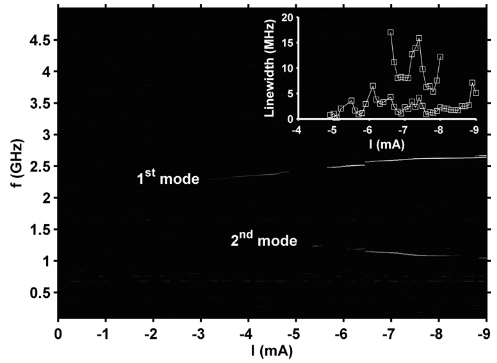

Figure 2: Microwave emission spectra as a function of applied bias current in the same device in H_{ext} = 5000 Oe at an angle of 88° w.r.t to the film plane. The inset shows the linewidths for both apparent modes.

8:54

EH-03. Microwave emissions in CoFeB-MgO tunnel junctions with perpendicular-anisotropy free layer at ultralow current densities.

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The use of spin transfer torque induced by electric currents to generate microwave signals in nanoscale magnetic devices has generated very large interest in recent years [1-4]. The key features of such microwave devices are frequency tunability, nanoscale size, broad working temperature range, and relatively easy integration with standard silicon technology. However, in present-day studies large current densities and large bias magnetic fields are required to create observable microwave signals. In our previous work [5-6], the interfacial perpendicular anisotropy between the ferromagnetic electrodes and the tunnel barrier of magnetic tunnel junctions (MTJs) was demonstrated to result in a decrease of the current density and elimination of the need for external magnetic fields. Here, we present microwave emission in MgO-based magnetic tunnel junctions having a planar polarizer and a perpendicular anisotropy free layer. Our samples were nanopillars with a structure of sub-layers/PtMn(15)/ $Co_{70}Fe_{30}$(2.3)/Ru(0.85)/$Co_{40}Fe_{40}B_{40}$(2.4) /MgO(0.8) /$Co_{20}Fe_{60}B_{20}$(1.62)/capping layers (thicknesses in nanometers). This structure was demonstrated to enable the excitation of large-angule free layer precession leading to a large output power at ultralow current densities (the critical current density $<1\times10^5$ A/cm^2), in the absence of a bias magnetic field. The measured maximum output power at zero bias magnetic field was over 10 nW. Figure 1 shows a typical power spectrum map of the device in the low current regime (0~-20 μA, where a positive current is defined as electrons flowing from the pinned layer to the free layer). The magnetic field and the bias current dependence of the peak frequency, linewidth, and the output power of the microwave spectrum are investigated in this study, and the origin of large output power is also discussed. Our results pave the way for constructing a low-power nanoscale microwave system.

[1] J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1(1996). [2] L. Berger, Phys. Rev. B 54, 9353 (1996). [3] S. I. Kiselev, et al., Nature 425, 380 (2003). [4] W. H. Rippard, Phys. Rev. Lett. 92, 027201(2004). [5] Z. M. Zeng,et al., ACS Nano 6, 6115 (2012). [6] Z. M. Zeng,et al., Sci. Rep. 3, 1426 (2013).

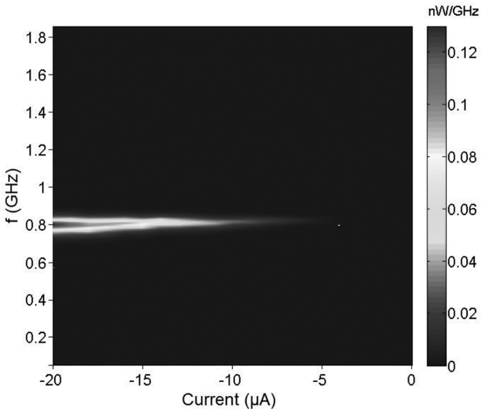

Figure: Power spectrum map of the spin-torque-driven oscillator with different dc currents in the absence of a bias magnetic field.

9:06

EH-04. Novel Bias-Field-Free Large Gain Spin-Transfer Oscillator.

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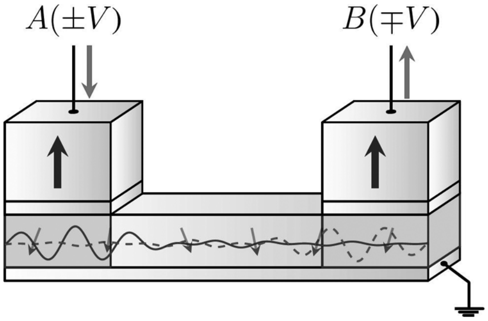
Oscillators constitute a very basic building block in modern electronics and are needed in, e.g., measurement, navigation, and communication systems. Their periodic output signals are used manifold, for example, for clocking digital circuits, generating electromagnetic waves, in high speed digital systems, and many more. Due to their nanoscale size, frequency tunability, broad temperature operation range, and CMOS technology compatibility, spin torque nano-oscillators (STNO) are very attractive for cost effective on-chip integration of microwave oscillators [1-3]. Recently, we proposed a novel non-volatile magnetic flip flop which shifts the logic operation from the CMOS domain and voltage/current signals to the magnetic domain and operates via spin wave superposition and spin transfer torque (STT) [4]. The structure consists of three magnetic stacks (two spin valve stacks for input and one magnetic tunnel junction stack for output) and a shared free magnetic layer, where the spin wave operations take place. During our simulations we found parameter regimes, where our structure exhibits large and stable oscillations in the MHz to GHz range without the need of an external magnetic field or a modulated current. We studied three different free layer sizes with 10nm, 20nm, and 30nm width; 40nm, 80nm, and 120nm length; and 3nm thickness and found size dependent large and stable magnetization oscillations ranging from 240MHz to 6Ghz, which are tunable by the applied current density in a range of about 200Mhz. The current densities required for the resonant oscillations range between 10^{11}A/m^2 and 2×10^{12}A/m^2. Additionally - due to its geometric structure - spin/micro waves can be extracted perpendicular to the shared free layer plane. Finally, we discuss possible applications as large power micro wave generators or spin wave sources. This research is supported by the European Research Council through the Grant #247056 MOSILSPIN.

[1] M. Tsoi, A. G. M. Jansen, J. Bass, W.-C. Chiang, M. Seck, V. Tsoi, and P. Wyder, "Excitation of a magnetic multilayer by an electric current," Phys. Rev. Lett., vol. 80, pp. 4281–4284, May 1998. [2] S. I. Kiselev, J. C. Sankey, I. N. Krivorotov, N. C. Emley, R. J. Schoelkopf, R. A. Buhrman, and D. C. Ralph, "Microwave oscillations of a nanomagnet driven by a spin-polarized current," Nature, vol. 425, no. 6956, pp. 380–383, Sep. 2003. [3] Z. Zeng, G. Finocchio, B. Zhang, P. K. Amiri, J. A. Katine, I. N. Krivorotov, Y. Huai, J. Langer, B. Azzerboni, K. L. Wang, and H. Jiang, "Ultralow-current-density and bias-field-free spin-transfer nano-oscillator," Sci. Rep., vol. 3, Mar. 2013. [4] T. Windbacher, H. Mahmoudi, V. Sverdlov, and S. Selberherr, "Rigorous simulation study of a novel non-volatile magnetic flip flop," SISPAD 2013.



The currents flowing through region A and B generate spin waves which travel through the shared free layer, superimpose and cancel each other partially (z-components); resulting in a circular oscillation in the xy-plane.

9:18

EH-05. Self-modulation in nanocontact spin torque oscillators.

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Modulation of spin torque oscillators (STOs) via external sources, critical for future communications applications, has been readily demonstrated [1, 2]. Here, evidence of self-modulation in nanocontact STOs will be discussed as well as its origin. Samples are based on a nanocontact STO geometry. A nanocontact of diameter, d, is defined via electron beam lithography on top of a spin valve with the following layer structure: Co(8 nm)/Cu(7 nm)/NiFe(4.5 nm). Measurements are performed in a cryogenic probe station utilizing a Halbach array of permanent magnets capable of a rotatable field with a fixed magnitude of 9.65 kOe. Signatures of self-modulation have been observed at a reduced temperature of 80 K. Spectra for applied field angles of 62°-90° on a sample with d=90 nm are shown in Fig. 1(a). For this range of angles the dominant mode is a propagating spin wave [3-5]. However, as clearly seen in Fig. 1(a) several other peaks, with lower power, are also evident and can be linked to a secondary low frequency (<11 GHz) mode and the corresponding modulation sidebands. To demonstrate this more clearly, three representative spectra taken at 66°, 75°, and 83° are shown in Fig. 1(b-d). Along with the primary high power propagating mode oscillating at a frequency f, the low frequency mode, oscillating at f_m, is apparent in all three spectra. Additionally, upper and lower sidebands appear at frequencies $f\text{-}f_m$ and $f+f_m$. As there is no external stimulus, other than the dc current, the appearance of these modulation sidebands clearly indicates a signature of self-modulation. Micromagnetic simulations reveal that a second low frequency mode, consistent with the periodic nucleation and subsequent annihilation of a vortex/anti-vortex pair, is generated under the nanocontact. This new oscillation mode coexists with the propagating mode, resulting in a strong intermodulation signal.

[1] M.R.Pufall, W.H. Rippard, S. Kaka, T.J. Silva, and S.E. Russek, *Appl. Phys. Lett.* **86**, 082506 (2005). **[2]** P.K. Muduli, Y. Pogoryelov, S. Bonetti, G. Consolo, F. Mancoff, and J. Åkerman, *Phys. Rev.B.* **81**, 140408 R (2010). **[3]** S. Bonetti, V. Tiberkevich, G. Consolo, G. Finocchio, P. Muduli, F. Mancoff, A. Slavin, and J. Åkerman, *Phys. Rev. Lett.* **105**, 217204 (2010). **[4]** M. Madami, S. Bonetti, G. Consolo, S. Tacchi, G. Carlotti, G. Gubbiotti, F.B. Mancoff, M.A. Yar, and J. Åkerman, *Nature Nanotechnology* **6**, 635 (2011). **[5]** R.K. Dumas, E. Iacocca, S. Bonetti, S.R. Sani, S.M. Mohseni, A. Eklund, J. Persson, O. Heinonen, and J. Åkerman, *Phys. Rev. Lett.* **110**, 257202 (2013).

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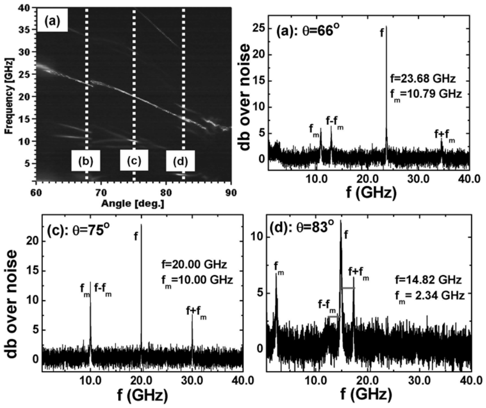

Fig. 1. (a) Measured frequencies as a function of the applied field angle. Selected spectra at field angles of (b) 66°, (c) 75°, and (d) 83° highlighting the primary mode at frequency f, a secondary mode at frequency f_m, and the corresponding modulation sidebands, $f\pm f_m$.

9:30

EH-06. The effects of Dzyaloshinskii-Moriya interaction on the ferromagnetic resonance response in nanosized devices.

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A precise understanding of unique thin-film magnetic systems anticipated for use in novel memory and sensor device technologies are important for a number of reasons and is often enabled by measurement of system parameters. In magnetic systems like magnetic tunnel junctions (MTJ) and spin-Hall-type systems, forms of spin-orbit coupling (SOC) play an important role via mechanisms such as crystalline anisotropy and spin-flip scattering, for example. Recently, there is growing evidence of another unique form of SOC known as Dzyaloshinskii-Moriya interaction (DMI)[1] having been observed in an increasing number of systems including systems such as W/Fe, W/Mn, Pt/CoNi, and even TaCFBMgO, which is particularly interesting, given the wide interest for STT-MRAM devices.[2,3,4] In such systems, typically assumed without DMI, ferromagnetic resonance (FMR) has been a widely used approach to extract magnetic parameters such as damping, effective magnetization, g-factor, and exchange. Given the recent evidence of DMI in several relevant systems, this work uses full micromagnetics simulations with DMI added to investigate its effects on the FMR response in nanometer sized devices to probe the potential for detecting DMI. Unique modes associated with DMI are observed, illustrated in Figure 1 showing computed spectral responses with associated resonant eigenmodes in systems with and without DMI, in conditions leading to two resonance peaks. Previously studied modes with symmetry are also found to reduce their symmetry in the presence of DMI.[5,6] Moreover, the observed DMI-related modes are shown, in some cases, to be uniquely accessible using DC field rotation, as illustrated in Figure 2, showing spectra for different DC field orientations between 0 (in-plane) and 90 (out-of-plane) degrees. Generally, initial states, spectra, as well as eigenmodes are found to depend significantly on DMI, which suggests that FMR may be a viable tool for detection, even in nanometer sized devices.