SCIENCE CHINA
Information Sciences

• LETTER •

October 2026, Vol. 69, Iss. 10, 209401:1–209401:2
https://doi.org/10.1007/s11432-025-4877-0

Nonlinearity modulation of auto-oscillations in three-terminal magnetic tunnel junctions

Zixi WANG[1], Wenlong CAI[1,2*], Ao DU[1], Zanhong CHEN[1], Lei ZHOU[1], Shiyang LU[1], Kewen SHI[1,2*] & Weisheng ZHAO[1,2*]

[1]*Fert Beijing Institute, School of Integrated Circuit Science and Engineering, Beihang University, Beijing 100191, China*
[2]*National Key Laboratory of Spintronics, International Innovation Institute, Beihang University, Hangzhou 311115, China*

Received 22 May 2025/Revised 5 September 2025/Accepted 19 March 2026/Published online 24 August 2026

Citation Wang Z X, Cai W L, Du A, et al. Nonlinearity modulation of auto-oscillations in three-terminal magnetic tunnel junctions. Sci China Inf Sci, 2026, 69(10): 209401, https://doi.org/10.1007/s11432-025-4877-0

Spin-torque nano-oscillators (STNOs), offering high current tunability, nanoscale size, and a wide output bandwidth, have emerged as viable candidates for nanoscale microwave generators, spectral analyzers, and next-generation intelligent computing architectures [1]. In particular, the tunability of their oscillating frequency is a distinctive feature that plays a crucial role in the efficient manipulation of microwave frequencies, rapid spectral analysis, and the design of neuromorphic devices [2]. Nonlinear auto-oscillation theory [3] introduces the nonlinear factor N, indicating the direct current-modulated frequency shift. However, experimental research on efficient N modulation remains limited. Previous studies have mainly explored the magnitude and direction of the external magnetic field ($H_{\rm ex}$); however, the strict constraint on $H_{\rm ex}$ considerably limits the output frequency and device structure. By modifying the free layer (FL) magnetization, e.g., via He^{+} irradiation, N of STNOs can also be modulated through changes in effective magnetization ($M_{\rm eff}$) [4]. However, ion implantation inevitably necessitates additional fabrication steps, potentially inducing undesirable damage to the thin films. In this study, we investigate the impacts of critical factors, including $H_{\rm ex}$, cobalt-iron-boron (CoFeB) FL thickness ($t_{\rm FL}$), and the synergistic interplay between spin-transfer torque (STT) and spin-orbit torque (SOT) currents [5], on N in three-terminal magnetic tunnel junctions (MTJs). Our findings provide a comprehensive understanding of the current-induced tunability of MTJ-STNOs, paving the way for further optimization in STNO-based applications.

Results. A schematic of the proposed device is presented in Figure 1(a). FLs with thicknesses of 1.1 and 1.3 nm were designed to investigate the effects of different magnetic anisotropy fields (H_k) and demagnetizing fields. Additional information on the fabrication process and experimental setup is provided in Appendixes A–C. The angle between the $H_{\rm ex}$ and the x-axis is denoted as θ.

First, we investigate the impact of $H_{\rm ex}$ on N. Figures 1(b) and (c) present the relationship between the power spectral density (PSD) and STT current density ($J_{\rm STT}$) across different in-plane $H_{\rm ex}$ in the 1.3 nm FL. The auto-oscillatory frequency, f, exhibits a clear linear dependence on the current and is fitted with a linear function (Figure 1(d)). Consequently, the extracted slope, $\mathrm{d}f/\mathrm{d}J_{\rm STT}$ (inset of Figure 1(d)), shows minimal variation. To comprehend the underlying mechanism of this phenomenon, we apply the nonlinear auto-oscillator theory. In this framework, the current dependence of f is expressed as follows [3]:

$$f(J) = f_{\rm FMR} + \frac{N}{2\pi}P, \qquad \frac{\mathrm{d}f}{\mathrm{d}\zeta} = J_{\rm th}\frac{\mathrm{d}f}{\mathrm{d}J} = \frac{N}{2\pi}\frac{1+Q}{(\zeta+Q)^2}, \tag{1}$$

where J represents the current density of the driving current, and $f_{\rm FMR}$ is the ferromagnetic resonance (FMR) frequency. P is the normalized power of the stationary precession. Additionally, $Q = 2\omega_M/\omega_0 - 1$ is the nonlinear damping coefficient, where ω_M and ω_0 denote the magnetization-related and FMR angular frequencies, respectively. $\zeta = J/J_{\rm th}$ denotes the dimensionless supercriticality parameter, where $J_{\rm th}$ represents the threshold J. In practical measurements, the linear dependence between J and f can be attributed to the relatively narrow variation range of J. This induces a negligible variation of ζ compared with Q in the denominator of (1). Therefore, to simplify the analysis, a linear fitting determined by (2) is applied to analyze N.

$$N = -\frac{\omega_H\omega_M\left(\omega_H + \frac{\omega_M}{4}\right)}{\omega_0\left(\omega_H + \frac{\omega_M}{2}\right)}, \begin{cases} \omega_H = \gamma\mu_0 H_{\rm ex}, \\ \omega_M = \gamma\mu_0 M_{\rm eff}, \\ \omega_0 = \sqrt{\omega_H(\omega_H+\omega_M)}. \end{cases} \tag{2}$$

Here, γ is the gyromagnetic ratio, and μ_0 is the vacuum permeability. $M_{\rm eff}$ is defined as $M_{\rm eff} = M_s - H_k$, where M_s is the saturation magnetization. Based on (2), the $H_{\rm ex}$ can modulate N by changing the Zeeman frequency term, ω_H. However, no significant changes are observed in the $\mathrm{d}f/\mathrm{d}J_{\rm STT}$. This phenomenon is attributable to the relatively small FL $M_{\rm eff}$ or the factor $(1+Q)/(\zeta+Q)^2$ in (1). Figures 1(e) and (f) illustrate the auto-oscillation behaviors of the 1.3 nm FL at different $H_{\rm ex}$ angles. As revealed in the figures, $\mathrm{d}f/\mathrm{d}J_{\rm STT}$ changes continuously with θ (Figure 1(g)), reflecting the strong dependence of N on θ of $H_{\rm ex}$. As θ increases, the precession axis of the FL magnetic moment, as well as the effective field, $H_{\rm eff}$, tilts gradually from the in-plane to perpendicular directions. Consequently, the $H_{\rm ex}$ projection along the perpendicular direction increases, leading to a shift of ω_H.

* Corresponding author (email: caiwenlong1993@buaa.edu.cn, shikewen@buaa.edu.cn, weisheng.zhao@buaa.edu.cn)

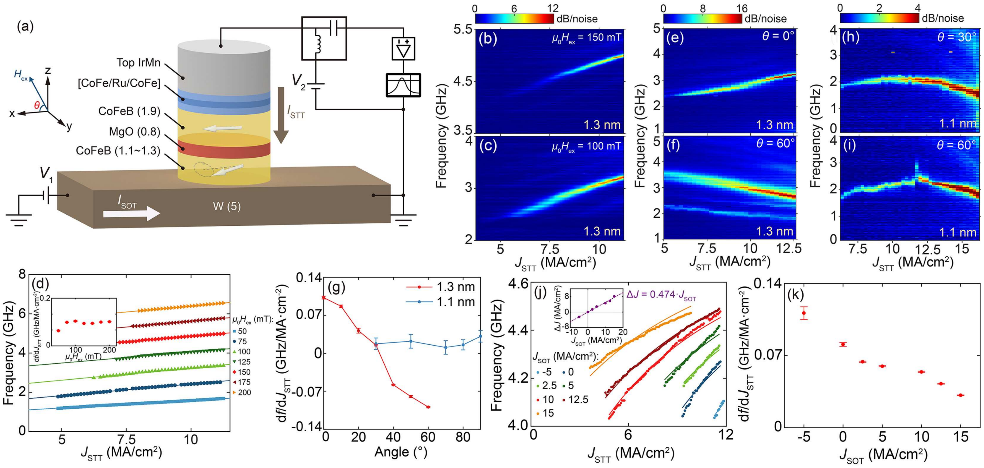

Figure 1 (Color online) (a) Schematic of the proposed magnetic tunnel junction. (b), (c) Power spectral density (PSD) vs. spin-transfer torque current density ($J_{\rm STT}$) under different magnitudes of in-plane external magnetic fields ($H_{\rm ex}$) in a 1.3 nm free layer (FL). (d) Current tunability of the frequency (f) at different magnitudes of $H_{\rm ex}$. The inset plots the slope, $df/dJ_{\rm STT}$, as a function of $H_{\rm ex}$. PSD vs. $J_{\rm STT}$ at different $H_{\rm ex}$ angles (θ) in (e), (f) 1.3 nm and (h), (i) 1.1 nm FLs, respectively. (g) Slope $df/dJ_{\rm STT}$ as a function of θ in samples with different FL thicknesses ($t_{\rm FL}$). (j) Frequency as a function of $J_{\rm STT}$ at different $J_{\rm SOT}$. The inset illustrates the relationship between $J_{\rm SOT}$ and the fitting parameter, ΔJ; the value of the correction term, η, can be estimated through linear fitting (plotted as a solid line). (k) Extracted $df/dJ_{\rm STT}$ vs. $J_{\rm SOT}$ plot.

Since the control of the $H_{\rm ex}$ requires stringent external conditions and additional device structures, we further investigate the impacts of different $t_{\rm FL}$ on N. We conduct similar measurements on an STNO with 1.1 nm FL (Figures 1(h) and (i)), after which the $df/dJ_{\rm STT}$ are plotted (Figure 1(g); see data analysis in Appendix D). The $df/dJ_{\rm STT}$ of the 1.1 nm FL shows a relatively small variation with θ compared with the 1.3 nm FL, indicating extremely low N. We attribute this phenomenon to the low $M_{\rm eff}$ of the 1.1 nm CoFeB layer caused by the rather high H_k associated with thinner films, compensating $M_{\rm eff}$ to approximately zero. Thus, the ω_M in (2) becomes sufficiently small that variations in $H_{\rm ex}$ exert a negligible effect on N. Consequently, N can be tuned by $t_{\rm FL}$, approaching zero at $t_{\rm FL}$ of 1.1 nm and providing a more intrinsic and robust approach for achieving zero nonlinearity in STNOs without relying on external factors, such as $H_{\rm ex}$. Moreover, our method offers a simpler, more fabrication-compatible alternative to He^+ irradiation, which requires additional fabrication steps and risks damaging thin films. This property can be utilized to minimize the output spectral linewidth [4] without compromising output power. Maintaining a stable output power that is unaffected by the driving current is crucial for microwave generators and neuromorphic computing applications [2].

The modulation of N by the combined effects of $J_{\rm STT}$ and the SOT current density ($J_{\rm SOT}$) is further investigated using the 1.3 nm FL (Figures 1(j) and (k)). The slope, $df/dJ_{\rm STT}$, decreases as $J_{\rm SOT}$ increases, demonstrating the electrical tunability of N. Complementary PSD measurements obtained by sweeping $J_{\rm SOT}$ under fixed $J_{\rm STT}$ are provided in Appendix E. To account for this behavior, we reformulate the supercriticality parameter, ζ, in (1) as $\zeta = (J_{\rm STT} + \eta J_{\rm SOT})/J_{\rm th,STT}$, where $J_{\rm th,STT}$ denotes the threshold of $J_{\rm STT}$. Here, $J_{\rm STT}$ becomes the independent variable and a correction term, $\eta J_{\rm SOT}$, is added. Therefore, a positive (negative) $J_{\rm SOT}$ can generate extra spin torque that promotes (suppresses) the oscillation, modifying $J_{\rm STT}$ by $\Delta J = \eta J_{\rm SOT}$. Theoretical calculations (solid lines in Figure 1(j)) are in good agreement with the experimental results (the small deviation is attributable to the thermal effect). The proportional relationship between ΔJ and $J_{\rm SOT}$ (inset of Figure 1(j)) also supports this model. Although $df/dJ_{\rm STT}$ cannot be further simplified to a constant during the analytical calculation, it can still be approximately estimated through linear fitting. Further discussions on different mechanisms, as well as the advantages and potential applications of electrical modulation, are provided in Appendix F. Furthermore, a detailed comparative analysis with previous studies is also provided in Appendix G.

Conclusion. In conclusion, we experimentally investigated the modulation of N in three-terminal MTJ-STNOs. Based on nonlinear auto-oscillation theory, our results provide a systematic understanding of how different factors influence N. The magnitude of $H_{\rm ex}$ exerts a minimal effect on N, whereas its direction effectively tunes N. N can also be tuned by $t_{\rm FL}$, approaching zero at 1.1 nm and offering a more intrinsic and robust approach that is independent of $H_{\rm ex}$. Furthermore, combining $J_{\rm STT}$ and $J_{\rm SOT}$ enables efficient N tuning through an electrical control, which can be explained by a refined model considering both currents. Overall, our findings offer new insights into current tunability, paving the way for the further optimization of STNO-based devices.

Acknowledgements This work was supported by National Key R&D Program of China (Grant No. 2022YFB4400200), National Natural Science Foundation of China (Grant Nos. T2394473, T2394474, 62271026, 62401026, 623B2015), China Postdoctoral Science Foundation (Grant No. 2023M740177), and National Post-doctoral Program for Innovative Talents (Grant No. BX20240455).

Supporting information Appendixes A–H. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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