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Magnetic modulation of terahertz waves via spin-polarized electron tunneling

Zuanming Jin[1], Caihua Wan[2], Xiufeng Han[2], Zhenxiang Cheng[3], Chao Zhang[4], Alexey. V. Balakin[1,5], Alexander. P. Shkurinov[1,5], Yan Peng[1], Guohong Ma[6], Yiming Zhu[1,*], Songlin Zhuang[1]

[1]Terahertz Technology Innovation Research Institute, University of Shanghai for Science and Technology, China

[2] Institute of Physics, University of Chinese Academy of Sciences, Chinese Academy of Sciences, China

[3] Institute for Superconducting and Electronic Materials, University of Wollongong, Australia

[4]School of Physics, University of Wollongong, Australia

[5] Department of Physics and International laser Center, Lomonosov Moscow State University, Russia,

[6] Department of Physics, Shanghai University, China

*Corresponding Author's e-mail address: ymzhu@usst.edu.cn

Abstract—**We demonstrate that the tunneling magneto-resistance (TMR) can be used to modulate terahertz (THz) wave propagation through a magnetic tunnel junctions (MTJ). Operating at the THz frequency range, a maximal modulation depth of 60% is reached for the parallel state of the MTJ with the thickness of 77.45 nm, by using a small magnetic field of 30 mT. The THz conductivity spectrum of the MTJ is governed by the spin-dependent electron tunneling. This findings open that the MTJ device will have potential applications in THz magnetic modulators, filtering and sensing.**

I. INTRODUCTION

It is noteworthy that THz transient has become increasingly important to investigate the light-matter interaction in spintronic materials, since many dynamic processes such as spin currents and magnetic spin waves oscillate with THz frequencies [1,2]. There have been numerous THz devices controlled by external magnetic fields are demonstrated for amplitude modulation, phase retardation, polarization control.

The magnetoresistance (MR) is an important spintronic effect to change the conductivity response and influence the THz electromagnetic wave propagation. In this work, we use single-cycle THz pulses to drive the spin-polarized charge across the FM/MgO/FM interface over picosecond time scales, as shown in Fig. 1 (a). We demonstrate that an external magnetic field (~30 mT) tends to align the magnetization of free FM layer with the pinned FM layer, leading to a strong attenuation on the propagating THz pulse. Our findings indicate that THz TMR effect to offer a solution towards spintronic THz amplitude modulators.

II. RESULTS

Fig. 1 (b) shows the typical time-domain THz transmitted signal E(t) through the MTJ multi-stack applied with a magnetic field H=30 mT (along the x axis), compared with that measured at H=0 mT. We see a significant attenuation of THz peak-to-peak values of the parallel orientation E_P, compared with E_{AP} at the antiparallel configuration. The temporal waveforms were squared and integrated over time, thus we calculate the THz intensities transmitted through the MTJ versus θ in the configuration of AP state, as shown in Fig. 1 (c). The solid line shows a $\cos^2\theta$ fit, which can be attributed to the anisotropic magnetoresistance (AMR). We found that the modulation of the THz intensity by AMR is around 16%.

As the $\mathbf{M}_{\text{free-layer}}$ is fixed along x axis, Fig. 1 (d) shows that I(φ) follows mainly the $\cos\varphi$ dependence, which again provides the strong and direct evidence of TMR. The full fitting (solid line) includes both the AMR (dotted line) and TMR (dashed line) contributions. We can find that TMR plays a significant role in the observed effect under an applied magnetic field. The maximum modulation depth obtained in our MTJ sample (~60%) is comparable to the THz magnetic modulator based on Fe_3O_4 nanoparticles (66%) [3]. While, the thickness of MTJ sample is 4-5 orders of magnitude less than the magnetically clustered particles.

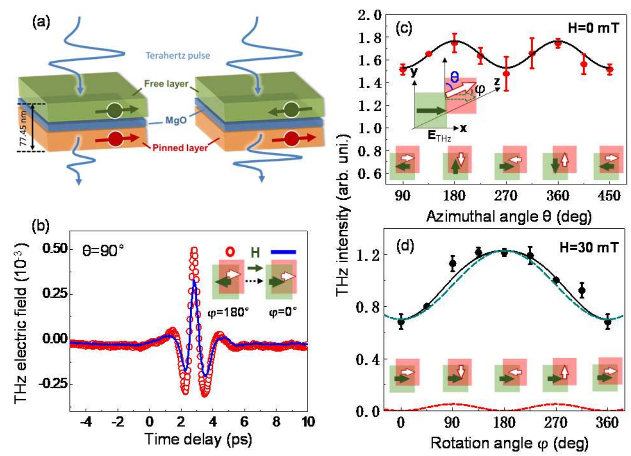

Fig. 1. (a) Schematic illustration of the THz tunneling magneto-resistance effect. (b) THz waveforms E(t) through the MTJ multi-stack at magnetizations are aligned in parallel and antiparallel states. (c) the θ and (d) φ dependences of THz intensity. Inset: the diagrams depict the orientation of the **H** field is along the x axis, which fixes the $M_{\text{free-layer}}$ (green arrow) along the x axis.

III. SUMMARY

In conclusion, we demonstrated the THz magnetic modulation by using THz TMR effect, which is governed by the spin-dependent electron tunneling on (sub-) picosecond timescale. The MTJ-based THz modulation not only combines a high modulation depth and low magnetic field requirements, but also shows the flexibility by the tunability of THz conductivity in response to the relative magnetization orientations.

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