Magnetic Semiconductors for the Future of VLSI

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***Abstract*—Spin as a property of electron, can be manipulated easily as its charge and is a perfect candidate for modern electronic devices. Charge of electron dissipates quickly unless an external force is constantly applied; on the other hand, spin can remain in its state for long period of time eliminating volatility. In case of magnetic semiconducting devices, materials could provide a new type of control in conduction. Traditional electronics are based on control of charge carriers; practical magnetic semiconductors would also allow control of quantum spin state. Implementation of non-volatile memory elements in logic circuits could bring several advantages such as instant on/off and run time re-configurability. Reduction of power consumption and interconnection delay are the two main targets of VLSI's. Development of such memory device has potential for exceeding the performance of traditional semiconductor-based memories, and may represent one of the major technologies for the 21st century.**

***IndexTerms*—Spintronics, Diluted Magnetic Semiconductors, Fluxtronics, VLSI, Spintronics in VLSI, Hybrid Circuits**

I. INTRODUCTION

An electron possesses two degrees of freedom; charge and spin. Both degrees of freedom have been individually utilized in semiconductor physics and magnetism, yielding a tremendous amount of practical applications and expansion of horizons in basic science. [1] Spintronics is a rapidly growing research field aimed at realizing new high-performance devices that takes advantage of the electron spin as well as of its charge. Spintronics is thought to be fusion domain of semiconductor physics and magnetism because both degrees of freedom in electrons are utilized simultaneously.

Semiconductor devices can display a range of useful properties such as passing current more easily in one direction than the other showing variable resistance, and sensitivity to light or heat. By doping or by application of electrical fields or light, the electrical properties of a semiconductor material can be modified and devices made from these semiconductors can be used for amplification, switching, and energy conversion. Magnetic semiconductors provide conduction by controlling both charge carriers and their quantum spin state. The main limitation of semiconductor device is it's storage of memory; also power consumption, size, and speed. The primary aim of a DMS is compatibility with existing semiconductor structures and materials. Semiconductor-DMS are based on traditional semiconductors, but are doped with transition metals instead of, or in addition to, electronically active elements. They are of interest because of their unique spintronics properties with possible technological applications.

II. SPINTRONICS

Spintronics also known as spin electronics or fluxtronics, is an emerging field of nanoelectronics which integrates the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid state devices.

In ferromagnetic materials there are certain domain in which the magnetic fields of the individual atoms align randomly. But this alignment is random and there exists no net magnetic field. When an external magnetic field is applied domain of the individual atoms line up in the direction of the applied field due to the nature of magnetic force. This enhances the applied magnetic field. This method of aligning the spins in the given direction is called spin polarization. This give rise to spin polarized current emerging from the ferromagnet. The photo excited electrons passing from the semiconductor into the ferromagnet have different transmission probabilities at the semiconductor/ferromagnet interface depending on their spin orientation with respect to the ferromagnet layer magnetization. In this way, a spin imbalance of the electron current can be detected and measured as a modulation of the photocurrent.

Injection of spin polarized carrier into semiconductor material is the major step in creating spin-based semiconductor devices. Spin of an electron can be controlled by the application of magnetic field [2]. The working of these devices relies on the alignment of spin in reference with the applied magnetic fields. All spintronic, or more specifically semiconductor spintronic, devices act according to the following simple scheme: (1) information is stored (written) into spins as a particular spin orientation (up or down); (2) the spins, being attached to mobile electrons, carry the information along a wire; and (3) the information is read at a terminal. Hence, the main three requirements for a spintronic device includes a source material for spin injection, a medium for transport of spin polarized electrons and an analyzer for spin detection or sensing. The long coherence time of spin makes spintronic devices attractive for memory storage and magnetic sensor applications, and potentially for quantum computing where electron spin would represent a bit of information. [15][16][17][25][27]

III. DILUTED MAGNETIC SEMICONDUCTORS (DMS)

A semiconductor is a substance, usually a solid chemical element or compound, which can conduct electricity under some conditions but not others, making it a good medium for the control of electrical current. The specific properties of a semiconductor depend on the impurities, or dopants, added to it. Common semiconductor compounds include gallium arsenide, indium antimonide, and the oxides of most metals. Of these, gallium arsenide (GaAs) is widely used in low-noise, high-gain, and weak-signal amplifying devices. If implemented in devices, these materials could provide a new type of control of conduction. [21] [24] Semiconductors can be grouped into three classes depending on the nature of materials and their magnetic properties: (a) a magnetic semiconductor, in which a periodic array of magnetic element is present; (b) a non-magnetic semiconductor, which contains no magnetic ions; and (c) a DMS containing a very small fraction of magnetic element or ions.

Diluted magnetic semiconductors (DMS) also referred to as semi magnetic semiconductors are semiconducting alloys whose lattice is made up in part of substitutional magnetic atom. There are several naturally occurring magnetic elements, by introducing these into materials as a dopant they can introduce favorable magnetic properties in a controllable fashion. DMS are semiconductors doped with transition metal atoms. The level of doping directly affects the magnetic properties of the DMS and it affects the Curie temperature. A Curie temperature that is above room temperature is crucial in order to exploit spin polarization in electronic devices. The main disadvantage of current DMS materials is that their Curie temperatures are below room temperature and result in a loss of magnetic ordering in everyday applications. Materials design of new functional DMS is presented based on first principles calculations. If there is an insufficient hole-concentration in the magnetic semiconductor, then the Curie temperature would be very low or would exhibit only paramagnetism. However, if the holeconcentration is high, then the Curie temperature would be higher, between 100-200 K. The term DMS applies generally to semiconductors in which a fraction of its constituent ions are replaced by magnetic ions. Ion-channeling experiments reveal that these films are single crystalline and have high Mn substitutionality, while variable temperature resistivity measurements reveal the strong Mn-hole interactions characteristic of carrier-mediated ferromagnetism in homogeneous. Much of the attention on DMS materials is due to their potential applications in what is dubbed as the spintronics devices, which exploit the spin in magnetic materials along with charge of electrons in semiconductors. Transition metals, which have partially filled d states and rare-earth elements, which have partially filled f-states are used as magnetic ions in DMS. The partially filled d or f states contain unpaired electrons, in terms of their spin, which are presumably responsible for exhibiting magnetic behavior [30] [33]. Although research on DMS application is still at the stage of exploration, this field has already present its wide spread future in practice. For example, inserting DMS material into magnetic metal and semiconductor, one can realize ejection of carriers with spin polarization into non-magnetic semiconductor, and this technique can be applied to make spin polarized light-emitting diode. While for certain ferromagnetic/non- ferromagnetic multilayer structures by tuning temperature and voltage, one can control carrier concentration in semiconducting layer and magnetic coupling between magnetic layers, this property can be used to produce new magnetic-controlled and photonic-controlled devices. [38] [39] [41]

IV. SPINTRONIC DEVICES

Spintronic Memristor

A memristor is a hypothetical non-linear passive two-terminal electrical component relating electric charge and magnetic flux linkage. The memristors electrical resistance is not constant but depends on the history of current that had previously flowed through the device, i.e., its present resistance depends on how much electric charge has flowed in what direction through it in the past; the device remembers its history; the so-called non-volatility property. When the electric power supply is turned off, the memristor remembers its most recent resistance until it is turned on again.

Among all spintronic memristive structures, the spin valve memristor with spin-torque-induced domain wall motion could be the most favorable one for its simplest structure. In fact, the fabrication process of such spintronic memristors is identical to the adult technology that was used to manufacture the spin valve based GMR head in a hard disk drive. Hence, we choose it as the objective of this research work. The spintronic memristor consisting of a long spin valve strip which includes two ferromagnetic layers: reference layer and free layer. The magnetization direction of reference layer is fixed by coupling to a pinned magnetic layer. The free layer is split by a domain-wall into two segments that have opposite magnetization directions to each other. The domain wall in the free layer could be moved by the spin polarized current. The resistance per unit length of each segment is determined by the relative magnetic directions of the free layer and reference layer: when the magnetization direction of the free layer in a segment is parallel (anti-parallel) to the reference layer, the resistance per unit length of the segment is low (high). Memristor technology brings out a whole new set of possibilities. All the AI circuits and neural networks in the past have been built on digital 1’s and 0’s, and although they can do a great job in intelligent operations, they are still basically zombies. No one has come even close to simulating consciousness. Memory for devices, universal memory replacing hard drives, RAM, flash, etc. in all computer device, complex self-learning neural networks and hybrid transistor/memristor circuits, non-volatile memory applications, programmable logic and signal processing, crossbar latches as transistor replacements or augmenters. [18] [22]

Magnetic Tunnel Junction (MTJ)

Magnetic tunnel junctions or MTJs are nanostructured devices within the field of spintronics. The experimental observation of sizable and tunable magnetoresistance (change of materials resistance due to external magnetic fields) is intimately related to the exploitation of not only charge of the electron but also its spin. The discovery of giant magnetoresistance (GMR) in multilayered ferromagnetic films separated by thin metallic spacers has initiated an enormous research interest, particularly also for a wealth of potential applications. Since then, the impact of MTJs on the field of spintronics has hugely expanded, particularly due to the enormous magnitude of the observed magnetoresistances at room temperature and its impact on potential applications.

When electrons are tunneling between two ferromagnetic metals, the magnitude of the tunneling current depends on the relative orientation of the magnetization of both electrodes. This can be understood from a few elementary arguments: (i) the tunneling current is proportional to the product of the electrode density of states (DOS) at the Fermi level; (ii) in ferromagnetic materials, the ground-state energy bands in the vicinity of the Fermi level are shifted in energy, yielding separate majority and minority bands for electrons with opposite spins; and (iii) assuming spin conservation for the tunneling electrons, there are two parallel currents of spin-up and spin-down character. As a result of these aspects, the current between electrodes with the same magnetization direction should be higher than those with opposite magnetization.In the field of spintronics, MTJs display magnetoresistance effects due to the spin dependence of the tunneling current when dealing with ferromagnetic electrodes. This has dramatically increased our knowledge of tunneling between ferromagnetic materials. MTJ research and development has made substantial progress over the past decade, fueled by two current and important commercial applications: HDDs and MRAM. This progress has enabled rapid technological advances in both applications. [36]

V. SPINTRONIC VLSI IN HYBRID CIRCUITS

Invention of transistor was the driving factor of growth in the VLSI. VLSI is basically transistors in a single chip. We can say that this is the upgraded from the embedded technology. It is the current level of computer microchip miniaturization and refers to microchips containing in the hundreds of thousands of transistors. Therefore, this technique provides less area/volume. Hence compactness, less testing requirements, less power consumption, higher reliability due to improve on-chip interconnects, higher speed, due to significantly reduced interconnection length, and significant cost savings. VLSI can be used in many fields which are, Defense, Navy, Air Force, etc. Using CAD tools, these modules are mapped onto the chip surface for automatic module with a goal of minimized interconnects area and signal delays. The chip is mentioned in terms of logic gates by using routing program and a cell placement. The implementation of non-volatile memory elements in logic circuits could bring several major advantages such as instant on/off, built-in function programmability (in LUT, PLD or FPGA) and run time re-configurability. Moreover, the implementation of non-volatile flip-flop registers, providing an efficient way of fighting the increasing dissipation due to leakage currents within today's CMOS logic circuits. Reduction of power consumption and interconnection delay are the two other targets for very large scale integrated circuits (VLSIs). Drastic increase of static power dissipation is being anticipated due to leakage current in beyond 45 nm CMOS technology. Logic-in-memory architecture, where memory elements are distributed over a logic-circuit plane, combined with non-volatile memory is expected to realize both ultra-low-power and shorten interconnection delay.

VI. APPLICATIONS

There are many applications for diluted semiconductors in VLSI which are integrated with latest devices which have high performance and some of them are;

Threshold Logic Gates

A threshold logic gate (TLG) essentially constitutes of summation of weighted inputs, followed by a threshold operation, where INi's are multiple binary inputs, Wi's are scalar weights with which the corresponding inputs are multiplied. The same TLG circuit can implement different Boolean functions by reconfiguring the weights, threshold, or both. In previous research, TLG has been implemented in CMOS and other bulk semiconductor technologies, such as CMOS look-up-tables (LUT), Single electron transistors and resonant tunneling diode.Such hardware implements suffer from power, delay and area overhead. Recent discovery of nano-scale memristor, whose resistance can be programmed with an applied electric field, has led to proposal of energy-efficient reconfigurable memristive TLG (MTLG). Compared with CMOS LUT based TLG design, such MTLG designs can potentially provide two orders lower energy consumption and high area density. However, due to the intrinsic high energy consumption and long programming delay of memristor (Ag-Ch, TiO2), the memristor based TLG suffers from high power and long delay in reconfiguration operation, thereby eschewing the benefits of reconfigurable logic computing. Moreover, the spintronic weight device also leads to low power and fast speed in reconfiguration operation of the proposed design. Compared with reconfigurable MTLG design, the proposed STLG consumes three orders lower reconfiguration energy, opening a new door for future post-CMOS, ultra-low energy reconfigurable computing era. [8]

Non Volatile Logic in Memory towards Low Power Computing

Every 18 months, the number of transistors can be doubled, which constitutes the well-known Moore's law. And the transistor size has scaled down following this famous law for almost 40 years. However, it becomes more and more difficult to maintain this law due to power issues, such as high static power caused by the intrinsic leakage currents, and as dynamic power due to the long interconnection delay. The static power comes mainly from the cache memory between the computing chip and main memory, the dynamic power is dominated by the large data traffic. They prevent computing from reaching high frequency (~4 GHz) and limit power efficiency. Both academics and industries are looking for the solutions to tackle these bottlenecks. [5]

The magnetic tunnel junction (MTJ) is one of the most important devices of spintronics. It is the basic element of modern hard drive read heads and MRAM storage cells. Thanks to its vertical structure, which can be integrated at the back-end process of CMOS, as well as its fast and low power data access operations, a number of research groups focus on this device to build ultra - lower power logic gates. Magnetoresistive RAMis one of the newest approaches to non-volatile memory and stores data in magnetic storage elements called magnetic tunnel junctions (MTJ's). MRAM has an especially promising future as it seeks to encompass all the desirable features of the other popular types of memory (non-volatility, infinite endurance, high-speed reading/writing, low cost). [32][37]

VII. CONCLUSION

Spintronics which deals with the spin of electron has a great potential to spin this current world to digital atomic world which has a capability of manipulating at atomic level and this can even be made further smaller during the integration with "NANOTECHNOLOGY". We make use of this spin of the electron, create new devices and circuits which is beneficial for the human life. Spintronics provides architectures which allow for dramatic reduction in energy consumption which in turn allows to proceed with miniaturization in accordance with Moore's law. Combined with the VLSI technology, MTJ makes it possible not only to realize non-volatile, high density, and fast random access memories, but also to construct nonvolatile VLSI logic circuits that have unprecedented low power capability and compactness that overcome the present limit of power and delay.Spintronics-related phenomena observed in ferromagnetic semiconductors are now being utilized in metal spintronic devices to realize next-generation VLSI's.

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