Symposium Spintronics
5-6 december2022

York TOHOKU KAISERSLAUTERN LEEDS Manchester spintec symposium

Challenges for Integrating 2D/TI Materials into SOT-MRAM

G. Talmelli on behalf of SOT-MRAM team

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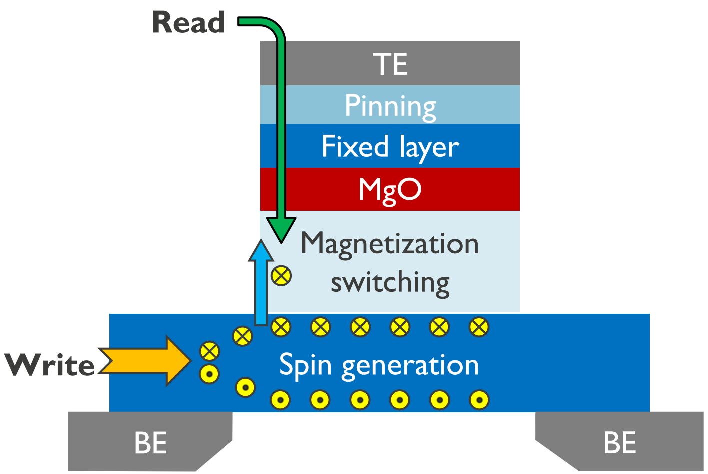
SOT-MRAM introduction



3-terminal device

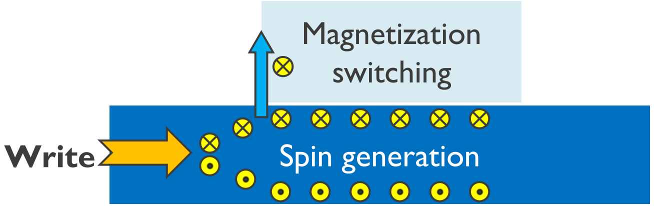
- Separate reading and writing paths
  - Writing mechanism: SOT
  - Reading mechanism: TMR
- Faster switching than STT-MRAM
  - High speed (0.1 - 1 ns)

Main challenge: ***Decrease of switching current → Increase of SOT efficiency***

- Solutions are strongly related to material engineering
- SOT efficiency controlled by SOT track (spin generation), Free layer and their interface
  - Usually quantified using SHA (θ_{SH})

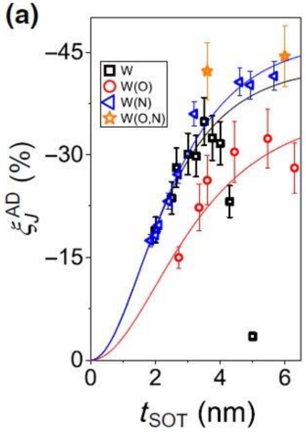
Where do topological insulators fit?

Typical system used: Heavy metal/Ferromagnet



W/CoFeB

SHA = 0.49



K.K.V. Sethu et al., Phys. Rev. Applied 16, 064009 (2021)

Proposal: Replacement of heavy metal with topological insulator (TI)

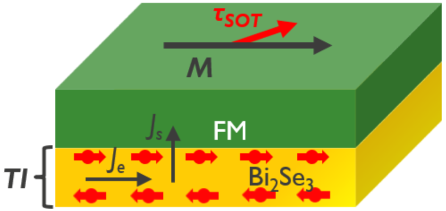


Table 1 | Comparison of room-temperature $\sigma_{s,\parallel}$ and $\theta_{s,\parallel}$ for Bi_2Se_3 with other materials

Parameter	Bi_2Se_3 (this work)	Pt (ref. 4)	β-Ta (ref. 6)	Cu(Bi) (ref. 23)	β-W (ref. 24)
$\theta_{\parallel}$	2.0–3.5	0.08	0.15	0.24	0.3
$\sigma_{S,\parallel}$	1.1–2.0	3.4	0.8	—	1.8

Very high SOT efficiency demo for Bi_2Se_3

A. Mellnik et al., Nature Lett. 511, 449 (2014)

Multiple systems proposed in literature with reported SHA x10 compared to heavy metals

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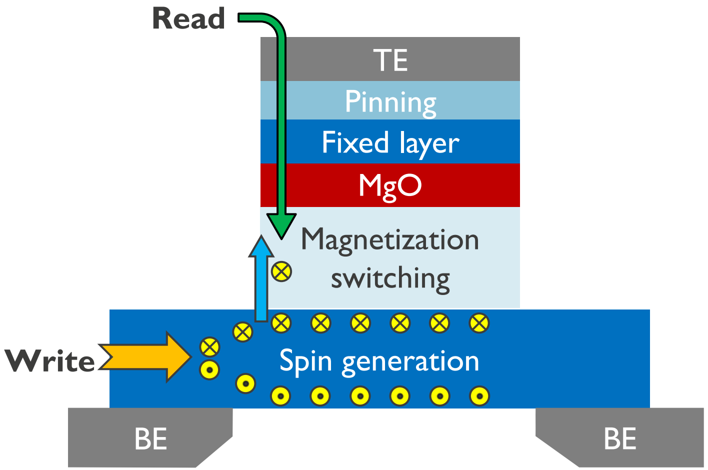
Challenges for TIs



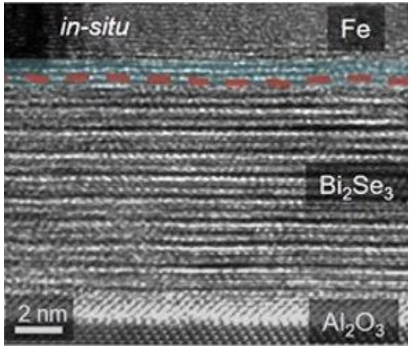
Requirements for SOT-MRAM

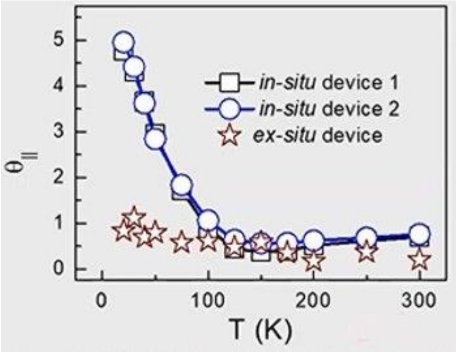
- PMA for Free and Reference layer
  - High TMR and high density
- Sputtering deposition
- 400°C Thermal budget
- Low switching current and power
  - Related to SHA but also SOT track resistivity

Can TI be easily integrated in SOT-MRAM?
Can they satisfy all the requirements?

Deposition technique

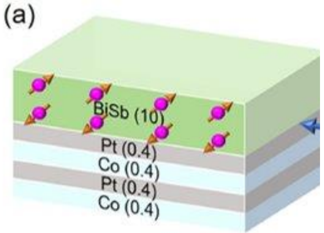
Large majority of TI is deposited via MBE

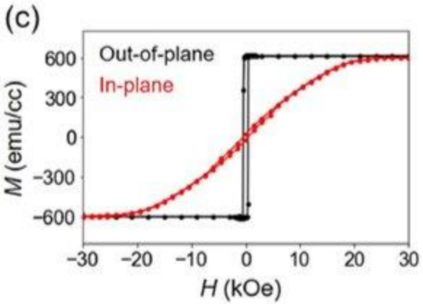




Y. Wang et al., APL 118, 062403 (2021)

First experiments in literature using sputtering





SOT materials	$\|\theta_{SH}\|$
Ta	0.15
Pt	0.08
W	0.4
$(Bi_{0.07}Sb_{0.93})_2Te_3$ (MBE)	2.5
Bi_2Se_3 (MBE)	3.5
Bi_xSei_{1-x} (sputtered)	18.6
$Bi_{0.85}Sb_{0.15}$ (sputtered)	10.7

T. Fan et al., Scientific Reports 12:2998 (2022)

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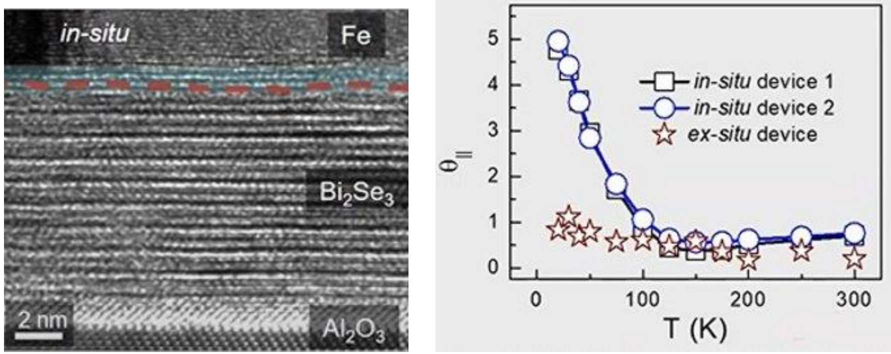

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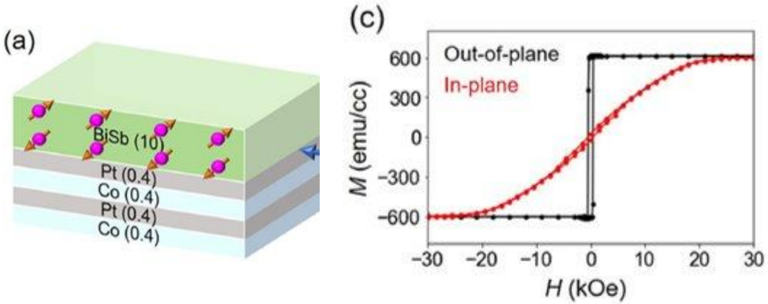

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T. Fan et al., Scientific Reports 12:2998 (2022)

Outline:

- Sputtered Bi_2Se_3 results
- Sputtered $Bi_{0.9}Sb_{0.1}$ results
- Ab-initio simulations

Deposition technique

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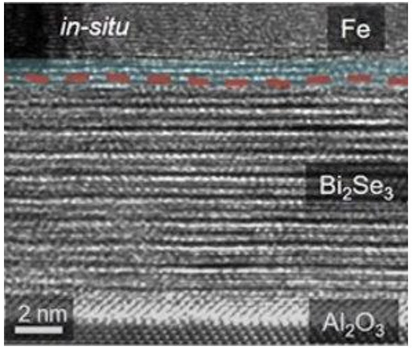

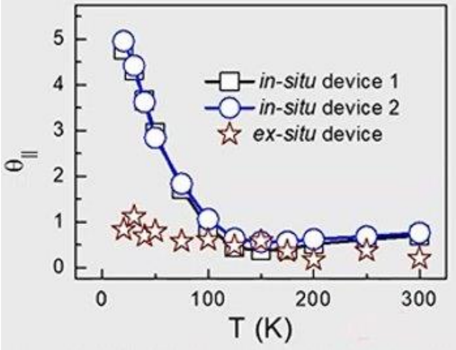

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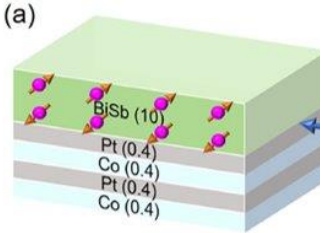

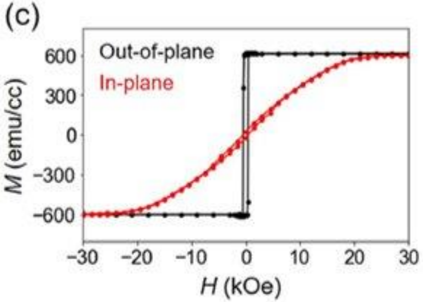

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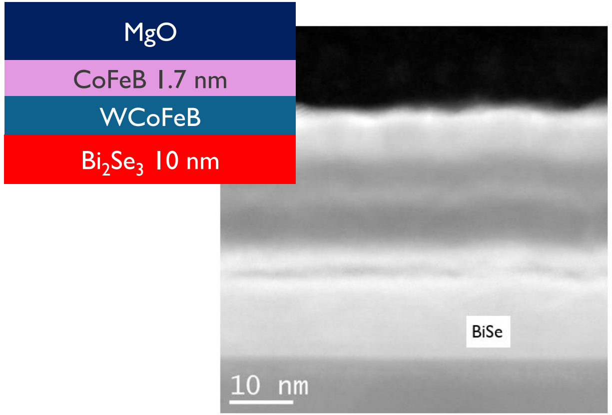
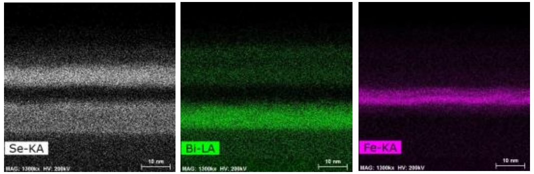
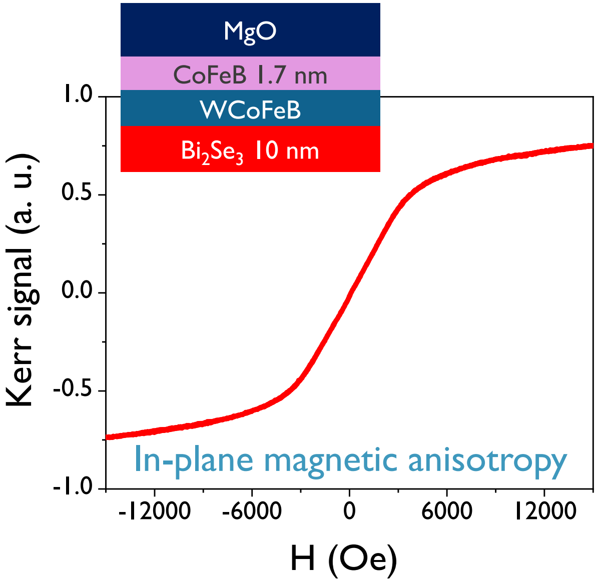
Bi_2Se_3 film exploration



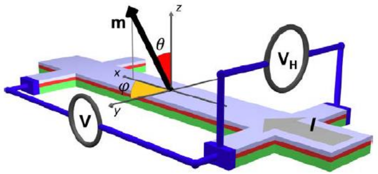


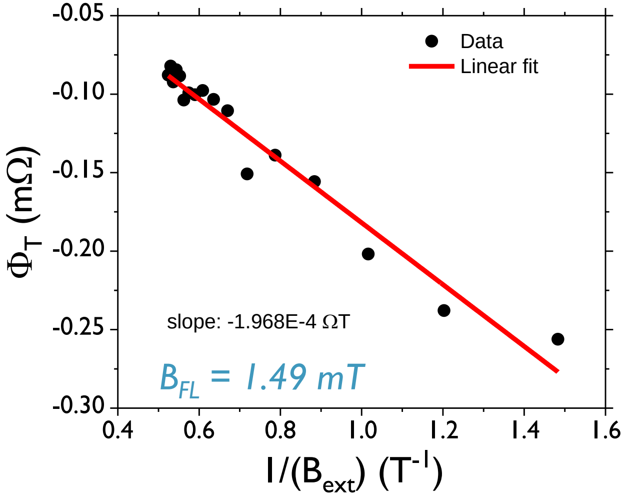
Polycrystalline layer

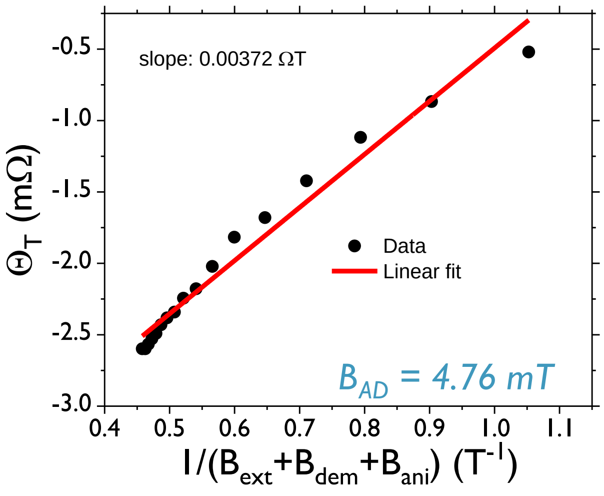
Magnetic properties



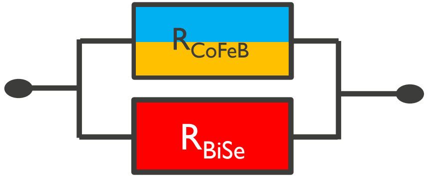
2nd Harmonic voltage







Parallel resistor model



ρ_{BiSe} = 600 μΩ.cm

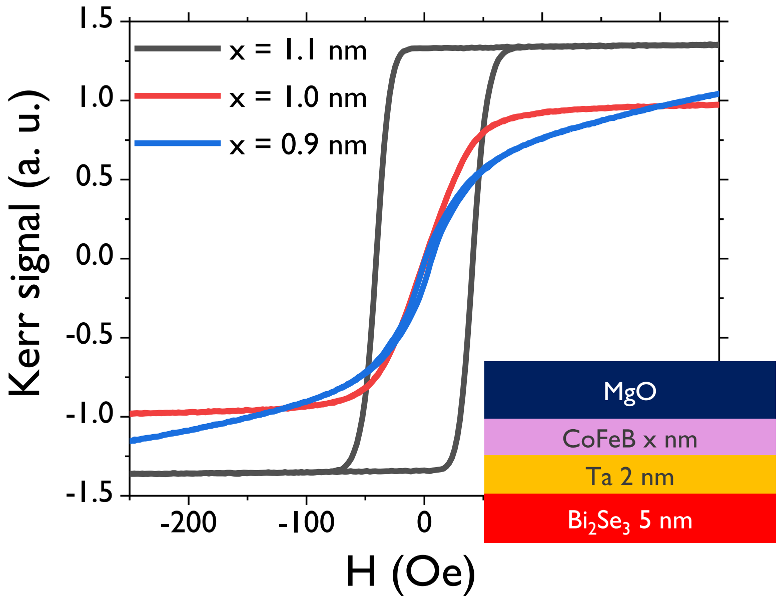
Spin Hall angle of 1.3

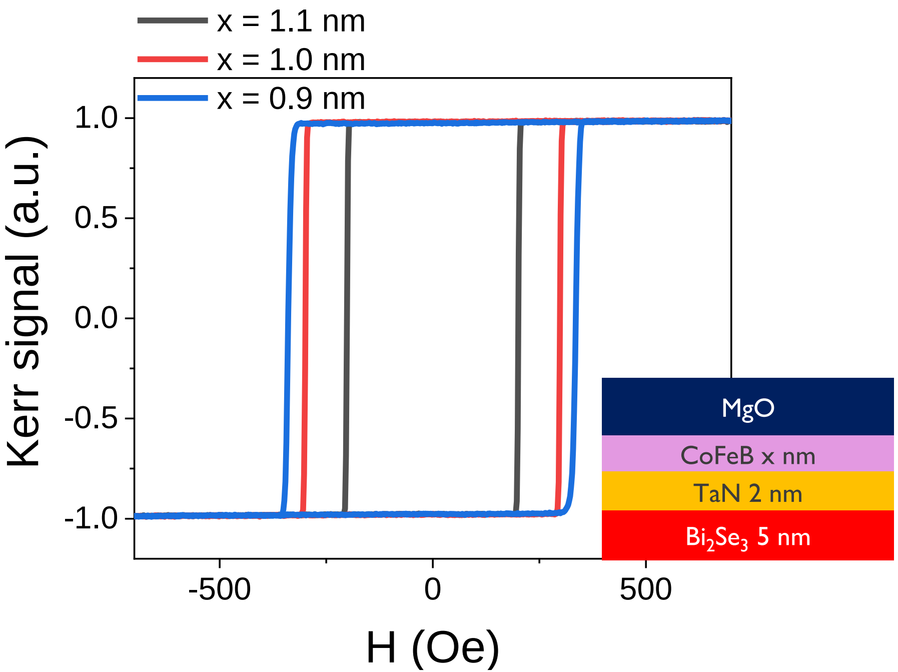
Effective SHA (J_{total}) = 0.75

Estimation of current through Bi_2Se_3 → **SHA**

All current through Bi_2Se_3 → **effective SHA**

Perpendicular magnetic anisotropy

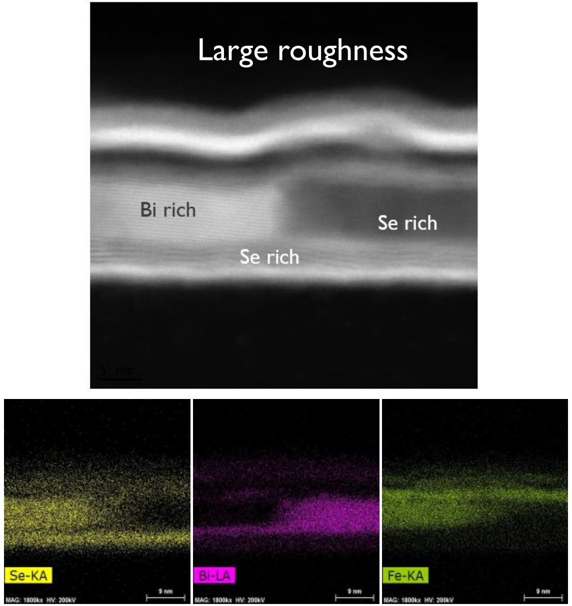




Both Ta and TaN spacers lead to PMA…
…but also to negative SHA related to those layers

Thermal budget

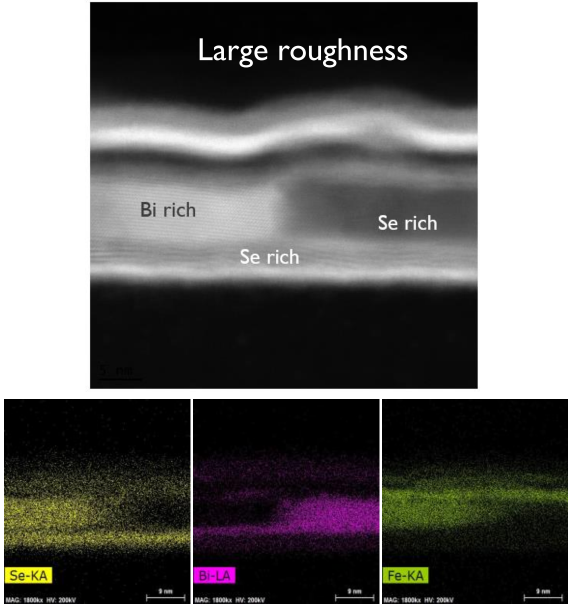
300°C annealing



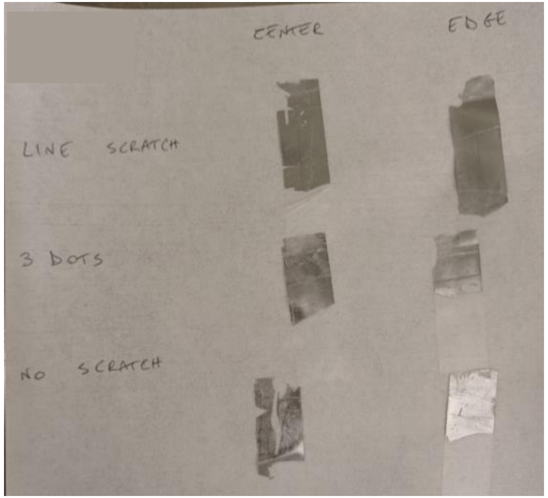
Strong diffusion observed in Bi_2Se_3 due to annealing!

Thermal budget

300°C annealing



Adhesion issues



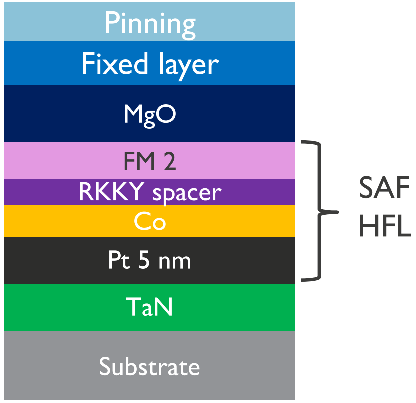
Can be solved using TaN

Strong diffusion observed in Bi_2Se_3 due to annealing!

Leads to loss of magnetic properties and delamination, preventing device fabrication

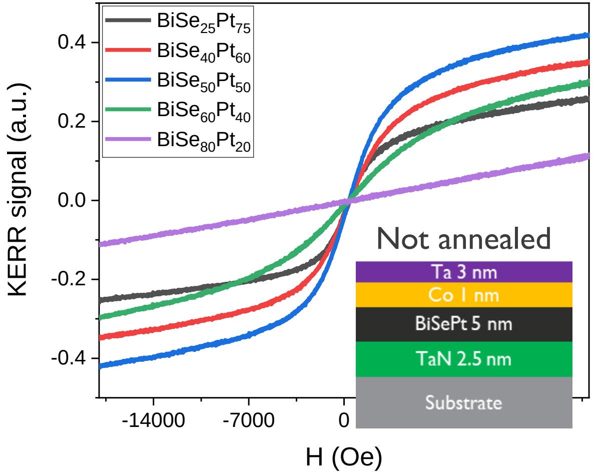
BiSe/Pt multilayers and alloys results

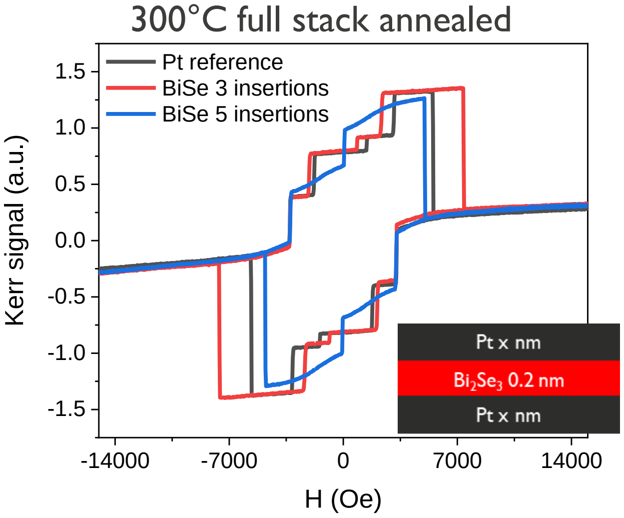
- Pt/Co interface leads to PMA
  - Compatible as SOT track/FL in SAF-HFL systems
- Integration of BiSe in 300°C compatible stack
  - Magnetic layers are not changed, only SOT track material
    - Total thickness kept constant to 5 nm



S. Couet, VLSI 2021 (2021)

Different choices for integration of BiSe/Pt





Loss of PMA for BiSe content larger than 20%

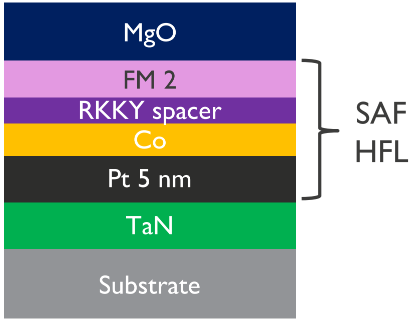
Adhesion issues happen as well above 25% content

BiSb exploration

Integration with SAF-HFL

Same approach of BiSe case

Reference stack

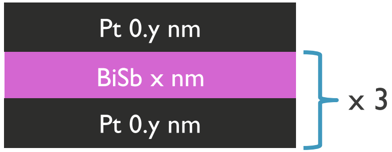


Pt replaced with:

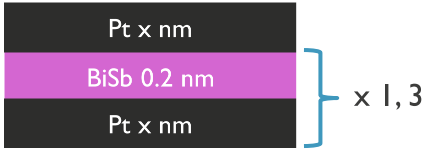
TI material only

BiSb/Pt multilayers

Thick BiSb



Thin BiSb



Total thickness of SOT track kept to 5 nm

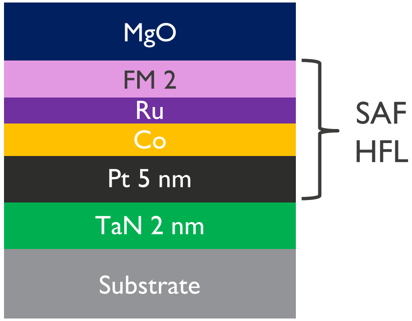
All samples annealed at 300C

BiSb exploration

Magnetic properties

Same approach of BiSe case

Reference stack



Pt replaced with:
TI material only

BiSb/Pt multilayers

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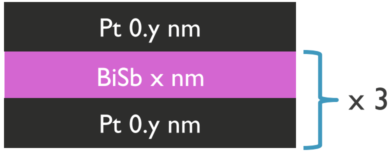
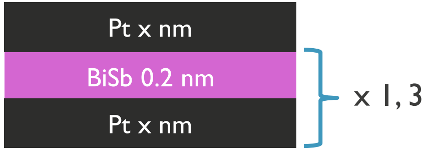


Thin BiSb



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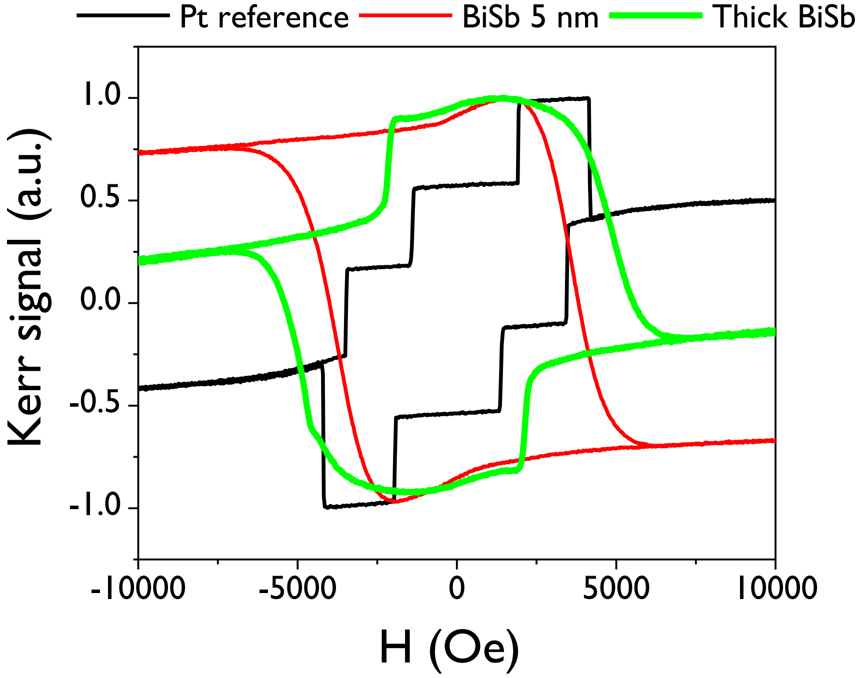

BiSb incorporation severely damages MTJ magnetic properties

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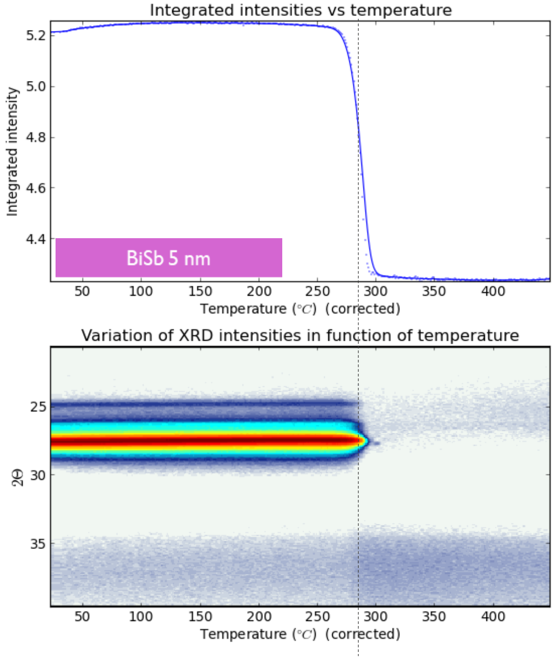
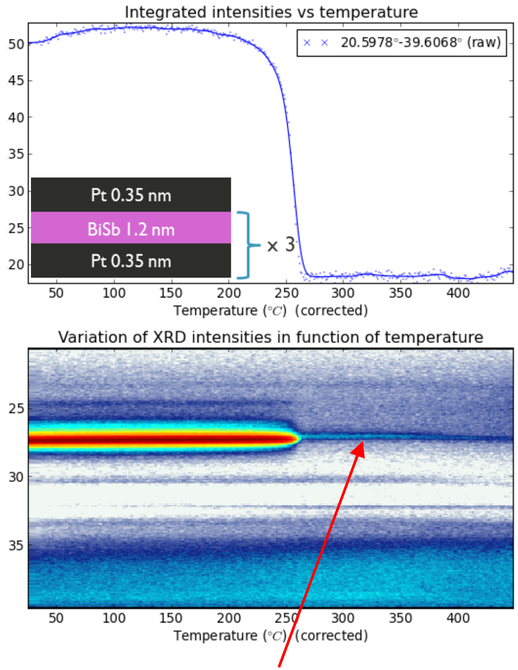
Courtesy of K. Opsomer
Gent University

In-situ-XRD – temperature dependence

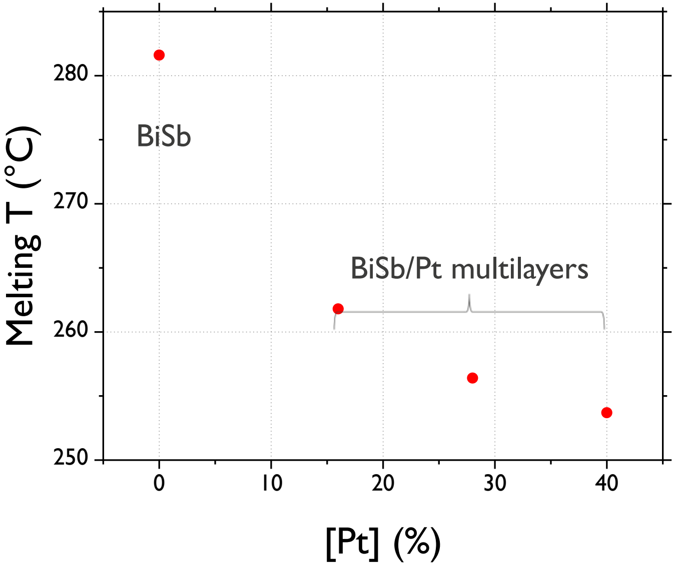


Melting T



Smaller BiSb peak above 300C?

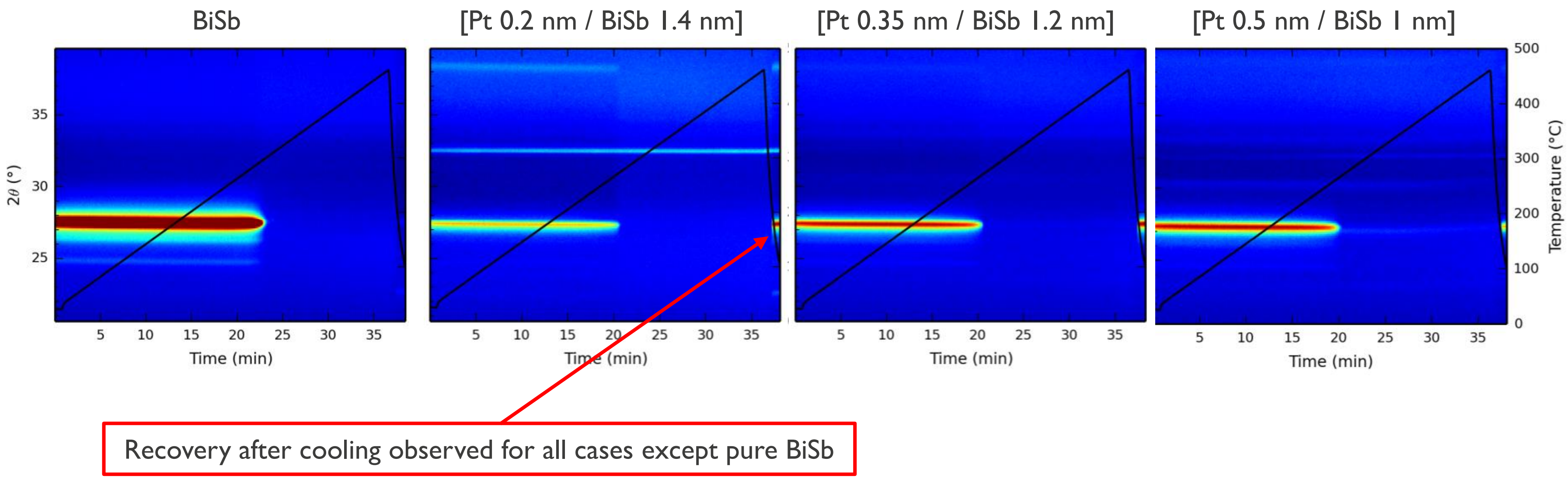
Slight decrease of melting T with Pt concentration



Melting temperature consistently below 300C

In-situ-XRD – time dependence

Courtesy of K. Opsomer
Gent University



Recovery after cooldown observed for BiSb multilayers

Is the recovery an indication that we can recover the SOT track after annealing?

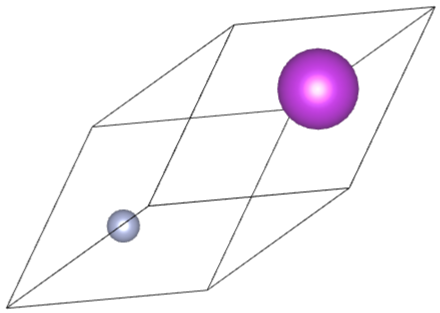
Courtesy of B. Van Troeye, K. Sankaran, G. Pourtois

Ab-initio simulations for next Bi-alloys

Goal: Increase thermal stability by increasing melting temperature

Two different proposals:

- Alloys containing elements of the same column than Bi in the periodic table
  - Assumption: Same crystalline structure is kept up to 50% of the sites substituted
- Identification of materials with high cohesion energies, without oxygen or sulfur elements, halogens and alkalines
  - From Material project database (Jainet al., APL Materials 1, 011002 (2013))



$$E_{coh} = N^{(1)}E_{at}^{(1)} + N^{(2)}E_{at}^{(2)} - E^{(1+2)}$$

Energy of isolated atom

Energy of crystal

DFT simulations considering:

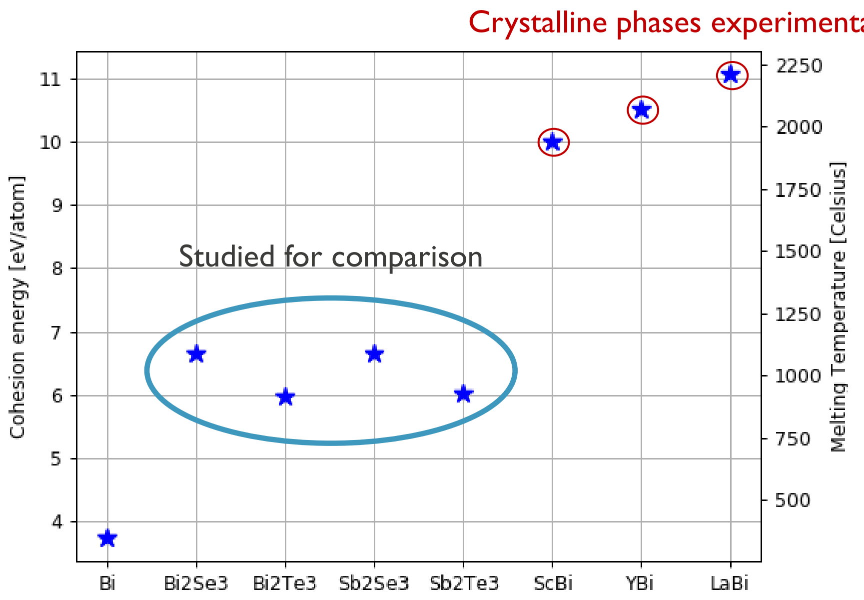
- exchange-correlation GGA-PBEsol
- pseudopotentials "Optimized Norm-Conserving Vanderbilt Pseudopotential”
- No spin and spin-orbit coupling

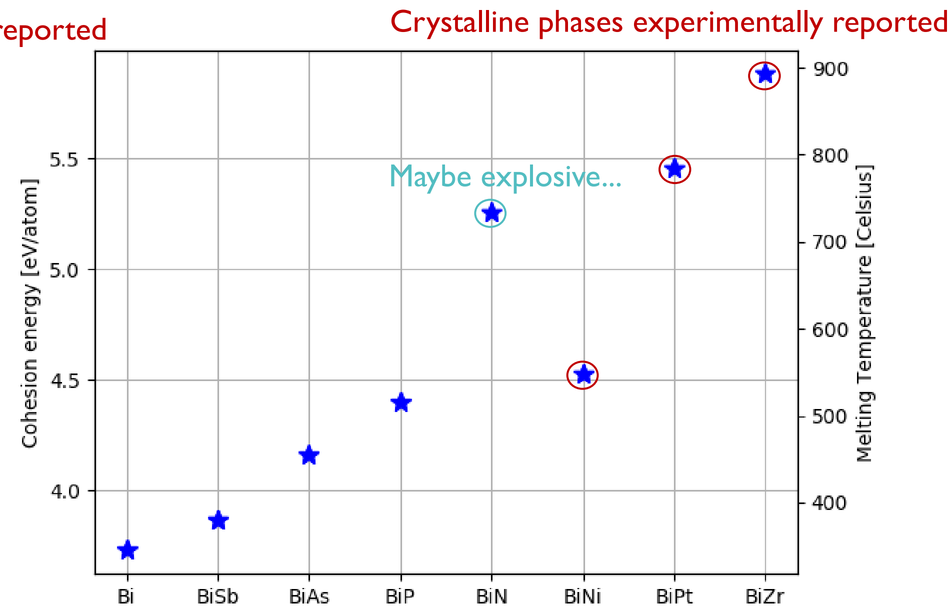
Computed quantity: cohesive energy

~ Empirical linear relationship between cohesive energy and melting temperature

Results

Courtesy of B. Van Troeye,
K. Sankaran, G. Pourtois





From computation several interesting materials came out to increase thermal budget

Apart from known Tis, other alloys show metallic behavior

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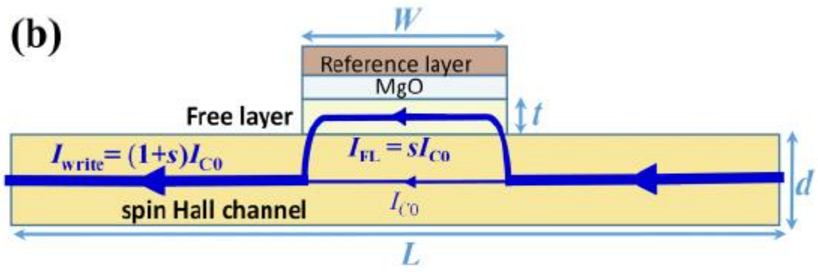
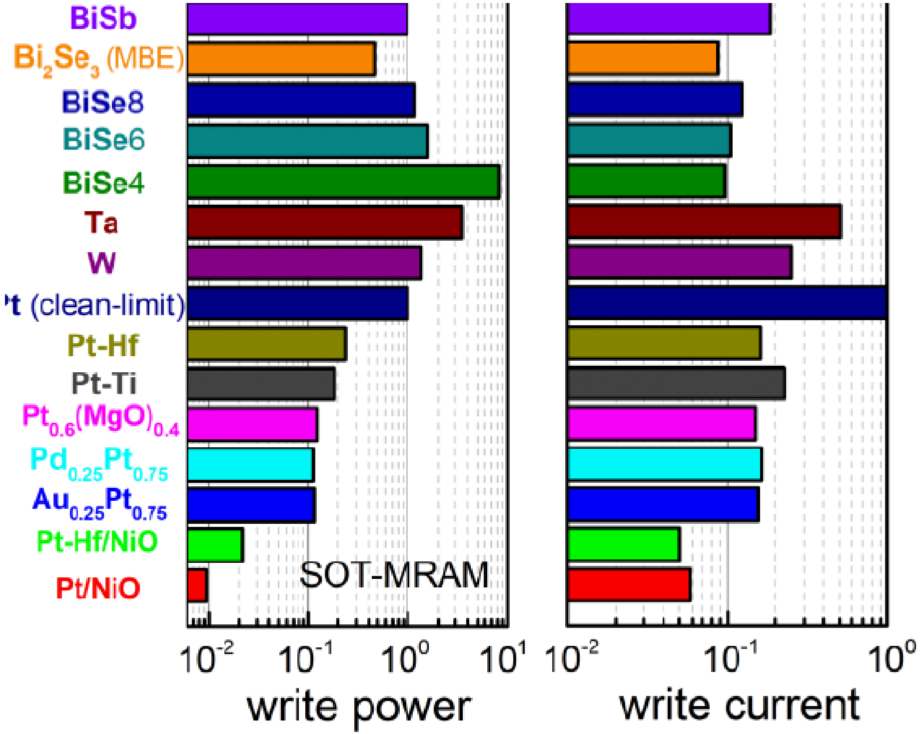
Switching efficiencies

Simplified model for estimation of current and power for switching considering current shunting in the FL



L. Zhu et al., Applied Physics Reviews 8, 031308 (2021)



Performance for TI and Pt/X are quite similar
Due to high resistivity power gain is lower than expected

Conclusion

- TIs represent an interesting class of materials for SOT-MRAM thanks to their high SHA but many challenges are left
  - Growth of PMA ferromagnets on high quality TIs deposited via sputtering
  - Bi diffusion due to thermal treatment leading to loss of PMA and delamination
  - High resistivity leading to current shunting and high power consumption
- Similar issues are found both in Bi_2Se_3 and BiSb
  - Polycristalline BiSe/CoFeB still has SHA x3 compared to W/CoFeB
  - Alloying the materials with Pt doesn't solve the challenges

Thanks to

D. Costa, K. Opsomer, B. Van Troeye, W. Janssens,
K. Sankaran, G. Pourtois, R. Carpenter and S. Couet

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