INTRODUCTION

New directions in spintronics

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Conventional microelectronics exploits only the charge degree of freedom of the electron. Bringing the spin degree of freedom to bear on sensing, radio frequency, memory and logic applications opens up new possibilities for ‘more than Moore’ devices incorporating magnetic components that can couple to an external field, store a bit of data or represent a Boolean state. Moreover, the electron spin is an archetypal two-state quantum system that is an excellent candidate for a solid-state realization of a qubit.

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1. Introduction

Conventional electronics uses the electric charge of the electron to store and process information. This approach has been wildly successful for several decades and has brought about a society where information technology is becoming ubiquitous. Indeed, the basic functioning of advanced economies is now utterly dependent on their information technology infrastructure, and the entire business model of this industrial sector assumes that tomorrow’s computer will be more powerful, and store more data, than today’s. This dizzying rate of improvement has been captured in Moore’s Law, a rule of thumb which states—to paraphrase—that computing power in the latest technology doubles roughly every 18 months. Nevertheless, fundamental laws of physics look set to bring this to a halt well within the next decade, unless new ‘more than Moore’ approaches are found.

One of the most promising is spintronics, where the magnetic property of the electron, its spin, is used to represent information. The carriers in the semiconductor materials used for conventional electronics are spin degenerate, and so spin plays no role there. For it to do so, a spin polarization is needed. The application of a magnetic field can generate some polarization through Pauli paramagnetism but the effect is weak and is lost as soon as the applied field is removed. Spontaneously spin-polarized electrons are found in Stoner [1] (itinerant) ferromagnets, and hence spintronic devices typically incorporate such materials. Among the elements, only the three-dimensional transition metals Fe, Co and Ni display ferromagnetism at room temperature and so the choice is

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restricted to these elements and their alloys and compounds; none is immediately compatible with the industry standard complementary metal oxide semiconductor (CMOS) process. The only commercialized spintronics devices to date either do not rely on CMOS at all, for instance hard disc read heads [2], or else are restricted to fabrication during the CMOS back-end process, such as magnetic random access memory (MRAM) cells [3].

Both these applications are based on magnetoresistive effects: the application of a magnetic field reconfigures the internal magnetic structure of the device, affecting the flow of spin-polarized currents and hence the device resistance. This effect is obviously useful as a magnetic field sensor, ideal for detecting bits written on a hard disc or reading out the magnetic state of an MRAM cell. While materials with higher spin polarization are sought to increase this effect and achieve higher fractional changes in resistance, which will probably be needed to move beyond storing bits to processing them, other phenomena have been discovered that present possibilities for other applications. For instance, the spin-transfer torque is the inverse effect of magnetoresistance, where the flow of a spin-polarized current can affect the internal magnetic configuration of a device [4]. This can be used to excite tunable microwave frequency dynamics in a spintronic nanostructure [5], with many possibilities for new types of radio frequency electronics. Moreover, electron spin is a natural two-state quantum system, making it an excellent candidate for a solid-state qubit [6].

A very comprehensive review of the topic of spintronics was given a few years ago by Žutić et al. [7]. A more recent, but much more brief, review of some current highlights was given last year by Bader & Parkin [8]. In this Theme Issue we look to the future, with some (we make no attempt to be exhaustive) of the new research directions being explored at present being reviewed by some of their best recognized practitioners. Each paper also gives some outlook to the future of the field.

2. Historical context

The field of spintronics was recently recognized by the award of the Nobel Prize in Physics for 2007 to Albert Fert and Peter Grünberg for their independent discoveries of the giant magnetoresistance (GMR) in Fe/Cr multi-layers [9,10]. Although the physics of spin-polarized transport in Stoner ferromagnets had been understood for many years at this point [11], their study had been restricted to bulk materials until the development of the molecular beam epitaxy (MBE) deposition technique gave rise to the ability to make magnetic nanomaterials engineered to atomic precision. The GMR is widely considered the first spintronic effect, even though the anisotropic magnetoresistance (AMR) [12] and anomalous Hall effect (AHE) [13] are effects that have been known since the nineteenth century that rely, ultimately, on the presence of spin-polarized currents for their explanation. The epithet ‘giant’ arose since the fractional change in resistance in these materials could be orders of magnitude larger than in the AMR.

Electron tunnelling through barriers made in thin film form can be traced back to the early 1960s. Giaever [14] first used a thin insulating barrier to probe the density of states in a superconductor and demonstrated the Bardeen–Cooper–Schrieffer (BCS)-predicted field dependence of the single particle gap. The results
were so important that Giaever received a Nobel Prize and for many years the technique was known as Giaever tunnelling. Probably the first application to magnetic films was that of Tedrow & Meservey [15] nearly a decade later. They pioneered the use of Giaever tunnelling with ferromagnetic electrodes such as Ni by showing that the Zeeman splitting of the BCS density of states could be used to extract values of the polarization. As the controversy ensued over the low values of polarization found for Ni (only a few per cent), centring on the extent of $s$ compared with $d$ electron contributions to the tunnelling current, a short paper was published by Julliere [16]. This paper is remarkable because it elegantly, and now famously, links the tunnelling conductance to the polarization of the electrodes and the fact that it has three times as many citations as there are words in the paper. Interest in tunnelling magneto-resistance (TMR) soared after the discovery by Moodera et al. [17] and Miyazaki & Tezuka [18] of room temperature values of the TMR of several per cent. These results indicated that new devices based on tunnel junctions might be possible and are directly linked to the TMR read head in hard discs and MRAM that are in use today. To make such applications possible, these first experiments were refined by people such as Gallagher et al. [19] and Parkin et al. [19,20] until TMR values of several 10s of per cent were possible. The understanding was that the amorphous aluminium oxide played no role in the tunnelling process other than to provide a barrier to metallic conduction. However, after the publications by Butler et al. [21] and Mathon & Umerski [22], the barrier became the most interesting element of a magnetic tunnel junction. The ideas they proposed had their origins in earlier work on coupling and transport in metallic multi-layers. Band matching at the interface between epitaxial materials became an interesting topic at the height of GMR. It was shown that the transmission coefficients for transport across the interface depend on the band matching and if the matching was better for one spin state than the other, then the transmission would be higher for that spin state. This effect was an example of spin filtering and both authors predicted a very efficient spin filtering that would exist at the interface between crystalline electrodes and insulators, in particular between epitaxial Fe and MgO. The experimental evidence for the predictions soon followed with examples of MBE-grown Fe/MgO from Yuasa et al. [23] and CoFe/MgO sputtered junctions from Parkin’s group at IBM [24]. By concentrating on improving the quality of the interface, the homogeneity of the barrier and the crystal orientation of the materials, TMR of 600 per cent has been realized. The promise of greater than 1000 per cent was thought to be fulfilled [25], albeit in a double-junction structure of CoFeB/MgO; however, in a sobering message to us all, the authors fell victim to an artefact of measurement electronics and have retracted [26] the original paper.

The ratio of a magnetic moment to its angular momentum is known as the gyromagnetic ratio and has been known to us since 1915 through the Einstein–de Haas effect and its reciprocal, the Barnett effect. When the moments of a magnet are aligned, there is a net change in angular momentum and, in the absence of an external torque, it will be conserved. This can be observed by, for example, magnetizing a rod along its length when suspended by a light string, whereupon it will rotate. The modern equivalent of this effect was predicted by Berger [27] and independently by Slonczewski [4], both of whom considered the consequences of the transfer of the angular momentum carried by a spin-polarized current to the...
magnetization of a thin film. Interestingly, both authors suggested a dynamical effect in which, should the current density be large enough, the magnetization of the film could be excited and emit spin waves. The first paper to test these new ideas was that of Tsoi et al. [28], who used a point contact to obtain the high current density needed to excite spin waves, which they observed in the resistance of the magnetic multi-layer. However, it was apparent that the effect of spin transfer torque could be used to reverse a magnetic element without the need for an external applied field; this promise for applications was seized upon by a number of authors, but significantly Buhrman’s group at Cornell University stole the march with papers that demonstrated the possibilities for two significant technological advances: moment reversal by spin transfer torque [29] and microwave emission generated by spin currents [5]. The former has progressed over time to offer very interesting applications, including the reversal by pure spin currents. The latter is the subject of intense research where the outstanding problem to be solved is that of coupling many nanomagnets together to realize power in the emission of microwaves.

3. New materials for spintronics

The ferromagnetic three-dimensional elements Fe, Co and Ni are the basis of all spintronic (and indeed almost all magnetic) technology. They are the only three elements to display ferromagnetic order at room temperature. In the first part of this Theme Issue, some of the most promising materials systems for the future are discussed. In the opening paper, Oogane & Mizukami [30] discuss the remarkable recent progress in the preparation of devices based on Heusler alloys. Predicted long ago, on the basis of electronic structure calculations, to possess the perfect spin polarization that is the defining characteristic of the half-metal [31], there have been extensive experimental efforts to realize this in a thin film suitable for a spintronic device. The extreme sensitivity of the spin polarization to defects in the ordered crystal lattice of these compounds has made this a long and arduous search, but excellent progress has recently been made.

Molecular and organic electronics is another very promising research area in its own right, and given the fact that carbon is a light element, and hence has a weak spin–orbit interaction—permitting long spin lifetimes—carbon-based systems are very promising as a platform of spintronic devices. Spin transport in carbon nanotubes [32] and graphene [33] has been demonstrated but the effects are difficult to realize reliably and such materials are far from being manufacturable at present. On the other hand, with organic light-emitting diodes already in widely available products, such as smartphone displays, the molecular approach to carbon-based electronics offers great promise. In this Theme Issue, Bergenti et al. [34] review the remarkable progress that has been made along these lines in the last few years.

Ferromagnetism is not the only type of spontaneous (‘ferro’) order that appears in nature [35]. Ferroelectricity and ferroelasticity are the most common examples. Multiferroics are materials that exhibit more than one type of order simultaneously. A magnetoelectric material has coupling between the magnetic and ferroelectric order parameters: not necessarily the same thing as a multiferroic. Velev et al. [36] review the prospects for these materials
in spintronics here. Of particular interest is the potential for being able to manipulate magnetization using electric fields, which will represent a significant energy saving over conventional approaches that require electric currents with their associated Joule heating [37].

Last in this part of the Theme Issue, MacDonald & Tsoi [38] review the prospects for the use of antiferromagnets in spintronics. Although naively one might suppose that the lack of a ferromagnetic spin polarization would prevent any spintronic phenomena from being possible, after a proper consideration of the elements of microscopic theory this turns out not to be the case. Nevertheless, there is little experimental progress in this area to date, although the lack of a ferromagnetic moment would mean that antiferromagnet-based spintronic devices would be robust against stray fields and could be densely packed owing to the lack of magnetic cross talk.

4. Physical phenomena

The reason to study new materials is to access new physical phenomena on which device functionality may be based. In the second part of this Theme Issue describes some of these. Computing performance typically means speed: how quickly may information be processed? In the context of spintronics, this involves answering the question ‘How fast may the magnetization state be changed?’ Magnetic moments arise from the angular momentum of moving electronic charges, and so torques must be applied to supply or extract the angular momentum needed to change magnetic states, which may only be done at a finite rate. The field of ultrafast magnetization dynamics is explored in the article by Keatley et al. [39], in which the ultimate speed limits on the operation of spintronic devices are considered.

The simplest spintronic devices are essentially one-dimensional, with the current flowing through each element in series. Moving to two-dimensional devices brings a new twist to proceedings, since spins may diffuse away from regions where they accumulate even if there is no electrical current flowing in that part of the circuit owing to charge drift. This allows the generation of pure spin currents that flow in the absence of any charge current, at least in that circuit branch [40]. Here, Otani & Kimura [41] review the various novel phenomena that may be accessed by these pure spin currents, and the ways they may be detected.

Torques on the magnetization induced by a spin-polarized current have been extensively studied in the past decade or so in the context of spin-transfer torques [42], where angular momentum is extracted from a spin-polarized current in order to excite magnetization dynamics such as switching or domain wall movement. Nevertheless, other torques exist, as was recently demonstrated by Miron et al. [43], who showed that an additional torque owing to Rashba spin–orbit coupling can reverse magnetization under the influence of a current. Here, Gambardella & Miron [44] review the foundations of this effect and look to its potential in the future.

Everything discussed up to this point concerns spin-polarized currents that contain very large numbers of spin-polarized carriers. The polarization of the current is defined as an average over all these carriers and is essentially a classical vector: the quantum character of the spin is lost. The last topic to be reviewed

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in this section is single electron spintronics, discussed by Dempsey et al. [45]. Here, the phenomenon of Coulomb blockade [46] is combined with ferromagnetic device components to manipulate spin-polarized carriers one by one. As well as giving rise to novel Coulomb blockade-related magnetoresistance phenomena, this ability to manipulate single spins in a circuit is an essential prerequisite for an electrically addressable spin qubit.

5. Devices and system architectures

In the last part of this Theme Issue, we look at the ways in which these ideas from physics and materials science may be exploited by the spintronic engineer to construct useful devices that can form part of a useful system. A review of various alternatives to hard drive technologies for mass storage, including MRAM, spin-transfer torque RAM and racetrack memory, has recently been given by Kryder & Kim [47]. They concluded that, without further research, hard discs would not be replaced for this purpose, although spintronic technologies were among the best candidates to do so with further development. Essentially this relies on addressing the high cost per bit of MRAM by moving to more advanced architectures such as the racetrack memory concept [48].

Hence, spintronics is well established in the arena of storing bits [49], yet the ability to use it to perform logic operations on them is still at an early stage, as all laboratory realizations of spintronic logic gates have used spin only as an internal state variable: conversion back to charge, involving amplification, prevents direct concatenation of gates (although proposals exist, such as that of Behin-Aein et al. [50], to overcome this problem). Nevertheless, the prospect of success may allow conventional computer architectures to be made faster, denser or more power efficient. On the other hand, spintronics can open up completely new opportunities, such as combining the storage and logic functions in the same device, allowing the construction of a so-called ‘chameleon processor’ that can constantly re-optimize itself for the computation at hand [51]. Another possibility is the spintronic memristor proposed by Wang et al. [52]. The memristor is the fourth passive circuit element, and has applications in memory [53] and novel forms of logic [54], including neuromorphic computing [55].

The magnetic nanopillar, in which current flows vertically through a multilayer stack, is a prototypical device geometry for current-perpendicular-to-the-plane GMR [56] and magnetic tunnel junction structures [17] as well as more elaborate devices such as those used in superconducting spintronics [57]. The topic of nanopillar fabrication and measurement, as well as the various phenomena that can be studied with them, are reviewed here by Blamire et al. [58].

The natural counterpart to the vertical nanopillar is the lateral magnetic nanowire. As well as being the basis of the lateral version of the racetrack memory [48], networks of such nanowires have been shown to be capable of performing Boolean logic [59], albeit in an implementation driven by a magnetic field (a NOT gate based on current-induced motion has recently been demonstrated [60]). The field of nanowires and domain walls is reviewed here by Hrkac et al. [61], who discuss memory, logic and more exotic applications such as nanowire-based cold atom circuits.

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No discussion of the future of information technology is complete without a discussion of quantum computing. Although quantum information science was once an obscure mathematical discipline, the invention by Shor of a quantum algorithm that can factor a large prime number in polynomial time (offering the prospect of breaking public key encryption schemes) caused it to become one of the most vibrant fields in the physical sciences [62]. Quantum information is represented by qubits (quantum bits), which are two-level quantum systems, of which the spin-$\frac{1}{2}$ of an electron is a canonical example [63]. In this Theme Issue, the efforts to build solid-state spin qubits are reviewed by Ardavan & Briggs [64]. In order to build a useful quantum computer, the qubits must be assembled into a system that satisfies the DiVincenzo criteria [65], each of which have arguably been satisfied individually for spin qubits: the outstanding challenge is to design a computer architecture that meets them all simultaneously.

6. Closing remarks

Although over two decades have elapsed since the discovery of the GMR, the field of spintronics remains in good scientific health. As we show here, new materials, phenomena and device concepts are constantly being found, and it is safe to predict that this Theme Issue can only be a snapshot of some of the most promising directions at the present time. Moreover, it is a field that has delivered one of the most commercially successful nanotechnologies to date, transforming the data storage industry into something unrecognizable from that which existed in the pre-GMR days. The pressing need for ‘more than Moore’ approaches to computing as CMOS approaches its fundamental limits, the world’s seemingly insatiable demand for digital data, both in consumer’s pockets and in the cloud, and the tantalizing prospect of quantum information technologies mean that it is not only the endlessly fascinating intellectual qualities of the topic that attract researchers. Indeed, one of the great pleasures of working in this field is the ability to push back the frontiers of physics while also making breakthroughs that can have an impact on multi-billion dollar global industries.

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