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JAPAN PRIZE

Commemorative Lectures

13:00-16:00, Wednesday, April 18, 2007
Keidanren Kaikan

2007 (23rd) Japan Prize Laureate

Prof. Albert Fert (France)
University of Paris-South
Born in 1938

Achievement:
The discovery of Giant Magneto-Resistance(GMR) and its contribution to development of innovative spin-electronics devices

Origins, Development and Future of Spintronics

Spintronics is a new field in research and technology at the interface between electronics and magnetism. It can be described as a new type of electronics exploiting the influence of the spin on the conduction properties of electrons. The roots of spintronics are in early works on the spin dependence of the conduction in ferromagnetic metals. However, its real start was only in the mid-eighties, when it became possible to fabricate magnetic multilayers composed of layers thinner than a few nanometers. This led to the discovery of the interlayer exchange coupling by Peter Grünberg in 1986 and finally, in 1988, to the discovery of the Giant Magnetoresistance (GMR). It turned out rapidly that the GMR not only could lead to important applications, but also was opening a new field of physics full of other transport phenomena induced by the spin of the electrons. Today this field is called spintronics. In my talk I will review the history of spintronics, with a particular focus on its roots and on the nascent directions of today.

The different electrical conductivities of electrons having different spin orientations (parallel to the magnetization or in the opposite direction) in a ferromagnetic has been first proposed by Mott to explain the variation of the conductance around the Curie temperature. At the end of the sixties, this was confirmed by series of experiments which also showed that very large differences between the conductivities of the "spin up" and "spin down" channels could be obtained by doping the ferromagnets with impurities of strongly spin-dependent scattering cross-sections. As a matter of fact, some experiments with metals doped with impurities of opposite spin asymmetries were already anticipating the concept of GMR. Then, in the mid-eighties, it became possible to fabricate multilayers of good quality and this led to the experiments on Fe/Cr multilayers which revealed the existence of interlayer exchange couplings and the GMR. Rapidly, the research on GMR became very active. In his commemorative lecture, Peter Grünberg will describe the main stages of this research, and in particular the development of the so-called spin valve structures which are now used in the read heads of the hard discs and in various devices.

Another important phenomenon in spintronics is the Tunnelling Magnetoresistance (TMR) of the Magnetic Tunnel Junctions(MTJ) which are tunnel junctions with ferromagnetic electrodes. The resistance of MTJ are different for the parallel and antiparallel magnetic configurations of their electrodes, which is now used to store the information in a new type of magnetic memory called MRAM (Magnetic Random Access Memory). The research on the TMR is currently very active and an important recent step was the transition from MTJ with amorphous tunnel barrier (alumina) to single crystal MTJ and especially MTJ with MgO barrier. A single crystal barrier filters the symmetry of the tunnelling wave functions, so that the TMR depends on the spin polarization of the electrodes for the selected symmetry and can be very high. Another promising direction is the research of highly spin-polarized materials called half-metals.

The study of the spin transfer phenomena is one of the most promising new fields of research in spintronics today. In spin transfer experiments, one manipulates the magnetic moment of a ferromagnetic body without applying any magnetic field but only by transfer of spin angular momentum from a spin-polarized current. The concept has been introduced by John Slonczewski and can be used either to switch a magnetic moment (memory cell for example), or to generate oscillations in the microwave frequency range. The spin transfer will be certainly used for the writing process in the next generation of MRAM. It will be also used for the development of STNOs (Spin Transfer Nano-Oscillator), a promising new type of high frequency oscillator. An important challenge of today, to obtain devices with a sufficient microwave power, is the synchronization of a large number of STNO, which raises interesting new problems of non-linear dynamics.

Spintronics with semiconductors is also very attractive as it can combine the potential of semiconductors (control of current by gate, coupling with optics, etc) with the potential of the magnetic materials (control of current by spin manipulation, non-volatility, etc). Several ways are followed. The first is with hybrid structures associating ferromagnetic metals with semiconductors. To solve the so-called "conductivity mismatch" problem, a spin-dependent interface resistance, typically a tunnel junction, is necessary for the injection/extraction of a spin-polarized current into/from a semiconductor at the interface with a ferromagnetic metal. Spin injection/extraction from metals through a tunnel contact has been now demonstrated, in spin LED. Another way is based on the fabrication of ferromagnetic semiconductors. GaMnAs has revealed very interesting properties, namely the possibility of controlling the ferromagnetic properties with a gate voltage, and also large TMR and TAMR (Tunnelling Anisotropic Magnetoresistance) effects...However its Curie temperature below room temperature rules out most practical applications. Several room temperature ferromagnetic semiconductors have been announced but the situation is not clear on this front yet. The research is now very active on a third way exploiting spin-polarized current induced by spin-orbit effects.

A recently emerging direction is spintronics with molecules. Very large GMR- or TMR-like effects are predicted by theory. Experimentally, a recent publication has shown that spin information can be transformed into large electrical signals using carbon nanotubes between spin-polarized electrodes. An advantage of carbon-based molecules is their long spin lifetime related to the weak spin-orbit coupling of carbon. Graphene-based devices are also very promising.

In less than twenty years, we have seen spintronics increasing considerably the capacity of our hard discs and getting ready to enter the RAM of our computers or the microwave emitters of our cell phones. Spintronics with semiconductors or molecules is also very promising. Another perspective, out of the scope of this lecture, might be the exploitation of the truly quantum mechanical nature of spin and the long spin coherence time in confined geometry for quantum computing in an even more revolutionary application. Spintronics will certainly take an important place in the technology of our century.

Prof. Dr. Peter Grünberg (Germany)
The Research Center of Solid State Physics
Born in 1939

Achievement:
The discovery of Giant Magneto-Resistance(GMR) and its contribution to development of innovative spin-electronics devices

Spin-Transfer Phenomena in Layered Magnetic Structures

Magnetic materials and particularly magnetic films constitute the basis for modern mass data storage and information technology, since the first hard disk drive was introduced in the 1950's. The broad research in the field of thin film magnetism has led to a deeper understanding of the physics of complex magnetic layer systems, laying the foundation for the breathtaking development in magnetic data storage capacity, which we witnessed for the past decades. In the last two decades, we also experienced a change in paradigm. Whereas most of the early work in thin film magnetism was focused on the magnetic properties of the material itself, the last 20 years have seen the interest to center more and more on spin-transport effects. They provide a more direct link to microelectronics, which is reflected in the advent of spintronics, a research field occupied with the exploitation of both charge and spin transport phenomena. The discovery of interlayer exchange coupling (IEC) in 1986 together with the discovery of Giant Magnetoresistance (GMR) two years later triggered a wide range of consecutive experiments on phenomena, which – like IEC and GMR – are based on the transfer of electron spins from one ferromagnetic film into another across a nonferromagnetic spacer.

The basic structures, which we are going to discuss in the following therefore are very similar. There are two ferromagnetic films A and C with magnetizations M1 and M2 separated by a non-magnetic interlayer B. For the films A and C generally only metals are considered, whereas B can be either metallic, semiconducting, or insulating. Various microscopic processes like elastic or inelastic electron scattering, reflection, and/or tunneling can occur during this transition and they can be spin-dependent, i.e. they depend on the orientation of the individual electron spin with respect to the local magnetization acting as a quantization axis.

Depending on the electronic nature of the interlayer material various phenomena are observed, for which the microscopic charge and spin transfer processes mentioned above are operative. In structures with metallic interlayers, oscillatory IEC is found in most cases, and is mainly due to spin-dependent interface reflectivities and multiple interference. Spin-dependent scattering in such fullymetallic structures is the primary mechanism leading to giant magnetoresistance GMR. Pushing the concept of spin-dependent scattering further, however,one arrives at another fascinating aspect. The transfer of spin momentum from one ferromagnetic layer (M_{fixed}) to the other carried by the electric current flowing perpendicular to the interfaces results in a torque on M_{free}. If the current density is high, the magnitude of the spin-transfer torques may be high enough to significantly affect the electrode magnetization. In this way, spintransfer torque can generate microwave magnetic excitations, which constitute current-driven magnetization dynamics. In low fields, current-induced magnetization switching (CIMS) can be observed , where depending on the current polarity the spin-transfer torque aligns M_{free} parallel or antiparallel to M_{fixed}, which is assumed to stay pinned.

For insulating and semiconducting interlayers, however, the situation is different. One observes mostly non-oscillatory IEC due to evanescent electronic states and spin-dependent tunneling processes across insulating barriers yields the tunneling magnetoresistance (TMR) effect as sketched. Nevertheless, CIMS has very recently been observed in structures with insulating interlayers too.

Theoretically the phenomena mentioned above are explained on the basis of spin-dependent transmission and interface reflection of the conduction electrons on their way from layer A to C and C to A across the interlayer B. While this picture is conceptually straightforward, it will be seen that a reliable prediction of the mentioned effects based on the materials parameters of the layers A, B, and C is difficult, if not contradictory in some cases.

In this seminar, we first focus ourselves to IEC in structures with insulating and semiconducting interlayers, review some of our own results for the Fe/Si/Fe system, compare them with data from the literature including metallic interlayers, and draw some conclusions . The structures with Si and MgO interlayers are so far the only ones, where IEC across non-metallic interlayers has been observed. It is surprisingly strong across epitaxially well-ordered Si, where it turns out to be stronger by almost one order of magnitude than even for most metallic interlayers. On the basis of current theories, one would expect from this finding also a strong TMR across Si barriers. However, the tunneling magnetoresistance turns out to be virtually nonexistent. On the other hand, MgO interlayers sandwiched between well-ordered or textured Fe with (100) orientation provide weak coupling and show "giant TMR" in excess of 500%. The discussion of this difference will first be based on free electron models and will then be briefly expanded to coherent tunneling. In this context, we shall also review our own TMR results on structures with films of polycrystalline Heusler alloys and CoFe separated by MgO, where we could obtain a remarkable TMR of 90% at room temperature (RT).

In the following we turn to metallic interlayers. After a brief discussion of GMR, we derive a physical picture of CIMS and compare it to IEC across metallic and insulating barriers. We then present our own results on CIMS in single-crystalline magnetic nanopillars.

Applications of the phenomena treated here are mainly in the area of magnetic information storage but also monitoring the position and motion of tiny little parts up to large vehicles like airplanes. New applications seem to evolve in biomedicine in the detection of antigenes. We will briefly touch on these possibilities.

Dr. Peter Shaw Ashton (United Kingdom)
Charles Bullard Professor of Forestry
Born in 1934

Achievement:
Contribution to the Conservation of Tropical Forest

Fifty years of decline yet fifty years of discovery: Science towards the sustainment of biodiversity

March 2007 marked the fiftieth anniversary of my arrival in Brunei Darussalam, as forest botanist in the late H.H. Sultan Omar's government. It was a dreamed-for experience for a young naturalist: twenty-six out of my thirty six months were spent in the longhouses or under canvas in the vast woods. Then, over 70% of Borneo was covered in primeval, uncut, forest. Now, little remains, even to the mountain tops, except in the national parks - themselves threatened by illegal harvesting, and inaccessible limestone peaks.

Tropical rain forests have declined so rapidly because the value to their owners is as capital to liquidate, but low in the medium term in comparison to tree crops – rubber, oil palm, industrial wood and fibre species. Their value is, rather, to us – to offset our carbon emissions but, more particularly, for their genetic information. It is now well known that tropical rain forests retain more than half the species diversity on land worldwide, and likely a similar proportion of genetic diversity. This genetic diversity is irreplaceable. It will eventually prove vital to its owners, and it is for us now. We are beginning to compensate forest owners for their carbon sequestration but, so far, remain free riders for their genetic information, of which we in the industrialised world will be principal beneficiaries.

Most of biodiversity is comprised of insects and micro-organisms. Their exceptional diversity in rain forests is due to their co-evolution with trees, which have evolved a unique diversity of chemical defenses, of potential pharmaceutical and other value. Single lowland forests in Borneo may include over one thousand tree species, more than three times those of North America and matched worldwide only in the western Amazon.

In 1957, the leading tropical botanists, including Dr. E.J.H. Corner and Dr. C.G.G. van Steenis in Asia, considered that this extraordinary tree species diversity, combined with their limited seed dispersal and lack of dormancy, implied that their co-existence was random; and that species associations change like a kaleidoscope over time and space, sustained by their equable and balmy climate. Such co-existence implies that the species are ecologically complementary, with profound implications for speciation and evolution. It also implies that management to favour or sustain individual species, or even groups, is unachieveable. Dr. Stephen Hubbell has substantiated their conjecture, by mathematically demonstrating its plausibility in his Unified Theory of Biogeography. The predictions of the theory are not incompatible with the opposite: that each rain forest tree species possesses at least one attribute by which it competitively succeeds. The theory serves though as a rigorous null hypothesis against which careful empirical observation and experiment can be measured. That has been my life's work. It has been accomplished by collaboration and encouragement, through my good fortune to have had exceptional graduate students and research colleagues and friends, most of them from the Asian tropics and from Japan, without which little could have been achieved.

As I explored Brunei's forested hinterlands, I became familiar with their tree species, especially the hardwood timber dipterocarps which dominate the canopy, and which proved to include 156 species in that small country. I noticed that each hill would possess a distinct species assemblage, repeated on other hills with similar geology and soil. Later, comparative quantitative analysis of species composition from plots in Borneo forests showed that composition varies with soil nutrients and drainage to such an extent that it overrides dispersal-mediated variation in relation to geographical distance, and species change across all but the most formidable geographical barriers.

The critical test of ecological specialization is whether the most closely related species are ecologically similar or distinct, especially those that comprise the series of related species which co-exist in species-rich rain forest tree communities. These most similar species are the most likely to face stringent competition. The test requires long-term observation of species' populations, which requires very large samples in species-rich forests, and experiment. The creation of the regional and global network of large tree demography plots of the Center for Tropical Forest Science has provided both the facility for such tests, and promoted the growth of an international community of researchers with the collegiate spirit so vital for the exchange and diffusion of ideas.

Co-occurring congeneric species studied so far at CTFS sites include species from the understorey, the canopy and pioneers in gaps. All have shown differences in responses either or both to light intensity, soil nutrients and moisture, and stature at reproduction.

These differences notwithstanding, the consistent direct physical competition between individuals of specific species pairs, in hyperdiverse communities of sessile organisms, is impossible. Such competition may instead be mediated by 'mobile links' such as pollinators. Research, on in the crowns of six co-occurring giant dipterocarps of *Shorea* section *Mutica*, has shown that flowering times occur in sequence, thereby inferring interspecific temporal separation which will enhance pollen receipt and lower stigma pollution. Evidence is growing that mortality of juveniles of commoner tree species is correlated with their distance apart, and that this is mediated by host-specific pathogens and predators. We predict that these pathogens, by restricting the long-term population density that rain forest trees can attain, provide the single major means whereby other species can fill the vacant space thereby created, thereby building species diversity.

Our international – and intergenerational – research effort has yielded basic information for sustainable management of the dwindling rain forest. On the one hand, its tree species are now known to be specific both to habitat and niches within their communities. Though limited seed dispersal imposes stochastic patterns at local scale, at a wider scale opportunities do exist for manipulation for given objectives, and for active management. On the other hand, simplifying these complex systems, especially attempts to grow native species in high density plantations, is seen to be fraught with long-term risks and costs.

Awareness of these opportunities and risks will take time to reach policy levels in rain forest-owning nations. It is in your and my interest to invest in the irreplaceable resource that is the genetic library of the tropical rain forest. Nations and cultures - such as that with which Japan is endowed - have demonstrated at home that a benign ethic towards forest is essential if policy is to be implemented. It is now up to all of us to expand that ethic into our international policies and actions. There is little time to spare.

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