Nanoscience Targeting Next Generation Innovative Devices

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Abstract- This paper provides an overview on recent development in materials researches targeting 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.

In this paper I will present some of the recent topics in this field referring to the recent achievements by the researchers affiliated to this project.

Rapid Development in Spintronics

The most exciting topic in materials science researches 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.

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 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

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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]

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] Thus human being succeeded in converting electricity to magnetization without coils.

Recent highlight in spintronics research is development of concept of the spin current.[19] 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.[20]

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[21], theoretically explained by Murakami et al.[22] and experimentally observed in n-type semiconductor by Kato et al.[23] 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.[24]

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. [25, 26] The most remarkable point is the voltage-controlled ferromagnetic coupling observed in the FET structure. [27] Tanaka succeeded in fabricating MTJ with high TMR ratio in $Ga_{1-x}Mn_xAs$. [28] Carrier-driven domain-wall motion with very low carrier density (~10^5A/cm^2) has also been observed in MS.[29] 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. [30]

The response time of magnetization reversal is usually limited by the spin dynamics which follow Landau-Lifshitz-Gilbert equation. Despite the fact Tsukamoto 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.[31] Mechanism of the fast magnetization reversal has not still been understood and under investigation.

We expect an opening of completely novel paradigm of electronics based on the spintronics to promote development of next-generation innovative devices.

Semiconductor technologies beyond Si-CMOS

Novel semiconductor nanodevices utilizing "stochastic resonance"[32] and their integration are now under investigation to realize state-of-the-art electronics hardware for noise-robust information processing. The stochastic resonance is a phenomenon that noise enhances response of a system, which plays an important role in nature and living things. Kasai designed, fabricated and characterized artificially controllable nanodevices in which the stochastic resonance takes place electrically. He integrated on semiconductor nanowire network structure to realize functionality for noise-robust information processing.[33]

Advances in performance and integration through conventional scaling of device geometries are now reaching their practical limits in planar MOSFETs. To overcome the limiting factors in planar MOSFETs, vertical structural arrangements called surrounding gate transistors (SGT) have been suggested as the basis for next-generation semiconductor devices. Fukada studies one dimensional Si and Ge semiconductor nanowires which are expected for the components in SGT.[34]

Transmission delay of wiring in a chip is a serious problem limiting the performance of the LSI. Intrachip optical interconnects will make it possible to enhance the performance of LSIs even in the post-scaling era. Takenaka is aiming at establishing fundamental technologies for one-chip super computers and photonic router chips using monolithic integration of Ge MOSFETs and Ge photodetectors on a Si substrate.[35]

Silicon power devices are facing limits of operating frequency, breakdown voltage, and power density. Wide gap semiconductors can replace silicon in high-temperature and power switching applications for high frequency devices, since they show higher saturation velocity and higher break-down voltage than conventional semiconductors. Among many wide gap materials III-V nitrides are the most intensively investigated materials for application to light emitting devices. It should also be noted that wide gap nitrides show quite large thermal conductivity, and is suited for solving the heat dissipation problem. Wide gap nitrides are therefore expected to have high potential in optical, electrical and thermal properties suited for optical interconnects and OEIC applications. However, the crystalline quality of the nitrides is far below that of silicon, because most of them suffer high density of misfit dislocations due to the lattice mismatch caused by heteroepitaxy on sapphire substrates. Use of nitride substrates for homoepitaxy has crucial importance to improve crystallinity of nitride materials. In our project Kangawa proposes a novel crystal growth process for AlN based on the first principle thermodynamic analysis. [36]

Nanocarbons and molecular electronics[37]

Carbon nanotube (CNT) was discovered by Iijima when he was observing carbon fibers using a high-resolution transmission electron microscope. [38] CNT is a seamless cylinder of carbon network by rolling a sheet of graphene, in which carbon atoms align to make a honeycomb-type hexagonal arrangement. Carbon nanotubes are classified into single wall nanotubes (SWNT) and multi wall nanotubes (MWNT). The radius of the cylinder ranges between 1 to 10 nm, and the length may be as long as 10 μm. On rolling up to form a cylinder the carbon network can be connected obliquely with a chiral vector ***Ch*** defined by a linear combination of two unit vectors $\boldsymbol{a}_1$ and $\boldsymbol{a}_2$ of hexagonal lattice as $\boldsymbol{Ch}=n\boldsymbol{a}_1+m\boldsymbol{a}_2$, where n and m are integers. Carbon atoms align in zigzags when n and m are zero. If n and m take equal nonzero values, i.e., $n=m\neq0$, and if the difference between n and m takes a value of multiple of three, carbon atoms make pairs to form an uneven armchair-like structure. CNTs with an armchair-like structure become metallic. On the other hand, for other combinations of (n, m), CNTs take the zigzag structure and become semiconducting.

Metallic CNT possesses a ballistic electronic transport property originated from the linear relationship between wavenumber k and energy E in the energy band dispersion curve. From the I-V characteristics it has been elucidated that the electron mean free path is as long as a few micrometers. Contrary to the copper wiring which suffers breaking down due to an electromigration for the current density exceeding 10^7A/cm^2, CNT is robust to a current density as large as 10^{10}A/cm^2. So the CNT can be an ideal conductor for wiring via in the next-generation devices.[39] The thermal conductivity of SWNT-CNT has been theoretically estimated by Berber et al. to be 6600 W/m·K, [40] which is far above that of diamond, 2000 W/m·K and is proved to be a promising material to overcome the heat dissipation problem in ULSI.

Field effect transistor (FET) employing the semiconducting CNT shows superior properties exceeding the Si MOSFET.[41] However, there are so many problems to be solved. The technology for discrimination and control of the chirality of CNT is still under development. It is also difficult to fabricate CNTs by self-organization at arbitrary point at which we design.

Recent research has revealed the peculiar nanoscale effects and edge effects in physical properties of graphene. In addition, the fine processing technology enables us to fabricate the electronic devices based on the nanographenes, and nano-carbon materials. Thus nano-carbons are attracting much attention all over the world as a promising key material for the innovative next-generation electronic devices. In our research project, Wakabayashi studies the electronic physical properties in the nano-carbon materials, and attempts to design the new electronic/spintronic devices based on nano-carbon with the support of the computational method.[42]

Organic Materials for flexible electronics[43]

Flexible electronics made with organic transistors may enable technologies such as low-cost sensors on product packaging and electronic paper displays. Thanks to recent development in organic LED, organic electronics has become the matter of interest for practical use. However, organic materials show electrical performances far below inorganic semiconductors. Therefore it is necessary to improve electronic transport properties represented by the low carrier mobility. Yasuda of our team aims to fabricate high-performance organic field-effect transistors using enhanced intrachain carrier transport along uniaxially aligned π-conjugated polymers.[44]

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.

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