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# Colossal magnetoresistance, half metallicity and spin electronics

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The development of spin-electronic devices based on oxide magnets is reviewed. After a discussion of colossal magnetoresistance in magnetic perovskites and an introduction of the concept of half metallicity, spin-electronic devices such as ferromagnetic tunnel junctions, grain-boundary junctions, ferromagnet-superconductor hybrids and spin transistors are presented in detail. The review concludes with an outlook on future developments.

**Keywords: spin electronics; colossal magnetoresistance; tunnel junction; spin transistor**

## 1. Introduction

Spin electronics is a new field of research in condensed matter physics and both experimental and theoretical understanding are in the initial stages. The development of spin electronics was stimulated by the current trend towards miniaturization in the electronics industry, which will reach a limit in the near future. This might lead to a paradigm shift from semiconductor devices towards magnetic components. At typical doping levels, the number of charge carriers in semiconductor nanostructures becomes small, eventually approaching the limit of single-electron devices. Since carrier densities in metals are much larger than in semiconductors, metallic devices based on macroscopic operation principles can be more favourably miniaturized. In semiconductors, currents are carried by electrons or holes, depending on doping, and the basic operational feature of semiconductor devices is the differential manipulation of these two types of current. In direct analogy, it is possible to label electrons by their spin orientation, and, thus, spin electronics uses the differential manipulation of currents with defined spin polarization as the fundamental principle of device operation. This principle is only sensible if the spin information can be transported over reasonable length-scales in solid-state devices. It was experimentally found that this is, indeed, possible, and that the spin-diffusion length, i.e. the length an electron can travel without losing its spin memory, is several microns in some metals. Since new electronic devices will have to be fabricated on nanometre scales in order to compete with the existing semiconductor technology, the spin-diffusion length is very long compared with a single electronic element.

Sources of spin-polarized electrons are itinerant ferromagnets. The energy bands in ferromagnets depend on the electron spin such that the energy levels for the two

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spin directions are shifted with respect to each other. Since the energy levels are filled hierarchically, in a ferromagnet there are more electrons of one spin direction present. The electrons are called majority and minority carriers, respectively. The magnetization of the ferromagnet is due to this spin imbalance and currents drawn from such a material are also spin polarized.

An early success story of spin electronics is provided by the discovery of giant magnetoresistance (GMR) in metallic multilayers in the late 1980s, which led to the development and mass production of GMR-based read heads for hard disks in less than ten years. These read heads are based on the use of multilayers composed of ferromagnetic layers separated by noble-metal interlayers with the electric current flowing parallel to the layers. The roadmap for industrial development of hard disk drives envisages new generations of read heads based either on spin valves or tunnel junctions. These are basically composed of two ferromagnetic layers separated by a noble metal or insulating layer, respectively; the electrical current flows perpendicular to the layers. Spin valves and tunnel junctions are also expected to form the building blocks of a two-terminal, non-volatile magnetic random access memory (MRAM). For further reading see de Boeck & Borghs (1999). Advantages of elemental ferromagnets are a high Curie temperature and advanced thin-film preparation techniques; the main disadvantage is the moderate degree of spin polarization of elemental ferromagnets such as iron (44%), nickel (11%) and cobalt (34%).

An important development in the field of spin-polarized transport came with the rediscovery of colossal magnetoresistance (CMR) in the manganites of the type $La_{0.7}Sr_{0.3}MnO_3$ (LSMO). The magnetic and electrical properties of these compounds were first investigated in the early 1950s. However, the fabrication of technologically important thin films and the observation of very large magnetoresistance values was first reported in the beginning of the 1990s. The magnetoresistance in the manganites was labelled 'colossal magnetoresistance' in order to distinguish it from the GMR observed in metallic multilayers. The recent revival was triggered by the great interest in magnetoresistive materials to be used as read heads for hard disks. The manganites were studied intensely and rapid progress was made in both the fabrication of high-quality films and the theoretical understanding of the transport mechanism. It was, however, soon realized that the intrinsic CMR is not technologically relevant, since large resistance changes are only obtained in high magnetic fields of the order of several teslas. Therefore, recent research activity has been focused on extrinsic magnetoresistance effects, i.e. effects related to electron tunnelling and spin-dependent scattering near grain boundaries, in the hope of engineering structures with high sensitivity to magnetic field. The extrinsic magnetoresistance is linked intimately to the spin polarization, and this was found to be very large, approaching 100%, thus giving the manganites a much greater potential for use in spin-electronic devices than have conventional ferromagnets. The main disadvantage of the manganites, in view of room-temperature applications, is the relatively low Curie temperature, being at most 380 K. Alternative materials are the oxide ferromagnet $CrO_2$, with a Curie temperature of 400 K, and the ferrimagnet $Fe_3O_4$, with a relatively high Curie temperature of 858 K. Both these compounds are believed to be 100% spin polarized, although they show only a small intrinsic magnetoresistance.

Oxide films are grown epitaxially by various deposition methods like pulsed laser deposition (PLD), magnetron sputtering or molecular beam epitaxy on single crystal substrates with a small lattice mismatch. Whereas the preparation techniques for

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manganite films are quite advanced and epitaxial manganite films have single crystal quality, magnetite films show degraded magnetic and electrical properties compared with bulk samples; this is due to the formation of antiphase boundaries. $CrO_2$ films are extremely difficult to fabricate. Manganite and magnetite films have been patterned using optical lithography on a micron scale; patterning on a submicron scale has not yet been reported and the achievement of high-quality nanostructures will present a formidable technological challenge. One advantage of manganite film technology is that it opens the possibility of integrating high-temperature superconductors that have a perovskite structure with a similar lattice constant. First experiments on such devices have enabled the probing of the superconducting state by the injection of spin-polarized currents from an adjacent magnetic layer.

In this work, the present status of spin-electronic devices based on oxide film technology is reviewed. The review starts with a brief overview on manganites and colossal magnetoresistance. Thereafter, the concept of half metallicity is discussed. These two sections constitute the fundamental basis for the development of oxide spin electronics. In § 4, first experiments on spin-electronic devices—namely, magnetic field sensors, ferromagnet-superconductor hybrids and spin transistors—are described. The review concludes with an outlook on future developments in spin electronics.

## 2. Colossal magnetoresistance in magnetic perovskites

The interest in magnetic perovskite materials of the type $RE_{1-x}A_xMnO_3$ was revived after the discovery of a large magnetoresistance in ferromagnetic $La_{0.7}Ba_{0.3}MnO_3$ thin films (von Helmolt *et al*. 1993). RE denotes a rare earth element such as La, Nd or Pr, and A denotes an alkaline earth such as Ca, Sr or Ba. The materials were originally synthesized and studied in the 1950s in polycrystalline form at the Philips Research Laboratories (Jonker & van Santen 1950; Volger 1953) and in single-crystal form by a Canadian group (Searle & Wang 1970). In this section, recent experimental and theoretical studies of the transport properties in the manganites are briefly reviewed. For an extensive review see Coey *et al*. (1999).

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High-quality single-crystal films are deposited on lattice-matched single-crystal substrates, especially $LaAlO_3$, $SrTiO_3$ and MgO, by PLD. In figure 1*a*, the resistivity (left axis) in zero field and an applied magnetic field of $\mu_0 H = 1$ T, the magnetization (right axis) and, in figure 1*b*, the magnetoresistance ratio $\Delta\rho/\rho_0 = [\rho(H) - \rho_0]/\rho_0$ of an epitaxial $La_{0.7}Ca_{0.3}MnO_3$ film of thickness 170 nm are shown as a function of temperature. The film is clearly ferromagnetic with a Curie temperature, $T_C$, of 224.7 K. The resistivity shows a maximum near the Curie temperature; below $T_C$ the resistivity is metallic, above $T_C$ it is semiconducting; the ferromagnetic transition is accompanied by a metal–insulator transition. As will be seen later, this is a consequence of the peculiar double-exchange mechanism (Zener 1951) that is characteristic of the manganites. The magnetoresistance is sharply peaked at the Curie temperature and has a maximum value of 42% in a magnetic field of 1 T.

The field sensitivity, however, is small with a maximum value at $T_C$ of 0.2% $mT^{-1}$. For comparison, in metallic multilayers typical values exceed 1% $mT^{-1}$ at room temperature. Since most applications require a large sensitivity in magnetic fields of a few milliteslas, the intrinsic magnetoresistance of manganites is hardly competitive with GMR structures.

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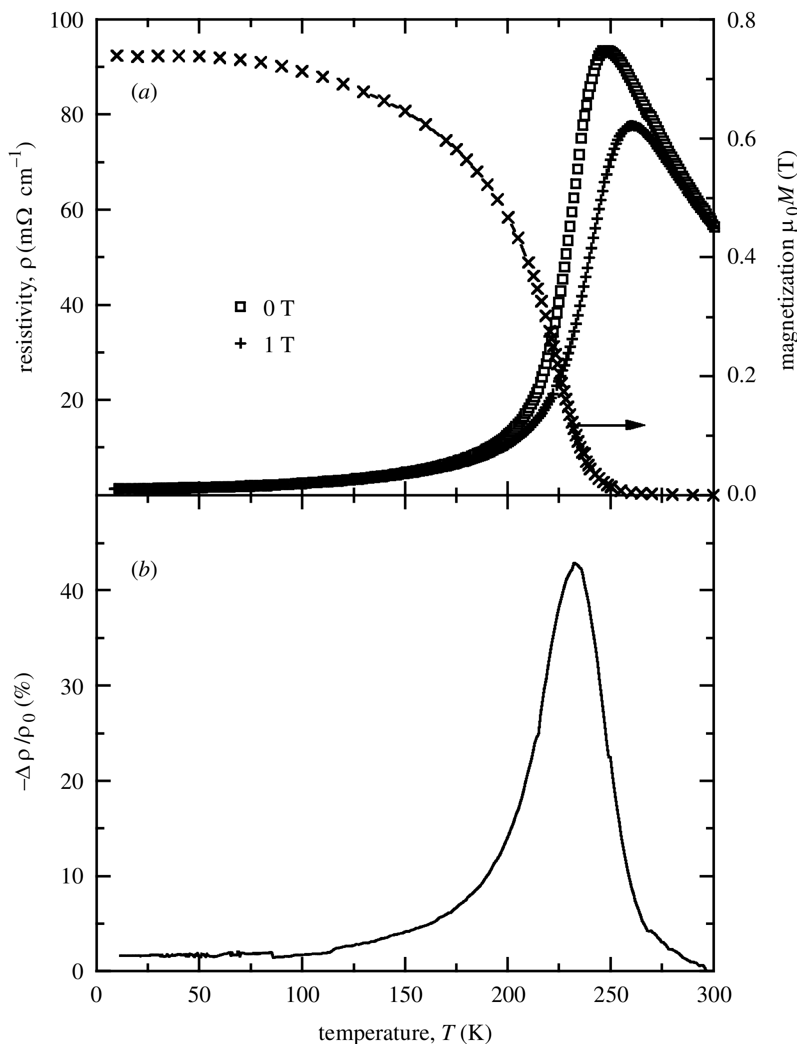


Figure 1. (*a*) Electrical resistivity (left axis), magnetization (right axis) and (*b*) magnetoresistance ratio in a magnetic field of 1 T of a single-crystal $La_{0.7}Ca_{0.3}MnO_3$ film on $LaAlO_3$. The resistivity was measured in zero field and $\mu_0 H = 1$ T; magnetization measurements were performed at 0.1 T parallel to the film. $\rho_0$ denotes the zero field resistivity.

The Curie temperature depends on the rare-earth and alkaline-earth ions as well as on the doping level, $x$, and the oxygen content (Ramirez 1997). The maximum Curie temperature was found to be 380 K for LSMO. The parent compound $LaMnO_3$ is an antiferromagnetic insulator that becomes a ferromagnetic metal in the doping range $0.15 < x < 0.5$; charge ordering is found for $x = 0.125$, 0.5 and higher doping levels. CMR is observed in the ferromagnetic regime and, therefore, this overview is confined to the doping level $x \sim 0.3$.

In order to explain the relation between ferromagnetism and metallic resistivity in the manganites, Zener (1951) introduced the concept of double exchange. Doping of $LaMnO_3$ with the divalent atoms Ca, Sr or Ba creates holes on the manganese

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sites and induces a mixed valence configuration with $(1-x)\cdot 100\%$ $Mn^{3+}$ (with an atomic state configuration $3s^2 3p^6 3d^4$) and $x \cdot 100\%$ $Mn^{4+}$ ($3s^2 3p^6 3d^3$). The crystal–field interaction in the octahedral Mn sites energetically splits the d-orbitals into three low lying $t_{2g}$ and two $e_g$ states. The $t_{2g}$ electrons form a tightly bound core spin $S = 3/2$ and interact, via Hund's rule coupling, with the itinerant $e_g$ electrons. Hopping between adjacent $Mn^{3+}$ and $Mn^{4+}$ ions occurs via the simultaneous hopping of the $e_g$ electron on $Mn^{3+}$ to a neighbouring oxygen atom and of an electron from this oxygen atom to the empty $e_g$ state of the $Mn^{4+}$ ion. Due to the strong on-site Hund's coupling, this double exchange is favoured by a ferromagnetic alignment of the manganese core spins; the hopping probability is proportional to $\cos(\Theta/2)$, where $\Theta$ denotes the angle between two Mn core spins. Therefore, a mutual dependence between ferromagnetism and metallic conductivity exists in the manganites. An applied magnetic field leads to a greater alignment of the core spins, and, thus, to a conductivity increase, especially in the vicinity of the Curie temperature; this is in qualitative agreement with experiment.

Recent theoretical investigations showed that the double-exchange model is not sufficient to explain the CMR (Millis *et al.* 1995; Röder *et al.* 1996). These studies indicate that the carriers interact strongly with the lattice vibrations (phonons) according to the Jahn–Teller effect. The Jahn–Teller effect denotes the tendency of magnetic ions in a high-symmetry crystal field to be displaced, i.e. to distort the crystal structure in order to remove degenerate energy levels. The strong electron–phonon coupling leads to the formation of polarons above $T_C$, i.e. electrons accompanied by a large lattice distortion (Millis *et al.* 1995). The polarons are assured to have magnetic character, leading to self-trapping, and the metal–insulator transition may be induced by the unbinding of trapped polarons (Röder *et al.* 1996). Although the existence of polarons above $T_C$ is well supported by transport measurements (Jaime *et al.* 1996; Ziese & Srinitiwarawong 1998), the nature of the metal–insulator transition, and the mechanism for CMR, have not yet been fully clarified. The manganites are an important system for the study of transport properties under the influence of a strong electron–phonon interaction, since the coupling strength can be varied by chemical doping.

## 3. Half-metallic magnets

The concept of half metallicity was introduced by de Groot *et al.* (1983) who were motivated by band-structure calculations on Heusler alloys of the type NiMnSb. The striking feature emerging in those calculations was metallic behaviour for the majority carriers, coexisting with semiconducting, or insulating, behaviour of the minority carriers; this was indicated by a gap in the minority carrier band structure.

In strong ferromagnets such as nickel, the electronic d-bands are known to be spin polarized such that the majority band lies below the Fermi level, whereas the minority band crosses the Fermi level. However, the s-bands are not spin split, leading to a finite density of states at the Fermi level in both sub-bands. The spin polarization, $P$, defined by the densities of majority (↑) and minority (↓) electrons,

$$P = \left\| \frac{n_\downarrow - n_\uparrow}{n_\uparrow + n_\downarrow} \right\|, \qquad (3.1)$$

has moderate values in elemental magnets. The situation is fundamentally different in half-metallic ferromagnets, which have a spin polarization of 100%. This feature

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makes half-metallic magnets the ideal candidates for use as sources or filters for spin-polarized currents in spin-electronic devices. The spin-diffusion length in half-metallic ferromagnets is assured to be very large, since elastic spin-flip processes from majority into minority states cannot occur.

In subsequent theoretical work, $CrO_2$, $Fe_3O_4$ and the manganites were found to be half metallic. The experimental verification of this property, however, has proved to be difficult. Experiments based on Andreev reflection in superconductor–ferromagnet (SF) junctions yielded spin-polarization values of 85% and 90% at 4.2 K for $La_{0.7}Sr_{0.3}MnO_3$ and $CrO_2$, respectively (Soulen *et al*. 1998). Ferromagnet–insulator–ferromagnet junctions indicate a spin polarization of *ca.* 83% for LSMO at 4.2 K in agreement with SF junctions (Viret *et al*. 1997). Recent Fermi-surface measurements confirmed band-structure calculations and indicated a high spin polarization in the hole-like Fermi-surface sheets (Livesay *et al*. 1999).

## 4. Spin-dependent devices

### (*a*) *Magnetic sensors based on grain-boundary magnetoresistance*

Much research activity has been devoted to the study of extrinsic magnetoresistive effects arising in the manganites near grain boundaries. These effects are large, since the double-exchange mechanism is very sensitive to the local crystallographic order. It was hoped that the low-field response near grain boundaries could be tailored to yield devices with a reasonable sensitivity. Several device geometries, e.g. single grain boundaries grown on bicrystal substrates (Mathur *et al*. 1997) and step–edge junctions (Ziese *et al*. 1999), have been investigated. It is generally found that the resistivity in polycrystalline samples is strongly enhanced and shows a broad maximum below the Curie temperature, whereas the magnetization shows essentially the same temperature dependence as in epitaxial films. The magnetoresistance increases with decreasing temperature (Hwang *et al*. 1996).

The low-field magnetoresistance of a step–edge array is shown in figure 2 at various temperatures. The step–edge array was fabricated by growing a 25 nm thick $La_{0.7}Ca_{0.3}MnO_3$ film on a $LaAlO_3$ substrate that was etched into a step–edge pattern. This consisted of 200 steps along [110] that were 140 nm high and 20 μm apart. Grain boundaries grow near the edges. In small magnetic fields the magnetoresistance ratio is, indeed, much larger than in epitaxial films reaching a maximal magnetic field sensitivity of *ca.* 0.8% $mT^{-1}$.

It was speculated that the grain-boundary transport mechanism is spin-polarized tunnelling through an insulating barrier. However, recent investigations revealed that a more appropriate model is inelastic tunnelling between ferromagnetic grains via manganese ions in a spin-glass-like barrier (Ziese 1999). Although a deep insight into the transport properties of the manganites was gained from the investigation of grain-boundary transport, it is very unlikely that grain-boundary devices will ever be applied as magnetic field sensors, since competitive magnetic field sensitivities are only achievable below 200 K.

### (*b*) *Ferromagnetic tunnelling junctions*

Ferromagnet–insulator–ferromagnet (FIF) tunnelling junctions were first studied by Julliere (1975); in recent years, interest in them has revived, since they can be

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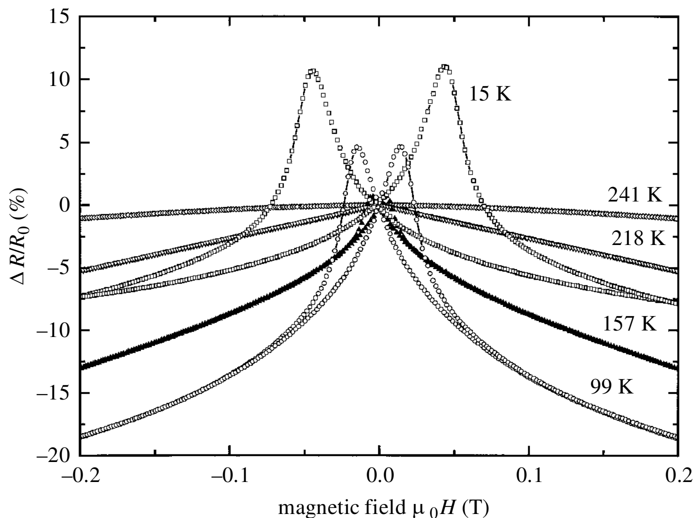


Figure 2. Magnetoresistance ratio $\Delta R/R_0$ of a step–edge array in low magnetic fields at various temperatures. The current flows across the steps. The array consists of 200 steps along [110], which are 140 nm high and 20 μm apart.

used as very sensitive magnetic-field sensors. In the absence of spin-flip scattering, the tunnelling magnetoresistance is given by

$$\frac{\Delta R}{R} \equiv \frac{R_{\uparrow\downarrow}}{R_{\uparrow\uparrow}} - 1 = \frac{1+P^2}{1-P^2} - 1. \tag{4.1}$$

$R_{\uparrow\uparrow}$ ($R_{\uparrow\downarrow}$) denotes the tunnelling resistance for parallel (antiparallel) electrode magnetization. The use of half-metallic ferromagnets as electrodes yields an infinite magnetoresistance and is, therefore, particularly interesting. However, the fabrication techniques for oxide materials are not yet sufficiently advanced to produce high-quality tunnelling junctions. Figure 3*b*, *c* shows the magnetoresistance at 4.2 K of two LSMO–$SrTiO_3$–LSMO tunnel junctions fabricated by the IBM group. Whereas the larger junction displays only a moderate magnetoresistance of *ca.* 33%, the small junction shows a large magnetoresistance response of *ca.* 400%. In figure 3*a*, the magnetic hysteresis loop of a single LSMO film is shown. The magnetoresistance maxima occur at the coercive field; different coercive fields of the two ferromagnetic electrodes in the trilayer structure are induced by thickness variation. The magnetoresistance decreases rapidly with increasing temperature (Lu *et al.* 1996) due to magnon scattering, inelastic tunnelling processes in the barrier, pinholes, and a reduced interfacial spin polarization.

Recently, initial experiments on double tunnel junctions have been performed by (Brückl *et al.* 1998). In such junctions in the Coulomb-blockade regime, the charging of the intermediate electrode is suppressed by the large Coulomb energy; electron transport occurs via simultaneous tunnelling of electrons to and from the intermediate electrode. This leads to a magnetoresistance

$$\frac{\Delta R}{R} = \left(\frac{R_{\uparrow\downarrow}}{R_{\uparrow\uparrow}}\right)^2 - 1,$$

being much larger than the magnetoresistance of a single junction (equation (4.1)).

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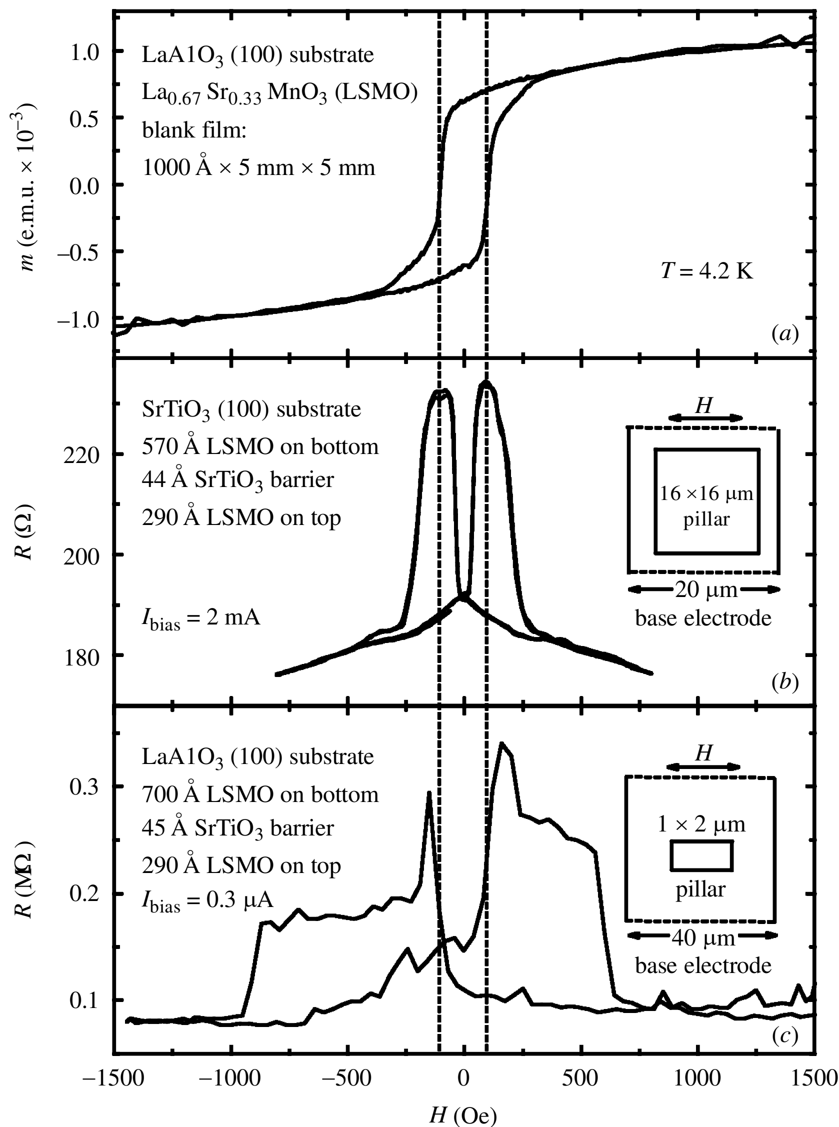


Figure 3. (*a*) Magnetization hysteresis of a LSMO film at 4.2 K. Resistance of a large-area (*b*) and a small-area (*c*) LSMO–$SrTiO_3$–LSMO tunnelling junction as a function of magnetic field at 4.2 K (reproduced from Sun (1998)). On the right schematics of a FIF tunnelling junction (*d*) and a double tunnel junction (*e*) are shown.

### (*c*) *Spin-polarized current injection into high-temperature superconductors*

Spin-polarized current injection from a manganite layer into the high-temperature superconductor $YBa_2Cu_3O_7$ has been investigated (Dong *et al.* 1997). In this experiment, the critical current of the superconducting film is found to decay strongly as a function of the injected spin-polarized current density. This result is tentatively attributed to pair breaking by a large density of non-equilibrium quasiparticles.

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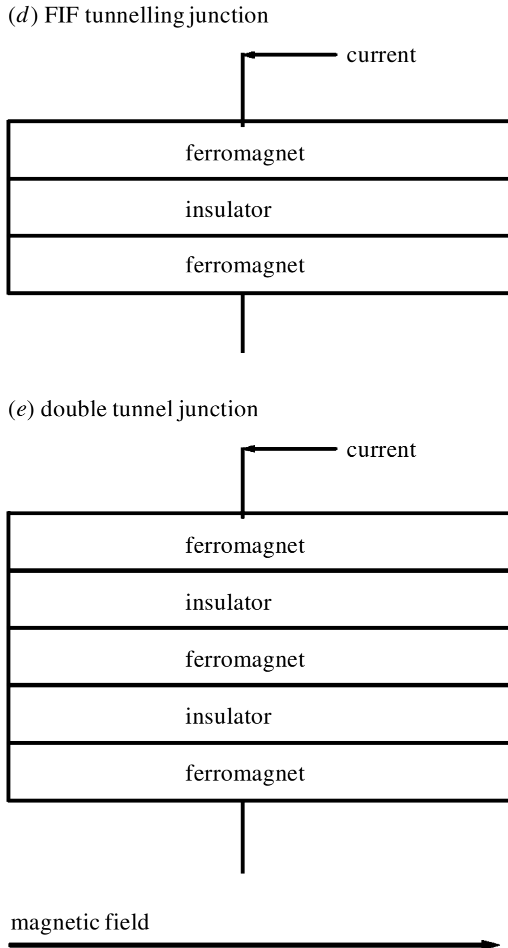


Figure 3. (*Cont.*)

## (*d*) *Spin transistors*

Two three-terminal devices, so-called spin transistors, have so far been proposed and realized. The Johnson transistor (Johnson 1993) is based on a trilayer geometry, whereas the Monsma transistor (Monsma *et al*. 1995) consists of a Co–Cr multilayer sandwiched between two silicon electrodes. These spin transistors have so far only been fabricated using conventional ferromagnets such as cobalt and permalloy ($Ni_{80}Fe_{20}$). In the following, the Johnson transistor or 'bipolar switch' will be discussed.

The geometry of the spin transistor is shown in figure 4*a*. It consists of a normal metal film, N, sandwiched between two ferromagnetic films F1, F2. A current is driven from the ferromagnetic electrode, F1, and is drained through the base, N. This current induces a spin accumulation, i.e. a non-equilibrium magnetization in the base. The density of majority carriers in the base is enhanced, whereas the minority carrier density is reduced; this is equivalent to a shift in the chemical potentials of the two carrier types. The collector electrode, F2, probes the chemical potential with respect

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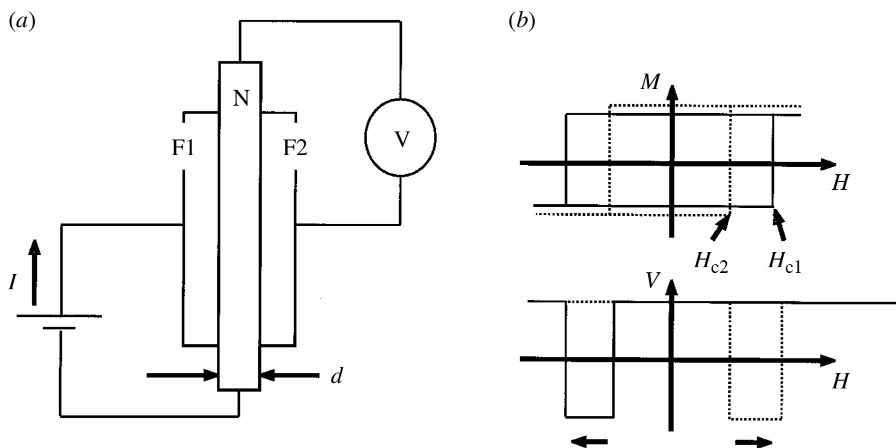


Figure 4. ($a$) Geometry of the spin transistor. ($b$) Magnetization hysteresis loops of the ferromagnetic electrodes F1, F2 and collector voltage for magnetic field sweeps starting at large positive (solid line) and large negative (dotted line) magnetic fields. The arrows indicate the sweep direction.

to a reference voltage given by a non-magnetic metal probe. If the magnetization in the electrodes F1, F2 is parallel ($\uparrow\uparrow$), the Fermi level in F2 aligns with the chemical potential of majority carriers in the base, whereas it is aligned with the minority Fermi level in the antiparallel state ($\uparrow\downarrow$). The collector voltage, i.e. the difference of the chemical potential for $\uparrow$ and $\downarrow$ spins in the base, is given by

$$V_{\uparrow\uparrow(\uparrow\downarrow)} = +(-)R_{\mathrm{s}}I, \tag{4.2}$$

with the spin-coupled interface resistance

$$R_{\mathrm{s}} = P_1 P_2 \frac{\rho\delta_{\mathrm{s}}^2}{Ad}; \tag{4.3}$$

where $\rho$ is the resistivity of the normal metal film of thickness $d$, $A$ is the area of the F1–N interface and $P_i$ the spin polarization of the ferromagnets. $\delta_{\mathrm{s}}$ denotes the spin-diffusion length. Equation (4.3) is valid in the thin film limit, $d \ll \delta_{\mathrm{s}}$.

The device operation is schematically shown in figure 4$b$. Two ferromagnetic electrodes with different coercive fields $H_{c1}$, $H_{c2}$ are used; the respective magnetization loops are shown in figure 4$b$. The collector voltage is also shown in figure 4$b$ for field sweeps starting at large positive (solid line) and negative (dashed line) magnetic fields, i.e. for parallel orientation of the two ferromagnets. In the field range $H_{c2} < \|H\| < H_{c1}$, the electrodes have antiparallel magnetizations and the transistor switches from $V_{\uparrow\uparrow}$ to $V_{\uparrow\downarrow}$. A bistable voltage output can be realized in zero field if the magnetic field sweep is halted before $H_{c1}$ is reached and the magnetic field is reduced to zero.

The amazing feature of equation (4.3) is the inverse proportionality to the base volume, $Ad$, that makes the structure highly suitable for miniaturization. The actual experiments were performed with relatively thick gold films, $0.1\,\mu\mathrm{m} \leqslant d \leqslant 5\,\mu\mathrm{m}$, and a large interfacial area of $A = 0.01\,\mathrm{mm}^2$. The observed interface resistance $R_{\mathrm{s}}$ was very small, of the order of $1\,\mu\Omega$. The rapid variation of $R_{\mathrm{s}}$ with $Ad$ would make these spin transistors competitive with semiconductor devices in the course of

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further miniaturization. Within a rigorous mathematical treatment, however, Fert & Lee (1996) showed that the spin relaxation within the ferromagnets has to be considered. This leads to a much larger effective thickness of the transistor base and to small saturation values of $R_s$ in metallic systems. Moreover, spin-flip scattering at the interfaces was found to be detrimental (Fert & Lee 1996).

Experiments on the Johnson spin transistor using half-metallic ferromagnets have so far not been reported. The great advantage of half-metallic magnets is the absence of spin relaxation within the magnets. Therefore, equation (4.3) is valid in this case. The polarization is $P_1 = P_2 = 1$. In order to preserve epitaxy throughout the structure, it is best to use an oxide normal layer such as $LaNiO_3$. A relatively short spin-diffusion length is expected in such an oxidic metal, imposing severe requirements on the fabrication techniques. Since no data are available on spin relaxation in oxides, quantitative estimates for the efficiency of an oxide spin transistor cannot be given.

The familiar semiconductor transistors have a power gain that is due to the non-linear current–voltage characteristics of pn-junctions. The Johnson spin transistor is completely different in this respect. Since it is fabricated from metallic elements, the current–voltage characteristics are linear and no power gain is achieved. The transistor, however, shows an impedance gain.

## 5. Conclusion and outlook

In recent years, astonishingly rapid progress has been made in both the fundamental study and the application of spin-polarized transport. Many concepts have emerged and are actively being investigated at the present time. Studies of conventional metallic systems led to the discovery of giant magnetoresistance in multilayers and to the development of high-quality spin-polarized tunnelling devices using conventional ferromagnets. The devices are already used or are currently engineered for use as magnetoresistive read heads for hard disks and are obviously highly market relevant.

Future developments are likely to occur in the following fields.

*Fundamental physics*

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This review shows that extensive progress has been made covering a wealth of phenomena, from fundamental transport processes in strongly correlated systems to single-electron tunnelling processes in double junctions. These studies will continue in the near future. The magnetic oxides are complex compounds requiring an elaborate fabrication process similar to high-temperature superconductors. The history of research into high-temperature superconductivity shows that the investigation of transport properties is intimately linked to crystal quality, and that each generation of improved materials reveals new fundamental physical properties. The same process is likely to occur during the course of CMR studies.

Investigation of spin-polarized electron tunnelling in oxide heterostructures is in its initial stages. Many problems have been identified and the fabrication of tunnelling devices will be improved by advances in the fabrication techniques as well as by the introduction of new concepts. The theoretical understanding of spin-polarized tunnelling—and of GMR—is far from complete, and the influence of band structure on the tunnelling process has to be clarified. The shortcoming of theoretical concepts is illustrated splendidly by the recent experimental observation of a reversed

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interfacial spin polarization controlled by the applied voltage (Sharma *et al*. 1999). Furthermore, the prospect of the manipulation of single electrons with well-defined spin orientation in double tunnel junctions opens up an interesting area of research.

### *Electronic devices*

Obvious applications of ferromagnetic oxide tunnel junctions are their operation as magnetoresistive read heads for a next generation of storage media and their use in MRAM devices. These aims will certainly be targeted; advances in multilayer fabrication techniques, as well as lithography on the nanometre scale, will be required. The fundamental problem of many oxide ferromagnets is their relatively low $T_C$; intense materials research in order to find magnetic oxides with higher Curie temperatures is under way.

The further development of spin electronics requires an active element with power gain comparable to a conventional semiconductor transistor. Since the amplification in semiconductor transistors is based on the nonlinearity of the current–voltage characteristics, it might be worthwhile to search for new spin-transistor designs along these lines. The investigation of double tunnel junctions with suitably tailored barrier materials seems to be most promising. A further requirement is the integration of spin-electronic devices into conventional semiconductor technology. One step in this direction has been made with the successful fabrication of high-quality manganite films on buffered silicon substrates. It would, however, be far more interesting to achieve the injection of spin-polarized carriers into semiconductors and create new devices based on spin-polarized electron and hole currents.

The development of working spin-electronic devices is expected in the near future. These might, however, not find an everyday use, but are more likely to be restricted to specific, high-performance applications such as supercomputing.

### *Laboratory instruments*

Scanning tunnelling microscopy (STM) relies on electron tunnelling between an atomically sharp tip and a clean surface. It facilitates the imaging of topographic surface features with an atomic resolution. An ST microscope combined with spin-polarized (SP) tunnelling can be developed into a powerful tool for the imaging of magnetic structures with a resolution down to the atomic scale. Such an SP ST microscope is required for the investigation of magnetic domains in structures such as spin-electronic devices and magnetic storage media on the nanometre scale. Furthermore, it can be used to measure the magnetic moments of single atoms, a feature yielding high potential to fundamental research in surface magnetism as well as to application in the storage media technology. First experiments using an SP ST microscope equipped with $CrO_2$ tips (Wiesendanger *et al*. 1990), ferromagnetically coated tungsten tips (Bode *et al*. 1998), and optically pumped GaAs tips (Suzuki *et al*. 1997) have been performed.

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Born 1964 in Uetersen, Schleswig-Holstein, Germany, Michael Ziese studied at the University of Hamburg, where he graduated with a diploma in physics in 1992. He obtained his PhD summa cum laude from the University of Bayreuth in 1995 with a study on flux-line lattice dynamics in superconductors. After working as a postdoc at Vrije Universiteit Amsterdam in 1995 and the University of Leipzig in 1996, he joined the magnetism group at Sheffield University as a research associate in January 1997. In October 1999 he joined the Physics Department at the University of Leipzig in order to undertake research for his Habilitation. Scientific interests include transport in oxides, especially colossal magnetoresistance materials and high-temperature superconductors. Recreational activities include books and family walks in the countryside.

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