Spin-related Nanosciences for Next Generation Innovative Devices

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Abstract- This paper provides an overview on recent development in spin-related materials-researches for next-generation innovative devices based on nanoscience in connection with the JST-PRESTO project "Materials and Processes for Next Generation Innovative Devices". Some of recent achievements of this project are also briefly reviewed.

Introduction

Silicon crystals used for semiconductor integrated circuits represented by CMOS are the materials indispensable to the contemporary information-based society, and can be regarded as the most basic material supporting today's living. Semiconductor manufacturing technologies are indivisibly related to nanotechnology, since they become more and more sophisticated as exemplified by the fact that the manufacturing accuracy of the CMOS micro-processing plunges into the nanometer range. Consequently the limit of 32 nm half pitch is approaching, at which micro-processing in silicon CMOS production line becomes extremely difficult, which in turn requires device development based on new concepts and/or new principles beyond conventional silicon CMOS technologies.

The PRESTO project "Materials and Processes for Next Generation Innovative Devices" for which I am dedicating myself as a Research Supervisor started in 2007 to overcome the limitation and break up a novel paradigm for next-generation device technology. The scope of this project involves spintronics materials, high-mobility wide-gap semiconductors, materials of strongly-correlated system including high temperature superconductors, quantum dots, nano-carbons, and organics.

Among the topics in materials researches listed above, the most exciting one may be spintronics. Spintronics (or spin-electronics) is the term to express a field of electronics utilizing both charge and spin degrees of freedom possessed by an electron, which have been treated independently until recently.

Spin-dependent Electronic Transport and Magneto-resistance

The phenomena of spin-dependent electrical transport such as spin-disordered scattering just below the Curie temperature and anisotropic magnetoresistance and anomalous Hall effect in

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ferromagnetic metals have been studied extensively and explained theoretically already in 1960's.[1, 2]. The situation has changed in the last decade of 20th century, when nanoscience and nanotechnology established in the semiconductor field spread to the field of magnetism. Grünberg found that two Fe layers separated by a Cr interlayer couple for a certain Cr thickness anti-parallel to each other could be aligned parallel to each other by applying an external magnetic field[3]. Eventually in 1988 he discovered a GMR effect of about 1% at room temperature in such a tri-layer system.[4] At the same time Fert's group independently discovered a GMR effect as large as 50% in a Fe/Cr superlattice at 4.2K by application of an external magnetic field of 1T.[5] Utilizing the idea of GMR, Parkin of IBM developed a magnetic sensor element "Spinvalve" [6], and introduced it to hard disk drives (HDD), which brought dramatic increase in the aerial record density of HDD. Thus human beings have obtained a mean to control even exchange interactions which has been considered to be inherent to individual material.

Further breakthrough in spintronics has been brought about by Miyazaki in 1995, who discovered the large tunneling magnetoresistance (TMR) of 18% at room-temperature in the magnetic tunnel junction (MTJ) consisting of ferromagnet/insulator/ferromagnet.[7] Although the spin-dependent tunneling phenomenon has been investigated from 80's,[8,9] practical application of TMR had not been realized due to difficulty in the control of the thin insulating layer until Miyazaki's group succeeded in fabricating very flat insulating layer without pinholes. The discovery initiated application of MTJ for the solid state magnetic memory MRAM and for high sensitivity HDD head. Theoretical predictions[10, 11] that extremely high TMR would be obtained by a use of MgO single-crystalline insulating layer instead of the amorphous Al-O layer initiated experimental challenges, and in 2004, Yuasa and Parkin independently succeeded in realizing a TMR ratio as large as 200% at room temperature by the introduction of a high quality MgO insulating layer.[12,13] The ratio has still been improved to as high as 500% at room temperature.[14]

Spin-Transfer Magnetization Reversal

In 1996, a new theoretical concept of the current-driven spin-transfer magnetization reversal was proposed by Slonczewski[15] and Berger[16] and was experimentally supported by Myers et al. in 2000.[17] Spin-polarized current injected from a ferromagnetic electrode transfers the spin-angular momentum to the counter ferromagnetic electrode to give rise to a magnetization reversal. Although a huge current density as large as 10^7-10^8A/cm^2 was necessary in the early stage of experiment using a GMR device, the recent technical development enabled to reduce it to a practical level of 10^6A/cm^2 by using a MgO-TMR device.[18] An effort to utilize the current induced magnetization switching to spatial light modulator has been done by Aoshima, who succeeded in observing the spin transfer switching phenomenon in current-perpendicular-to-plane Co_2FeSi spin valve by magneto-optical Kerr effect using visible light.[19]

In this way human being succeeded in converting electricity to magnetization without coils.

Concept of Spin Current and Spin-Hall Effect

Recent highlight in spintronics research is development of concept of the spin current.[20] Contrary to the charge current which is subjected to scattering by impurities and phonons leading to the short mean free path, the spin current undergoes less scattering at the instance of scattering leading to the longer mean free path, which in turn enables transferring information without energy dissipation. The spin-current can be observed not only in magnetic materials but in non-magnetic metals or even in nano-carbons: It was demonstrated by Shiraishi et al. that the spin current can be injected to a sheet of graphene by a careful experiment using a non-local magnetoresistance measurement.[21]

Since the spin current is defined as the difference between currents of the up-spin electrons and the down-spin electrons, no net charge current is necessary to produce the spin current if the flow directions of up- and down-spin electrons are opposite to each other. The spin Hall effect (SHE) is characteristic of the concept of the spin current: Contrary to the conventional Hall effect, Hall voltage is generated without an external magnetic field; an electric current induces spin current perpendicular to the direction of the current due to spin-orbit interaction, the idea having been proposed by Russian scientists[22], theoretically explained by Murakami et al.[23] and experimentally observed in n-type semiconductor by Kato et al.[24] Spatial imaging of the spin Hall effect and current-induced polarization in two-dimensional electron gases was demonstrated by the same group.[25] Saito et al. observed the spin voltage generated from a temperature gradient in a metallic magnet and name the phenomenon as spin-Seebek effect using a recently developed spin-detection technique that involves the SHE.[26]

Magnetic Semiconductors

Another important trend in spintronics is the magnetic semiconductor (MS). Mn-doped III-V semiconductors such as $In_{1-x}Mn_xAs$ and discovered by Munekata and Ohno are the first MS in which carrier-induced ferromagnetic coupling is confirmed. [27,28] The most remarkable point is the voltage-controlled ferromagnetic coupling observed in the FET structure. [29] Tanaka succeeded in fabricating MTJ with high TMR ratio in $Ga_{1-x}Mn_xAs$. [30] Carrier-driven domain-wall motion with very low carrier density (~10^5A/cm^2) has also been observed in MS.[31] However, in spite of a number of intensive studies, the Curie temperature Tc stays no higher than 250 K in Mn-doped III-V. Although a number of reports have been published on room temperature MS, origin of the magnetism is still under controversy. Among them Co-doped TiO_2 is considered as the most reliable MS material exhibiting carrier induced ferromagnetism at room temperature. [32]

Light-Induced Ultrafast Magnetization Reversal

The response time of magnetization reversal is usually limited by the spin dynamics which follow Landau-Lifshitz-Gilbert equation. Despite the fact Tsukamoto et al. have shown that light can directly interact with spin and demonstrated optical/thermal assisted control of spin dynamics in ferrimagnetic medium in less than picosecond timescale.[33,34] Mechanism of the fast magnetization reversal has not still been understood and under investigation.

Summary

I have introduced recent development in materials researches targeting next-generation innovative devices based on nanoscience, with a particular emphasis to spintronics. Some of recent achievements of the JST-PRESTO project “Materials and Processes for Next Generation Innovative Devices” are also briefly reviewed. We expect an opening of completely novel paradigm of electronics based on the spintronics to promote development of next-generation innovative devices.

References

[1] For example、G.K. White and R.J. Tainsh: Phys. Rev. Lett. **19** (1967) 165.

[2] A. Fert and I.A. Campbell: Phys. Rev. Lett. **21** (1968) 1190.

[3] P. Grünberg, R. Schreiber and Y. Pang: Phys. Rev. Lett. **57** (1986) 2442.

[4] G. Binasch, P. Grünberg, F. Saurenbad, W. Zinn: Phys. Rev. **B 39** (1989) 4828.

[5] M.N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friedrich, J. Chazelas: Phys. Rev. Lett. **61** (1988) 2472.

[6] S. S. P. Parkin, Z. G. Li and David J. Smith: Appl. Phys. Lett. **58** (1991) 2710.

[7] T. Miyazaki, N. Tezuka: J. Magn. Magn. Mater. **139** (1995) L231.

[8] R. Meservey, P.M. Tedrow, P. Flulde: Phys. Rev. Lett. **25** (1970) 1270.

[9] S. Maekawa, U. Gäfvert: IEEE Trans. Magn. **MAG-18** (1982) 707.

[10] W. H. Butler, X.-G. Zhang, T. C. Schulthess, J. M. MacLaren: Phys Rev. **B63** (2001) 054416.

[11] J. Mathon and A. Umerski, Phys. Rev. **B 63** (2001) 220403.

[12] S. Yuasa, A. Fukushima, T. Nagahama, K. Ando, Y. Suzuki: Jpn. J. Appl. Phys. **43** (2004) L588.

[13] S. S. P. Parkin et al., Nature Mater. **3** (2004) 862–867.

[14] Y. M. Lee, J. Hayakawa, S. Ikeda, F. Matsukura, H. Ohno : Appl. Phys. Lett. **90** (2007) 212507.

[15] J. Slonczewski: J. Magn. Magn. Mater. **159** (1996) L1.

[16] L. Berger: Phys. Rev. **B 54** (1996) 9353.

[17] E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, R. A. Buhrman: Science **285** (2000) 865.

[18] H. Kubota, Y. Suzuki and S. Yuasa: OYO BUTURI **78**, (2009) 231 (in Japanese).

[19] K. Aoshima, N. Funabashi, K. Machida, Y. Miyamoto, N. Kawamura, K. Kuga, N. Shimidzu and F. Sato: Appl. Phys. Lett. **91** (2007)52507.

[20] P. Sharma: Science **307** (2005) 531.

[21] M. Ohishi, M. Shiraishi, R. Nouchi, T. Nozaki, T. Shinjo, and Y. Suzuki: Jpn. J. Appl. Phys. **46** (2006) L605.

[22] M. I. Dyakonov and V. I. Perel: Sov. Phys. JETP Lett. 13 (1971) 467; M.I. Dyakonov and V.I. Perel: Phys. Lett. A **35** (1971) 459.

[23] S. Murakami, N. Nagaosa, S.C. Zhang: Science **301** (2003) 1348.

[24] Y.K. Kato, R.C. Myers, A.C.Gossard, D.D. Awschalom: Science **306** (2004) 1910.

[25] V. Sih, R. C. Myers, Y. K. Kato, W. H. Lau, A. C. Gossard and D. D. Awschalom: Nature Phys. **1** (2005) 31.

[26] K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa and E. Saitoh: Nature **455** (2008) 778.

[27] H. Munekata, H. Ohno, S. von Molnar, A. Segmüller, L.L. Chang, L. Esaki: Phys. Rev. Lett. **63** (1989) 1849.

[28] H. Ohno, A. Shen, F. Matsukura, A. Oiwa, A. Endo, S. Katsumoto, Y. Iye: Appl. Phys. Lett. **69** (1969) 363.

[29] H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y. Ohno, K. Ohtani: Nature **408** (2000) 944.

[30] M. Tanaka and Y. Higo: Phys. Rev. Lett. **87** (2001) 026602.

[31] M. Yamanouchi, D. Chiba, F. Matsukura, T. Dietl, and H. Ohno. Phys. Rev. Lett. **96** (2006) 96601.

[32] T. Yamasaki, T. Fukumura, M. Nakano, K. Ueno, M. Kawasaki: Appl. Phys. Express **1** (2008) 111302.

[33] A. Tsukamoto, K. Nakagawa, A. Itoh, A. Kimel, A. Tsvetkov, H. Awano, N. Ohta, A. Kirilyuk, and Th. Rasing: IEEE Trans. Magn. **40** (2004) 135.

[34] C. D. Stanciu, A. V. Kimel, F. Hansteen, A. Tsukamoto, A. Itoh, A. Kirilyuk, and Th. Rasing：Phys. Rev. **B 73** (2006) 220402(R).