Spin-Torque-Nano-Oscillator based neuromorphic computing assisted by laser

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Abstract—In spintronic-based neuromorphic computing systems (NCSs), the switching of magnetic moment in a magnetic tunnel junction (MTJ) or magnetic oscillation in spin torque nano-oscillator (STNO) is used to mimic biological neuron firing. Although using STNO reduces the power consumption significantly, still there is a huge gap between the power consumption of spintronic-based NCS and brain due to the high bias current. In this paper, the power consumption of the proposed STNO-based NCS is reduced by thermally assisting the STNO oscillation through a microwatt nanosecond laser pulse. The experimental results show the power consumption of STNOs in NCS reduces by 56% by heating them up to 100°C. The total power consumption of the proposed laser assisted oscillation-based NCS (LAO-NCS) is reduced by 46% at 100°C compared with a typical STNO-based NCS at room temperature.

Keywords— *neuromorphic computing system, laser, power efficient, STNO*

I. INTRODUCTION

The grand challenge of exascale computing, 10^{18} operations/second, calls for a dramatic change in hardware of the current petascale supercomputers. A paradigm shift is required to tackle the issue of processing the huge amount of images and videos that is the most time and power consuming task for the existing Von-Neumann computing machines (VNC). The most promising solution is the brain-inspired systems, so-called neuromorphic computing systems (NCSs), which overcomes the limitation of the word-at-a-time thinking of the VNCs by massive parallel data processing similar to the brain [1-5]. An NCS includes many parallel processors (neurons) communicating using simple messages (spikes) through programmable memory units (synapses). The current implementation of NCSs using CMOS technology is area and power inefficient [6]. Such inefficiencies have driven a significant effort to investigate beyond-CMOS NCSs. The spin-based devices integrated with electronics (i.e. spintronics) have opened a door for designers to implement low-power high-density NCSs. In spintronic-based NCSs, magnetic switching in magnetic tunnel junction (MTJ) [6] or magnetic oscillation in spin torque nano-oscillator (STNO) [7][8] is used to mimic neuron firing. While using oscillation of magnetic moment decreases the power consumption by an order of magnitude compared with magnetic moment switching (critical current: $\sim 10^6 \text{ Acm}^{-2}$ [9] vs $\sim 10^7 \text{ Acm}^{-2}$ [10]), still there is a huge gap between spintronic-based NCS and brain in terms of power consumption and speed. This is due to high power consumption and low speed of the traditional way of oscillating the magnetic moment through bias current. Hence, there is a crucial need for eliminating or decreasing the bias current in spintronic-based NCSs.

Fig. 1. (a) The schematic view of a MTJ as STNO and (b) the magnetization direction of MTJ free layer and torques acting on it.

In this paper, benefiting from heating up the STNO with a microwatt-nanosecond laser pulse, for the first time, we propose to design a laser-assisted oscillation-based NCS (LAO-NCS) to improve power consumption of the state-of-the-art NCSs by at least 46%; filling the huge gap of power consumption between the Brain and the NCSs.

A. Spin Torque Nano Oscillator

The schematic of the STNO is shown in Fig. 1 (a). It consists of a Pinned Layer (PL) with fixed magnetization and a Free Layer (FL) with changeable magnetization direction, which are separated by a tunneling oxide layer such as MgO , Al_2O_3 etc. Fig. 1 (b) shows the magnetization direction of the free layer (m) and different torques acting on it [7]. T_P describes the precession torque that leads to oscillation of m . T_D is the damping torque that aligns m with H_{eff} and T_{STT} is the spin-transfer torque caused by a bias current [8]. The interaction of T_{STT} and T_D determines the oscillatory orbit of m . As T_{STT} increases, m will be placed in an orbit farther than H_{eff} , which will lead to a lower frequency oscillation of m as shown in Fig. 1 (b) [11]. This is shown experimentally and through simulation that the frequency of the STNO can be locked to the frequency of an RF current passing through it [12][13] or an external oscillating RF field [14]. Moreover, the frequency of two STNOs can lock if they are close to each other [15]. In STNO-based NCS, frequency locking of STNO and comparing its output power with a threshold power are two mechanisms used to implement neuron firing. However, in all cases, an extremely high DC current (bias current) has to flow through the STNO to generate the required T_{STT} .

B. Effect of Raising Temperature on STNO

The dynamic behavior of the FL magnetic moment is modeled using Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation as follows [16]:

$$\frac{(1+\alpha^2)}{|\gamma|} \frac{\partial \hat{m}}{\partial t} = -\hat{m} \times \vec{H}_{\text{EFF}} - \alpha \hat{m} \times \frac{\partial \hat{m}}{\partial t} \times \vec{H}_{\text{EFF}} \quad (1)$$

where γ , α and $\hat{m}$ are the gyromagnetic ratio, Gilbert damping factor and magnetization of FL, respectively. $\vec{H}_{\text{EFF}}$ is the effective magnetic field acting on FL described by

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$\vec{H}_{EFF} = \vec{H}_{UA} + \vec{H}_{ex} + \vec{H}_{STT} + \vec{H}_{TF}$, where $\vec{H}_{UA}$, $\vec{H}_{ex}$, $\vec{H}_{STT}$ and $\vec{H}_{TF}$ are uniaxial anisotropy field, external magnetic field, current induced spin-transfer torque field and thermal fluctuations field, respectively. Increasing the temperature affects the dynamic behavior of the FL through decreasing the magnetization saturation (M_S) of it, decreasing the resistance of the STNO and increasing the dispersion of the initial deviation of the magnetic moment from easy axis due to higher thermal fluctuations.

Magnetization saturation: It is shown theoretically [17] and experimentally [18] that the dependency of M_S can be well described by Bloch's law as follows:

$$M_S(T) = M_S(0) \left(1 - (T/T^*)^{\frac{3}{2}}\right) \quad (2)$$

where T is the absolute temperature in Kelvin and $M_S(0)$ is the saturation magnetization at 0K, and T^* is a fitting factor. Equation (2) shows that increasing the temperature decreases $M_S(T)$. This leads to a degradation of the uniaxial anisotropy field, which decreases the minimum current required for FL magnetic oscillation.

Resistance: Two tunneling mechanisms contribute to the STNO resistance including electron spin-polarized direct elastic tunneling and spin independent tunneling. The total conductance of the STNO can be described as [19]

$$G(\theta) = G_T[1 + P_1 P_2 \cos \theta] + G_{SI} \quad (3)$$

where θ is the angle between the magnetization of the FL and the PL. P_1 and P_2 are the effective tunneling spin polarization of the magnetic layers. G_T is the pre-factor for direct elastic tunneling. The P_1 , P_2 and G_T parameters are temperature-dependent. Elevating the temperature increases G_T and reduces P_1 and P_2 [19]. As a result, R_P is almost independent of temperature while R_{AP} reduces approximately linearly with temperature. This has been experimentally shown in [19-21].

Thermal fluctuations: The effect of temperature on random fluctuating field can be modeled by $\vec{H}_{TF}$ while its x, y and z components have uncorrelated Gaussian distribution with zero mean and $\sqrt{(2\alpha k_B T)/(\gamma M_S V \Delta t)}$ standard deviation [22-24]. α , k_B , γ , V and Δt are Gilbert damping parameter, Boltzmann's constant, gyromagnetic ratio, the volume of the FL and the integration time step. Elevating the temperature increases the dispersion of $\vec{H}_{TF}$, which leads to an easier oscillation of FL magnetic moment. In order to explore the mentioned effects on oscillation behavior of STNO at elevated temperatures, different characteristics of STNO (resistance, TMR and output power of the oscillation) have been measured at different temperatures from 27°C up to 100°C in section III.

C. Memristor Behavior at Elevated Temperature

The conduction mechanism of the memristor can be modeled by two parallel conduction mechanisms including hopping conduction and Schottky thermionic emission [25] as follows:

$$I_{total} = \underbrace{2elv_{ph} N k_B T e^{\left(\frac{-W}{k_B T}\right)} e^{\left(\frac{-2l}{\zeta}\right)} \sinh\left(\frac{qlF}{k_B T}\right)}_{I_{hop}} + \underbrace{AT^2 e^{\left(\frac{-\phi_{B0} - \beta\sqrt{F}}{k_B T}\right)}}_{I_{Sch}} \quad (4)$$

where, k_B is the Boltzmann constant, l is the hopping distance, W is the hopping energy, ζ is the wave function localization, F is the applied field (converts from V), T is the

temperature, v_{ph} is the vibrational phonon frequency, A is the reduced effective Richardson constant multiplied by active device area, ϕ_{B0} is the barrier height, and β is the barrier lowering factor. N is proportional to the density of electrons in the conduction path multiplied by the relevant conducting area. Based on this model, which is well-fitted with experimental results, the temperature dependence of memristor resistance can be divided into two regions called cold and hot regions [25]. In the cold region ($T \leq 350K$), the state-dependent hopping conduction is dominant and the resistance of memristor is almost temperature insensitive. In the hot region, however, the Schottky emission of electrons determines the hot current and the memristor's resistance rapidly decreases with raising the temperature [25]. Noted, the trend of cold region (temperature independent) and hot region (temperature dependent) is independent of initial resistance state of memristor [25]. However, the resistance change of memristor in hot region depends on memristor's initial resistance.

II. PROPOSED LASER ASSISTED NEUROMORPHIC COMPUTING SYSTEM

Our novel envisioned LAO-NCS is shown in Fig. 2, which is a crossbar array of programmable memristors as synapses and the STNOs, assisted thermally by a narrow laser-pulse, as neurons. The resistance of the memristors can be tuned using an electric signal passing through them. The NCS operation starts with a *calibration* phase in which the NCS temperature will be elevated to 100°C and stabilized. Then, the NCS is ready for operation and the *processing* phase will be started. The processing phase can be divided into two steps including *stimulation* and *recovery* which will be repeated in sequence. In the *stimulation* step, the crossbar array sums weighted input currents passing them to the STNOs, which are already set in AP-state. In case, the weighted input currents are sufficiently large, the FL magnetic moment of STNO starts to oscillate that will be detected by a sensing circuit immediately [26-28], and translated to neuron's firing. Immediately after detecting the STNO oscillation, the *recovery* step begins. In the recovery step, the input corresponding to the fired neuron will be activated in the post NCS. Noted, one of the advantages of using oscillation instead of magnetic moment switching is that there is no need for switching back the FL magnetization. Hence, the recovery step can be done in a very short time (~600ps) compared with magnetic moment switching (~2ns) without extra energy consumption for switching back the magnetic moment. In our approach, the energy consumption needed for starting the STNO oscillation will be lowered

Fig. 2. The schematic view of the novel thermally assisted MTJ-based NCS. The MTJ and memristor act as neuron and synapse, respectively.

significantly by increasing the temperature of the STNO using a nanosecond laser pulse. In fact, increasing the temperature of the STNO will decrease its energy barrier, which leads to a low energy and low delay STNO oscillation. As a result, the energy consumption and the delay of the LAO-NCS decrease compared with typical spintronic-based NCS.

The neuron consists of the STNO and an activating transistor in series. Considering the fact that the transistor acts as a switch, heating it up has no significant impact on the overall performance of the LAO-NCS. The on-chip laser spot size in nanometer regime can be achieved through Vertical Cavity Surface Emitting Laser (VCSEL) [29-31]. The output power of VCSEL can be tuned through changing the supply voltage of its driver [31]. Hence, a CMOS interfacing circuit can easily control the laser output power by manipulating the supply voltage of the laser diode driver.

III. RESULTS

In order to evaluate the LAO-NCS, first, the effect of elevating the temperature on the STNO characteristics is measured. Then, based on the measured results, a behavioral model of STNO is designed to be used in HSPICE. The simulations of the LAO-NCS are performed by HSPICE simulator in 65nm CMOS technology. For memristor, the threshold adaptive memristor (TEAM) model [32] benchmarked with [25] is used.

A. Experimental measurement

In order to explore the effect of rising temperature on STNO characteristics, we used the STNO stack structure of Substrate/(100) Al₂O₃/(3) Ta/(30) CuN/(5) Ta/(17) Pt₃₈Mn₆₂/(2) CoFe₃₀/(0.85) Ru/(2.6) CoFe₄₀B₂₀/MgO wedge/(1.4) CoFe₄₀B₂₀/(10) Ru/(150) Cu/(30) Ru (thicknesses in nm). The CoFeB free layer has in-plane magnetization. The stack has the circular shape with diameter of 175nm. Fig. 3 (a) and (b) show the microscopic image of the STNO sample and the schematic view of deposited layer stack, respectively.

To evaluate the output power of STNO at different temperatures, the experimental setup of Fig. 3 (c) is utilized. The bias current is injected to the STNO through T₁ and T₂ terminals of the bias-tee. In case the bias current will be high enough, it leads to oscillation of STNO resistance. This resistance oscillation will provide a micro-volt oscillation at T₃ terminal of bias-tee. Finally, the micro-volt oscillation of the STNO is amplified by an amplifier and will be injected to spectrum analyzer in order to measure the oscillation characteristics of STNO. The heating plate is used to set the temperature of STNO at different temperatures above room temperature. Fig 4 (a) shows the PSD measured at different

temperature from 27°C to 100°C for 230μA bias current (the curves are offset by 10μV² along the vertical axis for clarity). Noted, the impedance mismatch in the acquired spectrum must be considered. The input impedance of the amplifier is 50Ω. Hence, considering the resistance mismatch between the amplifier and the STNO, the measured output power is only a fraction of actual emitted power of the STNO. In order to eliminate the effect of impedance mismatch, the integrated matched output power P_{out} of each device is calculated as follows [9]:

$$P_{out} = P_{measured} \left(\frac{(R_{STNO} + R_{Amp})^2}{4R_{STNO} \cdot R_{Amp}} \right) \quad (5)$$

where R_{STNO} and R_{Amp} are the resistance of STNO and input resistance of the amplifier, respectively. P_{measured} is the measured output power based on the spectrum analyzer output. Fig. 4 (b) shows the measured STNO resistance in P- and AP-state at different temperatures from 27°C to 100°C. The AP-state resistance is decreased with increasing the temperature and the P-state resistance is almost constant as predicted by equation (3) and as shown experimentally before [19-21]. As a result, the TMR ratio decreases by increasing the temperature (Fig. 4 (c)) that shows the typical behavior of MTJs as a function of the bias current. The matched output power (P_{out}) of STNO versus bias current at different temperatures from 27°C to 100°C is shown in Fig. 4 (d). By applying sufficient positive bias current, the oscillation will start and by further increasing the bias current, the oscillation amplitude increases which leads to higher output power. Although the decrease in TMR with bias and temperature appears detrimental, the total power increases as the input power increase dominates this TMR degradation. This is typically the case up to a certain point where the TMR decrease dominates or the breakthrough voltage of the tunnel barrier is reached. Noted, applying a negative bias current will not cause oscillation but increases the noise power which leads to higher P_{out}. In order to eliminate the effect of noise on P_{out}, the output power of negative bias currents are deducted from the output power of positive bias currents as shown in Fig. 4 (e). Elevating the temperature increases P_{out} as shown in Fig. 4 (d) and (e). This effect is also seen in spin Hall nano-oscillators (SHNOs) [33]. As a result, the minimum bias current needed to detect the STNO oscillation of the fired neuron by sensing circuit decreases. This decreases the general energy consumption of the STNO-based LAO-NCS as will be discussed in the next section.

B. Power consumption

The total power consumption of the LAO-NCS includes the power consumption of the spintronic layer (memristors

Fig. 3. (a) The microscopic image and (b) schematic view of the MTJ stack as STNO. (c) Schematic view of the experimental setup used for characterization of the STNO at different temperatures.

and STNOs), the CMOS interfacing circuit and the laser. Due to the fact that the calibration phase is done just one time at the beginning of the NCS operation, its power consumption has no significant effect on the total power consumption of the LAO-NCS and can be ignored. Fig. 5 shows the power consumption of an STNO and the memristors connected the STNO to the inputs in spintronic layer at different temperatures. The power consumption of STNO is calculated by measuring the power consumption at the stimulation step (the minimum required power consumption leads to STNO oscillation with sensible output power). The power consumption of STNO decreases by 56% while increasing the temperature to 100°C. This is due to the fact that heating up the STNO reduces its magnetization saturation and effective anisotropy field that tends to keep magnetization direction of FL aligned with the easy axis.

In order to calculate the power consumption of memristor array at elevated temperatures, first, the resistance reduction of memristors should be measured at different temperatures. However, the amount of resistance reduction not only depends on temperature, but also is a function of the initial resistance of memristor (weights) and the applied voltage (inputs). Hence, in order to estimate the average resistance reduction of memristor array, first, a 196x10 NCS is designed to recognize the handwritten digits in MATLAB. Then, using MNIST handwritten digits database [35] (size of the pictures is reduced to 14x14), the NCS is trained using 2000 training

Fig. 4. (a) The PSD measured at different temperature from 27°C to 100°C for 230μA bias current, the curves are offset by 10μV² along the vertical axis for clarity. (b) The AP and P states resistance, (c) the TMR ratio, (d) the integrated matched output power (P_{out}) and (e) the noiseless output power of STNO sample.

Fig. 5. The power consumption of an STNO and a column of memristors connecting the STNO to inputs at different temperature from room temperature to 100°C.

images and the weights are extracted. Considering the facts that the negative weights cannot be implemented by memristors, the negative weights are considered as zero. In the next step, the weights are mapped to the resistance of memristors in the array. In order to model the effect of temperature increase on the memristor's resistance, an equation is fitted to the experimental results of [25] for each initial conductance from 0.2μS to 21μS. Then, the fitted equations are used in MATLAB to determine the resistance of memristors at 100°C. Finally, 10000 test images have been applied to the modeled NCS in MATLAB and the power consumption reduction of memristor array is calculated for each test image. The average power consumption reduction of a column of memristors connecting their corresponding STNO to inputs is 61% by increasing the temperature to 100°C (Fig. 5). This is due to the resistance reduction of memristors and lower bias current passing through them at elevated temperatures. This means that lower currents pass through smaller resistances in each stimulation phase. The power consumption of the CMOS interfacing circuit and the laser source are estimated to be 15μW and 25μW to keep the temperature of spintronic layer around 100°C [36-37]. Noted, scaling the STNO technology (smaller STNO volume) leads to lower laser power consumption. Considering the fact that the power consumption improvement in the spintronic layer is much higher than the power consumption of the laser and the CMOS interfacing circuit, the total power consumption of the LAO-NCS decreases by 46% at 100°C compared with room temperature.

IV. CONCLUSION

To reduce the power consumption of future STNO-based NCSs, a microwatt-nanosecond laser pulse is utilized for the first time to ease the magnetic oscillation of the STNO through heating. The power consumption of the spintronic layer and the total power consumption of the proposed LAO-NCS are improved by 59% and 46% at $T=100^{\circ}\text{C}$ compared with operation at the room temperature. Noted, scaling the technology and increasing the temperature above 100°C leads to further improvement of the power consumption.

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