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Chronological Records and Development in the Field of Spintronics

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Abstract: ***Spintronics is one of the emerging disciplines that continue to revolutionize the thriving field of information technology. Information technology has been a wellspring of intellectual and economic vitality in the modern world. The goal of spintronics is to understand the interaction between the particle spin and its solid-state environments and to make useful devices using the acquired knowledge. Fundamental studies of spintronics include investigations of spin transport in electronic materials, as well as understanding spin dynamics and spin relaxation. In this paper the chronological development in the field of spintronics has been discussed in a detailed way.***

Keywords: spintronics; spin coulomb drag; transresistivity; spin drag; spin diffusion; Spin-valve; spin current; spin-flip; Dilute Magnetic Semiconductor (DMS)

1. Introduction

The discovery of Giant Magneto Resistance (GMR) in 1988, by Albert Fert from France and Peter Gurunberg from Germany opened up the vast field of research in Spintronics. Both of them were awarded Nobel Prize in Physics in the year 2007 for this discovery. Just after the discovery of GMR, Supriyo Datta and Biswajit Das of Purdue University proposed a field effect spin transistor [1] in year 1989. This transistor consists of two ferromagnetic electrodes, a source and a drain. A 2D electron gas with strong spin orbit coupling is used as conducting channel between two electrodes. A gate voltage is applied on the conducting channel to control the electron spin precession. Spin-polarized electrons are injected from a ferromagnetic source. When the electron spin reaching the drain is parallel to the magnetization in the drain, the electron enters the drain with a small resistance. On the other hand, if the spin is anti-parallel to the magnetization then it will be reflected at the interface. In this way, the switch "on" and "off" of the transistor are considered. In the Datta-Das transistor, the gate voltage is used to control the spin-orientation of electrons whereas, in conventional transistor, the gate voltage is used to control the motion of the electrons. When the two processes are compared the required energy to change the spin-orientation is much smaller, the time is much shorter and the efficiency is much higher in the Datta-Das transistor, than the conventional one. Unfortunately, Datta-Das transistor has not yet been realized in any laboratory throughout the world.

Development of Spintronics

However, after ten year, first GMR hard disk head was introduced by IBM in 1997 [2]. Along with IBM, Motorola, Honeywell (USA), Naval Research Laboratory (NRL), USA and many academic bodies and laboratories are involved in research and development of GMR and related devices [3,4]. A specific ferromagnetic material for use in spintronics was developed at University of Buffalo, New York in the year 2000. In year 2001, physists from University of Arkansas, have successfully injected a steam of electrons with identical spins in a semiconductor [5]. At the same time a breakthrough was achieved by the IBM when they introduce "Pixie Dust" in their hard drive data storage [6]. The "Pixie Dust" is the nick name for the Quadruple Disk Drive Density (QDDD). It is a three-atom thick layer of the element Ruthenium sandwiched between two magnetic layers which are Anti Ferromagnetically Coupled (AFC) media. It was then expected that AFC media will permit hard disk drives to store 100billion bits (gigabits) of data per square inch of disk area. Recently IBM's hard disk drive stores up to 25.7 gigabits per square inch of the disk area.

In the year2002, magnetic component memory was discovered in which spin polarization was used as a switching of a device [7]. This was a step forward in this field. Mim-Quyang and David Awschalom from the University of Calllifornia, Santa Barbara for the first time transferred electron spin across molecular bridges between quantum dots in 2003[8]. Quantum dots are beads of semiconductor materials which are very small with unique properties. They are intermediate between those of bulk semiconductor and individual molecules. One of their useful properties is fluorescence that produces distinctive colors determined by the size of the particles. It was the year 2004, that Jing Shi and colleagues from Utah University, US, made first organic spin-valve [9].

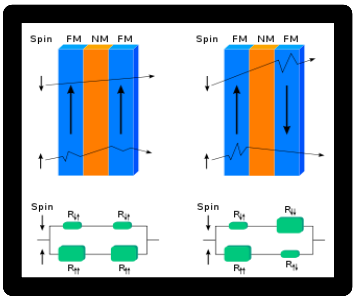

Figure 1: Spin-valve (Courtesy: Nature 427, 821-824 (2004))

Spin-valve is a layered structure of magnetic and non-magnetic materials, whose electrical resistance depends on the spin state of electrons passing through the device and can be controlled by an external magnetic field. Using this organic spin-valve structure in spintronic devices one can enhance GMR effects by 40% at low temperature. Meanwhile the Korean Institute of Science and Technology (KIST) and MIT's Francis Bitter have launched a 10 years programme for research and development in spintronics [10]. The new collaboration should jumpstart the field by combining each institution's expertise and technologies in the creation of new spintronic materials and the development of spintronic elements. KIST has strengths in process technology in spintronic elements, and MIT provides the underlying science and design technology in spintronic materials.

IBM scientists viewed a single electron spin with the help of a special Atomic Force Microscope (AFM) [11]. It is a very high resolution type of scanning probe microscope with resolution of the order of fractions of a nanometer. It was developed by Gerd Binnig and Henrich Rohrer in the early 1980s at IBM research centre, Zurich, for which they shared the Nobel Prize for physics in 1986. It is mainly based on the existence of a separation-dependency between any two bodies. It is the force between the tip and the substrate that is present at close separations. Typically, pyramidal silicon nitride tips are used, which have a radius of curvature of the order of 100 A^{o}. The force is detected by placing the top on a flexible cantilever that deflects proportionally to the exerted force. The deflection is then measured by some convenient procedure such as laser deflection etc. as shown in Fig:2.

In the year 2005, a new spintronic "speed record-2GHz" device (then the fastest memories) was devised by Hans Schumacher-*et al*, Germany [12]. The fastest version of a Magnetic Random Access Memory (MRAM) is a sandwich, consisting two magnetic layers, with a tunneling layer in between. When the magnetic layers are aligned, resistance in the cell is low; when they are counter aligned resistance is high. These two conditions establish the binary 1 or 0 states.

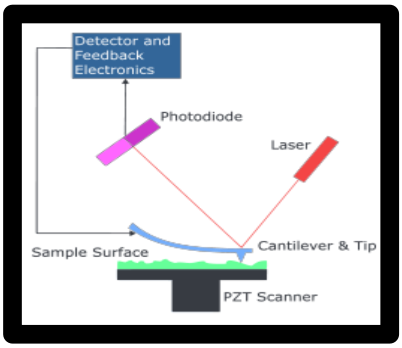

Figure 2: Block diagram of Atomic Force Microscope (AFM), Courtesy –Wikipedia

At the same time the Doping mechanism in semiconductor nano crystals was discovered by scientists at the University of Minnesota (Minneapolis, MN) and researchers at the Naval Research Laboratory (NRL; Washington DC)[13]. They showed that in order to incorporate, impurities must be able to bind to the nanocrystal surface for a long period of time to be embodied into the nanocrystal. This concept enabled the team to predict conditions favorable for doping in a wide variety of nanocrystal systems.

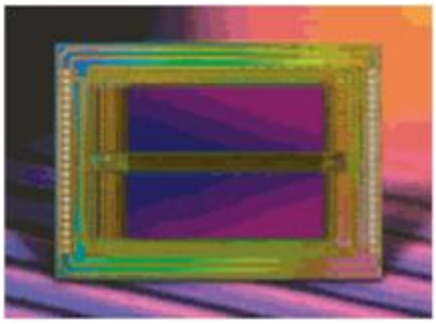

Figure 3: A 256-kb MRAM based on modern spintronics technology,
(Image courtesy of Motorola Corp.)

After that a team of Princeton scientists has turned semiconductor into magnets by the precise placement of metal atoms within a material [14]. This leads to a new material called Dilute Magnetic Semiconductor (DMS) [15]. DMS are based on traditional semiconductor but are doped with transition metals instead of electronically active element. Hideo Ohno and his group at the Tohoku University, China [16] were first to measure ferromagnetism in transition metal doped compound semiconductor such as Gallium Arsenide (GaAs), Indium Arsenide (InAs) doped with Manganese (Mn) known as GaMnAs/GaMnIn. These materials exhibited reasonably high Curie temperature that scales with the concentration of p-type charge carriers. Another such materials are Mn doped Indium Antimonide, Mn and Fe doped Indium Oxide etc.

A major invention in 2006 was the detection of Spin Hall Effect (SHE). It is a Transport phenomenon predicted by Russian Physicists M. I. Dyakonov and V. I. Perel [17]. It consists of the appearance of spin accumulation on the lateral surfaces of an electric current carrying sample. The signs of the spin directions are opposite on the opposite boundaries. Experimentally the SHE was observed in semiconductors more than 30 years after the prediction [18, 19]. The origin of SHE is in the spin-orbit interaction which leads to the coupling of the spin and charge current. This electric current induces a transverse spin current and vice-versa. D. Awschalom and colleagues at the centre of spintronics and computation at the University of California, Santa Barbara observed the current induced spin-polarization of electrons and the SHE in thin surface layers of ZnSe [20]. SHE occurs when an unpolarized charged current traverse a material with spin-orbit interaction, leading to a perpendicular spin current where up-spin accumulate on one edge of the sample and down-spin on other edge.

The year 2007 saw a major breakthrough in applying spin based electronics to silicon. A team of researchers injected electrons into silicon in such a way that their spins or magnetic orientations were aligned in one direction instead of the other. In the new device Appelbaum and co-workers [21], have injected electrons from a layer of Al through a thin layer of ferromagnet into a pure Si-crystal. Al contained a 50-50 mix of spin-up and spin-down electrons. The ferromagnet however blocks electrons of one spin while letting the others flow into the Si. They found that their ferromagnetic barrier gave Si a 1% excess of one spin type versus the other at the temperature of 85K. The scientists of University of California, San Diego had proposed a new spintronic circuit which is an interconnected series of logic gates. Each logic gate consists of five magnetic contacts lying on top of a semiconductor layer. The magnetic states of these contacts determined by the electron's spin corresponding to the '0' and '1' in each bit of information. The logic operation is performed by moving electrons between four of the magnetic contact and the semiconductor. The result of the operation is read by the fifth magnetic contact. The research is being continued on this proposed work, which was assumed to be more scalable and have greater computational capacity than conventional silicon circuits.

In 2008, IBM fellow, Stuart Parkin and his colleagues at the IBM, Almada Research Centre in San Jose, have described a new technology named "Race Track" [22].

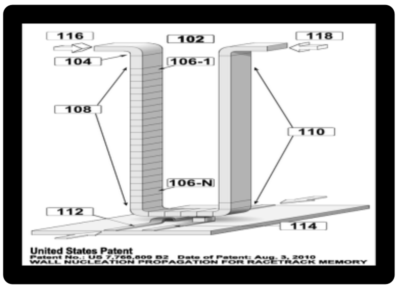

Figure 4: Race Track Memory
(Courtesy: Science Daily, April 11, 2008)

It was so named because the data "races" around the wire "track" could lead to solid state electronic devices with no moving parts. And therefore more durable, capable of holding far more data in the same amount of space than is possible today, with far lower cost and power consumption. It was assumed that the device would not only store vastly more information in the same space but, also require much less heat, and be practically unbreakable. This means massive amount of personal storage that could run on a single battery for weeks at a time and lasts for decades. They explained the interaction of spin polarized current with magnetization in the domain walls. This results in a spin-transfer torque on the domain wall causing it to move. The use of spin momentum transfer considerably simplifies the memory device as the current passed directly across the domain wall without the need for any additional field generators. Apart from this many Universities and research centers had announced several projects related to Spintronics. Some of them are IBM and ETH, Zurich University built jointly Nanotechnology Laboratory with Spintronics as one of the research target, Ohio University had launched a new research centre for Spintronics etc.

The year 2009 came with a new device called "spin-battery" [23] developed by researchers of University of Miami and at the Universities of Tokyo and Tohoku, Japan. It is a battery that is charged by applying a large magnetic field to nano-magnets in a device called a Magnetic Tunnel Junction (MTJ).

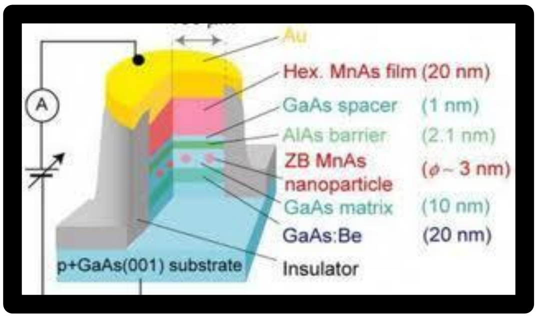

Figure 5: Spin-battery (Courtesy Science Daily, March 12, 2009)

The physics behind this technique is the use of nano-magnets to induce an emf. This new technique converts the magnetic energy directly into electrical energy without any chemical reaction [24].

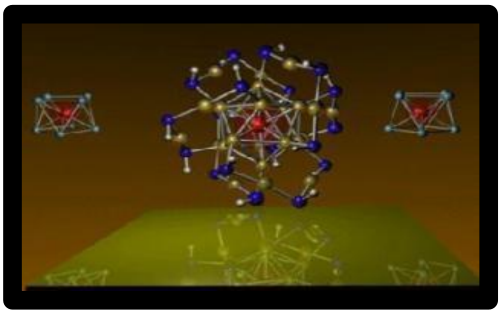

Figure 6: VCs8 and MnAu24(SH)18 magnetic super atoms that mimic a manganese atom. The MnAu24 cluster is surrounded by sulfur and hydrogen atoms to protect it against outside attack, thus making it valuable for use in biomedical applications.
(Credit: Image courtesy of Ulises Reveles, Ph.D, VCU.)

In the same year a team of scientists from Virginia CommonwealthUniversity discovered the "magnetic super atom" which is a stable cluster of atoms that can mimic different elements of the periodic table [25]. This super atom may be used to create molecular electronic devices for the next generation of faster computers with larger memory storage.

The first spin injected FET which is based on a semiconducting channel with two ferromagnetic electrodes, was demonstrated by a team of Korea Institute of Science and Technology [26]. The source and drain of the transistor was made of ferromagnetic materials and the injected spins are controlled by gate voltage. During this year another team of researchers at the University of Twent, Netherlands demonstrated the manipulation and detection of spin polarized electrons in silicon at room temperature [27]. They used careful design of the interface where the electrons enter the silicon. The pure material with precisely determined thickness was used in order to preserve the delicate spin polarization. This was an important step towards spin-electronics.

In year 2010, researchers from Ohio State University demonstrated that it was possible to fabricate a spintronic based chip that will run and process data on heat only [28]. They observed that Gallium Manganese Arsenide can

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convert heat into spin. A chip that runs on heat can be created by combining spintronics and thermoelectricity. They named the new chip as "Thermo-spintronics" chip. Such device can be mounted on regular microprocessor. The device is fed by the waste heat of the microprocessor. This will work both as a heat sink and as a second processor. It is possible to use the waste heat inside magnetic tunnel structures, which may be used to monitor and control "thermoelectric voltages" and current in highly integrated electronic circuits. In their experiments the scientists generated a temperature difference between the two magnetic layers and investigated the thermoelectric voltage generated thereby. It is observed that the thermoelectric voltage depends on the magnetic orientation of the two layers nearly as strongly as the electric resistance. By switching the magnetization, it is therefore possible to control the thermoelectric voltage and ultimately the thermal current flowing through the specimen.

Meanwhile, at the University of New South Wales, researchers have developed a way to reliably read the spin of a single electron [29]. They used a single atom of Phosphorus embedded in Silicon. They have named this device as "single electron pump". This semiconductor device allows the ejection of exactly one single electron per clock cycle into a semiconductor channel. It was the first time when such a single electron pump exactly deliver single electron with pre-defined spin polarization per pumping cycle at sufficiently high applied field. It thus delivers spin polarized electrons virtually on demand.
The year 2011, came with a great achievement, generation of spin current in Graphene [30, 31]. Graphene is a one atom thick material of carbon atoms tightly packed into a 2D packed honeycomb lattice.

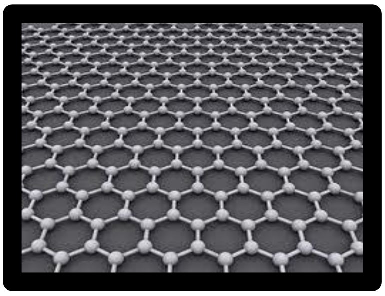

Figure 7: A block diagram of Graphene
(Courtesy: Nature, 438, 197-200 (2005)).

Graphene is a 2D building material for carbon materials of all other dimensionalities. It can be wrapped up into 0D buck balls, rolled into 1D nanotubes or stacked into 3D graphite. Graphene and, to a good approximation, its bilayer have simple electronic spectra: they are both zero-gap semiconductors (can also be referred to as zero-overlap semimetals) with one type of electrons and one type of holes. Researchers from City University, Hong Kong succeeded to generate a spin current in Graphene which could be used as Spintronics devices [32, 33]. The scientists used spin splitting in monolayer Graphene generated by ferromagnetic proximity effect and adiabatic quantum pumping. They can control the degree of polarization of the spin current by varying the Fermi energy, which is a very important aspect for meeting various application requirements. An ultimately large surface-to-volume ratio and high conductivity provided by graphene powder can lead to improvements in batteries' efficiency, taking over from carbon nanofibers used in modern batteries. Carbon nanotubes have also been considered for this application but graphene powder has an important advantage of being cheap to produce. So, the main market for graphite is the use of graphene powder in electric batteries.

Researchers from the universities of Utah, developed a new spintronic transistor at room temperature [34]. They used magnesium oxide as a "tunnel barrier". It helps the aligned electron spins to travel from one nickel-iron electrode through the Si-semiconductor to another Ni-Fe electrode. During the experiment the electrons retained their spins for 276 picoseconds, on this lifetime researchers calculated a distance of 328 nanometer travelled by the spin aligned electron through the silicon. In the same year a team of researchers, at the Universities of Strasbourg and KIT's institute of nanotechnology manufactured a spintronic nano switch by coating synthetic adhesives on magnesium molecules [35]. In this way the molecules fitted themselves on a nanotube without any interference. The newly fabricated components do not comprise alloys, metals or oxides but consists of soft materials such as molecules and carbon monotubes.

A new device known as Spin Transport in Organic Semiconductor (SPINTROS) has developed by European Research Council (ERC) [36]. In the University of Utah, USA a new centre on developing the Organic Spintronic Semiconductor was established under the leadership of Brain Saam [37]. Recently, IBM and ETH Zurich managed to create a persistent spin helix that kept the spin for 1.1 nanoseconds enough for a full cycle in a 1GHz processor. This is about 30 times longer than previously achieved [38,39]. Researchers managed to sustain the spin by using the GaAs based semiconductor material and a very low temperature (41K). Scientists at the Department of Energy (DOE) Brookhaven National Laboratory have precisely measured a key parameter of electron interactions called non-adiabatic spin torque that is essential to the future development of spintronic devices [40, 41]. A researcher and his colleague from the University of Arkansas have developed a better understanding of how Graphene-metal interfaces affect the movement of electrons through two terminal junctions [42].

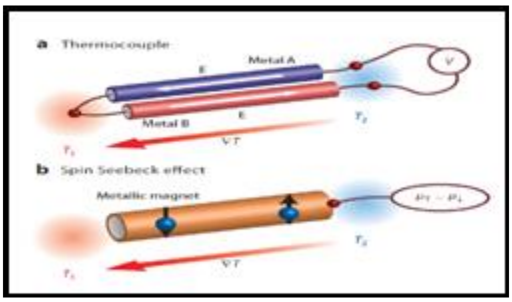

Figure 8: Illustration of a conventional thermocouple (a) and spin Seebeck effect (b).
(Courtesy: Science Daily, July 11, 2012)

Researchers are studying a new magnetic effect that converts heat to electricity. They have discovered to amplify it by thousand times, the so-called spin Seebeck effect. In this

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effect, the spin of electrons creates a current in magnetic materials, which is detected as a voltage in an adjacent metal. The spin-up and down bands have different Seebeck coefficients, leading to a spin voltage caused by the temperature gradient. The spin-dependent electrochemical potentials (μ) take on a spatial distribution along the temperature gradient so that one end is rich in down spins and the other is rich in up spins, as shown in figure 8.

Ohio State University researchers have figured out how to create a similar effect in a non-magnetic semiconductor while producing more electrical power. They've named the amplified effect the "giant spin-Seebeck" effect [43], and the university will license patent-pending variations of the technology. In a study Dhiraj Parsai and colleagues has established the “Miracle Material” called graphene as the world’s thinnest known coating for protecting metals against corrosion [44].

Figure 9: A light-sensitive graphene/polymer heterostructure.
(Credit: Image courtesy of National Physical Laboratory)

They found that Graphene whether made directly on Copper or Nickel or transferred onto another metal, provides protection against corrosion. Copper coated by growing a single layer of graphene through Chemical Vapor Deposition (CVD) corroded seven times slower than bare copper, and nickel coated by growing multiple layers of graphene corroded 20 times slower than bare nickel. Remarkably, a single layer of graphene provides the same corrosion protection as conventional organic coatings that are more than five times thicker. Graphene coatings could be ideal corrosion-inhibiting coatings in applications where a thin coating is favorable, such as microelectronic components (e.g., interconnects, aircraft components and implantable devices).

The Semiconductor Research Corporation, and the Defense Advanced Research Projects Agency (DARPA) had awarded a $28 million five-year grant to open the Center for Spintronic Materials, Interfaces, and Novel Architectures, or C-SPIN. This is a multi-university and industry research center that aims to develop technologies for spin-based computing and memory systems. C-SPIN's research areas include perpendicular magnetic materials, spin channel materials (including topological insulators, monolayer MoS2 and graphene), spintronic interface engineering, spin devices and interconnects and spintronic circuits and architectures [45].

Meanwhile researchers from the Japanese RIKEN institute have shown that spin information in some materials can travel much further than previously thought. They managed to measure the spin diffusion in detail by using two magnetic contacts to inject the spin signal into a thin silver wire. This enhances the amount of spin polarization present in the wire. Using a third contact that picks the signals, they were manage to manage the polarization degree at several distances along the wire.

A new spintronics-based logic prototype chip specifically aimed towards text search systems have jointly developed by team of researchers from NEC and Tohoku's University. They developed new multi-functional CAM cells for text-search logic. The new CAM cells are able to avoid searching for long index texts when searching for short lengths of text within a large amount of index data [46].

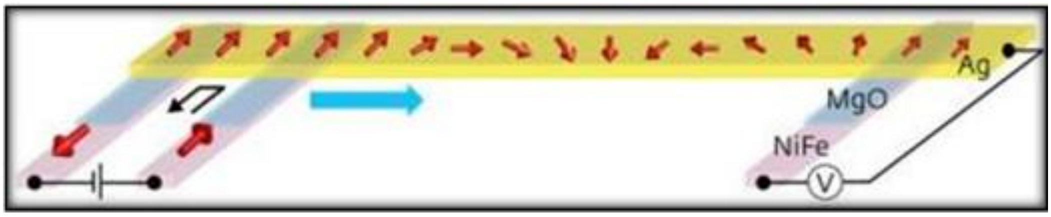

Figure 10: Setup to measure spin signal into a thin silver wire
(Courtesy: Spintronics_info.com)

Researchers from the University of Utah developed Spintronics devices that can convert heat into electricity. Those thermoelectric devices work at room temperature and don't require a continuous external magnetic field. This device can convert even minute heat emitted by hand-held electronic devices such as laptops, etc. into useful electricity [47].

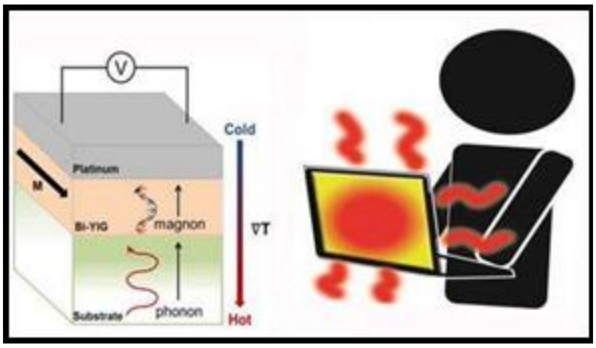

Figure 11: Schematic of the spintronic thermoelectric device fabricated by the University of Utah’s researchers.

Courtesy: http://phys.org/news/2014-03-spintronic-thermoelectric-power-energy-efficient.html

Researchers at the University of California at Riverside found a way to introduce magnetism in graphene while still preserving electronics properties. This may represent a significant step forward in the use of graphene in chips and electronics, since doping in the past induced magnetism but damaged graphene's electronic properties. this method can also be used in spintronics - chips that use electronic spin to store data [48].

A device capable of controlling magnetism at a lower current level than conventional spintronics devices has been developed by a research team of International center for Materials Nanoarchitectonics (MANA) consisting of postdoctoral fellow Takashi Tsuchiya (currently at Tokyo University of Science), group leader Kazuya Terabe, and Director Masakazu Aono. The new device was fabricated by combining a solid electrolyte with a magnetic material, and enabling insertion/removal of ions into/from the magnetic material through application of voltage. Because the device has a simple structure and is capable of high integration, it may lead to the development of totally new high-density high-capacity memory devices with low power consumption.[49]. The new device is simple in structure, and it combines a solid electrolyte with a magnetic material. The researchers believe that such a device could in the future be used to make a high-density very low-power memory device.

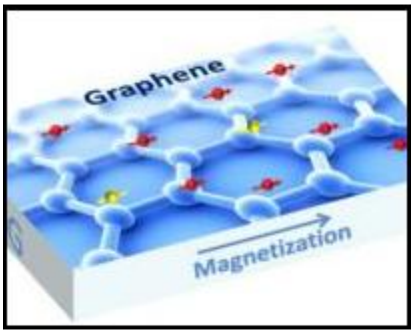

Figure 12: Magnetic graphene
(Courtesy: Enterprises AI)

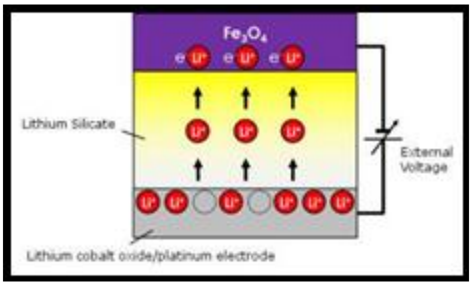

Figure 13: A device capable of controlling magnetism at a lower current
https://www.spintronics-info.com/files/spintronicsinfo/low-current-Fe3O4-spintronics-device-structure-MANA-img_assist-400x232.jpg

Spin filtering has been theoretically predicted, and previously seen only for high-resistance structures at cryogenic temperatures. This is the first time that researchers from the US Naval Research Laboratory (NRL) demonstrated the effect at room temperatures, and with very low resistance in arrays of multiple devices[50].The NRL researchers developed their own technology to grow a large multi-layer graphene film directly on a smooth, crystalline nickel alloy film. They then patterned the film into arrays of cross-bar junctions.

A research team led by scientists at the Department of Energy’s Lawrence Berkeley National Laboratory (Berkeley Lab) discovered an unexpected magnetic property in a two-dimensional material. [51,52] The scientists found that a 2-D van der Waals crystal, part of a class of material whose atomically thin layers can be peeled off one by one with adhesive tape, possessed an intrinsic ferromagnetism. It shows that magnetic anisotropy is an inherent property in the 2-D material under consideration.

As the field Spintronics is very interesting and trendy so, lots of work is going on in all over world. In year 2018 researchers from Montana State University and Lawrence Berkeley National Laboratory developed a new thin film from iron, cobalt and manganese that claims an average atomic moment potentially 50 percent greater than the Slater-Pauling limit -a magnetization density of 3.25 Bohr magnetons per atom, far ahead of the previously considered maximum of 2.45. [53].

In the same year researchers from Intel and the University of California in Berkeley developed a new scalable spintronics logic device, which is magneto-electric spin-orbit (MESO) logic device that offers dramatic improvement over current Complementary metal–oxide–semiconductor CMOS technology. [54, 55]

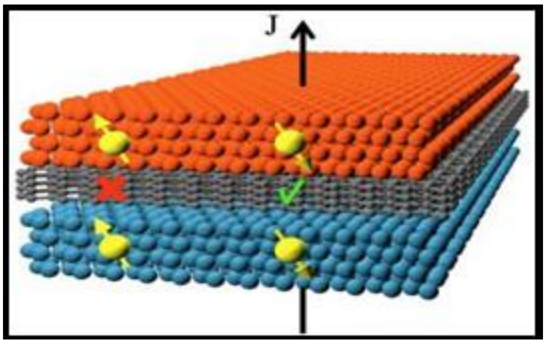

Figure 14: Spin Filtering Device
Courtesy: https://www.spintronics-info.com/files/spintronicsinfo/NRL-spin-filtering-graphene-junction-img_assist-400x318.jpg

The device uses advanced quantum materials, especially correlated oxides and topological states of matter, for collective switching and detection
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In the year 2019 Researchers from Japan's Tohoku University have developed a nonvolatile microcontroller unit (MCU) which achieves both high performance and ultra-low power by utilizing spintronics-based

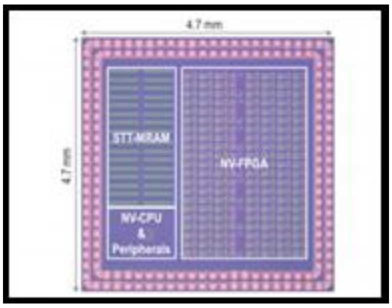

Figure 15: Nonvolatile microcontroller unit
Courtesy: https://www.spintronics-info.com/files/spintronicsinfo/Spintronics-MCU-200Mhz-Tohoku-Feb-2019-img_assist-350x269.jpg

VLSI design technology and STT-MRAM memory. It is a solid-state structure that is proficient for realizing extremely fast magnetic storage devices with ultralow power consumptions.[56]

Researchers from Kiel University and European colleagues designed and fabricated single molecular spin switches. The newly developed molecules feature stable spin states and do not lose their functionality upon adsorption on surfaces.[57]. The spin states of the new compounds are stable for at least several days. The new molecules have three properties that are coupled with each other in such a feedback loop: their shape (planar or flat), the proximity of two subunits, called coordination (yes or no), and the spin state (high-spin or low-spin). Thus, the molecules are locked either in one or the other state. Upon sublimation and deposition on a silver surface, the switches self-assemble into highly ordered arrays. Each molecule in such an array can be separately addressed with a scanning tunnelling microscope and switched between the states by applying a positive or negative voltage. It is a breakthrough in this field.

Figure 16: Single molecular spin switch
Courtesy: https://media.eurekalert.org/multimedia_prod/pub/web/220479_web.jpg

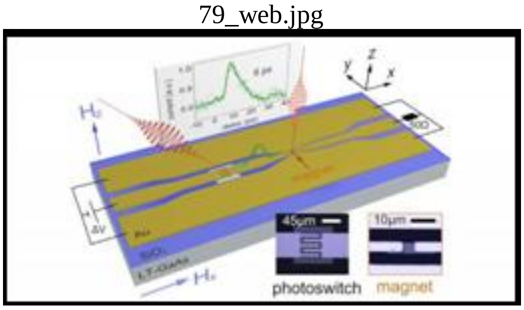

Figure 17: A schematic of the experimental design used to create the ultrafast magnetization switching.
Courtesy: https://news.berkeley.edu/wp-content/uploads/2020/10/Figure1_CPWb_BN.jpg

An international group of researchers, led by the CNRS, developed a new technique that can switch magnetization in only six picoseconds, which is almost 100-times faster than current state-of-the-art spintronics. The new technique is also highly efficient. The experimental design used to create the ultra-fast magnetization switching included an optical pump directed at the photoconductive switch, which converts the light into 6-picosecond electric pulses. The structure guides these pulses toward the magnet. When the pulses reach the magnet, they trigger the magnetization switching. [58, 59, 60]

2. Summary

Spintronics is a multidisciplinary field whose central theme is the active manipulation of spin degrees of freedom in solid-state systems. At present much effort is focused on the development of DMS which are expected to meet all demands made by spintronics. It is still in the research phase, and we hope that this new technology can be used in labs to look at problems that interest researchers. As spintronics become industrialized, we expect this could become a routine technique to check the quality of devices. The main goal of spintronics is to replace everything -- from computers to memory devices -- to have higher performance and less energy consumption. However, one major hurdle for spintronics researchers has been the difficulty in detecting the flow of spinning electrons in real time.

So, there is a continuing need for fundamental studies before the potential of spintronic applications is fully realized. Developments in the field of spintronics continue to be strongly dependent on the exploration and discovery of novel material systems. For example, one of the most exciting recent developments was the theoretical prediction and experimental verification of dissipation less spin edge currents in a class of gapless semiconductors known as topological insulators. An array of novel transport and thermoelectric effects dependent on the interplay between spin and charge currents have been explored theoretically and experimentally in recent years. In summary, the field of spintronics continues to expand into new realms, with a rich and synergistic interplay between theory, experiment, and applications. Spintronics promises to have significant impact in the worlds of science and technology.

References

[1] S. Datta and B. Das, Appl. Phys. Lett. 56, 665, (1990)
[2] Katine, *et al*, Phys. Rev. Lett. 84, 3149 (2000).
[3] Subcommittee on Nanoscale Science, Engineering and Technology *National Nanotechnology Initiative: the Initiative and its Implementation Plan* 28–30 National Science and Technology Council, Washington, DC, 2000); available athttp://www.nano.gov/html/res/nni2.pdf>.
[4] Nanotechnology Research Directions:IWGN Workshop Report(eds Roco, M. C., Williams, S. &Alivisatos, P.) Ch. 6 (World Technology Evaluation Center, Baltimore, Maryland, 1999); available at: <http://www.wtec.org/loyola/nano/IWGN. Research.Directions/>.
[5] V. LaBella*et al*, Science, **292,** 1518 (2001).

[6] Computer Weekly.com (May 24, 2001)
[7] Nanotechweb.org (June 15, 2011)
[8] Science Daily, (May 8, 2012)
[9] Jing Shi *et al*, Nature 427, 821-824 (2004)
[10] MIT news, (Nov. 23, 2004)
[11] G. Binnig *et al*, Phys. Rev. Letts. 56(9), 930-933 (1986)
[12] Schumacher, Appl. Phys. Lett, (2005)
[13] P. Espinasse, SPIE, Oemagazine (October 30, 2005)
[14] H. Kato, T. Okuda, Y. Okimoto, Y. Tomioka, K. Oikawa, T. Kamiyama and Y. Tokura, Phys. Rev. B 69, 184412 (2004).
[15] Kelvin, Schwartz *et al*, Phys. Rev. Letts. 97(3), (2006)
[16] T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, Science 287, 1019 (2000).
[17] M. I. Dyakonov and V. I. Peril; Sov. Phys., JEPT Letts. 13, 467 (1971)
[18] Y. Kato, R. C. Myers, A. C. Gossard, D. Awschalom, Science Daily, 306, 5703 (2004)
[19] J. Wounderlich, *et al* Phys. Rev. Letts. 94(4), 047204 (2005)
[20] D. Awschalom, N. Samarth *et al*, Phys. Rev. Letts. 97, 126603 (2006)
[21] Science Daily, June2, 2007
[22] S. Parkin, Science Daily, April 11, 2008
[23] P. N. Hai *et al*, Nature 10, 07879 (2009)
[24] S. C. Barnes, Science Daily, March 12, 2009
[25] Science Daily, June 16, 2009
[26] Han Suk-Hee, Science Daily, Sept 20, 2009
[27] Science Daily, Nov. 27, 2009
[28] J. Heremans and R. Myers, Science Daily, Oct. 28, 2011
[29] S. P. Giblin *et al*, Cornell University Lib., Condensed Matt. 104 (2012)
[30] V. Kashcheyevs and B. Kastner, Phys. Rev. Letts., 104, 186805 (2010)
[31] K. S. Novoselov, *et al*, Nature, 438, 197-200 (2005)
[32] Y. Zhang, *et al*, Nature, 438, 201-204 (2005)
[33] Spintronics_info.com, Jan. 26, 2011.
[34] Science Daily, Aug. 12, 2011.
[35] Spintronics_info.com, March 23, 2011
[36] Spintronics_info.com, June 21, 2011.
[37] Spintronics_info.com, March 9, 2011.
[38] Spintronics_info.com, Sept. 11, 2011.
[39] Spintronics_info.com, Aug. 15, 2012.
[40] Science Daily, Aug. 13, 2012.
[41] Science Daily, Aug. 28, 2012.
[42] Spintronics_info.com, Aug. 29, 2012
[43] Science Daily, July 11, 2012
[44] Science Daily, Sept. 18, 2012.
[45] Spintronics_info.com, Jan. 18, 2013.
[46] Spintronics_info.com, Jan. 27, 2013.
[47] Spintronics_info.com, Mar. 26, 2014
[48] Graphene_info, Jan.27, 2015
[49] Nanowerk, June 27, 2016
[50] Spintronics_info.com, Dec. 22, 2016
[51] https://www.lbl.gov/
[52] Spintronics_info.com, Apr.30, 2017
[53] R. J. Snow, H. Bhatkar, A. T. N'Diaye, E. Arenholz, Y. U. Idzerda. **Large moments in bcc FexCoyMnz ternary alloy thin films**. *Applied Physics Letters*, 2018; 112 (7): 072403 DOI: 10.1063/1.5006347
[54] SasikanthManipatruni*etal*, Nature 565, pages35–42(2019)
[55] Auth, C. et al. A 10 nm high performance and low-power CMOS technology featuring 3rd generation FinFET transistors, self-aligned quad patterning, contact over active gate and cobalt local interconnects. In *Electron Devices Meeting 2017*, 29.1.1–29.1.4 (IEEE, 2017).
[56] Spintronics_info.com, Feb.26, 2019
[57] Alexander Köbke*et al Nature Nanotechnology* (2019), DOI: 10.1038/s41565-019-0594-8
[58] KaushalyaJhuria*et al*, Nature Electronics, Oct.26, 2020
[59] Liu, Y. & Yu, G. MRAM gets closer to the core. *Nat. Electron.* **2**, 555–556 (2019).
[60] Manchon, A. et al. Current-induced spin–orbit torques in ferromagnetic and antiferromagnetic systems. *Rev. Mod. Phys.* **91**, 035004 (2019).