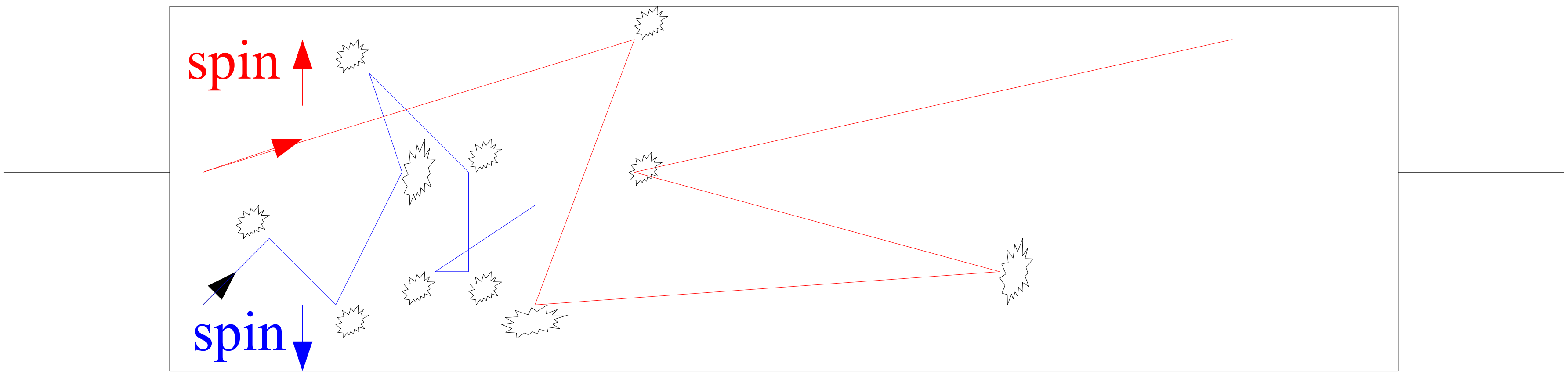
Spin disorder scattering in the paramagnetic state :

$$\rho_m = k_F(m\Gamma)^2 J(J+1)/4\pi e^2 z h^3$$

No spin disorder scattering in the full ferromagnetic state so $\rho_m(T)$ drops sharply below T_C. Short range spin disorder scattering is dominant near T_C.

Mott's statement about spin-up and spin-down electrons was perfectly correct for low temperatures $T \ll T_C$ (in fact for all three transition ferromagnets Fe, Co and Ni) but there was no experimental evidence for it for thirty years.

$\lambda(\text{up}) >> \lambda(\text{down})$



Low T : Spin up and spin down electrons conduct current independently and in parallel, so i(total) = i(up) + i(down)

or $1/\rho = 1/\rho(\text{up}) + 1/\rho(\text{down})$

High T : frequent scattering of electrons by magnons so spin memory is lost ; each electron is up as often as down, and so finally by Tc there is onlyone mixed current.

1964 :

Parallel currents : $1/\rho = 1/\rho_{up} + 1/\rho_{down}$ or

$$\rho_{LT} = \rho_{up}\rho_{down}/(\rho_{up}+\rho_{down})$$

Currents mixed by spin flips : $\rho_{HT} = (\rho_{up} + \rho_{down})/4$

So $\rho_{HT}/\rho_{LT} = (1+\alpha)^2/4\alpha > 1$ $\alpha = \rho_{down}/\rho_{up}$

Introducing a momentum conserving spin flip term $\rho_{updown}(T)$ gives

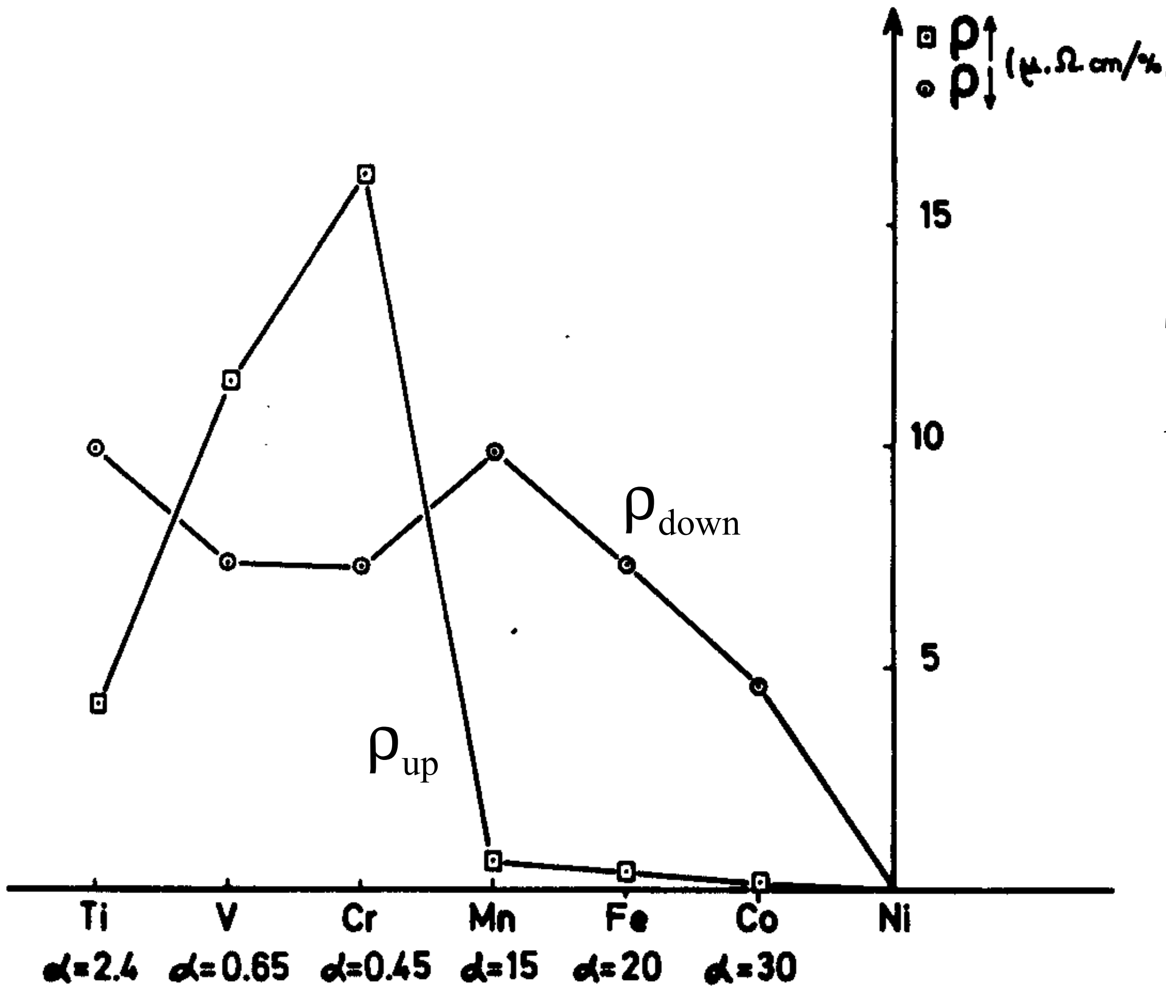
$$\rho(T) = [\rho_{up}\rho_{down} + \rho_{updown}(\rho_{up} + \rho_{down})]/[\rho_{up} + \rho_{down} + 4\rho_{updown}]$$

Cadaquès
~ 1963

Article publié dans "Le Monde" du 9 janvier 2004 :
Albert Fert, professeur à l'université de Paris-Sud et directeur de l'unité mixte de physique CNRS-Thales, s'est interrogé au début de sa carrière sur l'utilité pratique du métier de scientifique.
"J'avais beaucoup d'autres passions, la photographie, le cinéma, le rugby,...."....

Campbell, Fert and Pomeroy, Phil Mag 1967

arXiv.org/0711.4478



Thesis
Albert Fert (1970)

Figure V.1 - Résistivités résiduelles (par %) des impuretés de métaux de la première série de transition dans le nickel.

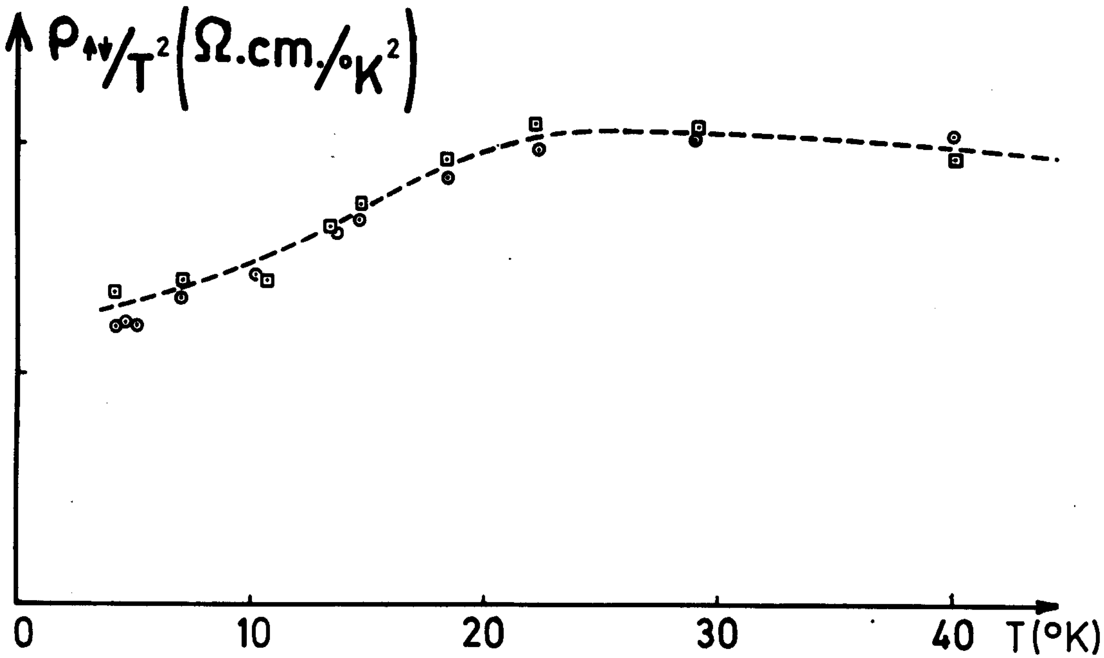


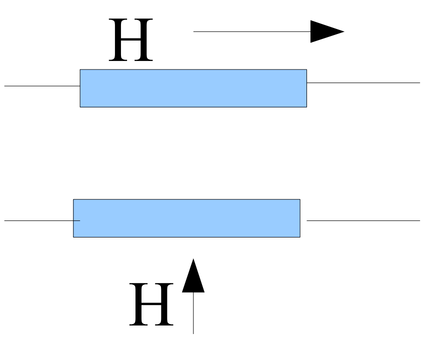
Figure III.17 - Variation expérimentale de $\rho\uparrow\downarrow/T^2$ en fonction de T pour le fer.

⊙ valeurs déduites de la résistivité d'alliages Fe Mn

⊡ valeurs déduites de la résistivité d'alliages Fe Cr

Resistivity anisotropy : Smit (1951) had shown that spin-orbit mixing between an s-band and a d-band $(L^+S^-)^2$ was anisotropic. But he did not know anything abour parallel current conduction. Using Smit's result, one predicts $\Delta\rho/\langle\rho\rangle = \gamma\,(\alpha\text{-}1)$

This is what is observed, finally giving the explanation of the resistivity anisotropy effect observed by Kelvin 110 years earlier.



Thesis Olivier Jaoul (1974)

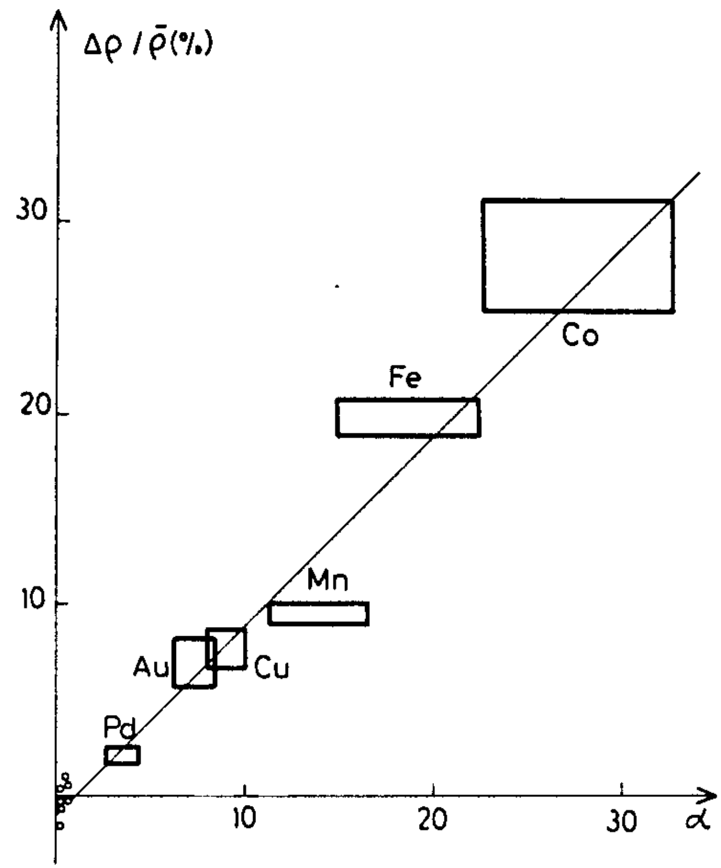


Fig. 14. Resistivity anisotropy of Ni based alloys at 4.2 K as a function of $\alpha = \rho_{0\downarrow}/\rho_{0\uparrow}$. The straigh line is $\Delta\rho/\bar{\rho} = 0.01\,(\alpha - 1)$ (after Jaoul et al. 1977).

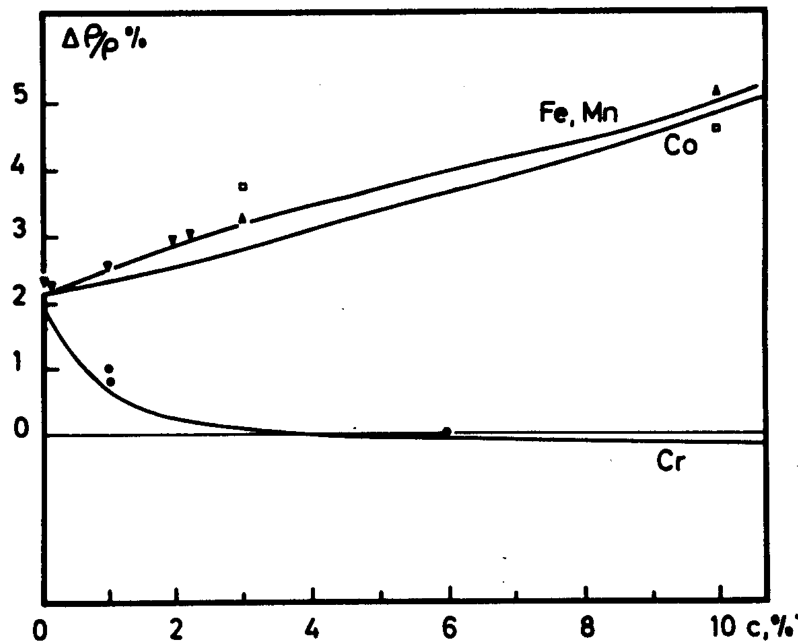


Figure VII.5 - Résultats expérimentaux et courbes calculées pour $\frac{\Delta\rho}{\rho} = \frac{\rho_{//} - \rho_{\perp}}{\rho_{\perp}}$ à 293°K.

Data on Ni based alloys at 293°K.

This effect was used extensively in magnetoresistive detector heads from 1971. The optimal RT effect is for permalloy (Ni_3Fe) which was chosen empirically from the begining.
(first used for bubble domain memories by W. Strauss (Bell) 1970)

From 1969 onwards many contributions from groups in :

- Strasbourg (Cadeville, Gauthier, Durand, Loegel,...),

- Eindhoven (Dorleijn, Miedema),

- Leeds (Grieg)

and elsewhere.

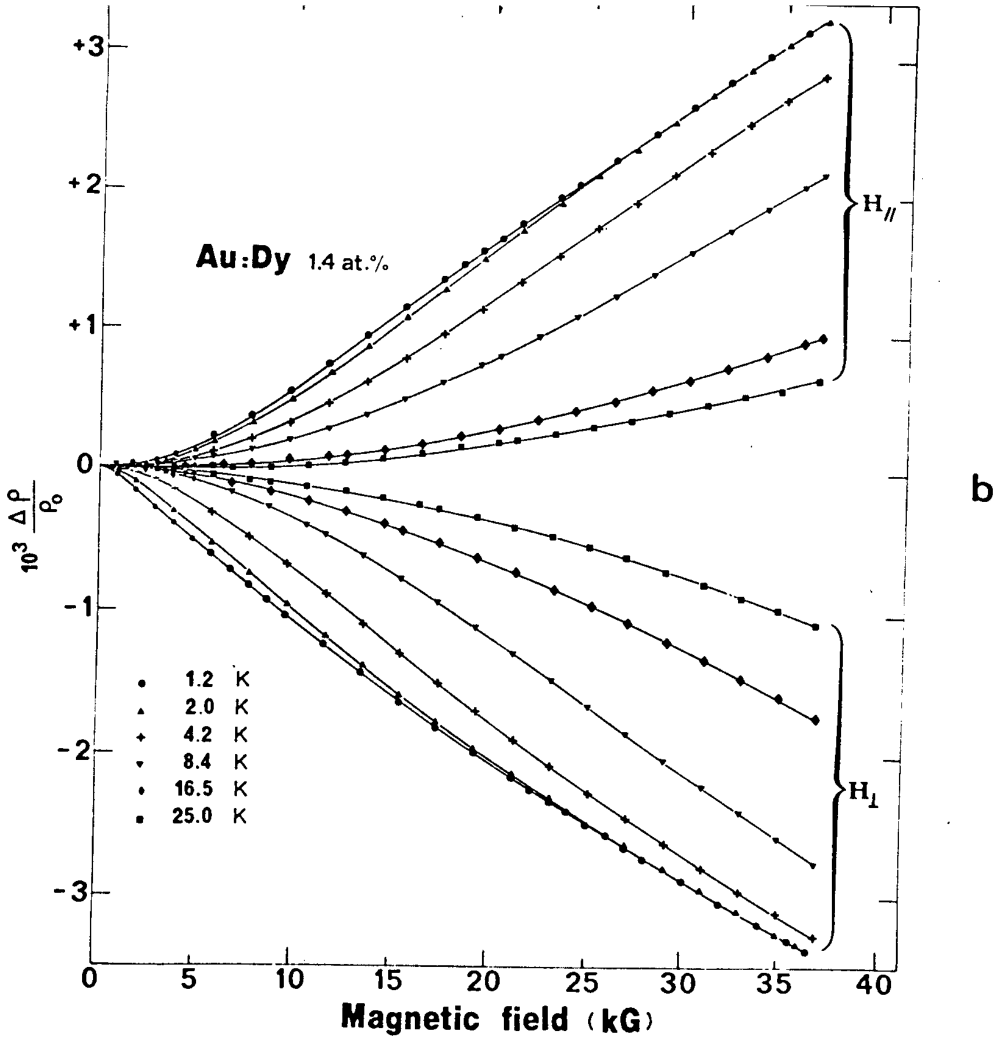


Fig. IV-1: (a) Magnétorésistance relative d'un alliage cristallin dilué AuGd en fonction du champ appliqué à plusieurs températures. On peut remarquer que la magnétorésistance est la même pour les deux directions du champ magnétique.

(b) Magnétorésistance relative d'un alliage cristallin dilué AuDy en fonction du champ appliqué à plusieurs températures. Dans ce cas, la magnétorésistance est anisotrope. (IV-1)

Thesis Alain Friederich (1975). Resistivity anisotropy of **Au**Dy 1.4%

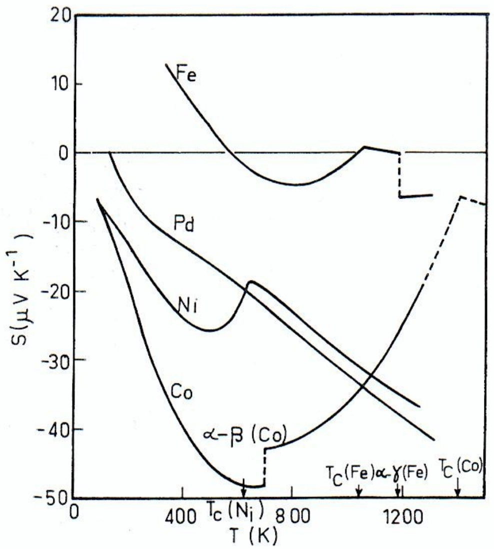


Fig. 20. The absolute thermoelectric power of Ni, Fe, Pd and Co (Laubitz et al. 1976).

Thermoelectric effect in ferromagnetic metals and in Pd.

Korenblit and Lazarenko (1971) suggested that the well is due to electron-magnon scattering : scattering of a spin-down electron to spin-up means creating a magnon which needs positive energy.

Normalized thermoelectric effect in Heusler alloys (Hamzic et al 1984)

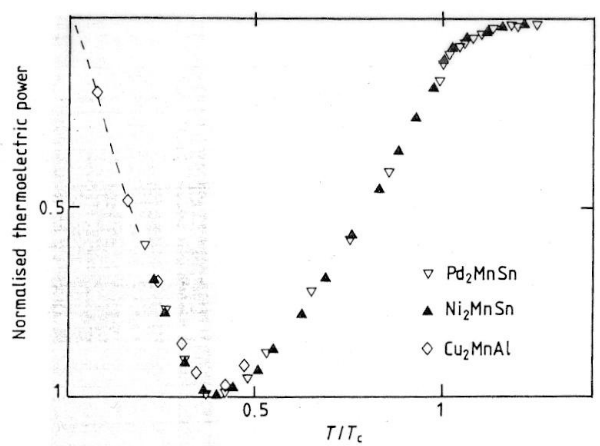


Figure 4. Normalised thermoelectric powers $(S(T) - AT)/[S(0.4\,T_c) - A(0.4\,T_c)]$. A is estimated for each alloy from the high-temperature slope.

Laboratoire de Physique des Solides, Orsay. 21.11.1980.

W. Cheng

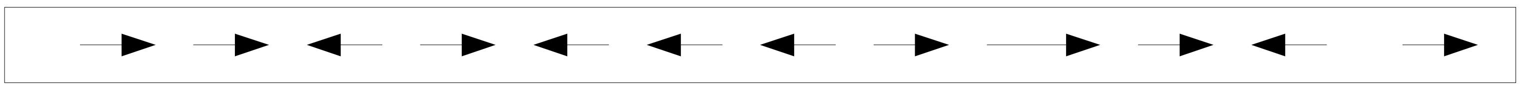
A. Fert I.A. Campbell P. Garoche

S. Senoussi

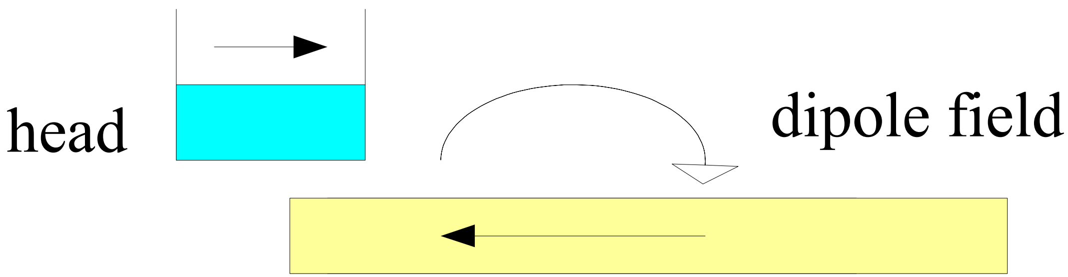
W.Geldart

G. Creuzet A. Hamzic

Magnetic recording for tape recorders, hard discs, ...
Write with induction coil which imposes the direction of magnetization of each small magnet. Easy to overwrite.



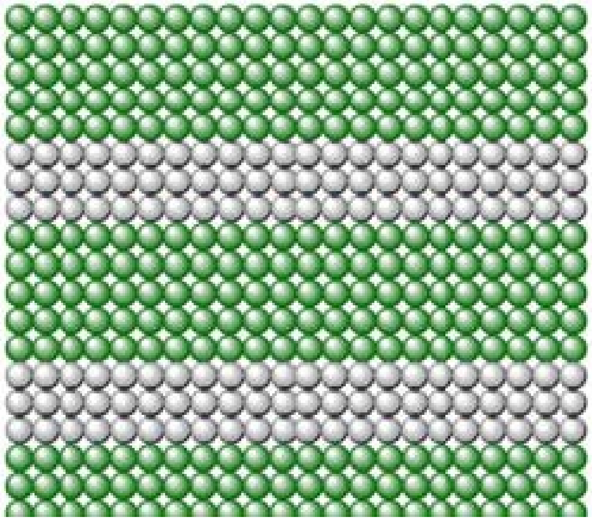
Detection :



Detect the dipole field by :

- same induction coil
- AMR magnetoresistance head. Dipole stray field turns the direction of the magnetization in the head, changes resistivity, electrical signal as output. High detection speed, high sensitivity, small size, so high recording density.

(can also use optical, magneto-optical recording....)



Superlattice

Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange

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Institut für Festkörperforschung, Kernforschungsanlage Jülich G.m.b.H., Postfach 1913, D-5170 Jülich, West Germany

Received 31 May 1988 Published 7 March 1989

The electrical resistivity of Fe-Cr-Fe layers with antiferromagnetic interlayer exchange increases when the magnetizations of the Fe layers are aligned antiparallel. The effect is much stronger than the usual anisotropic magnetoresistance and further increases in structures with more than two Fe layers. It can be explained in terms of spin-flip scattering of conduction electrons caused by the antiparallel alignment of the magnetization.

Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices

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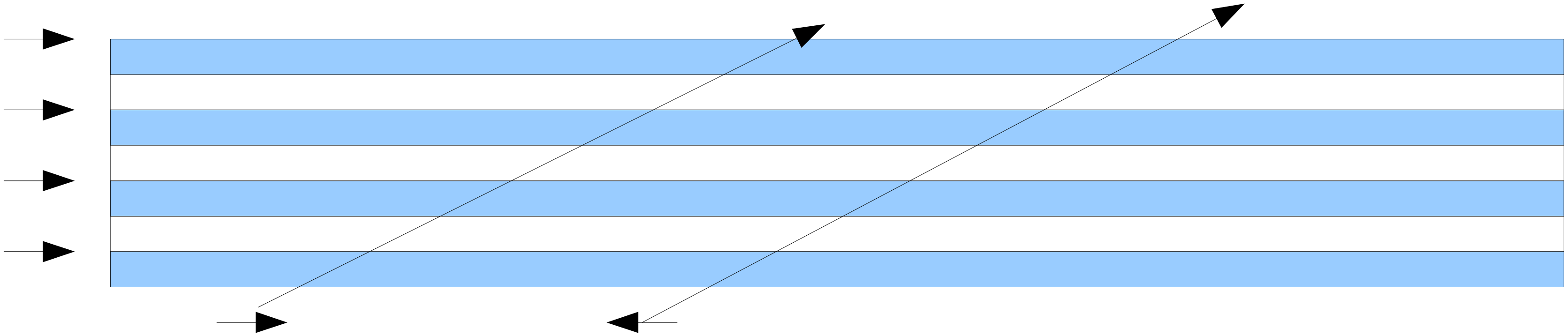
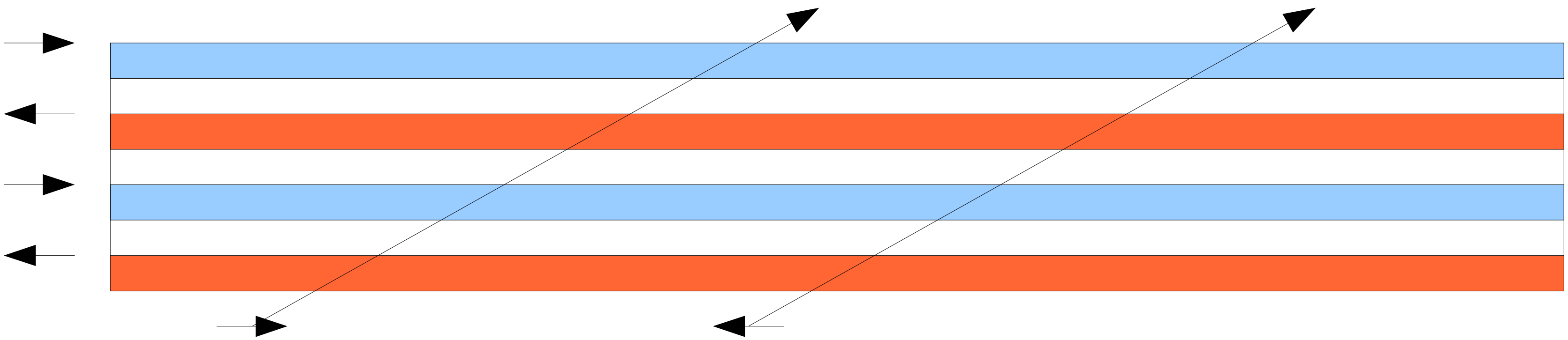
We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecularbeam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers: For example, with tCr=9 Å, at T=4.2 K, the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.

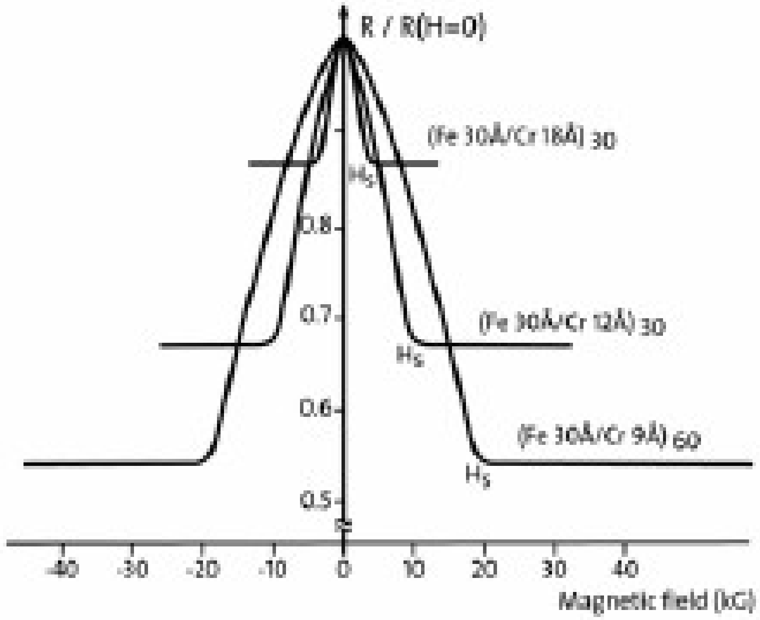
sample magnetized (field applied)



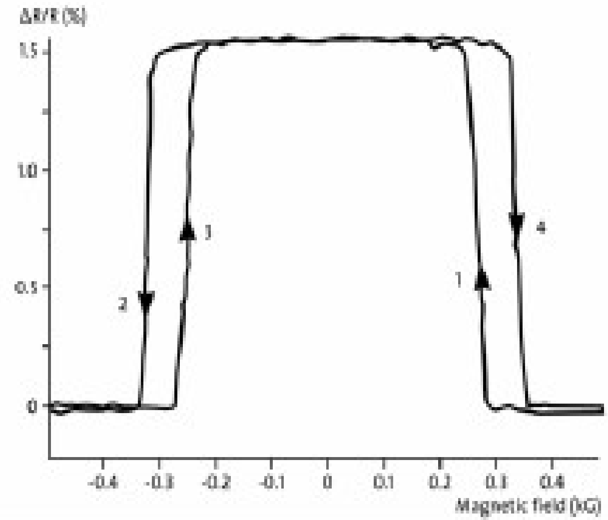
same sample demagnetized (no field applied, spontaneous state)



magnetic layer : M up : blue, M down : red
non-magnetic layer : white
Conduction electron conserves its spin direction.
Layer thickness ~ nanometres.



Baibich et al



Binasch et al

J.P. Renard et al
(Orsay)
PRB 1 jan 1988
Au/Co/Au/Co/Au
anisotropy perp
to film plane

« The Co bilayer exhibits a drastic enhancement of the MR effect »

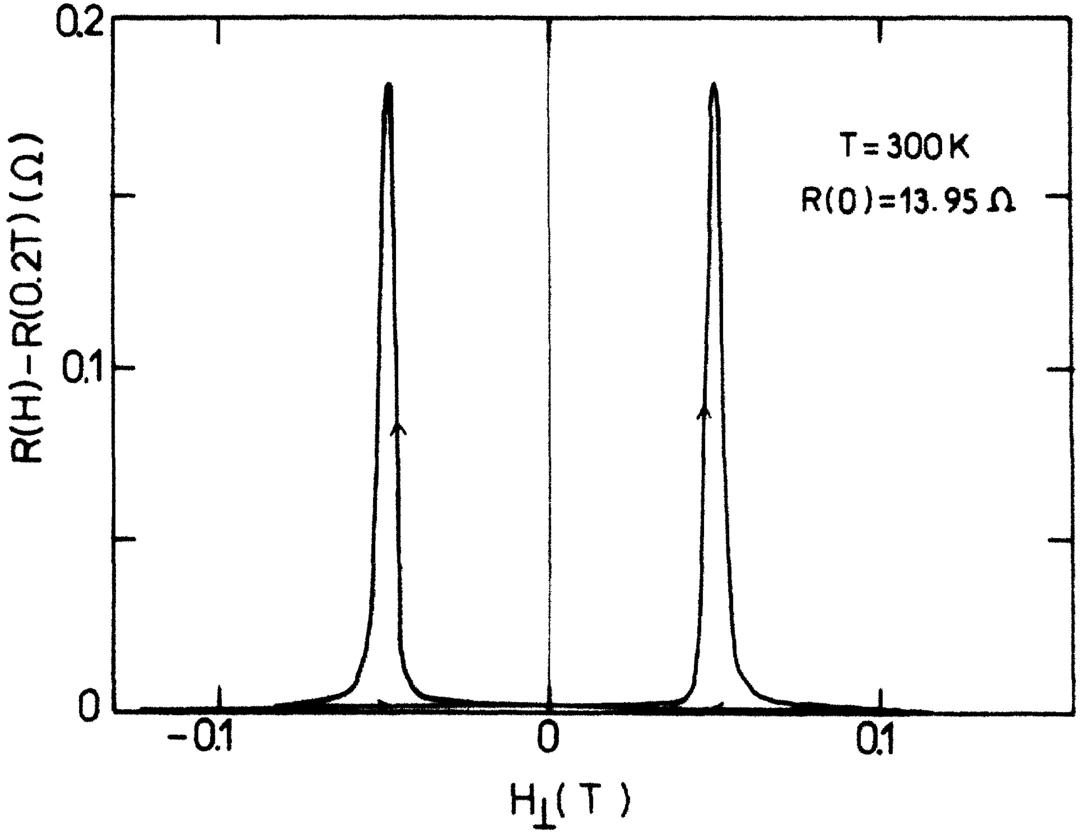


FIG. 3. Room-temperature perpendicular magnetoresistance of sample 3: Au/Co (0.76 nm)/Au (3 nm)/Co (0.76 nm)/Au. The coercive field is H_c=493 G and $\delta R_c/R$=1.3%.

Enhanced magnetoresistance of ultrathin (Au / Co)n multilayers with perpendicular anisotropy

E. Vélu, C. Dupas, D. Renard, J. P. Renard, and J. Seiden

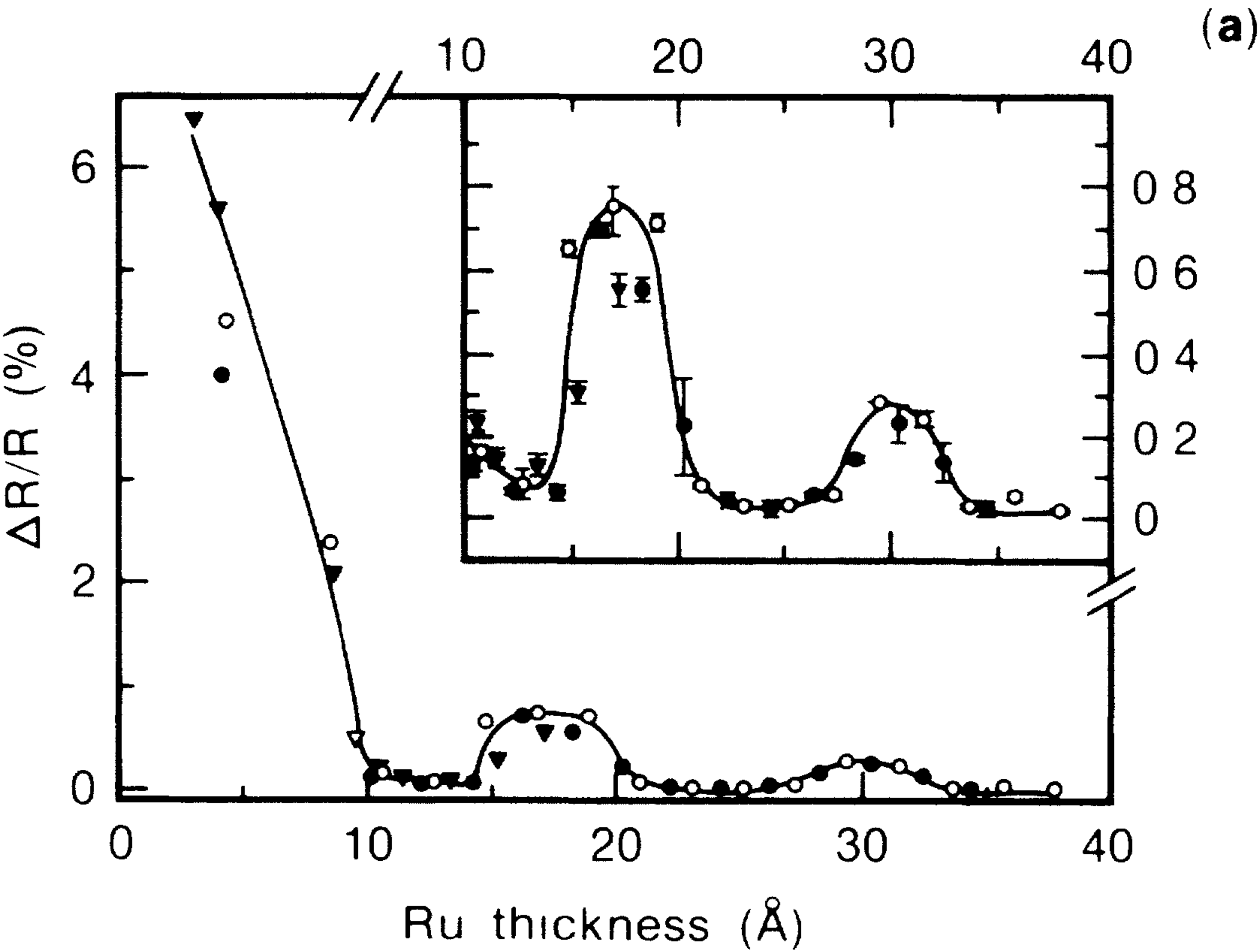
Received 20 July 1987   Published 1 January 1988

Stuart Parkin, IBM Almaden

He was the first to use **sputtering techniques** to create GMR structures, which consist of thin magnetic layers separated by non-magnetic metals. ....

In 1991, he discovered that slight changes in the thickness of the non-magnetic spacer layer caused large oscillations between parallel and anti-parallel magnetic alignment. And in 1994, Parkin and his IBM Research colleagues used this basic information to design and create GMR elements for what proved to be the most sensitive disk-drive read/write head made at that time. Subsequently, IBM introduced the GMR head in its disk-drive products in 1997. GMR/TMR now used in **all of the world's production of disk drives**. The GMR head has been a key enabler of the more than 30-fold increase in disk-drive data densities from 1997 to 2006.
2.4 to more than 70 gigabits per square inch. (Now in 2008, > 250 gb/sqinch.)

~ 5 billion GMR heads are in use in the world



Parkin 1991

Dieny, Parkin
et al
IBM Almaden
1991
Spin Valve

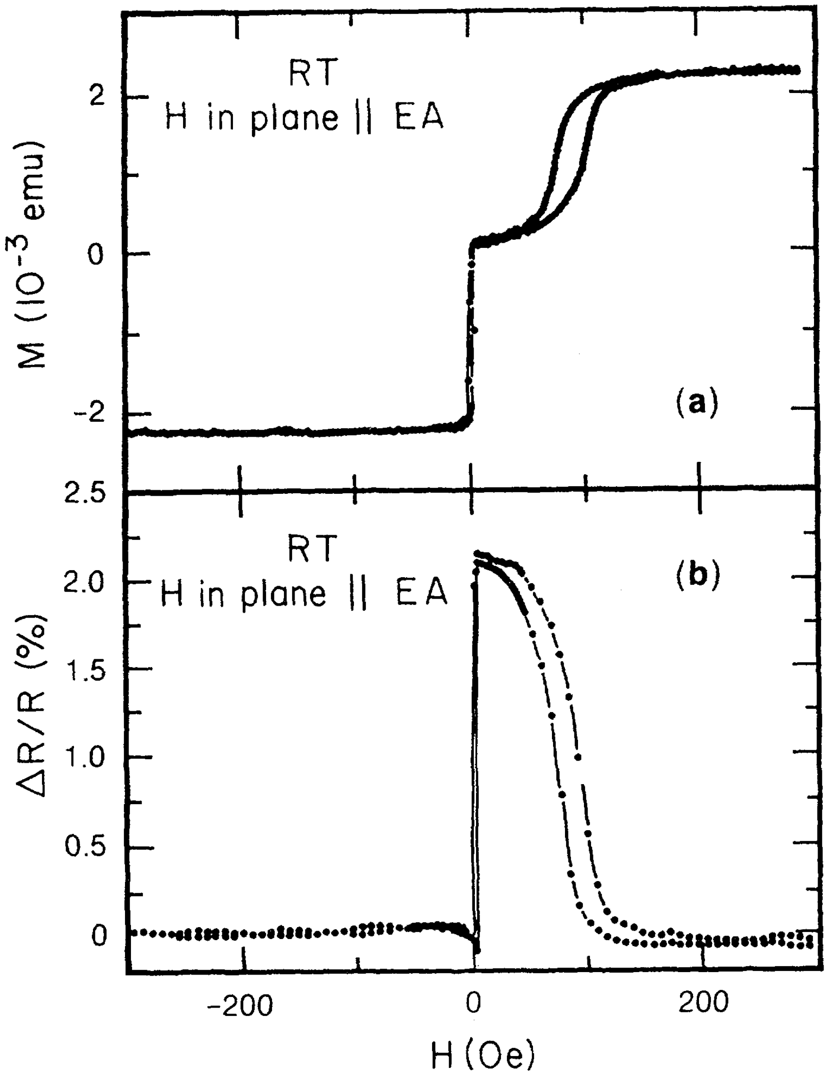
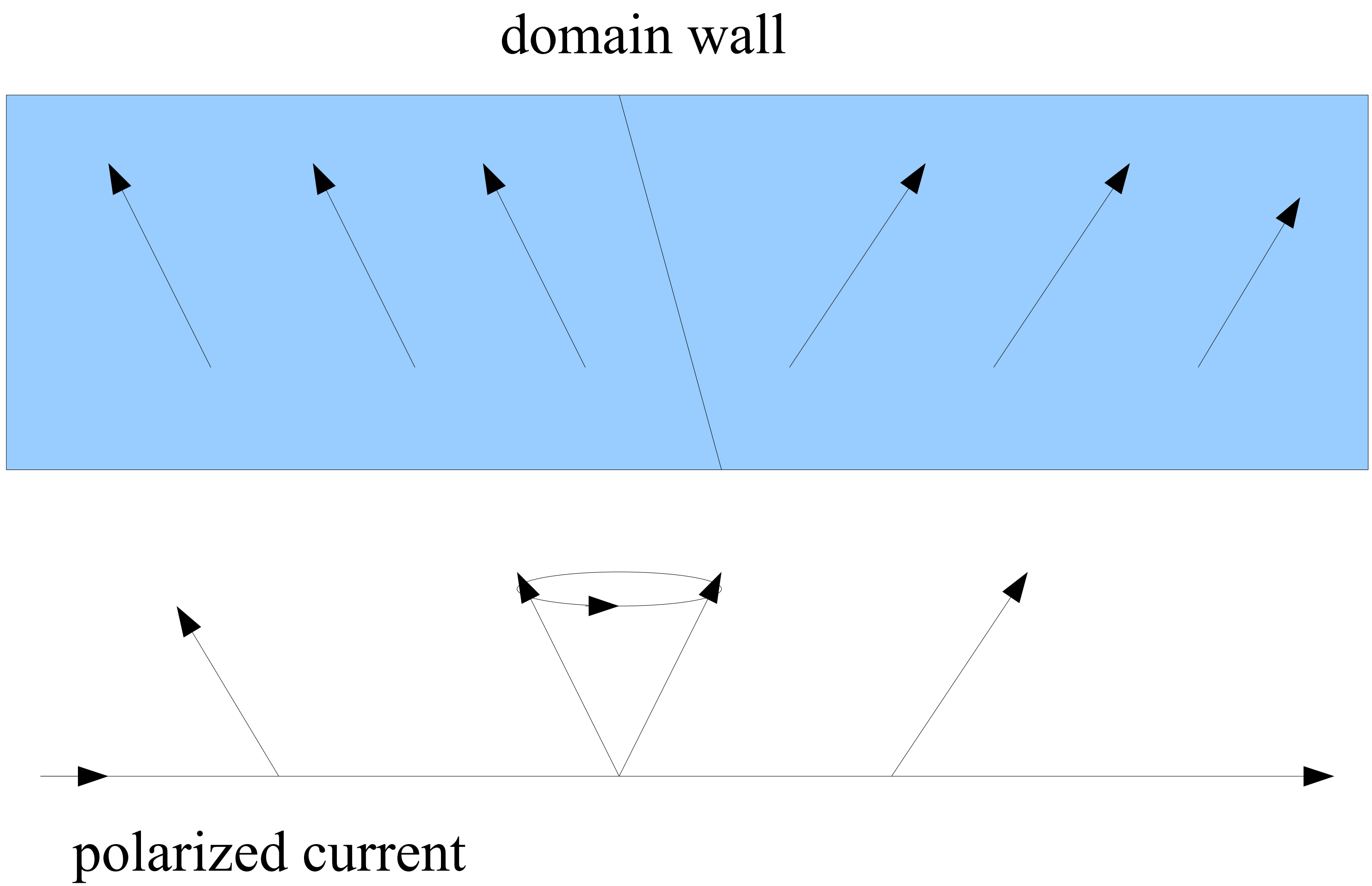
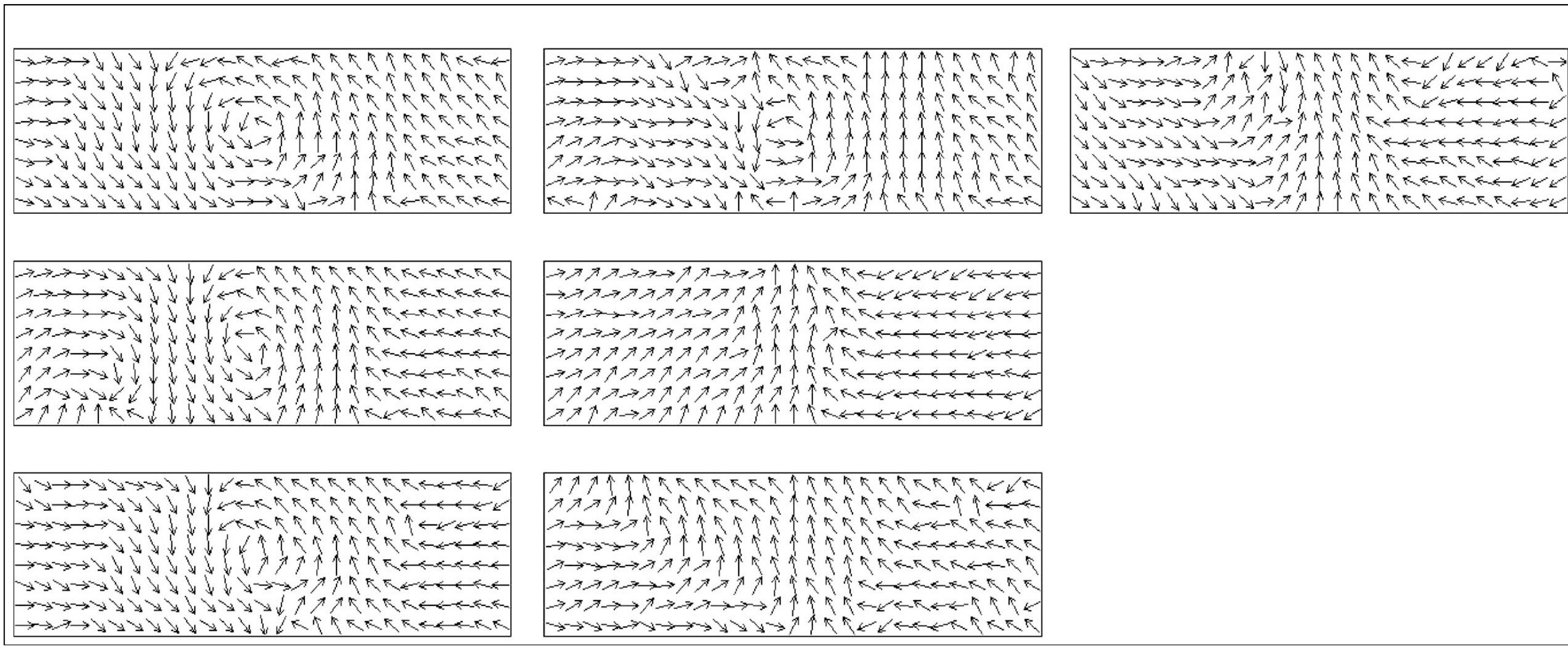


FIG. 1. Magnetization curve (a) and relative change in resistance (b) for Si/(150-Å NiFe)/(26-Å Cu)/(150-Å NiFe)/(100-Å FeMn)/(20-Å Ag). The field is applied parallel to the exchange anisotropy field created by FeMn (EA). The current is flowing perpendicular to this direction.

Spin torque
(Slonczewski, Berger)

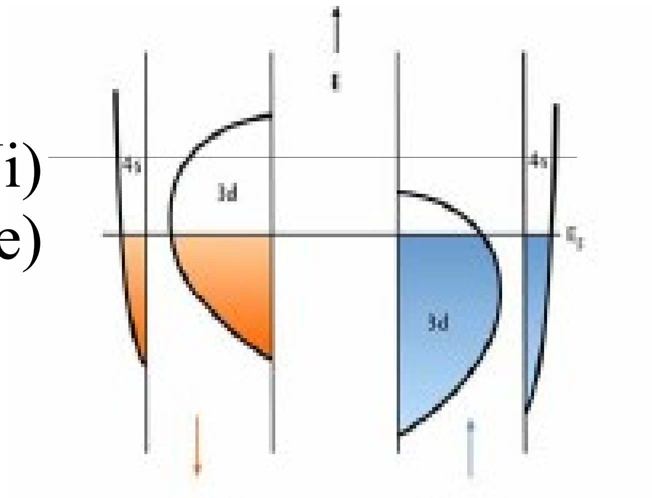
Conservation of angular momentum pushes domain wall



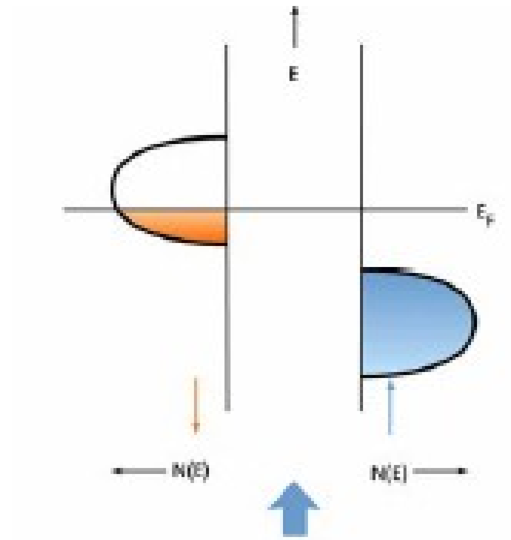


Klaui et al 2005 spin polarized scanning electron microscopy permalloy. Configurations after successive current pulses.

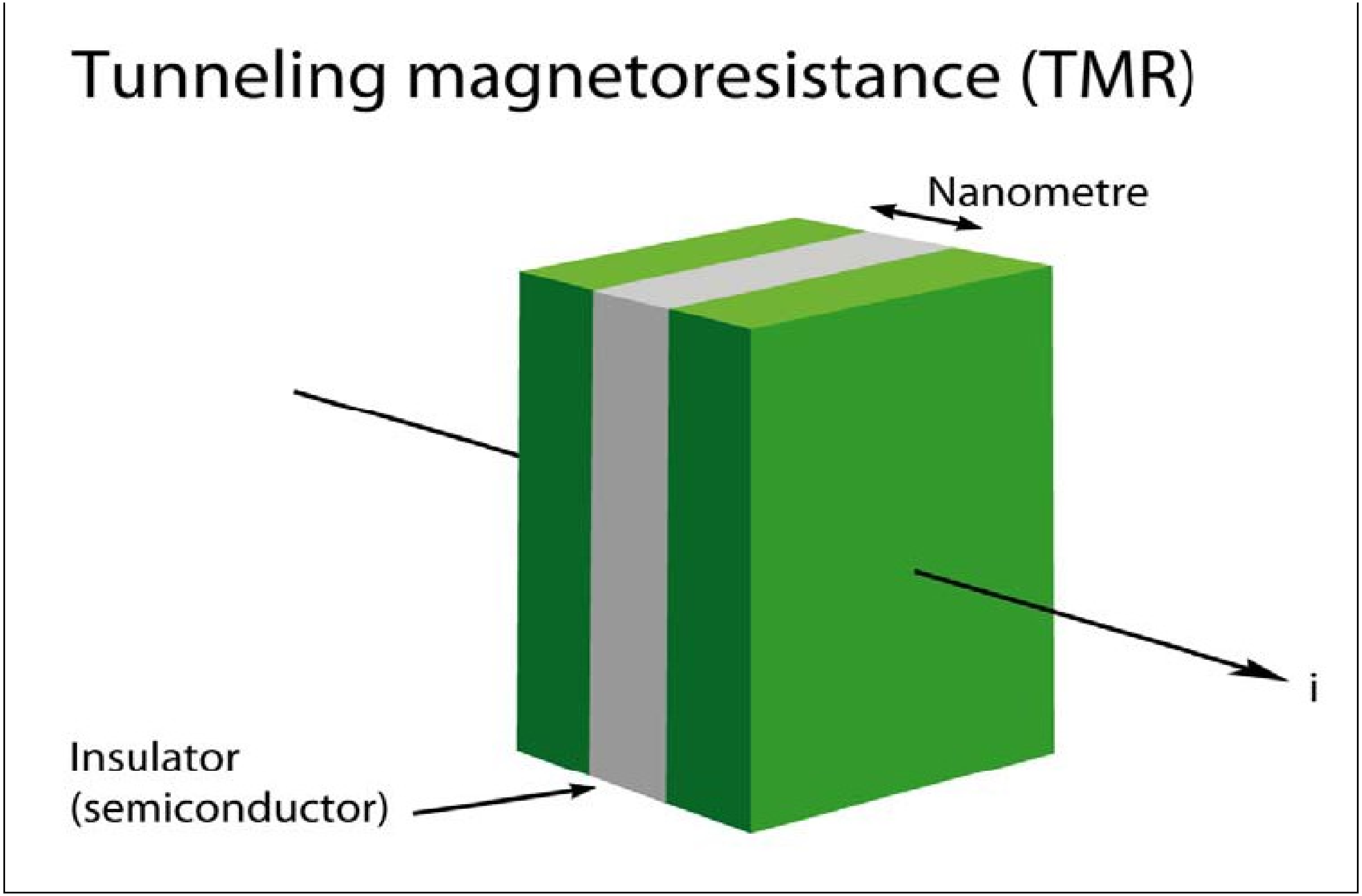
E_fermi(Ni)
E_fermi(Fe)



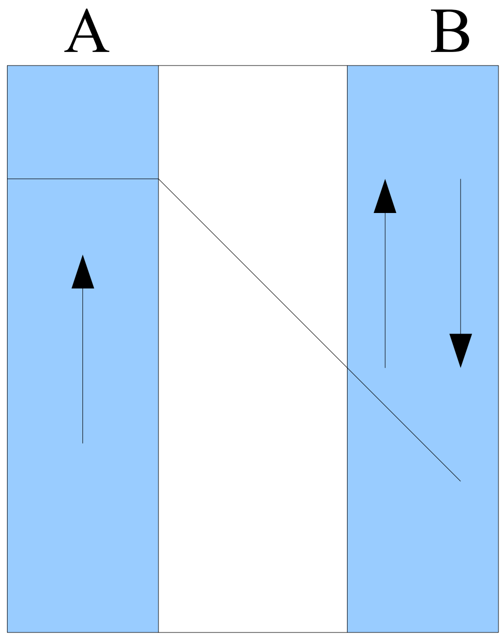
Transition ferromagnet
(e.g. Ni, Co, Fe)



Half metal e.g. CrO_2

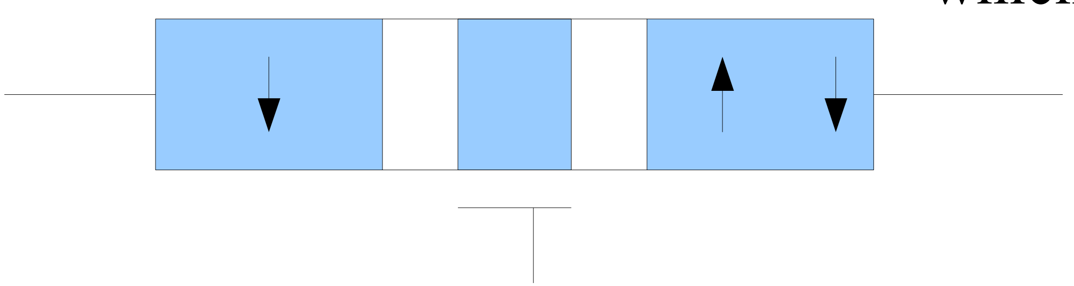


M. Julliere (INSA Rennes) 1975 Fe/Ge/Co. 14% at 4.2K



The tunnel rate from A to B through insulator will depend on polarization of B

Isolated island whose potential can be modified. « transistor » which is sensitive to field



« Spintronics » was coined by Lucent Technologies in 1998 as « an electronic device in which the direction the electron spin is pointing is just as important as its charge ».

Further developments :
- spin injection into semiconductors
- memories
- quantum computing ?
-....

About 1500 patents mention GMR

The canonical example of « nano- » actually being essential to the development of a huge industry.

Physics of the iPod awarded Nobel Prize

The Associated Press

Published: October 9, 2007

STOCKHOLM: Albert Fert of France and Peter Grünberg of Germany were awarded the 2007 Nobel Prize in Physics on Tuesday for a discovery that has shrunk the size of hard disks found in computers, iPods and other digital devices.

"The MP3 and iPod industry would not have existed without this discovery," Borje Johansson, a member of the Royal Swedish Academy of Sciences, said. "You would not have an iPod without this effect."

10th December 2007 Stockholm

Scientific Background on the Nobel Prize in Physics 2007

The Discovery of Giant Magnetoresistance

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

http://nobelprize.org/nobel_prizes/physics/laureates/2007/phyadv07.pdf

The start of the list of citations in the Nobel Prize summary article :

1. W. Thomson, "On the Electro-Dynamic Qualities of Metals: Effects of Magnetization on the Electric Conductivity of Nickel and of Iron", Proceedings of the Royal Society of London, **8**, pp. 546–550 (1856–1857).

2. I.A. Campbell and A. Fert, "Transport Properties of Ferromagnets" in *Ferromagnetic Materials*, ed. E.P. Wohlfarth, North-Holland, Amsterdam, Vol. 3, p. 747 (1982).

3. G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn, "Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange", Phys. Rev. B **39**, 4828 (1989).

4. M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas, "Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices", Phys. Rev. Lett. **61**, 2472 (1988).

etc.

Conclusion

The blossoming of “magneto-transport” into “spintronics”
is firmly based on a whole series of earlier fundamental advances at the conceptual level, whose relevence often only became apparent after a long time lag. To know far in advance just what studies would become vital was virtually impossible.

The breakthrough represented by the GMR and beyond is an exemplary evolution from “pure” research to work having immense practical consequences.
The Nobel Prize award corresponds not only to the specific discovery of GMR but to the symbolic impetus that this discovery and its implementation gave to the dawning of the immense field of nano-science.

Medaille d'or
2003

GMR heads are comprised of four layers of thin material sandwiched together into a single structure:

1. Free Layer: This is the sensing layer, made of a nickel-iron alloy, and is passed over the surface of the data bits to be read. As its name implies, it is free to rotate in response to the magnetic patterns on the disk.
2. Spacer: This layer is nonmagnetic, typically made from copper, and is placed between the free and pinned layers to separate them magnetically.
3. Pinned Layer: This layer of cobalt material is held in a fixed magnetic orientation by virtue of its adjacency to the exchange layer.
4. Exchange Layer: This layer is made of an "antiferromagnetic" material, typically constructed from iron and manganese, and fixes the pinned layer's magnetic orientation.

W.H. Nernst
1864-1941
Nernst-Ettingshausen effect 1886
Professor Göttingen

Solvay meeting 1911