GRAPHENE AND 2DM VIRTUAL CONFERENCE & EXPO

10 ANNIVERSARY

Graphene online 2020 October 19-23

SPIN-ORBIT TORQUES IN MoS_2-GRAPHENE BASED HETEROSTRUCTURES

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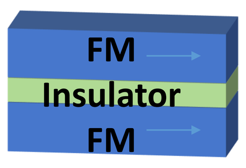
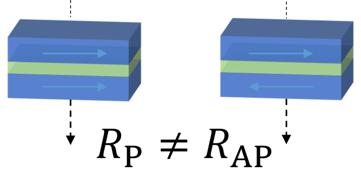
I. Motivation

Basics of magnetic memories (MRAM)



Two configurations:

"0" Parallel — **"1"** Antiparallel



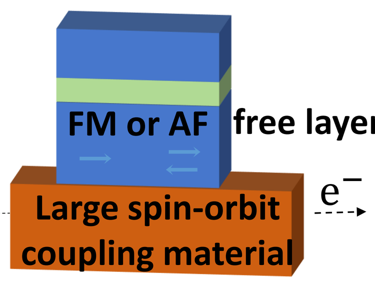
$R_P \neq R_{AP}$

Spin orbit torque (SOT)

✓All-electrical switching (highly efficient)

✓Transverse geometry

Charge-to-spin conversion leads to SOT



OUR AIM

2D materials for SOT?

- Study the charge-to-spin conversion using 2D materials with large spin-orbit coupling (MoS_2)
- And interfaced with graphene (proximity effect, refs [2,3])

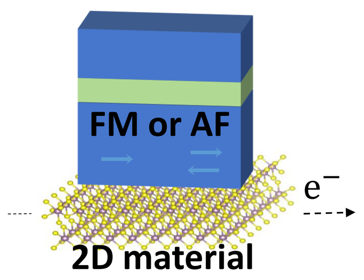
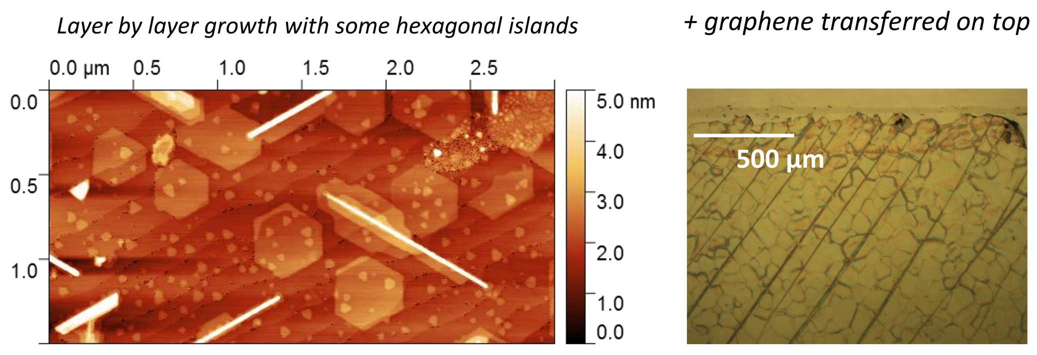


Figure adapted from ref [1]

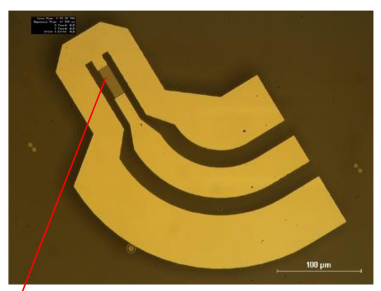
II. Device fabrication

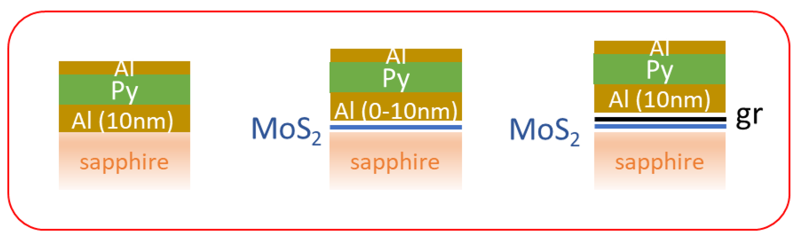
1. MoS_2 grown on sapphire. Graphene grown on Pt foil is detached and dry-bonded to the MoS_2/sapphire substrate.



2. Low-temperature growth (by molecular beam epitaxy) of metallic spacers (Al layer of 0 to 10nm) and ferromagnet (Py, 5nm) on top of MoS_2 or MoS_2/gr. A 2nm-Al capping prevents Py from oxidation.

3. Device fabrication: rectangular stacks defined by laser lithography and RIE are embedded in coplanar waveguides for high frequency dynamics experiments.



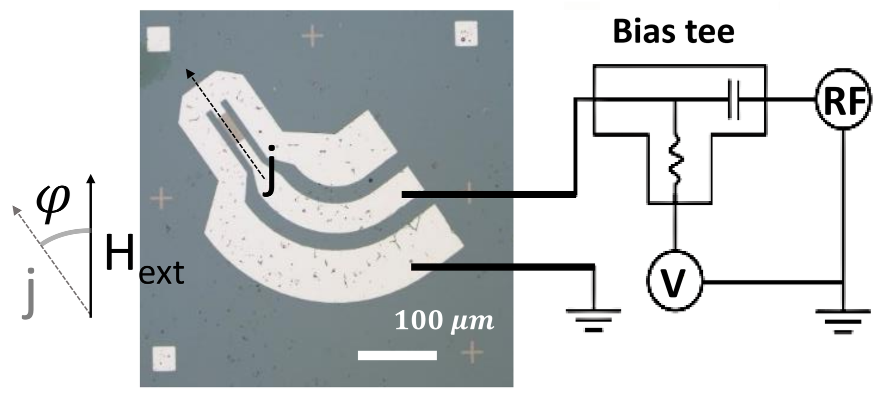


III. Spin-torque ferromagnetic resonance (ST-FMR)

Experimental setup for ST-FMR

Amplitude-modulated GHz current is injected into the sample, and an in-plane external magnetic field is applied.

The voltage, measured via a lockin detection (V_{mix}), is proportional to the change of the sample resistance due to **anisotropic magnetoresistance (AMR)**. This allows us to probe the magnetization dynamics.

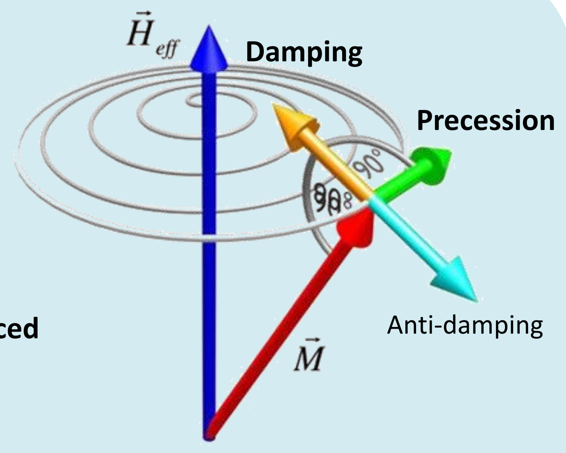


Magnetization dynamics

Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{d\vec{M}}{dt} = -\gamma\mu_0(\vec{M}\times\vec{H}) + \alpha\left(\vec{M}\times\frac{d\vec{M}}{dt}\right) + \vec{T}_{demag} + \vec{T}_{Oe} + \vec{T}_{FL} + \vec{T}_{DL}$$

Precession — Damping — Spin-current-induced



Field-like torques (odd in M) → $\boldsymbol{m}\times\boldsymbol{s}$

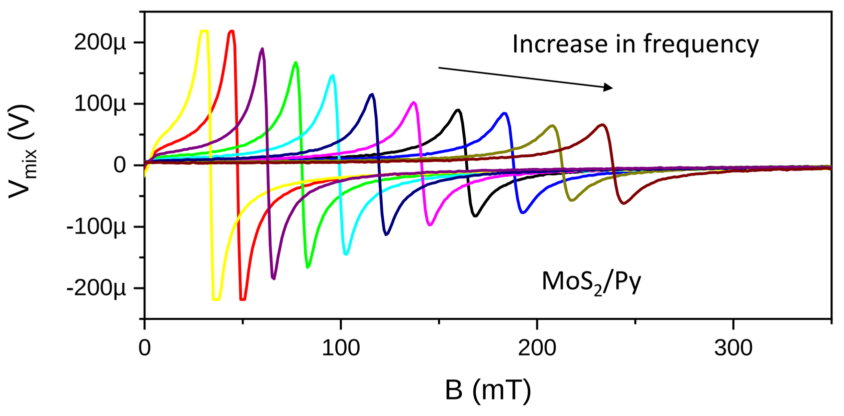
Damping-like torques (even in M) → $\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{s})$

$$V_{mix} = \frac{\Delta R\, I_{rf}^2 \cos^2\varphi\,\sin\varphi}{\alpha(2B_{res}+\mu_0 M_S)}\left[\frac{\partial B_{AD}}{\partial I_{rf}}F_S(B) + \frac{\partial(B_{Oe}+B_{FL})}{\partial I_{rf}}\sqrt{1+\frac{\mu_0 M_S}{B_{res}}}\,F_A(B)\right]$$

V_{mix} can be seen as a sum of symmetric and antisymmetric contributions (V_S and V_A, respectively)

IV. Characterization by ST-FMR

ST-FMR at different frequencies to extract M_{eff} and Gilbert damping α



From measurements for **different frequencies** (GHz) of RF current (with a fixed angle between the current and the magnetic field) it is possible to extract the effective magnetization (M_{eff}) and the Gilbert damping (α), as follows:

- f vs. B_{res} (Kittel fit) → μM_{eff}

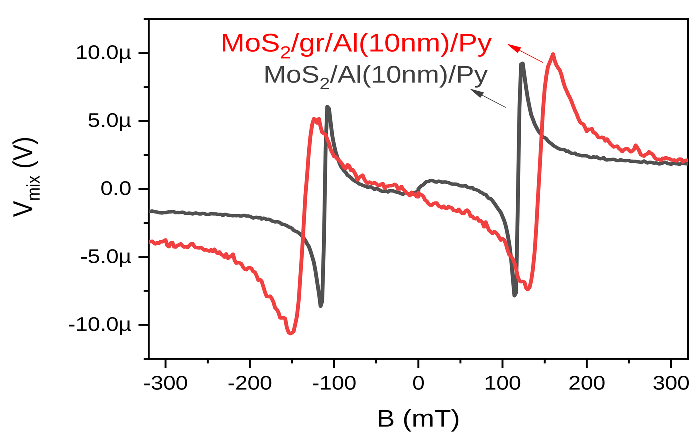
$$freq = g\sqrt{(B_{res}+B_0)(B_{res}+B_0+\mu M_{eff})}$$

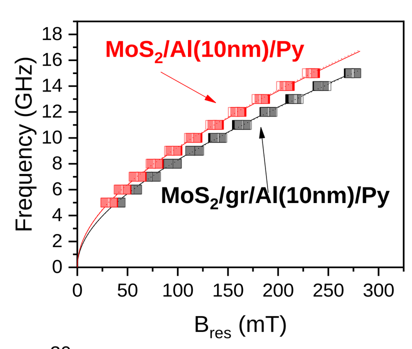
$$\rightarrow M_{eff}\left(\frac{A}{m}\right) = \frac{10^4}{4\pi}\mu M_{eff}(mT)$$

- Linewidth (ω) vs f → α

$$\omega = \omega_0 + \frac{2\alpha}{g} freq$$

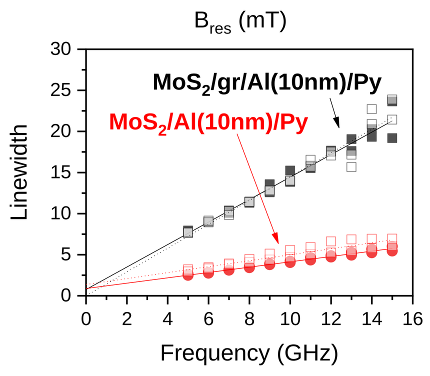
Comparison for the spectra (at fixed frequency) obtained for the samples **with and without graphene spacer**:





MoS_2/gr/Al/Py: M_{sat}=6.1x10^5 A/m (uM= 770mT)

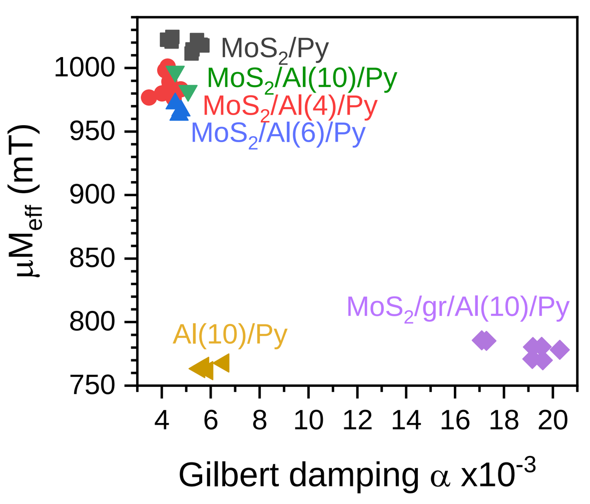
MoS_2/Al/Py: M_{sat}=7.9x10^5 A/m (uM= 990mT)



MoS_2/gr/Al/Py: α=0.019

MoS_2/Al/Py: α=0.0045

M_{eff} and α: comparison between stacks, various devices



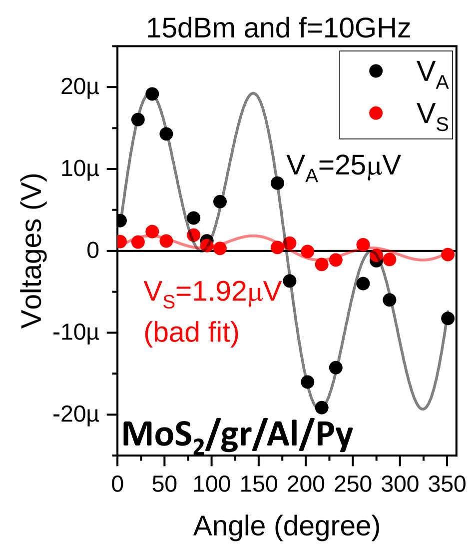
Extracted **effective magnetizations** show a stricking difference between samples with MoS_2 and samples without MoS_2 or with graphene spacer.

Seeing that $M_{eff} = M_s - \frac{2K}{\mu_0 M_s}$, where K is the perpendicular anisotropy energy density, and M_{sat} is supposed to be the same, different magnetic anisotropy could maybe explain these results.

Extracted **Gilbert damping parameter** is enhanced for the heterostructure containing graphene.

V. ST-FMR angular dependence

Angular dependence of ST-FMR for MoS_2/gr-based heterostructures

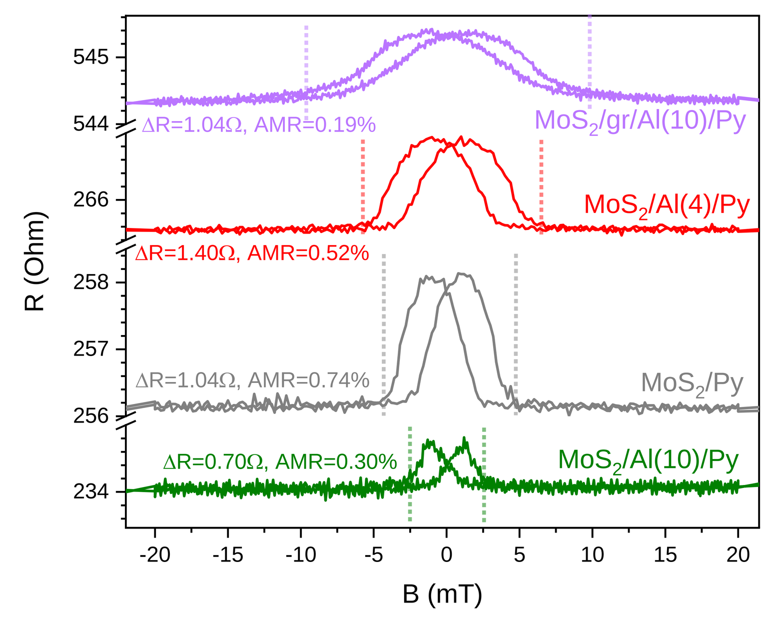


Symmetric and antisymmetric voltages (V_S and V_A, respectively) are extracted from ST-FMR curves measured varying the angle between the current and the external magnetic field B.

As an example, results for sample MoS_2/gr/Al/Py are shown, together with fits to $V\cos^2\varphi\sin\varphi$.

Angular dependence of all tested samples show large field-like torque (antisymmetric voltage) and negligible damping-like torque (symmetric voltage).

VI. Characterization by AMR (DC current)



AMR measured by applying a DC current of 50 µA and sweeping the magnetic field B in the sample plane and perpendicular to the current direction.

Difference in the AMR for different samples suggests different magnetic properties of the Py(5nm) layer even though the growth was done simultaneously.

(devices of 25x75µm²)

VII. Conclusions

MoS_2 and MoS_2-graphene-based heterostructures were fabricated and measured by spin-torque ferromagnetic resonance (ST-FMR). The insertion of a graphene spacer results in enhanced Gilbert damping parameter. However, differences in extracted effective magnetizations as well as for the measured anisotropic magnetoresistance suggest differences in the stack may affect the growth and therefore the magnetic properties of the Py film. Angular dependence of the ST-FMR shows negligible damping-like torque but large field-like torque. Further studies are required to determine the contributions of Oersted field or of Rashba to the latter.

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ACKNOWLEDGEMENTS

We acknowledge support from the European Union Horizon 2020 research and innovation program under contract 881603 (Graphene Flagship), from MINECO with grant FJCI-2016-28645 and from EU through MSCA-IF project 840588 GRISOTO.

Graphene online 2020