New Spintronics Paradigm

Spin Hall Effect and Spin Current Technology

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OVERVIEW: Recently, the major focus in spintronics research has gradually shifted from magneto-resistive phenomena with flowing electric current to those of pure spin current controlled by spin-orbit coupling. The spin Hall Effect (SHE) is a relativistic spin–orbit coupling phenomenon that can be used to electrically generate or detect spin currents in non-magnetic systems. The SHE was first observed experimentally by Hitachi less than 10 years ago. This article reviews the experimental results since then that have established the basic physical understanding of the phenomenon, and the role that several of the spin Hall devices have had in the demonstration of spintronic functionalities and physical phenomena. The spin Hall device studies are placed in a broader context of the field of spin injection, manipulation, and detection in non-magnetic conductors.

INTRODUCTION

THE late 20th century was the era of electronics. In the 21st century, however, circuits are coming up against power consumption limits due to the Joule heating effects of electron flow. A promising alternative that has been attracting much attention is a new technology called "spintronics," in which the electron's spin (its angular momentum) is used as a medium of information in place of electron itself.

Despite considerable effort, using pure spin for information processing without current flow has proved difficult. Instead, the first successful industrial application for spintronics was its use in hard disk drive (HDD) heads where spin is used together with charge current. A 2007 Nobel Prize was awarded for the discovery of giant magnetoresistance (GMR), an effect that is utilized in recent HDDs along with tunneling magnetoresistance (TMR). Hitachi was also pursuing research and development (R&D) into these technologies at that time, and has since also applied them to semiconductor memories, specifically magnetic random access memory (MRAM).

Hitachi Cambridge Laboratory (HCL) started work around 2004 on a new generation of spintronics that was based on pure spin current, meaning a spin current without any flow of charge current. This is fundamentally different to spin-polarized current, which involves the flow of both spin and charge current. While the use of pure spin current has possible applications in HDDs, its greatest potential impact currently lies in low-energy applications. Having worked on this form of spintronics for ten years, HCL is now recognized as the world's leading research institute in the field.

This article presents a basic explanation of this new form of spintronics and reviews recent progress.

Spintronics research at HCL has focused on how to utilize pure spin current in devices. The key objectives in the path to achieve this goal include finding and understanding ways of generating, controlling, detecting, and utilizing spin current. To this end, HCL's first step was to focus on understanding the basic properties of spin current.

The SHE is a relativistic spin–orbit coupling phenomenon. It is of particular importance to the development of transistor-like devices because it can be used to generate or detect spin currents electrically in non-magnetic systems. Accordingly, this article focuses on experimental results that have established a basic physical understanding of the phenomenon, and the role that several of spin Hall devices have had in the demonstration of spintronic functionalities and physical phenomena. These experiments are described in chronological order, and further categorized into semiconductor or metal spin Hall devices, and into optical or electrical spin Hall experiments. The spin Hall device studies are placed in a broader context of the field of spin injection, manipulation, and detection in non-magnetic conductors.

BACKGROUND OF SHE

The SHE was first predicted 40 years ago[(1), (2)] when theorists Dyakonov and Perel proposed that an unpolarized electrical current should lead to a transverse spin current in systems with relativistic spin–orbit coupling. In their picture, spin–orbit coupling enters SHE via the Mott scattering of electrons on unpolarized impurities, which results in spatial separation of electrons with opposite spins. The effect has Hall symmetry, because the polarization axis of the spins is perpendicular to the plane of the transverse spin current and the driving longitudinal electrical current. Concepts for the experimental detection of the phenomenon were not introduced until almost 30 years after the original theoretical work[(3), (4)].

Hirsch proposed a device in which a spin current is generated by SHE in one part and injected into another part where it is detected by the inverse spin Hall Effect (iSHE). In the iSHE, the spin current generates a transverse current of charge, causing an accumulation of charge at the edges of the sample that can be detected electrically[(3)]. Relying on both SHE and iSHE simultaneously for observing the phenomenon turned out to be experimentally challenging, and the method was realized only recently. The proposal[(3)] that SHE has an inverse counterpart has, nevertheless, played a key role in establishing the basic physics of the phenomenon and in utilizing the effect as a tool for both the electrical injection and electrical detection of spin currents in non-magnetic materials.

Zhang suggested that the edge spin accumulation produced by SHE could be detected electrically using an attached ferromagnetic probe[(4), (5)]. The method is based on measuring the dependence of the electrochemical potential at the detection ferromagnetic electrode on the relative orientation of the magnetization of the electrode, and the accumulated spins in the non-magnetic system underneath it. It took several years to demonstrate the viability of this method.

The experimental discovery of SHE was prompted by theoretical work that approached the SHE physics from a different angle. Inspired by studies of the intrinsic nature of the closely related anomalous Hall Effect, Hitachi predicted that a spin-dependent transverse deflection of electrons in non-magnetic systems can originate directly from the relativistic band structure of the conductor without involving Mott scattering[(6-9)]. The intrinsic SHE proposal triggered an intense theoretical debate[(10-14)]. Unlike the first reports[(3), (4)], which considered the extrinsic, scattering-induced SHE[(1)] and electrical detection schemes designed for metals, the intrinsic SHE proposals focused on semiconductors and suggested that the optical activity of these materials be utilized for detecting SHE. In particular, circularly polarized electroluminescence was suggested in reference 8 and the magneto-optical Kerr effect in references 8 and 9. These methods were used in the first measurements of the SHE phenomenon. Kato et al.[(15)] employed a magneto-optical Kerr microscope to scan the spin polarization across the channel, whereas Hitachi (Wunderlich et al.[(16)]) used coplanar *p-n* diodes to detect circularly polarized electroluminescence at opposite edges of the spin Hall channel (see **Fig. 1** and reference 17). Remarkably, Hitachi (Wunderlich et al.) ascribed the observed signal to the intrinsic SHE whereas the first report ascribed it to the extrinsic SHE.

OPTICAL APPROACH TO SHE

Spin Injection and Detection[(16), (17)]

A traditional way of generating spin-polarized photo-carriers in semiconductors is by absorption of circularly polarized light[(18)]. Because of the optical selection rules, the out-of-plane spin polarization of photo-carriers is determined in this technique by the helicity and degree of the circular polarization of vertically incident light. To demonstrate the SHE, Hitachi developed a novel *p-n* junction light-emitting diode (LED) micro-device as shown in **Fig. 1**, in a similar spirit to the one proposed but distinct in that it couples two-dimensional hole and electron doped systems. Its coplanar geometry and the strong spin-orbit coupling in the embedded two-dimensional hole gas (2DHG), whose small thickness diminishes current

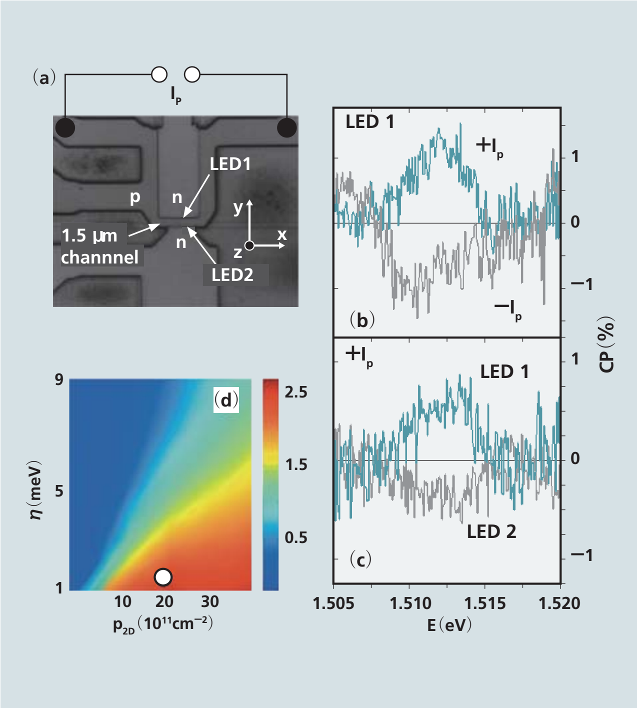

Fig. 1 | SHE experiment.

The figure in the top-left (a) shows a scanning electron microscopy (SEM) image of the SHE LED device. The top (LED 1) or bottom (LED 2) *n* contacts are used to measure the electroluminescence(EL) at opposite edges of the two-dimensional hole gas (2DHG) *p* channel parallel to the SHE driving current *Ip*. Graph (b) shows the along z-axis circular polarization (CP) measured by active LED 1 for two opposite *Ip* current orientations. Graph (c) shows z-axis polarization measured with fixed *Ip* current and for biased LED 1 or LED 2. Graph (d) shows the theoretical intrinsic SHE conductivity in units of e/8π versus quasi-particle lifetime broadening and two-dimensional (2D) hole density. The parameters corresponding to our 2DHG, indicated by a white dot, fall into the strong intrinsic SHE part of the theoretical diagram.

induced self-field effects, are well suited for inducing and detecting the SHE.

When an electric field is applied across the hole layer, a non-zero out-of-plane component of the spin is optically detected whose sign depends on the sign of the field and is opposite for the two edges, consistent with theory predictions.

The LEDs were fabricated in aluminum gallium arsenide (AlGaAs) / gallium arsenide (GaAs) hetero-structures grown by molecular-beam epitaxy and using modulation donor [silicon (Si)] and acceptor [beryllium (Be)] doping in (Al,Ga)As barrier materials. The planar device features were prepared by optical and electron-beam lithography. Two wafers were investigated that differed in the 3-nm undoped AlxGa1-xAs spacer at the upper interface, with wafer 1 having x = 0.5 and wafer 2 x = 0.3. The hetero-structures are *p*-type; the band bending leads to the formation of an empty triangular quantum well in the conduction band at the lower interface and an occupied triangular quantum well near the upper interface, forming a 2DHG. The coplanar *p-n* junction is created by removing acceptors from a part of the wafer by etching, leading to population of the previously depleted conduction band well and depletion of the 2DHG in that region.

A micro-device that allows such a response to be induced and detected is shown in **Fig. 1**(a). A *p*-channel current, *Ip* = 100 μA, is applied along the *x* direction, and the circular polarization (CP) of the light propagating along the *z* axis is measured while biasing one of the LEDs at either side of the *p* channel. The diode has a rectifying *I-V* characteristic, and the onset of the current is accompanied by electroluminescence (EL) from the *p* region near the junction step edge. The current, I_{LED} = 100 μA, is dominated by electrons moving from the n to the *p* region; the opposite hole current is negligibly small due to lower mobility of holes. According to **Fig. 1** (b) and (c), the detected polarization of 1% represents a lower bound of the SHE induced spin accumulation at the edge because the emitted light intensity decreases only gradually when moving from the biased junction towards the opposite side of the 2DHG channel.

Spin Transfer

A micro-device with two co-planar LED used by Hitachi, et al.[(16), (17)] to detect SHE is shown in **Fig. 2**. Devices were patterned from a semiconductor hetero-structure as used in **Fig. 1**, 90 nm of GaAs, and an *n*-doped AlGaAs/GaAs hetero-junction underneath. In the unetched part of the wafer, the top hetero-junction was populated by two-dimensional (2D) holes of a sheet density 2×10^{12} cm^{-2}, whereas the 2D electron gas (2DEG) at the bottom hetero-junction was almost depleted. The *n*-side of the coplanar *p–n* junction was formed by removing the *p*-doped surface layer from part of the wafer.

The 1 to 10-μm-wide channels in the experimental devices[(16), (17)] were formed in the unetched part of the epitaxial grown layer with the 2DHG. The etched-off regions of the wafer outside the channel make the channel edges act as coplanar *p–n* diodes with an effective recombination width of ~100 nm. Also consistent with the SHE phenomenology, opposite polarizations were detected at opposite edges of the 2DHG channel.

The amplitude of the measured SHE signals (at 4 K) reached ~1% in these experiments. The 2DHG studied[(16), (17)] was in the strong spin–orbit coupling regime, $\Delta_{SO}\tau/\hbar \approx 4$, which favors the intrinsic SHE mechanism. A quantitative microscopic description of the measured edge-spin-accumulation signal was developed and further experimentally tested[17].

Theoretical analysis pointed out that the length scale of the edge spin accumulation is defined in the strong spin–orbit coupling regime by the spin–orbit precession length $L_{so} = v_F \tau_{so}$, where $\tau_{so} = \hbar\pi/\Delta_{so}$ is the precession time of the spin in the internal spin–orbit field and v_F is the Fermi velocity. With increasing strength of the spin–orbit coupling, the edge-spin-accumulation region narrows down and, simultaneously, the amplitude of the spin polarization increases.

For the experimental parameters of the 2DHG, L_{so} ~10 nm and the calculated amplitude of the edge spin polarization was 8%, in good agreement with the 1% polarization of the measured electroluminescence signal, which was averaged over the ~100 nm sensitivity range of the co-planar light-emitting diode. Measurements in a device with a 10-μm wide 2DHG channel confirmed the theoretical expectation that the SHE edge spin accumulation is independent of the channel width (for widths larger than L_{so})[17].

Fig. 3 shows that the spin-injection Hall effect (SIHE) signals can also change sign at a given Hall cross when moving the spot across the optically active region around the *p-n* junction, that is, when effectively shifting the spin-injection area. At large reverse biases, the optically active region extends a few micro-meters deep in the *p*-channel. As we move the laser spot across the junction towards

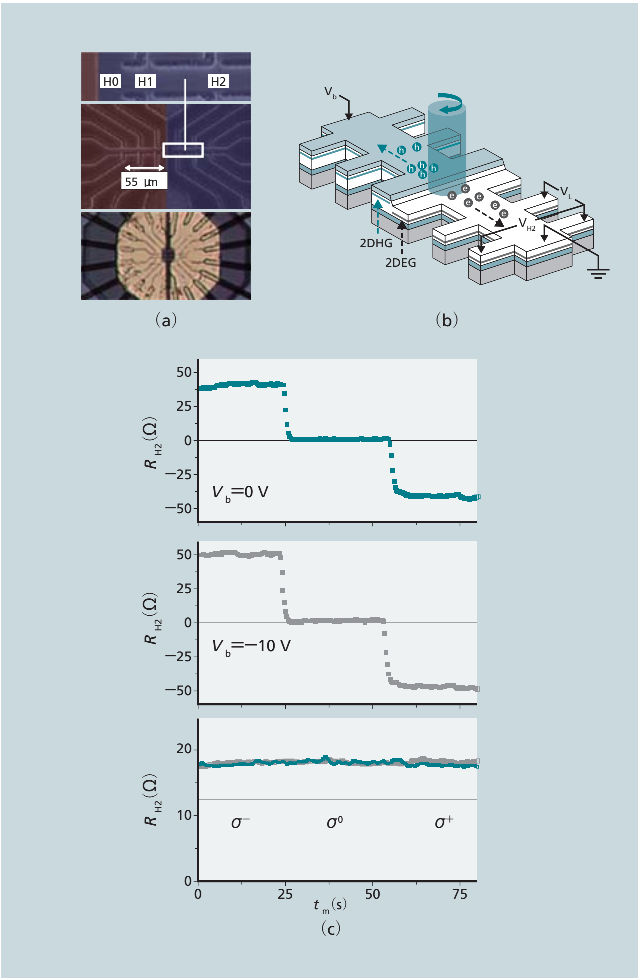

Fig. 2 | Micro-device with Two Co-planar LED.
Figure (a) shows a micrograph of the co-planar *p–n* junction device with masked Hall bars (lower panel) and images of the spin-injection Hall effect (SIHE) devices without the gold masks (upper panels). Figure (b) shows a schematic diagram of the wafer structure of the two-dimensional electron gas (2DEG)–2DHG *p–n* diode and of the SIHE measurement set-up. Graph (c) shows steady-state SIHE signals changing sign for opposite helicities (σ+ and σ −) of the incident light beam. Measurements were carried out at the 2DEG Hall cross H2 at a laser wavelength of 850 nm, zero and reverse bias of -10V and 4 K.

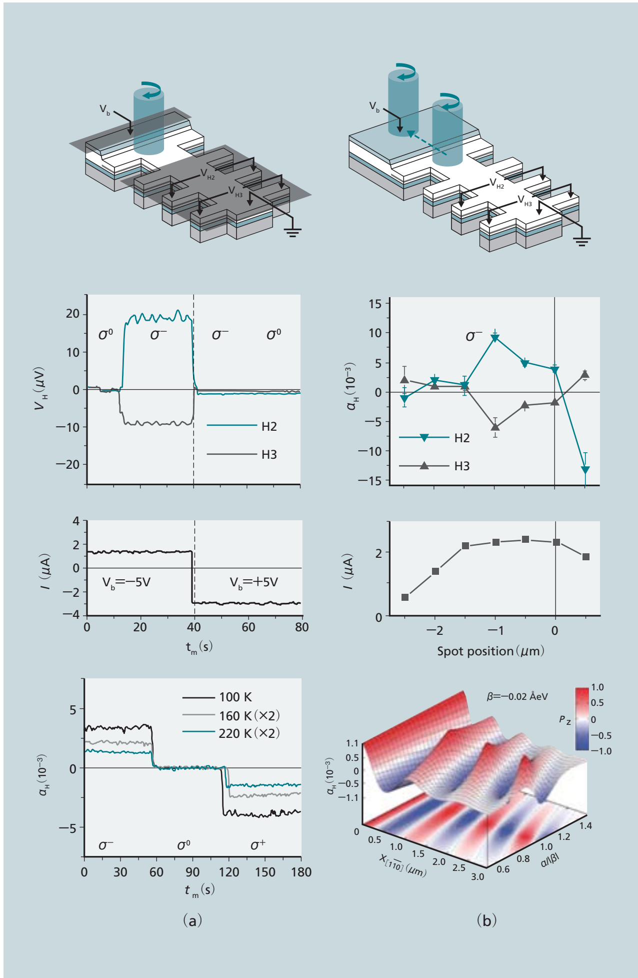

Fig. 3 | Temperature dependence of measured SIHE and theoretical model.
Graph (a) shows SIHE measurements at the 2DEG Hall cross H2 at 100, 160 and 220 K. These data demonstrate the realization of a transverse-voltage spin-photovoltaic effect without any magnetic elements in the structure or an applied magnetic field, and a functionality of the device as a solid-state electrical polarimeter. Graph (b) shows the microscopic theory of the SIHE assuming spin–orbit coupled band-structure parameters of the experimental 2DEG system. The color-coded surface shows the proportionality between the Hall angle and the out-of-plane component of the spin.

the p-channel, we observe simultaneous variations of the signals at both measured Hall crosses in the n-channel. Additionally, Fig. 3 (a) shows measurements in a sample that showed rectifying p-n junction characteristics at temperatures up to 240 K. The data demonstrate that the SIHE is readily detectable at high temperatures.

Spin Transistor and Basic Logic

To utilize optical spin injection by a circularly polarized laser beam for observing the iSHE and for employing the effect in experimental opto-spintronic and spin-transistor devices, Hitachi and collaborators (Wunderlich et al.[19], [20]) used the above confirmed lateral p–n diode[16], [17]. In our original SHE measurements[16], [17], the p–n junctions were fabricated along the edges of the 2D hole channel and under forward bias could detect the spin state of recombining electrons and holes through polarized electroluminescence. In later work[19], [20], on the other hand, the spin Hall channel was fabricated in the etched part of the epitaxial layer with the 2DEG, the channel was oriented perpendicular to the p–n junction, and the diode was under zero or reverse bias, operating as a photocell as shown in Fig. 4.

The Hall signals were detected electrically on multiple Hall-crosses patterned along the channel. Two regimes of operation of the device were distinguished: One was referred to as the spin-injection Hall effect regime, in which the reverse-bias charge current is drained behind the Hall crosses at the opposite end of the channel from the p–n junction injection point [see Fig. 4 (a)]. The other regime corresponds to the iSHE measurement, because in this case the charge current is drained before the Hall crosses, allowing only the pure spin-current to diffuse further in the channel [see Fig. 4 (b)]. In both cases the measured transverse electrical signals were consistent with the spin Hall phenomenology[19-21]. The sign of the voltage was opposite for opposite helicities of the incident light, that is, opposite spin polarizations of injected photo-electrons. Moreover, the amplitude of the electrical signals was found to depend linearly on the degree of circular polarization of the light, rendering the device an electrical polarimeter[19]. The electrical signals were observable over a wide temperature range with spin Hall angles of 10^{-3}-10^{-2}. The measured 2DEG was in the weak spin–orbit coupling regime, $\Delta so\tau/\hbar \sim 0.1$, and the measured data were consistent with the extrinsic spin Hall mechanism19.

A distinct feature of the iSHE experiments in the 2DEG is the observed spin precession due to internal Rashba and Dresselhaus spin–orbit fields[19-21]. As the spin diffusion length scales approximately[20] as $Lso2/w$, it was possible to observe a few spin precessions in channels of a width w = 1 μm for Lso ~1 μm of the studied 2DEG. The corresponding oscillations of the spin Hall voltages were consistently observed by measuring at different Hall crosses along the channel or by shifting the laser spot, that is, the spin-injection point (see Fig. 4). The lateral iSHE channels also allow top-gate electrodes to be placed in between the Hall crosses, as shown in Fig. 4 (c). (The gates were formed by unetched regions of the wafer.) The strength of the Rashba and Dresselhaus spin–orbit fields[22] and, therefore, also the spin precession can be manipulated electrically in the device as shown in Fig. 4 (c). To demonstrate an AND logic functionality, two gates were fabricated on top of

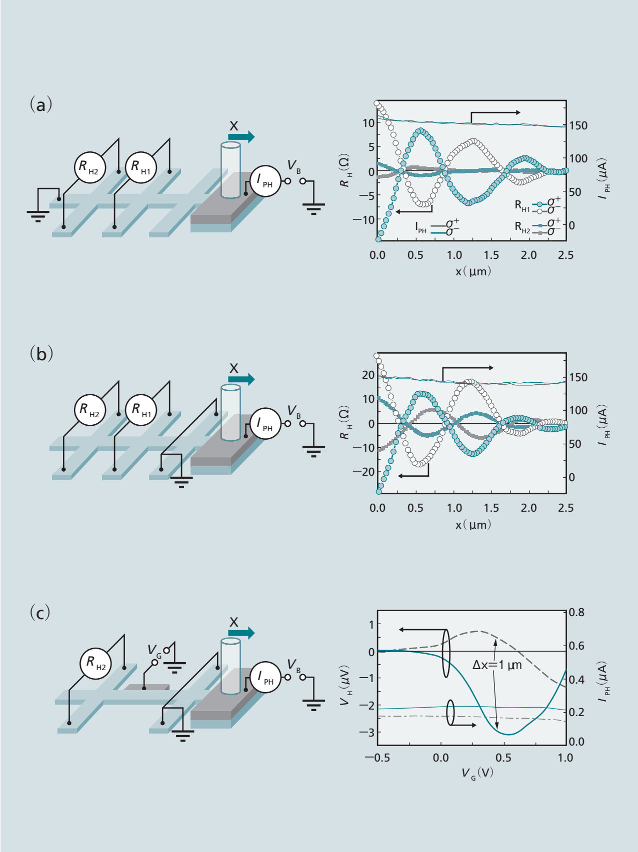

Fig. 4 | iSHE-based transistor.
Figure (a) shows a schematic of the SIHE measurement set-up. The Hall resistances, RH = VH/IPH, where V_H is the Hall voltage and I_{PH} is the photocurrent for the two opposite helicities of the incident light are plotted as a function of the focused light spot position, that is, of the position of the injection point. V_B is the p–n junction bias voltage, $\sigma+$ and $\sigma-$ are the helicity of the polarized light. Similarly figure (b) shows the schematic for iSHE. Figure (c) shows the schematic of the spin Hall transistor and the experimental Hall signals as a function of the gate voltage (VG) at a Hall cross placed behind the gate electrode for two light spot positions with a relative shift of 1 μm[20].

the channel and the Hall electrical signal was measured at a cross placed behind both gates, as shown **Fig. 5**. Intermediate gate voltages on both gates represented the input value 1 and gave the largest electrical iSHE signal, representing the output value 1. When a large reverse gate voltage was applied to any of the two gates, representing input value 0, the electrical iSHE signal disappeared, that is, the output was 0.

SPIN HALL DEVICES WITHOUT LIGHT

In recent years, semiconductive spin Hall devices have entered the realm of metals by not requiring light for their operation[23-25]. The hybrid semiconductor/metal-ferromagnetic structures have for a long time suffered from the resistance mismatch problem. As the spin transport relies on different conductivities for spin-up and spin-down electrons and is governed by the least conductive part of the device, the effects are weak in devices in which

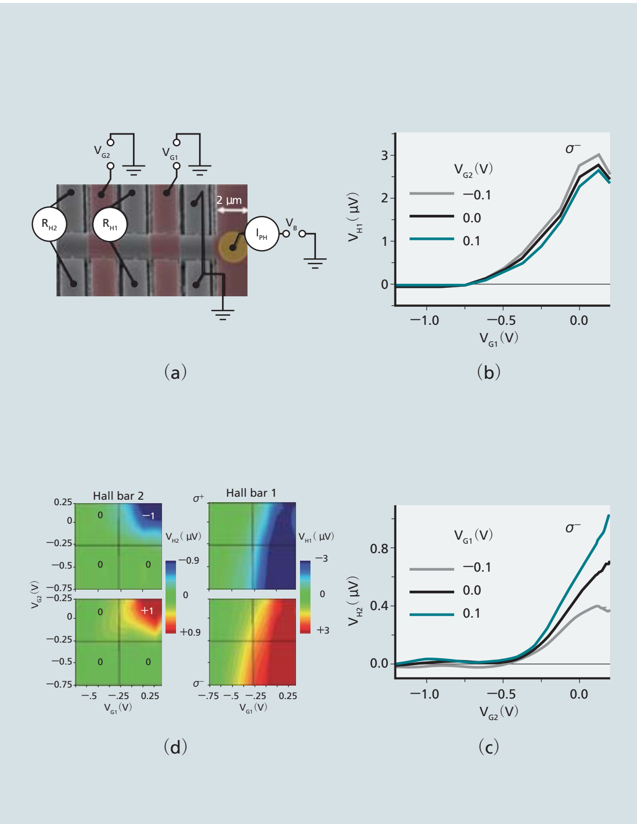

Fig. 5 | AND Gate.
Figure (a) shows a scanning electron micrograph and schematics of the device with two detecting Hall crosses H1 and H2 and one gate placed before cross H1 and the second gate placed behind cross H1 and before cross H2. Gates and *p*-side of the lateral *p*-*n* junction are highlighted in red. The focused laser beam is indicated by the yellow spot. Graph (b) shows the Hall signals at cross H1 measured as a function of the first gate voltage. Graph (c) shows the Hall signals at cross H2 measured as a function of the second gate voltage. Graph (d) demonstrates the spin AND logic function by operating both gates (input signals) and measuring the response at Hall cross H2 (output signal). Measured data at cross H1 are also shown for completeness[20].

the non-magnetic semiconductor with equal spin-up and spin-down conductivities dominates the resistance of the device. The introduction of a highly resistive tunnel barrier between the ferromagnetic metal electrode and the semiconductor channel can solve the problem[26]. (The tunneling resistance is spin dependent because of the exchange-split bands on the ferromagnet side of the tunnel junction.)

Garlid et al. reported an all-electrical measurement of SHE in epitaxial iron/indium gallium arsenide (Fe/InGaAs) hetero-structures with an *n*-type InGaAs semiconductor channel and a Schottky tunnel barrier at the Fe/InGaAs interface[28]. A transverse spin current generated by an ordinary charge current flowing in the InGaAs was detected by measuring the spin accumulation at the edges of the channel. An important aspect of the experiment was the ability to tune the strength of the spin–orbit interaction between different samples by changing the indium (In) content, and to vary the conductivity of the samples. This allowed the different contributions to the spin Hall conductivity to be extracted. As expected in *n*-doped three-dimensional (3D) semiconductors, the observed spin Hall conductivity was dominated by the extrinsic mechanism.

Hitachi and collaborators (Olejnik et al.) demonstrated the iSHE detection in a semiconductor combined with an electrical spin injection and manipulation[28], [29]. In a GaAs microchannel with an Fe Schottky injection contact, the spin current in the lateral semiconductor channel [see **Fig. 6** (a)] was detected by iSHE and the spin polarization was simultaneously measured using an additional Fe electrode. The spins in the channel were manipulated by the Hanle spin precession induced by an applied magnetic field and by a drift induced by an applied electrical bias[30]. As shown in **Fig. 6** (b)–(d), the output iSHE and non-local spin-valve signals are suppressed or enhanced depending on the electrical bias, that is, the device acts as an electrically controlled spin modulator. Qualitatively, the modulation of the spin signal can be explained by a shift of the injected spin polarization profile from the injection electrode in the direction towards the detection electrodes in the case of the positive drift current or away from the detectors in the case of the negative drift. This relates to the possibility of accumulating spin current using voltage, something that needs to be considered to achieve further functionality.

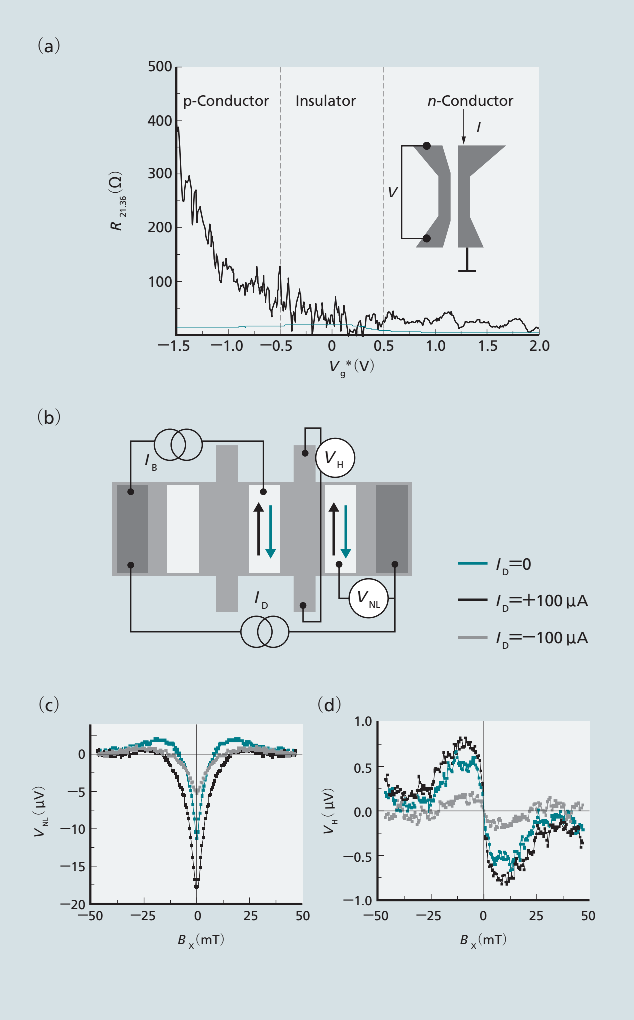

Fig. 6| Electrical spin Hall devices in semiconductors.
Graph (a) shows spin injection by SHE and detection by iSHE in a gated H-shaped device. The inset schematic shows the measurement set-up for current injection (I) and voltage (V). The black curve shows the non-local iSHE resistance signal. The blue curve indicates the residual voltage owing to current spreading. Figure (b) shows the experimental set-up for a semiconductor iSHE device with electrical modulation of the spin signal. The experimental non-local spin-valve (V_{NL}) and iSHE (V_H) signals in the in-plane field Bx measured at constant spin-injection bias current I_B = 300 μA and at three different drift currents I_D are depicted in graphs (c) and (d) [(28),(34)].

SPIN ORBIT EXCHANGE PHYSICS AND UTILIZATION OF INTERFACIAL SPIN OF ANTI-FERROMAGNETIC MATERIALS

Hitachi also aims to open an alternative route towards anti ferromagnetic (AFM) spintronics which reintroduces the leading role of spin–orbit coupling. In this approach, the stringent requirements on the GMR/TMR are circumvented by considering instead the tunneling anisotropic magnetoresistance (TAMR) and the Coulomb-blockade anisotropic magnetoresistance (CBAMR) effects. We also demonstrate that spin-orbit coupling can be employed to control magnetic anisotropies in the AFM in a way that leads to reorientation of the staggered moments required for observing the above anisotropic transport effects.

Previous studies of the TAMR and CBAMR in ferromagnets have shown that anisotropic magnetoresistance phenomena can be extended from bulk to nanoscale devices, can have large magnitudes and do not require spin-coherent transport throughout the structure[(30), (31)].

In transition-metal ferromagnets a generic principle has been outlined, based on studies of magnetocrystalline anisotropies and of the TAMR and CBAMR, that the magnetic anisotropy phenomena are maximized in bimetallic systems combining large spontaneous moments on the 3d shell of a transition metal, and large magnetic susceptibility and spin-orbit coupling on the 5d shell of a noble metal. Since manganese (Mn) carries the largest moment among transition metals and most of the bimetallic alloys containing Mn order antiferromagnetically, the goals of strong magnetic anisotropy phenomena and of AFM spintronics appear to merge naturally together. In our relativistic ab initio study we consider the manganese gold (Mn_2Au) AFM for which recent theoretical calculations predicted a record Néel temperature of 1500 K among Mn-based AFM alloys. The generic nature of the proposed anisotropy phenomena is confirmed by calculations in the conventional bimetallic AFM manganese iridium (MnIr) [(32)].

A spin valve is a traditional microelectronic device in which high- and low-resistance states are realized by using both the charge and spin of carriers. Spin-valve structures used in modern hard-drive read heads and magnetic random access memories comprise two ferromagnetic electrodes whose relative magnetization orientations can be switched between parallel and antiparallel configurations, yielding the desired giant or TMR effect[(1)]. Hitachi succeeded in being the first in the world to demonstrate more than 100% spin-valve-like signals in a nickel iron/iridium manganese/magnesium oxide/platinum (NiFe/IrMn/MgO/Pt) stack with an AFM layer on one side and a nonmagnetic metal on the other side of the tunnel barrier[(32)].

Ferromagnetic moments in NiFe are reversed by external fields of approximately 50 mT or less, and the exchange-spring effect of NiFe on IrMn induces rotation of antiferromagnetic moments in IrMn, which is detected by the measured TAMR[(3)]. Hitachi's work demonstrates a spintronic element whose transport characteristics are governed by an anti-ferromagnet. It demonstrates that sensitivity to low magnetic fields can be combined with large, spin-orbit-coupling-induced magnetotransport anisotropy using a single magnetic electrode. The anti-ferromagnetic tunneling anisotropic magnetoresistance provides a means to study magnetic characteristics of anti-ferromagnetic films by an electronic transport measurement.

Magnetization-dependent chemical potential shifts in the relativistic band structure of magnetic materials have rarely been discussed in the scientific literature(34). This reflects the conceptual difficulty in describing the chemical potential shifts by quantitative theories, the lack of direct measurements of the effect, and the lack of proposals in which the phenomenon could open unconventional paths in microelectronic device designs.

The theories could account for chemical potential shifts due to the distortion in the dispersion of the spin-orbit coupled bands but for principle reasons omit possible shifts of the vacuum level with respect to band edges, in other words, possible shifts in band line-ups in realistic hetero-structure systems. In experiments reported to date, the magnetic materials have been integrated into a conventional design for a magneto-electronic device (that is, embedded in the transport channel), and the chemical potential shifts could be inferred only indirectly from the measured data. The work presented here addresses the above two basic experimental points by demonstrating direct measurements of chemical potential shifts in a spin-orbit coupled ferromagnet, and by demonstrating a spintronic device that operates without spin currents. That is, a functionality that goes beyond the common concepts of spintronics.

Spin phenomena and functionalities have been incorporated in the transport channel of single-electron transistors (SETs), both in the leads and/or in the island. Observed effects include spin accumulation on the island and large TMR(9). In particular, large magnetoresistances due to magneto-Coulomb oscillations of CBAMR, associated with chemical potential effects, have been observed in SETs with ferromagnetic leads or islands.

These studies showed that transport through the channel can be controlled by shifts of the chemical potentials at individual components of the SET channel, induced by the Zeeman coupling to the external magnetic field or by magnetization rotation and relativistic spin-orbit coupling. The latter phenomenon can yield low-field hysteretic magneto-resistances of huge magnitudes and, due to its origins in spin orbit coupling, is related to anisotropic magnetoresistance in conventional ohmic or tunneling devices. The chemical potential anisotropy has also been observed in (Ga,Mn)As tunnel devices(33).

This explanation relates not only to the sensing of spin, but also to several highly efficient spin injection methods or potential energy phenomena like the spin Seebeck effect.

OUTLOOK

Experiments in spin Hall devices performed so far have established the basic physics of SHE and iSHE, showed that the intrinsic and extrinsic mechanisms can contribute to the phenomenon, and that SHE and iSHE are universal to metal and semiconductor systems (3D and 2D) with spin–orbit coupling. The planned future direction for research at Hitachi(19), (20), (34) includes world-first experiments that may contribute to a better understanding of this problem.

The utility of SHE and iSHE as an electrical spin injector and detector in non-magnetic systems means that a variety of new spintronic functionalities can be explored. Devices combining electrical spin detection by iSHE with electrical spin manipulation have been recently demonstrated, which makes spin transistors another potentially fruitful area of spin Hall research. Some devices are reported to act as a spin analogue of a field-effect transistor(5), (20), (34), (35). The gate electrode in these devices can control the spin–orbit coupling(20), (34) or the interfacial spin interactions(35) by changing the electric field strength across the film or the Fermi level position. Finally, while Hitachi continues to lead the world in this field, the level of understanding remains at a basic level. In planning the future direction of its research, Hitachi intends not only to build on its current work, but also to advance this understanding toward real-world applications that can contribute to the fields of computing and energy.

REFERENCES

(1) M. I. Dyakonov et al., "Possibility of orienting electron spins with current," JETP Lett.13, pp. 467–470 (1971).

(2) M. I. Dyakonov et al., "Current-induced spin orientation of electrons in semiconductors," Phys. Lett. A 35, pp. 459–460 (1971).

(3) J. E. Hirsch, "Spin Hall effect," Phys. Rev. Lett. 83, pp. 1834–1837 (1999).

(4) S. Zhang, "Spin Hall effect in the presence of spin diffusion," Phys. Rev. Lett. 85, pp. 393–396 (2000).

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(5) M. Johnson et al., "Interfacial charge–spin coupling: Injection and detection of spin magnetization in metals," Phys. Rev. Lett. 55, pp. 1790–1793 (1985).

(6) M. Onoda et al., "Topological nature of anomalous Hall effect in ferromagnets," J. Phys. Soc. Jpn 71, pp. 19–22 (2002).

(7) T. Jungwirth et al., "Anomalous Hall effect in ferromagnetic semiconductors," Phys. Rev. Lett. 88, 207208 (2002).

(8) S. Murakami et al., "Dissipationless quantum spin current at room temperature," Science 301, pp. 1348–1351 (2003).

(9) J. Sinova et al., "Universal intrinsic spin-Hall effect," Phys. Rev. Lett. 92, 126603 (2004).

(10) S. Murakami, in "Advances in Solid State Physics," Vol. 45 (ed. Kramer, B.), pp. 197–209, Springer (2005).

(11) H-A. Engel et al., in "Handbook of Magnetism and Advanced Magnetic Materials" Vol. 5 (ed. Parkin, H. K. S.) pp. 2858–2877, Wiley (2007).

(12) J. Sinova et al., in "Spintronics" (eds T. Dietl et. al.) Semiconductor and Semimetals Series Vol. 82, pp. 45–87, Elsevier (2008).

(13) E. M. Hankiewicz et al., "Spin-Hall effect and spin-Coulomb drag in doped semiconductors," J. Phys. Condens. Matter 21, 253202 (2009).

(14) R. Raimondi et al., "Spin–orbit interaction in a two-dimensional electron gas: A SU(2) formulation," Preprint at http://arXiv.org/abs/1110.5279 (2011).

(15) Y. K. Kato et al., "Observation of the spin Hall effect in semiconductors," Science 306, pp. 1910–1913 (2004).

(16) J. Wunderlich et al., "Experimental observation of the spin-Hall effect in a two dimensional spin–orbit coupled semiconductor system," Phys. Rev. Lett. 94, 047204 (2005).

(17) K. Nomura et al., "Edge-spin accumulation in semiconductor two-dimensional hole gases," Phys. Rev. B 72, 245330 (2005).

(18) F. Meier et al., "Optical Orientation and Femtosecond Relaxation of Spin-Polarized Holes in GaAs," North Holland (1984).

(19) J. Wunderlich et al., "Spin-injection Hall effect in a planar photovoltaic cell," Nature Phys. 5, pp. 675–681 (2009).

(20) J. Wunderlich et al., "Spin Hall effect transistor," Science 330, pp. 1801–1804 (2010).

(21) T. Jungwirth et al., "Spin Hall effect devices," Nature Materials 382, 11 (2012).

(22) S. Datta et al., "Electronic analog of the electro-optic modulator," Appl. Phys. Lett. 56, pp. 665–667 (1990).

(23) L. Vila et al., "Evolution of the spin Hall effect in Pt nanowires: Size and temperature effects," Phys. Rev. Lett. 99, 226604 (2007).

(24) S. Mizukami et al., "Effect of spin diffusion on Gilbert damping for a very thin permalloy layer in Cu/permalloy/Cu/Pt films," Phys. Rev. B 66, 104413 (2002).

(25) K. Ando et al., "Electric detection of spin wave resonance using inverse spin-Hall effect," Appl. Phys. Lett. 94, 262505 (2009).

(26) A. B. Shick et al., "Spin-orbit coupling induced anisotropy effects in bimetallic antiferromagnets: A route towards antiferromagnetic spintronics," Phys. Rev. B 81, 212409 (2010).

(27) E. S. Garlid et al., "Electrical measurement of the direct spin Hall effect in Fe/InxGa$_{1}$ − xAs heterostructures," Phys. Rev. Lett. 105, 156602 (2010).

(28) K. Olejnik et al., "Spin Hall and non-local spin valve detection of electrically injected and manipulated spins in a semiconductor," Preprint at http://arxiv.org/abs/1202.0881 (2012).

(29) K. Olejnik et al., "Detection of Electrically Modulated Inverse Spin Hall Effect in an Fe=GaAs Microdevice," Phys. Rev. Lett. 109, 076601 (2012).

(30) B. Huang et al., "Experimental realization of a silicon spin field-effect transistor," Appl. Phys. Lett. 91, 072501 (2007).

(31) B. G. Park et al., "Tunneling Anisotropic Magnetoresistance in Multilayer-(Co/Pt)/AlOx/Pt Structures," PRL 100, 087204 (2008).

(32) B. G. Park et al., "A spin-valve-like magnetoresistance of an antiferromagnet-based tunnel junction," Nature Materials 10, 347 (2011).

(33) C. Ciccarelli et al., "Spin gating electrical current," Applied Physics Letters 101, 122411 (2012)

(34) C. Brüne et al., "Evidence for the ballistic intrinsic spin Hall effect in HgTe nanostructures," Nature Phys. 6, pp. 448–454 (2010).

(35) K. Ando et al., "Electrically tunable spin injector free from the impedance mismatch problem," Nature Mater. 10, pp. 655–659 (2011).

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