A Current Controlled Random-Access Memory Employing the Vortex Handedness

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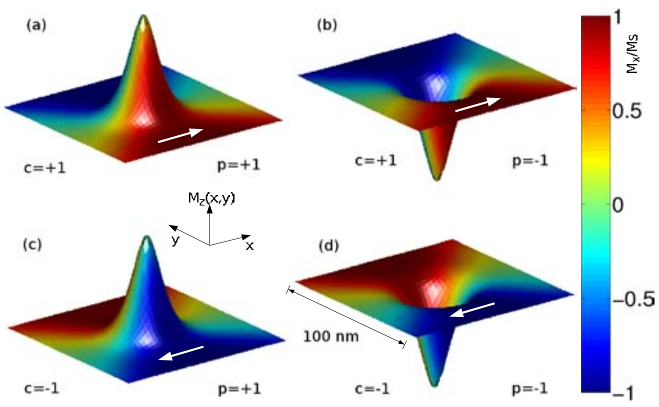
Motivation

The perception that magnetization dynamics is tunable by spin-polarized currents triggered an intensive investigation of novel ferromagnetic storage devices within the last years. The current influences the magnetization via its Oersted field and the spin-transfer torque. Compared to a magnetic field, an electrical current is much more appropriate to control a device since it can be handled with high precision and can be spatially restricted.
We present the theoretical foundation for a non-volatile memory device based on magnetic vortices. The Vortex Random-Access Memory employs the vortex handedness, i.e., the product of two intrinsic vortex properties, the core polarization and the chirality.

Magnetic vortex



The fourfold degenerated ground state of a magnetic vortex in a thin-film element with chirality $c \pm 1$ and core polarization $p \pm 1$. The white arrows illustrate the sense of rotation of the in-plane magnetization. The in-plane magnetization curls around a sharp singularity in the center, where the magnetization is forced out-of-plane to minimize exchange energy. The height indicates the out-of plane magnetization M_z while the colors visualize the x-component of the in-plane magnetization M_x normalized to the saturation magnetization M_s.

- Despite its complex structure the magnetic vortex in many ways behaves as a quasi-particle only characterized by the polarization p, the chirality c, and the coordinates X and Y of the vortex core in the sample plane as illustrated above.

Harmonic oscillator model for current- and field-driven magnetic vortices

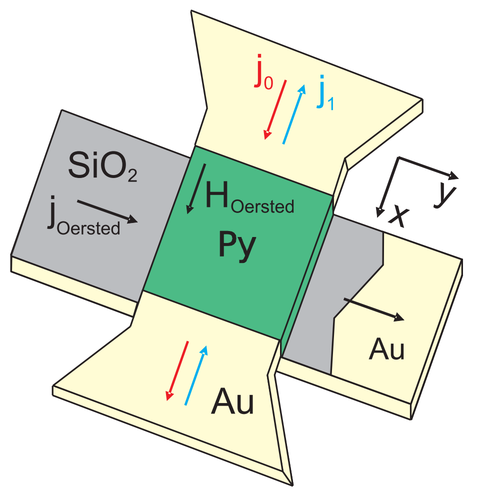
- A magnetic vortex excited by a homogeneous alternating current or an alternating external magnetic field performs harmonic oscillations. [3, 4]
- The strayfield constitutes the confining force and can be modeled for small excitations as a harmonic oscillator.
- The equation of motion for current and magnetic field applied in x-direction reads

$$\begin{pmatrix}\dot{X}\\ \dot{Y}\end{pmatrix} = \begin{pmatrix}-\Gamma & -p\omega\\ p\omega & -\Gamma\end{pmatrix}\begin{pmatrix}X\\ Y\end{pmatrix} + \begin{pmatrix}-v_\mathrm{j} - \frac{\Gamma^2}{\omega^2+\Gamma^2}\frac{\xi-\alpha}{\alpha}v_\mathrm{j}\\ \frac{p\omega\Gamma}{\omega^2+\Gamma^2}\frac{\xi-\alpha}{\alpha}v_\mathrm{j}\end{pmatrix} - \frac{v_\mathrm{H}\omega c}{\omega^2+\Gamma^2}\begin{pmatrix}p\omega\\ \Gamma\end{pmatrix}. \tag{1}$$

with

- the free angular frequency $\omega = -pG_0 m\omega_r^2/(G_0^2 + D_0^2\alpha^2)$,
- the damping constant $\Gamma = -D_0\alpha m\omega_r^2/(G_0^2 + D_0^2\alpha^2)$,
- the driving velocity due to the magnetic field H $v_\mathrm{H} = \gamma Hl/(2\pi)$ with the edge length l,
- the driving velocity of the current $v_\mathrm{j} = b_j j$,
- the coupling constant between the current and the magnetization $b_j = P\mu_B/[eM_s(1+\xi^2)]$ with the spin polarization P, the saturation magnetization M_s, the degree of non-adiabaticity ξ [2], and the phenomenological Gilbert-damping parameter α,
- the resonance frequency of the vortex due to the demagnetizing field [3] ω_r,
- and the constants of the gyrovector and dissipation-tensor G_0, D_0 [5], respectively.

The writing mechanism



A single Vortex Random-Access Memory (VRAM) cell with collinear current and Oersted field. One part of the current creates a homogeneous Oersted field by passing the cells in a strip-line underneath, the other part flows through a distinct cell. This yields a parallel arrangement of electrical current and magnetic field.

- The steady-state solution of Eq. 1 with harmonic current excitation, for which the magnetic field and the electrical current density are of the form $H(t) = H_0 e^{i\Omega t}$ and $j(t) = j_0 e^{i\Omega t}$, yields

$$\begin{pmatrix}X\\ Y\end{pmatrix} = \frac{e^{i\Omega t}}{\omega^2 + (i\Omega+\Gamma)^2} \times \begin{pmatrix}-\frac{\Gamma}{\omega}\frac{\xi}{\alpha}v_\mathrm{j}\omega & + & (v_\mathrm{H}cp - v_\mathrm{j})\, i\Omega\\ (v_\mathrm{H}cp - v_\mathrm{j})\, p\omega & + & \frac{\Gamma}{\omega}\left(v_\mathrm{H}cp + \frac{\xi-\alpha}{\alpha}v_\mathrm{j}\right) ip\Omega\end{pmatrix} \tag{2}$$

  under the assumption that the squared Gilbert-damping parameter is small ($\alpha^2 \ll 1$) and thus the damping constant is small compared to the frequency ($\Gamma^2 \ll \omega^2$).

- At resonance ($\Omega = \omega$) and for weak damping ($\Gamma \ll \omega$) the steady-state vortex motion is a circle with radius

$$R(v_\mathrm{H}, v_\mathrm{j}, \Gamma, cp) = \sqrt{(\Re X)^2 + (\Re Y)^2} = \frac{|v_\mathrm{H}cp - v_\mathrm{j}|}{2\Gamma}, \tag{3}$$

  which depends on the vortex handedness cp.

- When the driving velocities of field and current are equal ($|v_\mathrm{H}| = |v_\mathrm{j}|$), Eq. 3 yields a doubling or a quenching of the gyration amplitude dependent on the handedness.

Quantitative estimations

- The critical velocity for switching does not depend on specific properties of the driving force.
- For permalloy Guslienko estimates $v_\text{switch} \approx 320\,\mathrm{m/s}$ while Yamada et al. found $v_\text{switch} \approx 250\,\mathrm{m/s}$, "regardless of the excitation current density". [6]
- For permalloy structures (exchange constant of $A = 13 \times 10^{-12}\,\mathrm{J/m}$, lateral sample size of 200 nm and a thickness of 20 nm), the critical current density is $1.3 \times 10^{11}\,\mathrm{A/m^2}$ for pure current excitation and a critical velocity of $320\,\mathrm{m/s}$.
- This corresponds to a current of ≈ 0.5 mA and an absorbed power of $2.7\,\mu$W.
- For a writing time of about 10 ns this yields an energy cost of about 27 fJ per storage cell.
- With optimized ferromagnetic materials it should be possible to decrease the critical current density by several orders of magnitude and increase the storage density by a factor of 20 or more.

References

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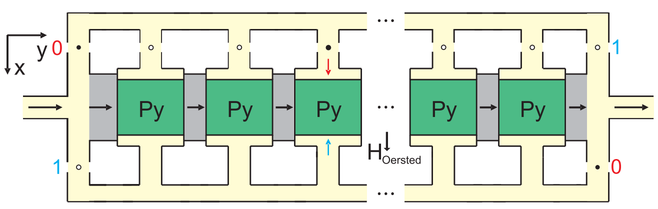
The reading mechanism

- For the reading mechanism it is necessary to determine the product cp, as neither the core polarization p nor the chirality c is unambiguously determined by the writing procedure.
- In the absence of current and field, precession or stagnancy of precession of the vortex holds no information about the actual memory state of the VRAM cell.
- To read out the information a lower current density compared to the writing current density can be used, which has neither an influence on the polarization nor on the chirality.
- For parallel current and field reading collimates in the task of distinguishing a vortex at rest ($cp = +1$) from a rotating vortex ($cp = -1$).
- The rotating vortex creates a time-varying magnetic flux which could be measured by placing a pickup coil (induction loops) above the storage cell or by detecting resistance changes.
- The VRAM cell can be read an infinite number of times without affecting its binary state.

Properties of the VRAM

- The amplitude of gyration depends on the sign of the handedness cp.
- For $cp = 1$ the rotation amplitude behaves complementary to the case when $cp = -1$ without the need to determine the absolute values p or c.
- A distinct cp-state can be obtained by vortex-core switching.
- Advantage: Only one current pulse is needed, this concept avoids reading before writing.
- The same mechanism can be used for the reading process.
- The VRAM can be operated with an AC-current or short current pulses.
- The proposed arrangement reduces the fourfold degenerate vortex ground state to two distinct cp states with two representations representing the single Bit.

Possible technical realization of a VRAM



The cells are arranged in a two-dimensional array, from which one row is depicted. The high-ohmic permalloy squares constitute the memory cells while the gold strip-lines supply the read-write current. Open (filled) circles symbolize open (closed) switches that are used to store information in an individual cell. The numbers 0 and 1 denote the switches which have to be activated to write the according bit in the activated cell. The shown configuration writes a binary "zero" into the third cell (red arrow).

Conclusions

In a collinear current and field arrangement, we established a one-to-one correspondence of the product of chirality and core polarization to the binary values "zero" and "one".

The VRAM needs not be read or erased preceding the writing and, in general, allows an infinite number of read and write operations.

The VRAM concept is non-volatile and fulfills the stability requirements for a memory device, since the vortex state is stable against temperature and magnetic fields as long as they remain in the millitesla regime. The VRAM shows a good scaling behavior, in general no material fatigue, and is foremost a fast memory concept.

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