PERSPECTIVES: APPLIED PHYSICS

Switching with Hot Spins

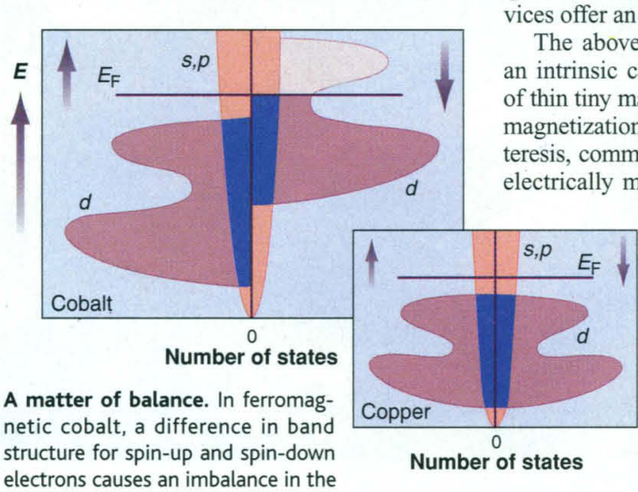
Jo De Boeck

Useful electronic devices rely on the precise control of electronic charge. Yet in all devices used today, we neglect the fact that nature has given electrons a spin. An electron's spin can take on two possible orientations, which for a population of spins yield a combined magnetic moment. In a normal metal, copper, for example, these two spin populations are in perfect balance, and no net magnetic moment is found. In a ferromagnetic metal, such as cobalt, a clear imbalance in spin population occurs (see figure), resulting in majority and minority spin states. The scattering processes for free electrons in such a metal depend on their spin state. On page 407 of this issue, Monsma *et al.* (*1*) report a novel transistor architecture that makes use of spin-dependent scattering in an interesting new way.

The research teams of Fert (University of Paris-Sud, France) and Grunberg (Forschungszentrum Jülich GmbH, Jülich, Germany) were the first to demonstrate that this property of spins can actually be observed (*2*). Take a metallic multilayer film consisting of a periodic arrangement of thin sheets of a ferromagnetic metal with spacers made of normal metal. The magnetic moments of the neighboring ferromagnetic sheets of the multilayer assume a certain zero-field arrangement, which can be tailored to be antiparallel. The presence of an external magnetic field will align these moments, and a reduction in the electrical resistance of the multilayer can be observed. The effective resistance change can easily exceed 10%, sometimes to over 100%. This is quite surprising for a metallic system and hence was named the giant magnetoresistance (GMR) effect.

Some hands-on experience with this effect can be gained with the latest generation of magnetic storage devices. Turn on your computer and read some data from one of the highest end high-capacity disk drives. The magnetic bits on the spinning disk alter the alignment of the magnetic moments in a metal-ferromagnet sandwich, called a spin valve, in the read-write head (*3*). The spin valve's GMR effect translates the information into an electric signal. The trend is that increasing amounts of data can be stored on these disk drives, thanks to the electron spin.

The spin-dependent transport in these metallic multilayer structures occurs at the Fermi level. Monsma *et al.* have demonstrated that spin-dependent scattering of electrons above the Fermi level can be exploited in a metal-base transistor-like structure (*1*). This can be achieved by launching electrons from a semiconductor emitter into a very thin metallic base consisting of a magnetic multilayer as described above. The electrons are called "hot" because they enter the base at about 0.7 eV above the Fermi level owing to the Schottky barrier at the emitter-base contact. These hot electrons traverse the metal-ferromagnet interfaces in the spin-valve base, but most of them do not overcome the Schottky barrier at the base-collector contact, because they lose energy in the scattering processes. Those electrons that do enter the collector will be strongly influenced by the magnetic alignment of the base. When the magnetic layers in the base are aligned antiparallel, the collector current is low, because of large spin-dependent scattering. A 15% higher collector current is found upon alignment of the magnetic layers (at room temperature). An external magnetic field that changes this alignment can be detected with high sensitivity by monitoring the change of the collector current. This device has promise for high signal-to-noise ratios.



A matter of balance. In ferromagnetic cobalt, a difference in band structure for spin-up and spin-down electrons causes an imbalance in the density of states at the Fermi level E_F (**above**). Scattering processes therefore depend on the electron spin state. In nonmagnetic metals such as copper there is no such imbalance (**right**).

Interestingly, this device prototype was manufactured with a low-temperature wafer-bonding technology, which should prove quite useful in other areas where dissimilar substrates are to be united.

In magnetic recording, navigation, automotive "drive-by-wire" systems, and robotics, such devices will be valuable because of their ability to measure magnetic fields with high precision (*7*). The magnetic sensor market is large and growing fast, and the use of the spin-dependent properties of the electrons is soon to be commonplace.

What about semiconductor-integrated circuits? The mainstream semiconductor industry is frantically trying to avoid quantum effects in the operation of submicrometer transistors. However, facing the end of its downsizing adventure for standard electronic devices, the nanoelectronics community has no choice but to exploit the effects of quantum mechanics. Electron spin devices offer an appealing route.

The above-described spin valve has an intrinsic capability, being composed of thin tiny magnets, to remember its last magnetization state. This magnetic hysteresis, common to ferromagnets, can be electrically measured through the component's GMR effect. Hence, one can integrate an array of ultrasmall spin valves on a chip, write binary data by setting the magnetic state of the spin valve, and read out the written state through the GMR effect. This type of integrated circuit performs the function of a magnetic solid-state memory with the great advantage of nonvolatile storage and unlimited read-write cycles. By making the bits addressable one-by-one for writing and reading, a magnetic random access memory (MRAM) is achieved. Prototypes are out, technology is maturing, and new, improved spin-transport memory cells that use magnetic tunnel junctions (*4*) are under development. The MRAM will enter the nonvolatile memory market to compete with flash and ferroelectric random access memory (*5*).

With this promising perspective in mind, researchers are taking up new challenges in the field of spin-dependent transport (*8*). Of particular note are the efforts to use spin-polarized current in other device geometries, instead of just a resistor as in the case of a spin valve. Three terminal devices, mimicking the features of the transistor, have been proposed. The hot-electron spin-valve transistor created by Monsma *et al.* (*1*), for instance, resembles a metal-base transistor. Although the cur-

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rent gain is still very low, the intrinsic presence of rectifying Schottky diodes is an advantage for MRAM applications.

Another ferromagnet-semiconductor combination resembles a field effect transistor (FET). A FET comprises a source and a drain contact to send current through a semiconductor channel and a gate terminal to modulate the carrier density in the channel. Assume that you make a semiconductor FET with a magnetic metal for a source and a drain contact (*6*). The current in the channel will be magnetically polarized by the magnetic source contact. The magnetic drain picks up the current but shows a higher affinity for aligned spins. Hence, the current through the device will depend on the magnetic contact alignment and the result is a spin switch. Furthermore, upon application of a gate voltage, the electric field perpendicular to the channel translates to an effective magnetic field for the charged particles passing through it. The effect of this magnetic field is a precession of the magnetic polarization of the channel current and for a given magnetic state of the drain, the electric current can be modulated.

The majority-minority spin situation in a metal may lead to all-metal components showing spin-switch operation (*9*). Metals are more suited for extreme nanoscale device sizes because of the higher number of available conduction electrons compared with semiconductors. At the nanoscale, magnetic single electron effects in Coulomb blockade may become apparent. But first, we need to become better acquainted with the way electron spins behave in microstructured devices, of whatever material combination they are fabricated.

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PERSPECTIVES: ASTROPHYSICS

Giant Planets to Brown Dwarfs: What Is in Between?

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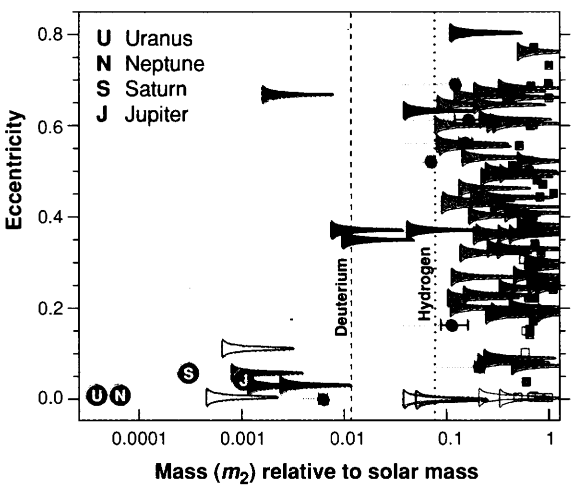
The discovery of planets orbiting nearby sunlike stars has shown that planetary systems can be surprisingly diverse and has raised many new questions about how they formed. The initial discovery in 1995 of the planet around the star 51 Pegasi by Mayor and Queloz (*1*) at the University of Geneva was a surprise because it is a planet with mass about that of Jupiter's and an orbital period of only 4.2 days. This implies that it is 20 times closer to its star than Earth is to the sun. The method of detection is based on the observation of periodic variations in Doppler shifts of the light from the star caused by wobbling, because of the gravitational pull of the planet. Although this method gives an accurate measurement of the object's orbital period and eccentricity, the mass deduced represents only the minimum possible mass. The Doppler effect reveals only the changes in the star's velocity along our line of sight. This means that we can only measure $m_2[\sin(i)]$, where m_2 is the mass of the planet and i is the angle of orbital inclination. The planet around 51 Pegasi has at least 0.44 Jupiter masses (M_J). Seven additional planets around solar-type stars have since been discovered with values of $m_2[\sin(i)]$ ranging from 0.44 to 6.84 M_J (*2*).

Where do we set the dividing line that distinguishes these massive planets from brown dwarfs? What are the mechanisms leading to the formation of massive planets and brown dwarfs? Brown dwarfs are frustrated stars that have insufficient mass to trigger nuclear reactions in their core. They are expected to have masses smaller than the hydrogen-burning limit of about 0.075 solar masses ($M_\odot$) but probably larger than the deuterium-burning limit of 0.013 $M_\odot$, or about 13 M_J. Companion brown dwarfs to solar-type stars have also been found by the Doppler shift method. Because of their large masses, one may attempt to detect them using astrometric measurements. This method of detection infers the presence of the companion by measuring the position of the star as it orbits the center of mass of the entire system. The advantage is that it gives the orbital inclination and therefore the real mass of the companion.

At a recent meeting on extrasolar planets, Mayor *et al.* reported that they had determined the orbital inclinations of about half of the previously known brown dwarf candidates using precise astrometric data from the HIPPARCOS satellite (*3*). The figure illustrates the behavior of the orbital eccentricities versus the mass of companions of solar-type stars. In all cases of brown dwarfs that were examined by the astrometric method, the determination of the orbital inclination i resulted in a mass m_2 in the range of stars at the bottom of the main sequence, above or very close to the hydrogen-burning limit. The strong decrease in the num-



From planet to star. Objects less than 0.075 $M_\odot$ cannot burn hydrogen, and those less than 0.013 $M_\odot$ cannot burn deuterium. Companions with $m_2[\sin(i)]$ larger than 0.075 $M_\odot$ have orange symbols, candidate brown dwarfs are represented in blue, and probable giant planets are represented in red. The jovian planets are shown for comparison. The probability of having a mass m_2 larger than the minimum measured value $m_2[\sin(i)]$ is proportional to the symbol width. The objects identified by data from the HIPPARCOS satellite are represented by horizontal dotted lines from $m_2[\sin(i)]$ to the real mass m_2 [data from (*3*)]. The open symbols are for systems with orbits short enough to have probably been affected by tidal circularization. Circles (giant planets and objects initially thought to be brown dwarfs) or squares (stellar masses) indicate objects with known mass.

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