Spin-orbit torques and spin-pumping in Metal/SrTiO_3-based two-dimensional electron gases studied by ferromagnetic resonance techniques

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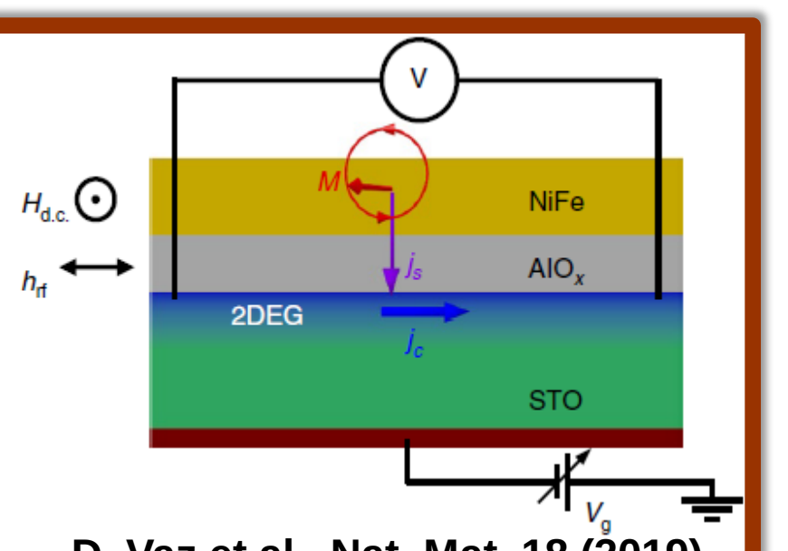
ABSTRACT

- **We study spin-orbit torques by spin-torque ferromagnetic resonance (ST-FMR)**
- **Non-volatile electric-control of the 2D electron gas (2DEG) resistivity is demonstrated in ST-FMR devices**
- **Metal-barrier thickness and temperature dependences of the charge-to-spin conversion in Metal/SrTiO_3 systems are reported**

2DEG in SrTiO_3 systems

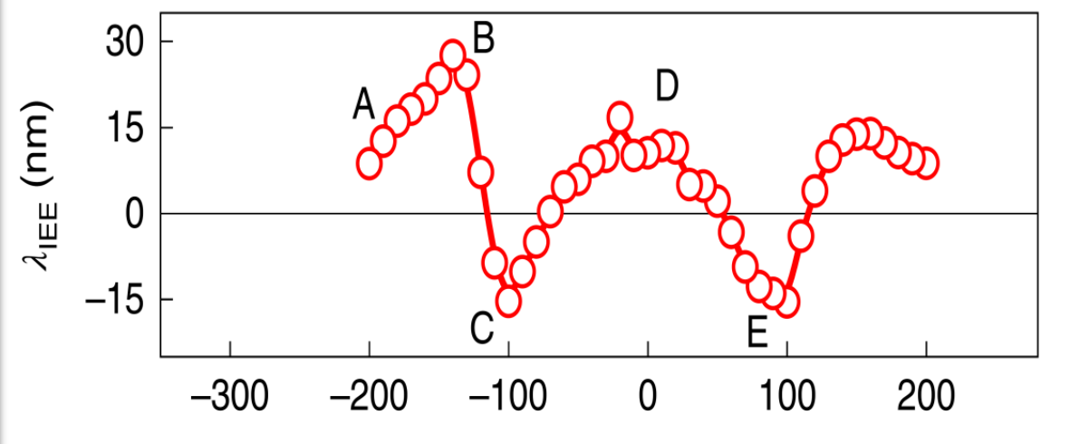
2DEG at metal/STO interface

- Possibility to tune the 2DEG properties
- Back-gate voltage (Vg) modulation
- Influence on spin-charge interconversion rates



D. Vaz et al., Nat. Mat. 18 (2019)

Large spin-to-charge conversion

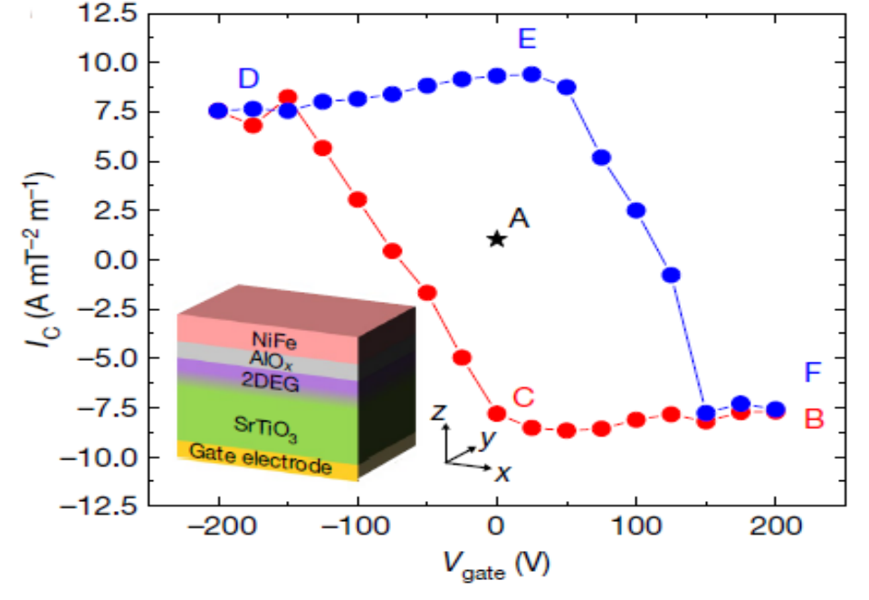


High Efficiency:
λ_{IEE} ~ 30 nm
(0.2 nm in Pt)

Spin-pumping measurements: Back-gate voltage modulation in oxide 2DEG

D. Vaz et al., Nat. Mat. 18 (2019)

Non-volatile electric-control of the spin-charge conversion



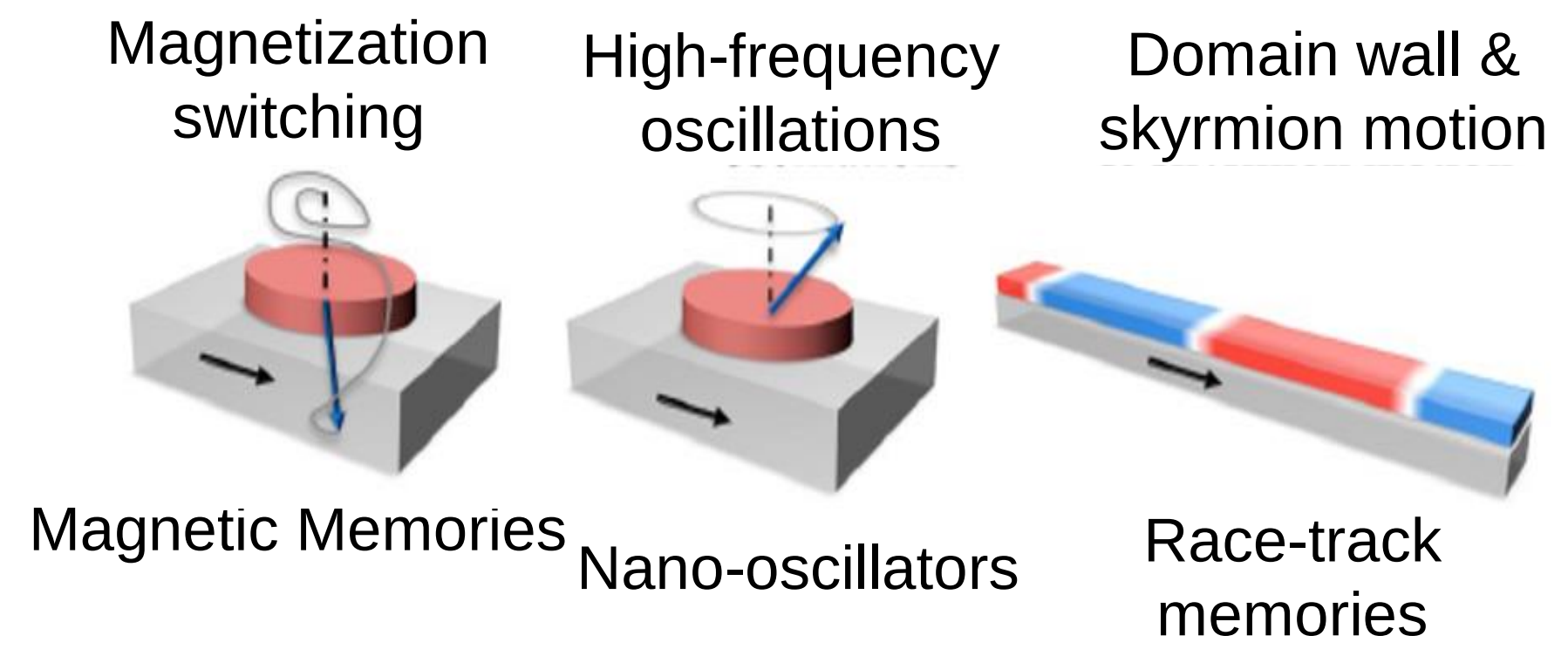
Ferroelectric phenomenon

P. Noel et al., Nat. 580 (2020)

Spin-orbit torques in MRAMs

- Current-induced magnetization switching for memory applications (SOT-MRAMs)
- For now: memory applications made of spin Hall materials → large SOT in heavy metals
- Drawback : SOT sign & conversion efficiency are fixed by materials

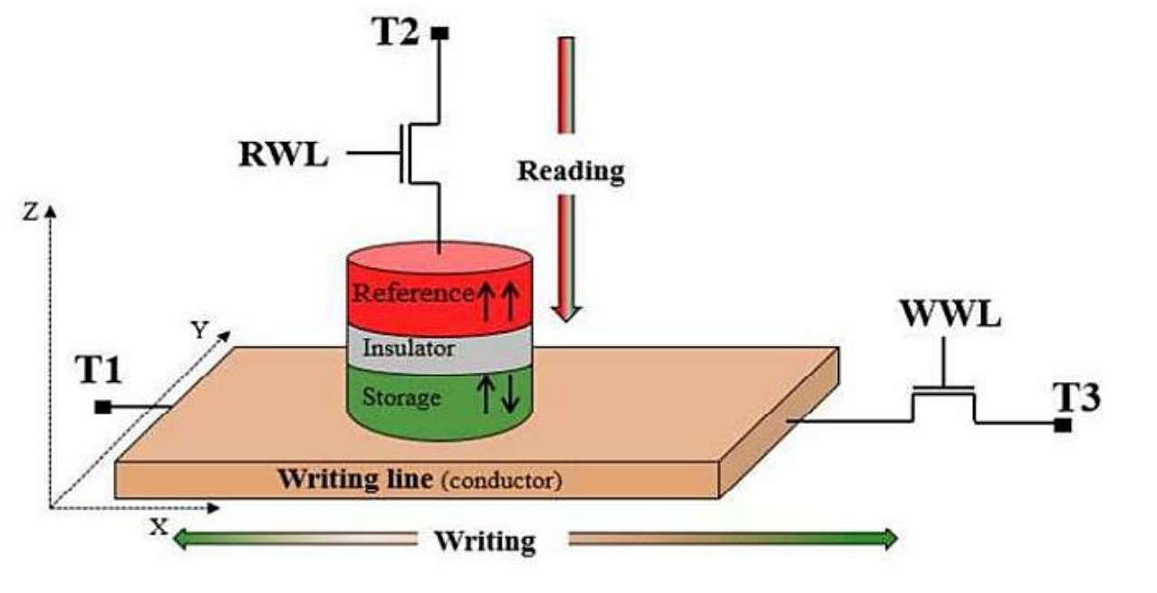
Electric-control in STO = new degree-of-liberty → SOT efficiency modulation



Magnetization switching | High-frequency oscillations | Domain wall & skyrmion motion

Magnetic Memories | Nano-oscillators | Race-track memories

Manchon et al., Rev. Mod. Phys. 91 (2019)



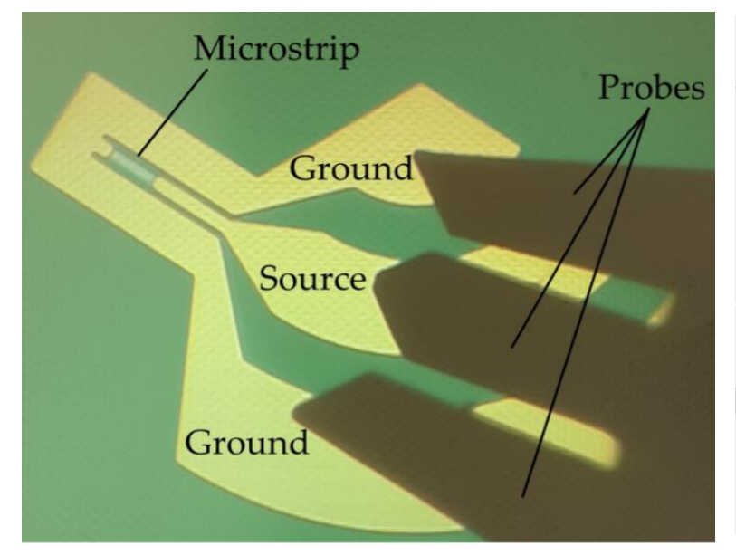
SOT - MRAMs

M. Kharbouche-Harrari et al., Conference on Design of Circuits and Integrated Systems (2018)

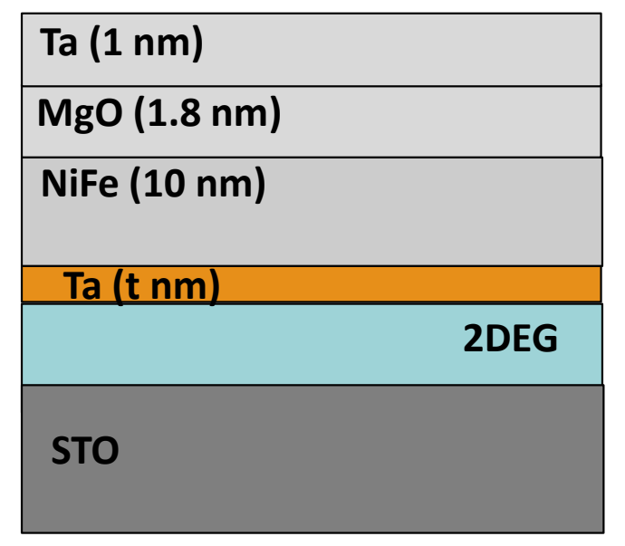
ST-FMR in STO

- Ferromagnetic resonance driven by spin-orbit torques
- Coplanar waveguide matched to STO dielectric constant
- Spin-obit torques: - Field-induced torque
  - Damping-like torque
  - Field-like torque

  } Due to Spin Hall or Rashba-Edelstein effects



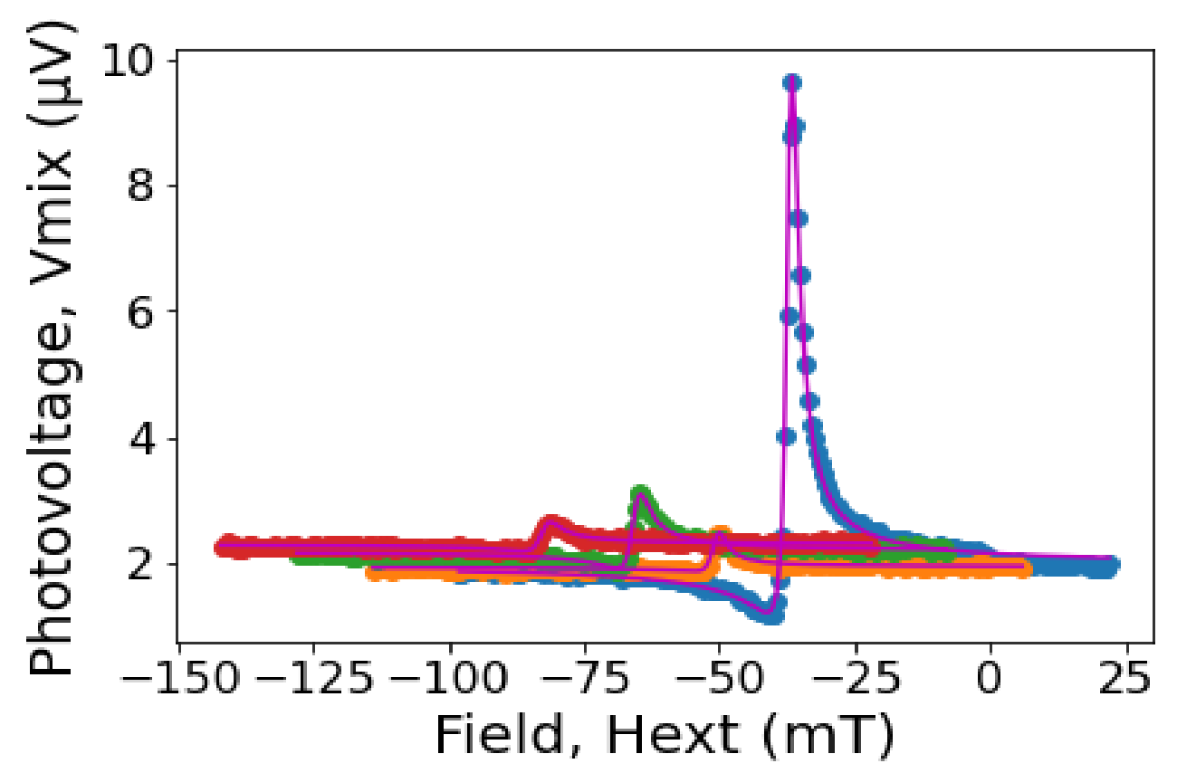
ST-FMR device



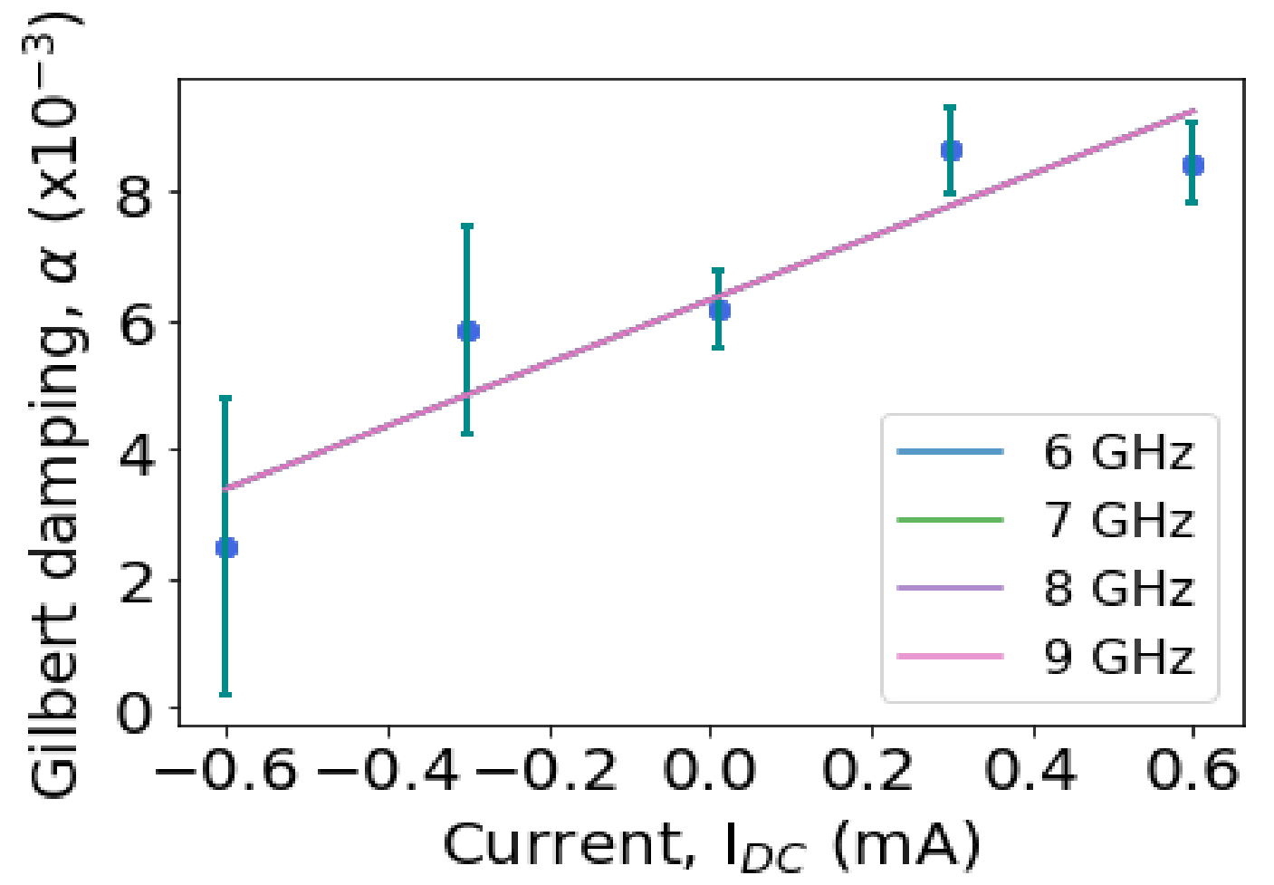
Microstrip

Metal barrier thickness dependence at 10K

STO/Ta(0.6nm)/NiFe(10nm)/MgO/Ta



ST-FMR signals at 12 dBm and 0.3 mA

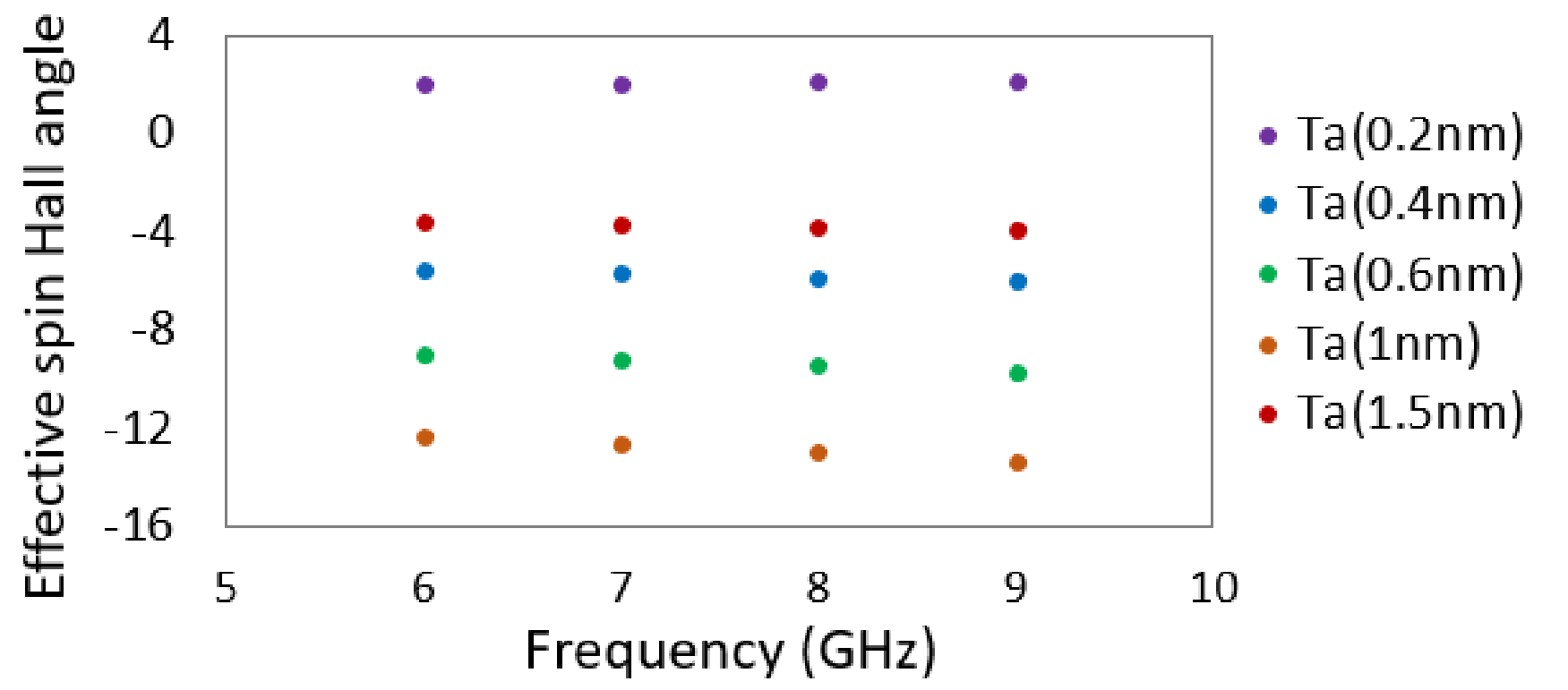


Damping modulation with injected DC charge current

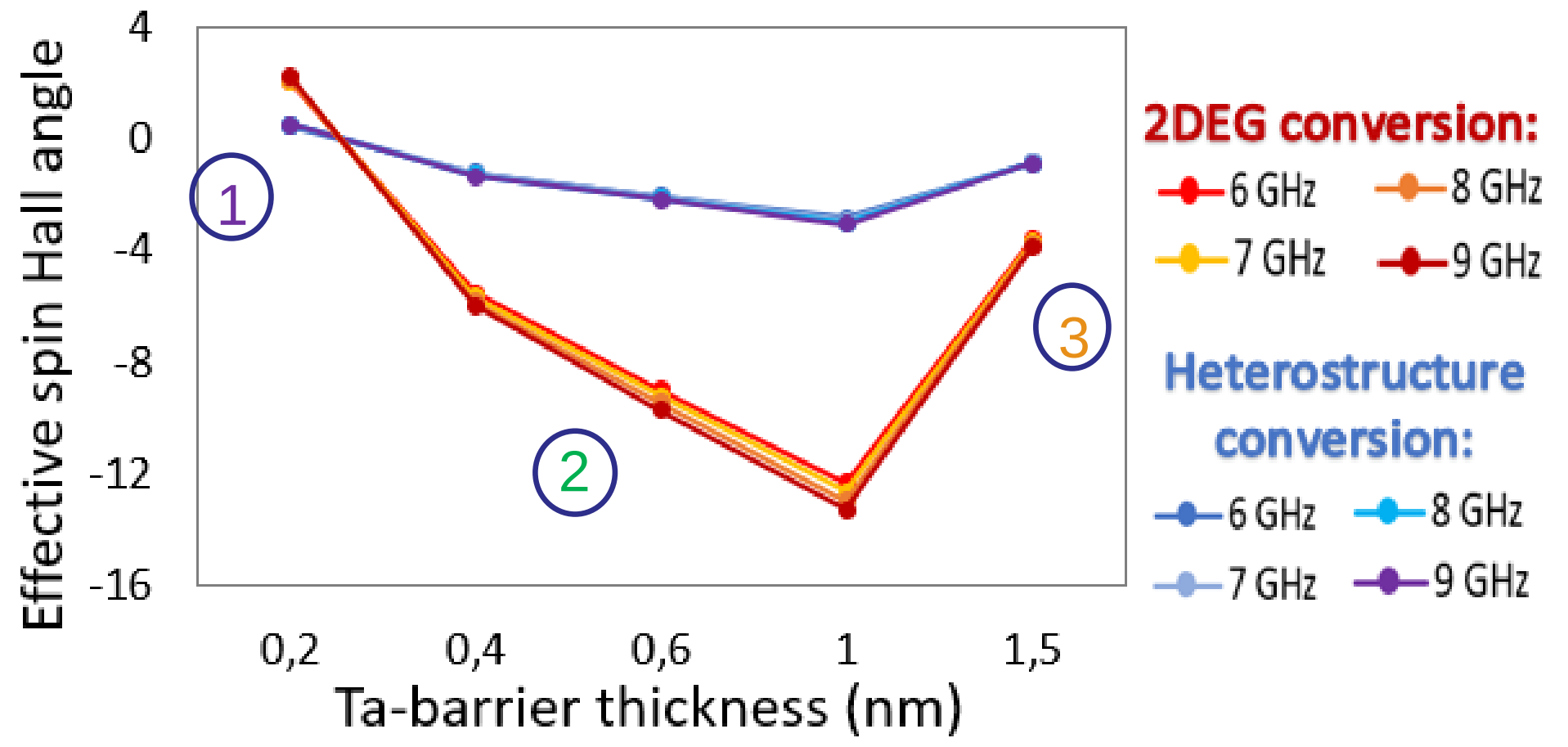
- ST-FMR signals: Lorentzian functions
- Analysis method: modulation damping*. Effective spin Hall angle Θ^*_{tot} extracted from the linear dependence of the damping α with the injected DC charge current

*L. Liu et al., Phys. Rev. Lett. 106 (2011)

Ta-barrier thickness dependence



2DEG conversion: Effective spin Hall angle versus frequency for different Ta-barrier thicknesses



Ta-barrier thickness dependence of the effective spin Hall angle in the 2DEG and in the whole heterostructure (2DEG +Ta/Py interface)

- From magnetotransport measurements at 10K, we have R_{NiFe} = 90.2 Ω and R_{tot} = 80.2 Ω → R_{2DEG} = 722,4 Ω

Portion of charge current passing through the 2DEG is : $\frac{R_{NiFe}}{R_{NiFe}+R_{2DEG}}$ = 11,1%.

- At least 2 charge-to-spin conversion contributions: 1) in the 2DEG 2) at the Ta/Py interface

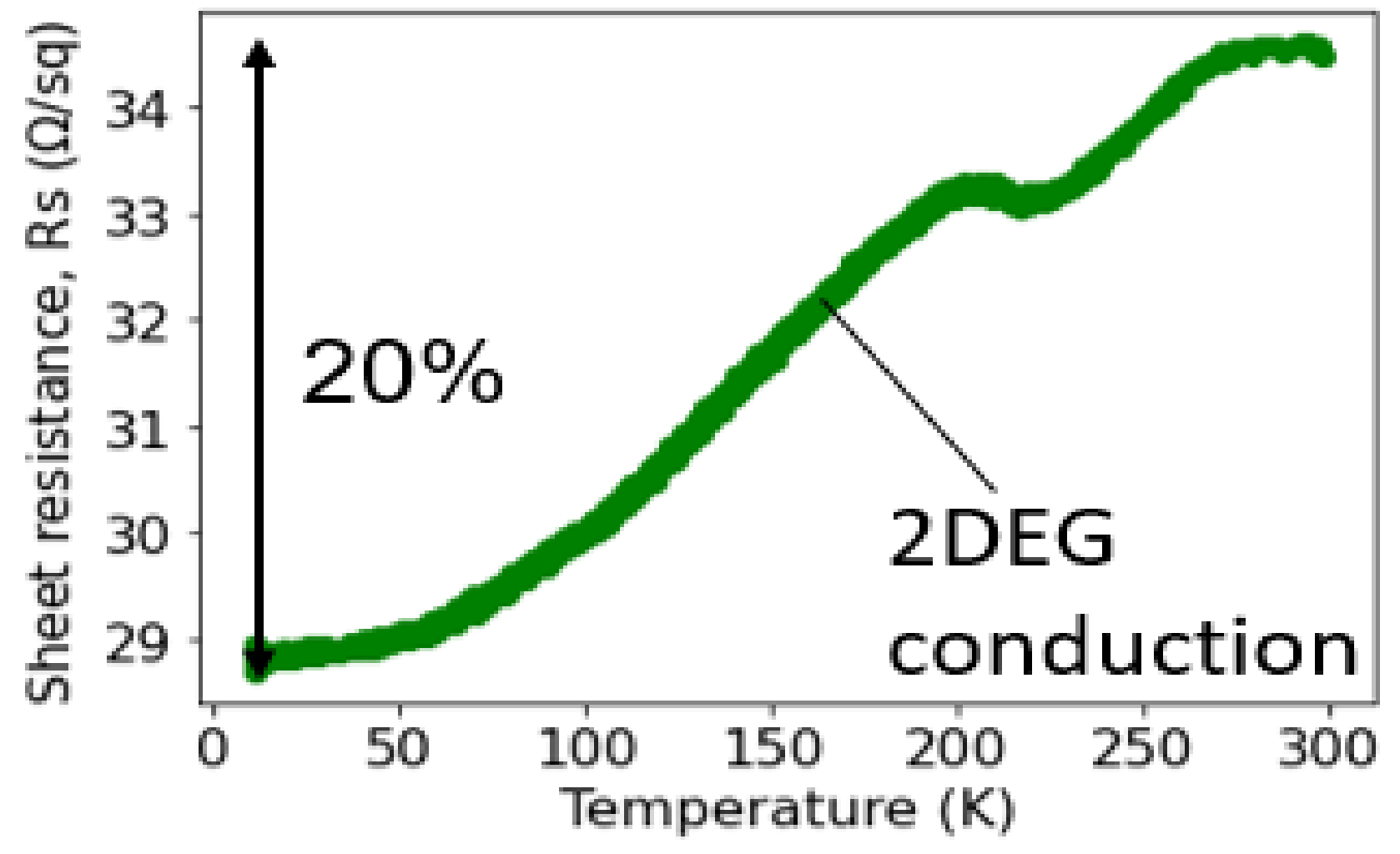
① STO/Ta/NiFe reference sample without 2DEG. Ta layer is not thick enough to enable 2DEG formation.

② For t_{Ta} = 0.4, 0.6 and 1 nm, Ta layer thickness thick enough to allow 2DEG formation → strong contribution of the 2DEG. Ta layer is thin enough to have a weak barrier effect. Both 2DEG and Ta(oxidized)/Py interface contribute to the conversion.
$\Theta^*_{tot} = \Theta^*_{2DEG} + \Theta^*_{Ta/Py\ interface}$

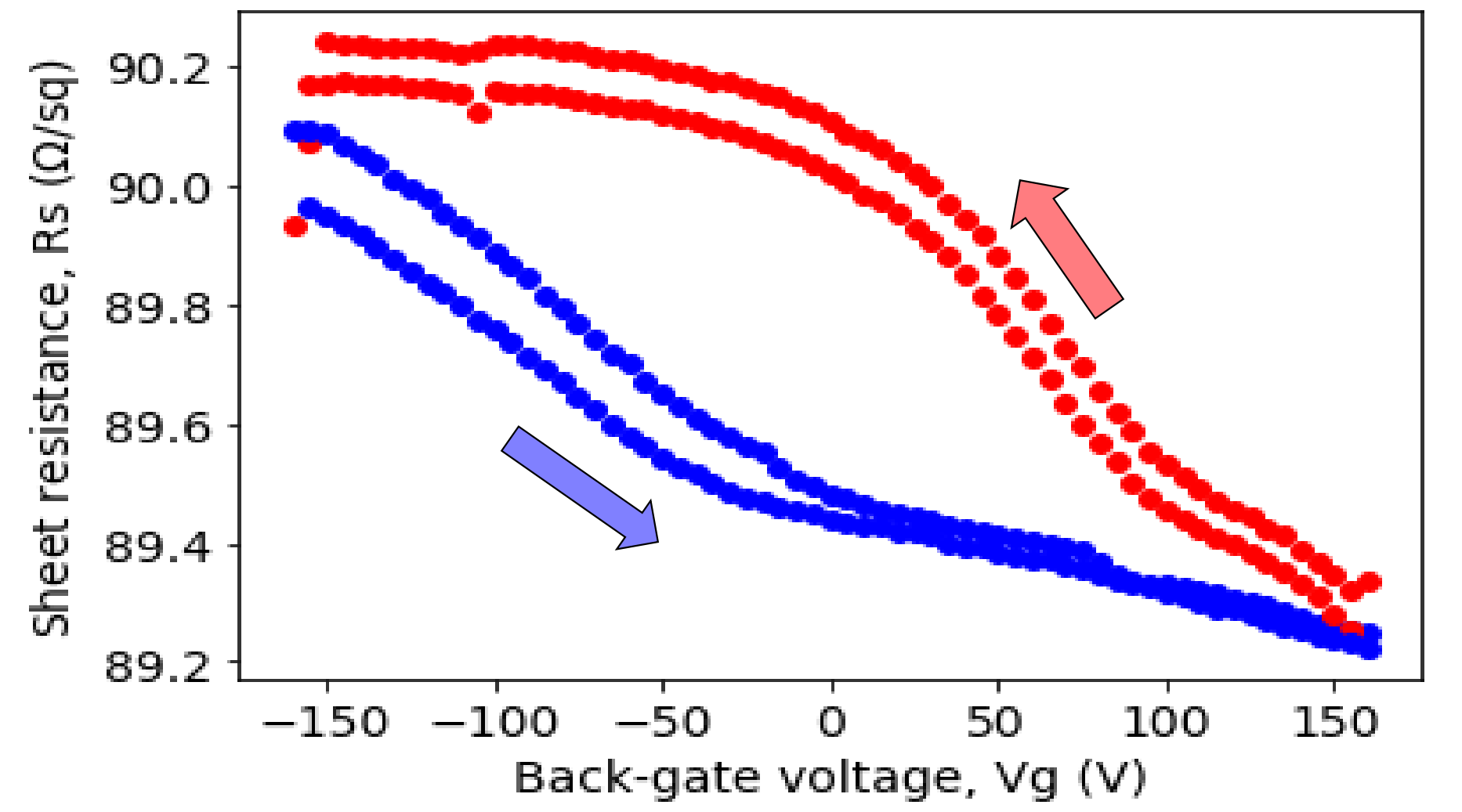
③ High 2DEG contribution to the conversion but thick Ta layer → possible strong barrier effect. Only small part of the conversion in the 2DEG is detected, together with lower conversion at Ta(oxidized)/Py interface due to lower Ta oxidation

2DEG at Ta/STO interfaces

STO/Ta(1nm)/NiFe(10nm)/MgO/Ta



Temperature dependence of the sheet resistance



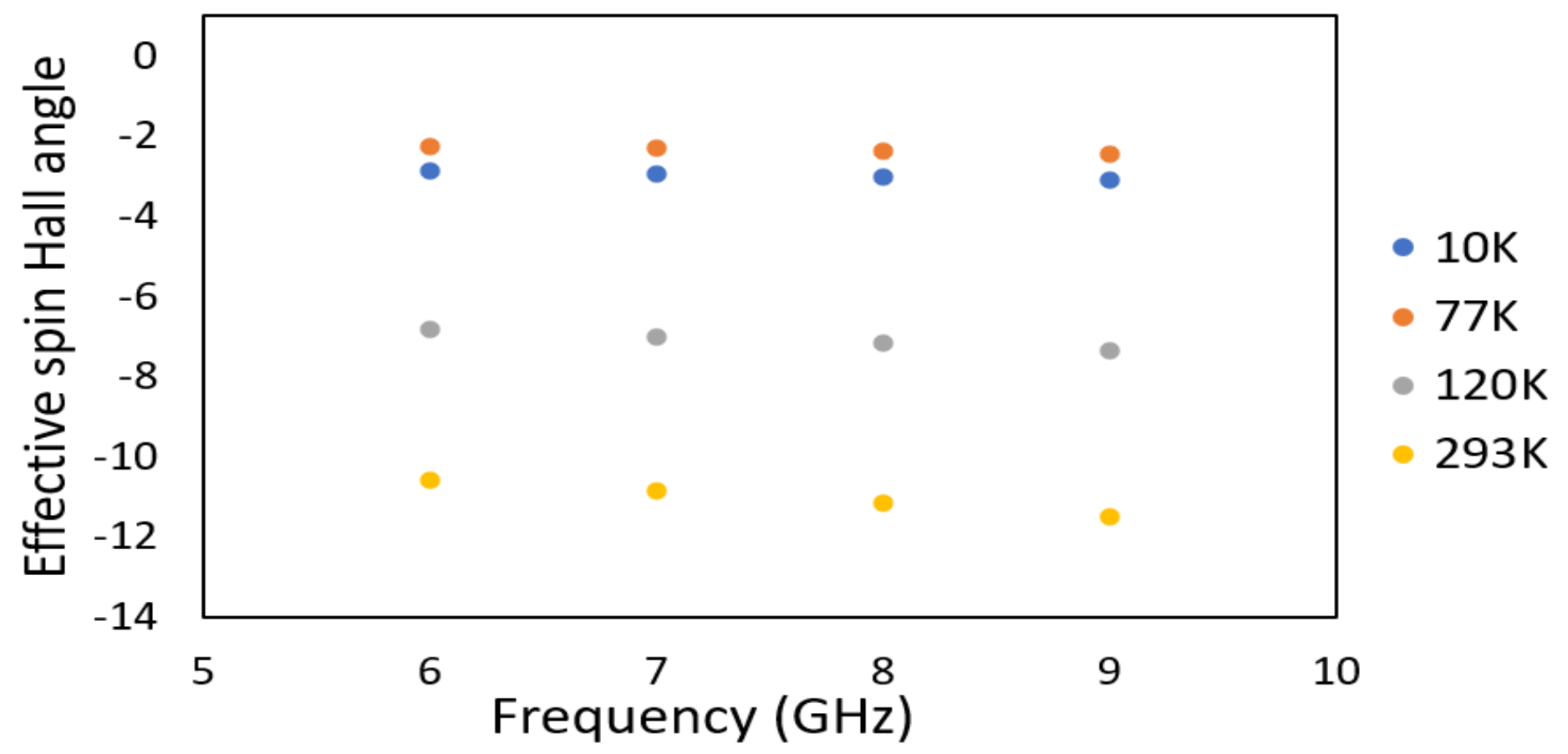
Non-volatile electric-control of the sheet resistance of the 2DEG in ST-FMR devices at 10K

- Decreasing sheet resistance with decreasing temperature → **signature of the 2DEG**

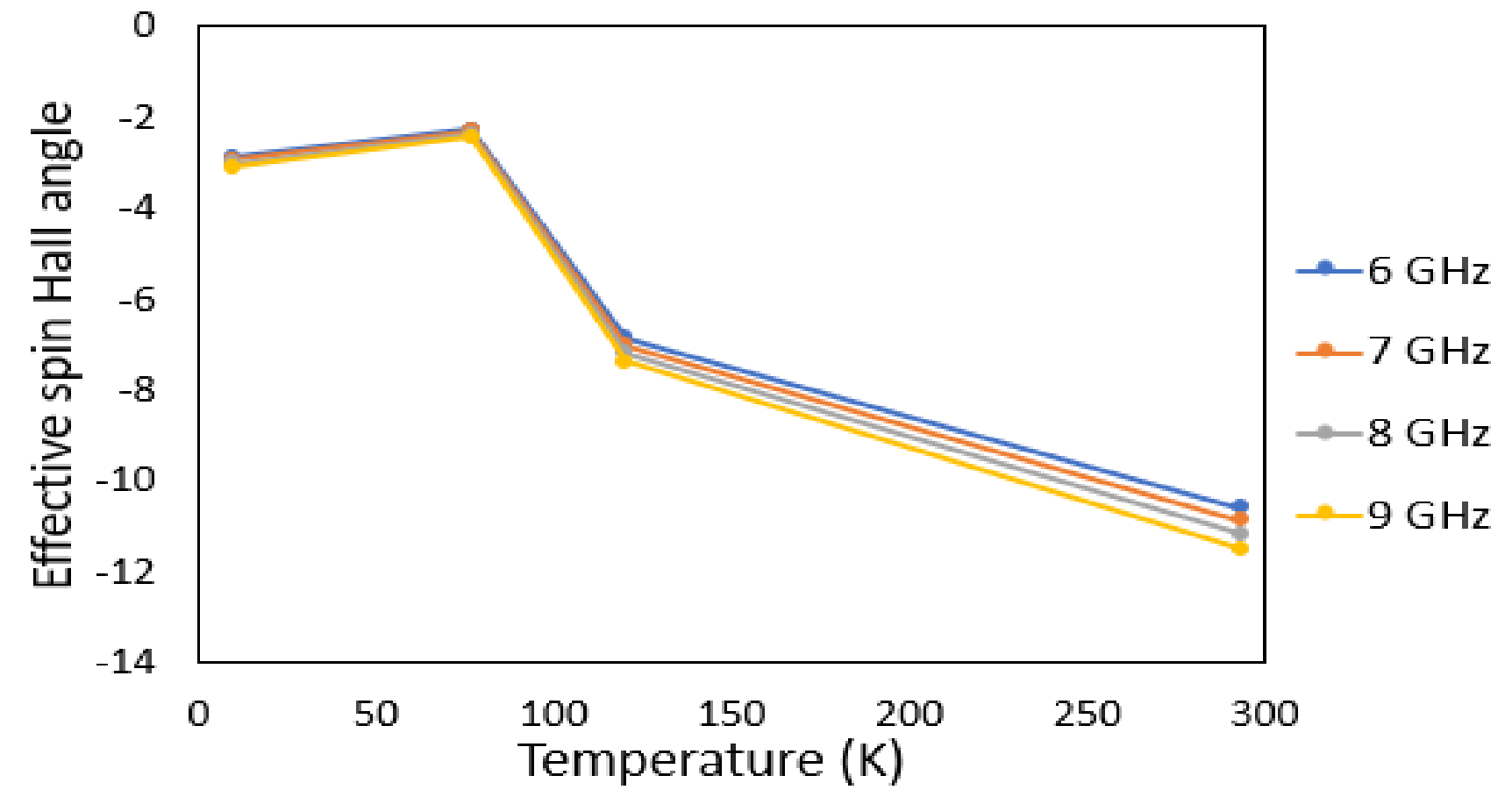
- 2 resistance states :
- Lower state = electron enrichment
- Higher state = electron depletion
- Inversed hysteresis cycle → **Charge trapping**

Preliminary results on temperature dependence

STO/Ta(1nm)/NiFe(10nm)/MgO/Ta



Heterostructure conversion: Effective spin Hall angle versus frequency for different temperatures



Temperature dependence of the heterostructure charge-to-spin conversion

When temperature ↗ :
- 2DEG conductivity ↘ (Fig.1)
- BUT electron energy ↗ → **electron tunneling* through the Ta-barrier**

⇨ **Possible better detection of the charge-to-spin conversion in the 2DEG**

* Y. Wang et al., Nano Lett. 17 (2017)

CONCLUSIONS

- **Spin-orbit torques generated via the ST-FMR technique**
- **Formation of the 2DEG at Ta/STO interface**
- **Increasing 2DEG conductivity with decreasing temperature**
- **Non-volatile electric-control of the 2DEG resistivity by applying a back-gate voltage**
- **Optimum charge-to-spin conversion for t_{Ta} = 1 nm. Good balance requiered:**
  - **if Ta layer is too thin (ex 0,2 nm): no 2DEG creation**
  - **If Ta layer is too thick (ex: 1,5 nm): barrier effect**
- **Effective spin Hall angle increases with increasing barrier thickness from 0.4 to 1 nm**
- **Possible better detection of the charge-to-spin conversion in the 2DEG due to electron tunneling through the Ta-barrier for increasing temperature**

ACKNOWLEDGEMENTS

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