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Citation for published version (APA):

DOI:
10.1063/1.3562299

Document status and date:
Published: 01/01/2011

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
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Download date: 01. Nov. 2023
Tunable magnetic domain wall oscillator at an anisotropy boundary

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(Received 2 December 2010; accepted 8 February 2011; published online 11 March 2011)

We propose a magnetic domain wall (DW) oscillator scheme, in which a low dc current excites gigahertz angular precession of a DW at a fixed position. The scheme consists of a DW pinned at a magnetic anisotropy step in a perpendicularly magnetized nanostrip. The frequency is tuned by the current flowing through the strip. A perpendicular external field tunes the critical current density needed for precession, providing great experimental flexibility. We investigate this system using a simple one-dimensional model and full micromagnetic calculations. This oscillating nanomagnet is relatively easy to fabricate and could find application in future nanoscale microwave sources.

As predicted theoretically, the magnetization of a free magnetic layer in a multilayer nanopillar can oscillate at GHz frequencies caused by the spin transfer torque exerted by a dc spin-polarized current. These magnetic oscillations at the nanoscale could find application in the area of radio-frequency (rf) devices, such as wide-band tunable rf oscillators.

However, the fabrication of such nanopillar devices is particularly hard and the frequency and the output power cannot be tuned independently. An alternative oscillating nanomagnet is a precessing magnetic domain wall (DW). It is already widely known that DWs precess during motion at GHz frequencies caused by the spin transfer torque exerted by a dc spin-polarized current. These magnetic oscillations at the nanoscale could find application in the area of radio-frequency (rf) devices, such as wide-band tunable rf oscillators.

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Experiments have been reported on rf-driven DW resonance phenomena, but for use as an rf source, a DW device needs to convert a dc current to an rf signal. Recently, several such devices have been proposed in theory, but significant obstacles must be overcome before an experimentally feasible device can be produced. The most promising scheme to date was proposed in Ref. 11, using a DW pinned at a constriction in a nanostrip with large perpendicular magnetic anisotropy (PMA). The key for achieving DW precession at low dc currents is to minimize the energy barrier between the Bloch/Néel stability regions by a dc external field. At this position, the energy barrier between both walls is minimal and, therefore, oscillations are easily excited by dc currents.

To characterize the behavior of this DW oscillator as a function of current and field, we first investigate its dynamics using a 1D model. Starting from the Landau–Lifshitz–Gilbert equation with spin-torque terms and parameterizing the DW using the collective coordinates $q$ (DW position), $\psi$ (in-plane DW angle), and $\Delta$ (DW width) we get

$$
\Delta(q)\psi - \alpha q = \beta u + \frac{\gamma \Delta(q) \delta \epsilon}{2M_s \delta q},
$$

where $\beta$ is the Gilbert damping parameter, $u$ is the external field, and $\gamma$ is the gyromagnetic ratio. The function $\Delta(q)$ is the energy barrier between the Bloch and Néel stability regions, which is given by

$$
\Delta(q) = K_1 \sin^2 \frac{\pi q}{L} + K_0 \cos^2 \frac{\pi q}{L},
$$

where $K_1$ and $K_0$ are the exchange and uniaxial anisotropy constants, respectively, and $L$ is the nanostructure width.

FIG. 1. (Color online) Sketch of the perpendicularly magnetized strip with a step in the magnetic anisotropy (from $K_0$ to $K_1$) and associated DW potentials in the absence and presence of an external magnetic field. At a properly tuned field, the DW energy minimum might shift to the Bloch/Néel transition point, where it is easy to excite DW precession $\psi$ by a spin-polarized current ($u$).

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\[ \dot{\psi} + \alpha \Delta(q) \dot{\psi} = -u - \frac{\gamma \Delta(q)}{M_s} K_d(q) \sin 2\psi, \]

where \( u = (g \mu_B P / 2 e M_s) \) is the spin drift velocity, representing the electric current, with \( g \) the Landé factor, \( \mu_B \) the Bohr magneton, \( P \) the spin polarization of the current, \( J \) the current density, and \( e \) the (positive) electron charge. \( M_s \) is the saturation magnetization, \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the Gilbert damping constant, and \( K_d \) is the transverse anisotropy. The term \( \dot{\psi} / \dot{q} \) is the derivative of the DW potential energy, which was obtained by assuming that the DW retains a Bloch profile symmetric around its center \([m_z = \text{tanh}(\psi / \Delta)]\). Using our geometry sketched in Fig. 1, this yields \( \dot{\psi} / \dot{q} = 2 \mu_0 M_s H - (K_0 - K_1) \text{sech}^2(q / \Delta(q)) \). Here, we have made the additional assumption that the effective perpendicular anisotropy \((K = K_u(1/2) \mu_0 N_s M_s^2)\) changes instantly from the high value \( K_0 \) to the lower value \( K_1 \) at the position \( q = 0 \). This is appropriate if the anisotropy gradient length is smaller than the DW width, which can be achieved using a He\(^+\) focused ion beam (FIB).\(^{17}\) The transverse anisotropy constant \( K_d \) represents the energy difference between a Bloch (\( \psi = 0 \) or \( \pi \)) and Néel (\( \psi = \pm \pi / 2 \)) wall and results from demagnetization effects. Therefore, it depends on the dimensions of the magnetic volume of the DW, given by the DW width \( \Delta \), the width of the magnetic strip \( w \), and its thickness \( t \). We estimate the demagnetization factors \( N_x, N_y, \) and \( N_z \) of the DW by treating it as a box with dimensions \( 5.5 \Delta \times w \times t.\(^{18}\)

The effective DW width \( 5.5 \Delta \) was determined from micromagnetic simulations: if \( w = 5.5 \Delta \) the Bloch and Néel walls have the same energy and the transverse anisotropy \( K_d = (1/2) \mu_0 \mu_s (N_y - N_z) M_s^2 \) vanishes because \( N_y = N_z \).

In the absence of transverse anisotropy \( (K_d = 0)\), an analytical solution exists to the system of Eqs. (1) and (2). The DW will precess at a constant frequency \( f \) proportional to the current,\(^{\text{III}}\)

\[ 2\pi f = \psi = -\frac{u}{\alpha \Delta}; \quad (K_d = 0), \]

while the DW remains at a fixed position \((\dot{q} = 0)\). For the case \( K_d \neq 0 \), however, the system is solved numerically. We use parameters typical for a Co/Pt multilayer system, with \( M_s = 1400 \text{ KA/m} \), \( A = 16 \text{ pJ/m} \), and \( e = 0.2 \). For the moment, we assume only adiabatic spin-torque (\( \beta = 0 \)). For the effective anisotropy at the left side of the boundary, we choose \( K_0 = 1.3 \text{ MJ/m}^3 \) (corresponding to \( K_u = 2.5 \text{ MJ/m}^3 \)). By ion irradiation, this can be reduced to arbitrarily low values such as \( K_1 = 0.0093 \text{ MJ/m}^3 \) \((K_d = 1.2 \text{ MJ/m}^3)\) at the right of the boundary. For the calculation of the transverse anisotropy, we use the geometry \( w = 60 \text{ nm} \) and \( t = 1 \text{ nm} \). The very low \( K_1 \) leads to a DW that is wide (\( \Delta = \sqrt{A / K_1} \approx 41 \text{ nm} \)) relative to the wire width, which ensures stability of the Néel wall in the right region, whereas a Bloch wall is stable in the left region \((\Delta_0 = 3.5 \text{ nm})\). At the boundary, the anisotropy is not constant within the DW volume leading to a nontrivial dependence of \( \Delta \) on position \( q \). Under the given assumptions, the derivative of internal DW energy equals \( \sigma_{\text{DW}} / q = (K_0 - K_1) \text{sech}^2(q / \Delta(q)) \). By using the fact that \( \sigma_{\text{DW}} = 4A / \Delta \), numerical integration yields \( \Delta(q) \) as presented in the inset of Fig. 2(a). The fact that the DW width depends on the position implicitly leads to a time-dependent DW width \( \Delta \), which we take into account by updating \( \Delta(q) \) at every integration step. Time variations in \( K_d \) are taken into account as well, because it depends on \( \Delta \).

Solutions of the precession frequency at various fields and current densities are plotted in Fig. 2(a). The results differ from the purely linear behavior predicted by Eq. (3) in two ways. First of all, because of the energy barrier \( K_d \) between the Bloch and Néel walls, a critical current density needs to be overcome before precession occurs. Of the curves shown, a field of 70 mT yields the lowest critical current, so apparently this field brings the DW close to the Bloch/Néel transition point. The second deviation from linearity is seen at high current densities, where an asymmetry between nega-
tive and positive current densities exists. This arises solely from the change in the DW width: with increasing positive (negative) current density, the equilibrium DW position is pushed to the left (right), where the DW becomes narrower (wider). This behavior is sketched in the insets of Fig. 2(a).

To confirm the validity of our 1D approximation, we simulate the same system using micromagnetic calculations. The strip is 400 nm long, 60 nm wide, and 1 nm thick and divided into cells of $4 \times 4 \times 1$ nm$^3$. Snapshots of the spin structure during precession are shown in the insets of Fig. 2(b). The results in Fig. 2(b) qualitatively match our simplified 1D model, with slightly lower frequencies. However, the critical current needed for precession is somewhat larger in the simulations as compared to the 1D model, which is shown in Fig. 2(c), where the field dependence of the critical current is plotted for both methods. We attribute this to an observable deviation from the 1D profile in the simulations, which leads to inhomogeneous magnetization fields posing additional energy barriers between the Bloch and Néel states. At $\mu_0 H = 65$ mT, $u_{\text{crit}} \approx 2$ m/s is minimized, which corresponds to an experimentally feasible current density $J = 9 \times 10^{10}$ Am$^{-2}$ assuming a spin polarization $P = 0.56$ in Co/Pt.

Although the nonadiabatic $\beta$-term in Eq. (1) greatly affects the dynamics of moving DWs, we found only minor consequences for a pinned oscillating DW. Simulations at varying $\beta$ could be reduced to a single $f(u, H)$ curve by a simple correction to the external field $H' = H + (\beta u / \mu_0 \gamma \Delta)$. We argue that this DW oscillator scheme has several advantages over prior schemes. First of all, one does not need complicated nanostructuring of geometric pinning sites, as FIB irradiation readily creates pinning sites without changing the geometry and with a spatial resolution in the nanometer range when a focused He beam is used. Second, initialization of a DW at an anisotropy boundary is inherently simple; the area with reduced anisotropy has lower coercivity and is, therefore, easily switched by an external field. Third, many DW oscillators can be introduced in a single wire by an alternating pattern of irradiated and nonirradiated regions, and all DWs can be initialized at the same time. Fourthly, the external magnetic field provides the unique flexibility to tune the critical current needed for precession. The field might be cumbersome in device applications, but by correctly tuning the anisotropy $K_I$ a low critical current density at zero field is also possible. The main advantage of DW oscillators over the conventional nanopillar geometry is the ability to tune the frequency independent of the microwave output power. This can be achieved by letting the DW act as the free layer of a magnetic tunnel junction (MTJ) grown on top of the DW and with the approximate dimensions of the DW ($20 \times 60$ nm$^2$), in a three-terminal geometry. Interestingly, the output power of such a device might exceed that of a conventional spin torque oscillator (STO), since the DW exhibits full angular precession in contrast to the small-angle precession of most STOs, at a similar feature size. An estimate of the output power can be made using the parameters of an STO MTJ, namely, a low resistance-area product (1.5 $\Omega \mu\text{m}^2$), a TMR ratio of 100% and a maximum bias voltage of 0.2 V. Under these assumptions, we estimate a maximum rf output power $P_{\text{rms}} \approx 23 \mu$W. The output power can be further increased by producing arrays of DW oscillators which are coupled through dipolar fields, spin waves and/or the generated rf current. Simulations show that slightly different DW oscillators in parallel wires indeed oscillate at a common frequency due to stray field interaction.

In conclusion, we have introduced a DW oscillator scheme, in which a low dc current excites gigahertz precession of a DW pinned at a boundary of changing anisotropy in a PMA nanostrip. The frequency of the precession is tuned by the dc current amplitude. A perpendicular external field tunes the critical current needed for precession. The system is well-described by a 1D model, which gives results almost identical to micromagnetic calculations.

This work is part of the research program of the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organisation for Scientific Research (NWO). We thank NanoNed, a Dutch nanotechnology program of the Ministry of Economic Affairs.

22. See supplementary material at http://dx.doi.org/10.1063/1.3562299 for a micromagnetic movie of two stray field coupled oscillators.