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CoFeB-based spin Hall nano-oscillators

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Abstract—We demonstrate magnetization auto-oscillations driven by pure spin currents in spin Hall nano-oscillators based on CoFeB/Pt bilayers. Despite the very low anisotropic magnetoresistance of CoFeB (0.026%), a substantial microwave signal power can be detected, even at room temperature, indicating that a sizable spin wave amplitude is generated. Spin torque ferromagnetic resonance measurements reveal that the generated auto-oscillation lies below the ferromagnetic resonance of CoFeB, and is therefore well described by a self-localized spin wave bullet mode.

Index Terms—Spin Hall nano-oscillators, Spin torque ferromagnetic resonance, CoFeB

I. INTRODUCTION

Over the last decade, the use of spin-polarized currents to excite persistent magnetization oscillations and induce novel spin wave dynamics has received tremendous attention in the field of spintronics (Berger 1996) (Slonczewski 1996) (Deac et al. 2008) (Liu et al. 2012) (Bonetti et al. 2010) (Rippard et al. 2004) (Bertotti et al 2005) (Krivorotov et al. 2005) (Rippard et al. 2006). For example, the spin torque nano-oscillator (STNO), which produces highly tunable microwave signals (Bonetti et al. 2010) (Rippard et al. 2004), has shown particular promise. Such STNOs are typically based on a trilayer structure where a partial spin polarization is provided by a "fixed" magnetic layer separated from a "free" layer, which is subjected to the influence of spin torque, by a non-magnetic spacer. More recent investigations have also shown that *pure* spin currents can be induced via the spin Hall effect (SHE) using non-magnetic metal thin films with strong spin-orbit interactions, such as Pt and Ta (Liu et al. 2011) (Hirsch 1999) (Murakami et al. 2003) (Miron et al. 2011). Recently, the SHE has been utilized in a new category of oscillator devices called spin Hall nano-oscillators (SHNOs) (Demidov et al. 2012) (Liu et al. 2013) (Ulrichs et al. 2014) (Demidov et al. 2014).

SHNOs rely on concentrating the electric charge current to a nanoscopic region between two pointed Au electrodes, which are typically separated by <200 nm, and lithographically defined on top of a NiFe/Pt bilayer. This localized electric current passes through the Pt, which generates a pure spin current via the SHE that flows towards the NiFe, locally modify its damping. If the intrinsic positive damping of the NiFe is fully compensated by a source of negative damping, provided by the SHE generated pure spin current, auto-oscillation modes can be stabilized.

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To date, all SHNOs have been based on NiFe/Pt bilayers. However, CoFeB is arguably a much more versatile and interesting magnetic material that not only has a very low intrinsic damping (Wang et al. 2014) , but can also exhibit perpendicular magnetic anisotropy (PMA) (Ikeda et al. 2010) and even Dzyaloshinkii-Moriya interactions (DMI) (Torrejon et al. 2014) under the appropriate conditions. From a more applied standpoint, CoFeB is a crucial material for magnetic tunnel junctions (MTJs) utilized in spin-transfer-torque magnetoresistive random access memory (STT-MRAM) and as read heads for high density magnetic recording technologies (Ikeda et al. 2010) (Torrejon et al. 2014) (Mangin et al. 2006) (Lee et al. 2011). In this Letter, we have implemented SHNOs using CoFeB/Pt bilayers and studied the effect of in-plane magnetic fields on the induced auto-oscillations.

II. EXPERIMENTS

The $Co_{40}Fe_{40}B_{20}$ (5 nm)/Pt (6 nm) bilayer is deposited at room temperature onto 20 mm × 20 mm sapphire substrates using magnetron sputtering in a chamber with a base pressure better than 5 $\times 10^{-8}$ Torr. The Ar process gas pressure was maintained at 3 mTorr for all layers. Before deposition of the metal films the sapphire substrates were first annealed at 1300 °C in air (Simeonov et al. 2009) (Ulrichs et al. 2013).

The film was then patterned into 4 µm diameter circular mesas by electron beam lithography (EBL) and subsequent ion milling. Needle-shaped Cr (2 nm) / Au (150 nm) electrodes were fabricated on top of the disk center by lift-off through a resist mask defined with EBL, as shown in Fig. 2(a). The gap between the tips of the electrodes was reliably controlled to be between 50-200 nm. Subsequently, a 40 nm thick SiO_2 layer was sputter-deposited to protect the devices from the final processing steps and improve heat flow away from the devices during operation. Finally, a coplanar waveguide, defined by photolithography and lift-off, allows for electrical characterization of the SHNOs.

The magnetic properties of the extended CoFeB/Pt bilayers were studied using an alternating gradient magnetometer (AGM) and broadband field swept ferromagnetic resonance (FMR) techniques. The generated auto-oscillation signal was first amplified using a broadband 4–8 GHz +60 dB microwave amplifier and analyzed in the frequency domain using a spectrum analyzer. The dc current was fed to the device via a 40 GHz bias tee connected in parallel with the transmission line. All measurements were performed at room temperature**.**

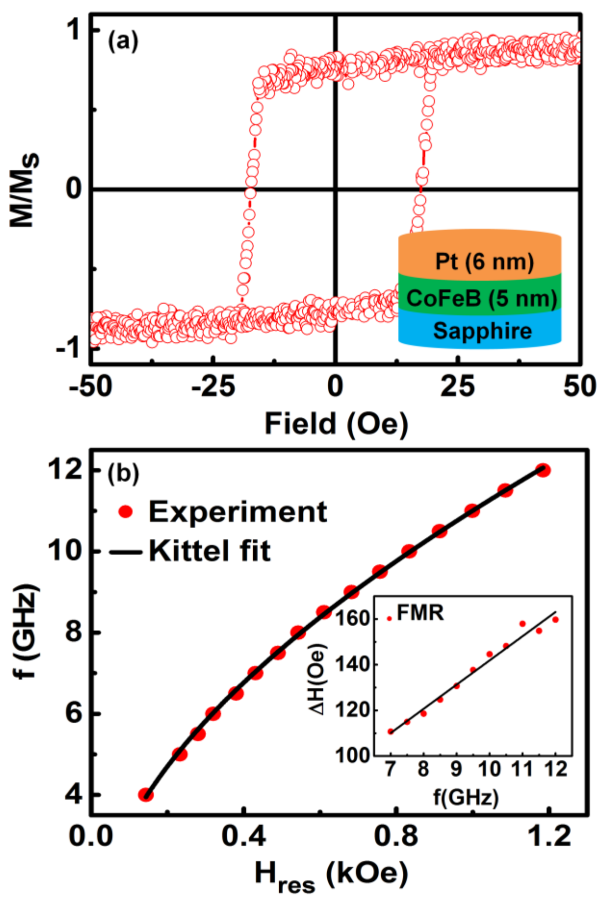

Fig. 1. (a) In-plane hysteresis loop of a $Co_{40}Fe_{40}B_{20}$(5 nm)/Pt(6 nm) bilayer showing low coercivity of 18 Oe. (b) Ferromagnetic resonance (FMR) frequency versus applied in-plane magnetic field for the same bilayer yielding an effective M_S of 1.28 T; Inset: FMR linewidth vs. frequency yielding a damping of α = 0.016 and an inhomogeneous broadening of ΔH_o = 36 Oe.

III. RESULTS AND DISCUSSION

Fig. 1(a) shows hysteresis loop of a CoFeB(5 nm)/Pt(6 nm) bilayer as measured by an AGM with the applied field parallel to the film plane. The measured hysteresis loop indicates a dominant in-plane magnetization due to thin-film shape anisotropy. The coercive field was measured to be 17.5 Oe. In addition, significant information about the dynamic properties of the bilayers was obtained through FMR measurements. FMR spectra were measured over a 4–12 GHz frequency range with the applied field parallel to the film plane. The resulting spectra were then fit with a sum of symmetric and anti-symmetric Lorentzian contributions (Liu et al. 2012). As expected, the dependence of FMR resonance field on frequency shows excellent agreement with the Kittel equation (Kittel 1948), as shown in Fig. 1(b, main panel).

From this fit the saturation magnetization ($\mu_0 M_s$ = 1.28 T) and the gyromagnetic ratio (γ/2π = 29.7 GHz/T) were obtained. The FMR linewidth (*ΔH*) is plotted as a function of frequency, as shown in Fig. 1(b, inset). The inhomogeneous broadening (ΔH_0 = 35.8 Oe) and Gilbert damping constant (α = 0.0157) were obtained with a linear fit to the equation: $\Delta H = \Delta H_0 + 4\pi\alpha f/\gamma$ (Liu et al. 2014). The increased damping compared to 6e-3 for single CoFeB films (Conca et al. 2014) can be attributed to spin pumping into the adjacent Pt layer (Tserkovnyak et al. 2002) .

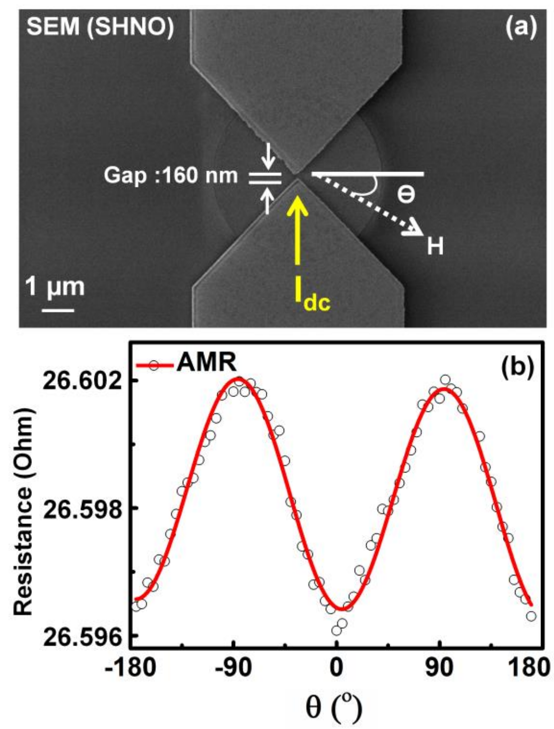

Fig. 2. (a) An SEM image of an SHNO with a Au contact gap size of 160 nm and disk diameter of 4 μm; ϴ is the in-plane angle. (b) Anisotropic magnetoresistance (AMR) response as a function of the in-plane applied field angle, ϴ.

Figure 2(a) shows a scanning electron microscopy (SEM) image of our SHNO device with a gap size of 160 nm. We first investigated the angular dependence of the SHNO device resistance, Fig. 2(b), by applying an in-plane saturating magnetic field of 500 Oe at an angle, ϴ, as indicated in Fig. 2(a). The angular dependence is consistent with the anisotropic magnetoresistance (AMR) effect (Ranieri et al. 2008). The amplitude of the AMR is rather small, 0.026%, compared to that typically found in NiFe (0.12 %) (Liu et al.

2013). In order to observe auto-oscillation, it is best to work at an angle where small changes in the angle show the largest changes in AMR.

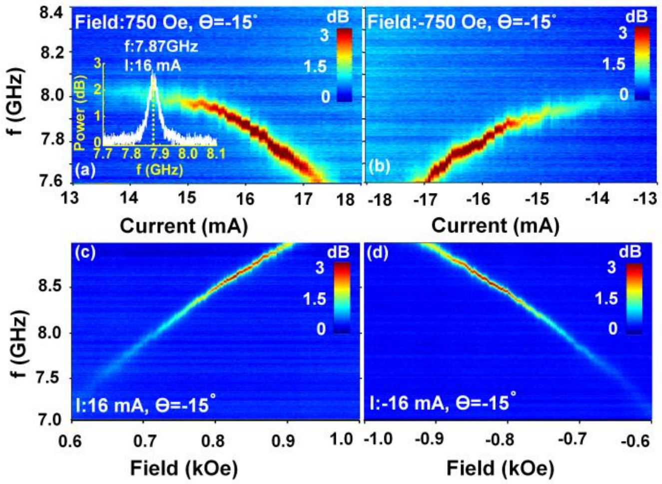

Fig. 3. Auto-oscillations as a function of dc current for an applied field along Θ = -15° of magnitude (a) +750 Oe and (b) -750 Oe. The inset in (a) shows the power spectral density at a measurement current of 16 mA. Auto-oscillations as a function of applied field for a fixed dc current of (c) +16 mA and (d) -16 mA.

Figure 3(a) shows the auto-oscillation frequency generated in the SHNO device as a function of dc current (13-18 mA) with a +750 Oe in-plane magnetic field applied along the Θ = -15° direction. The frequency of the auto-oscillation mode monotonically decreases, or redshifts, with increasing current. Figure 3(a, inset) highlights a single power spectrum of the generated microwave signal at 16 mA exhibiting a linewidth of 43.3 MHz. Similarly, auto-oscillations were observed when the sign of the applied magnetic field and dc current was reversed, as shown in Fig. 3(b), and exhibit a similar redshift as the magnitude of the applied current is increased. Field swept measurements at a fixed dc current of +16 and -16mA are shown in Figs. 3(c) and 3(d), respectively. As was similarly observed in the current swept measurements in Figs. 3(a) and 3(b), a measurable auto-oscillation response was only observed whenthe sign of the dc current and field were the same, as expected due to the symmetry of the spin Hall Effect (Demidov et al. 2014) (Jamali et al. 2013) (Chernyshov et al. 2013).

To better understand the relation of the observed auto-oscillation to the spin wave spectrum of CoFeB, we measured the FMR response of the device using spin torque ferromagnetic resonance (ST-FMR) (Liu et al. 2013). With zero dc bias current a pulsed rf current (3–11 GHz P_{rf}= +7.5 dBm) was applied to the SHNO device while the applied magnetic field swept from 0-1500 Oe. The injected rf signal induces oscillations of the magnetization due to a combination of the Oersted field and spin torque. A mixing of the resulting periodic AMR with the injected rf current produces a dc rectified voltage, measured using a lock-in amplifier, at the FMR condition. The ST-FMR spectra are well fit with a sum of a symmetric and an anti-symmetric Lorentzian functions. As shown in Fig. 4(a), we find that the observed auto-oscillation mode in range of 13 mA to 18 mA dc current at 750 Oe applied field always lies below the FMR frequency, consistent with the existence of a localized spin wave mode in the CoFeB.

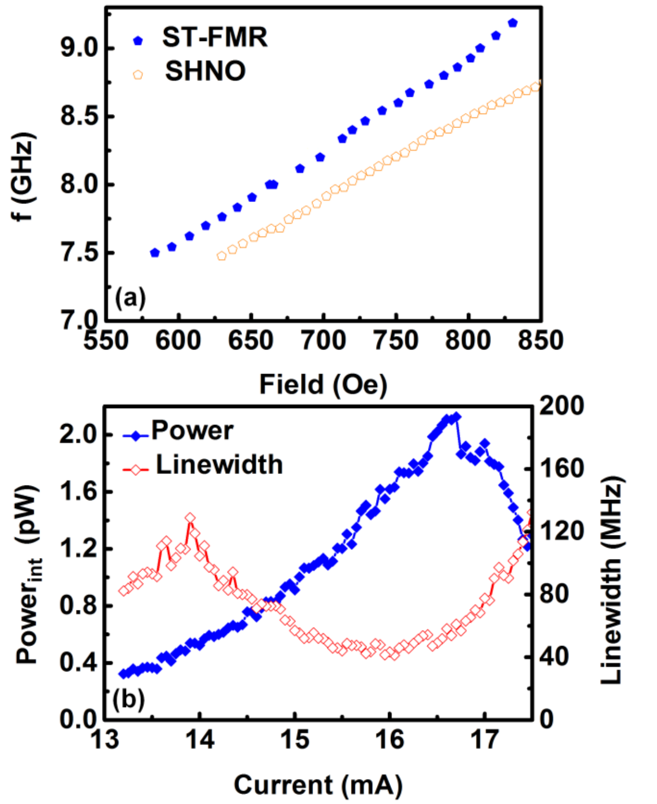

Fig. 4. (a) Auto-oscillations and ST-FMR response as function of applied field. (b) Integrated power and linewidth as a function of applied current for a +750 Oe field applied along the Θ = -15° direction.

In order to quantitatively investigate the observed auto-oscillation mode, we extracted the integrated power and linewidth as a function of current, as shown in Figure 4(b). The minimum linewidth, 43.3 MHz, was measured at 16 mA with a +750 Oe applied field along the Θ = -15° direction. It is difficult to directly benchmark our results with the existing electrical characterization of NiFe/Pt SHNOs, as those devices did not show measurable auto-oscillations and the linewidth diverged at room temperature. One contribution to the observed linewidth is due to fluctuations in the amplitude and the nonuniform magnetization dynamics due to thermal activation, devices edges, or inhomogeneous dc current injection that cause different parts of the device to oscillate at slightly different frequencies (Taniguchi et al. 2014).

Furthermore, from Figure 4(b), we can observe that, as integrated power increases, the linewidth decreases; this is consistent with the theory of nonlinear oscillators, which predicts that the thermal linewidth decreases with increasing oscillation power (Slavin et al. 2008) (Kim et al. 2008).

In conclusion, we have experimentally demonstrated auto-oscillations in CoFeB-based SHNO devices where the magnetization dynamics are driven by *pure* spin currents generated via the SHE in an adjacent Pt layer. The observed spin wave mode lies below the FMR frequency, indicating a self-localized mode for in-plane bias fields. In contrast to prior studies on NiFe/Pt SHNO devices, we are able to observe sizable and low linewidth auto-oscillations at room temperature. Owing to its unique attributes, e.g. the ability to exhibit PMA, DMI, low damping, and technological utility in MTJs, the demonstration of a functional SHNO based on CoFeB is an important step forward for future studies of magnetodynamics driven by pure spin currents.

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