A Modern Review of the Spintronic Technology: Fundamentals, Materials, Devices, Circuits, Challenges, and Current Research Trends

Muhibul Haque Bhuyan
American International University-Bangladesh

A Modern Review of the Spintronic Technology: Fundamentals, Materials, Devices, Circuits, Challenges, and Current Research Trends

Muhibul Haque Bhuyan

***Abstract*—**Spintronic, also termed spin electronics or spin transport electronics, is a kind of new technology, which exploits the two fundamental degrees of freedom- spin-state and charge-state of electrons to enhance the operational speed for the data storage and transfer efficiency of the device. Thus, it seems an encouraging technology to combat most of the prevailing complications in orthodox electron-based devices. This novel technology possesses the capacity to mix the semiconductor microelectronics and magnetic devices' functionalities into one integrated circuit. Traditional semiconductor microelectronic devices use only the electronic charge to process the information based on binary numbers, 0 and 1. Due to the incessant shrinking of the transistor size, we are reaching the final limit of 1 nm or so. At this stage, the fabrication and other device operational processes will become challenging as the quantum effect comes into play. In this situation, we should find an alternative future technology, and spintronic may be such technology to transfer and store information. This review article provides a detailed discussion of the spintronic technology: fundamentals, materials, devices, circuits, challenges, and current research trends. At first, the fundamentals of spintronics technology are discussed. Then types, properties, and other issues of the spintronic materials are presented. After that, fabrication and working principles, as well as application areas and advantages/disadvantages of spintronic devices and circuits, are explained. Finally, the current challenges, current research areas, and prospects of spintronic technology are highlighted. This is a new paradigm of electronic cum magnetic devices built on the charge and spin of the electrons. Modern engineering and technological advances in search of new materials for this technology give us hope that this would be a very optimistic technology in the upcoming days.

***Keywords*—**Spintronic technology, spin, charge, magnetic devices, spintronic devices, spintronic materials.

I. INTRODUCTION

THE prevailing semiconductor-based electronic and optoelectronic devices exploit the charges of electrons and holes to get any function done for us, such as data storage, data transfer, rectification, inversion, modulation, light transmission, light propagation, etc. Since we need devices with a higher processing speed and lower power consumption, therefore device sizes are being scaled down into the nanometer regime from the past, and we are now on the verge of the fundamental limit of scaling [1], [2]. Therefore, we need new technology and engineering-based solutions that can provide the same functionalities. In search of such solutions, a novel arena of semiconductor electronics evolved and it is now known as spintronic. Spintronic utilizes both spin and charge of electrons to make new types of devices viz. sensors, memory, and logic gates with the same properties of the existing devices based on the charge of electrons only. According to the traditional semiconductor integrated circuit manufacturing industry, the number of transistors incorporated inside a semiconductor integrated circuit doubles about every 18 months as per Moore's law [3]. In such type of integrated circuit, the applied electric field controls the carrier flow, i.e., the positive or negative charges of electron or hole to operate the device. Then again, in the magnetic data storage devices, the electron spin is used to operate it as spin can originate magnetic moment [4]. In this context, spintronic comes with very high prospects as one of the key technologies for the next generation semiconductor electronics. The two prospects of this technology are (1) zero-emission of energy and (2) replacement of the existing CMOS technology [5]. Based on the first prospect, the flow of current due to electron spin does not emit any energy, such as heat. This eliminates the heating problems of the Integrated Circuits (ICs). On the other hand, based on the second perspective, we need to fabricate devices beyond CMOS transistors as we are approaching its integration and operation limits. Due to these two key-problem solution capabilities through the spintronic, it has generated lots of interest among the researchers working on semiconductor devices. As such, this paper discusses in detail the fundamentals, materials, devices, circuits, challenges, and current research trends of spintronic technology.

M. H. Bhuyan is with the Department of Electrical and Electronic Engineering (EEE), Southeast University, 251/1 & 252 Tejgaon Industrial cum Commercial Area, Dhaka 1208, Bangladesh (corresponding author, phone: 88-01815-657346; e-mail: muhibulhb@seu.edu.bd).

II. SPINTRONIC FUNDAMENTALS

The requirements of reduced power consumption and higher operational speed of the ICs yield a fast reduction of device feature size. But the device miniaturization is now approaching its fundamental limits, thus the semiconductor manufacturing and process industries are confronted with several critical challenges [1], [2]. New and innovative devices alternative to the CMOS devices are essential. Spintronics technology can meet these requirements. Basic issues of this technology are covered in this section.

A. Ferromagnetism in Spintronics

For information technology to thrive ahead, spintronics technology is at the forefront [6]. When we want to discuss the spintronics-based magnetic semiconductor devices, ferromagnetism comes first [7], [8]. Ferromagnetism is defined as the property of a material for which the material can generate permanent magnetism or can attract the other magnets [9]. This property is found in a material when electrons are aligned to each other in the same direction inside the crystal lattice structure as shown in Fig. 1 and are denoted by the up arrow signs (↑↑↑↑↑) [10]-[12]. In other words, all electrons possess the same spin, either up spin or down spin. When all electrons align in parallel with the same spin then they can induce a large amount of net magnetization even when there is no magnetic field as revealed in Fig. 2 [12]. When a ferromagnetic material is kept in a magnetic field, the association of the applied magnetic field strength (*H*) and its magnetization (*M*) becomes non-linear, and then it unveils a hysteresis loop as presented in Fig. 3 [12]. This loop reveals four vital parameters that govern the suitability of applying this material in various devices. These four parameters are saturation magnetization (M_s), remanence (M_r), coercivity (H_c), and loop area as depicted in Fig. 3 [12], and are defined in the next paragraphs:

1. The saturation magnetization (M_s) is defined as the final value of magnetization in the ferromagnetic hysteresis loop after applying a sufficiently large value of the magnetic field intensity so that saturated magnetization is obtained and after this if the value of magnetic field intensity is raised further, the magnetization value remains almost constant.
2. Remanence (M_r) is defined as the magnetization value revealed in a ferromagnetic material even after removal of the applied magnetic field intensity. This phenomenon is observed due to the retaining of the partial parallel alignment of the spin after magnetizing the material. Therefore, to demagnetize the material, heating is required until Curie temperature is reached or an oppositely directed magnetic field is applied.

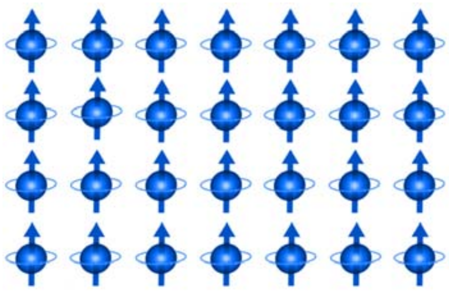

Fig. 1 One state of electron spin (up) to form ferromagnetism [11]

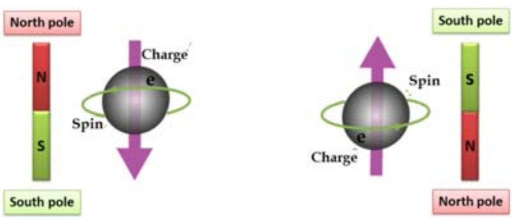

Fig. 2 The two states of electron spin (up and down) and the mechanism of ferromagnetism formation for both cases [11]

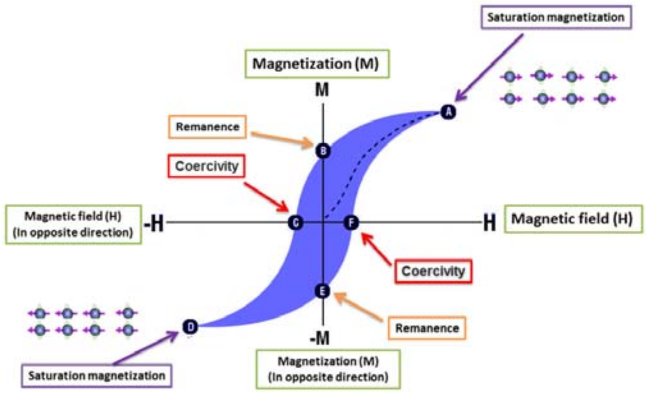

Fig. 3 Ferromagnetic hysteresis loop (*M-H* curve) observed in the ferromagnetic materials [11]

3. Coercivity (H_c) is defined as the opposition provided by the ferromagnetic material when it is tried to be magnetized or demagnetized with the application of external magnetic field intensity.
4. The Loop Area of a ferromagnetic material loop is defined as the amount of magnetic energy expended as heat energy in the material. It can be obtained by integrating the area under the *M-H* curve of Fig. 3 [12].

If the ferromagnetic hysteresis loop's area is narrower, the ferromagnetic material is called soft, and if the area is wider, the ferromagnetic material is called hard material [13]. This area is an important parameter because this determines how fast the electronic device can operate. If the area is narrow then the magnetism reversal process is faster as the current direction is changed. For example, if it is needed to store data in the magnetic hard drive then the process can be completed quickly. As such, the narrower hysteresis loop area dissipates small energy in the device [13]. Similarly, the magnetic cores used in transformers and electric motors are fabricated from soft ferromagnetic materials due to the negligible energy dissipation and hence produce less heat in the machine. On the other hand, many memory devices, viz. acoustic recording, hard disk drives, credit cards, random access memory (RAM), microprocessor, cache memory, etc. are commonly created from hard type ferromagnetic materials due to the high values of remanence and coercivity of these materials. The high values indicate that the data stored in the memory cannot be obliterated simply [14].

B. Working Principle of Spintronic Devices

The basic operation of the spintronic devices depends on two important issues of the electron:

1. Any two adjacent cells containing electrons can have reverse spin direction, and
2. Only two adjacent cells can cooperate.

Now, if two adjacent electrons in a row have up spins then it is considered as binary logic '1', and if they have down spins then it is considered as binary logic '0'. But if one electron between the two adjacent electrons on an electron cell has an up spin and the other one has a down spin then that electron cell is called a quantum dot. When a very weak DC magnetic field is applied then it causes a Zeeman splitting effect between the up and down spins. If this weak field favors up spin orientation and if one cell has up spin and the other one has down spin then the cell will possess the up spin. In the same way, if this weak field favors down spin orientation and if both cells have down spin then the cell will possess the up spin, otherwise it will possess the down spin [15].

C. Physics of Spintronics

The word 'spintronics' comes from the two words, viz. spin and electronics. An electron's spin can be organized by applied magnetic field intensity and thus can be polarized to regulate the flow of electric current. That means, we want to develop a semiconductor that is capable to create an impact on the magnetic property of the device. Since the device now has two degrees of freedom to electronics, viz. charge and spin, thus, it would afford a vital extent of flexibility and functionality to the forthcoming electronics devices. Above room temperature, this new generation of spintronics devices will bring revolutionary changes in terms of electrical and optical properties. This new branch of spintronics was evolved in the late 1980s when the 'giant magnetoresistance (GMR) effect' was discovered [16]. The GMR effect arises if a magnetic field is applied to line up the spin of electrons in the material, and hence a huge change of its resistance [17].

When the electrons move through a non-magnetic material then they have random spins as such the net spin effect is zero. But if an external magnetic field is applied then their spins are aligned in the same direction. This effect was discovered in a device having multiple strata of electrically conducting materials, such as alternating magnetic and non-magnetic layers for the first time. Such type of device was called 'spin valve' because an applied magnetic field to the device can reverse the spin of its electrons that is all up spin may become all down spin or vice-versa. In this process, resistance is changed so that the device can act as a valve to change the electric current flow [18], [19].

D. Spin Hall Effect

To comprehend spintronics entirely, we need to know how to employ the spin-polarized electrons in the conductor. Like the classical Hall Effect in any material, there is another phenomenon for the spintronics device called the spin Hall Effect. To obtain the classical Hall Effect, a magnetic field is employed with the electric current in the normal direction. Thus, the Hall voltage is created in the third direction vertical to both electric and magnetic field [20]. In contrast, the spin Hall Effect [21] is a transport phenomenon comprising the presence of spin gathering on the side planes of a device flowing electric current. The opposite planes have opposite spins similar to the opposite charges found on the opposite side planes of the current-carrying conductors in the cases of classical Hall Effect for which the charges build up at the two opposite planes at the boundaries to compensate for the Lorentz force working on the charged particles inside the materials due to the magnetic field. The spin Hall Effect is only a spin-based phenomenon.

E. Spin Injection into Semiconductors

According to Moor's Law, the trend of transistor counts is getting doubled every ten years, and as such their sizes are also getting progressively reduced, ultimately attaining at the atomic levels [22]. But if the transistor counts can be increased further then we can enhance the performance parameters. The main goal of research on spintronics is to gradually relieve the semiconductor industry from the dependence on the charge of electrons by including the spin of electrons also so that with the two degrees of freedom of an electron, we can incorporate more transistors and hence more functionalities in the devices to come in the future. For example, if we can inject spin-polarized current into the Silicon from the ferromagnetic material then we can increase its performance, such as reducing the power consumption and increasing the speed of operation. An investigation was carried out by a group of researchers at the interface magnetization of $SrTiO_3$/ $La_{0.5}Ca_{0.5}MnO_3$/$La_{0.7}Sr_{0.3}MnO_3$ heterojunctions and it was found that a new spin-polarized current injection can induce the interface magneto-electric effect [23].

III. Spintronic Materials

To realize spintronics-based devices and circuits and use the same for various technical applications, we need to find suitable materials for it. We know that spintronics creates bonding among three properties of the materials, such as ferromagnetic, semiconducting, and ferroelectric together in a single or hetero-structure of the material. However, there should be some criteria to select a particular material for realizing spintronics. From the literature, we found two such major criteria, viz. 1) the ferromagnetism (FM) must be kept approximately at room temperature (i.e., ~300 K), and 2) the material should have applications based on the existing technology [24]. In the past, the researchers mainly focused on GaAs or MnAs and InAs or MnAs materials. These were mainly used as the host materials for infra-red light-emitting diodes, lasers, GaAs-based high-speed digital electronics, InAs-based magnetic sensors, etc. For example, GaAs/(In, Ga)As-based light-emitting diode covered with Fe was demonstrated by injecting spin-polarized electrons from a metal into a semiconductor [25]. The circular polarization degree of the observed electroluminescence discloses a spin injection efficiency of 2%. However, though very low to be used in practical applications, the highest possible Curie temperatures obtained were 110 K and 35 K for GaAs or MnAs and InAs or MnAs materials respectively [24]. Even for ternary alloys, such as $(In_{0.5}Ga_{0.5})_{0.93}Mn_{0.07}As$, the obtained Curie temperature was also 110 K. In the dilute magnetic semiconductor (DMS) materials, for example, GaN, MnN, GaP, MnP, ZnO, MnO and $ZnSiGeN_2$, $MnSiGeN_2$ the FM property was found at room temperature, and it can be applied in several novel devices, like spin-polarized light emitters and spin field-effect transistors [26]. A III-V semiconductor of $In_{1-x}Mn_xAs$ ($x \leq 0.18$) material grown using molecular-beam epitaxy (MBE) at 300 °C is also found to possess FM properties [27].

When the GMR effect was discovered in the metallic multilayers, the era of the first-generation spintronics began and it impacted the mass data storage device-making industries. When the focus was shifted to the integration of the magnetic and semiconductor materials together to have new capacities of the electronic devices, the era of second-generation spintronics started.

In the beginning, the spin phenomena were explored within the conventional FM materials. However, the study of spin generation, relaxation, and spin-orbit coupling in non-magnetic materials started recently with the arrival of hybrid spintronics and it has the greatest promises in the progress of the technical fields. The hybrid spintronic devices include FM metal and alloys, half-metallic materials, and two-dimensional (2D) materials, etc. The FM and alloys possess spontaneous magnetization and high Curie temperature (T_C), the half-metallic materials enjoy high spin polarization near the Fermi level (E_F), and the 2D materials confirm unique band structures with the Fermi-Dirac cone and valley degree of freedom (DoF) of the charged particles. Due to the continuous improvement in the device growth technology, like synthesizing the epitaxial hybrid spintronic materials, the new structures and properties of the spintronic materials are being evolved from the atomic dimensions and hetero-interfaces [28].

Not only the group-IV materials, but also the group III-V, and II-VI semiconductors and their nanostructures have spin injection and detection with the 2D materials, for example, graphene, transition metal dichalcogenides (TMDs), and topological insulators (TIs). This new trend was found very interesting due to their long spin lifetime and strong spin-orbit coupling induced spin-momentum locking because of which we may probably have the electronic transport without any power dissipation. Besides, applied light and electric fields in Mn-based III-V and II-VI diluted magnetic semiconductors can inject spin and tune magnetism [29].

We are heading towards the next-generation electronic devices and this would be based on the 2-D FM semiconductors, but we cannot progress with it as FM coupling is very fragile and the Curie temperature (TC) is very small. One group of researchers reported a general mechanism by which they had demonstrated how to improve the FM coupling in 2-D semiconductors without any need for the mobile carriers. They discovered that the super-exchange-driven FM is mainly linked to the virtual exchange gap based on a model named double-orbital, and they also showed that if this gap is lowered by iso-valent alloying then it is possible to augment the FM coupling considerably. The FM coupling in two semiconducting alloy compounds, such as $CrWI_6$ and $CrWGe_2Te_6$ monolayers are calculated to be enhanced by 3-to-5 times by not using any carriers based on the 2-D CrI_3 and $CrGeTe_3$ materials that are experimentally available [30]. Likewise, at room temperature FM semiconductor is realized under a small in-plane strain of 4% and thus their findings developed the knowledge on FM semiconductors and exposed a new arrival for realistic execution of spintronics devices from such materials.

Some research results on spintronic materials with the FM property were obtained for the transparent transition metal-doped titanium dioxide (TiO_2), which was recommended for realizing the spintronics devices [31]. Besides, for spin-FET devices, several substrate materials viz. InAs, InAlAs, etc., and some 2-D materials viz. graphene, silicone, etc. were proposed as the channel materials. On the other hand, various FM and half-metallic electrodes viz. Co, Ni, CrO_2 were used in these devices as the contact materials [32].

IV. Spintronic Devices

To design the real-time efficient spintronic devices, there are several vital parameters to be checked, such as the ability to inject spin-polarized carriers electronically, transport carriers efficiently within the host semiconductor or conducting oxide, detect or collect the spin-polarized carriers, and control carriers transport by external fields, such as gate bias. When the researchers first found the spin current-induced switching in magnetic heterostructures, they started to become hopeful concerning the real-world spintronic device realization [33]. Likewise, gate voltage applied to the semiconductor quantum well could yield the control of spin-orbit interaction in the spintronic devices. They have the advantages of very low power consumption and extremely high packing density and made them a good choice for memory devices [34].

The first-ever marketable product based on the GMR, by harvesting the benefits of spintronics technology, is the read heads of the magnetic hard disk drives (HDD) used in computers by IBM [35]. Data are stored and recorded in tiny areas of magnetized iron or chromium oxides. A ‘read head’ can access these data by sensing the little fluctuations of the magnetic field as the disk revolves beneath the head. Thus, the electrical resistance of the head is changed, and hence it is called magnetoresistance. However, due to the discovery of the Tunneling Magneto-resistance (TMR), the magnetic tunnel junction (MTJ) device has been fabricated to be utilized to implement the Magneto-resistive Random Access Memory (MRAM) device. This device offers the benefits of 1) non-volatility with infinite read-write cycles, 2) high-speed of the order of sub-10 ns regime, 3) ability to reconfigure the logic functions, 4) high memory bandwidth, and 5) high packing density [36], [37].

Spintronic devices integrate the benefits of magnetic and semiconductor materials to have faster, smaller-sized, versatile, robust, non-volatile, and low-power consuming devices than the conventional semiconductor devices to make silicon-based integrated chips and circuit elements. The present market value of spintronics devices is increasing day by day due to the growing demand for MRAM devices in the spintronics market, which was estimated globally at $362.7 million in 2019, and is anticipated to cross the $12,845.6 million by 2030 [38], [39].

Spintronic devices based on spin flipping can provide the high switching speed of the order of picoseconds), and hence can overcome the operational speed barrier of CMOS-based devices. There are various kinds of spintronics devices and a few of them are described in the following sub-sections.

A. GMR Devices

GMR device is a kind of metal-based spintronics device. It was discovered in 1988. It is an effect of quantum mechanical magnetoresistance. When a thin film structure of alternating FM and nonmagnetic layers, such as Fe/Cr multi-layer, Fe/Cr/Fe tri-layer, etc. is created then such effect is exhibited. This effect can reduce the electrical resistance of the order of 80% when a magnetic field is imposed, and hence is used commercially by the HDD manufacturers. The resistance reduces in the multilayer due to the applied magnetic field that tries to align the magnetic moments and thus scattering of electrons is weak. Parallel spin also saturates the magnetization of the consecutive FM layers. When there is no magnetic field, the magnetizations of the FM layers become antiparallel, and hence scattering of electrons is strong and thereby increasing the resistance [40]. The GMR ratio is defined by (1):

$$GMR = \frac{R_{AP} - R_P}{R_P} \times 100\% \tag{1}$$

where R_{AP} and R_P mean the resistances at antiparallel and parallel states respectively. The higher value of the GMR ratio is desired to have the higher value of the sensitivity.

B. Tunnel Magneto Resistance Devices

The tunnel magneto-resistance (TMR) effect is a fundamental spintronic phenomenon based on which the TMR device is fabricated. It is also a kind of metal-based spintronics device and was discovered in 1995. A barrier layer with insulating property is prepared in between two layers of FM material. The electron spins of these two layers have the same direction, and thus the electron scattering is reduced, and hence the barrier layer with thin thickness can allow the electrons a low-resistance path to transit through it by the tunneling phenomenon [41]. The incoherent tunneling is normally demonstrated in the AlO_x-based MTJ. The TMR ratio is defined by (2) as per Julliere's model [42].

$$TMR = \frac{2P_1P_2}{1 - P_1P_2} \times 100\% \tag{2}$$

where P_1 and P_2 are the spin polarizations of two FM layers respectively. The highest TMR ratio at room temperature was found as 70.4% in AlO_x-based MTJs [43]. The TMR device is now the standard technology for read-heads of current HDD.

C. Semiconductor Spintronics

Spin polarization can be generated in the semiconductors in various ways to harness accompanying spin degrees of freedom. There are three approaches of which as per the first approach, it may be generated using circularly polarized light or electrically injected spin to be exploited in the non-magnetic semiconductor materials [44]. According to the second approach, the first electrons are confined in a quantum dot, and then the spin-based exchange communication amongst these electrons becomes significant even in the absence of magnetic ions. As per the third approach, transition metal (magnetic) ions are introduced to increase the exchange communication between the bound carriers and the contained electrons in the magnetic ions. This develops hole-induced FM in group III-V FM semiconductor materials, such as InAs and GaAs if alloyed with Mn [45]. As such, we can incorporate FM with the prevailing nonmagnetic hetero-structure materials to realize the spin-based phenomena in the semiconductor materials. We can manipulate the magnetization methods in a FM semiconductor electrically. In that case, the low-density carriers are accountable for the FM. The coercive force H_C can be employed to reverse the charged carrier density and hence magnetization by applying an external electric field to the gate of hetero-structure [46].

D. Spin Diode

Like conventional diodes, spin diodes are also two-terminal devices. It is designed by inserting the device between two antiferromagnetic materials. The resistance of the device can be changed if the antiferromagnetic axes' orientations are altered, this will ultimately change and magnify the resonant frequency of the spin diode three times. The properties of the spin diode also depend on the spin polarization of its carriers and hence the diode current. There are many applications of spin diodes, such as spin torque diodes may be used as energy harvesters at microwave frequency, microwave generators with a dc bias current, signal rectifiers, low pass filter [47], diode-based logic families [48], etc.

E. Spin LED

The spin-based light-emitting diode (LED) uses FM electrode on the semiconductor LED structure The electro-luminescence phenomenon in LED comprising metal/insulator/semiconductor (MIS) assembly with the FM electrode for the magnetization was observed. The materials used here are Co, Fe, and NiFe as FM metals, Al_2O_3 as an insulator, and AlGaAs as a semiconductor, and thus the hetero-structure is obtained. Thus, the spin-injection is attained from the FM material to the semiconductor without any applied magnetic field. However, the spin-injection efficiency is very poor, approximately 1% at room temperature [49].

For the first time, all-semiconducting hetero-structured devices were realized. A group of researchers injected spin-polarized electrons into a non-magnetic semiconductor, like GaAs through a II-VI diluted magnetic semiconductor (DMS) $Be_xMn_yZn_{1-x-y}Se$ used as a spin aligner [49].

Electroluminescence with nearly pure circular polarization (CP) at room temperature (RT) together with electrical helicity control has been demonstrated by a lateral-type spin-polarized Light-Emitting Diodes (LT-spin-LEDs) consisting of AlGaAs/GaAs double-hetero-structures and the crystalline AlO_x(x-AlO_x) tunneling barrier [50].

F. Spin Transistor

A spin transistor is a novel device that combines the working principles of a traditional transistor with the spin of a magneto-resistive device. They may be used in the new form of ICs exploiting spin degrees of freedom. This novel transistor was first proposed in 1990 in pursuit of an optical device with a perpendicularly oriented polarizer and an analyzer [51]. The remarkable aspects of spin transistors are their nonvolatile information storage and reconfigurable output features, unreachable features of conventional transistor-based circuits, and these are highly beneficial and appropriate for numerous novel IC designs. In the novel ICs, spin transistors can be used in nonvolatile and reconfigurable logic-based circuits [52].

G. Spin FET

Spin Field-Effect Transistor (spin-FET) is one of the most fascinating spintronic devices. It comprises a FM electrode and semiconductor channel together with a stratum of electrons in the channel. However, the source and drain electrodes are made of FM metals that supply the spin-polarized electrons to the semiconductor channels. An extra electric field controls the supply and rotation of electron spins in the channel through the gate electrode connected to the semiconductor material. If the electron spins of the channel and FM drain (FMd) are aligned in the same direction then such electrons can drift from the channel into the FMd. Instead, if the electron spins are not lined up in the same direction, then such electrons cannot drift from the channel into the FMd. However, the alignment of electron spins can be controlled by the gate electrode [53].

H. Spin BJT

A variety of spin equivalent orthodox transistors was already proposed by different researchers. Of them, we found two varieties of spin-BJTs viz. Unipolar Spin Junction Transistor (USJT) very much similar to the orthodox BJT and Bipolar Spin Junction Transistor (BSJT) which is similar to the orthodox BJT with the only exception of an FM based on it and a non-zero equilibrium spin polarization. It is an assembly of three layers that are used as emitter, base, and collector; the central layer is the base that possesses antiparallel spin to the other two lateral layers that possess the same spin. These spins are the majority spins (like majority carriers in orthodox BJT) in the respective layers. Now if all layers have the same majority charge carriers, then the device is called unipolar (USJT) and if the majority charged carriers of the base and to that of the emitter and collector are with different polarity then the device is called bipolar (BSJT). If two side layers are held and the central layer is switched by an external magnetic field then the magnetic transistor operation is possible having the on-off patterns based on the spin direction of the mid-layer [54].

I. Magneto-Resistive Random Access Memory (MRAM)

MRAM is a kind of solid-state storage IC. It writes and preserves the data as stable magnetic states and reads data by calculating the resistance of the devices to identify their magnetic states. The commercially-produced MRAM devices and the vast majority of MRAM technologies being developed for future commercial MRAM devices are based on MTJ devices [55]. Though the read operation is based on resistance calculation the write operation is based on changing the magnetic states. The MRAM technologies differ in the methods of setting up the magnetic states during the write operation. Of these, methods Stoner-Wolfarth field switching, Savtchenko field switching, spin-torque switching, and thermally assisted field or spin-torque switching methods are mentionable. Savtchenko field switching-based toggle MRAM device [56] and spin-torque switching-based MRAM device [57] have already been commercialized.

A low-power 0.18 μm, 4Mb MRAM with a new magnetic switching mode was also found in the literature. The memory is based on a 1-Transistor, 1- MTJ bit cell with five metal layers having a cell area of 1.55 μm^2 for each bit. Performance improvement of this new architecture and switching mode was observed for this MRAM over the orthodox MRAM [58].

We know that the current memory devices like SRAM and DRAM used in computers need electricity to store data. As such, most of the RAMs are volatile memories i.e., they lose data when power is turned off. However, the novel MRAM is a non-volatile memory because the MRAM is based on MTJ devices. MTJ is a three-layer device with a thin insulating layer between two FM. Thus, a few electrons can cross the barrier rather they can tunnel through the FM layers when they have the same spins. However, if spins are opposite this tunneling cannot happen. That is, MRAM requires electricity to change the spin direction but not to grip them since it stores data by the magnetic field, not by an electric field. Besides, MRAMs occupy less area, have a large storage area, require low cost, respond faster than Electrically Erasable Programmable Read-Only Memory (EEPROM) and Flash Memory at least one hundred times, can provide reliability in high temperature, can radiate and interfere at a high level, can erase the previous data before writing the new data [59].

J. Spin Valve with GMR

Spin-valve is principally a kind of magnetic switch that is turned on and off through an applied magnetic field to change the magnetic spins of the charge carriers. It is used in HDD to read stored data from the spinning platters of HDDs. Spin valve is one of the most common among several types of spintronic devices already been commercialized. It consists of two FM layers detached by a very thin non-FM film. When they have parallel spins, electrons can traverse them easily, and when they have anti-parallel spins, very few electrons can pass these levels. In a spin valve, the interchange of coupling between the magnetic layers is inhibited by splitting them using a dense nonmagnetic layer in between them. One of the magnetic layers is restrained by interchanging the bias with an anti-FM material layer, viz. FeMn. Then the other magnetic layer is kept free to shift in a weak magnetic field. To avoid the impact of low Curie temperature of the anti-FM material, a coupled multilayer with Co/Ru is used very often [60].

K. Spin Filter

The spin filter can detect spin accumulation. It can separate the unlike spin alignments depending on their energies. Thus, it can permit the acquisition of spin-polarized charge carriers made by non-magnetic electrodes using the magnetic tunnel barrier. It is found that magnetic tunneling through FM semiconductors can be altered by an applied magnetic field. The non-linear exchanges between spin accumulation and charge can also facilitate the transformation of spin accumulation into charged currents even if there is no applied magnetic field. The degree to which the spin polarization will occur is governed by the incident energy and direction of the electrons [61].

V. Application Areas of Spintronic

There are many application areas where spintronic devices and circuits are being utilized successfully. In the following subsections, some of these areas are discussed.

A. Quantum Computers

Spin-based quantum computing is prominent know-how to implement quantum computers at various levels. In the semiconductor, quantum dots are employed to trap discrete charges and their accompanying spins to be used as quantum bits (qubits) that are defined by the spin state of a single electron confined in the quantum dots. Quantum computing requires a high level of external control, long quantum coherence time, high storage capacity (as the number quantum bits increases, storage capacity increases exponentially), fast processing speed, parallel computation, etc. Various physical structures were suggested to fabricate the quantum computers, but daunting hindrances for even a simple structure is a few hundred qubits. The researchers tried to use the electron spin as the qubit in numerous ways and means. One such method was to make the spin of 2-D electrons floating on the surface of the liquid helium (He) for qubits. The electrons can then be held electrostatically and deployed similar to that in the semiconductor hetero-structures. Since they are in the vacuum, therefore the spins on He suffer less de-coherence [62]. However, architecture for quantum computer processing based on silicon complementary metal-oxide-semiconductor (CMOS) technology was also proposed by another group of researchers. They used a transistor-based control circuit with charge-storage electrodes to operate a thick and scalable 2-D qubit system. The qubits were combined through exchange interactions and controlled using a microwave cavity, and measured by the gate-based dispersive readout. They implemented a spin qubit surface code as well [63].

B. PCB Defect Detection Using GMR

Printed Circuit Boards (PCBs) are extensively being used to implement various electronic circuits and devices. However, it must be free from all defects for reliable operation of the circuit. Several chemical and mechanical steps are required to make a PCB, but sometimes these steps may be harmful to our designed product. Commercially available testing methods for PCB, such as Automatic Visual Inspection (AVI) cannot detect some of the actual defects. To alleviate this problem, a high-speed, low-cost, non-contacting, portable method is used based on Eddy Current Testing (ECT) in which ECT probes, used to detect the PCB faults, are based on AMR or GMR sensors due to their low noise, wide frequency range, low cost, better directional, and high output. ECT probes are made of coil and spin valve-based GMR sensors that can accurately detect any faults on the PCB surface [64].

C. GMR in Magnetic Recording

GMR-based spin valve sensors are used in HDD. The main reason for using a spin valve is that it is flexible because it can be altered by increasing additional layers or exchanging the materials used in a particular layer. To get high-density recording status, separate read and write transducers are used and optimized accordingly [65].

D. Current Sensor Based on GMR

GMR can be used as current sensors to be employed in the smart grid. Such sensors are cost-effective and useful for observing steady-state and transient conditions. When current flows through a wire, it creates a magnetic field that can be measured by using the GMR sensor positioned at a very close position to the wire. The wire is wrapped around a magnetic ring. GMR sensor is then inserted in between the ring and wire. A wheat stone bridge connected to the device converts the magnetic signal into a voltage signal. The GMR sensor can sense magnetic fields from DC to 1 MHz of frequency. In a smart grid, the current fluctuates from 1 μA to 200 kA at the frequency ranges from DC to 100 MHz. GMR effect-based current sensors are used to measure the current due to its high linearity, high sensitivity, small volume, simple structure, and low cost. GMR sensors can be employed even in large-scale distributed systems to acquire real-time data for the smart grid [66].

E. Magneto-Logic Gates

To improve the computational performance of conventional CMOS-based logic circuits consisting of combinational and sequential logic blocks for Boolean functions evaluation, single or multi-layer MTJ transistors can be used. In one research paper, it was found that the logic state is ascertained by the single-layer MTJ's resistance known as the TMR, which depends on the relative magnetization polarity of the free and fixed layers, that is MTJ is a two-level resistor. The resistance becomes high if the magnetic layers are in an antiparallel arrangement, and low if they are in a parallel arrangement. The high and low resistances are marked as logic-1 and logic-0 respectively. The layer polarity can be altered by changing the applied magnetic field. The output voltage of the MJT is a maximum of 100 mV, but it is not too sufficient to incorporate with a semiconductor. To have the AND/OR logic operation, MJTs may be connected in series or parallel. Such a method reduces the surface area occupation of the device and the leakage current. This process requires fewer step numbers and superior flexibility in their operation and uniformity also [67].

In another model, the researchers proposed spin-transfer torque-driven magneto-logic NOR and NAND gates using a spin valve pillar, wherein the logic task is done by spin-polarized logic input currents. This job is assisted by the concurrent existence of a fixed applied magnetic field [68].

The ultimate target of computer technology is to compute or evaluate through the Boolean functions and then store the digital data in the same device to improve the processing performance and hence save time, energy, and storage area. By using nano-magnetic and non-volatile logic gates this target can be achieved. If we can store our data in the magnetized states of nano-magnets then we can double our memory capacity as well. Regrettably, many such acclaimed gates based on this nano-magnet do not fulfill the seven vital criteria of a Boolean logic gate, viz. concatenability, non-linearity, isolation between input and output, gain, universal logic implementation, scalability, and error resilience. Besides, their energy-delay products and error rates are also higher than that of the orthodox transistor-based logic gates. As such, a group of researchers proposed a non-volatile nano-magnetic logic gate that can be controlled by the applied voltage and possessed all the crucial features of the desired logic gate. In addition to that, the energy-delay product of this gate is ~2 orders of magnitude less than that of other nano-magnetic (non-volatile) logic gates and ~1 order of magnitude less than that of CMOS-based (volatile) logic gates. The error-resilience was found superior to that of the other known nano-magnetic logic gates [69].

F. Spin Valve Sensors

During magnetic recording, sensors need to be sensitive and capable of handling large signals than that by the magnetic resistive sensors. In that case, spin valves may be used by fabricating the sensor structure comprising spin-valve layer deposition, patterning of the shape, and leads [70].

VI. Advantages of Spintronic Devices and Circuits

There are huge numbers of advantages that we may get using spintronics devices instead of their electronic counterpart. The important advantages are listed as follows from the literature surveyed already in the previous sections:

- In spintronics, to represent information as zeros and ones in binary format, the two spin states of the electrons are used. To change the binary state, we need to flip the electron spin rather than change the current as we do in electronic devices. So, the spintronics devices consume very low power and hence they are very power-efficient devices.
- Spin states of the electrons can be flipped quickly, and hence the data transfer in spintronics devices takes place very rapidly.
- Electron spin does not depend on its given energy, thus the spintronic devices are non-volatile; that is, once the information is sent to the device, it remains there without changing its value even after a power failure or the device is shut down. No extra electrical source is required to retain its data in the memory.
- Spintronics devices like MRAM are reliable under heat stress or cosmic-ray exposure. Therefore, the MRAM is used in Airbus aircraft to avoid such harsh effects when cruising at high altitudes.
- The storage capacity of spintronics devices, like MRAM, is very large.
- Spintronics devices are very small-sized. For example, small-sized MRAM devices may be integrated into smaller packages.
- The lifespan of spintronics devices is long.
- Spintronics devices are low-cost.
- Spin-based devices have high gain.
- The manufacturing cost of spintronics devices is low.

VII. Challenges of Spintronic Devices

Despite so many advantages, there are lots of challenges of spintronics devices. These are discussed in this section.

The major difficulty is the realization and production of spin-based magnetic devices. To overcome the difficulties or challenges scientists and researchers are trying to develop novel materials based on magnetism or spin of electrons and novel devices as well. The challenges of spintronics devices are discussed below.

Ultrafast switching magnetism is required for spintronic memory and logic devices. However, there are several hurdles to incorporating ultrafast magnetic phenomena into spintronics devices. To obtain ultrafast magnetization, electrical current flow is required and the current comes from the semiconductor transistor, which has a minimum gate delay on the order of picoseconds. Reading of the magnetic state is done electrically, which necessitates a large magnetoresistance from an MTJ. The switching energy needs to be minimized, and it needs device dimensions in the nanoscale regime. Another challenge is getting a very highly precise uniform spread of the magnetic tunnel transistor's junction because high-density MRAM will require at least 50-ohm resistance. The basic building block of MRAM is MTJ.

Spin-based devices, materials, and concepts are developed at RT conditions. But there is a growing demand for its application in the high-temperature regime also. Spintronics devices are made of several magnetic materials, such as nickel (Ni), iron (Fe), cobalt (Co), etc., and their alloys [71]; but these are not generally used with conventional semiconductor devices. Hence, it becomes very troublesome in pattern and adding the magnetic materials into the silicon-based processing and fabrication systems.

VIII. Current Research Trends on Spintronic Devices

There are several areas of spintronic devices where research works are still going on. Some of these areas are mentioned in the following subsections.

A. Spin Photovoltaics

Sunlight absorbed by the semiconductor materials in a solar cell can produce electrical energy. In the p-n junction, there are lots of semiconducting layers fabricated one after another. If one of the layers is replaced by a FM material then the resultant cell is called a spin photovoltaic cell. In such type of cell, non-polarized light creates an electric field internally and thus the holes and electrons are separated toward two electrodes and thereby create photo-generated potential across the device terminal and hence the non-polarized photo-current is generated. The effect of such spin-polarization, properties of FM layer materials on spin tunneling, spin-polarized electrons extraction without the CP, etc. may be the interesting research areas of spin photovoltaics. Besides, the spectrum of the excitation light energy for the solar cell at various temperatures, use of magnetic insulator/non-magnetic metal bi-layer to create spin current, enhancing efficiency by finding novel organic, inorganic, or hybrid structure of materials, spin-orbit coupling (SOC) process of such materials, optical absorption and stability of spin solar cells, inverse spin Hall effect, etc. may be studied. The SOC is needed for the light-induced molecular processes that can flip the spin state. This process has many applications in the fields of molecular photonics, bio-photo-sensors, photo-dynamic treatment, etc. [72].

B. Molecular Spintronics

The photovoltaic effect may also be obtained using the Magnetic Tunnel Junction Molecular Spintronics Devices (MTJMSD), which may be fabricated through covalent bonding of Organometallic Molecular Clusters (OMC) in between two FM electrodes at the top and bottom edges of the MTJ. The novel research works are going on contact materials, electrode materials, MTJMSD structure, and fabrication processes, temperature effect, organic magneto-resistance, organic LED, coupling, current suppression, efficiency, application as logic and memory devices, etc. [73].

C. Transport in Spin Valve

Another area of research is on spin-valve fabrication, its material study, such as crystal structure and physical properties of the materials, temperature effect, magneto-resistance property, organic spintronics based spin valve, FM contacts as spin injector and detector, etc. [74].

D. Spin Hall Measurements

Simple and efficient model equations derivation to find the spin Hall angle, field, potentials, etc. for the FM heterostructures have wide research scopes and opportunities. The measurement methods may also be studied and modified to get better results of spin Hall measurement, which may also be performed on several materials [75].

E. Spin Mechanics

Phonon, that is lattice vibration, may be united to the electron spin and magnons, to create spin current [76] by the mechanical vibration and sound energy. The vital connection between the magnetic and elastic energies is called the magneto-elastic effect, which may cause a spin current that may ultimately be converted into the charge current via inverse spin Hall Effect or inverse Edelstein Effect [77]. Therefore, these are the areas of research on spin mechanics.

F. Spin based Neuromorphic Computation

Due to some limitations, spin-transfer torque-based all-spin logic devices did not get matured. Then an alternative method named Spin-Torque Nano-Oscillators (STNOs) evolved [78]. The STNO assembly can be operated with low charge currents without any bias magnetic field or voltage, with output powers of the order of tens of nW in MHz to GHz frequency ranges to make it fit for high-speed digital circuits. Thus, we can downsize the device of the order of tens of nanometers [79]. This is indeed a very good research area. The more research areas may be on the network of compact arrays of STNOs, the STNOs dynamics of neighboring oscillators, the coupling mechanism in neuron networks [80], neuromorphic computing based on STNOs, fabrication of high-density networks of STNOs, energy optimization at the atto-Joule scale to obtain the brain-like activities, development of online learning algorithm and offline self-learning mechanism, etc. [81].

Neuromorphic circuits differ from the Boolean logic circuits and enhancing their speed of operation and data transfer rate, improvement of circuit or network architecture, etc. may be the other areas of current research [82].

G. Spin based Smart Life

Smart life is possible to realize by utilizing spintronics. This can be done in several ways. For example, we can ensure efficient and sustainable energy generation, distribution, consumption, and monitoring, stable and reliable power supply, intelligent transportation facilities, and cost-effective healthcare solutions, etc. To implement this, we need to integrate the Internet of Things (IoT), ICT infrastructure, and Wireless Spintronic Sensor Networks (WSSNs) to attach trillions of devices through its spintronic sensors and gather data for analysis and decision making. Therefore, the applied research areas on spintronic devices and sensors may come from various technical and non-technical activities, such as current sensing, power transmission, and distribution, line monitoring, smart grid, energy management and pricing, vehicle detection, and monitoring, bio-detection, human and their movement identification, healthcare services, smart surveillance and supervision, public services, city planning, disaster management, and relief operation, etc. All these applications together can help us realize smart living through the integration of IoT with spintronic sensor technology [83].

IX. Conclusion

The influences of spintronics are becoming formidable day by day. As the conventional semiconductor devices are being scaled down towards their fundamental limits of around a few nanometers, and faster and computation-efficient devices are being demanded in smaller dimensions at low cost to the device manufacturers, there is no other alternative in front of the researchers and device designers to fulfill such demands but to use the spin-base devices. This demand of the device market can only be fulfilled if we can enhance the quality and accessibility of our current technology as well as devise new technologies that may resolve existing challenges. To carry on the fast pace of innovations, significant developments of materials science, lithography, device miniaturization, device manufacturing are compulsory. The positive thing is that the progress towards understanding and implementing the spintronics devices with two degrees of freedom is getting momentum as a huge number of researchers are doing their best to address the pertinent challenges distinctly from diverse aspects. This paper discussed several issues of spin-based electronics from its fundamentals, materials, devices, circuits, advantages, challenges, and towards current research trends for a novel upcoming technology for the next generation of nano-electronics devices fabrication. This will give some insight and ideas for future researchers on spintronics.

REFERENCES

[1] H. Ilatikhameneh, T. Ameen, B. Novakovic, Y. Tan, G. Klimeck and R. Rahman, "Saving Moore's Law Down to 1 nm Channels with Anisotropic Effective Mass," Scientific Reports, Nature, vol. 6, 31501, 2016. https://doi.org/10.1038/srep31501.

[2] M. H. Bhuyan, "History and Evolution of CMOS Technology and its Application in Semiconductor Industry," Southeast University Journal of Science and Engineering (SEUJSE), ISSN: 1999-1630, vol. 11, no. 1, June 2017, pp. 28-42.

[3] M. H. Bhuyan, "Analytical Modeling of the Pocket Implanted Nano Scale n-MOSFETs," PhD Thesis, EEE Department, BUET, Dhaka, Bangladesh, 2011, ch. 1.

[4] H.-L. Zhao, "Quantum mechanical calculation of electron spin," Open Physics, vol. 15, no. 1, 2017, pp. 652-661. https://doi.org/10.1515/phys-2017-0076.

[5] A. Hirohataa, K. Yamadab, Y. Nakatanic, I.-L. Prejbeanud, B. Diényd, P. Pirroe, and B. Hillebrands, "Review on Spintronics: Principles and Device Applications," Journal of Magnetism and Magnetic Materials, vol. 509, September 2020, https://doi.org/10.1016/j.jmmm.2020.166711.

[6] Y. P. Feng, L. Shen, M. Yang, A. Wang, M. Zeng, Q. Wu, S. Chintalapati, and C.-R. Chang, "Prospects of spintronics based on 2D materials," WIREs Computational Molecular Science, vol. 7, e131321, April 2017, doi: 10.1002/wcms.1313.

[7] A. Gupta, R. Zhang, P. Kumar, V. Kumar, and A. Kumar, |Nano-Structured Dilute Magnetic Semiconductors for Efficient Spintronics at Room Temperature," Journal Magnetochemistry, vol. 6, no. 1, pp. 1-22, March 2020, https://doi.org/10.3390/magnetochemistry6010015.

[8] T. Yu-Feng, H. Shu-Jun, Y. Shi-Shen, M. Liang-Mo, "Oxide magnetic semiconductors: materials, properties, and devices," Chinese Physical Society and IOP Publishing Ltd., Chinese Physics B, Volume 22, Number 8, 2013, https://doi.org/10.1088/1674-1056/22/8/088505.

[9] F. J. Pinski, J. Staunton, B. L. Gyorffy, D. D. Johnson, and G. M. Stocks, "Ferromagnetism versus Antiferromagnetism in Face-Centered-Cubic Iron," Physical Review Letters, American Physical Society, vol. 56, 2096, 12 May 1986, https://doi.org/10.1103/PhysRevLett.56.2096.

[10] R. Peierls, "On Ising's model of ferromagnetism," Mathematical Proceedings of the Cambridge Philosophical Society, vol. 32, no. 3, pp. 477-481, 1936. doi:10.1017/S0305004100019174.

[11] S. M. Yakout, "Spintronics: Future Technology for New Data Storage and Communication Devices, Journal of Superconductivity and Novel Magnetism," vol. 33, pp. 2557-2580, 31 May 2020, https://doi.org/10.1007/s10948-020-05545-8.

[12] M. E. McHenry and D. E. Laughlin, "Magnetic properties of metals and alloys," In: D. Laughlin, and K. Hono, (eds.), "Physical Metallurgy (5th Edition), pp. 1881-2008. Elsevier Inc., 2014.

[13] O. Clemens, A. J. Wright, K. S. Knight, P. R. Slater, "On the soft magnetic properties of the compounds of the series $Na_xMn_{4.5-x/2}(VO_4)_3$ and the magnetic structure of h.t.-$Mn_3(VO_4)_2$(x = 1)," Journal: Dalton Transactions, vol. 42, issue 22, pp. 7894-7900, January 2013, https://doi.org/10.1039/C3DT32974G.

[14] A. P. Jadhav, A. Hussain, J. H. Lee, Y. K. Baek, C. J. Choi, and Y. S. Kang, "One pot synthesis of hard phase $Nd_2Fe_{14}B$ nanoparticles and $Nd_2Fe_{14}B$/a-Fe nanocomposite magnetic materials," New Journal of Chemistry, vol. 36, pp. 2405-2411, 2012.

[15] K. P. Thooyamani, V. Khanaa, R. Udayakumar, "Wireless Cellular Communication using 100 Nanometers Spintronics Device Based VLSI," Middle-East Journal of Scientific Research, vol. 20, issue 12, pp. 2037-2041, January 2014.

[16] A. Fert, F. N. V. Dau, "Spintronics, from giant magnetoresistance to magnetic skyrmions and topological insulators," Comptes Rendus Physique, vol. 20, Issues 7-8, 2019, pp. 817-831, ISSN 1631-0705, https://doi.org/10.1016/j.crhy.2019.05.020.

[17] N. F. Mott, "The electrical conductivity of transition metals," Proceedings of Royal Society of London, Serial A, Mathematical and Physical Science, vol. 153 (880), 1936, pp. 699-717.

[18] Q. H. Qin, H. X. Wei, and X. F. Han, "Linear magnetic field response spin valve with perpendicular anisotropy ferromagnet layer," Journal of Applied Physics 103, 07E906, 2008, https://doi.org/10.1063/1.2830968.

[19] A. Jitariu, C. Ghemes, N. Lupu, and H. Chiriac, "Magnetic particles detection by using spin valve sensors and magnetic traps," AIP Advances, vol. 7, 056616 January, 2017.

[20] E. Hall, "On a New Action of the Magnet on Electric Currents," American Journal of Mathematics, vol. 2, issue 3, pp. 287-292, doi: 10.2307/2369245. JSTOR 2369245.

[21] M. I. Dyakonov and V. I. Perel, "Current-induced spin orientation of electrons in semiconductors," Physics Letters A, vol. 35, no. 6, p. 459, 1971, doi:10.1016/0375-9601(71)90196-4.

[22] M. H. Bhuyan, "Analytical modeling of the pocket implanted nanoscale n-MOSFET," PhD Thesis, Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, 2011.

[23] F. Fang, Y. Yin, Q. Li, and G. Lüpke, "Spin-polarized current injection induced magnetic reconstruction at oxide interface," Scientific Reports, vol. 7, 40048, 2017, https://doi.org/10.1038/srep40048.

[24] V. G. Kantser, "Materials and structures for semiconductor spintronics," Journal of Optoelectronics and Advanced Materials, vol. 8, no. 2, April 2006, pp. 425-438.

[25] H. J. Zhu, M. Ramsteiner, H. Kostial, M. Wassermeier, H.-P. Schönherr, and K. H. Ploog, "Room-Temperature Spin Injection from Fe into GaAs," Physical Review Letters, American Physical Society, vol. 87, issue 1, pp. 016601-4, June 2001, 10.1103/PhysRevLett.87.016601.

[26] S. J. Pearton, C. R. Abernathy, D. P. Norton, A. F. Hebard, Y. D. Park, L. A. Boatner, and J. D. Budai, "Advances in wide bandgap materials for semiconductor spintronics," Materials Science and Engineering, vol. 40, no. 4, February 2003, pp. 137-168.

[27] H. Munekata, H. Ohno, S. von Molnar, Armin Segmüller, L. L. Chang, and L. Esaki, "Diluted magnetic III-V semiconductors," Physical Review Letters, American Physical Society, vol. 63, issue 17, pp. 1849-1852, October 1989, doi: 10.1103/PhysRevLett.63.1849.

[28] W. Liu, P. K. J. Wong, Y. Xu, "Hybrid spintronic materials: Growth, structure and properties," Progress in Materials Science, vol. 99, 2019, pp. 27-105, https://doi.org/10.1016/j.pmatsci.2018.08.001.

[29] T. Dietl and H. Ohno, "Ferromagnetic III-V and II-VI semiconductors," MRS Bulletin, vol. 28, no. 10, October 2003, doi: 10.1557/mrs2003.211.

[30] C. Huang, J. Feng, F. Wu, D. Ahmed, B. Huang, H. Xiang, K. Deng, and E. Kan, "Toward Intrinsic Room-Temperature Ferromagnetism in Two-Dimensional Semiconductors," Journal of American Chemical Society, vol. 140, issue 36, pp. 11519-11525, 2018, https://doi.org/10.1021/jacs.8b07879.

[31] Y. Matsumoto, M. Murakami, T. Shono, T. Hasegawa, T. Fukumura, M. Kawasaki, P. Ahmet, T. Chikyow, S.-ya Koshihara, H. Koinuma, "Room-Temperature Ferromagnetism in Transparent Transition Metal-Doped Titanium Dioxide," Science, vol. 291, issue 5505, pp. 854-856, 02 Feb 2001, doi: 10.1126/science.1056186.

[32] G. F. A. Malik, M. A. Kharadi, F. A. Khanday and N. Parveen, "Spin Field Effect Transistors and their applications: A survey," Microelectronics Journal, ISSN: 0026-2692, vol. 106, p. 104924, December 2020, doi: https://doi.org/10.1016/j.mejo.2020.104924.

[33] M. Ziese and M. J. Thornton (eds.), "Spin Electronics", Springer Verlag, Berlin, 2001.

[34] S, S. P. Parkin, "Spintronic Materials and Devices: Past, present and future!" IEEE, 2004.

[35] C. Tsang, R. E. Fontana, T. Lin, D. E. Heim, V. S. Speriosu, B. A. Gurney, M. L. Williams, "Design, fabrication and testing of spin-valve read heads for high density recording," IEEE Transaction on Magn., vol. 30, issue 6, pp. 3801-3806, 1994. https://doi.org/10.1109/20.333909.

[36] T. Endoh, F. Iga, S. Ikeda, K. Miura, J. Hayakawa, M. Kamiyanagi, H. Hasegawa, T. Hanyu, and H. Ohno, "The Performance of Magnetic Tunnel Junction Integrated on the Back-End Metal Line of Complimentary Metal," Japanese Journal of Applied Physics, vol. 49, no. 4, pp. 04DM06, 2010, 10.1143/jjap.49.04dm06.

[37] S. Yamamoto and S. Sugahara, "Nonvolatile Static Random Access Memory Using Magnetic Tunnel Junctions with Current-Induced Magnetization Switching Architecture," Japanese Journal of Applied Physics, vol. 48, no. 4, pp. 043001, 10.1143/jjap.48.043001.

[38] https://www.psmarketresearch.com/market-analysis/spintronics-market, accessed on 24 April 2021.

[39] https://www.businesswire.com/news/home/20200409005311/en/Global-

Spintronics-Market-Worth-12.84-Billion-by-2030---Rising-Demand-for-MRAMs-is-a-Key-Driving-Factor---ResearchAndMarkets.com, accessed on 24 April 2021.

[40] E. Y. Tsymbal and D. Pettifor, "Perspectives of giant magneto-resistance," Solid State Physics, vol. 56, pp. 113-237, 2001.

[41] M. Sato, S. Umehara, and T. Ibusuki, "Tunneling magnetoresistance (TMR) device, its manufacture method, magnetic head and magnetic memory using TMR device," US Patent, US8072714B2, USA, assigned to Fujitsu Ltd., 2011, https://patents.google.com/patent/US8072714.

[42] T. Miyazaki and N. Tezuka, "Giant magnetic tunneling effect in Fe/Al_2O_3/Fe junction," Journal of Magnetism and Magnetic Materials, vol. 139, no. 3, pp. L231-L234, 1995.

[43] D. Wang, C. Nordman, J. M. Daughton, Z. Qian, and J. Fink, "70% TMR at room temperature for SDT sandwich junctions with CoFeB as free and reference Layers," IEEE Transaction on Magnetics, vol. 40, no. 4, pp. 2269-2271, Jul. 2004.

[44] I. Žutić, J. Fabian, and S. D. Sarma, "Spin-Polarized Transport in Inhomogeneous Magnetic Semiconductors: Theory of Magnetic/ Nonmagnetic p-n Junctions," Physical Review Letters, vol. 88, 066603, 29 January 2002.

[45] A. H. MacDonald, P. Schiffer, and N. Samarth, "Ferromagnetic semiconductors: moving beyond (Ga,Mn)As," Nature Materials, vol. 4, pp. 195-202, March 2005, https://doi.org/10.1038/nmat1325.

[46] D. Chiba, M. Yamanouchi, F. Matsukura, and H. Ohno, "Electrical Manipulation of Magnetization Reversal in a Ferromagnetic Semiconductor," Science, American Association for the Advancement of Science, vol. 301, issue 5635, pp. 943-945, 15 August 2003, doi: 10.1126/science.1086608.

[47] S. Louis, V. S. Tiberkevich, J. Li, O. Prokopenko and A. N. Slavin, "Spin Torque Diode with Perpendicular Anisotropy Used for Passive Demodulation of FM Digital Signals," IEEE International Magnetics Conference, 2018, pp. 1-2, doi: 10.1109/INTMAG.2018.8508129.

[48] J. S. Friedman, N. Rangaraju, Y. I. Ismail and B. W. Wessels, "A Spin-Diode Logic Family," in IEEE Transactions on Nanotechnology, vol. 11, no. 5, pp. 1026-1032, Sept. 2012, doi: 10.1109/TNANO.2012.2211892.

[49] T. Manago and H. Akinaga, "Spin-polarized light emitting diode using metal/insulator/semiconductor structures," Applied Physics Letters, vol. 81, 694, 2002; https://doi.org/10.1063/1.1496493.

[50] N. Nishizawa and H. Munekata, "Recent progress in spin-LED: realization of pure circular polarization EL at room temperature with current density of 10 A/cm^2," Proc. SPIE 11090, Spintronics XII, 1109034, 10 September 2019; https://doi.org/10.1117/12.2527862.

[51] S. Datta, "How we proposed the spin transistor," Nature Electronics, vol. 1, p. 604, November 2018, doi: https://doi.org/10.1038/s41928-018-0163-4.

[52] S. Sugahara and J. Nitta, "Spin-Transistor Electronics: An Overview and Outlook," in Proceedings of the IEEE, vol. 98, no. 12, pp. 2124-2154, Dec. 2010, doi: 10.1109/JPROC.2010.2064272.

[53] G. Wang, Z. Wang, J. Klein and W. Zhao, "Modeling for Spin-FET and Design of Spin-FET-Based Logic Gates," IEEE Transactions on Magnetics, vol. 53, no. 11, pp. 1-6, Nov. 2017, Art no. 1600106, doi: 10.1109/TMAG.2017.2704881.

[54] S. Bandyopadhyaya and M. Cahay, "Are spin junction transistors suitable for signal processing?," Applied Physics Letters, vol. 86, p. 133502, 2005, doi: https://doi.org/10.1063/1.1883722.

[55] D. Apalkov, B. Dieny and J. M. Slaughter, "Magnetoresistive Random Access Memory," Proceedings of the IEEE, vol. 104, no. 10, pp. 1796-1830, October 2016, doi: 10.1109/JPROC.2016.2590142.

[56] L. Savtchenko, A. Korkin, B. N. Engel, N. D. Rizzo, J. A. Janesky, "Method of writing to scalable magnetoresistance random access memory element," US Patent 6545906 B1/2003.

[57] U. K. Klostermann et al., "A Perpendicular Spin Torque Switching based MRAM for the 28 nm Technology Node," IEEE International Electron Devices Meeting, 2007, pp. 187-190, doi: 10.1109/IEDM.2007.4418898.

[58] M. Durlam et al., "A 0.18 □m 4Mb toggling MRAM," IEEE International Electron Devices Meeting 2003, 2003, pp. 34.6.1-34.6.3, doi: 10.1109/IEDM.2003.1269448.

[59] C.-L. Su, R.-F. Huang, C.-W. Wu, C.-C. Hung, M.-J. Kao, Y.-J. Chang, W.-C. Wu, "MRAM defect analysis and fault modeling," IEEE International Conference on Test, Charlotte, NC, USA, 26-28 October 2004, pp. 124-133, doi: 10.1109/TEST.2004.1386944.

[60] S. M. Thompson, "Magnetoresistive Heads: Physical Phenomena," Editors: K. H. J. Buschow, R. W. Cahn, M. C. Flemings, B. Ilschner, E. J. Kramer, S. Mahajan, P. Veyssière, Encyclopedia of Materials: Science and Technology, Elsevier, 2001, pp. 5095-5101, ISBN 9780080431529, https://doi.org/10.1016/B0-08-043152-6/00885-8.

[61] G.-X. Liu, L.-H. Shen, W.-Y. Ma, L. Yuan, "Electron-spin filter based on a novel magnetic nanostructure with zero average magnetic field," Chinese Journal of Physics, ISSN 0577-9073, vol. 54, issue 1, February 2016, pp. 121-126, https://doi.org/10.1016/j.cjph.2016.03.013.

[62] S. Lyon, "Spin-based quantum computing using electrons on liquid helium," Physical Review A, vol. 74, 2003, doi: 10.1103/PHYSREVA. 74.052338.

[63] M. Veldhorst, H. G. J. Eenink, C. H. Yang, and A. S. Dzurakm, "Silicon CMOS architecture for a spin-based quantum computer," Nature Communication, vol. 8, 1766, 2017, https://doi.org/10.1038/s41467-017-01905-6.

[64] T. Dogaru and S. T. Smith, "Giant magnetoresistance-based eddy-current sensor," IEEE Transactions on Magnetics, vol. 37, no. 5, pp. 3831-3838, September 2001, doi: 10.1109/20.952754.

[65] J. R. Childress and R. E. Fontana Jr., "Magnetic recording read head sensor technology," C. R. Physique, vol. 6, pp. 997–1012, 2005.

[66] Y. Ouyang, J. He, J. Hu, S. X. Wang, "A current sensor based on the giant magnetoresistance effect: design and potential smart grid applications," Sensors, vol. 12, no. 11, pp. 15520-15541, 9 November 2012, doi: 10.3390/s121115520.

[67] S. Lee, S. Choa, S. Lee and H. Shin, "Magneto-Logic Device Based on a Single-Layer Magnetic Tunnel Junction," IEEE Transactions on Electron Devices, vol. 54, no. 8, pp. 2040-2044, August 2007, doi: 10.1109/TED.2007.900683.

[68] C. Sanid and S. Murugesh, "Spin-Transfer-Torque Driven Magneto-Logic Gates using Nano Spin-Valve Pillars," Japanese Journal of Applied Physics, IOP Publishing, vol. 51, article 063001, 2012, doi: 10.1143/jjap.51.063001.

[69] A. K. Biswas, J. Atulasimha, S. Bandyopadhyay, "An error-resilient non-volatile magneto-elastic universal logic gate with ultralow energy-delay product," Scientific Reports, vol. 4, article 07553, December 2014, doi: 10.1038/srep07553.

[70] D. E. Heim, R. E. Fontana, C. Tsang, V. S. Speriosu, B. A. Gurney and M. L. Williams, "Design And Operation Of Spin Valve Sensors," Digests of the Magnetic Recording Conference 'Magnetic Recording Heads', Minneapolis, MN, USA, 13-15 September 1993, pp. 26-27, doi: 10.1109/MRC.1993.662395.

[71] C. Tannous and J. Gieraltowski, "Magnetic Properties: From Traditional to Spintronic," In: S. Kasap and P. Capper, Springer Handbook of Electronic and Photonic Materials. Springer Handbooks, Springer, Cham. https://doi.org/10.1007/978-3-319-48933-9_4.

[72] C. M. Marian, "Spin–orbit coupling and intersystem crossing in molecules," Journal of WIREs Computational Molecular Science, vol. 2, issue 2, April 2012, pp. 187-203, doi: https://doi.org/10.1002/wcms.83.

[73] P. Tyagi and C. Riso, "Molecular spintronics devices exhibiting properties of a solar cell," Journal of Nanotechnology, vol. 30, no. 49, p. 495401, September 2019, doi: 10.1088/1361-6528/ab3ab0.

[74] K. Zhao, Y. Xing, J. Han, J. Feng, W. Shi, B. Zhang, and Z. Zeng, "Magnetic transport property of NiFe/WSe2/NiFe spin valve structure," Journal of Magnetism and Magnetic Materials, ISSN 0304-8853, vol. 432, 2017, pp. 10-13, https://doi.org/10.1016/j.jmmm.2017.01.066.

[75] Y. Deng, M. Yang, Y. Ji, and K. Wang, "Estimating spin Hall angle in heavy metal/ferro-magnet hetero-structures," Journal of Magnetism and Magnetic Materials, ISSN 0304-8853, vol. 496, 2020, p. 165920, https://doi.org/10.1016/j.jmmm.2019.165920.

[76] M. Matsuo, J. Ieda, K. Harii, E. Saitoh, and S. Maekawa, "Mechanical generation of spin current by spin-rotation coupling," Physical Review B, American Physical Society, vol. 87, issue 18, pp. 180402-4, May 2013, doi: 10.1103/PhysRevB.87.180402.

[77] M. Xu, J. Puebla, F. Auvray, B. Rana, K. Kondou, and Y. Otani, "Inverse Edelstein effect induced by magnon-phonon coupling," Physical Review B, American Physical Society, vol. 97, issue 18, pp. 180301-4, May 2018, doi: 10.1103/PhysRevB.97.180301.

[78] N. Locatelli, V. Cros and J. Grollier, "Spin-torque building blocks," Nature Materials, vol. 13, pp. 11-20, 2014, doi: https://doi.org/ 10.1038/nmat3823

[79] Z. Zeng, G. Finocchio, B. Zhang, et al. "Ultralow-current-density and bias-field-free spin-transfer nano-oscillator," Scientific Report, Nature, vol. 3, p. 1426, 2013, doi: https://doi.org/10.1038/srep01426.

[80] J. Torrejon, M. Riou, F. Araujo, et al., "Neuromorphic computing with nanoscale spintronic oscillators," Nature, vol. 547, pp. 428-431, 2017, doi: https://doi.org/10.1038/nature23011.

[81] M. Romera, P. Talatchian, S. Tsunegi, et al., "Vowel recognition with

four coupled spin-torque nano-oscillators," Nature, vol. 563, pp. 230-234, 2018, doi: https://doi.org/10.1038/s41586-018-0632-y.

[82] D. E. Nikonov and I. A. Young, "Benchmarking Delay and Energy of Neural Inference Circuits," IEEE Journal on Exploratory Solid-State Computational Devices and Circuits, vol. 5, no. 2, pp. 75-84, December 2019, doi: 10.1109/JXCDC.2019.2956112.

[83] X. Liu, K. H. Lam, K. Zhu, C. Zheng, X. Li, Y. Du, C. Liu, and P. W. T. Pong, "Overview of Spintronic Sensors With Internet of Things for Smart Living," IEEE Transactions on Magnetics, vol. 55, no. 11, pp. 1-22, Nov. 2019, Art no. 0800222, doi: 10.1109/TMAG.2019.2927457.

Muhibul Haque Bhuyan (MIEEE2005–) became a Member (M) of the World Academy of Science, Engineering and Technology in 2005, born in Dhaka, Bangladesh on 25 July 1972. He did his BSc, MSc, and PhD degrees in Electrical and Electronic Engineering (EEE) from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh in 1998, 2002, and 2011 respectively.

Currently, he is working as a Professor of the Department of Electrical and Electronic Engineering of Southeast University, Dhaka, Bangladesh. He led this department as the Departmental Chairman from 1st March 2016 to 10 March 2021. Previously, he worked at the Green University of Bangladesh, Dhaka as a Professor and Chairman of the EEE Department; Daffodil International University, Dhaka, Bangladesh as an Assistant Professor and Head of ETE Department; Presidency University, Dhaka, Bangladesh as an Assistant Professor and American International University Bangladesh (AIUB), Dhaka as a Faculty Member since June 1999. He also worked as a Researcher in the Center of Excellence Program of Hiroshima University, Japan from July 2003 to March 2004. He has served as an Adjunct Faculty at AUST, IIUC, EWU, DIU, PU, etc. So far, he has published over 60 research papers in national and international journals and presented over 40 research works at national and international conferences. His research interests include MOS device modeling, biomedical engineering, control system design, online practices of teaching and learning, outcome-based engineering education, assessment, and evaluation. He is a program evaluator of the Board of Accreditation of Engineering and Technical Education (BAETE), Dhaka, Bangladesh under IEB.

Prof. Bhuyan is a Member of IEEE, USA, Executive Member of Bangladesh Electronics and Informatics Society (BEIS), and Fellow of the Institution of Engineers Bangladesh (IEB). He is a regular reviewer and technical/editorial/organizing committee member of several national and international journals and conferences. He was the Organizing Chair of the IEEE 22nd International Conference on Computer and Information Technology (ICCIT) held at Southeast University, Dhaka, Bangladesh during 18-20 December 2019. He is the recipient of the Bangladesh Education Leadership Awards (Best Professor in Electrical Engineering) in 2017 from the South Asian Partnership Awards, Mumbai, India.