SPINTRONICS TECHNOLOGY: A REVIEW

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Abstract— **Existing semiconductor electronic and photonic devices utilize the charge on electrons and holes in order to perform their specific functionality such as signal processing or light emission. The relatively new field of semiconductor spintronics seeks, in addition, to exploit the spin of charge carriers in new generations of transistors, lasers and integrated magnetic sensors. Spintronics utilizes the electron's spin to create useful sensors, memory and logic devices with properties not possible with charge based devices. This paper reviews the past successes, and the current and future prospects of spintronic materials and devices. Two and three terminal tunnel-junction based sources of highly spin polarized current are described as one component of possible spintronic logic devices, which have the potential for much lower power operation than charge based devices. This describes a new paradigm of electronics based on the spin degree of freedom of the electron. Recent advances in new materials engineering hold the promise of realizing spintronic devices in the near future.**

***Keywords*— Spintronics, TMR, MRAM**

I. INTRODUCTION

Two of the most successful technologies in existence today have created the Si Integrated Circuit industry and the data storage industry. In the case of ICs, the number of transistors on a chip doubles about every 18 months according to Moore's law. For magnetic hard disk drive technology, a typical desk-top computer drive today has a 40GB per disk capacity, whereas in 1995 this capacity was 1GB per disk. Since 1991, the overall bit density on a magnetic head has increased at an annual rate of 60–100%. The integrated circuits operate by controlling the flow of carriers through the semiconductor by applied electric fields. The key parameter therefore is the charge on the electrons or holes. For the case of magnetic data storage, the key parameter is the spin of the electron, as spin can be thought of as the fundamental origin of magnetic moment [1].

The characteristics of ICs include high speed signal processing and excellent reliability, but the memory elements are volatile (the stored information is lost when the power is switched-off, as data is stored as charge in capacitors, i.e. DRAMs). A key advantage of magnetic memory technologies is that they are non-volatile since they employ ferromagnetic materials.

The emerging fields of semiconductor spin transfer electronics seeks to exploit the spin of charge carriers in semiconductors. Among this new class of devices are spin transistors operating at very low powers for mobile applications that rely on batteries, optical emitters with encoded information through their polarized light output, fast non-volatile semiconductor memory and integrated magnetic / electronic / photonic devices (''electromagnetism-on-a-chip''). A proposed technology tree for spin-based devices is shown in Fig. 1

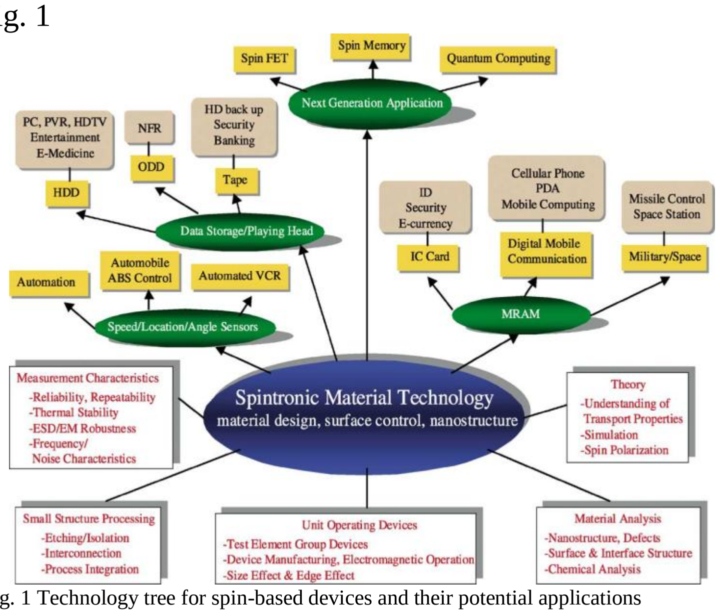

Fig. 1 Technology tree for spin-based devices and their potential applications

Spintronics are highly promising as a key technology for next generation [4]. They have the following two prospects: (1) Zero-emission energy and (2) replacement of CMOS technology (*i.e.*, beyond CMOS). From the first prospect, electron spin currents carry and emit no energy and no heat. This strong advantage resolves heat problems in large-scale integration circuits, personal computers, and also any systems loading them. From the second viewpoint, it is a desirable subject for human life to realize devices beyond CMOS FETs, which are approaching its integration and operation limits. Although many materials and technologies have challenged this, it has not yet been realized. Spintronic devices based on some kinds of ideas must realize this. For instance, operation utilizing spin flipping leads to extremely high switching devices (e.g., in Pico-seconds), which overcomes operation speeds of CMOS FETs and LSIs. There are two approaches for spintronics:

A) *Metal-based spintronics*

After the discovery of giant-magneto resistance (GMR) in magnetic (metal) multilayer's in 1988, which quickly became the standard technology for read-heads of current hard disk drives, a large tunnel-magneto resistance (TMR) between two magnetic metals separated by a thin insulator was demonstrated at room temperature in 1994 [5]. This magnetic tunnel junction (MTJ) is currently the preferred device for a magnetic random access memory (MRAM) cell. There are challenging device level issues to be solved, however, when MRAM technology is to be pushed beyond Gbit in scale; some of them being resolved by the emergence of the MgO-barrier MTJ [6, 7]. Beyond MRAM, there are schemes to utilize nonvolatility of MRAM not only as a memory but a part of reconfigurable logic-in-memory, which may provide a solution for today's memory bandwidth bottleneck [8].

B) *Semiconductor Spintronics*

There are several ways to create spin polarization and harness associated spin degree of freedom in semiconductors. One can create spin polarization by the use of circularly polarized light or electrical spin-injection and then utilize it in nonmagnetic semiconductors [9, 10, 11]. Or when electrons are confined in a quantum dot, the spin-dependent exchange interaction among them becomes important even without magnetic ions. The third approach is to introduce transition metal (magnetic) ions, which gives rise to exchange interaction between band carriers and the electrons localized at the magnetic ions. This has been shown to lead to hole-induced ferromagnetism in the case of InAs and GaAs alloyed with Mn [12], which made it possible to integrate ferromagnetism with existing nonmagnetic heterostructures, allowing exploration of a new dimension of spin-dependent phenomena in semiconductors. By the use of insulating-gate field-effect transistor structure to modulate carrier concentration, reversible electrical switching of the ferromagnetic phase transition and coercive force has been realized .CIMS has been observed at much lower current density than those in the metallic structures, either in the form of current-induced domain wall motion [13, 14] or in the form of magnetization rotation in nano-pillars. Because CIMS in semiconductors can be seamlessly integrated into semiconductor structures, ferromagnetic semiconductors may prove to be useful in developing spintronic devices that combine magnetization switching with other spin-related effects, once the transition temperature of these materials reaches well beyond room temperature.

II. MATERIAL SELECTION FOR SPINTRONICS

There are two major criteria for selecting the most promising materials for semiconductor spintronics. First, the ferromagnetism should be retained to practical temperatures (i.e. >300 K). Second, it would be a major advantage if there were already an existing technology base for the material in other applications. Most of the work in the past has focused on (Ga, Mn)As and (In, Mn)As. There are indeed major markets for their host materials in infra-red light-emitting diodes and lasers and high speed digital electronics (GaAs) and magnetic sensors (InAs). In samples carefully grown single-phase by molecular beam epitaxy (MBE), the highest Curie temperatures reported are 110 K for (Ga, Mn)As and 35 K for (In, Mn)As. For ternary alloys such as (In0.5Ga0.5)0.93Mn0.07As, the Curie temperature is also low 110 K. A tremendous amount of research on these materials systems has led to some surprising results, such as the very long spin lifetimes and coherence times in GaAs and the ability to achieve spin transfer through a heterointerface, either of semiconductor–

semiconductor or metal–semiconductor. One of the most effective methods for investigating spin-polarized transport is by monitoring the polarized electroluminescence output from a quantum well light-emitting diode into which the spin current is injected. Quantum selection rules relating the initial carrier spin polarization and the subsequent polarized optical output can provide a quantitative measure of the injection efficiency [15,16,17].

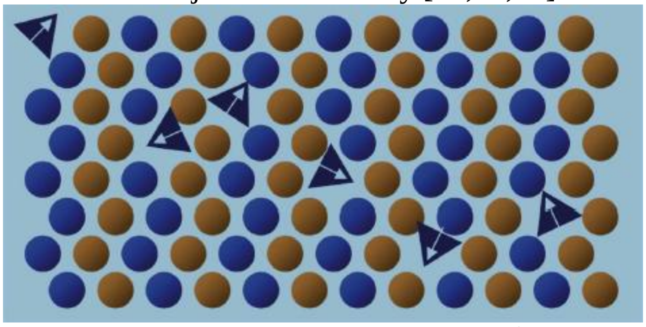

Fig. 2 Semiconductor matrix with high concentrations of magnetic impurities (i.e. Mn), randomly distributed (defects), can be insulators.

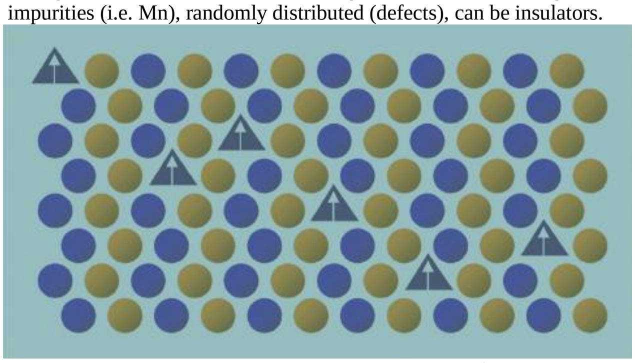

Fig 3 For the cases where there is high concentrations of carriers (i.e. (Ga, Mn)As where Mn ions behave as acceptors and provide magnetic moment)

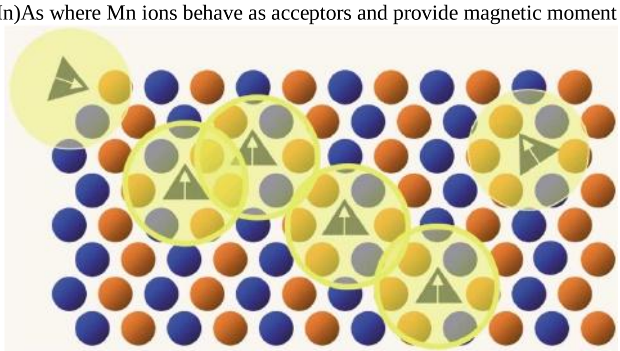

Fig 4 Below certain temperatures, a percolation network is formed in which clusters the holes are delocalized and hop from site to site.

There are a number of essential requirements for achieving practical spintronic devices in addition to the efficient electrical injection of spin-polarized carriers. These include the ability to transport the carriers with high transmission efficiency within the host semiconductor or conducting oxide, the ability to detect or collect the spin-polarized carriers and to be able to control the transport through external means such as biasing of a gate contact on a transistor structure. The observation of spin current-induced switching in magnetic heterostructures is an important step in realizing practical devices [18]. Similarly, spin orbit interaction in a semiconductor quantum well could be controlled by applying a gate voltage [19]. Combined with the expected low power capability of spintronic devices, this should lead to extremely high packing densities for memory elements.

III. Fundamentals of Spintronics

The rapid decrease in computational power and increase in speed of integrated circuits is supported by the very fast reduction of semiconductor devices feature size. Due to constantly introduced innovative changes in the technological processes, the miniaturization of MOSFETs by Moore’s law successfully continues. The 32-nm MOSFET process technology by Intel, involves new high-k dielectric/metal gates, which represents a major change in the technological process since the invention of MOSFETs. Although alternative channel materials with mobility higher than in Si were already investigated, it is believed that Si will still be the main channel material for MOSFETs beyond the 22-nm technology node [24, 25].

With scaling apparently approaching its fundamental limits, the semiconductor industry is facing critical challenges. New engineering solutions and innovative techniques are required to improve CMOS device performance. Strain-induced mobility enhancement is one of the most attractive solutions to increase the device speed, which will certainly maintain its key position among possible technological innovations for future technology generations [25]. In addition, new device architectures based on multigate structures with better electrostatic channel control and reduced short channel effects will be developed. A multigate MOSFET architecture is expected to be introduced for the 16-nm technology node. Combined with a high-k dielectric/ metal gate technology and strain engineering, a multigate MOSFET appears to be the ultimate device for high-speed operation with excellent channel control, reduced leakage currents, and low-power budget.

A) Physics of Spintronics

Spintronics is also called spin-electronics, where the spin of an electron is controlled by an external magnetic field and polarize the electrons. These polarized electrons are used to control the electric current. The goal of Spintronics is to develop a semiconductor that can manipulate the magnetism. Once we add spin degree of freedom to electronics, it will provide significant versatility and functionality to future electronics products. Magnetic spin properties of electrons are used in many applications such as magnetic memories, magnetic recording (read, write), etc.

The realization of semiconductor of semiconductors that is ferromagnetic. Above room temperature will potentially lead to a new generation of Spintronics devices with revolutionary electrical and optical properties. The field of Spintronics was born in the late 1980s with the discovery of the "giant magneto resistance effect". The giant magneto resistance (GMR) effect occurs when a magnetic field is used to align the spin of electrons in the material, including a large change in the resistance of a material.

In spintronics, information is stored and transmitted using another property of electron, acts like a compass needle, which points either up or down to represent the spin of an electron. Electrons moving through a nonmagnetic material normally have random spins, so the net effect is zero. External magnetic fields can be applied so that the spins are aligned. The effect was first discovered in a device made of multiple layers of electrically conducting materials: alternating magnetic and nonmagnetic layers. The device was known as "spin valve" because when a magnetic field was applied to the device, spin of its electrons went from all up to all down, changing its resistance so that the device acted like a valve to increase or decrease the flow of electrical current, called Spin Valves.

B) Spin Hall Effect

In order to realize spintronics as a fully operational technology, the ability to manipulate spin polarized electrons with in a conductor is necessary. A phenomenon called the spin Hall effect may be the solution. In the regular Hall effect, in a magnetic field is placed perpendicular to the direction of current. The reason for this is the electrons in the current flow in a conductor; a bias voltage will be created perpendicular to both across the conductor.

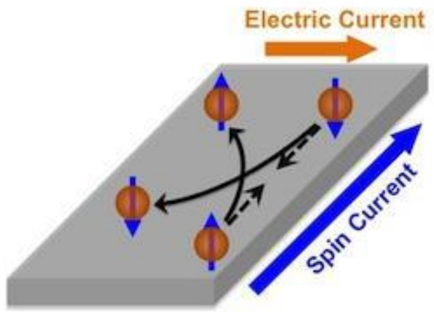

Fig. 5 Spin Hall Effect

C) Spin Injection into Semiconductors

The goal of spintronics research is to eventually relieve present information technology from solely relying on the charge of electrons. This spin degree of freedom of an electron has shown to be a very viable candidate to save the microelectronics industry from the result of "Moor's Law" which describes a trend of electrical components getting increasingly smaller, eventually reaching atomic scales.

Just recently, researchers have successfully injected spin polarized current into Silicon from ferromagnet. Since Si has no nuclear spin, there are no hyperfine interactions, resulting in very spin preservation for electrons inside the semiconductor.

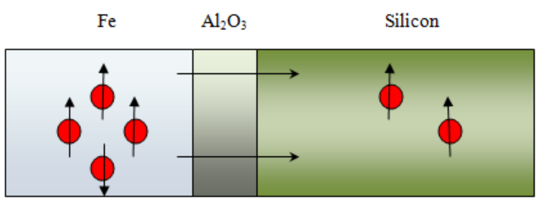

Fig. 6 Spin Injection in Semiconductor

IV. SPINTRONICS DEVICES

Recording devices, such as computer hard disks, already employ the unique properties of the materials. Data are recorded and stored any tiny areas of magnetized iron or chromium oxides. A "read head" can read this information by detecting minute changes in the magnetic field as the disk rotates underneath it. This induces changes in the head's electrical resistance, also known as magnetoresistance. Recent discovery of Tunneling

Magnetoresistance (TMR) has lead to the idea of magnetic tunnel junction that has been utilized for the MRAM (Magnetic Random Access Memory). Here, one has two magnetic layer separated by an insulating metal oxide layer. Electrons are able to tunnel from one layer to other only when magnetizations of the layers than in the standers GMR devices, known as “spin valves”. Spintronic devices, combining the advantages of magnetic materials and semiconductors, are expected to be fast, non-volatile and consume less power. They are smaller than s 100 nanometers in size, more versatile and more robust than the conventional ones making up silicon chips and circuit elements. The potential market is expected to be worth hundreds.

A) Spin Transistor

The basic idea of spin transistor, as proposed by Suprio Datt and Biswajit Das, is to control the spin the spin orientation by applying a gate voltage, as shown in fig.3. A spin –FET, as depicted below, consists of ferromagnetic electrodes and semiconductor channels that contain a layer of electrons and a gate electrode attached to the semiconductor. The source and drain electrodes are ferromagnetic (FM) metals. The spin-polarized electrons are injected from the FM source electrode (FMs), and after entering the semiconductor channels they begin to rotate. The rotation can be controlled by an applied electric field through the gate electrode. If the spin orientation of the electron channels is aligned to FM drain (FMd) electrode, electrons are able to flow into the FM drain electrode. However, if the spin orientation is flipped in the electron layer electrons cannot enter the drain electrode. In this way, with the gate electrode the orientation of the electron spin can be controlled.

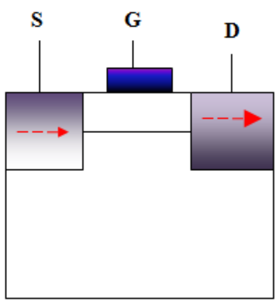

Fig.7 Schematic views of classical spin FET[S: Source, G: Gate, D: Drain]

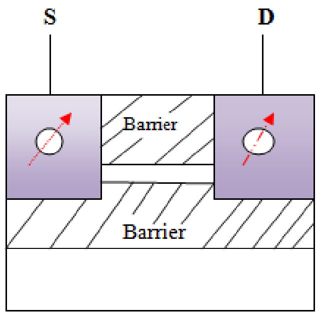

Fig.8 New approach suggested by Bandyopadhyay and Cahay [24]

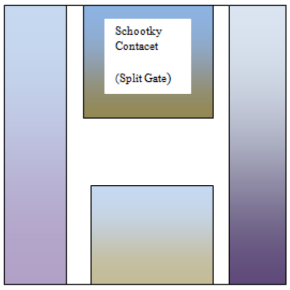

Fig.9 Top view of split gates

B) Spin (Magnetic) BJT

In a magnetic transistor, magnetized ferromagnetic layers replace the role of n and p-type semiconductors. Much like in a spin-valve, substantial current can flow through parallel magnetized ferromagnetic layers. However if say, in a three layer structure, the middele layer is antiparallel to the two side layers; the current flow would be quite restricted, resulting in a high overall resistance. If two outside layers are pinned and the middle layer allowed to be switched by an external magnetic field, a magnetic transistor could be made, with on and off configurations depending on the orientation of the middle magnetized layer. Magnetic (spin) transistors are good candidates for logic (spin logic).

C) Spin Valve with Giant Magneto Resistance

Spintronic device that currently has wide commercial application is the spin valve. Most modern hard disk drives employ spin- valves to read each magnetic bit connected on the spinning platters inside A spin-valve is essentially a spin “switch” that can be turned on and off by external magnetic fields. Basically it is composed of two ferromagnetic layers separated by a very thin non-ferromagnetic layer. When these two layers are parallel, electrons can pass through both easily, and when they are anti-parallel, few electrons will penetrate both layers. The principles governing spin-valve operation are purely quantum mechanical.

D) Spin LED's

Recently, efficient spin injection has been successfully demonstrated in all semiconductor tunnel diode structures by using a spin- polarized DMS as the injector in one case, and using a paramagnetic semiconductor under high magnetic field as a spin filter in the other. In such a case, spin- polarized holes and unpolarised electronics are injected from either side and recombine in a quantum well. The polarization of the injected holes can be left-circularly polarizes light in the electroluminescence spectra.

Among such devices the simplest seems to be the concept of a light emitting diode (LED) with one of the contact layers made ferromagnetic by incorporation of transition metal impurities, a so-called spin LED [17].

V. CONCLUSIONS

To continue the rapid pace of discoveries, considerable advances in our basic understanding of spin interactions in the solid state along with developments in materials science, lithography, miniaturization of optoelectronic elements, and device fabrication are necessary. The progress toward understanding and implementing the spin degree of freedom in metallic multilayers and, more recently, in semiconductors is gaining momentum as more researchers begin to address the relevant challenges from markedly different viewpoints.

This paper presents a summary of Spintronics (spin based electronics), is new upcoming technology for next generation of microelectronics/nanoelectronics devices with scaling apparently approaching its fundamental limits; the semiconductor industry is facing critical challenges.

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