Giant Magnetoresistance in Magnetic Layered and Granular Materials

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Magnetoresistance—the change in electrical resistance of a material in response to a magnetic field—has made it possible to read information on magnetic media, such as computer hard disks. This phenomenon is the consequence of the ability of magnetic fields to change and thereby control the scattering of conduction electrons in metals so that the flow of electrical charge can be varied readily. Today, for example, permalloy (a mixture of nickel and iron) is used as a magnetoresistive sensor in reading heads used in magnetic hard disk drives in computers. Recent experiments on layered materials, however, have shown an even more dramatic effect, called giant magnetoresistance, that makes these structures candidates for reading heads in the next generation of information storage systems.

Although there were reports of unusual magnetoresistive effects in layered structures (*1*), it was Albert Fert and his coworkers at the Université de Paris–Sud and Thomson CSF who discovered that the application of magnetic fields to atomically engineered materials known as magnetic superlattices greatly reduced their electrical resistance (*2*); that is, he found that superlattices had a giant magnetoresistance (Fig. 1). A similar, albeit diminished, effect was simultaneously recorded by Peter Grünberg and his group at Jülich for a magnetic sandwich structure (*3*).

Superlattices are a special form of multilayered structures, artificially grown under ultrahigh vacuum conditions by alternately depositing on a substrate several atomic layers of one element, say iron, followed by layers of another, such as chromium. With molecular beam epitaxy, one can grow single crystal ultrathin films of each element. By stacking magnetic atoms into layers and alternating them with nonmagnetic layers, it has been possible to form magnetic superlattices whose electrical resistances are readily controlled by magnetic fields which reorient (align) the moments of the magnetic layers relative to one another. While all metals have an inherent, albeit small, magnetoresistance owing to the Lorentz force that a magnetic field exerts on moving electrons, metallic alloys containing magnetic atoms have a giant magnetoresistance because the scattering which produces the electrical resistance is controlled by a magnetic field.

Fert's original observation of giant magnetoresistance was made on iron-chromium superlattices with nearly perfect crystallinity that were grown by molecular beam epitaxy (MBE). Subsequently, Stuart Parkin at IBM Almaden not only has reproduced these results with sputtered samples that are grown much more rapidly than the MBE samples but also observed oscillations in the magnetoresistance as the thickness of the nonmagnetic spacer layers is varied; these oscillations mirror changes in the coupling between the magnetic layers (*4*). While at first it was thought that the antiferromagnetic coupling was tied to the giant magnetoresistance, Virgil Speriosu and his group at IBM Almaden, along with others, showed that while it was necessary to have antiparallel alignment to obtain magnetoresistance, the antiferromagnetic coupling is not a prerequisite (*5*). Since then, other combinations of magnetic and nonmagnetic metallic multilayered structures have been studied. Recent studies (6) on sputtered samples of cobalt-copper revealed magnetoresistances at room temperature that are 4 times larger than those for iron-chromium and 13 times greater than those for permalloy films currently used as magnetoresistive sensors, for instance, in magnetic reading heads.

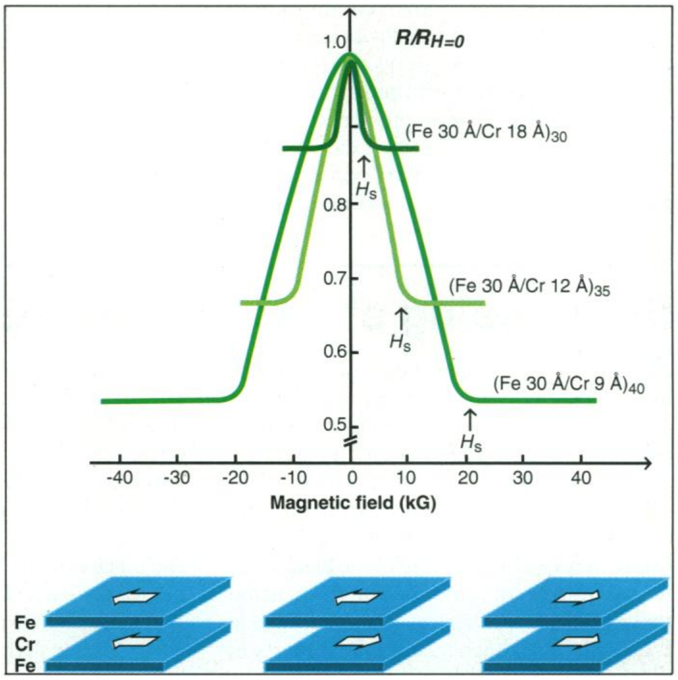

Fig. 1. Resistivity (normalized to its value in zero field) versus magnetic field for three iron-chromium superlattices at T = 4.2 K. The thickness of the ferromagnetic iron layer is held fixed at 30 Å, while the nominally nonmagnetic chromium layer thickness varies from 9 to 18 Å. The resistivity is maximum when the magnetic moments of successive iron layers are antiparallel (see the schematic of the two representative layers below the curve at H = 0 kG). It drops off as the applied field aligns the magnetic moments, denoted by the right and left diagrams for positive and negative fields, respectively. As the thickness of the chromium layer decreases, the magnetoresistance increases as well as the field H_s needed to align the moments. [Adapted from Baibich *et al.* (*2*), courtesy of A. Fert]

In the past month an entirely new window on giant magnetoresistance has been opened with the near simultaneous announcement of large effects for ferromagnetic granules in nonmagnetic metal films, such as cobalt precipitates in copper, by two independent groups (*7*). These stunning results raise the possibility that it will be possible to engineer (develop) materials that are simpler to grow than the multilayered structures and that will exhibit giant magnetoresistance.

Experimental and theoretical studies are under way to understand better the origins of the giant magnetoresistance in metallic superlattices and in nonmagnetic metallic matrices containing magnetic granules. Unresolved questions include: (i) the role of interfaces in producing the scattering which gives rise to the magnetoresistance; these interfaces occur either between different layers which make up the superlattice or between the ferromagnetic granules and the nonmagnetic matrix; (ii) identification of the optimum metallic and magnetic elements needed to form the structure; (iii) determination of ways to increase sensitivity, that is, to reduce the magnetic field required to achieve a change in electrical resistance; and (iv) the understanding of processes which produce the temperature dependence of the magnetoresistance, so that

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one can retain the giant magnetoresistance up to room temperature.

Groups in at least ten countries have focused attention on these questions. Therefore, we can anticipate rapid developments of both the basic understanding of the physics underlying giant magnetoresistance and the synthesis of new multilayered structures and magnetic precipitates with even larger changes in their electrical resistance for smaller externally applied magnetic fields.

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Dendritic Spines: Convergence of Theory and Experiment

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Dendritic spines, small protrusions covering the surface of many neurons, have fascinated anatomists ever since Ramon y Cajal first described them at the turn of the century. Until recently, their small size has precluded direct measurement of their functional properties. Nevertheless, spines have long been investigated from a theoretical point of view. Experimental and computational studies now seem to be converging toward a common viewpoint—that spines allow biochemical, rather than electrical, compartmentalization within neurons.

Spines are numerous. They represent the major postsynaptic target of excitatory synaptic input. As many as 15,000 spines, at a density of two spines per micrometer of dendritic length, cover the surface of a layer V pyramidal cell in the visual cortex (*1*). In cerebellar Purkinje cells, the number can be as high as 200,000. In contrast, the γ-aminobutyric acid (GABA)–containing stellate cells in the neocortex and hippocampus are characterized by an almost total absence of spines. Spines are the major postsynaptic target of excitatory synaptic input.

Spines are tiny. Their precise morphology has been revealed by three-dimensional electron microscopic reconstructions carried out by Wilson and his co-workers in the neostriatum (*2*) and by Harris and Stevens in the hippocampus (*3*) (Fig. 1). In these rat hippocampal CA1 pyramidal cells, the dimensions of spines are quite variable. Necks range in length from 0.08 to 1.58 μm and in diameter from 0.04 to 0.46 μm. The volume of the spine neck and head ranges from 0.004 to 0.56 μm^2. Spines are so small that at a resting calcium concentration of 80 nM only about three free calcium ions would be found in a spine with the average spine head volume of 0.051 μm^3.

The shape of dendritic spines, in particular the length and diameter of the spine neck, can change during neuronal development or in response to behaviorally significant stimuli (such as light, social interaction, motor activity) (*4*). High-frequency electrical stimulation of specific hippocampal pathways—sufficient to induce long-term potentiation (LTP)—have also been reported to alter spine morphology, leading to larger spine heads, changes in the shape of the spine stem, an increased incidence of concave spine heads, and more synapses on the shaft (*5*). However, it is unclear what direct role, if any, these changes have in causing changes in synaptic efficiency.

What functional role might spines play? Because dendritic spines are so closely associated with excitatory synaptic traffic, they seem ideally suited to modulate information processing in the brain. Thus, they have been subject to analysis by theoreticians. Rall (*6*) argued that the spine neck offers a significant resistance to the electrical charge flowing from the synapse on the spine head to the dendrite and, ultimately, to the cell body. Thus, changing the morphology of the spine neck can lead to significant changes in the somatic excitatory postsynaptic potential (EPSP), providing a possible anatomical substrate for long-term memory. This basic insight was refined and extended (*7*), showing that for fast synaptic inputs the critical factor in determining the spine's electrical behavior is the ratio g_{syn}/g_{neck} [the stimulus-induced conductance increase at the spine head divided by the spine axial (neck) conductance]. If this ratio is small, the synaptic stimulus does not change the membrane potential much and so behaves as a current source. Because the area of a spine is very small, practically no charge loss occurs through the membrane of the spine head or neck; all of the synaptic current injected into the head reaches the base of the spine. Thus, changing the spine dimensions cannot provide a mechanism for potentiation. On the other hand, if g_{syn} is large compared to g_{neck}, the EPSP in the spine will approach the synaptic reversal potential, and the synaptic stimulus will behave as a fixed voltage source. In this case, increasing the spine neck resistance by stretching the spine stem or by reducing its diameter reduces the dendritic EPSP. Crick (*8*) exploited this possibility for his "twitching spine hypothesis": the idea that contractile proteins in the spine provide a mechanism for very rapid (that is, subsecond scale) changes in spine shape that might underlie short-term information storage.

Experimental estimates of the fast [AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazole propionic acid)] component of

Fig. 1. A dendrite with numerous spines. An 8.5-μm-long dendrite from a CA1 pyramidal cell of the rat hippocampus, with a diameter ranging from 0.51 to 0.73 μm and about three spines per micrometer. [Adapted from (*3*) with permission. © Society for Neuroscience]

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