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Spin-Hall-assisted magnetic random access memory

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We propose a write scheme for perpendicular spin-transfer torque magnetoresistive random-access memory that significantly reduces the required tunnel current density and write energy. A sub-nanosecond in-plane polarized spin current pulse is generated using the spin-Hall effect, disturbing the stable magnetic state. Subsequent switching using out-of-plane polarized spin current becomes highly efficient. Through evaluation of the Landau-Lifshitz-Gilbert equation, we quantitatively assess the viability of this write scheme for a wide range of system parameters. A typical example shows an eight-fold reduction in tunnel current density, corresponding to a fifty-fold reduction in write energy, while maintaining a 1 ns write time. © *2014 AIP Publishing LLC*.
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Magnetoresistive random-access memory (MRAM) offers distinct advantages over conventional high-speed memory technologies (Static RAM and Dynamic RAM), notably including data retention after power shutdown.[1] The technology has therefore been subject to considerable research for decades, only to intensify in recent years with the invention of the magnetic tunnel-junction (MTJ) and the spin-transfer torque[2,3] (STT) effect. The use of MTJs allows for efficient conversion of magnetic to electronic information[4,5] while STT enables far more efficient and scalable switching compared to early magnetic-field-based designs.[6] The first STT-based MRAMs are currently being released onto the market,[7] but several challenges remain. Research is focused on reducing the critical current density required in the writing process, while maintaining data stability and readability.[6] An important step in this direction is the migration to magnetic systems showing perpendicular magnetic anisotropy (PMA); a uniaxial anisotropy favoring out-of-plane magnetization. Such systems offer increased stability at small lateral dimensions while requiring less current density for magnetization reversal.[8]

The memory state of a single MTJ is defined by the magnetization direction of the "free" magnetic layer relative to that of the "reference" magnetic layer; the latter having a higher magnetic anisotropy by definition. Due to the uniaxial anisotropy, only two stable states exist, with the free layer magnetization $\mathbf{M}$ pointing parallel or anti-parallel to the fixed layer magnetization $\mathbf{M}_{\mathbf{ref}}$. In conventional STT-MRAM, switching of the free layer is achieved by injecting a current into it from the fixed layer, picking up a spin polarization along the direction of $\mathbf{M}_{\mathbf{ref}}$. This polarized current exerts a torque $\tau_{ST} \propto (\mathbf{M} \times \mathbf{M}_{\mathbf{ref}} \times \mathbf{M})$ on $\mathbf{M}$, as described by Slonszewski.[2] At the start of a switching event, this torque is zero, as $\mathbf{M}$ is parallel to $\mathbf{M}_{\mathbf{ref}}$ in the two stable states. Magnetization reversal relies on random thermal fluctuations to disturb this initial alignment, which can take several nanoseconds.[9,10] This so-called incubation delay limits the speed and power efficiency of MRAM and becomes increasingly relevant for faster memories. Attempts to reduce incubation delay have been undertaken, mostly involving a second tunnel barrier and an in-plane magnetized fixed layer,[11–15] but this method severely complicates the MTJ growth and intrinsically increases the device resistance.

In this paper, we introduce a writing scheme for perpendicular STT-MRAM employing the spin-Hall effect[16] (SHE), which has been shown to be a viable method of spin injection in recent experiments.[17–20] In this scheme, the STT writing process is assisted by a current pulse passed through the electrode below the MTJ, injecting an in-plane polarized spin current into the free layer through the SHE. We will demonstrate through numerical simulations that a sub-nanosecond SHE pulse is sufficient to enable STT-switching without any incubation delay, reducing the bit write energy by as much as 98% in a typical system.

We study magnetization dynamics at room temperature in a perpendicularly magnetized MTJ free layer (see Figure 1) on top of a thin (4 nm) electrode composed of tantalum, which is known[17] to exhibit a large spin-Hall angle $\theta_{\mathrm{SH}} = 0.15$. Two currents densities are used to achieve magnetization reversal: (i) a tunneling current density J_{STT}, spin-polarized along the reference layer magnetization direction $\hat{\mathbf{m}}_{\mathrm{ref}} = \hat{\mathbf{z}}$, and (ii) a current density J_{SHE} passed through the bottom electrode, injecting into the free magnetic layer a spin current polarized along $\hat{\boldsymbol{\sigma}}_{\mathrm{SHE}} = \hat{\mathbf{y}}$ via the spin-Hall effect.[16] The free layer is approximated as being uniformly magnetized at all times, so that its magnetic behavior may be described using the Landau–Lifshitz–Gilbert (LLG) equation.[21] A complete description of this equation, the used parameters, and the numerical integration method is included in the Supplementary Information.

The magnetization reversal process was studied for a wide range of device properties, current densities, and pulse timings. In the examples discussed here, we focus on a

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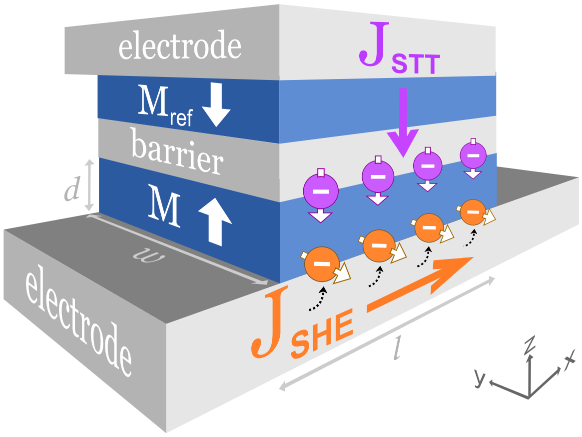

FIG. 1. Schematic overview of the simulated system. The magnetic element *M* is affected by two currents: a tunneling current J_{STT}, which is spin-polarized by the MTJ reference layer M_{ref}, and a current J_{SHE} running through the adjacent electrode, injecting a y-polarized spin current into the magnetic layer via the spin-Hall effect.

particular device with free layer dimensions of $l = 200$ nm, $w = 100$ nm, and $d = 0.6$ nm. A thermal stability of $\Delta \equiv E_b/E_{th} = 40$ at room temperature is imposed, with E_b the energy barrier separating the two stable magnetization states and E_{th} the thermal energy. Three characteristic examples of such simulations are shown in Figure 2, illustrating the value of the SHE-assisted writing scheme. First, conventional STT-switching using $J_{STT} = 2.0$ MA/cm^2 is found to take 8 ns, roughly half of which can be attributed to incubation delay (panels *a* and *d*). Second, a short (0.5 ns) pulse of SHE current, at $J_{SHE} = 30.0$ MA/cm^2, is found to have an immediate yet modest effect on the magnetization (panels *b* and *d*). Third, combining the two currents is found to completely eliminate incubation delay, resulting in a switching time of 2 ns (panels *c* and *d*). This particular example of SHE-assisted switching thus demonstrates a fourfold reduction in switching time.

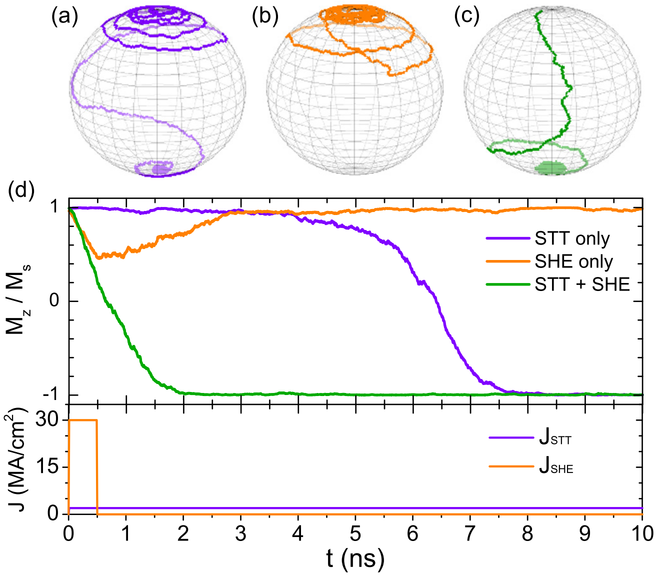

FIG. 2. Magnetization trajectories as induced by (a) an out-of-plane polarized DC current, (b) a 0.5 ns in-plane polarized current pulse, and (c) a combination of both. The z-component of each trajectory is plotted as a function of time in panel d, along with the applied current pulses. Thermal fluctuations are clearly visible.

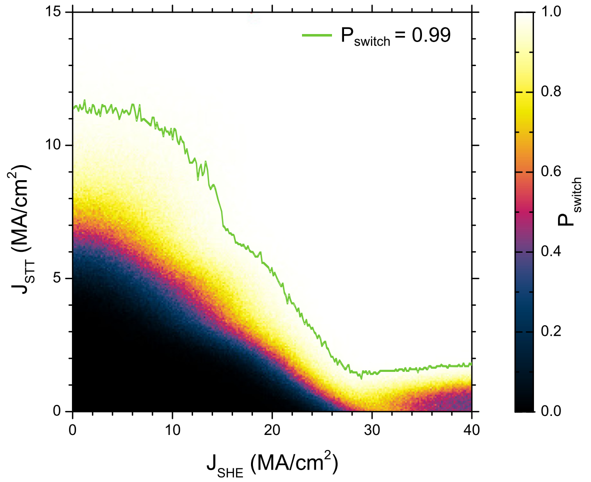

FIG. 3. Switching probability P_{switch} out of 256 attempts as a function of the pulse current densities J_{STT} and J_{SHE}, with pulse durations of 1.0 ns and 0.5 ns, respectively. For each value of J_{SHE}, the minimum J_{STT} required to yield $P_{switch} \geq 0.99$ is emphasized (green line).

We now seek to systematically assess the proposed writing scheme by exploring the relevant parameters space. To make this task manageable, we constrain the problem to one specific timing scheme: a 1.0 ns STT pulse assisted by a 0.5 ns SHE pulse, both started at $t = 0$. This choice of a short STT pulse time makes incubation delay especially relevant for the total switching time, whereas the effect of the SHE pulse was found to saturate within 0.5 ns in exploratory simulations. Using this scheme, the switching probability P_{switch} (defining a switching event by the condition $M_z < 0$ at $t = 10$ ns) is determined for a wide range of pulse current densities J_{STT} and J_{SHE}, as shown in Figure 3.

Switching at a probability of 0.99 (the green line in Figure 3) is found to require $J_{STT} = 11.5$ MA/cm^2 in the absence of SHE-assistance. This current density can be drastically reduced through SHE-assistance: a minimum of $J_{STT} = 1.5$ MA/cm^2 is observed for $J_{SHE} = 28$ MA/cm^2. Note that this relatively high value of J_{SHE} is experimentally attainable in similar devices even at DC.[18] For this particular device, the SHE-assisted write scheme thus offers up to an eight-fold reduction in tunnel current density requirement for switching using a 1.0 ns STT current pulse. Such a reduction has two major advantages: (i) the write power consumption is reduced, as will be computed in detail below, and (ii) the voltage across the barrier can be drastically reduced, exponentially increasing the device lifetime.[22]

Closer inspection of Figure 3 provides more insights regarding the SHE-assisted writing process. First, the $P_{switch} = 0.99$ trace shows no appreciable reduction in J_{STT} below $J_{SHE} \approx 6$ MA/cm^2. Below this threshold, the canting induced by the SHE pulse is smaller than the thermal fluctuations. Further simulations confirm that the threshold scales with system temperature. Second, for $J_{STT} = 0$ MA/cm^2, we observe that $P_{switch} = 0.50$ at $J_{SHE} = 28$ MA/cm^2, indicating that the magnetization settles in a random state. This suggests that the magnetization is pulled fully in-plane by a SHE pulse of this magnitude, explaining why further increases of J_{SHE} yields no further reduction in J_{STT}. Third, increasing J_{SHE} beyond 30 MA/cm^2 decreases P_{switch}

towards 0.50 for low J_{STT}, resulting in a "tail" in the phase diagram at high J_{SHE}. This is found to result from precessional motion around the in-plane demagnetization field during the SHE pulse. Indeed, the "tail" is absent in structures with an aspect ratio of 1. This precessional effect also explains the region near $J_{\mathrm{SHE}} = 30\,\mathrm{MA/cm}^2$ where $P_{\mathrm{switch}} > 0.50$ for $J_{\mathrm{STT}} = 0\ \mathrm{MA/cm}^2$.

Having established that the SHE-assisted write scheme allows for a drastic decrease in STT current density, we now investigate the impact on the total write energy per bit. We approximate the MTJ as a 0.5 kΩ resistor (based on the used dimensions and a typical RA-product of 10 Ω $\mu\mathrm{m}^2$) addressed through metallic leads and a transistor, providing an additional resistance which we estimate at 0.5 kΩ. As discussed above, switching by STT alone occurs at $J_{\mathrm{STT}} = 11.5\ \mathrm{MA/cm}^2$, corresponding to a current of 2.3 mA. The required driving voltage thus equals 2.3 V, yielding a total energy consumption of $E = I \times V \times \Delta t = 5.29$ pJ. Note that a voltage drop of 1.15 V across the MTJ is close to reported values of the barrier breakdown voltage, indicating that switching by a 1.0 ns write pulse is problematic in conventional STT-MRAM. In a SHE-assisted cell, on the other hand, the required STT current density can be reduced to $1.5\ \mathrm{MA/cm}^2$, as discussed above. This corresponds to a current of 0.30 mA and a more agreeable driving voltage of 0.30 V. The energy consumption of the STT-pulse is dramatically reduced, to 90 fJ. The additional energy consumption due to the SHE pulse is negligible at 9 fJ,[23] yielding a total energy consumption of 99 fJ. The SHE-assisted write scheme thus offers roughly a fifty-fold reduction in power consumption per write event for this particular system.

After demonstrating the potential of the SHE-assisted write scheme in a particular device, we investigate the general applicability of the scheme. Phase diagrams similar to Figure 3 are constructed for a broad range of system dimensions, magnetic properties, and pulse timings.[23] The system is found to be particularly sensitive to two parameters: the lateral dimensions and the applied in-plane magnetic field. First, when reducing the device area (adjusting the magnetic anisotropy to maintain a thermal stability of 40), the value of J_{SHE} required to significantly reduce J_{STT} quickly grows prohibitively large. At lateral dimensions of 80×40 nm, for instance, minimizing J_{STT} requires $J_{\mathrm{SHE}} = 100\,\mathrm{MA/cm}^2$, which is unrealistically high. Second, application of a small magnetic field B_{x} (along the flow direction of J_{SHE}) has a dramatic effect on the magnetization dynamics, as seen also in experiments.[17–19] Directional switching with $P_{\mathrm{switch}} > 0.99$ is possible without any STT current when using specific values of B_{x} and J_{SHE} (around 7 mT and $24\,\mathrm{MA/cm}^2$, respectively, for this device), cutting the write energy by a factor over one thousand.

In summary, we have shown through simulations that the incubation delay in writing perpendicularly magnetized STT-MRAM cells can be eliminated by using an in-plane polarized spin current pulse generated via the spin-Hall effect. Depending on the system parameters, significant decreases in either the writing time or the write energy per bit can be achieved. Specifically, switching of a 200 × 100 nm bit within 1.0 ns was demonstrated at an eight-fold reduced write current density, corresponding to a fifty-fold reduction in the write energy per bit. We believe that SHE-assisted STT-MRAM has substantial potential for specific applications in the near future.

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[23] See supplementary material at http://dx.doi.org/10.1063/1.4858465 for simulation details, power consumption calculations, and a complete overview of obtained results.