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Quantum ballistics

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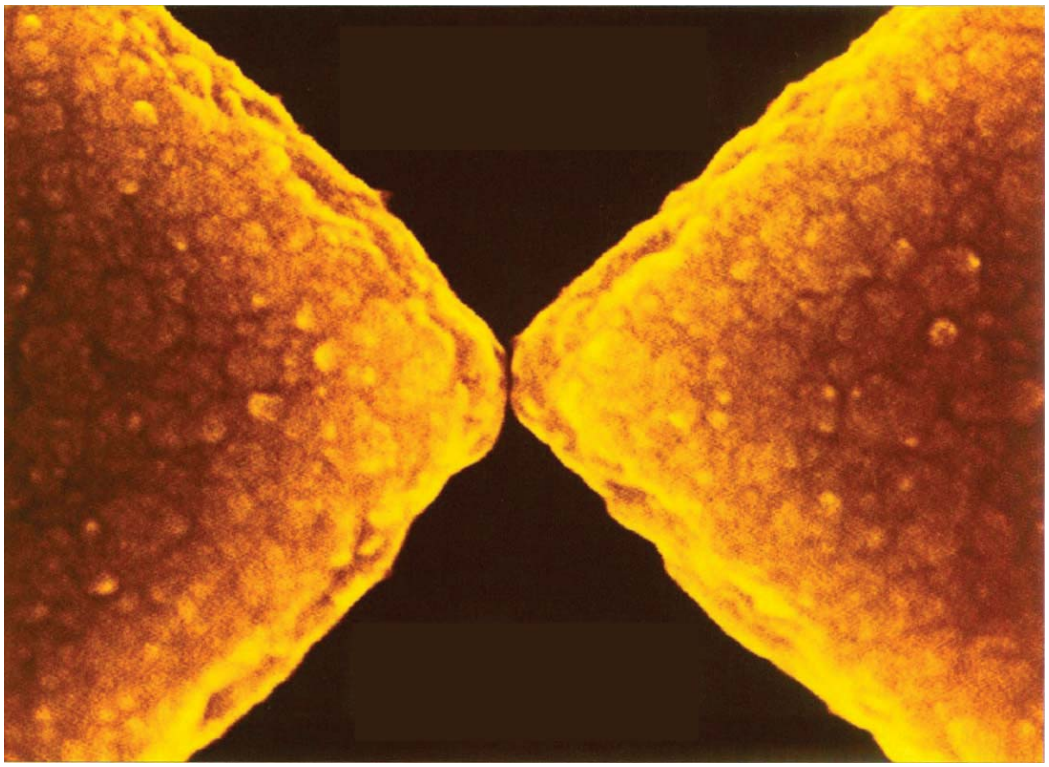
A new quantum-mechanical effect called ballistic anisotropic magnetoresistance (BAMR) could shrink transistors by a factor of 100 and lead to ultra-dense data-storage devices.



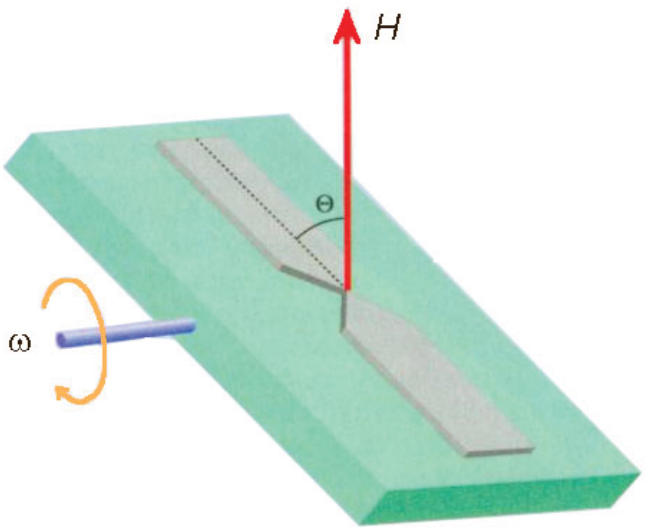
A scanning electronic micrograph of a 100 nm wide point contact between two cobalt electrodes across which researchers have observed quantized conductance.

For the last 40 years, computer-chip manufacturers have been constantly improving the performance of their products by shrinking the size of transistors—the building blocks of processors and memory chips. Having gone from dimensions of a few microns in the early 1970s to 45 nm in Intel's latest prototypes, the number of transistors that can be etched on a given area of silicon has been doubling every 18 months. This exponential trend, which is known as Moore's law, has been the driving force behind the relentless miniaturization of microelectronic devices. However, we are now approaching the physical limits of existing technology. Chips are getting too hot and are now so small that electrons can tunnel between the transistor electrodes and degrade device performance. Unless we can find a way to solve these problems, within a decade it will be impossible to reduce the size of semiconductor transistors any further.

There is an even more aggressive trend in the data-storage industry, whereby the capacity of disk drives has been doubling every 12 months since the first hard drive was introduced in 1956. The maximum amount of information that can be stored on a hard drive is limited by the size of the magnetic particles on the surface of the disk, as well as by the size of the "head" used to read and write the data. Recently, the US firm Seagate Technology built a drive with a storage density of 420 gigabits per square inch. To read the information from such dense media we require a sensing device with similar dimensions to the magnetic particles (for example, for a storage density of 100 gigabits per square inch the particles on the hard disk have dimensions of about 150 x 40 nm). This means that we will eventually need to find new ways to achieve higher storage densities.

Spintronics could allow us to continue in our quest for miniaturization beyond the limits of current technology. This is because in addition to exploiting the charge of electrons (as in conventional microelectronics), spintronics takes advantage of the electron's intrinsic angular momentum, or spin, to encode and process information. This quantum-mechanical property effectively turns an electron into a tiny compass needle, which therefore causes the electrical resistance of a magnetic material to increase or decrease depending on the direction of an external magnetic field. Called anisotropic magnetoresistance, and discovered by William Thomson (later Lord Kelvin) in 1856, this phenomenon currently forms the basis of the most promising spintronic devices.

1. BAMR in the lab



In a conventional conductor, electrical resistance is the result of electrons scattering off atoms and impurities. But strange things can happen when the conductor becomes so small that electrons can pass freely or "ballistically". In order to study this regime, Andrei Sokolov and co-workers at the University of Nebraska fabricated two arrow-shaped electrodes that point towards one other and are connected by a chain of single cobalt atoms. They then measure the resistance of this 'point contact" as it rotates with an angular velocity, ω, in a strong magnetic field, *H*, thereby altering the relative direction of the current and of the magnetization direction of the chain (with a rotation period of about 20 s). As the angle Θ changes between 0 and 180° (measured with respect to the plane of the electrodes), the resistance of the point contact goes from high to low via ballistic anisotropic magnetoresistance (see figure 2).

Magnetic spin-off

Over the past 30 years several new forms of magnetoresistance have been discovered that have helped to bring spintronics to fruition. One of these is anisotropic magnetoresistance (AMR). While all types of magnetoresistance allow the resistance of a magnetic material to be "high" or "low" just like in a conventional transistor, AMR arises when an electric current flows through a magnetic conductor in an external magnetic field. Electrons align their spins with the direction of the field and have a distinct orientation with respect to the atomic orbitals and thus the crystallographic axis of the conductor. But as the spins of the electrons are affected by the magnetic field generated by their orbital motion—an effect known as spin-orbit coupling—the resistance becomes proportional to the angle between the spin and current direction (i.e. it is anisotropic). We can therefore turn the output of an AMR device on or off by switching the direction of the external magnetic field. AMR was first used in commercial magnetic read-heads in 1992, but has since been superseded by "giant magnetoresistance" (GMR) and "tunnel magnetoresistance" (TMR), in which the difference between the resistance in the on and off states is much larger than with AMR.

Being extremely sensitive to atomic-scale features, magnetoresistance has huge potential to drive the sizes of transistors or read-heads down further. As devices continue to shrink, however, we have to be aware of the fact that quantum mechanics can drastically alter the behavior of matter. For instance, when an electron travels along a narrow wire in the *z* direction, its momentum is quantized in the perpendicular *x-y* plane. Since only one electron is allowed to possess a given momentum, to increase the current one needs to enlarge the thickness of the wire to allow an electron with a different *x-y* momentum to pass through it. As a result, the current—and hence resistance—may take on only discrete values, as opposed to being continuous as in a conventional electronic circuit.

The race for experimental evidence of this quantized resistance began 50 years ago, just after it was predicted by the late IBM physicist Rolf Landauer. However, while the effect has been demonstrated in certain semiconductors and simple metallic systems, the magnetic materials that are suitable for spintronic applications have a much more complex electronic structure that makes it difficult to observe quantized resistance and even harder to control the magnetoresistance. Indeed, the first observation of ballistic magnetoresistance in a nanocontact in 1999 met with major skepticism as the effect could also be explained as being the result of known magnetostatic processes that have nothing to do with quantum mechanics.

Earlier this year, however, the present author and colleagues at the University of Nebraska in the US and at the Institut de Physique et de Chimie des Materiaux de Strasbourg (IPCMS) in France observed a form of magnetoresistance called ballistic anisotropic magnetoresistance (BAMR). In addition to providing a brand new signature of quantum mechanics, this phenomenon could play an important role in the design of future atomic-scale logic units, memory cells and magnetic read-heads.

Claims of discovery

In Landauer's 1957 prediction he showed that the electrical conductance of a narrow ID conductor is quantized in units of $2e^2/h = 7.75 \times 10^{-5}\ \Omega^{-1}$, where *e* is the charge on the electron, *h* is Planck's constant and the factor of two reflects the fact that electrons have two possible spin orientations: "up" or "down." In order to observe this phenomenon, the electrons must flow ballistically (*i.e.* without scattering), which means the length of a conductor has to be comparable to the mean free path of the electrons. In addition, the width of the conductor has to be comparable to the de Broglie wavelength of the electrons, so that their transverse momentum becomes quantized.

In a metal the de Broglie wavelength is just a few angstroms, so the ID conductor or "point contact" needs to be about the same size as a single atom to observe these effects. (Increasing the cross section of the constriction allows electrons with different momenta to be transmitted so that the conductance becomes $2Ne^2/h$, where *N* is the number of electronic states contributing to the current.) Observing such quantized conductance in metals is extremely challenging because it is difficult to change the size of such a tiny point contact in a controlled manner. For instance, small rearrangements of the

atomic structure in the contact region can lead to discrete changes in conductance that can confusingly mimic the quantized conductance caused by quantum effects.

Nevertheless, a number of experiments have demonstrated quantized conductance in simple metals that have just one valence electron, such as sodium (J Krans *et al.* 1995 *Nature* **375** 767), gold (H Ohnishi *et al.* 1998 *Nature* **395** 780) and silver (K Terabe *et al.* 2005 *Nature* **433** 47). The next logical step has been to extend this list of materials, in particular to ferromagnetic metals. These materials provide a promising way to engineer spintronic devices because they naturally store spin information. However, conductance quantization is much more complicated in ferromagnetic materials.

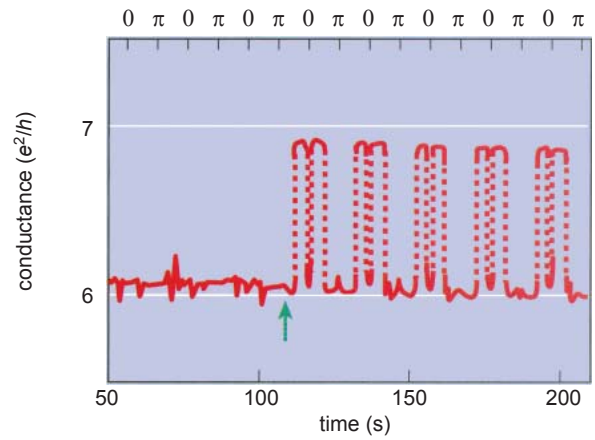
Firstly, the so-called magnetic exchange interaction causes the spin-up and spin-down electrons in a ferromagnet to have different energies. As a result, the electron energy bands are split into two spin sub-bands so that the conductance is quantized in smaller units of e^2/h rather than $2e^2/h$, which leads to several interesting effects. Secondly, the orbitals of atoms in ferromagnetic metals—such as nickel or cobalt—can overlap, which means that even a single-atom contact can conduct in different ways. Additional difficulties in studying magnetoresistance with magnetic point contacts arise from magnetostatic forces produced by magnetized samples, which maybe quite strong on the nano-scale.

In 1999 Nicolas Garcia and co-workers at the Laboratorio de Física de Sistemas Pequenos Nanotechnologia in Madrid showed that the resistance of two nickel electrodes separated by a ballistic conductor can be changed by almost a factor three in a low magnetic field (*Phys. Rev. Lett.* **82** 2923). They called the effect ballistic magnetoresistance (BMR), which they claimed had a maximum value of 280% when the relative magnetic alignment of the two electrodes changed from being parallel to antiparallel. This can be compared with less than 10% for AMR and just 10-15% obtained from other forms of magnetoresistance such as GMR or TMR. Then, in 2002, Harsh Chopra and Susan Hua at the University of Buffalo in the US used an improved fabrication technique to obtain a magnetoresistance effect as high as 3000% (*Phys. Rev. B* **66** 020403), and several other groups demonstrated similarly large changes in resistance.

These values were simply too big to be explained by the theory underlying BMR, which prompted other researchers to suggest that the results are better explained by experimental artefacts rather than by the presence of ballistic magnetoresistance. For example, in 2003 William Egelhoff and co-workers at the National Institute of Standards and Technology (NIST) and Seagate Technology in the US argued that magnetic effects can cause atoms in the wires that are connected to the point contact to move, thereby distorting the contact in such a way that can mimic ballistic transport (*J. Magn. Magn. Mater.* **287** 496).

The following year, a symposium was held at the Magnetism and Magnetic Materials/Intermag conference in Anaheim, California, on the controversy surrounding the experimental claims of BMR. At the time, the only consensus in the scientific community was that "more experiments are needed".

2. Step change



In a ballistic conductor, the conductance is defined by the number of channels, *N*, available for electrons to pass though it As conduction in a metal is dominated by electrons near the Fermi energy, a shift of the electron-energy levels due to spin-orbit coupling may change the value of Wand produce quantized conductance changes: Ne^2/h, where *e* is the charge on the electron an *h* is Planck's constant. Without an external magnetic field (to the left of the arrow) the conductance of a sample is stable and is not affected by time or mechanical rotation. When the magnetic field is turned on (to the right of the arrow), the spin of the electrons align in the direction of the field and form an angle with the current At a certain angle the strength of the spin-orbit interaction is just enough to add another channel for current to flow through, with corresponding variations in conductance of e^2/h. The periodic change in conductance shown arises because the sample is being rotated in a magnetic field.

However, it turned out to be nearly impossible to design an experiment that could unambiguously discriminate artefacts from those expected from Landauer's theory, since we had no proven way to stabilize macroscopic wires at the atomic level.

Ballistic breakthrough

That situation changed in 2005, when theorist Evgeny Tsymbal and colleagues at the University of Nebraska proposed a new way to observe quantized conductance in magnetic point contacts. They predicted that in a ferromagnetic wire the number of conduction channels, and consequently the conductance, changes when the magnetization of the ballistic conductor alters its direction with respect to the current (*Phys. Rev. Lett.* **94** 127203). Unlike BMR, which is a property of two magnetic electrodes separated by a ballistic conductor, this new phenomenon—called ballistic anisotropic magnetoresistance (BAMR)—is a property of the ballistic contact itself. In essence, BAMR describes quantum conductance in a magnetic field.

Similar to AMR, the origin of BAMR lies in the spin-orbit interaction that couples the orbital motion of electrons to their spin. In a normal, continuous conductor this coupling causes a change in resistance due to anisotropy in the way electrons are scattered. But in a ballistic conductor the spin-orbit interaction

To increase the storage density of hard drives, we need smaller magnetic "bit cells" and read-heads.

can alter the number of electronic channels that are available to pass the point contact. In other words, since conduction in a metal is dominated by electrons near the Fermi energy, the small shift of the energy levels due to spin-orbit coupling may either add an electron or remove it from the current.

Tsymbal and colleagues calculated that for an idealized chain of nickel atoms the spin-orbit interaction has no effect when the magnetization is perpendicular to the current (corresponding to the minimal strength of spin-orbit coupling), but that the interaction "splits" some electronic states when the magnetization is parallel (corresponding to maximal spin-orbit coupling). This changes the value of N in the Landauer formula, and therefore the conductance undergoes a step change. All we have to do to observe this change—and thus demonstrate BAMR—is therefore to make a small point contact and monitor the resistance while changing the relative orientation of a magnetic field and an electric current (see figure 1).

To fabricate point contacts we take a "pre-pattern" electrode etched using conventional nanofabrication techniques and then employ one of three different methods to build an atomic-size junction: mechanically stretching or compressing the contact region, thus forming a "breaking junction"; passing a large current density across the pre-patterned constriction to stimulate atomic displacements; or electrochemically depositing additional atoms from a solution by applying an appropriate potential. The first two methods are particularly suitable when working in a high-vacuum, low-temperature environment. The third method, on the other hand, can be employed under ambient conditions, and also produces less mechanical stress or damage in the contact region than the first two methods.

Earlier this year the present author and colleagues at Nebraska decided to extend earlier work by Bernard Doubin (currently at the IPCMS) and construct a point contact use electrochemical deposition to test the theoretical prediction of BAMR (*Nature Nanotech.* **2** 171). We fabricated two metal electrodes from silicon and bonded them to the substrate in such a way as to eliminate mechanical instabilities, thereby making our experiment less vulnerable to the artefacts described by Egelhoff. Using first optical lithography and then focused ion-beam lithography the electrodes were shaped like arrowheads and pointed towards each other with a narrow gap of about 100 nm in between (see figure on page 27). We then integrated the sample into an electrochemical cell and carefully electrodeposited a magnetic material to close the gap and form the point contact. We wanted to deposit atoms slowly so that we had enough time to measure the conductance while varying the angle of the external magnetic field.

After carrying out a series of experiments with nickel point contacts, we observed some deviation from the angular dependence expected for AMR—but no quantized steps as predicted for BAMR. We therefore continued our experiments with cobalt, and soon discovered a surprisingly sharp step-like behavior in the current as a function of angle. Although it is difficult to determine the absolute value of a resistor inside an electrochemical cell, for instance due to the nonlinear current-voltage characteristic of such cells, our best estimate was that most of the observed steps were between six and seven quantum units (see figure 2). This is exactly what is predicted for a chain of cobalt atoms just one atom thick. Furthermore, we occasionally observed steps that were twice as large—plus sequential steps as a function of field angle. Although such behavior was not predicted in the idealized models of Tsymbal and colleagues, our data turned out to perfectly fit to the theory of BAMR given the more complex electronic structure of real samples.

Almost simultaneously a similar result was observed by Michel Viret from CEA Saclay, France, based on iron breaking junctions (*Eur. Phys. J. B* **51** 1), although the stability of these fragile structures could affect the results. Indeed, Dan Ralph of Cornell University has recently suggested that a comparable effect to the BAMR signal seen in this and our experiments could be caused by the motion of atoms in samples fabricated using electro-migration, which could throw the subject of magnetoresistance back into controversy once again.

Tiny transistors

The experimental observation of ballistic magnetoresistance allows us to study a new quantum effect that may have important practical implications. In particular, the tiny size of the features in our experiment—roughly the dimensions of a single atom — is 100 times smaller than those in the most advanced prototype field effect transistors. Therefore, BAMR could replace traditional transistors in memory devices and allow information to be stored on media that have atomic-size bit-cells. It also promises ultra-small read-heads or magnetic sensors for the hard-disk storage industry.

There are several challenging problems that need to be solved in order to turn this optimistic vision into reality. These include finding ways to synthesize such nano-scale point contacts; to control their structural, magnetic and mechanical properties; and to make the effect fully reproducible. But whatever engineers do to maintain the miniaturization trend encapsulated by Moore's law, BAMR is a new quantum-mechanical effect that they will eventually run into when designing new spintronic or other devices at the atomic scale.