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 conductors, 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, 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.
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. In a II-VI semiconductor, the II element is substituted by nonmagnetic atoms and the I element by magnetic atoms. 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 paramagnetic properties, as we will discuss later, it was recently reported that a p-doped II-VI DMS undergoes a ferromagnetic transition at low temperatures. In IV-VI DMS (Pb,Sn,Mn)Se, ferromagnetism was also observed at low temperatures, which is attributed to the hole-mediated RKKY interactions.

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. Subsequently, ferromagnetic properties were discovered in p-type (In,Mn)As, and in 1996 the growth of (Ga,Mn)As—a GaAs-based DMS—and ferromagnetic transitions in p-type (Ga,Mn)As were reported. The highest ferromagnetic transition temperature $T_C$ of (Ga,Mn)As obtained so far is 110 K ($\text{Mn concentration } x=0.053$).

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

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. The lattice constant of (Ga,Mn)As is slightly larger than that of GaAs, resulting in compressive strain. Using a buffer layer of InGaAs, which has a larger lattice constant than (Ga,Mn)As, the sign of the lattice strain can be changed to allow the easy axis of magnetization to be oriented perpendicular to the plane.

The ferromagnetic transition temperature can be determined in various ways, such as: (1) the temperature dependence of remanent magnetization; (2) an Arrott plot ($M^2$ vs $B^2$) plot of 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. 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 $T_C$. 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.

2.2.2 Magnetotransport characteristics

Depending on the Mn composition, (Ga,Mn)As exhibits either metallic conduction or insulator-type conduction. 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 magnetotransport characteristics (Hall resistance $R_{Hall}$ and sheet resistance $R_{Sheet}$) of a sample with metallic conduction ($x=0.053$, sample thickness $= 200$ nm) are shown in Fig. 1(a).

![Magnetotransport characteristics in (Ga,Mn)As](image-url)
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 $T_I$ from the Arrhenius plot ($T = T_I$ and Curie-Weiss plot ($T >> T_I$). Figure 1(c) shows the temperature dependence of the quantity $(R_{\text{arr}}/R_{\text{rt}})$, which is proportional to the spontaneous magnetization determined by the former method, from which it can be seen that $T_I$ is 110 K. The value of $T_I$ 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 $T_I$ by the mean field model. This is known as Zener ferromagnetism. It should be noted that this is not the same mechanism as the double exchange interaction also proposed by Zener.

We used a 6x6 Luttinger-Kohn hamiltonian that takes sp-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 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 $T_I$ by the mean field model. This is known as Zener ferromagnetism. It should be noted that this is not the same mechanism as the double exchange interaction also proposed by Zener.

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First principle calculation also has shown that the ferromagnetic state is stable in a hypothetical zinc-blende GaAs:MnAs superlattice. Again, the half-metallic state is predicted.

The double resonance mechanism is also proposed for the ferromagnetism of (Ga,Mn)As, from the electronic state calculated by the tight-binding approximation.

### 2.4 Room-temperature ferromagnetic semiconductors

Here we discuss the factors that should be considered in order to achieve $T_I$ 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 $x \beta = p$. For example, in (Ga,Mn)As, if a hole density of $p = 3.5 \times 10^{19} \text{cm}^{-3}$, which is achieved in the $x = 0.053$ sample, can be obtained, then it should be possible to achieve a $T_I$ 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 $T_I$ 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 ($\beta x = 1/a^2$, where $a$ is the lattice constant).

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. The first principle calculation also shows that the ferromagnetic state is stable for V, Cr, or Mn doped GaN.

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.

### 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 $10^{19} \text{cm}^{-2}$. Shortly after a theory of ferromagnetic transition based on p-d exchange interactions was put forward, ferromagnetism was observed below 1.8 K in modulation doped (Cd,Mn)Te quantum well (8 nm, $p = 2 \times 10^{11} \text{cm}^{-2}$). It has also been observed that a ferromagnetic transition takes place in a thin film (about 500 nm thick) of (Zn,V,Mn)Te and (Be,Er,Mn)Te (where $x \leq 0.1$) with $p = 10^{19-10^{20}} \text{cm}^{-3}$ ($T < 3 \text{K}$).

A succession of recent reports have mentioned ferromagnetic transition temperatures above room temperature—320 K in a II-VI, chalcogenide (Cd,Mn)GeP$_2$, 290-380 K in (Zn,Cr)O, room-temperature ferromagnetism in TiO$_2$:Co, and over 400 K in CrAs and CrSb with a zinc-blende structure. 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 semi-
conductors that are essential for utilizing electronic and 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, 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 Elliot–Yafet effect), and electron-hole exchange interaction (the BJR–Aronov–Kikkus effect). 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 excitons with circularly polarized light. The introduction of quantum confinement also modifies such factors as mobility, symmetry, excitonic effects, locality, and doping, resulting in a significant change of the spin relaxation process. In GaAs, for example, the reported electron spin relaxation time is distributed over a wide range from a few ps to several tens of ns. In particular, the D'yakonov-Perel' effect (which predominates at room temperature) depends strongly on the crystallographic orientation of the growth direction.

### 3.2 Injection of spin into semiconductors

Spin injection is a critical requirement for the development of spintronics. Schmidt et al. analyzed the spin injection in a ferromagnetic metal/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%.

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). We have fabricated a light-emitting p-n diode consisting of an InGaAs 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 of (Ga,Mn)As, and confirmed that spin injection takes place in a zero field.

### 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. In such 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. Recently, exchange interactions between a quantum dot with a controlled spin state and an electrode (the Kondo effect) have also been observed.

### 3.4 Spin coherence

When a magnetic field is applied perpendicular to the carrier spin, the spin undergoes Larmor precession about the field. The dynamics
ics of carrier spin in semiconductors has been investigated by time-resolved optical measurements of the temporal development of the precession. 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} and have demonstrated that spin can be transported over macroscopic scales of 100 µm without loss of coherence, as shown in Fig. 3. 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.

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, 64) in GaAs/AlGaAs (110) quantum wells, 64) and in GaAl. 65) 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, 65) 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. 65)

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 constant of 0.05 deg/cm/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. 74)

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,MnAs, In,MnAs 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. 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 InGaAsInP quantum wells, the spin relaxation time is no more than a few ps at room temperature. It has also been shown that ultra-fast optical switching can be achieved entirely optically by optically extracting the difference between left and right circularly polarized light components.

4.4 Photoinduced magnetism

Koshizaka 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. 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.77 Akinaida 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.82

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 multilayer can be produced, then it will be possible to integrate them into existing semiconductor circuitry. This section discusses the magnetic transport characteristics of magnetic/non-magnetic semiconductor heterostructures.

5. Electron Spin Devices

The large magnetoresistance effect arising from spin-dependent scattering in multi-layered films of magnetic metals83 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,84,85 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/magnetic 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.86 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 holes87.
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. Figure 6 shows a recently reported example. In the stepped part where the magnetization is antiparallel, the tunneling resistance increases. When the AlAs film that constitutes the tunnel barrier is 4-monolayer thick, tunnel magnetoresistance ratio of 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.

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. 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.

The observation 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 instead of changing the temperature. Using a channel consisting of a 5 nm thickness of (InxGa1-xMn)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. 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 \( V_W = +125 \) V in the applied voltage modulates the number of holes by ± several percent, and \( T_C \) is modulated by approximately ±1 K.

6. Quantum Spin Devices

As the data 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. 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. 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 \(^{28}\text{Si}\) has no nuclear spin. Therefore, any intentionally doped nuclear spin stands out and has a long relaxation time. Kane has proposed a Si-based

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**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, the effect is approximately 30%.

**Fig. 7** Tunnel magnetoresistance ratio of 72% for a magnetic field applied in the [100] direction (T).
quantum computer that uses a silicon MOS structure with a doped $^{31}$P (nuclear spin 1/2), as shown in Fig. 8. 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. 

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. 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%).

6.3 Electron spin quantum computers

Yablonovitch et al. have proposed an electron spin resonance (ESR) transistor based on SiGe. 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 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, 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. 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-
nomina 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

References

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 field109). (Ga,Mn)N with ultrafast coherent spin manipulation through optical Stark effect114) have been both demonstrated. Proposals for spin diodes and transistors115,116) and for all silicon quantum computers117) have also been made.