SPINTRONICS

A path to spin logic

Read-heads based on the manipulation of spin have already revolutionized the performance of magnetic data storage devices. The development of more-complex spin-devices using carbon nanotubes could enable the next logical step in spintronics.

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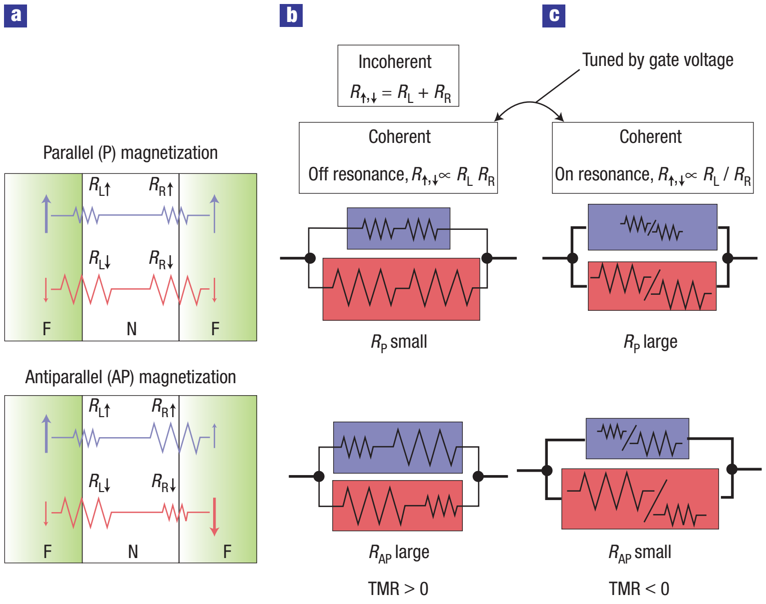

Figure 1 Scheme of a ferromagnet/non-magnet/ferromagnet (F/N/F) spin-valve and rules for resistance addition. **a**, Large and small arrows indicate that the electron spin has the same direction as the majority and minority carriers respectively in left (L) and right (R) ferromagnets. The total resistance R consists of two parallel (spin-up, or ↑, and spin-down, or ↓) channels. **b**, In an incoherent spin-valve, each channel's resistance is the sum of two resistors in series. The total resistance when the magnetization of the two contacts are parallel (R_P) is lower than when they are antiparallel (R_{AP}) because the spin-up channel (with its two small resistors) dominates the parallel combination. In this case, the tunnelling magnetoresistance, TMR = $(R_{AP} - R_P)/R_P$ is positive. **c**, In a coherent spin-valve two cases are possible: away from resonant transmission, the resistance for each spin channel is proportional to the product of the two resistances R_L and R_R, also resulting in positive TMR (see part **b**). Near resonance, in the case of an asymmetric junction ($R_L >> R_R$), the resistance for each spin channel is proportional to the asymmetry in the junction resistances, in which case R_{AP} is lower and the TMR becomes negative. The resonance condition can be easily tuned by a gate voltage, which in turn enables the sign of the TMR to be reversed.

The anticipated end of Moore's law scaling in microelectronics has spurred researchers to explore more-exotic schemes for computation. One such approach comes from the emerging field of spin electronics or 'spintronics'[1], which seeks to manipulate and use the spin (rather than the charge) that all charge-carriers possess, to perform sensing, computing and related functions. This approach has already met with some commercial success, with devices based on exploiting the magnetic moment associated with spin to read magnetically stored information, leading to substantial improvements in the performance of computer hard drives and magnetic random-access memories (MRAMs)[2,3]. But for advanced functions, such as signal processing and digital logic, two-terminal devices such as those are of limited use. Although more-complex devices — in which there is independent control over the spin currents flowing between two terminals due to the application of a voltage to a third terminal — have long been considered theoretically[1,4], realizing them in a laboratory has proved elusive. On page 99 of this issue, Sahoo and colleagues[5] demonstrate just such a three-terminal device, whose magnetoresistive response can not only be varied but completely reversed.

The simplest embodiment of the prototypical two-terminal spintronic device — known as a spin-valve — on which the read-heads of modern computer hard drives and MRAMs are based, consists of a non-magnetic material sandwiched between two ferromagnetic electrodes. The flow of carriers through a spin-valve is determined by the direction of their spin (up or down) relative to the magnetic polarization of the device's electrodes. In general, this means that when the magnetization of the two electrodes are parallel, current flow is permitted, and when they are antiparallel it is restricted. The difference in resistance between a spin-valve's antiparallel and parallel states is known as its magnetoresistance, and is usually positive (that is, the resistance of its antiparallel state is higher than that of its parallel state).

The device developed by Sahoo *et al.*[5] relies on a related phenomenon known as tunnelling magnetoresistance (TMR)[1–3], in which transport from one ferromagnetic electrode to another occurs not by simple extended state conduction, but by quantum tunnelling across a non-magnetic region. Its structure consists of a carbon nanotube (CNT) contacted by two ferromagnetic electrodes and placed above an insulated gate electrode. Although similar to that of the theoretically proposed semiconductor-based spin field-effect transistor, or spin FET[1,4,6], the authors' use of a CNT as the non-magnetic element in their device is central to its success. CNTs are superb conductors of charge[7] and have long been thought to be excellent spin conductors[8]. However, the tunability of the TMR in a CNT spin-valve arises from another special property of the CNT — its nanoscale size. Current is conducted in a CNT with the involvement of only a few electronic quantum states, enabling the quantum-mechanical phase of propagating electrons to be preserved over its entire length, which makes their device essentially a phase-coherent spin-valve.

The total resistance of a spin-valve can be thought of as being determined by the resistance of two separate conducting channels — one for spin-up carriers and the other for spin-down carriers. For a conventional (incoherent) spin-valve, the total resistance is a simple arithmetic sum of the contact resistance of non-magnetic channel with the left and right electrodes — that is, it behaves like two resistors connected in series. But for a coherent spin valve, these resistances are no longer additive, and the rules that determine this resistance are dependent on whether the quantum state carrying the current is aligned, or at resonance, with the Fermi level of the electrodes (see Fig. 1). Using the same mechanism that governs the operation of a conventional silicon FET, the position of these current-carrying states relative to the electrodes is easily controlled by the field on the nearby gate, which enabled the authors not only to tune the magnitude of the TMR of their device but change its sign as well. Moreover, using a relatively straightforward quantitative model of this effect, the authors were able to reproduce the data from their devices with impressive accuracy.

Owing to the fact that the operation of these devices relies on current conduction through only a few quantum states, at present they can only be operated at low temperatures — a significant drawback for their use in practical spintronic circuits. However, the energy spacing of the quantum states of a CNT is resolved near room temperature so long as the device length is short enough, down to around 20 nm, not out of reach of modern lithographic patterning techniques. This would also require increasing the TMR (which typically decreases as a function of temperature), but with the recent report of record-breaking values of TMR[9], even this may be achievable with a suitable choice of material at the insulating interface. Such devices would open the way for room-temperature 'spin-logic' in which the signal from one spin device is used to electrically control the signal in another, and enable spintronics to move beyond the read-heads of hard-drives and into computer chips themselves.

REFERENCES

1. Žutić, I., Fabian, J. & Das Sarma, S. *Rev. Mod. Phys.* **76,** 323–410 (2004).
2. Maekawa, S. & Shinjo,T. *Spin Dependent Transport in Magnetic Nanostructures* (Taylor & Francis, New York, 2002).
3. Parkin, S. S. P. *et al. Proc. IEEE* **91,** 661–680 (2003).
4. Datta, S. & Das, B. *Appl. Phys. Lett.* **56,** 665–667 (1990).
5. Sahoo, S. *et al. Nature Phys.* **1,** 99–102 (2005).
6. Schapers, Th., Nitta, J., Heersche, H. B. & Takayanagi, H. *Phys. Rev. B* **64,** 125314 (2001).
7. Dürkop T., Kim, B. M. & Fuhrer, M. S. *J. Phys. Condens. Matter* **16,** R553–R580 (2004).
8. Tsukagoshi, K., Alphenaar, B. W. & Ago, H. *Nature* **401,** 572–574 (1999).
9. Parkin, S. S. P. *et al. Nature Mater.* **3,** 862–867 (2004).