Cutting Edge 1

General Report

Semiconductor Spin Electronics

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This paper reviews the basic principles of how spin can be employed in semiconductor electronics, and reports on a number of possible applications of semiconductor spin electronics where progress is currently being made. First we will present an overview of the spin phenomena that occur in III-V ferromagnetic semiconductors and their heterostructures (the starting point for the new development), and in non-magnetic semiconductor quantum wells and nanostructures. We will then discuss optical spin devices such as optical isolators, and electron spin devices such as magnetoresistance elements. Finally, we will review proposals for quantum spin devices that utilize the quantum mechanical nature of spins.

Keywords: semiconductor, spin, ferromagnetic semiconductor, III-V compound semiconductor

1. Introduction

The remarkable developments currently being made in the fields of electronics and information technologies have been made possible by exploiting the properties of electron charge and spin. Integrated circuits used for data processing use the charge of electrons in semiconductors, while data storage media such as hard disks use the spin of electrons in a magnetic material. Recently, various types of spin polarization have been formed in semiconductors, such as carrier spin, spin in introduced magnetic atoms, and nuclear spin of constituent atoms, and it has been shown that new functions can be implemented by injecting, transporting and controlling these spin states. This is resulting in the emergence of a new field—semiconductor spin electronics (or semiconductor spintronics)—involving the use of spin states inside semiconductor materials.

The semiconductors currently used in integrated circuits, transistors and lasers, such as silicon and gallium arsenide (GaAs), are non-magnetic in which the carrier energy is almost independent of the spin direction. However, in nanostructures where devices approach the limits of miniaturization, exchange interactions have more pronounced effects and the presence of spin becomes more tangible. In magnetic semiconductors, which have both properties of magnetic materials and semiconductors, these exchange interactions can give rise to pronounced spin-related phenomena—not just in nanostructures but also in more conventionally sized devices. Advances in materials science has led to the development of ferromagnetic semiconductors based on the III-V compound semiconductors already used for electronic devices,[1,2] and due to progress made in the research of non-magnetic semiconductor quantum structures and nanostructures, it is becoming possible to clearly express and control the degrees of freedom in charge and spin.

Semiconductor spin electronics may be divided into two fields. One might be referred to as *semiconductor magneto-electronics*, where attempts are being made to implement new functions by incorporating magnetic functions into semiconductors by using magnetic semiconductors (semiconductor materials that are also magnetic) or combinations of semiconductors and magnetic materials. For example, it is thought that this field will lead to the realization of semiconductors devices such as optical isolators, magnetic sensors and non-volatile memories that can be integrated into semiconductor devices and circuitry. If the magnetism or spin can be controlled by light or electric fields, then it should be possible to develop entirely new devices having functions that have not been available before.

The other field is probably best referred to as *semiconductor quantum spin electronics*. In this field, the main focus is on using the quantum mechanical nature of spin in semiconductors. For example, since the various types of spins in non-magnetic semiconductors have a much longer coherence time than electrical polarization and can be controlled by light or electric fields, it is comparatively easy to manipulate spin as a quantum-mechanical entity. Such properties lend themselves to the development of solid-state quantum information processing devices. In this way, spin in semiconductors is heralding a new era both in classical and quantum physics and technology.

Section 2 of this paper discusses the new ferromagnetic semiconductors, Section 3 discusses the physical properties of spin in semiconductor structures, and sections 4, 5 and 6 discuss the applications of optical, electronic and quantum devices respectively. Our conclusions appear in section 7.

2. New Ferromagnetic Semiconductors

In this section we will present an overview of the ferromagnetic properties observed in diluted magnetic semiconductor (DMS) materials, where a portion of the atoms in a non-magnetic semiconductor are substituted by magnetic atoms (thus they are called *diluted* magnetic semiconductors). Especially, we will describe the properties of III-V DMS materials.

III-V DMS's exhibit ferromagnetism and provide new degrees of freedom based on the magnetic cooperative phenomena in the semiconductor heterostructures used in transistors and lasers. By using an epitaxially-grown III-V magnetic/non-magnetic heterostructure, it becomes possible to look for new phenomena such as spin-dependent tunneling, magnetoresistance, and spin-dependent light emission. In this sense, it can be regarded as a prototype for semiconductor spin electronics, from which we can learn what can be done by the spin degree of freedom in semiconductors.

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2.1 Diluted magnetic semiconductors

In the 1980s, research in DMS focused mainly on II-VI semiconductors such as (Cd,Mn)Te and (Zn,Mn)Se.[3] In a II-VI semiconductor, the II element is substituted by an equivalent valence of magnetic transition metal atoms, making it possible to achieve a high density of magnetic atoms and to fabricate quantum structures. In a II-VI DMS, the optical characteristics such as Faraday effect are greatly modulated by magnetic fields due to the exchange interaction (*sp-d* interaction) between the *s* and *p* orbitals of nonmagnetic atoms and the *d* orbitals of the magnetic atoms.[3] However, it is generally difficult to control conduction by doping in II-VI semiconductors, which is one of the major obstacles for the use of II-VI semiconductors as electronic materials.

Although II-VI DMS generally exhibit antiferromagnetism, spin-glass and/or paramagnetism properties, as we will discuss later, it was recently reported that a p-doped II-VI DMS undergoes a ferromagnetic transition at low temperatures.[4,5] In IV-VI DMS (Pb,Sn,Mn)Se, ferromagnetism was also observed at low temperatures, which is attributed to the hole-mediated RKKY interactions.[6]

2.2 III-V ferromagnetic semiconductors

The equilibrium solubility of magnetic impurities in III-V semiconductors is low, and under ordinary crystal growth conditions it is impossible to introduce a high density of magnetic atoms. In 1989, Munekata *et al.* used low-temperature molecular beam epitaxy (LT-MBE; deposition temperature approx. 250°C) to achieve non-equilibrium crystal growth, and thereby succeeded in suppressing the surface segregation of Mn and the formation of second phases, allowing them to perform epitaxial growth of an alloy of InAs and Mn, (In,Mn)As on a GaAs substrate.[7] Subsequently, ferromagnetic properties were discovered in p-type (In,Mn)As,[8] and in 1996 the growth of (Ga,Mn)As[9]—a GaAs-based DMS—and ferromagnetic transitions in p-type (Ga,Mn)As were reported.[10] The highest ferromagnetic transition temperature T_c of (Ga,Mn)As obtained so far is 110 K (Mn cocentration x=0.053).[11]

Since (Ga,Mn)As can be epitaxially grown on a GaAs substrate, it is compatible with GaAs/(Al,Ga)As quantum structures. It has therefore become an indispensable material for the study of semiconductor spin electronics, and is being actively researched in recent years.[12-15]

2.2.1 Magnetic properties

The easy axis of magnetization in (Ga,Mn) As grown on GaAs (001) planes is oriented within the plane due to lattice strain.[10] The lattice constant of (Ga,Ma)As is slightly larger than that of GaAs resulting in compressive strain. Using a buffer layer of (In,Ga)As, which has a larger lattice constant than (Ga,Mn)As grown on it, the sign of the lattice strain can be changed to allow the easy axis of magnetization to be oriented perpendicular to the plane.[16]

The ferromagnetic transition temperature can be determined in various ways, such as: (1) the temperature dependence of remanent magnetization, (2) an Arrott plot (M^2-B/M plot) using the magnetic field dependence of the magnetization near the transition temperature, or (3) a Curie—Weiss plot of the magnetic susceptibility in high-temperature paramagnetic regions. These methods all produce almost the same T_C values.[17] The relationship between T_C and x is given by $T_C = 2000x$ K up to around x = 0.053, and further increase of x decreases T_C.[11] The reason for this decrease is not understood. It has been confirmed that (Ga,Mn)As with its easy axis of magnetization perpendicular to the plane has a striped magnetic domain structure like an ordinary ferromagnetic material.[18]

2.2.2 Magnetotransport characteristics

Depending on the Mn composition, (Ga,Mn)As exhibits either metallic conduction or insulator-type conduction.[11,19] Figures 1(a) and (b) show the magnetotransport characteristics (Hall resistance R_{Hall} and sheet resistance R_{sheet}) of a sample with metallic conduction (x=0.053, sample thickness = 200 nm). As Fig. 1(a) shows, the anomalous Hall effect—which is proportional to the magnetization perpendicular to the plane—dominates in (Ga,Mn)As. Since the magnetization is small in a DMS thin film, magnetization measurement using the anomalous Hall effect is better in terms of measurement sensitivity than direct magnetization measurement. The mag-

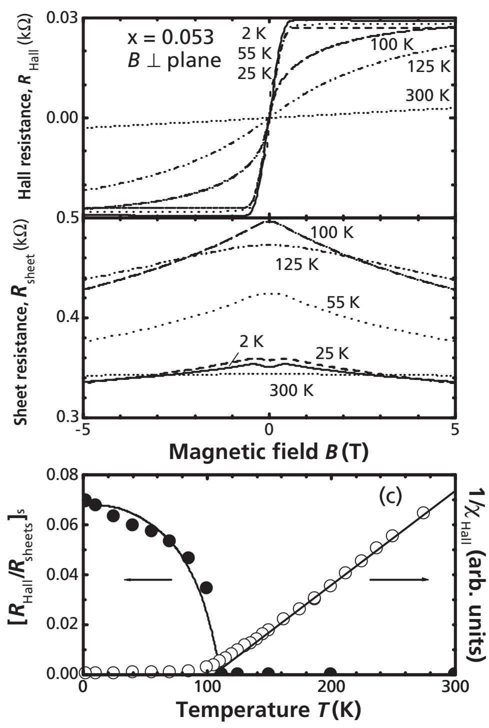


Fig. 1 Magnetotransport characteristics in (Ga,Mn)As (Mn composition x = 0.053, 200 nm thick).
(a) Temperature dependence of the Hall resistance R_{Hall}. The magnetic field B is applied perpendicular to the surface of the sample. The anomalous Hall effect, which is proportional to the magnetization perpendicular to the plane, is predominant. (b) Temperature dependence of sheet resistance R_{sheet}. The resistance value increases due to critical scattering close to the ferromagnetic transition temperature of 110 K. The negative magnetoresistance effect also reaches its maximum near the transition temperature. (c) The temperature dependence of spontaneous magnetization as determined by an Arrott plot of R_{Hall}/R_{sheet}, which is proportional to magnetization (black circles), and a Curie-Weiss plot (white circles). Here, χ_{Hall} is the magnetization ratio determined from the anomalous Hall effect. The solid lines show the results of curve fitting to the temperature dependence of spontaneous magnetization calculated from the Brillouin functions. This figure shows that the ferromagnetic transition temperature is about 110 K.

netization determined by the anomalous Hall effect may be weighted by the conductivity, however.

Using the anomalous Hall effect term, it is possible to determine T_C from the Arrott plot ($T \sim T_c$) and Curie-Weiss plot ($T >> T_c$). Figure 1(c) shows the temperature dependence of the quantity $(R_{Hall}/R_{sheet})_s$ which is proportional to the spontaneous magnetization determined by the former method, from which it can be seen that T_C is 110 K. The value of T_C determined from the transport characteristics agrees well with the value obtained from magnetization measurements.

2.3 Mechanisms of ferromagnetism

2.3.1 A model based on the mean field theory

In a model based on the mean field theory, the temperature dependence of the magnetic susceptibility above the transition temperature is assumed to be given by the Curie-Weiss law, and the *sp-d* interactions are regarded as the effective magnetic field acting on the carrier system. When spontaneous magnetization and holes are present, spin-splitting occurs in the valence band and the energy of the carrier system decreases as a result. At the same time, the spontaneous magnetization increases the free energy of the localized magnetic spins. This free energy penalty decreases with lowering temperature and at a certain temperature the energy gain and loss balances. This is T_C by the mean field model.[20] This is known as Zener ferromagnetism.[21] It should be noted that this is not the same mechanism as the double exchange interaction also proposed by Zener.

We used a 6×6 Luttinger-Kohn hamiltonian that takes *p-d* interactions into account to calculate the carrier energy in the valence band. Only the valence band is taken into account as the conduction of (Ga,Mn)As is p-type. In the calculation for (Ga,Mn)As we assumed the band parameters to be those of GaAs, and we used a value of $N_0\beta = -1.2$ eV for the *p-d* interaction determined from core-level photoemission spectroscopy (N_0 is the density of cation sites, and β is the *p-d* exchange integral).[22] Also, in the calculation, we used an enhancement factor of 1.2 due to the carrier-carrier interaction calculated from the local spin density approximation.[23] The value of T_C calculated in this way agrees well with the experimental value. The value of T_C for (Zn,Mn)Te calculated in the same framework also agrees well with the experimental value. Ferromagnetism is difficult to occur in n-type materials, because of the smaller magnitude of the *s-d* interaction $N_0\alpha \sim 0.2$ eV (where α is the *s-d* exchange integral) of DMS. The fact that the easy axis of magnetization of (Ga,Mn)As is strain-dependent and the peculiar temperature dependence of magnetic circular dichroism[24] can also be explained in terms of the valence band structure using this model. On the other hand, it has been pointed out that other factors such as low energy spin-wave excitation and disorder must be considered when calculating T_c.[26]

2.3.2 Models based on d-electrons

By first principle calculation of the electronic states of (In,Mn)As, Akai showed that when holes are present, the half-metallic ferromagnetic state becomes stable. He discussed the ferromagnetism being as a result of double exchange interactions caused by hopping of *d* holes.[27]

First principle calculation also has shown that the ferromagnetic state is stable in a hypothetical zincblende GaAs/MnAs superlattice. Again, the half-metallic state is predicted.[28, 29] The double resonance mechanism is also proposed for the ferromagnetism of (Ga,Mn)As, from the electronic state calculated by the tight-biding approximation.[30]

2.4 Room-temperature ferromagnetic semiconductors

Here we discuss the factors that should be considered in order to achieve T_C higher than room temperature. According to the mean field model, it is first essential to increase the density of magnetic atoms x and the hole density p (and it is also necessary to satisfy $x>p$).[25] For example, in (Ga,Mn)As, if a hole density of $p=3.5\times10^{20}$ cm^{-3}, which is achieved in the x=0.053 sample, can be obtained, then it should be possible to achieve a T_c beyond room temperature by increasing the Mn density to x=0.15. Assuming it is possible to achieve a magnetic atom density and hole density similar to those of (Ga,Mn)As, then a high T_c is expected in wide-gap semiconductors such as GaN or ZnO. This is because of the light mass of the constituent elements and the small lattice constant, which result in a small spin-orbit interaction, a large effective carrier mass, and a large *p-d* exchange interaction ($N_0\beta \propto 1/a^3$, where a is the lattice constant).[25]

First principle calculations have shown that ferromagnetism is stable in a DMS based on a wide-gap semiconductor. When ZnO is doped with a high concentration of a transition metal, doping with Mn results in antiferromagnetism (or ferromagnetism if simultaneously doped with holes), while V, Cr, Fe, Co and Ni result in half-metallic ferromagnetism, and Ti and Cu result in paramagnetism.[31] The first-principle calculation also shows that the ferromagnetic state is stable for V, Cr, or Mn doped GaN.[32]

A modulation-doped superlattice structure has been proposed in which a well is formed by a II-V DMS (Cd,Mn)Te, in which the host atoms can be replaced by a high density of magnetic atoms, and a barrier is formed by the C-doped III-V semiconductor AlAs. It has been shown by first principle calculation that holes supplied from carbon acceptors accumulate in the (Cd,Mn)Te well, making the ferromagnetism stable.[33]

2.5 II-VI and other ferromagnetic semiconductors

Advances in techniques for doping in II-VI semiconductors have made it possible to achieve carrier densities in excess of 10^{19} cm^{-3}.[34] Shortly after a theory of ferromagnetic transition based on *p-d* exchange interactions was put forward,[35] ferromagnetism was observed below 1.8 K in modulation doped $(Cd_{0.975}Mn_{0.025})Te$ quantum well (8 nm, $p=2\times10^{11}$ cm^{-2}).[4] It has also been observed that a ferromagnetic transition takes place in a thin film (about 500 nm thick) of $(Zn_{1-x}Mn_x)Te$ and $(Be_{1-x}Mn_x)Te$ (where $x\leq0.1$) with $p = 10^{19}$-10^{20} cm^{-3} ($T_c <$ 3 K).[5,36]

A succession of recent reports have mentioned ferromagnetic transition temperatures above room temperature—320 K in a II-IV-V_2 chalcopyrite $(Cd_{1-x}Mn_x)GeP_2$,[37] 290-380 K in (Zn,Co)O,[38] room-temperature ferromagnetism in TiO_2:Co,[39] and over 400 K T_C's in CrAs and CrSb with a zinc-blende structure.[40] There is little doubt that further advances will be made in the future.

3. Spin Properties in Non-Magnetic Semiconductor Structures

Along with the developments in ferromagnetic semiconductors, great progress in understanding and manipulating spin properties in non-magnetic semiconductor structures have also been made over the last decade. This section describes important aspects of spin-dependent phenomena in non-magnetic semiconductors that are essential for utilizing electronic and nuclear spin degrees of freedom, which involve spin relaxation and spin injection in quantum structures, spin-dependent transport, and spin coherence.

3.1 Spin relaxation in quantum structures

Carrier spin relaxation in semiconductors has been studied both theoretically and experimentally,[41)] and in recent years the spin relaxation times have been extensively studied by time-resolved optical measurements using femtosecond pulse lasers. Major spin relaxation mechanisms in semiconductors include spin-orbit interactions originating from the lack of the inversion symmetry (the D'yakonov—Perel' effect), band-mixing (the Elliott—Yafet effect), and electron-hole exchange interaction (the Bir—Aronov—Pikus effect).[41)] The relative importance among these mechanisms depends not only on such material properties as the spin-orbit coupling and the fundamental band gap, but also on parameters as dimension, temperature, kinetic energy, scattering time, and doping.

In a quantum structure, the degeneracy of light and heavy holes is lifted, and it is thus possible to achieve 100% spin-polarized carriers by resonant excitation of electron-heavy hole exciton with circularly polarized light. The introduction of quantum confinement also modifies such factors as mobility,[42)] symmetry,[43-45)] excitonic effects,[46)] locality,[47)] and doping[48)], resulting in a significant change of the spin relaxation process. In GaAs, for example, the reported electron spin relaxation time are distributed over a wide range from a few ps to several tens of ns.[49)] In particular, the D'yakonov-Perel' effect (which predominates at room temperature) depends strongly on the crystallographic orientation of the growth direction.[45)]

3.2 Injection of spin into semiconductors

Spin injection is a critical requirement for the development of spintronics.[50-52)] Schmidt *et al*. analyzed the spin injection in a ferromagnetic metal/two-dimensional electron (semiconductor)/ferromagnetic metal structure in a diffusive regime, and pointed out that since the semiconductor parts—where the electrical conduction is not dependent on spin—have high resistance, the overall change in resistance is very small when the magnetization of the ferromagnets is changed from parallel to anti-parallel. According to this model, it is difficult to achieve efficient spin injection into semiconductors in a diffusive regime unless the degree of spin polarization in the ferromagnetic metal is close to 100%.[53)] (Rashba pointed out that the use of tunnel junction for spin injection can be used to overcome the difficulty associated with the diffusive transport.[53)])

On the other hand, since magnetic semiconductors can be grown epitaxially on semiconductors and their conductivity is of a similar order to that of non-magnetic semiconductors, it is expected that highly efficient spin injection and a large magnetoresistance can be obtained when they are used as spin polarizers and spin analyzers. The injection of spin in p-n junctions using magnetic semiconductors has recently been confirmed by measuring the polarization of the light emitted as a result of the recombination of the injected spin-polarized electrons (holes) and unpolarized holes (electrons).[54-56)] We have fabricated a light-emitting p-n diode consisting of an (In,Ga)As quantum well sandwiched between a p-type ferromagnetic semiconductor (Ga,Mn)As and n-GaAs, as shown in Fig. 2(a). As Fig. 2(b) shows, we observed hysteresis in the degree of polarization of the emitted light at temperatures below the T_c of (Ga,Mn)As, and confirmed that spin injection takes place in a zero field.[55)]

3.3 Spin-dependent transport characteristics in quantum dots

In quantum dots where the electron transport is dominated by the Coulomb blockade, it is possible to control the number of occupying electrons (even or odd) by varying the gate voltage.[57)] In such few electron systems, spin (magnetism) plays a predominant role in the transport properties via exchange interaction. This behavior is expected to prove useful for functions such as spin filters and spin memories.[58,59)] Recently, exchange interactions between a quantum dot with a controlled spin state and an electrode (the Kondo effect) have also been observed.[60,61)]

3.4 Spin coherence

When a magnetic field is applied perpendicular to the carrier spin, the spin undergoes Larmor precession about the field. The dynam-

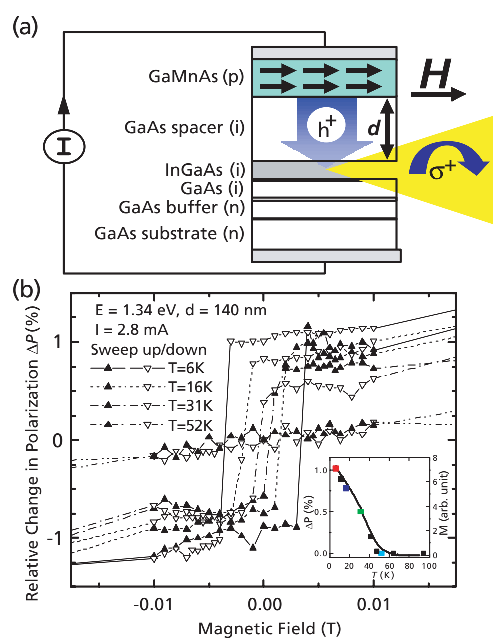
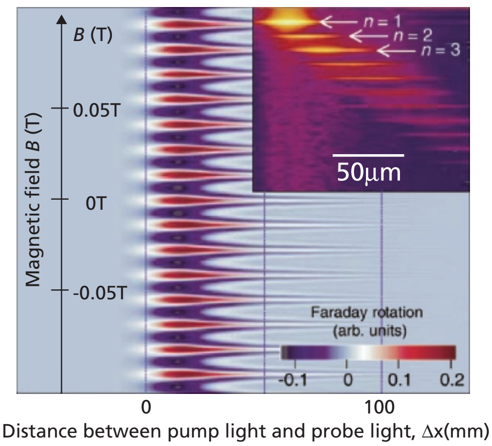


Fig. 2 Injection of spin-polarized holes into a light-emitting p-n diode using a ferromagnetic semiconductor (Ga,Mn)As. (a) Sample structure. Spin-polarized holes h+ travel through the non-magnetic GaAs and recombine with spin-unpolarized electrons in the (In,Ga)As quantum well. *I* represents the current, and σ+ represents circularly polarized light emitted from the edge of the quantum well. (b) The dependence of the polarization ΔP of the emitted light on the magnetic field *B* at each temperature. The solid and hollow symbols represent the degree of polarization when the magnetic field is swept in the positive and negative directions, respectively. The magnetic field was applied parallel with the easy axis of magnetization of the (Ga,Mn)As. The inset depicts the temperature dependence of the residual magnetization *M* in (Ga,Mn)As, where the degree of polarization of the zero magnetic field seen in the emitted light (squares) exhibits the same temperature dependence as the magnetization.

Fig. 3 Coherent transport of spin packets when an electric field is applied to n-GaAs,[65] according to the time-resolved Faraday rotation measurements. The vertical axis shows the magnetic field B, and the horizontal axis shows the distance Δx between the pump light and the probe light. The measurements were made at 1.6 K. The excited electron spins precess about the magnetic field, and a large rotation angle (i.e. spin polarization) is observed when the period of this precession matches the period Δt of the excitation pulses. At time t, the spin phase of electrons excited by the nth pulse is given by $\omega(t+n\Delta t)$, where ω is the Larmor frequency. The inset shows the electron spin components generated at Δx, n periods previously (i.e. at $t-n\Delta t$).



ics of carrier spin in semiconductors has been investigated by time-resolved optical measurements of the temporal development of the precession.[62,63] Kikkawa *et al*. have shown that the spin relaxation time can be extended to 100 ns in bulk n-GaAs with a doping density of 10^{16} cm^{-3},[64] and have demonstrated that spin can be transported over macroscopic scales of 100 μm without loss of coherence, as shown in Fig. 3.[65] Also, Malajovich *et al*. have shown that spin coherence can even be transported across semiconductor junctions with different band gaps and g values, such as GaAs/ZnSe heterojunctions.[66]

It has been shown that electron spin coherence is maintained for periods of at least a few nanoseconds in n-type ZnCdSe/ZnSe quantum wells,[67] in GaAs/AlGaAs (110) quantum wells,[68] and in GaN,[69]. These observations raise the possibility of application of confined electronic states to spin memory and nuclear spin manipulation.

3.5 Interaction between carrier spin and nuclear spin

To design and implement a solid state quantum computer that uses nuclear spin as a quantum bit, it is necessary to clarify the dynamics of interaction between electron spin and nuclear spin. So far, in semiconductors and its quantum structures, electron spin polarization have been measured to investigate the hyperfine interaction involving the Overhauser effect and the Hanle effect,[41,70,71] and over the last few years more light has been shed on the dynamics of the Overhauser effect from the time-resolved pump-probe measurements.[72-74]

4. Optical Spin Devices

4.1 Optical isolators

Light with a wavelength of 0.98 μm is going to be used for the excitation of the latest erbium-doped optical fiber amplifiers that support internet backbones. This wavelength region is absorbed by iron, so it is not possible to use conventional garnet single-crystal optical isolators. Semiconductor optical isolators based on a II-VI DMS, (Cd,Mn)Te, which has low absorption and a large Faraday rotation, is being developed. Since a II-VI DMS is paramagnetic at room temperature, a magnetic field is needed to obtain Faraday rotation. A Verdet's constant of 0.05 deg/Oe·cm is currently achievable at 0.98 μm using (Cd,Mn,Hg)(Te,Se). In this case, an insertion loss of 0.8 dB can be achieved at the module level. This is the first commercially available semiconductor spin electronics device.[75]

4.2 Integrated optical isolators

When the bandwidths of network reach Gb/s at the end users, it becomes necessary to integrate lasers and isolators using the same semiconductors to realize high-performance low-cost devices. Magnetic semiconductors based on III-V compounds, such as (Ga,Mn)As, (In,Mn)As and their mixed crystals, can be integrated together with GaAs- and InP-based lasers, and have a large Verdet's constant of a similar order to that of II-VI isolators near the band edge,[76] and are thus promising materials for use in integrated optical isolators.

It is also possible to increase magneto-optical activity by introducing fine particles of MnAs (semimetal), which is ferromagnetic at room temperature, into thin films of GaAs.[77] Magneto-optical effects can further be enhanced by incorporating one-dimensional semiconductor photonic crystals.[78] Model calculations have shown that the resulting Faraday effect is determined by the loss associated with the MnAs fine particles and the confinement of the electromagnetic field by the photonic crystal.

The fabrication of (Cd,Mn)Te magneto-optical waveguides on GaAs substrates has also been reported,[79] and it has been confirmed that the waveguide mode can be changed by varying the external magnetic field.[80]

4.3 Ultra-fast optical switches

Tackeuchi *et al*. were the first to apply circularly polarized pump probe methods for the measurement of spin relaxation in semiconductor quantum structures, and have shown that the spin relaxation time of an AlGaAs/GaAs quantum well is 32 ps.[81] When spin polarization is generated in a quantum well by an external light, the absorption for right and left circularly polarized light changes while the polarization is present. By using this effect to extract optical signals only when spin polarization is present, very fast optically controlled gate switches can be constructed. In particular, in quantum wells containing different V atoms between barrier and well, such as InGaAs/InP quantum wells, the spin relaxation time is no more than a few ps at room temperature. It has also been shown that ultrafast optical switching can be achieved entirely optically by optically extracting the difference between left and right circularly polarized light components.

4.4 Photoinduced magnetism

Koshihara *et al*. showed that ferromagnetism can be induced by photogenerated carriers at low temperatures in heterostructures made of magnetic semiconductor (In,Mn)As and non-magnetic semiconductor GaSb.[83] This effect is illustrated in Fig. 4(a) and (b). Since the (In,Mn)As layer is only 12 nm thick, the incident light is absorbed by the GaSb layer, where it produces electron-hole pairs which are split by the internal electric field, causing the holes to accumulate in the (In,Mn)As layer at the surface. Since (In,Mn)As exhibits hole-induced ferromagnetism, the holes generated by the incident light cause a transition to a ferromagnetic state by presetting the hole density in the (In,Mn)As film so that it is already on the point of becoming ferromagnetic. Although this mode of operation is only achieved at low temperature, it opens up a range of new possibilities and is attracting considerable interest as a result.

On a related theme, Haneda *et al*. have grown GaAs with Fe particles, and have observed optically induced magnetization at room temperature.[84] Akinaga *et al*. have discovered optically-induced magnetoresistance effects at room temperature in a structure where granular MnSb crystals are grown on a GaAs (111)B substrate and capped with GaAs.[85]

It should be noted that if a magnetic semiconductor laser can be produced, then it will be possible to vary its wavelength by an external magnetic field. For example, the wavelength of an optically excited (Cd,Mn)Te multiple quantum well laser has been shown to shift to lower energies at a rate of 3.4 meV/T.[86] If a large effective g value is achieved at room temperature in an active layer of semiconductor lasers, then such devices should find a number of applications starting in the field of spectroscopy.

5. Electron Spin Devices

The large magnetoresistance effect arising from spin-dependent scattering in multilayered films of magnetic metals[87] is now being used in the magnetic read heads of hard disks. A large tunnel magnetoresistance is also obtained in tunneling junctions where an insulating film is inserted between magnetic materials,[88,89] which is likely to find applications in magnetic sensors, magnetic memories and recording elements. If magnetic transport characteristics such as these are implemented using ferromagnetic/nonmagnetic semiconductor heterostructures, then it should be possible to integrate them into existing semiconductor circuitry. This section discusses the magnetic transport characteristics of magnetic/non-magnetic semiconductor heterostructures.

5.1 Spin-dependent scattering and interlayer coupling

In a ferromagnetic/non-magnetic/ferromagnetic semiconductor tri-layer structure, a spin-dependent scattering effect similar to that of metallic magnetic structures is observed whereby the resistance increases when the two ferromagnetic layers have antiparallel magnetization. Figure 5 shows an example of the spin-dependent scattering measured in a (Ga,Mn)As/(Al,Ga)As/(Ga,Mn)As tri-layer structure.[90] Due to differences in the coercive force, the region where the magnetizations of the ferromagnetic layers are antiparallel appears as a stepped part in the hysteresis of the magnetization curve obtained by Hall measurements. In this antiparallel region, the sheet resistance is found to increase due to spin-dependent scattering. Although the magnetoresistance ratio is small, it is important to note that the spin does not relax in the valence band where a large spin orbit interaction is present. Minor loops measured in the same tri-layer structure showed the presence of ferromagnetic interlayer coupling. Results of polarized neutron reflectometry on (Ga,Mn)As/GaAs superlattices also showed the presence of the ferromagnetic interlayer coupling between (Ga,Mn)As layers, which may be mediated by holes[90].

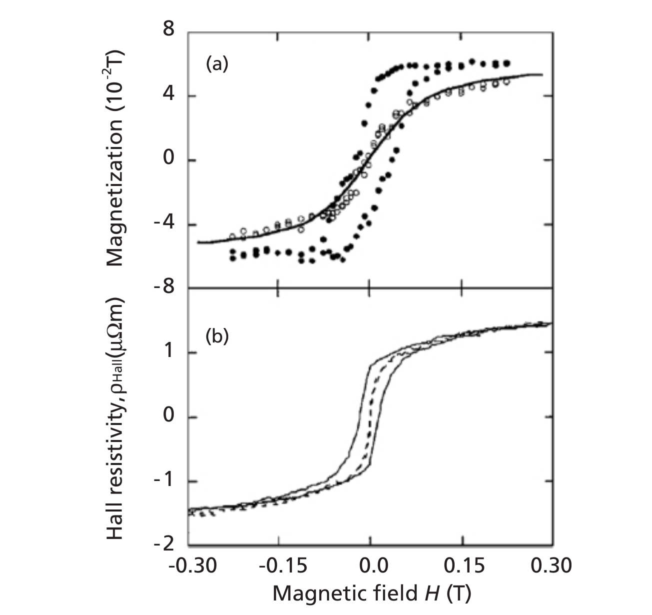


Fig. 4 (a) Magnetization curves and (b) Hall resistivity of a 12 nm thick ($In_{0.94}Mn_{0.06}$)As layer on a GaSb buffer layer at 5 K, before and after exposure to white light. The white and black circles in (a) correspond to the results obtained before and after exposure, respectively. The layer is paramagnetic before exposure, but after exposure the magnetization increases and it exhibits distinct hysteresis, indicating that it has become ferromagnetic (the theoretical curve is shown by the solid line). (b) Similar behavior appears in the Hall resistance—after exposure (solid line) it exhibits hysteresis that was not apparent before exposure (dashed line).[83]

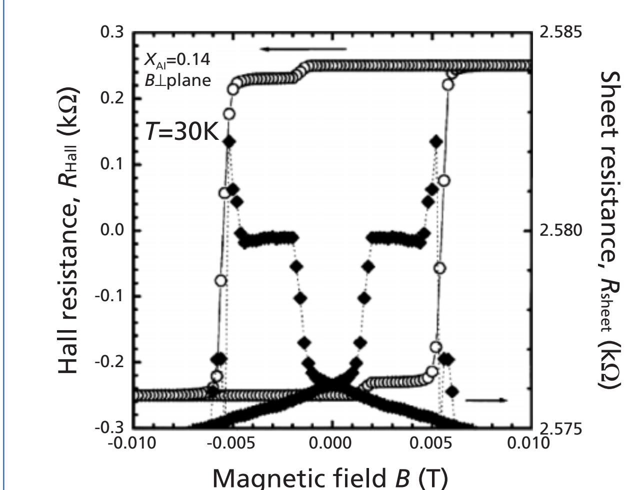


Fig. 5 The magnetic field dependence of Hall resistance (o) and sheet resistance (♦) in a (Ga,Mn)As/(Al,Ga)As/(Ga,Mn)As tri-layer structure. The magnetic field is applied perpendicular to the sample surface. By employing a Al composition 0.14 in the (Al,Ga)As, and by using a buffer layer of (In,Ga)As, the easy axis of magnetization is oriented perpendicular to the sample surface. In this way, by applying a magnetic field perpendicular to the sample surface, the anomalous Hall effect can be used to measure the parallel/antiparallel state of the magnetization. The region where the stepped part can be seen in the Hall resistance corresponds to the state where the magnetization is antiparallel, and in this region the sheet resistance is found to increase due to spin-dependent scattering.[90]

5.2 Tunneling magnetoresistance effects and tunneling effects

Tunneling effects have also been observed in (Ga,Mn)As/AlAs/(Ga,Mn)As tri-layer structures.[91-93] Figure 6 shows a recently reported example.[93] In the stepped part where the magnetization is antiparallel, the tunneling resistance increases. When the AlAs film that constitutes the tunneling barrier is four-monolayer thick, tunnel magnetoresistance ratio over 70% has been obtained. This suggests that the spin polarization in (Ga,Mn)As has a high value of at least 50%.

Splitting of the emitter's valence band due to spontaneous magnetization has also been observed by using a resonant tunneling diode with a (Ga,Mn)As emitter.[94,95]

5.3 Magnetoresistance effects in magnetic material/semiconductor hybrid structures

Unique magnetoresistance effects are expected from systems where fine particles of magnetic material are embedded in or formed on the surface of a semiconductor. In the case of (Ga,Mn)As, fine particles of MnAs separate out into the (Ga,Mn)As matrix when it is subjected to heat treatment.[96] However, the presence of MnAs has little effect on the room-temperature transport characteristics, possibly because of a Schottky barrier formation around the MnAs particles. On the other hand, Akinaga *et al*. investigated the magnetic field dependence of current-voltage characteristics in molecular beam epitaxially grown MnSb clusters on the sulfur treated GaAs substrate, and observed a very large magnetoresistance up to a magnetoresistance ratio of 10,000% at room temperature.[97] The resistance observed here is positive; it increases as a magnetic field is applied. The mechanism behind this expression of magnetoresistance has yet to be clarified.

5.4 Controlling ferromagnetism with an electric field

Recently, we have used field-effect transistor structures to vary the hole concentrations in magnetic semiconductor layers, and have successfully turned the carrier-induced ferromagnetism on and off by varying the electric field without changing the temperature.[98] Using a channel consisting of a 5 nm thickness of $(In_{0.97}Mn_{0.03})As$, we varied the hole concentration by using a polyimide insulating gate, and observed the channel magnetization via the anomalous Hall effect.

Figure 7 shows the magnetic field dependence of Hall resistance at 22.5 K in the vicinity of the ferromagnetic transition temperature T_c. When a gate voltage of $V_G = +125$ V is applied, the magnetization decreases and the hysteresis disappears. On the other hand, when a voltage of $V_G = -125$ V is applied, the hysteresis becomes more clearly apparent and the magnetization increases. This demonstrates that the device can switch ferromagnetic phase on and off by the applied electric field that changes carrier concentration in the channel region. As the figure shows, a swing of $V_G = \mp 125$ V in the applied voltage modulates the number of holes by ± several percent, and T_c is modulated by approximately ±1 K.

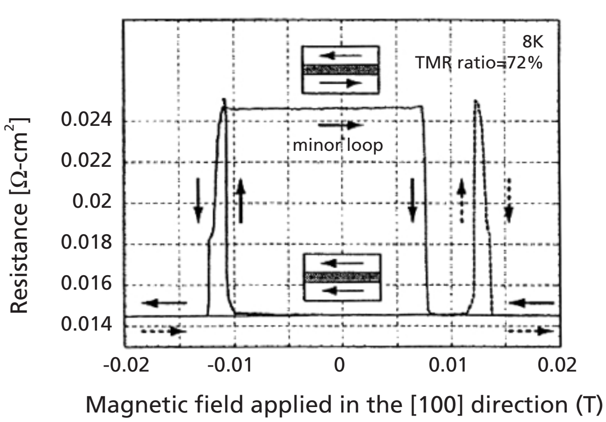


Fig. 6 Tunnel magnetoresistance effect in a (Ga,Mn)As/AlAs/(Ga,Mn)As tri-layer structure, measured at a temperature of 8 K. The solid and dotted arrows indicate positive and negative magnetic field sweeping directions, respectively. The (Ga,Mn)As layers are 50 nm thick, and the Mn composition in these layers are 0.04 and 0.033. The AlAs layer is 1.6 nm thick Since the easy axis of magnetization lies within the plane of the sample, a magnetic field is applied parallel to the sample surface. When a magnetic field is applied along the [100] direction, a tunneling magnetoresistance effect of over 70% is observed, and when a magnetic field is applied along the [110] direction, this effect is approximately 30%.[93]

6. Quantum Spin Devices

One of the goals of semiconductor spin electronics is to implement quantum information processing based on semiconductor devices using the long spin coherence times of electron spins and nuclear spins. The use of semiconductors has various benefits for implementing quantum computers—not only are they solid state materials and suitable for large-scale integration, but they also allow dimensional freedom to be controlled by quantum confinement, and allow various characteristics to be controlled by external fields such as light and electric or magnetic fields. This section introduces proposals of solid-state quantum computers using spin in semiconductors.

6.1 Quantum computing using spins in quantum dots

A number of proposals have been made for quantum computers using a single-electron spin state in quantum dots as quantum bits, since it offers a two-level system close to the ideal case and it has relatively long coherence time.[99-101] To distinguish one quantum bit to be operated on from other quantum bits, the resonant frequency is shifted by, for example, applying a local magnetic field and this frequency is used for operation on the quantum bit. In a quantum computer proposed by Loss *et al*., instead of subjecting the system to external electromagnetic waves, the temporal development of local exchange interactions between the target quantum dot and other neighboring quantum dots or ferromagnetic materials is introduced by a gate allowing the spin to be manipulated.[99] The use of solid-state (semiconductor) technology is thus advantageous in the way that it allows spin to be controlled electrically.

6.2 Quantum computing using nuclear spin

For silicon, the majority isotope ^{28}Si has no nuclear spin. Therefore, any intentionally doped nuclear spin stands out and has a long relaxation time. Kane has proposed a Si-based

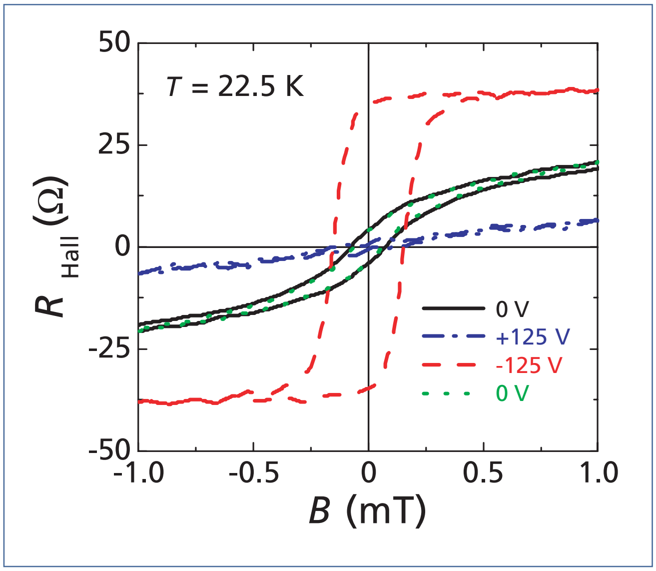


Fig. 7 Gate voltage dependence of Hall resistance in an (In,Mn)As FET structure close to the ferromagnetic transition temperature. When a gate voltage of V_G=-125 V is applied, hysteresis is clearly observed. On the other hand, when V_G=+125 V, the hysteresis disappears. This demonstrates that the applied field is able to switch the device between ferromagnetic and paramagnetic states.[98)]

quantum computer that uses a silicon MOS structure with a doped ^{31}P (nuclear spin 1/2), as shown in Fig. 8.[102)] The nuclear spin of ^{31}P acts as a quantum bit (qubit). It also acts as a donor that binds an electron. To manipulate the target's nuclear spin, a voltage is applied to a gate electrode located above the ^{31}P or between the neighboring ^{31}P. This way the hyperfine interactions, which are determined by the overlap of electron wave functions and nuclear spin, are controlled and shift in nuclear magnetic resonance frequency is obtained.[102)]

To implement a quantum computer that uses nuclear spin, isotopic control of the host semiconductor crystal is essential. So far useful experimental results such as greatly improved thermal conductivity have been obtained by controlling the isotopes.[103,104)] Recently, Ito et al. succeeded in refining silicon to produce single crystals consisting of 99.924% ^{28}Si, which has much greater isotopic purity than natural silicon (where the abundance ratio of ^{28}Si is 92.2%).[105)]

6.3 Electron spin quantum computers

Yablonovitch *et al*. have proposed an electron spin resonance (ESR) transistor based on Si/SiGe.[106)] In their model, a qubit is an electron spin state bound to a donor impurity in a quantum well consisting of two SiGe layers with different compositions. To manipulate the spin, a gate voltage is applied so that the electron wavefunction is localized to one of the SiGe layers. Since Si and Ge have different *g* values, the resonant frequency of the localized electron spin can be controlled by shifting the position of the wavefunction by gating.

This method is suitable for high-speed operation because the manipulation of quantum bits can be performed at the electron spin resonant frequency. Another advantage is that, since it uses Ge, the effective mass of electrons is smaller and the device dimensions can be increased to a size capable of being fabricated by existing micro-processing techniques (about 200 nm). Although the spin-orbit interaction in Ge is larger compared to that in Si, the electron spin coherence time is expected to be similar to that of Si (about 1 ms), which is long enough to allow computations to be performed provided that suitable error correction is applied.

6.4 Detecting spin

To obtain the final results of a quantum computation, one needs to read out a single nuclear spin or an electron spin state. Various methods have been proposed for doing this, such as spin filters using tunneling barriers of ferromagnetic material,[107)] and a method that involves using a single electron transistor (SET) to read out the spatial distribution of an electron wave function depending on the spin state.[108)] The development of such device technologies is an important area for future work in the realization of quantum computers.

7. Conclusion

Semiconductor spin electronics (semiconductor spintronics) is the subject of increasingly intense study in two directions: semiconductor magneto-electronics, which is expected to produce practical results in the near future, and semiconductor quantum spin electronics, which is set to become an important research topic for the 21st century. In this paper we have reviewed the significant progresses made in this field over the last 10 years, and covered possible applications of this emerging technology. We now have a better understanding of and control over spin related phe-

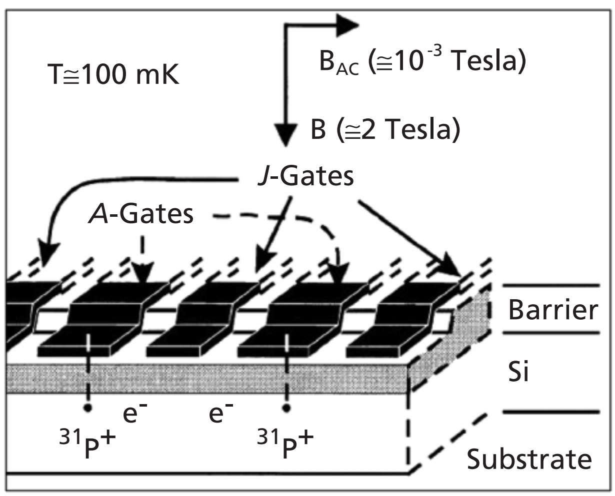


Fig. 8 A schematic illustration of a quantum computer proposed by Kane, in which nuclear spins $^{31}P^+$ embedded in a isotope-free ^{28}Si is used as a quantum bit.[102)] The overlap between the electrons and the $^{31}P^+$ is controlled by the A gates, thereby varying the resonant frequency of the nuclear spin via hyperfine interaction. The J gates control the overlap of the electron wavefunctions between two neighboring $^{31}P^+$, allowing the manipulation of two quantum bits.

nomena in structures consisting of magnetic and semiconductor materials, such as III-V ferromagnetic semiconductors, and in non-magnetic semiconductor quantum/nanostructures. We are, however, at the very early stage of a learning curve on the use of spin degree of freedom in semiconductors. The Japanese research community has been supported by a program "Spin Controlled Semiconductor Nanostructures" (1997-1999)* from the Ministry of Education and has contributed in a number of aspects of semiconductor spin electronics, especially in the area of materials science and physics. This research field is currently relying heavily on a US DARPA program called SPINS (Spins in Semiconductors, Program Manager Stuart Wolf) started in the year 2000, which supports a broad spectrum of research mainly in the United States. In order to develop semiconductor spintronics further, in particular quantum spin electronics involving the manipulation of coherent spin states, which may take decades to develop, a variety of comprehensive and dynamic research and development programs are needed. They have to involve specialists from a broad spectrum of fields ranging from materials, device and circuit technology to system design and computer science. We sincerely hope that this review article is of some use in raising interests of graduate students and researchers as well as establishing links with researchers in other fields, as it is vitally important for the further

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development of the field as electronics.

* See http://www.ohno.riec.tohoku.ac.jp/ for a summary of the report of the program.

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Note added in proof

Since this article, which is a translation of an article written in Japanese, was completed a number of important developments as well as proposals have been reported. This small note is by no means complete but it is added to aid the readers to learn about the very latest developments in the field[109]. (Ga,Mn)N with T_C=940 K has been reported.[110] Room temperature spin injection from Fe into semiconductor has been reported by two groups[111]. Electron spin injection using band tunneling from p-type ferromagnetic semiconductor has been realized[112]. Coherent electron spin sourcing[113] and ultrafast coherent spin manipulation through optical Stark effect[114] have been both demonstrated. Proposals for spin diodes and transistors[115, 116] and for all silicon quantum computers[117] have also been made. JSAP

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