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Analysis of Three-Dimensional Magnetic Domain Wall Racetrack Memory

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ABSTRACT: An overview of magnetic racetrack operation and components necessary to successfully realize this memory technology is presented. Fundamental physical concepts of adiabatic and non-adiabatic spin-torque transfer is presented and used to explain how bits of information are read, written, and pushed through ferromagnetic racetracks. Recent developments in the controlled movement of domain walls in magnetic nanowires by short pulses of spin-polarized current give promise of a nonvolatile memory device with the high performance and reliability of conventional solid-state memory but at the low cost of conventional magnetic disk drive storage. Resonant amplification of spin-torque transfer via pulsed current operation has been proposed to overcome issues with current density. The racetrack memory comprises an array of magnetic nanowires arranged horizontally or vertically on a silicon chip. Individual spintronics reading and writing nanodevices are used to modify or read a train of ~10 to 100 domain walls, which store a series of data bits in each nanowire. This racetrack memory is an example of the move toward innately three-dimensional microelectronic devices.

KEYWORDS: Racetrack Memory (RM), Domain Walls (DW)

I. INTRODUCTION

Over the past decade, a rich new field combining materials science and physics has developed around manipulating the spin of electrons in magnetic and semiconducting devices. This field, called spintronics, has opened up the potential for a myriad of previously unimaginable new devices with applications in memory storage and logic. Memory storage technologies in particular have received increased attention due to the high energy consumption and volatility of static and dynamic random access memory (RAM), the slow read and write times of hard disk drives (HDD), and the cost of flash memory and solid-state drives (SSD). Among the most promising of the spintronics memory solutions is the concept of magnetic race track memory, which stores bits of information in the magnetization orientation of regions in a channel-shaped ferromagnetic structure.

The operation of racetrack memory is analogous to a solid-state, non-volatile shift register. On one end of the racetrack, bits may be written into the racetrack via changing the magnetization direction in the ferromagnetic material in the racetrack. From here, the bit is pushed along the racetrack and may be read by magneto-resistive tunnel junctions farther down the track, see Fig. 1 and 2. One of the true advantages to racetrack memory lies in the ability to orient the racetrack upwards and store bits in a larger 3-dimensional space. However, preliminary prototypes of this memory device operate in two dimensions.

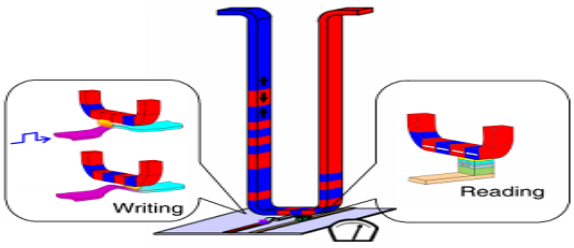

Fig.1 Conceptual design of a magnetic racetrack memory structure. Blue and red colored regions indicate domains of opposite magnetization to one another but in plane with the racetrack direction.

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The proposed memory density, read/write speeds, and scalability of this device make it the strongest candidate for a form of universal memory. However, the practicality is severely limited by high current densities required to move domain walls and the reliability of domain wall motion through the racetrack [1].

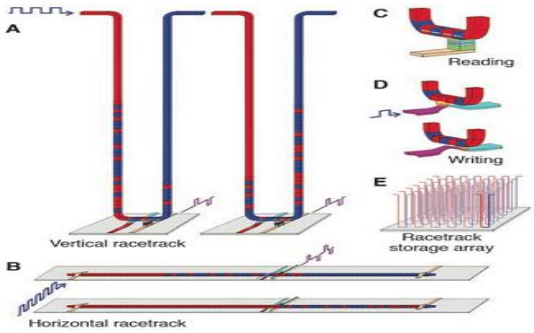

Fig. 2 (A) Bending of ferromagnetic racetracks in the vertical direction could allow for higher area density bit storage. Red and blue regions indicate areas of different magnetization orientation. (B) Horizontal racetracks offer better initial prototypes due to ease of fabrication and accessibility of the device for characterization. (C) Magneto-resistive tunnel-junctions for sensing the resistance, corresponding to magnetization, across the domain. (D) A method of writing bits by moving the stray field from a neighbouring domain wall into and out of range of the racetrack. (E) Concept design of a high-density magnetic racetrack array.

In addition, the exact contributions to spin-induced magnetic flipping and domain wall motion are highly dependent on the materials used and structure of the device. Several solutions and models have been proposed to alleviate these issues, including patterned notches along the ferromagnetic racetrack, pulsed current to move the domain walls, and experimentation with different soft and hard magnetic materials. Ideally, reading and writing elements will require low current densities to write bits of information and not affect neighbouring bits. The current parallel to the racetrack must also push all the sequential domain walls along in a uniform, controlled manner. Lastly, the domain walls must be pinned in discrete intervals by structures that do not significantly increase the current density and have sufficient tolerance so as to prevent multiple domain walls from moving into the same bit area. The exact geometry of proposed racetrack memory models is visualized in Fig 2.

II. OPERATING PRINCIPLES

The operation of magnetic racetrack memory requires three essential components: (1) reading elements such as magneto-resistive tunnel junctions that detect the tunnelling resistance across a ferromagnetic region, (2) writing elements such as nearby wires that produce a localoersted field or spin-torque transfer devices that change a bit by transferring angular momentum from spin-polarized currents, (3) a means by which domain walls may be pushed through the ferromagnet layer, typically via pulsed spin-polarized currents [1], and (4) a method of reliably restricting the position of domain walls to discrete distance intervals (i.e. notched patterns along the racetrack). With each of these requirements comes a unique set of constraints and limitations. Ideally, reading and writing elements will require low current densities to write bits of information and not affect neighbouring bits. The current parallel to the racetrack must also push al lthe sequential domain walls along in a uniform, controlled manner. Lastly, the domain walls must be pinned in discrete intervals by structures that do not significantly increase the current density and have sufficient tolerance as to prevent multiple domain walls from moving into the same bit area. The exact geometry of proposed race track memory model is visualized in Figure 2.

III. READING INFORMATION FROM THE RACETRACK

To read the state of a domain in the magnetic racetrack, a magneto-resistive tunnel junction senses the resistance of spin-polarized current across the bit. A magneto-resistive tunnel junction is a device composed of two ferromagnetic layers separated by a thin oxide. In each ferromagnetic material, the density of states is spin dependent because the

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internal magnetic field gives rise to a Zeeman splitting of electron energy levels aligned with and against the field. As a result, a larger number of states are available to electrons oriented along the field therefore allowing for lower resistance. When the two ferromagnetic materials are aligned in the same direction, the resistance may be described by two large resistors in series and also in parallel with two small resistors in series. When the two ferromagnetic materials are aligned anti-parallel, the equivalent resistance may be described by a small and large resistor in series and also in parallel with another small and large resistor in series. The second configuration results in a much larger total resistance than the first, and helps to account for the total change in resistance between the two orientations. The magnetic tunnel junction may be characterized by its tunnelling magneto-resistance ratio (TMR) defined by

$$TMR = \frac{Rap - Rp}{Rp} \qquad (1)$$

Where R_{ap} is the resistance in the anti-parallel configuration and R_p is the resistance in the parallel configuration. A high TMR makes it easier for on-chip electronics to accurately detect the state of the bit.

The oxide tunneling layer is also a critical component of the tunnel junction. It both isolates the two ferromagnetic regions and restricts the movement of carriers to quantum mechanical tunneling. When a bias is applied to the junction in the parallel configuration, the probability of tunneling is much larger than when the ferromagnets are perpendicularly configured, corresponding to a lower resistance state. Recent work has demonstrated that marked improvements in spin-polarization efficiency have been possible by replacing aluminum oxide (AlOx) tunnel junctions with MgO junctions due to symmetry effects and that majority charge carrier states decay more slowly across the insulator than the minority state [2]. In general, this effect is enhanced by choosing ferromagnetic materials whose symmetries for spin-up and spin-down electrons differ. The result is a small overlap between wave functions on either side of the oxide when configured anti-parallel and larger overlap when configured parallel, leading to a very large TMRs that increase with widening MgO layers. Thus, with greatly changing values of resistance for both magnetization orientations, it is easy to accurately detect the state of the domain on the racetrack.

IV. WRITING INFORMATION TO THE RACETRACK

Spin-torque transfer and stray-fields from neighbouring domain walls are two methods that can be used to write bits onto the racetrack. Using the induced magnetic field from current through a wire is another option, but will not be discussed because it requires high current densities and can affect neighbouring domains. First, for writing elements using spin-torque transfer effects it is crucial to model the magnetization of the material under different currents.

V. SHIFTING DOMAIN WALLS DOWN THE RACETRACK

In RM, DWs are shifted along the racetrack by nanosecond current pulses using the phenomenon of spin-momentum transfer. When a current is passed through a magnetic material, it becomes spin-polarized because of spin-dependent diffusive scattering, and so carries spin angular momentum. When the spin-polarized current is passed through a DW, the current transfer's spin angular momentum to the wall, thereby applying a torque to the moments in the DW, which can result in motion of the wall. The direction of motion of the DWs is independent of the magnetic charge of the DW, whether head to head or tail to tail, so that an entire sequence of DWs can be shifted along the racetrack. The magnetic columns need to be sufficiently narrow (<~100 nm) for the spin momentum transfer interaction of the current with the DW to dominate over the self-field of the current. Thus, the racetracks are composed of nanowires of magnetic material approximately 100 nm or less in diameter and one to several tens of micrometers tall, thereby accommodating ~10 to 100 DWs per racetrack. The cost of storing one data bit in the RM is lowered as the number of DWs (n) that are stored in an individual racetrack increases, and, moreover, the average time needed to read a particular bit is independent of n if the distance between DWs is kept constant.

One of the most challenging aspects of RM is the controlled and reliable motion of a series of DWs, which are the data bits, backward and forward along the racetrack. The ultimate performance of RM will depend both on the current density required to move DWs and the velocity at which the DW pattern can be shifted along the racetrack. Thus, a detailed understanding of the magnetization dynamics of DWs and their interaction with spin-polarized current is the key for the successful development of RM.

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VI. DOMAIN WALL DATA BIT

Current-driven DW motion has been studied in just a small number of magnetic materials, both "soft" and "hard", in in-plane and perpendicularly magnetized nanowires, respectively. In hard materials, the magnetization direction is determined largely by the direction of the magnetic anisotropy fields, which are intrinsic to the material. In contrast, the magnetization direction in magnetically soft nanowires is defined by the geometrical shape and form of the nanowire. Here we focus on horizontal racetracks with rectangular cross-sections fabricated from thin films of soft magnetic alloys composed of iron, nickel, and cobalt. In these cases, the internal structure of the DW and its width are largely derived from magneto-static fields determined by the shape of the racetrack [3]. In particular, the DW width scales approximately with the nanowire width.

For the nanowire dimensions studied - widths ranging from 100 to 500 nm and thicknesses ranging from 10 to 50nm - the DW states with the lowest energies have either transverse (T) or vortex (V) wall structures [4] [5] (Fig. 3, A and B). The vortex structure is favoured in thicker or wider nanowires because it is flux closed with reduced surface charge (and, thereby, demagnetizing fields) at the nanowire edges. In larger nanowires, even more complex DW structures can be found (Fig. 3 B). It is common to find both (T) and (V) DW structures in a given nanowire, for a wide range of nanowire widths and thicknesses, even when the DW energies are substantially different (Fig. 3 A).Even when only vortex DWs are energetically stable, several metastable vortex structures can be observed: The chirality of the vortex can be either clockwise or anticlockwise, and the vortex core polarity (that is, the direction of the out-of-plane vortex core magnetization) can be either negative or positive (Fig. 3 B). Both the chirality and the polarity of the vortex strongly affect the DW dynamics. For example, the pinning strength of a notch depends on the DW chirality [6].

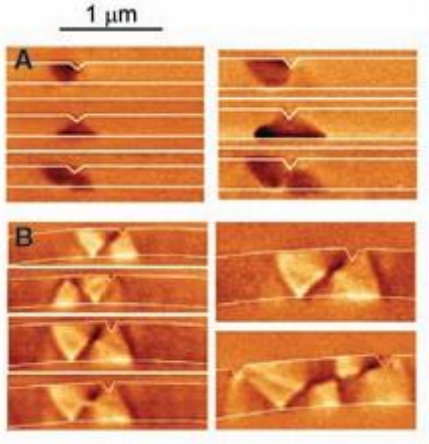

Fig. 3 (A) Structure of tail-to-tail DWs observed in thin 10-nm-thick nanowires with widths of 200 nm (left) and 300 nm (right). From top to bottom, images show DWs with anticlockwise transverse, clockwise transverse, and anticlockwise vortex structures. (B) Structure of head-to-head DWs observed in 40-nm-thick nanowires with widths from 200 to 400 nm. The leftmost four images show examples of vortex DWs with clockwise and anticlockwise chiralities, both with negative core polarity (top two images on the left, for a nanowire width of 200 nm), and clockwise vortex walls with negative and positive core polarities (bottom two images on the left, width 300 nm). The two images on the right show examples of structures found in a 400-nm-wide nanowire: a vortex wall with clockwise chirality and negative polarity (top) and a more complex structure comprising two vortices and one anti-vortex for a DW pinned between two neighbouring notches (bottom).

VII. RESONANT AMPLIFICATION OF DW MOTION

In order to build a RM with stable bits, the DWs are located at specially fabricated pinning sites, suitably spaced along the racetrack. This means, however, that the current densities needed to move the DWs between these sites might be too high for practical use, in particular for nanowires formed from a single layer of Perm alloy. A novel method for lowering the critical current density of pinned DWs was recently demonstrated, which involves using short current pulses with particular lengths, matched to the innate precessional frequency of the pinned DW [7] [8]. It has long been

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realized that many properties of a DW can be described as if the DW has a mass, just like a mechanical oscillator; a DW confined in a potential well resonates at a natural frequency when subjected to an excitation. This means that the amplitude of the DW's oscillatory motion can be resonantly amplified by properly engineering the profile of the current excitation, thereby substantially reducing the critical current (Fig. 4).

When a small current is applied, the DW's position within the potential well and its energy undergo damped oscillations, eventually reaching a stationary state but with an increased energy proportional to the current (Fig. 4A, c). When the current is turned off, the DW oscillates toward its original equilibrium position at the bottom of the pinning potential. The details of the DW's trajectories during and after current excitation are strongly influenced by the duration of the current excitation (Fig. 4A. d and e). When the current pulse length is matched to approximately a half integer of the DW's precessional period the DW can have sufficient energy to be driven out of the pinning site; whereas for pulses just a half integer period longer (or shorter), the DW's energy is lower and it remains confined. Thus, the probability of depinning a DW from a pinning site oscillates with the current pulse length, which is a direct manifestation of the current-induced precessional excitation of the DW.

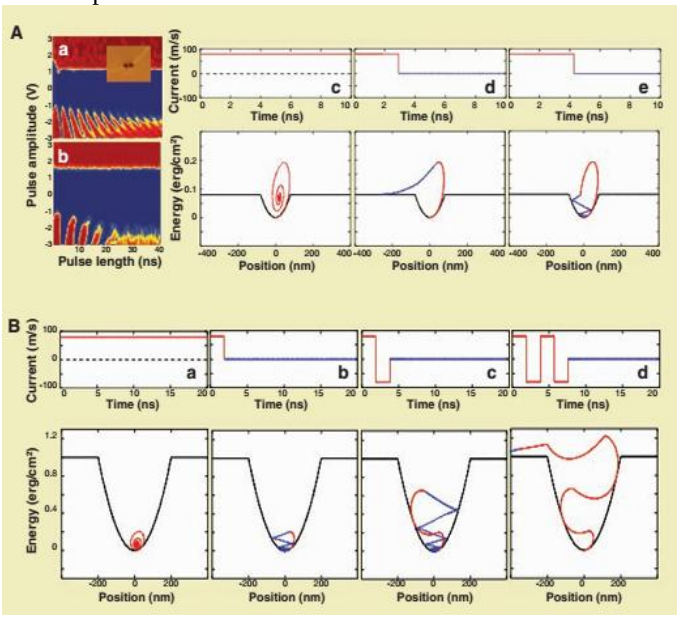

Fig. 4 (A) Experimental observation of the DW oscillation confined in a potential well. (B)Analytical calculations of the dynamics of a DW pinned in a deep potential well. The DW trajectory in the energy/position space is plotted for dc current.

Experimental observation of this effect is shown in Fig. 4A, a and b, for two nanowires with different widths. The DW is pinned at a local defect in the curved region of the L-shaped nanowires. For negative voltages, the depinning probability oscillates with the current pulse length according to the mechanism described above [7], but with a longer period in the narrower wire because of the higher mass of the DW in the latter case. A magnetic field was applied to aid the DW's motion so that the oscillatory depinning effect was observed only for one current direction (here, negative).

When the pinning potential is deeper, a single current pulse with the same amplitude as in the previous example does not allow the DW to be depinned (Fig. 4B, b). However, just like a mechanical oscillator, the DW's energy can be resonantly enhanced by applying a series of current pulses synchronized with the oscillatory motion of the DW. This is illustrated in Fig. 4B, c and d, for the case of current pulses each exactly 1/2tplong, but with successive pulses of opposite polarities. The DW energy increases with each successive pulse until it is larger than the potential depth and the DW can be depinned. This takes places at much lower currents than is otherwise possible with dc current or a single current pulse.

For the resonant amplification of DW motion to be useful in RM, it is important that depinning be achieved for a short series of pulses. Resonant amplification (in this case leading to the reduction of the depinning field) is substantial

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for just a single bipolar pulse and saturates for short trains of pulses (two to eight, depending on the depinning direction).

VIII. CONCLUSION

There is much discussion about the possibility of developing 3D silicon microelectronic devices to overcome the limitations of the further scaling of complementary metal oxide semiconductor transistors. These typically involve the thinning and stacking of several silicon chips in packages or the use of silicon through-wafer. RM is a 3D technology that is relatively simple in concept and potentially inexpensive to fabricate. By using the essentially unused space above the surface of a silicon wafer for storing data (in columns of magnetic material) and by bringing these data to the surface of the wafer for reading and manipulating the data, an intelligent 3D memory chip can be built with unsurpassed data storage capacities. Moreover, RM, by storing data as the direction of a magnetization vector, has no obvious fatigue or wear out mechanism, which plagues many non-volatile memory technologies today that store information by physically moving atoms (such as phase-change or ferroelectric memory).

RM encompasses recent advances in the field of metal spintronics. Magneto-resistive devices based on the manipulation of the flow of spin-polarized current through metallic hetero-structures composed of sandwiches of thin ferromagnetic electrodes separated by ultrathin metallic [typically copper] or dielectric layers [the most useful being MgO] have proven to be invaluable for sensing data bits in magnetic HDDs. Indeed, the first device-the spin valve-enabled a thousand fold increase in the storage capacity of such drives in the past decade. The second device-the magnetic tunnel junction (MTJ)-is in the process of supplanting the spin valve because of its higher signal. MTJs also form the basis of modern magnetic RAMs (MRAMs), in which the magnetic moment of one electrode is used to store a data bit. Whereas MRAM uses a single MTJ element to store and read one bit, and HDDs use a single MTJ to read all ~100 GB of data in a modern drive, RM uses one device to read ~10 to 100 bits. Depending on the number of DWs per racetrack and the velocity of the DW, the average access time of RM will be 10 to 50 ns, as compared to 5 ms for an HDD and perhaps ~10 ns for advanced MRAM.

Specification	**Approximate value**
Diameter of racetrack	≤ 100nm
Height of racetrack	~ 1 to 10 mm
No. of domains per racetrack	~ 10 to 100
Current pulse duration	14ns
Current density	~ $3x10^8$ A/cm^2
Magnetic field that assist DW motion	~ 25 Oe

Table. [1]

RM uses spin-polarized current not only for sensing but also for manipulating magnetic information. Recent experiments establish its basic principles. DWs can be moved with nanosecond long current pulses over distances of several micrometers and at high velocities exceeding 100 m/s. Moreover, DW motion using current alone enables moving a series of adjacent DWs (of alternating charge) in lockstep in one direction or the other by using current pulses of one sign or the other. However, there remain important challenges to overcome. Among these is the demonstration of the highly reliable motion of a series of ~10 to 100 DWs along the racetrack, and the reduction of the current density required for DW motion below the dc threshold values currently needed at room temperature, while maintaining high DW velocity. Further understanding of the interaction of spin-polarized current with magnetic moments is essential. Exploring a wide variety of materials and hetero structures may provide new insight into DW dynamics driven by current, making possible DW-based memory and possibly logic devices that were previously inconceivable.

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