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Theoretical study on Topological Insulator based Spintronic Tristable Multivibrator

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Abstract

We propose a novel spintronic circuit design analogue to a digital latch for asynchronous applications. It employs a U-shape 2D topological insulator with three terminals connected to ferromagnetic (FM) contact layers. A preliminary study has been carried out to investigate the behaviours of the spin polarization of the currents via non-equilibrium Green's function (NEGF) formalisms. The device can be operated between three stable magneto-logic gates, and a spin-transfer-torque mechanism is used to switch the magnetization of the free FM layers at contacts by just controlling two voltage levels at the three input terminals. The proposed device has the potential for the future generation of novel spintronic devices.

1. Introduction

Recently, strong topological insulator (TI) materials have attracted a lot of attention from the device engineering community due to their unique properties induced by the spin orbit coupling (SOC) which drives the spin up and down electrons in clockwise and anti-clockwise direction along the edges in equilibrium condition, whereas the central region exhibits insulating behavior [1]. Most attractively, this spin-dependent current along the edges/surface (2D/3D) are dissipationless due to lack of backscattering, and are robust against perturbations that do not break time reversal symmetry, like non-magnetic impurities and weak disorders [2, 3]. Therefore, the study on the novel functional devices based on TI materials will be very important in this emerging field. In this work, firstly, we investigate spin-transport for a three-terminal U-shaped device based on mercury-telluride (HgTe) quantum well (QW) (2D TI), and demonstrate spin separation mechanism for unpolarized current as input, resulting in close to 100% spin polarization (Figure 2 of [3]). Furthermore, the spin transfer torque (STT) has conceptually been recommended for logic devices [4], to switch the spin-transistors and use free-layer magnetization as capacitive analogue for storing information. Combining these two unique characteristics, therefore, we introduce a spintronic analogue of latch (bistable multivibrators) that is commonly used in digital circuits, and the basic building block of asynchronous integrated circuit design, and design a tri-stable multivibrator which outputs three stable magneto-logic states (MLS) (Table I), but is only driven by the binary electronic logic states (ELS) i.e. by switching between two voltage levels at three terminals. Finally, the technical challenges are discussed.

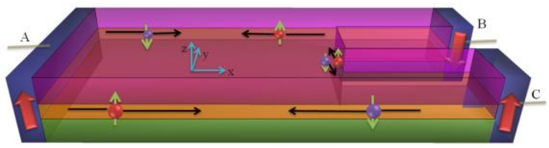

Figure 1: Device Structure. HgTe Quantum Well (middle orange layer) sandwiched between CdTe (green and magenta layers) with thin film magnetic terminals (e.g. CoFeB) (blue) and spin current on edges. Up and Down spin are +z and –z polarized respectively.

2. Theory and Methodology

To obtain both the edge and bulk states concurrently for a 2D TI such as HgTe, we implement a real-space tight-binding (TB) Hamiltonian with nearest neighbour interaction [5]. The spin dependent currents are calculated at low temperature via NEGF formalism that gives both equilibrium and non-equilibrium currents. However, the former, which circles along the boundary of TI even in ab-

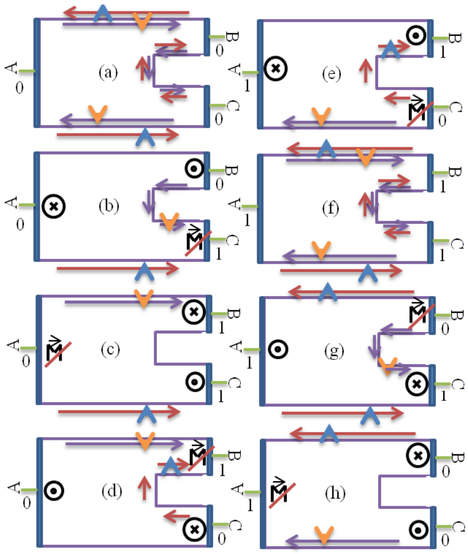

Figure 2: Spin Polarized (SP) Electron in top Cross Section of device. (a)-(h) correspond to Input Logic driven from unpolarized battery as per Table I. Channel edges are along x-axis, magnetic layer along y-axis and the electrons are polarized orthogonal to the page (z-axis). Arrows depict the direction of up/down electron flow. All three terminals are coated with thin films of Magnetic Layer. Magnetization states for all configurations are shown in black at each terminal. Crossed M vector denotes Demagnetized state. Circled dot and cross correspond to +z and –z Magnetization respectively. Equilibrium States: (a) and (f) retain their Magnetization states. Non-Equilibrium States: (b) and (e) are in 1_M state; (c) and (h) are in 0_M state; (d) and (g) are in -1_M state; (b)-(e),(g)-(h) only non-equilibrium spin current are shown. Equilibrium current will still be circulating along the boundary and sum to zero. Moreover, Magnetization states will not be affected because of its equal influx and outflux at all terminals.

sence of an external bias, sums to zero due to sanctity of time reversal symmetry of our device. Furthermore, by coupling LLG equation with NEGF formalism we solve for the STT acting on the nanomagnetic films at the three contacts to effectuate the magnetic switching.

3. Results and Discussion

Figure 1 illustrates the U-shaped structure of studied tristable multivibrator with HgTe QW channel, connecting to three nanomagnetic thin film contacts at the terminals A, B and C, controlled by the binary voltage biases. Due to the unique transport properties, pure helical spin state separation for U- shaped device can be generated as shown for '011' (Figure 3(a) of [3]) and '100' (Figure 4(a) of [3]) inputs. Based on this phenomenon, we further investigate the spin current under all the ELS as shown in Fig. 2. Next, the spin flux at the drain terminal transfers its spin angular momentum to the magnetic moments of the FM film to align the drain's magnetization, parallel to the spin polarization. However, since the source is driven from the unpolarized voltage supply, it accumulates the opposite spin in non-equilibrium condition due to lack of energy states for their forward transport, thereby aligning it anti-parallel to drain. For example, as logic switches from '0' to '1' at terminal A, i.e. Fig 2(d) to Fig 2(e), MLS switches from -1M to +1M. It is because, in the initial state, terminal C drives up-spin to terminal B to magnetize it in +z and itself become –z magnetized, A sources down-spin to B to magnetize it in –z and itself become +z magnetized whereas A and C are in electrostatic equilibrium and therefore no magnetizing current flows between them. However, in the final state, the contact B and A get into equilibrium, but terminal C now drives spin down current to magnetize terminal A in –z and up-spin current to magnetize B to +z via STT effect. Output logic states, like in latch, are retained for input '000' and '111', because of equilibrium with no net current flow. We summarize all of the operating models in Table I.

Technical Challenges: To practically operate this device, there are still few technical issues. Firstly, in a 2D-TI, the spins are z-polarized (helical fermions [1]) i.e. orthogonal to plane and henceforth contact magnetization is along + z-axis. In principle, shape anisotropy for most of thin nanomagnet films will force magnetization in y-axis. However, it can be solved by using materials with strong magneto-crystalline anisotropy in z-axis for STT based switching, like CoFeB. However, since materials with strong crystalline anisotropy mandate larger spin current density for switching, the experimentalists can achieve it in the following ways: a) make the magnetic film very thin to increase the spin flux density; b) place a magnetic quantum dot (QD) between TI and contacts because QD can be switched for lower spin current densities; c) Use a superlattice of HgTe to accumulate more spin current. Moreover, a sufficiently wide channel is recommended to minimize the coupling between two edges of the same terminal and the contacts are expected to be in demagnetized

TABLE I
TRUTH TABLE FOR INPUT-OUTPUT STATES

Input Logic Gray Code			Spin Current*		Magnetization States			Output State
A	B	C	Top Edge	Rear Edge	A	B	C	
0_e	0_e	0_e	x	x	NC	NC	NC	NC
0_e	0_e	1_e	x	$\uparrow_{CA}$ $\downarrow_{CB}$	$\downarrow z$	$\uparrow z$	DM	1_M
0_e	1_e	1_e	$\downarrow_{BA}$	$\uparrow_{CA}$	DM	$\downarrow z$	$\uparrow z$	0_M
0_e	1_e	0_e	$\downarrow_{BA}$ $\uparrow_{BC}$	x	$\uparrow z$	DM	$\downarrow z$	-1_M
1_e	1_e	0_e	x	$\uparrow_{BC}$ $\downarrow_{AC}$	$\downarrow z$	$\uparrow z$	DM	1_M
1_e	1_e	1_e	x	x	NC	NC	NC	NC
1_e	0_e	1_e	$\uparrow_{AB}$ $\downarrow_{CB}$	x	$\uparrow z$	DM	$\downarrow z$	-1_M
1_e	0_e	0_e	$\uparrow_{AB}$	$\downarrow_{AC}$	DM	$\downarrow z$	$\uparrow z$	0_M

0_e: Electronic Logic Low; 1_e: Electronic Logic High;
1_M: Magnetic Logic High; 0_M: Magnetic Logic Intermediate; -1M: Magnetic Logic Low;
x: Equilibrium; NC: No Change; DM: Demagnetized
$\uparrow$z: +z Magnetization; $\downarrow$z : -z Magnetization;
*: Subscripts denote up/down spin current (z polarized) direction (e^- flow is opposite to current direction)
NOTE: Output state describes the Finite State Machine (FSM) at 'B'

state at large widths; however, non-localized spin current may result in domain wall formation. As a result, though nanomagnet film is still effectively demagnetized, the local magnetization dynamics may affect spin transport. Alternatively, for small widths the demagnetizing current is equivalent to only a charge current and may not be able to demagnetize the film. Therefore, the magnetization history of nanomagnet will be retained (non-volatile) whose effect needs to be examined.

3. Conclusion

We theoretically study a spintronic tristable multivibrator using 2D TI (HgTe) as channel, which is an analogue of latch in digital circuitry and henceforth will empower design of asynchronous spintronic circuits that can exploit both electron charge and spin. Fundamentally, device leverages on STT mechanism and nanomagnet thin films to flip and store magneto-logic states respectively. Moreover, we have also discussed some technical challenges of such devices, and respective solutions.

Acknowledgments

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