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Giant magnetoresistance: history, development and beyond

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With the discovery of giant magnetoresistance (GMR), research effort has been made to exploiting the influence of spins on the mobility of electrons in ferromagnetic materials and/or artificial structures, which has lead to the idea of spintronics. A brief introduction is given to GMR effects from scientific background to experimental observations and theoretical models. In addition, the mechanisms of various magnetoresistance beyond the GMR are reviewed, for instance, tunnelling magnetoresistance, colossal magnetoresistance, and magnetoresistance in ferromagnetic semiconductors, nanowires, organic spintronics and non-magnetic systems.

giant magnetoresistance, spintronics, ferromagnetic semiconductors, spin dependent scattering, tunnelling magnetoresistance

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1 Background

Currently, it is well known that the electron has an essential role in many physical phenomena, such as electricity, magnetism and thermal conductivity. In 1838, the concept of an indivisible quantity of electric charge was first theorized to explain the chemical properties of atoms. Till 1897 the electron was identified as a particle [1]. The concept of spin was first proposed by Pauli. However, till 1928, when Dirac derived his relativistic quantum mechanics, electron spin was well explained and known as an intrinsic angular momentum characterized by quantum number s=1/2. Since then, it has been realized that beside mass and charge, electron has an intrinsic spin properties. However, electron charges and spins have been considered separately. For example, in conventional electronics, the electron charges are manipulated by electric fields, while in classical magnetic recording technologies, the electron spins are used through its macroscopic form, the magnetization of a ferromagnet. Until recent observations of the giant magnetoresistance (GMR) in magnetic multilayers [2,3], in which the motion of electrons can be affected by the force or magnetic field acting on the electron spins, it was realized that there are strong coupling between these two intrinsic properties of electrons. Since then, exploiting the influence of spins on the mobility of electrons in ferromagnetic materials and/or artificial structures becomes one of the intensely researched area in physics, and has introduced the novel idea termed spintronics [4], which possibly can be utilized in the next generation high-speed, low-cost electronic devices.

The first observation of magnetoresistance (MR) was made by Kelvin [5] in 1857 when he measured the resistance behaviour of iron and nickel in the presence of a magnetic field (later known as anisotropic magnetoresistance (AMR) [6]), which was 40 years before electrons were experimentally observed. Here, MR is the change of the electrical resistance of a material under applied external magnetic field. Although the mechanism of AMR is differ-

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ent to that of GMR, which will be further discussed later, they are both derived from the interactions between electrical current and the magnetism of the host. Magnetism in a ferromagnetic material derived from the spin-splitting effects, which is a result of the quantum exchange interactions between the electrons. As a result of the spin-split band structures, the density of states for the spin-up and spin-down electrons at Fermi level is different and exhibits altered conduction properties. In AMR, the difference in resistance between the parallel and perpendicular applied magnetic field is the result of the electron spin-orbital coupling induced difference in scattering cross-section area [6]. The first generation magnetic sensors were based on the AMR effect though the magnitude of AMR was only a few percent. GMR is based on the spin dependent scattering effects, which was first proposed to explain the anomalous resistivity trends exhibited by bulk ferromagnetic materials doped with impurities by Mott [7]. The solution lies in the "two-channel model" which treats spin-up and spin-down electrons as two relatively independent conduction channels, that is, spin-flip scattering between two channels is neglected on the studied timescale. Because of the spin-polarized band structure of ferromagnetic transition metals, the electron mean free path is much smaller, because conduction electrons may make transitions to the partial filled *d* states, leading to stronger scattering and larger resistivity. Since the unoccupied *d* states are also responsible for the ferromagnetism, hence, there is a direct connection between the electrical transport and magnetic properties. Later on, some pioneer research on spin dependent scattering was performed by Fert and Campbell [8]. The "two-current model" is the basis of spintronics and the interpretation of the spintronics is generally based on a simplified version of the model neglecting spin mixing.

2 The GMR effects: observation, theory, and applications

2.1 Observation and classical experimental results

The fast development in thin film preparation technologies, such as sputtering, evaporation and molecular beam epitaxy, has a critical role for the observation of GMR effects, because this enables the precise control of growing ferromagnetic metal thin films in the nanometer scales necessary for the emerging of novel phenomena. Grünberg et al. [9] first reported the antiferromagnetic interlayer exchange coupling in the Fe/Cr/Fe trilayers. Later on, in the Fe/Cr/Fe trilayers, they observed an enhanced room temperature MR up to 1.5% [10] (see Figure 1). Baibich et al. [11] independently observed a huge MR around 50% at low temperature in Fe/Cr magnetic superlattices grown by molecular beam epitaxy (Figure 2), which is a result of the spin-dependent

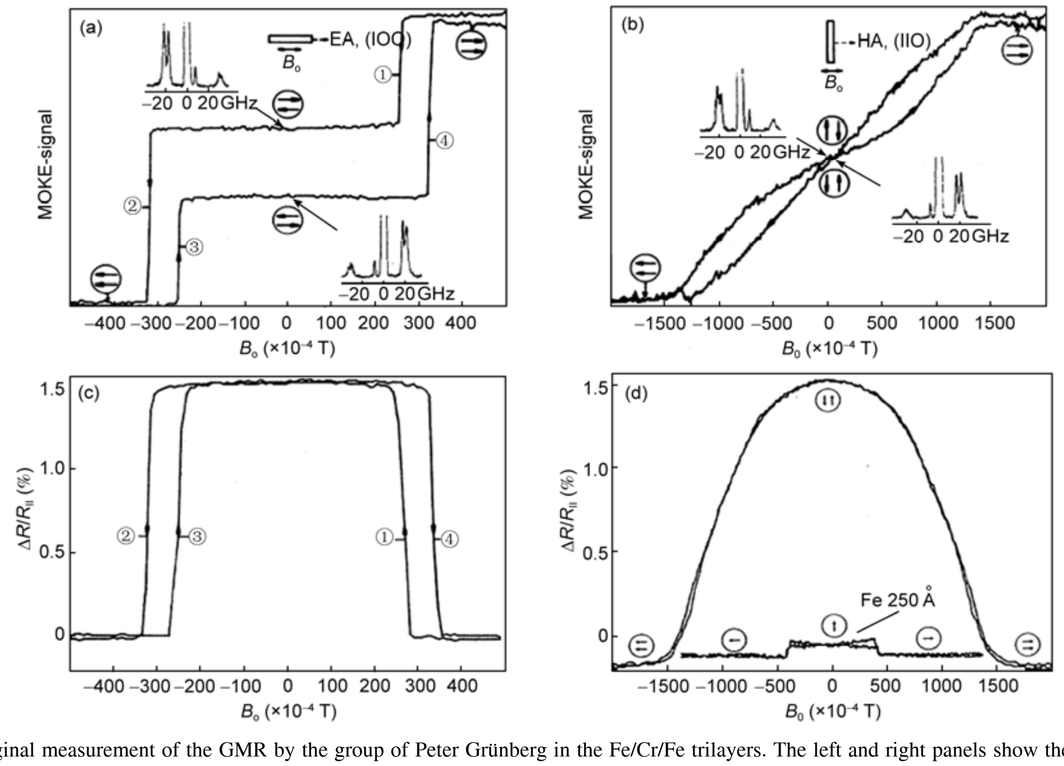

Figure 1 Original measurement of the GMR by the group of Peter Grünberg in the Fe/Cr/Fe trilayers. The left and right panels show the results with the magnetic field applied along the easy and hard axes in the plane of the multilayer, respectively. (a) and (b) show the magnetization curves measured using the magneto-optic Kerr effect. (c) and (d) show the CIP MR measured at room temperature. The insets to the magnetization curve show the light scattering from spin waves signifying antiferromagnetic coupling. Inset (d) also shows the AMR of a 25 nm Fe film. Copyright 1989 American Physical Society, reproduced from ref. [3] with permission.

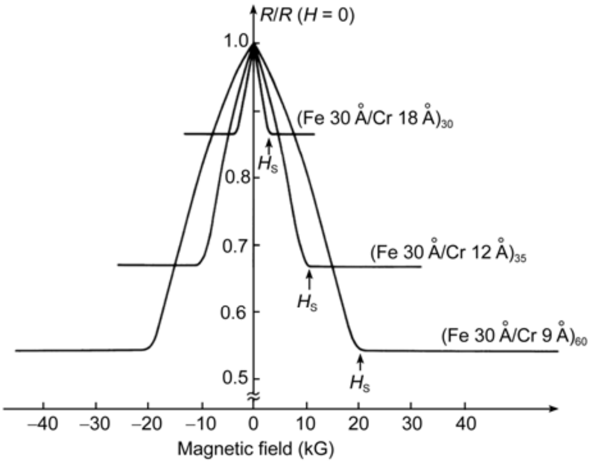

Figure 2 Original measurement of the GMR by the group of Albert Fert in three Fe/Cr magnetic superlattices at 4.2 K. During the measurements, both the current and the applied field were applied in the film plane and were parallel to the [1 1 0] axis. Copyright 1988 American Physical Society, reproduced from ref. [2] with permission.

transmission of the conduction electrons between the Fe layers through Cr layers. Not only they observed GMR, but also they identify it as a new spin-dependent phenomenon with promising technical applications.

A further milestone in the exploration of the GMR was the observation that both the exchange coupling strength and MR oscillate with the thickness of non-magnetic interlayer in metallic multilayers prepared by magnetron sputtering [12–15]. As shown in Figure 3, the oscillation could be observed up to room temperature [13]. Direct evidence of the spin polarization oscillations in the Cu layers of Fe/Cu multilayers was obtained by nuclear magnetic resonance [16]. Later on, GMR and/or oscillation of interlayer coupling in mulitlayers with different materials have been widely explored, for example in Co-Nb/Pd [17], Fe/Ag [18], Fe/Pd [19], Fe/Mo [20] and (Co-Ag)/Ag [21]. Among the various candidates, Co/Cu system is of special interest because it has good lattice matching between Co and Cu,

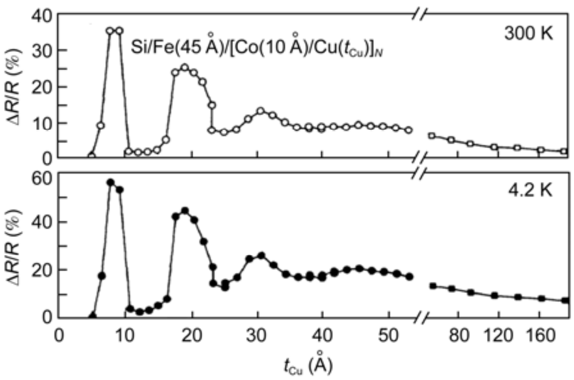

Figure 3 Dependence of the saturation MR on the Cu interlayer thickness for Si/Fe(45 Å)/[Co(10 Å)/Cu(t_{Cu})]$_N$ superlattices. N=16 for t_{Cu} below 55 Å and N=8 for t_{Cu} above 55 Å. Copyright 1991 American Physical Society, reproduced from ref. [13] with permission.

resulting in low dislocation density at the interface and consequently demonstrating low extrinsic spin independent scattering processes. For example, at room temperature, GMR larger than 65% has been achieved in Co/Cu multilayers [22]. Both the large room temperature GMR effects and the fast and simple sputtering preparation technique have enabled the commercial preparation of GMR devices.

Although the first observation of GMR is in antiferromagntically coupled magnetic mulitlayers, both antiferromagnetic interlayer exchange coupling and multilayer structures are not a prerequisite for the GMR effect. The key factors are that spin polarized current must retain its spin while travelling between two magnetic regions where the scattering is determined by the local magnetic orientation. The relative magnetic orientation of the two magnetic regions must be tunable by applied magnetic field.

Dupas et al. [23] demonstrated that GMR could be obtained in Au/Co systems without antiferromagnetic interlayer exchange coupling but composed of magnetic layers with different coercivity. Dieny et al. [24] indicated that GMR could be achieved in spin valve structure by introducing antiferromagnetic pinning layer into the sandwiches of uncoupled ferromagnetic layers separated by ultrathin nonmagnetic layer. The advantage of spin valve structures is that the magnetic moments in magnetic free layer could be reversed in a relatively small magnetic field, which is important for practical applications. More studies of GMR based on spin-valve multilayers can be found elsewhere [25].

The observation of GMR in granular single films by Berkowitz et al. [26] and Xiao et al. [27] indicates that layering of different materials is not required as long as the basic criteria for GMR is satisfied. Sang et al. [28] also reported a GMR in CoAg granular film prepared by using ion beam co-sputtering technique. In these alloy films single domain ferromagnetic particles are surrounded by non magnetic matrix. The particle diameters become the critical length scales in the granular systems as it determines not only the Coulomb energy of single particle but also the inter-particle distances. A comprehensive theory of the GMR in granular systems is discussed by Zhang et al. [29]. If we further considering the non-magnetic layer is the domain wall between the single domains, GMR effect might emerge in multidomain materials in proper condition depending on the dimensions of the domain and domain wall [30]. By constraining the domain wall, it is possible to enter a ballistic transport regime. For example, by making nanocontacts to the Ni wire, the MR for a contact with a few atoms approaches 280% at room temperature under 100 Oe external field [31]. However, the detailed mechanism responsible for the GMR effects in the ballistic regime is still unclear [32].

In earlier reports, the studies were based on the current in the film plane (CIP-GMR) geometry. Zhang et al. [33] theoretically predicted the existence of GMR effects in multilayers with current perpendicular to the film plane (CPP-

GMR), which has been experimental confirmed in the Ag/Co system [34]. Compared to the CIP-GMR, CPP-GMR usually has a large MR magnitude as shown in Figure 4. This is because the scaling length of the CIP geometry is the electron mean free path, which is smaller than the spin diffusion length in the CPP geometry [35]. Also its higher symmetry of CPP geometry allows it to be more suitable for quantitative theoretical simulations, which give more direct access to the fundamental parameters of the spin-polarized transport. However, because of the relative thin thickness of devices, CPP-GMR usually has a much smaller resistance, which is more difficult to be detected. New directions for the CPP-GMR geometry include studies of hot-electron transistor and ballistic transport behaviours. More details could be found elsewhere [36,37].

Since the observation of GMR, huge numbers of studies have been published, a series experimental studies focusing on various parameters has been done, that is, composition, nonmagnetic layer thickness, magnetic layer thickness, roughness, impurity, outer-boundary, temperature and angularity that can determine the magnitude of GMR which has been summarised in a recent review [38].

2.2 Theoretical models

The GMR can be qualitatively understood based on the Mott's "two current model". As previously mentioned, there are two main points proposed by Mott. First, the conductivity in metals can be described in terms of two independent parallel conduction channels of electrons, that is, channels of spin-up and spin-down electrons. Second, in ferromagnetic metals the scattering rates of the spin-up and spin-down electrons are quite different, that is, scattering rates are spin-dependent. As shown in Figure 5, we consider a collinear magnetic configuration, where the scattering is strong for electrons with spin antiparallel to the magnetization direction. For the parallel aligned magnetic layers (left panel in Figure 5), the up-spin electrons pass through the structures with little scattering, while the down-spin are strongly scattered within both ferromagnetic layers. Since two conduction channels are parallel to each other, the total conduction is primarily determined by the highly conductive up-spin electrons and shows a low resistance state. On the contrary, for the antiparallel aligned magnetic layers (right panel in Figure 5), each channel is scattered strongly within one of the ferromagnetic layers, and show a high resistance state [39]. This simple resistor model is based on the assumption that the electron mean free path for both spin channels are longer than the layer thickness, which is not always justified for real systems. Also, it is not possible to predict the asymptotic behaviour of GMR for large layer thickness.

The first classical model of GMR was developed by Camley and Barnaś [40], which is based on solving the Boltzmann transport equation with spin-dependent scattering at the interfaces. It shows that GMR depends on the ratio of the layer thickness to the electron mean free path, and the asymmetry in scattering from spin-up and spin-down electrons. Later, they further included bulk scattering into previous model [41], and identified that diffusive scattering at the interfaces was the primary mechanism for GMR in Fe/Cr system, while spin-dependent scattering within ferromagnetic layers was dominate in permalloy. Using a path-integral method, the multilayer effect for the

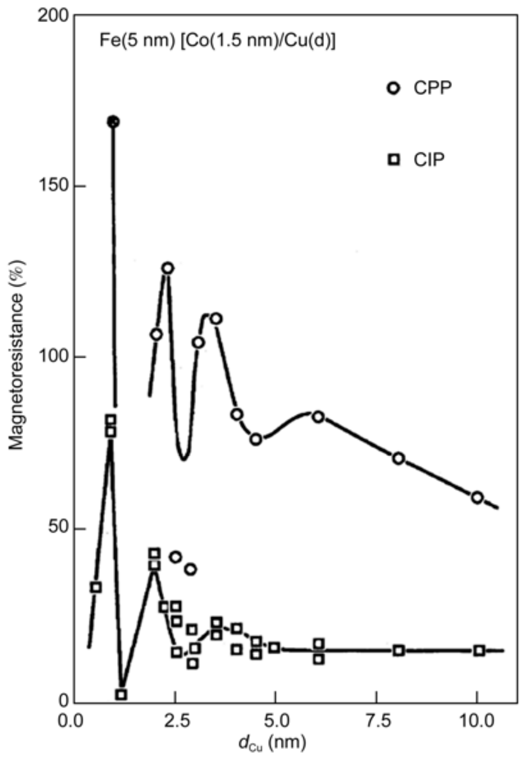

Figure 4 Nonmagnetic Cu space layer thickness dependence of both the CPP and CIP GMR. Copyright 2002 Elsevier Science B.V., reproduced from ref. [35] with permission.

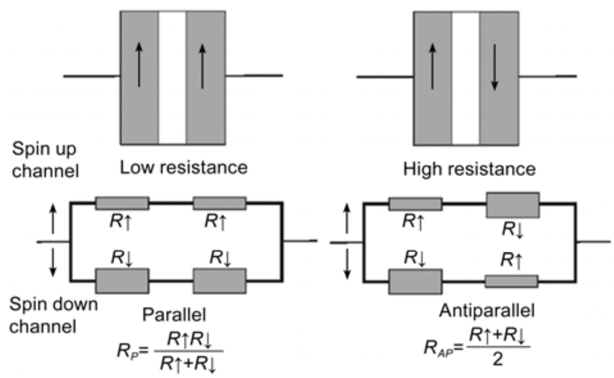

Figure 5 Schematic of the resistor model for GMR. For the parallel state (left panel), the spin-up channel is the majority spin channel in both the ferromagnetic layers, experiencing a low resistance. For the antiparllel state (right panel), each spin channel has been strongly scattered in one of the ferromagnetic layers, showing a high resistance. Copyright 2008 IOP Publishing Ltd, reproduced from ref. [39] with permission.

enhancement of the GMR in $(Fe/Cr)_n/Fe$ sample can be explained [42]. Valet and Fert [43] published a semiclassical model also based on the free-electron Boltzmann equation for use in the CPP geometry, which provided a method to separate clearly the volume and interface contributions to the spin-dependent scattering. Semiclassical free-electron models suffer from the lack of an accurate description of the electronic structures. In addition, semiclassical model is unable to describe quantum effects, when system thickness approaches the electron mean free path where quantum effect becomes non-neglectable. The first free-electron quantum model is given by Levy et al. [44,45], using the Kubo linear response theorem. Camblong et al. [46] used the same model but within a real space approach to avoid the local approximation for the conductivity, and indicated that the quantum interference and size effects are neglected. Similar conclusion was obtained in the spin valve structures when using the real space quantum mechanical approach to considering the bulk spin dependent scattering [47]. The relationship between the exact quantum approaches, semiclassical approaches and an approximate quantum approaches have been systematically studied by Zhang et al. [48].

Unlike in the above mentioned free-electron theories, a single-band tight-binding model is another method to describe the electronic structures of a material in terms of localized atomic orbital. Asano et al. [49] first used a single band *s*-valent tight binding model to study the effects of interface roughness and bulk disorders on both CIP- and CPP-GMR. Later Itoh et al. [50] introduced the single-cell coherent potential approximation into the single band tight binding model to study the physical origin of the difference between the CIP- and CPP-GMR. A real-space Green-function technique, in which the scattering is treated exactly, was used by Todorov et al. [51] in order to study the Ohmic resistivities and GMR. Both the density of states of the *d* band and the elements of the *s-d* scattering matrix were taken into account by Li et al. [52], in which model the oscillation of GMR with spacer thickness was successfully achieved.

As has already been mentioned above, free-electron and single-band models oversimplified the electronic structures of the magnetic multilayers, primarily neglecting the contributions from the *d* bands and/or the hybridization between *sp* and *d* electrons to the electrical transports, which are critical for both ferromagnetism and GMR. Hence, more accurate multiband models are needed to take into account the above mentioned effects. Several notable attempts have been made. For example, Schep et al. [53] have illustrated the crucial role of the hybridization between the conducting *sp* and localized *d* bands for the GMR in the ballistic regime, where the sample dimensions are smaller than the electron mean free path. By incorporating a more accurate band structure into the semiclassical transport theory, for example, constant relaxation approximation used by Oguchi [54], spin-dependent but state-independent relaxation time approximation used by Zahn et al. [55], state dependent relaxation time approximation used by Binder et al. [56], and interface atoms intermixing used by Butler et al. [57], the effects of impurities on the GMR were studied. In order to describe the intrinsic structural defects such as vacancies, lattice distortions and grain boundaries more precisely, Tsymbal et al. [58] included defect scattering within a multiband tight-binding theory and a quantum-mechanical approach to electrical transport.

First principle model for electron structure together with quantum mechanical formula for the electronic transport is a powerful tool to study GMR, as this allows a self-consistent way to treat electronic structures and includes the contribution from charge and spin transfer at the interfaces. Butler et al. [59,60] have developed first principle model suitable for both CIP-GMR and spin valve devices. Blass et al. [61] included the spin-orbit coupling in their calculation, where by simultaneously determining contributions to the GMR coming from both electronic structures and spin-dependent scattering of impurities, they were able to calculate resistivity without adjustable parameters. As the difficulties in accurately describing the magnetic disorders at interface, the spin-orbital scattering, and the exact electronics structures remain, increasingly powerful theoretical tools and increasingly accurate theoretical models are needed to fully elucidate the physics behind GMR.

2.3 Applications

Unlike many scientific discoveries for which future applications are only predicted, GMR has been identified for its practical use. The period between the discovery of GMR and its commercial availability as magnetic sensors was relatively short. The first commercial GMR sensor was introduced in 1995 [62] and the first commercial GMR read heads for use in hard disk drives was produced by IBM in 1997. Currently, GMR magnetic sensors have already found wide applications in different fields such as data storage, engineering biology and space science [63].

The largest technological application of GMR is in the data storage industry. The first magnetoresistive head was introduced in early 1990s using AMR effect. The data storage density is about 0.1 Gb/in^2 in 1991. Currently, it can achieve more than 500 Gb/in^2. By using novel material, such as Heusler alloys, or by using novel device design, such as using a nano-oxide layer to confine the current, changing to perpendicular recording media, it is possible to further increasing GMR effects, which may shed light to the device design below dimensions of 30 nm. A recent review about data storage is given by Childress et al. [64]. There has been considerable effort for developing a magnetic random access memory (MRAM) which has the advantages of non-volatility, low energy consumption and radiation hardness.

The successful commercialization of GMR sensors in hard disk read heads has lead the way to the following applications, where small-size, high-speed, high-sensitivity are needed. First, it can be used for industrial current sensoring, IC current monitoring, such as milliwattmeters, electrical isolators, electronic compasses as well position, angle and rotation-speed sensing [65]. Second, in civil engineering, GMR sensors are related to the detection of the Earth's magnetic field perturbations produced by specifically considered ferreous bodies. Third, the nano-granular film with large GMR effect can work as a sensor for brushless DC motors [66]. Fourth, GMR commercial sensors with high operating range up to 2 mT and high temperature dynamic range may found practical application in Aerospace [67]. Finally, it can be used as biological sensors for molecule tagging [68].

3 Influence of GMR

The discovery of GMR has greatly stimulated the researches on various MR phenomena, for example, tunnelling magnetoresistance (TMR), MR in ferromagnetic semiconductors and granular films, colossal magnetoresistance (CMR), ordinary MR, and geometry MR.

3.1 TMR

The fundamental difference between a CPP-GMR structure and a TMR device is that the non-magnetic metallic interlayer in a CPP-GMR structure is replaced by a thin insulating layer. Conductivity is carried by electrons tunnelling through the insulating barrier to the available states on the other side. Hence, the total resistance is determined by the available electron states of both the ferromagnetic electrodes and the available channels inside the insulator. The TMR effect has been observed by Julliere [69] in Fe/Ge-O/Co system which exhibited a MR ratio of 14% at 4.2 K. It received little attention because it was observed at low temperature and was hard to reproduce. Miyazaki et al. [70] and Moodera et al. [71] reported large (18% at room temperature) and reproducible TMR effects based on amorphous Al_2O_3 insulating layer. By optimizing the ferromagnetic electrodes candidates and the growth condition for the Al_2O_3 layer, the room temperature TMR ratio could be increased up to 70%. A room temperature TMR as large as 158% was obtained in polycrystalline $Zn_{0.41}Fe_{2.59}O_4$ sample, in which large TMR was attributed to the high spin polarization of $Zn_{0.41}Fe_{2.59}O_4$ grains and antiferromagnetic correlations between the magnetic domains on both side of the insulating α-Fe_2O_3 boundaries [72]. Since the current through vertical direction in magnetic tunnel junctions (MTJs), it is possible to reduce the lateral size by lithographic techniques. Together with its large MR ratio, MTJs are new concept of MRAM, which has been introduced to the market in recent years.

One further milestone in the development of TMR is the theoretical predication of over 1000% TMR in MgO based MTJs [73,74] and Yuasa et al. [75] and Parkin et al. [76] experimentally reported the room temperature TMR of 200% in Fe/MgO/Fe MTJs. A TMR ratio of about 600% was obtained recently [77]. Later, giant TMR has also been reported in Co/MgO/Co, FeCo/MgO/FeCo and CoFeB/MgO/CoFeB MTJs [78,79]. A key reason for these MTJs to have a large TMR effects is that the particular single crystal barrier could filter the symmetry of the tunnelling electron wave functions, leading to high spin polarization of the conducting electrons. Recent progress of the MgO based MTJs is reviewed by Yuasa et al. [80].

There are other methods to obtain high spin polarization ratio which could lead to giant TMR effect. The first method is using half metallic ferromagnetic electrodes with a 100% spin polarization ratio, such as CrO_2, $La_{1-x}Sr_xMnO_3$, and Fe_3O_4. For example, a TMR about 1800% at 4 K has been achieved by using $La_{2/3}Sr_{1/3}MnO_3$ [81]. Secondly, ferromagnets of the family of Heusler alloys are also promising candidates, where a room temperature TMR ratio of 90% has been reported [82]. Finally, a ferromagnetic insulator could be used as a spin filter to provide high spin polarization ratio, and eventually utilized for large TMR effects [83,84].

3.2 CMR

Jin et al. [85] reported a negative MR up to 127000% at 77 K in La-Ca-Mn-O films, which is more than three orders of magnitude larger than the typical GMR effect and is termed CMR. The family of manganese oxides $(R,A)MnO_3$ (R = rare earth element, La, Y, etc., A = divalent alkaline earth element) is thereafter called CMR materials. The CMR has a different mechanism compared to GMR, and it is a magnetically introduced insulator to metal phase transitions. The strong competing interactions of magnetic, electronic and lattices degrees of freedom (spin, charge, orbital) inside manganese oxides lead to extremely rich phase diagrams and complex physics properties. Zener double exchange interaction, where ferromagnetic interaction of $3d$ magnetic moments is mediated by spin-polarized conduction electrons, and Jahn-Teller lattice distortion, where the distortion of oxygen octahedral around Mn^{3+} ions lifts the degeneracy of $3d$ e_g electronic states, has the crucial role in both the magnetic and transport behaviours. The observation of CMR at high magnetic field and low temperature limits its practical application. Recent reviews on the magnetic transport properties in the manganites are given by Dörr [86] and Nagaev [87].

3.3 MR in ferromagnetic semiconductors

Semiconductors spintronics offer a promising opportunity towards the development of hybrid devices that could perform all the logic, communications and storage within the same devices, by simultaneously manipulating both the charge and spin degree of freedom. As schematically shown in Figure 6, the concepts of spin-field effect transistors, in which the spin transport in the semiconductor channel between two spin polarized sources and drains with tuneable carrier density by conventional field effect gates, have been proposed by Datta et al. [88]. Because of the "conductivity mismatch", it is difficult to inject a spin-polarized current from a magnetic metal into semiconductor [89]. Several different solutions were proposed. Using a tunnel contacts [90] or Schottky barriers [91] could help to reduce the spin accumulations effects. Inducing the spin polarized current by spin-orbit coupling effects, that is, the spin Hall effects [92], is also another promising method. Another important idea for semiconductor spintronics is based on the fabrication of ferromagnetic semiconductors. The well-accepted diluted magnetic semiconductor $Ga_{1-x}Mn_xAs$ was discovered by Ohno et al. [93]. Though the Curie temperature has reached 190 K [94], it is still far below room temperature. Since the breakthrough of a theoretical predication of above room temperature ferromagnetism in Mn-doped ZnO [95], ferromagnetic semiconductors based on transition metal oxide has become a research focus in the past decades. In the following we would summarize some known mechanisms of the MR in ferromagnetic semiconductors.

(1) A classical positive magnetoresistance (PMR) arises from the action of Lorentz force on the mobile carriers. For electrons in closed orbits, the $MR \sim aH^2/(b^2+cH^2)$, where *a*, *b* and *c* are parameters depending on the carrier conductivity and mobility. It is quadratic in low fields, and it saturates in high magnetic fields [96].

(2) If the electron orbital is limited by sample dimensions, that is, the electrons move in an open orbit, the PMR due to Lorentz force on the two band model is quadratic in low field, but it is unsaturated at high magnetic field ($PMR \sim H^2$).

(3) A PMR may also derive from the giant conduction bands splitting effects either induced by strong *s*-*d* exchange interaction [97] or by Zeeman splitting effects [98]. This PMR is usually found in a weak magnetic field, followed by a negative MR or saturated at higher magnetic field.

(4) If the electron transport is dominated by the variable range hopping mechanism in a semiconductor, we could expect a large PMR under applied magnetic field due to a sharp decrease in the overlap of the wave-function "tails"

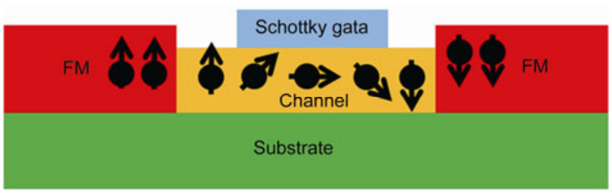

Figure 6 Schematic of the proposed Datta-Das spin-FET [88].

between the different states [99], which is purely a orbital effect.

(5) In particular systems, as a result of a large Zeeman splitting, some fractions of localized states can be occupied by two electrons. In this case, a large PMR is also expected with the linear magnetic field dependence at weak field limit and saturate at high magnetic field [100,101].

(6) A negative magnetoresistance (NMR) in diluted magnetic semiconductors often results from the quantum corrections to conductivity of disordered system, that is, from the destructive effect of magnetic field on constructive interference related to self-crossing trajectories. In the weak localization regime $k_F l \gg 1$, where k_F is the Fermi wave vector and l is the mean free path, this NMR can be quantitatively calculated [102–104].

(7) A NMR could also arise from the high order expansion of *s*-*d* exchange Hamiltonian as proposed by Reuss et al. [105]. A semiempirical expression of this NMR follows $\rho_H/\rho_0 = 1 - a^2 \ln(1+b^2H^2)$. Parameters a and b are complex functions of spin scattering, exchange interaction integral, density of states at the Fermi level, magnetization, effective Lande factor of the localized magnetic moment. A signature for this NMR mechanism is that the linear relationship between fitting parameter b and $1/T$ [106].

NMR has also been attributed to the spin-dependent hopping or magnetic field induced change in the Anderson localization length [107]. As we can see, the diluted magnetic semiconductors are a fast developing research area, however, it suffers from its weak magnetization as well as the weak spin dependent transport properties, especially at room temperature. An alternative way has been developed by Yan et al. [108], where samples were prepared by alternately sputtering thin (usually less than 1 nm) ferromagnetic metal (Co, Fe) layers and oxide (ZnO, TiO_2, In_2O_3 etc) layers. In such a way, concentrated magnetic semiconductor with a high concentration of transition metal were obtained, which demonstrated a large magnetization, that is, 581 emu/cm^3, large NMR i.e., 11%, and large magneto-optical Kerr rotation at room temperature [108,109].

Thermal assisted spin dependent variable range hopping is the dominated transport mechanism at low temperature for these magnetic semiconductors with high transition metal concentrations. A spin-dependent variable range hopping model [110,111] is established by considering both the electron-electron Coulomb interaction ($E_{Co} = e^2/\varepsilon r$), the spin-spin exchange interactions ($E_{ex} = -(J/r)\cos\theta$) and the hard gap energy, where ε is the dielectric constant, r is the hopping distance, J/r is the effective exchange coupling coefficient between two carriers, and θ is the angle between the spin in the initial and final states. As shown in Figure 7, good agreement between the theoretical predication and experimental observation indicates that the underlining physics has been well understood. According to the spin-dependent variable range hopping model, the spin polariza-

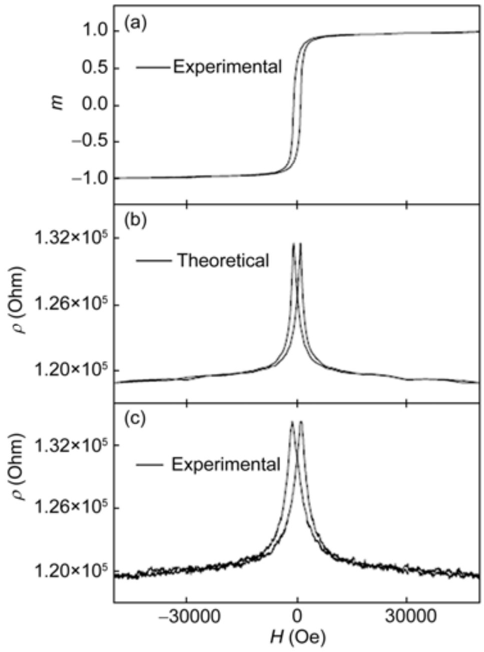

Figure 7 Direct comparison among the experimental *m-H* curve (a), the theoretical *ρ-H* curve by spin dependent variable range hopping model (b), and the experimental *ρ-H* curve (c) measured at 5 K for the $Ti_{0.24}Co_{0.76}O_2$ magnetic semiconductor film. Copyright 2006 IOP Publishing Ltd, reproduced from ref. [110] with permission.

tion of the $Zn_{0.28}Co_{0.72}O$ concentrated magnetic semiconductor is estimated to be $P = 29.6\%$ [110].

3.4 MR in nanowires and organic systems

Driven by the needs for miniaturization in modern technology, more attention has been given to nanoscale systems, which are not merely miniature forms of bulk materials, but instead can bring about many emergent phenomena [112, 113]. Nanostructures such as nanowires, nanotubes, and nanoparticles have a large surface to volume ratios, which could greatly enhance the ferromagnetism through surface defects or composition inhomogeneity [114]. MR of individual oxide nanowires has been studied, where *s-d* exchange induced spin splitting of conduction band is responsible for the low field PMR, while suppression of weak localization effect dominates the high field NMR [115,116]. In addition, as shown in Figure 8, a large PMR could arise from the spin filter effect in half metallic Fe_3O_4 nanowires, where only one channel of spin carriers can contribute to the conduction [117]. Furthermore, the MR in nanowires could be modulated by applying a gate voltage [115,117].

A recently emerging direction is organic spintronics, where organic materials are applied to control spin-polarized

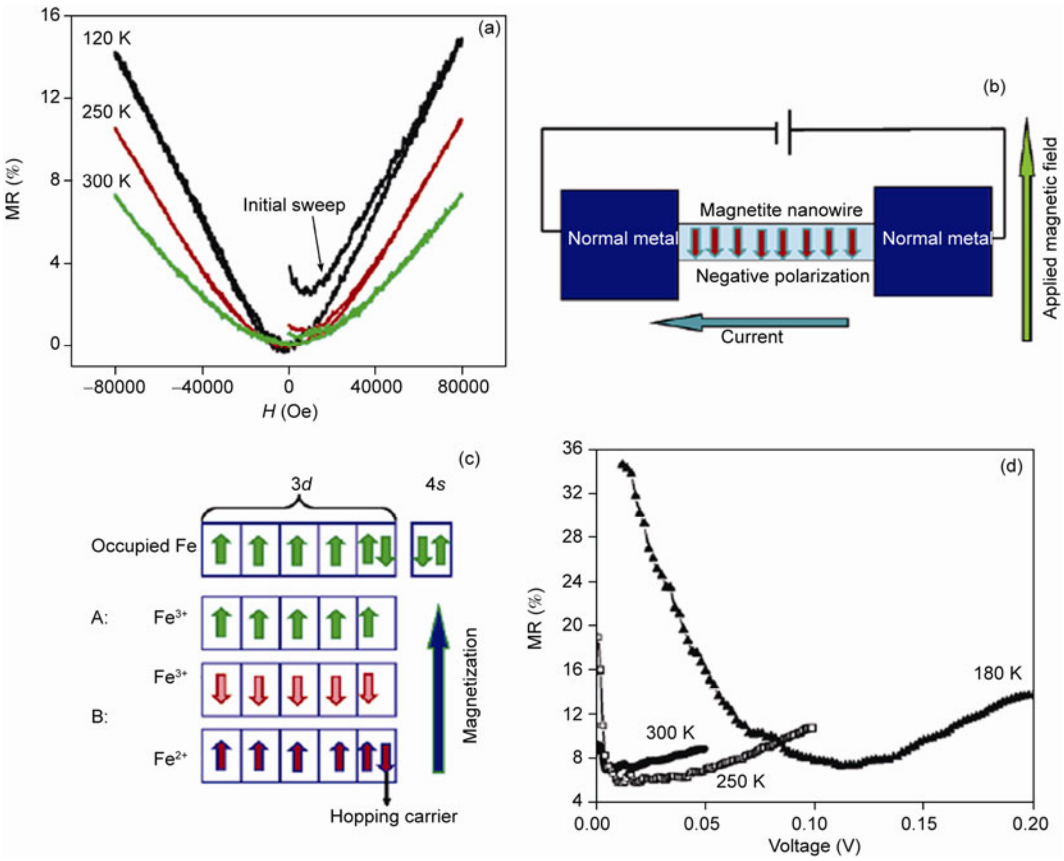

Figure 8 (a) MR of individual Fe_3O_4 nanowires measured at different temperatures. (b) Schematic of the device. (c) FM order of Fe_3O_4, where the minority carriers are responsible for the transport. (d) Bias dependence of MR for the Fe_3O_4 nanowire-based devices. Copyright 2006 American Chemical Society, reproduced from ref. [117] with permission.

signal. Large GMR- or TMR-like effects have been theoretically predicted [118,119], and a GMR up to ~300% has been reported by Suan et al. [120] in organic spin valves. Several review papers about recent progress in organic spintronics are given by Naber et al. [121] and Sanvito [122]. Carbon nanotubes with a small spin-orbit coupling, hence, long spin lifetime have been of recent research interest. For example, as shown in Figure 9, Hueso et al. [123,124] demonstrated that in devices formed by carbon nanotubes channel and $La_{0.7}Sr_{0.3}MnO_3$ electrodes, the MR at 5 K was 61%. Cai et al. [125] demonstrated that the high field MR could be tuned from PMR to NMR by simply applying pressure in the single wall canbon nanotubes. The organic spintronics devices composed of carbon nanotubes and half metallic ferromagnetic electrodes combine a number of advantages that are responsible for the observation of a large PMR, that is, a long spin lifetime of electrons in carbon nanotubes, a short dwell time of electrons because of their high Fermi velocity in nanotubes, a high spin polarization ratio of electrodes and a high effective spin injection ratio at interfaces.

3.5 MR in nonmagnetic systems

Large MR can be found in non-magnetic materials, where sample geometry and disorders have a critical role. For example, Xu et al. [126] reported a linear PMR up to 200% in non-magnetic silver chalcogenides; Solin et al. [127] discovered a geometric MR up to 750000% at room temperature in non-magnetic narrow gap InSb, which is a result of the field dependent deflection of current around the inhomogeneity; Wan et al. [128] demonstrated a MR effect of 150000% in $In/SiO_2/Si/SiO_2/In$ devices, where MR is enhanced by a large spatial variation of the mobility.

Another emergent research area in recent years is the two dimensional electron gas (2DEG) at insulating oxide interfaces, first reported in $LaAlO_3/SrTiO_3$ hetero-structures by Ohtomo and Hwang [129]. In $LaAlO_3/SrTiO_3$ 2DEG system, PMR is usually attributed to the enhanced scattering effect, because of the enhancement of electron transit path as a result of the Lorenz force deduced cyclotron precession, while NMR is because of the reduced scattering as a result of the alignment of interfacial ferromagnetic regions [130].

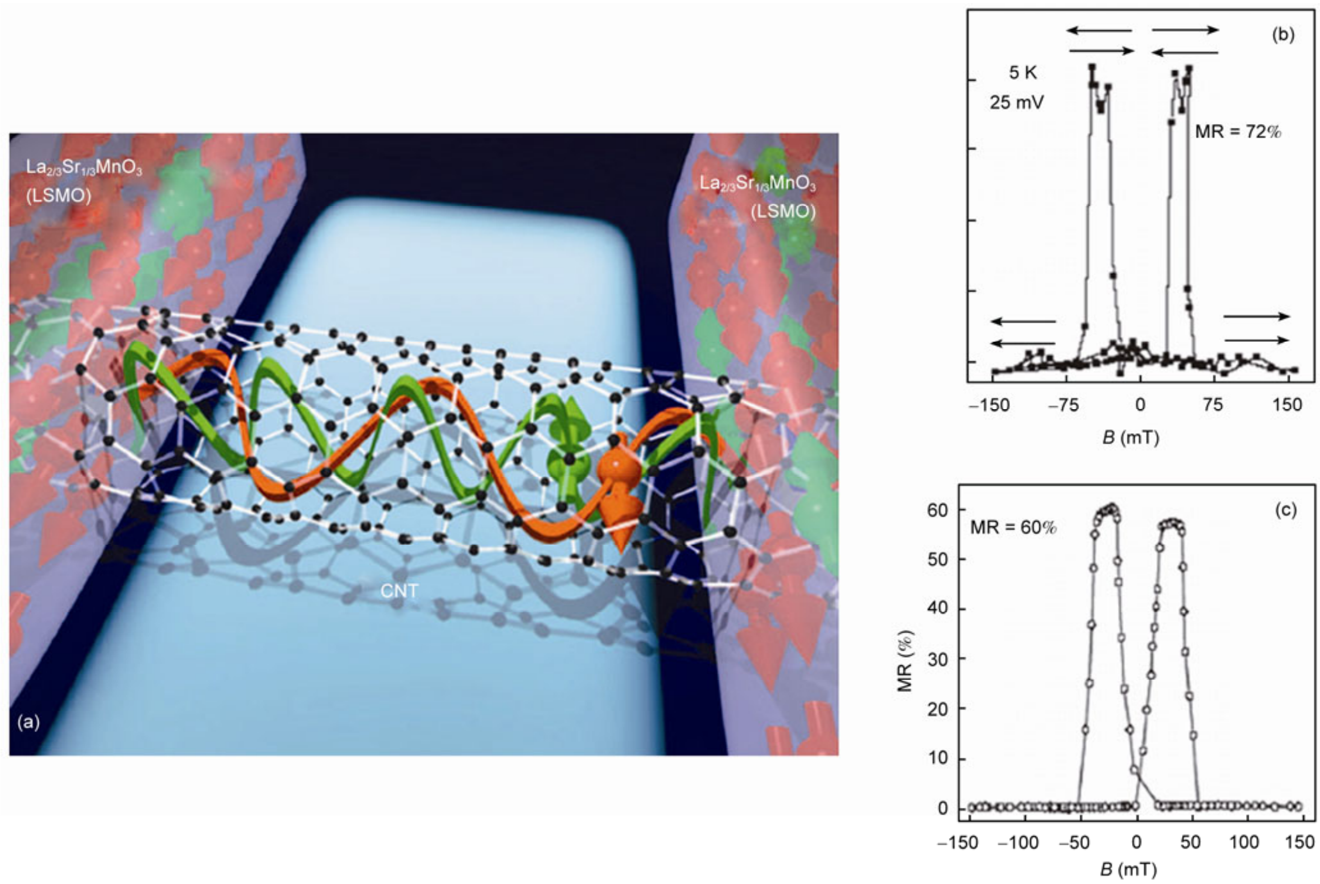

Figure 9 (a) Artistic view of spin transport through a carbon nanotube (CNT) between magnetic (LSMO) electrodes. (b) and (c) are the low temperature experimental data. A contrast of 72% and 60% is obtained between the resistances for the parallel (high field) and antiparallel peaks magnetic configurations of the source and drain. Copyright 2008 American Physical Society, reproduced from ref. [124] with permission.

It is believed that sample inhomogeneity [131] and/or spin-orbit coupling [132] have an important role on the electrical transport behaviour in this system.

4 Concluding remarks

In the last two decades, GMR has become an expending research area that crosses the borders between physics, biology, engineering and material science. Though the basic physical picture for GMR seems simple, an in-depth theoretical understanding suffers from the actual description of band structures and defect scattering. Most importantly, it introduced the idea of spintronics. GMR together with TMR has already enters the random access memory and data storage of computers. Research on the spintronics with semiconductors, nanowires, organic materials, and with oxide interfaces opens fascinating new research fields and holds a promising perspective for the next generation multiple functional devices with better scalability, lower power dissipation, and increasing variability.

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