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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. © *2011 American Institute of Physics*. [doi:10.1063/1.3562299]

As predicted theoretically,[1] 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.[2–5] 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 currents (and fields) above the so-called Walker limit.[6] Obviously, for a continuously operating oscillator it is vital that the DW remains at a fixed position, but for commonly used in-plane magnetized materials (i.e., $Ni_{80}Fe_{20}$) a high current density is needed for Walker precession, leading to undesired DW displacement motion.

Experiments have been reported on rf-driven DW resonance phenomena,[7–10] 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,[11–13] but significant obstacles must be overcome before an experimentally feasible device can be produced. Perhaps the most viable 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 for DW transformation between the Bloch and Néel types (Fig. 1). In wide strips, Bloch walls have the lowest magnetostatic energy, whereas the Néel wall is preferred in very narrow strips.[14] By locally reducing the wire width at the constriction, this energy barrier is minimized, leading to a low critical current. However, at the constriction the wire width needs to be trimmed to a challenging 15 nm, and also the DW needs to be initialized at the correct position, leading to cumbersome experimental schemes.

In this letter, we propose a different scheme, inspired by our recent experimental observation that a DW in a nanowire can be controllably pinned at a magnetic anisotropy step created by ion irradiation.[15–17] Interestingly, the anisotropy also controls the width of a DW and, therefore, it controls whether the Bloch or Néel wall is stable. One can thus tune the anisotropy values at both side of the boundary in such a way, that a Bloch/Néel wall is stable in the two respective regions (Fig. 1). A DW can be pinned exactly at the transition point 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. We study the feasibility of this approach by a one-dimensional (1D) model and micromagnetic simulations and discuss its advantages in terms of ease of fabrication, experimental flexibility and scalability.

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), ψ (in-plane DW angle), and Δ (DW width),[11,14] we get

$$\Delta(q)\dot{\psi} - \alpha\dot{q} = \beta u + \frac{\gamma\Delta(q)}{2M_s}\frac{\partial\epsilon}{\partial q}, \tag{1}$$

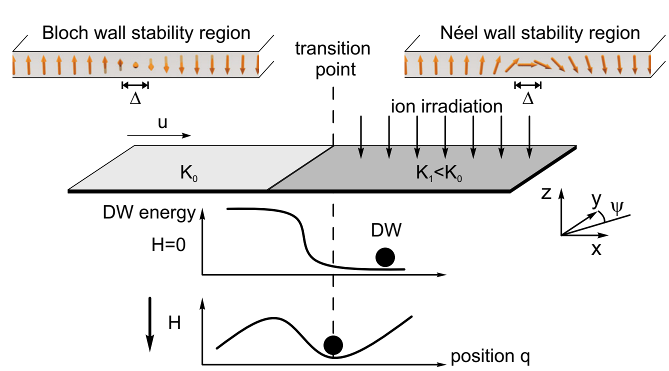

FIG. 1. (Color online) Sketch of the perpendicularly magnetized strip with a step in the magnetic anisotropy (from K_0 to K_1) and associated DW potentials in the absence and presence of an external magnetic field. At a properly tuned field, the DW energy minimum might shift to the Bloch/Néel transition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

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$$\dot{q} + \alpha\Delta(q)\dot{\psi} = -u - \frac{\gamma\Delta(q)}{M_\mathrm{s}}K_\mathrm{d}(q)\sin 2\psi, \qquad (2)$$

where $u=(g\mu_\mathrm{B}PJ/2eM_\mathrm{s})$ is the spin drift velocity, representing the electric current, with g the Landé factor, μ_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, γ is the gyromagnetic ratio, α is the Gilbert damping constant, β is the nonadiabaticity constant, and K_d is the transverse anisotropy. The term $\partial\epsilon/\partial q$ is the derivative of the DW potential energy, which was obtained by assuming that the DW retains a Bloch profile symmetric around its center $[m_z=\tanh(x/\Delta)]$. Using our geometry sketched in Fig. 1, this yields $\mathrm{d}\epsilon/\mathrm{d}q=2\mu_0M_\mathrm{s}H-(K_0-K_1)\mathrm{sech}^2[q/\Delta(q)]$. Here, we have made the additional assumption that the effective perpendicular anisotropy $(K=K_u-(1/2)\mu_0N_zM_\mathrm{s}^2)$ 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 π) 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 Δ, 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 5.5Δ was determined from micromagnetic simulations: if $w\approx 5.5\Delta$ the Bloch and Néel walls have the same energy and the transverse anisotropy $K_\mathrm{d}=(1/2)\mu_0(N_x-N_y)M_\mathrm{s}^2$ vanishes because $N_x\approx N_y$.

In the absence of transverse anisotropy ($K_\mathrm{d}=0$), 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,[11]

$$2\pi f = \dot{\psi} = \frac{-u}{\alpha\Delta}, \quad (K_\mathrm{d}=0), \qquad (3)$$

while the DW remains at a fixed position ($\dot{q}=0$). For the case $K_\mathrm{d}\neq 0$, however, the system is solved numerically. We use parameters typical for a Co/Pt multilayer system, with $M_\mathrm{s}=1400$ kA/m, $A=16$ pJ/m, and $\alpha=0.2$. For the moment, we assume only adiabatic spin-torque ($\beta=0$). For the effective anisotropy at the left side of the boundary, we choose $K_0=1.3$ MJ/m^3 (corresponding to $K_{\mathrm{u},0}=2.5$ MJ/m^3). By ion irradiation, this can be reduced to arbitrarily low values such as $K_1=0.0093$ MJ/m^3 ($K_{\mathrm{u},1}=1.2$ MJ/m^3) at the right of the boundary. For the calculation of the transverse anisotropy, we use the geometry $w=60$ nm and $t=1$ nm. The very low K_1 leads to a DW that is wide $(\Delta_1=\sqrt{A/K_1}\approx 41$ 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 ($\Delta_0\approx 3.5$ nm). At the boundary, the anisotropy is not constant within the DW volume leading to a nontrivial dependence of Δ on position q. Under the given assumptions, the derivative of internal DW energy equals $\mathrm{d}\sigma_\mathrm{DW}/\mathrm{d}q=(K_0-K_1)\mathrm{sech}^2[q/\Delta(q)]$. By using the fact that $\sigma_\mathrm{DW}=4A/\Delta$, 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 Δ, 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 Δ.

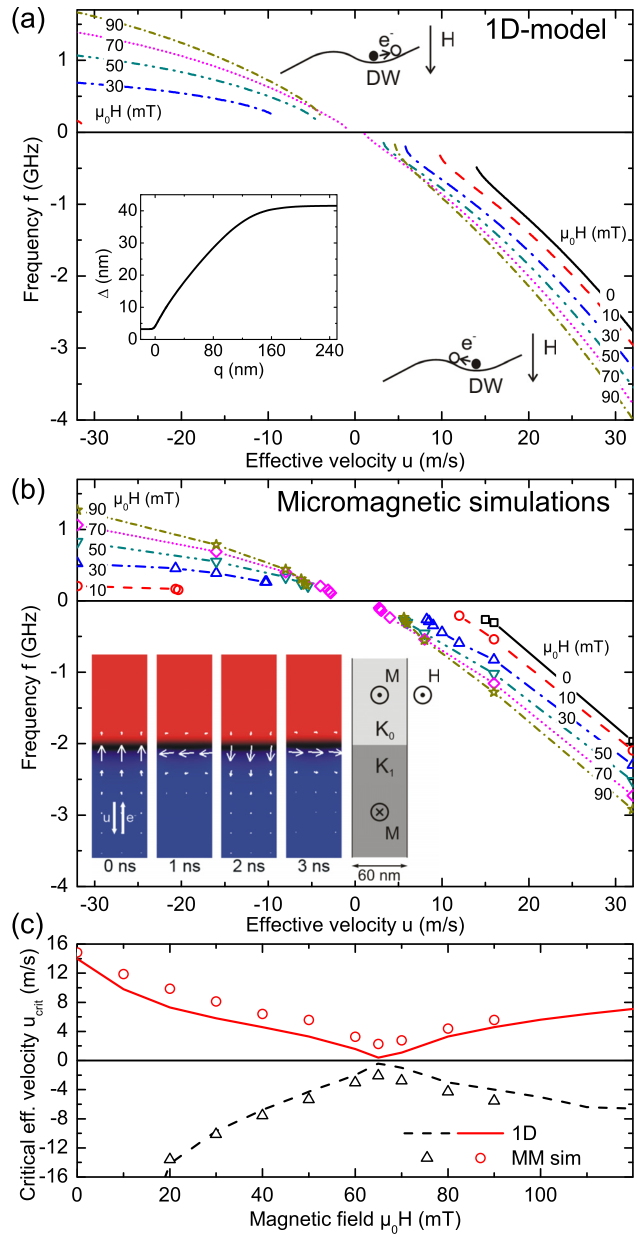

FIG. 2. (Color online) (a) 1D-model solution of DW precession frequency as function of current density at various fields. Positive (negative) f indicates clockwise (counterclockwise) precession. Sketches show the potential landscape of the DW and the displacement due to the electron flow. The inset graph shows the equilibrium DW width as function of position. (b) Similar to (a) but obtained from micromagnetic simulations. The inset shows snapshots of the spin structure during simulation ($\mu_0H=70$ mT and $u=4$ m/s). (c) Critical effective velocity (current) as a function of applied field, obtained using the two methods.

Solutions of the precession frequency at various fields and currents 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 negative 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.[19] The strip is 400 nm long, 60 nm wide, and 1 nm thick and divided into cells of $4\times4\times1$ 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 demagnetization fields posing additional energy barriers between the Bloch and Néel states. At $\mu_0 H \approx 65$ mT, $u_{\mathrm{crit}} \approx 2$ m/s is minimized, which corresponds to an experimentally feasible current density $J \approx 9\times10^{10}$ Am^{-2} assuming a spin polarization $P=0.56$ in Co/Pt.[20]

Although the nonadiabatic β-term in Eq. (1) greatly affects the dynamics of moving DWs,[6] we found only minor consequences for a pinned oscillating DW. Simulations at varying β could be reduced to a single $f(u,H)$ curve by a simple correction to the external field $H^\star = H + (\beta u/\mu_0 \gamma \Delta)$.

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.[17] 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_1 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 (20×60 nm^2), in a three-terminal geometry.[13] 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,[21] namely, a low resistance-area product (1.5 $\Omega\ \mu$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 $P_{\mathrm{rms}} = 23$ μW. 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.[22]

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.

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