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Low operational current spin Hall nano-oscillators based on NiFe/W bilayers

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We demonstrate highly efficient spin Hall nano-oscillators (SHNOs) based on NiFe/ β -W bilayers. Thanks to the very high spin Hall angle of β -W, we achieve more than a 60% reduction in the auto-oscillation threshold current compared to NiFe/Pt bilayers. The structural, electrical, and magnetic properties of the bilayers, as well as the microwave signal generation properties of the SHNOs, have been studied in detail. Our results provide a promising path for the realization of low-current SHNO microwave devices with highly efficient spin-orbit torque from β -W. *Published by AIP Publishing.*
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Spin Hall nano-oscillators (SHNOs) are promising microwave signal generators with a high degree of frequency tunability, both via the electrical current and the magnitude and direction of an external magnetic field.¹ These SHNOs operate on the basis of spin-orbit torque (SOT),² which is produced when a spin current, created via the spin Hall effect^{3–8} in a metal with high spin-orbit coupling (e.g., Pt,⁹ W,^{10,11} Ta¹²), is absorbed by an adjacent ferromagnetic layer. SOT can act as a negative spin-wave damping in the ferromagnet and above a certain threshold current, it can sustain a steady state auto-oscillation of the local magnetization.

To date, most SHNOs have been based on NiFe/Pt,^{2,13–20} YIG/Pt,^{21,22} and CoFeB/Pt,²³ with SOT produced by a Pt layer. Many other heavy metals, such as W,^{10,11} IrCu,^{24,25} and CuBi,²⁶ have however been investigated, revealing that the so-called spin Hall angle (θ_{SH}), which describes the charge current to spin current conversion efficiency, can exceed that of Pt. W is particularly interesting, as it has two different structural phases, called α and β , with an order of magnitude difference in resistivity ($\rho_\alpha < \rho_\beta$), and a much larger θ_{SH} in the β phase.^{10,11,27} However, β -W can only be obtained under restricted conditions, such as well-controlled slow deposition rates, no heating, and thin layer thicknesses.

In this study, we demonstrate the fabrication and operation of nano-constriction based SHNOs employing β -W as the heavy metal. We find a large negative value of $\theta_{SH} = -0.385$ and a corresponding dramatic reduction of the SHNO threshold current by over 60% compared to Pt-based SHNOs.^{2,13–19,21–23}

All thin films were deposited at room temperature on c-plane sapphire substrates using magnetron sputtering in a 2.5 mTorr Ar atmosphere, in an ultra-high vacuum (base pressure below 1×10^{-8} mTorr) AJA Orion 8 sputtering system. First we carried out a detailed study of the thickness dependence of the W film resistivity in films deposited at a rate of 0.07 Å/s. Figure 1 shows that, as the thickness increases, the

W resistivity decreases exponentially from a very high value ($\sim 400 \mu\Omega \text{ cm}$) at a thickness of 3 nm and finally drops to a near constant value of $\sim 30 \mu\Omega \text{ cm}$ for thicknesses of 12 nm and above, which is close to the bulk W resistivity. This indicates that films with a thickness below 10 nm are primarily of β -phase, and a W thickness of 5 nm was therefore chosen for the fabrication of SHNO devices.

Prior to the device processing, a bilayer consisting of 5 nm Ni₈₀Fe₂₀ (Py) and 5 nm β -phase W was deposited, with the thicknesses predetermined from X-ray reflectivity measurements on calibration films. High-resolution transmission electron microscopy (HR-TEM) (Figure 1-inset) confirms the thicknesses of the bilayer and also shows that the Py/ β -W interface is well-defined without any significant intermixing. The distance between lattice fringes in the W-layer was found from a fast Fourier transformation to be approximately 2.50 Å, i.e., close to the (0 0 2) plane of β -W.²⁸ This confirms that the β -W crystal structure is indeed realized in the stack.

To fabricate SHNOs, the bilayer was patterned into an array of $4 \mu\text{m} \times 12 \mu\text{m}$ rectangular mesas using photolithography and dry etching. Nano-constrictions with the width

FIG. 1. Resistivity vs. thickness for W thin films. Inset: Cross-section HR-TEM image of the stack and the result of fast Fourier transformation of the W-layer.

^{a)}H. Mazraati and S. Chung contributed equally to this work.

varying from 80 to 160 nm were subsequently fabricated in the center of these mesas by a combination of e-beam lithography and Argon ion milling. To determine θ_{SH} of tungsten, 6 μm -wide bars were fabricated simultaneously next to the SHNO mesas, and characterized using spin-torque-induced ferromagnetic resonance (ST-FMR) measurements. Finally, a conventional ground-signal-ground (GSG) waveguide and electrical contact pads for wide frequency range microwave measurement were fabricated using lift-off photolithography and Cu/Au sputtering on top of both the SHNO nano-constrictions and ST-FMR bars.

A schematic of the device structure, an atomic force microscopy (AFM) image, and a scanning electron microscopy (SEM) image of the fabricated 100 nm-wide nano-constriction SHNO device are shown in Figure 2(a), where the direction of the applied in-plane field and current are also defined: the field angle $\phi = 0^\circ$ along $+x$ and $+90^\circ$ along $+y$, while a negative (positive) current means electrons flow along $+(-)y$.

The linear nano-constriction width dependence of the SHNO resistance shown in Figure 2(b) indicates that the device-to-device variation during the fabrication process was moderate. ST-FMR measurements based on homodyne detection were then carried out on 6 μm bar-shaped devices, using a 313 Hz-pulse-modulated microwave signal and a dc current injected simultaneously through rf and dc ports, respectively, of a bias-tee. The dc voltage response (V_{dc}) from the 313 Hz modulated microwave input is detected also through the dc port of the bias-tee using a standard lock-in amplifier.^{21,29–32} Figures 3(a) and 3(b) show the resonance peaks extracted from the detected ST-FMR output spectra with the in-plane magnetic field (H_{IP}) swept from 0 to

2500 Oe at different constant frequencies f of the injected microwave signal.

Microwave measurements were carried out using our custom-built setup in which a dc current was driven into the SHNO and the output microwave signal was picked up separately via the bias-tee. The output signal was amplified by 35 dB using a broadband (0.1–20 GHz) low-noise amplifier (LNA) prior to an R&S FSQ26 spectral analyzer. Results of the microwave measurement in the applied in-plane and out-of-plane (OOP) fields are shown in Figures 4 and 5, respectively. All measurements were performed at room temperature.

Figure 3(a) shows the ST-FMR results of a 6 μm -wide bar-shaped device in an in-plane magnetic field (H_{IP}) applied along $\phi_H = 30^\circ$ and swept from 0 to 2.5 kOe. All ST-FMR spectra have been fitted to a function consisting of one symmetric and one antisymmetric Lorentzian having the same resonance field and linewidth⁹

$$V_{dc} = \frac{V_S \Delta H^2 + 4V_A (H_{IP} - H_r) \Delta H}{4(H_{IP} - H_r)^2 + \Delta H^2} + V_{\text{offset}}, \quad (1)$$

where H_r is the resonance field of the measurement spectra, ΔH is its linewidth (full-width half maximum, FWHM), V_S and V_A are the coefficients of the symmetric and antisymmetric Lorentzian functions, respectively, and V_{offset} is a constant offset voltage.

The color plot of the ST-FMR spectra is shown in Figure 3(a). The dependence of the resonance field (H_r) on the microwave frequency shows good agreement with the Kittel formula (solid red line),³³ and by considering the gyromagnetic ratio of $\gamma/2\pi = 28 \text{ GHz/T}$, the extracted effective magnetization from the fit is $\mu_0 M_{\text{eff}} = 0.71 \text{ T}$. The inset in Figure 3(a) shows the

FIG. 2. (a) Schematic of the device structure and the configuration of the applied magnetic field. Inset: AFM image of the active nano-constriction area with zoomed-in SEM image of the nano-constriction. (b) Device resistance vs. constriction width. Inset: AMR measurement for constriction width = 100 nm.

FIG. 3. (a) ST-FMR measurement on a 6 μm -wide bar-shaped structure. Inset: ST-FMR linewidth vs. frequency. (b) ST-FMR linewidth vs. current in an in-plane magnetic field along $\phi = 30^\circ$ (black dots) and 210° (red dots).

FIG. 4. Power spectral density (PSD), extracted linewidth, and integrated power of the auto-oscillations for (a) in-plane, and (b) out-of-plane magnetic fields.

linewidth, ΔH (white dots) as a function of frequency, together with a linear fit³³ $\Delta H = \Delta H_0 + 4\pi\alpha f/\gamma$ (red line), from which an inhomogeneous broadening (ΔH_0) of 1.8 Oe and a Gilbert damping (α) of 8.32×10^{-3} can be extracted.

To extract the spin Hall angle θ_{SH} , we then investigated the current-induced linewidth changes originating from the SOT of the W layer. Figure 3(b) shows how the linewidth depends linearly on the device current, with positive current providing a negative damping when the field is along $\phi = 30^\circ$ (black circle), and positive damping when the field direction is reversed to 210° (red circle). The spin Hall angle, defined as the ratio of the spin and charge current densities $\theta_{SH} = J_s/J_c$, is then extracted from the slopes in Figure 3(b) using the following equation:^{9,11,34}

$$\theta_{SH} = \frac{\frac{\delta\Delta H/\delta I_{DC}}{\sin \phi}}{\frac{2\pi f}{\gamma} (H_{IP} + 0.5M_{eff})\mu_0 M_s t 2e} \frac{R_{Py} + R_W}{R_{Py}} A_C, \quad (2)$$

FIG. 5. Threshold current vs. constriction width in an 800 Oe in-plane magnetic field at $\phi = 20^\circ$. Inset: threshold current extraction through a linear fit of $1/\text{power}$ versus current at low current.

where M_s is the saturation magnetization, and t is the thickness of the magnetic layer, e is the electron charge and $\hbar$ is Planck's constant, R_{NiFe} and R_W are the resistances of the NiFe and tungsten layers, and A_C is the cross-sectional area of the measured device. We obtained $\theta_{SH} = -0.385 \pm 0.009$, which is comparable to previous studies.^{10,21}

We now turn to the SHNOs. Figure 4(a) shows the measured power spectral density (PSD) vs. SHNO drive current from a 140 nm wide nano-constriction in a field of $H_{IP} = 400$ Oe along $\phi = 20^\circ$. The auto-oscillation frequency, linewidth, and integrated power are extracted by fitting the peaks of all spectra with a Lorentzian function. Whereas the auto-oscillation frequency only depends weakly on the drive current, both the linewidth and the integrated power shows a rapid exponential improvement up until $I_{DC} = -0.9$ mA, reaching a minimum linewidth of about 10 MHz, and a maximum power of about 1 pW. Above this current level, the auto-oscillation frequency decreases, and both linewidth and power deteriorate, possibly indicating the appearance of a different mode.^{18,35,36}

When the applied field is tilted out-of-plane ($\theta = 80^\circ$; $\phi = 20^\circ$) and increased to 8 kOe to align the Py magnetization (Figure 4(b)), the current dependence changes character to a much more non-monotonic frequency, with an initial red shift at low current, which changes to a clear blue shift at higher current. In contrast to the in-plane case, the integrated power shows a monotonic improvement with current, and the linewidth improves to about 2 MHz, i.e., close to an order of magnitude better than in the in-plane case. As shown in Ref. 20 this non-monotonic frequency behavior results from a gradual change in the location of the auto-oscillations. At low currents, the auto-oscillations start from the edges of the nano-constrictions. With increasing current, the auto-oscillation region then expands into the nano-constriction, and the point of maximum spin wave intensity moves inward. In this process, the mode center experiences a varying field landscape with the net effect being a frequency red-shift as the mode leaves the edges followed by a blue-shift as it further expands inward.

The large spin Hall angle is expected to have a strong beneficial impact on the threshold current (I_{th}) for microwave signal generation. To evaluate this, we measured more than 20 SHNOs with different nano-constriction widths ranging from 80 to 160 nm. I_{th} is determined from linear fits of the inverse microwave power vs. current,^{37,38} as shown in the inset of Figure 5; all the measurements were carried out with $H_{IP} = 0.08$ T and $\phi = 20^\circ$. Figure 5 shows that I_{th} depends linearly on the nano-constriction width, and the values observed are more than 60% lower than those from previous reports on Pt-based SHNOs.^{2,13,14,16–18,21,23}

The effective threshold current flowing through the W layer, shown on the right-hand y-axis of Figure 5, can be calculated by considering the ratio of the Py and W resistivities. This shows that a current of only about 75 μ A in W can excite Py auto-oscillations in a 80 nm nano-constriction. From a linear fit to all the measured devices, we can calculate the effective threshold current density in our W-based SHNOs to be $J_{th,eff} \simeq 2 \times 10^7$ A/cm².

We have demonstrated a reliable fabrication and operation of W/Py based nano-constriction SHNOs. Our devices

achieved a significant reduction in the threshold current of more than 60% compared to Pt/Py devices. Our findings thus lay out a definite development path for low-current SHNOs using highly efficient spin orbit torque from a W layer.

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