Magnetic studies of epitaxial thin films of noncollinear Weyl antiferromagnet Mn_3Sn

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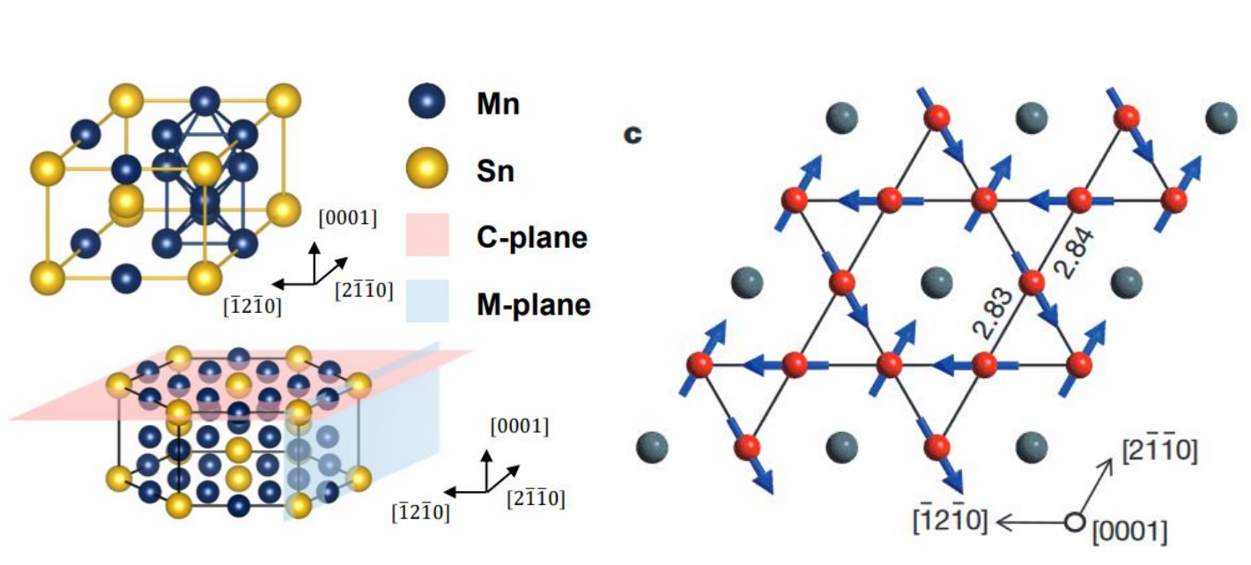
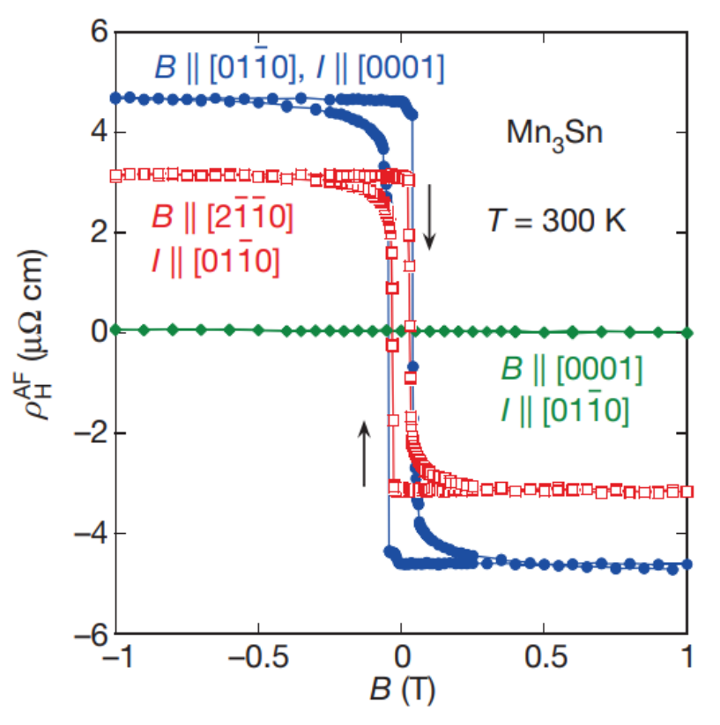
Introduction

A unique spin structure of the non-collinear antiferromagnetic (AFM) Mn_3Sn has been known for decades, but only relatively recent studies have shown that this highly advantageous AFM host offers FM-like properties [1]. A number of inspiring spintronics functionalities have been documented in epitaxial Mn_3Sn thin films [2], however, for further exploration comprehensive characterization of the material is of a great importance. The spin structure of Mn_3Sn is the result of a fine balance between exchange and Dzyaloshinskii-Moriya interactions, and magnetic anisotropy. Therefore, even minute changes in the structure of the material have a great impact. Magnetometry is an indispensable investigation tool here, however AFM thin layers pose a formidable challenge. Due to nearly perfect moment cancelation and very small volumes of the thin layers their magnetic signals are at the verge of practical limits of standard volume magnetometry. The situation worsens by the unavoidable presence of bulky substrates, supporting the thin films. For example, magnetic response of MgO substrates alone strongly confuses the response of Mn_3Sn layers.

Non-collinear antiferromagnetic Mn_3Sn

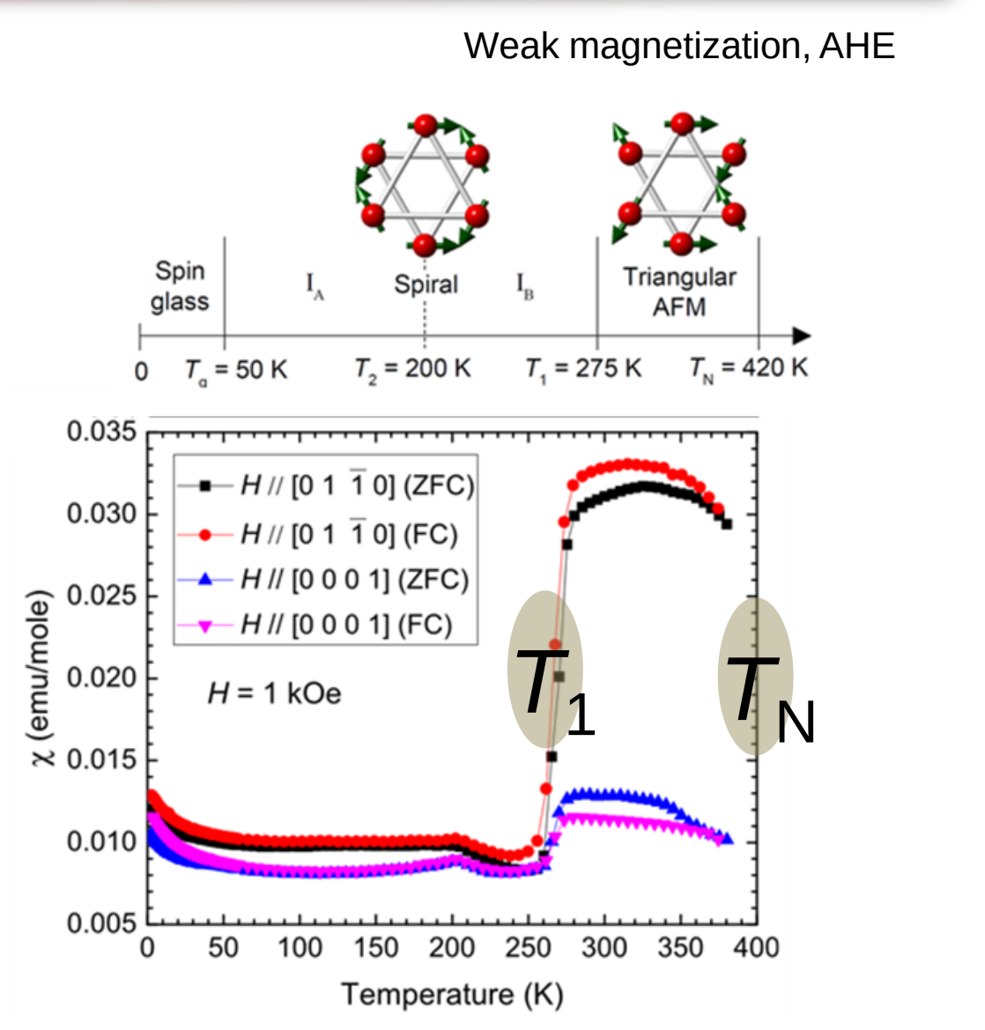


D0_{19} crystal structure with the chiral-spin structure in kagome lattice-plane [1]



Magnitude of anomalous Hall effect comparable with ferromagnet [1]

Weak magnetization, AHE



Magnetic studies in wide temperature range indicative of a spin glass, spiral, and inverse kagome triangular AFM phases [3].

EXPERIMENTAL

Magnetometry studies of thin AFM layers

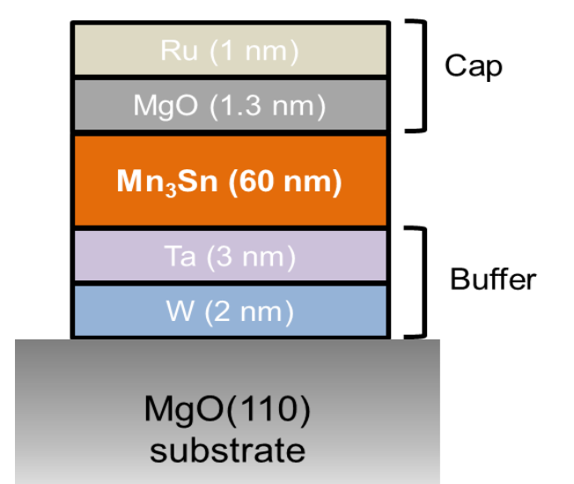
Challenge:

Mn_3Sn layers (10 – 100 nm) – weak magnetic response

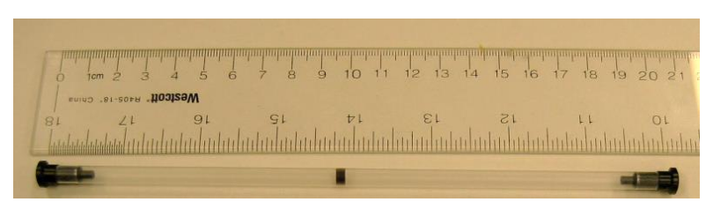
MgO substrates (0.5 mm) – strong magnetic response

- Diamagnetism of MgO lattice
- Paramagnetism (PM) – unintentional Fe dopant vary between samples (MgO substrates)

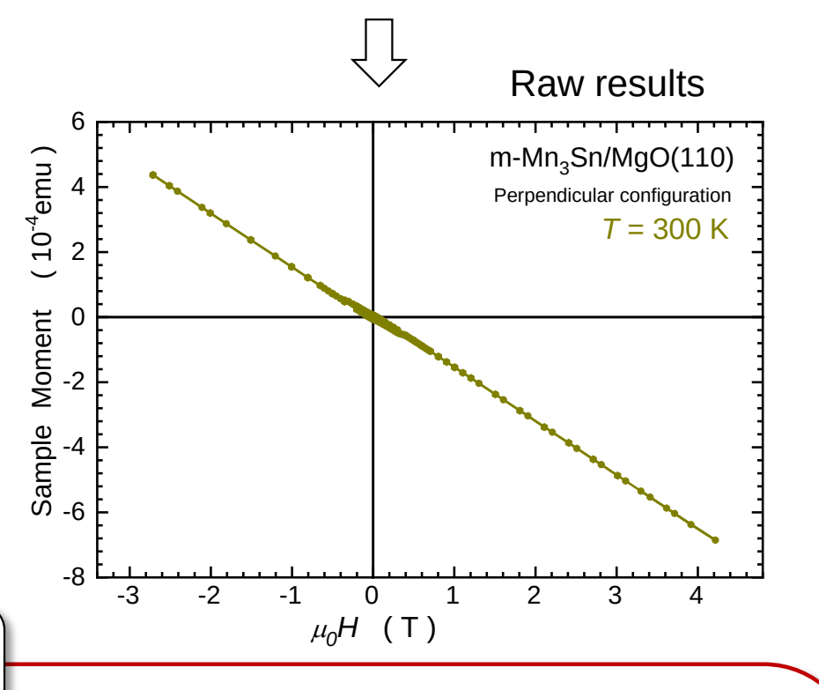
a general (universal) reference substrate sample cannot be used



Integral magnetometry
signal from bulky substrate and the layer of interest is measured at the same time.

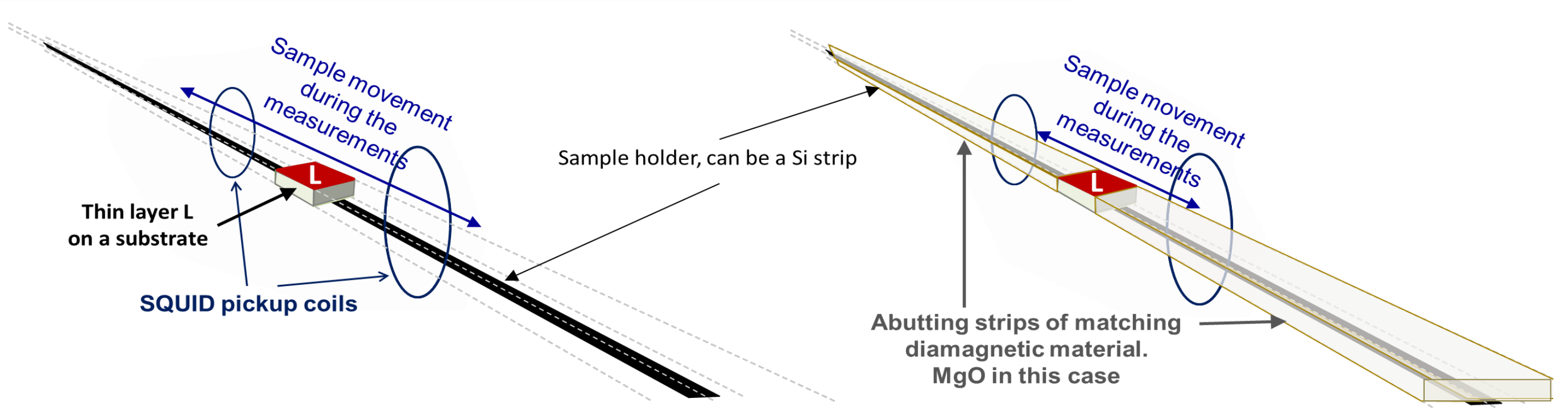


Drinking straws – the standard sample holders for MPMS magnetometer **(not applicable here)**

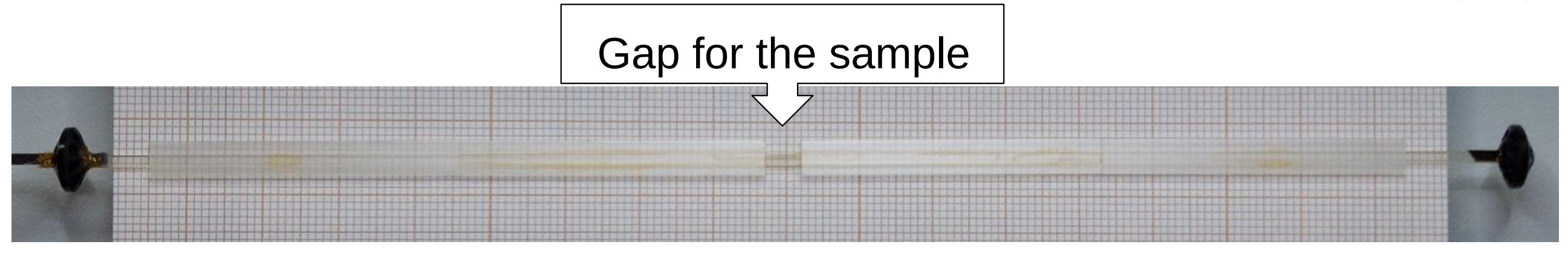


Our method of choice: *in situ* compensation [4]

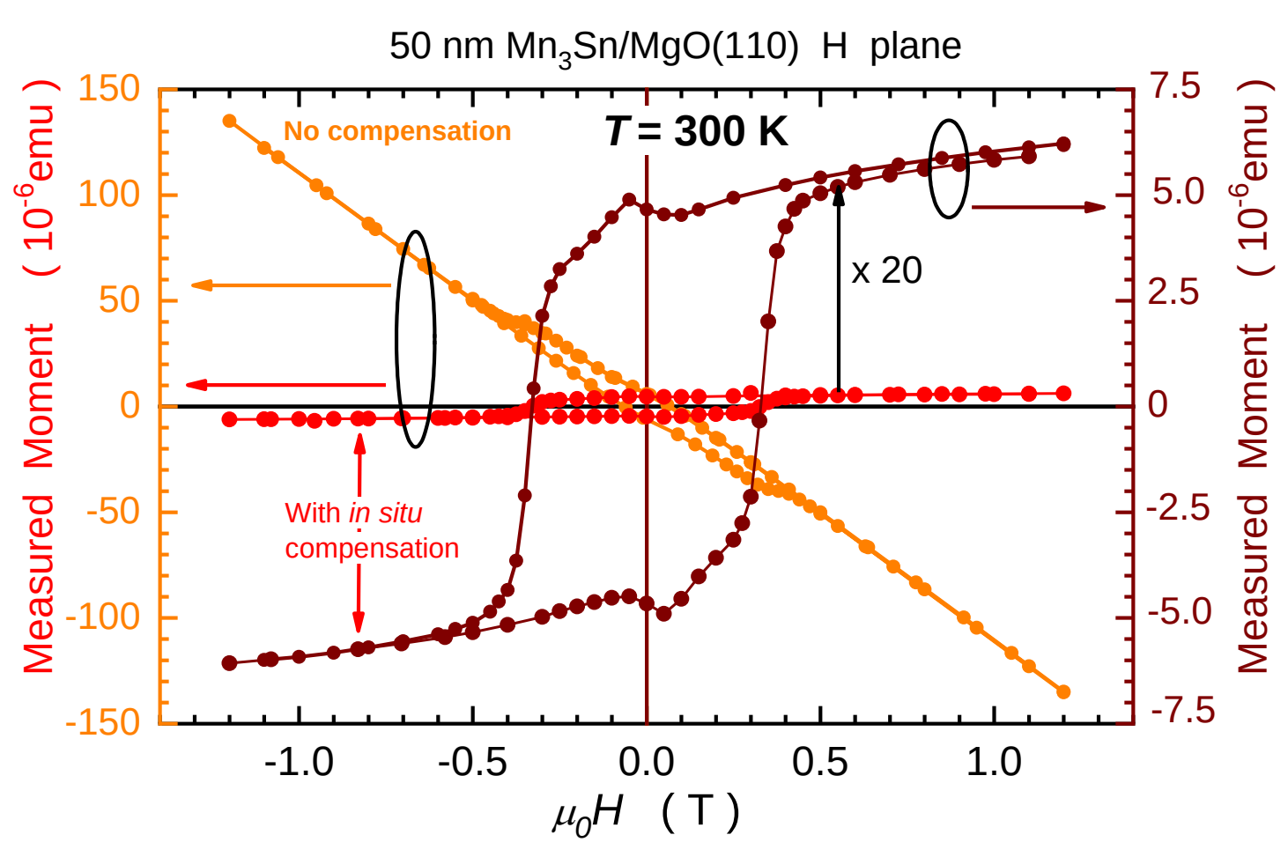
Basic concept:



Final assembly:
(a home made device)

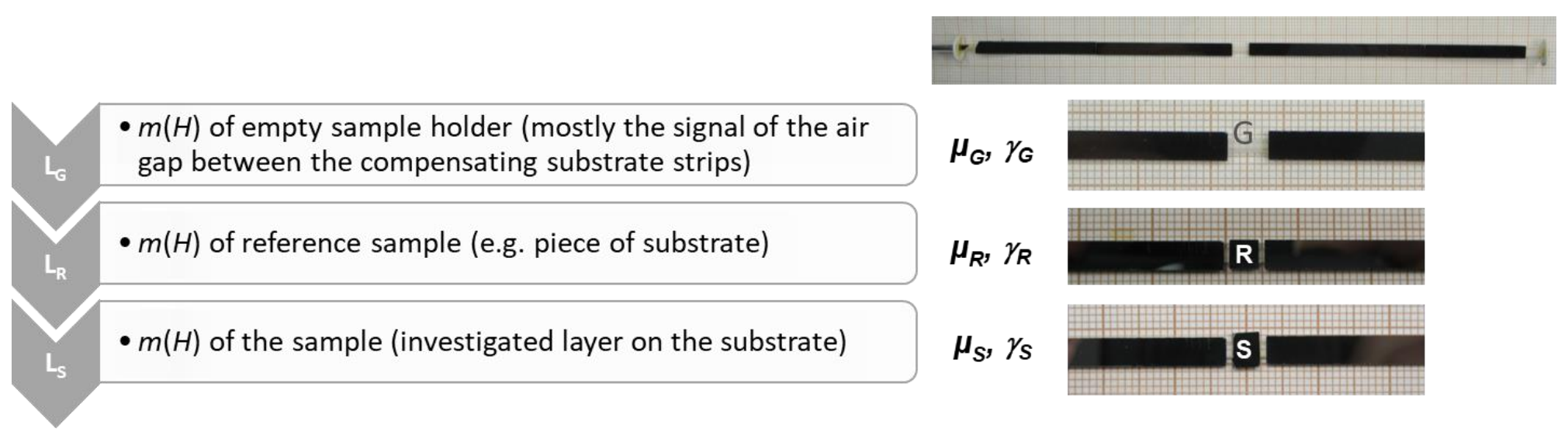


In situ compensation of the diamagnetic background of the substrate – a 10-fold reduction of the substrate signal ⇒ **increased sensitivity and credibility of measurements**



We end up with a more reliable result which almost straightforwardly yields a signal of the deposited magnetic stack is established.

In general 3 measurements are needed:



- $m(H)$ of empty sample holder (mostly the signal of the air gap between the compensating substrate strips)
- $m(H)$ of reference sample (e.g. piece of substrate)
- $m(H)$ of the sample (investigated layer on the substrate)

$$L_X\gamma_X = L_S - L_R - \beta L_G$$

$$\beta = \frac{\mu_R\gamma_R - \mu_S\gamma_S}{\mu_G\gamma_G}$$

Different masses **μ**, dimensions and shapes of the gap and the samples – different the strength of the coupling with SQUID pick-up coils. The correction factors **γ** has to be taken into account!

Conclusions

Magnetometry

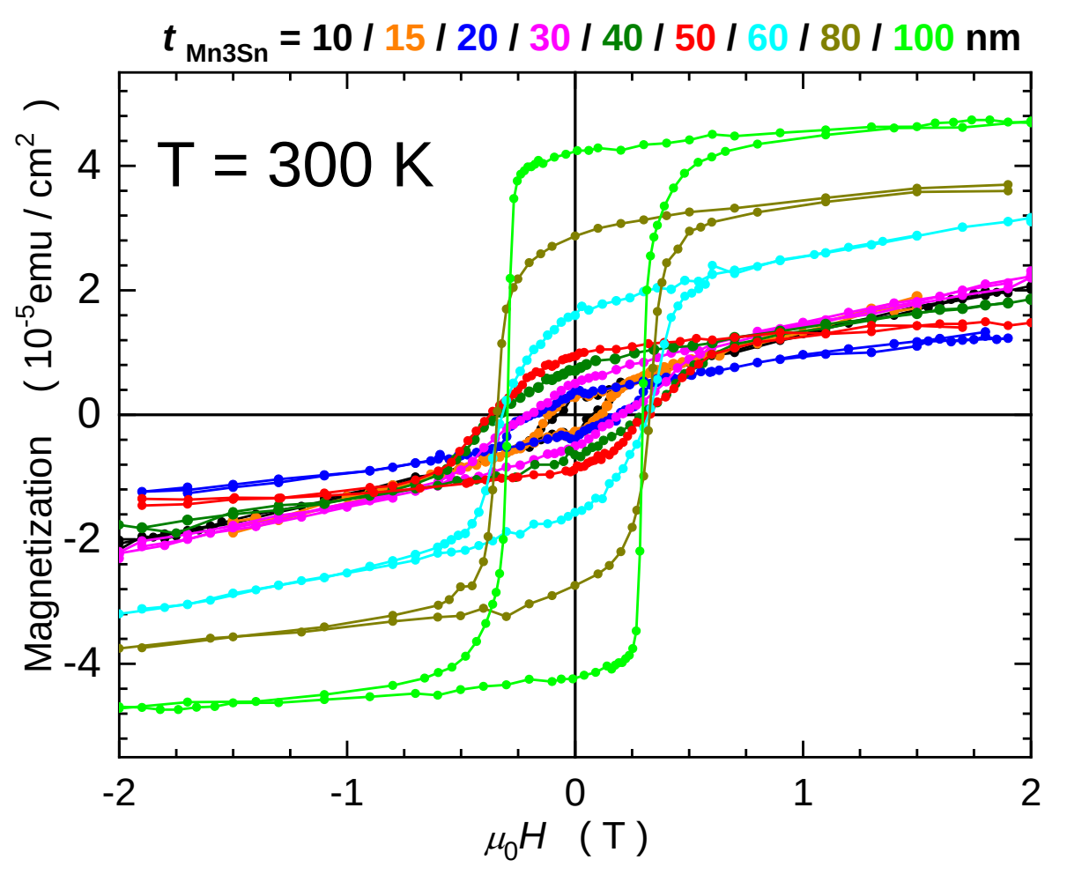
- A detailed knowledge about the magnetic properties of the substrates supporting thin magnetic layers of interest is important in precise volume magnetometry, but becomes a „must have” commodity in the case of antiferromagnetic layers, when magnetic signals to detect are very weak.
- Epi-ready MgO substrates contain undesirable magnetic properties such as **a paramagnetic** component, strongly a straightforward volume magnetometry of thin layers (few tens of nm) of canted Mn_3Sn and other antiferromagnetic compounds.
- **Basic *in situ* compensating approach** offers at least 10-fold reduction the magnetic signal of the substrate.

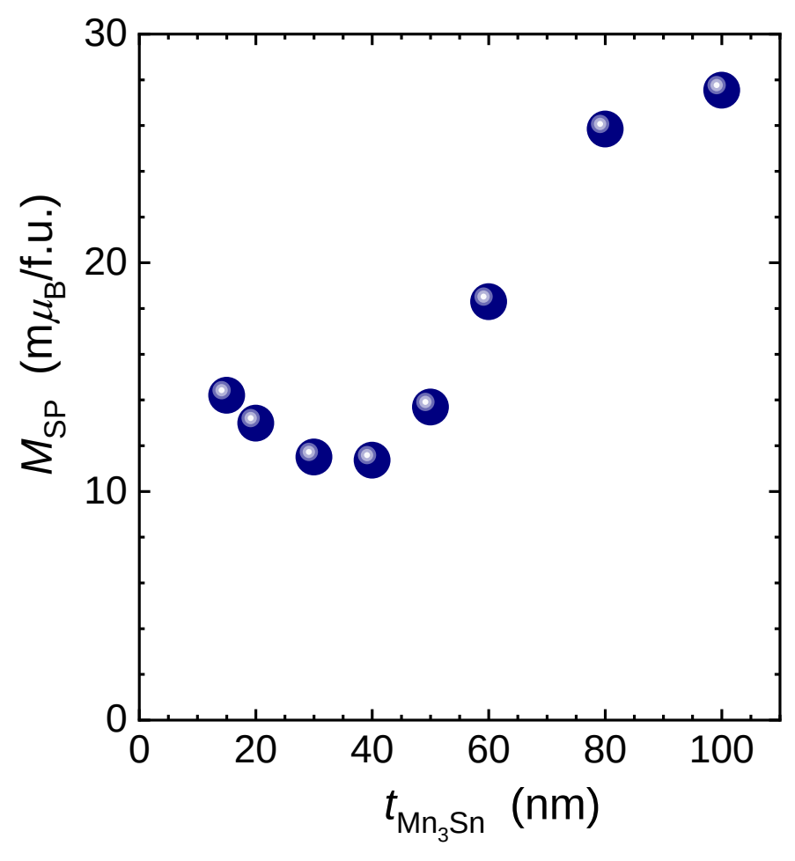
Magnetization of Mn_3Sn thin layers

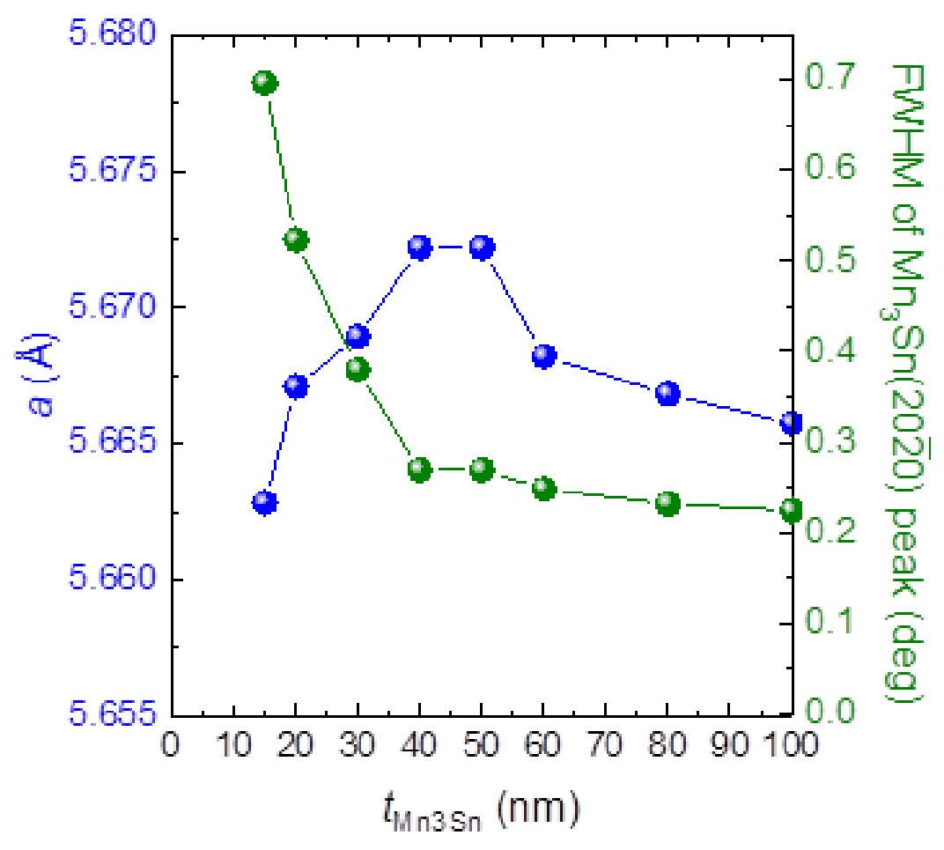
- Spontaneous magnetization at 300 K correlates with the inverse of the basal plane *a* lattice parameter.
- The Néel temperature in thin Mn_3Sn layers is consistently lower than in bulk Mn_3Sn.
- T_N and T_1 increase with the layer thickness due to improvement of the crystalline quality.

RESULTS & DISCUSSION

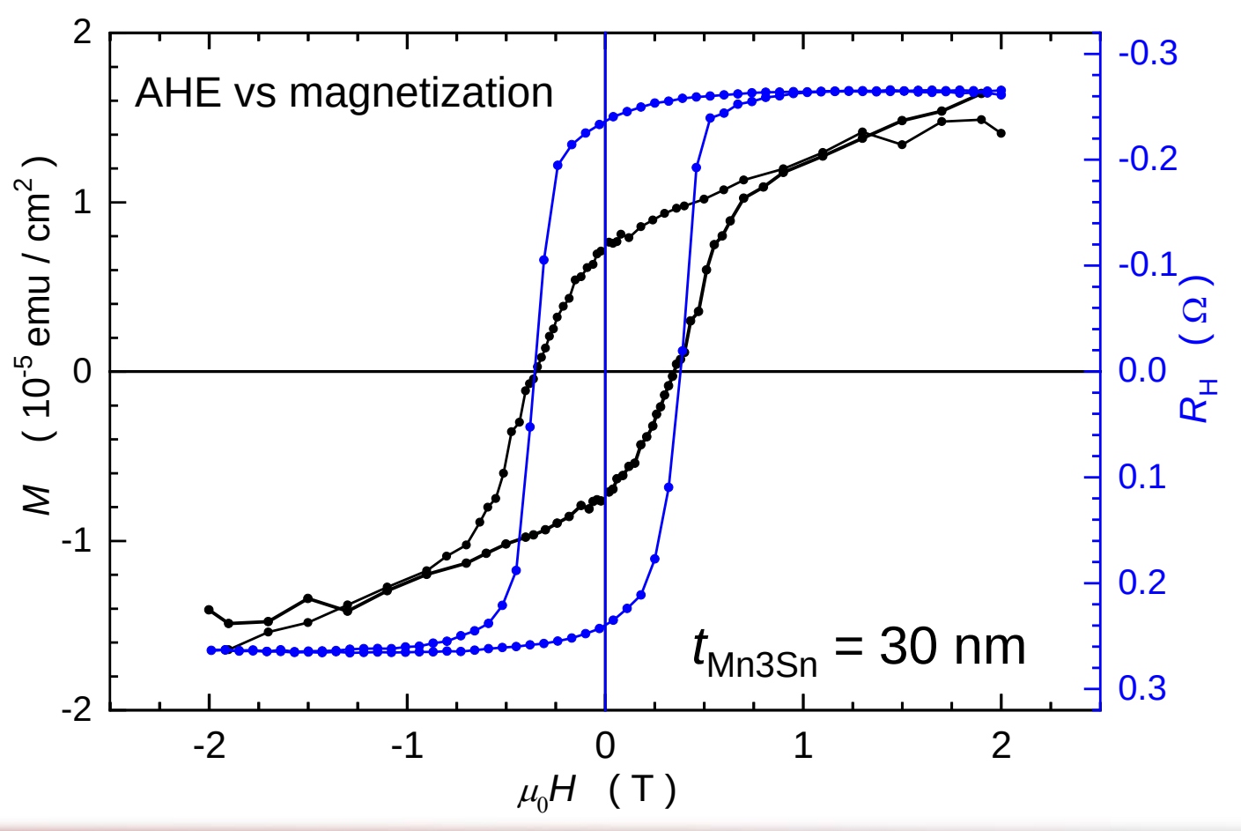
Magnetization - layer thickness dependence



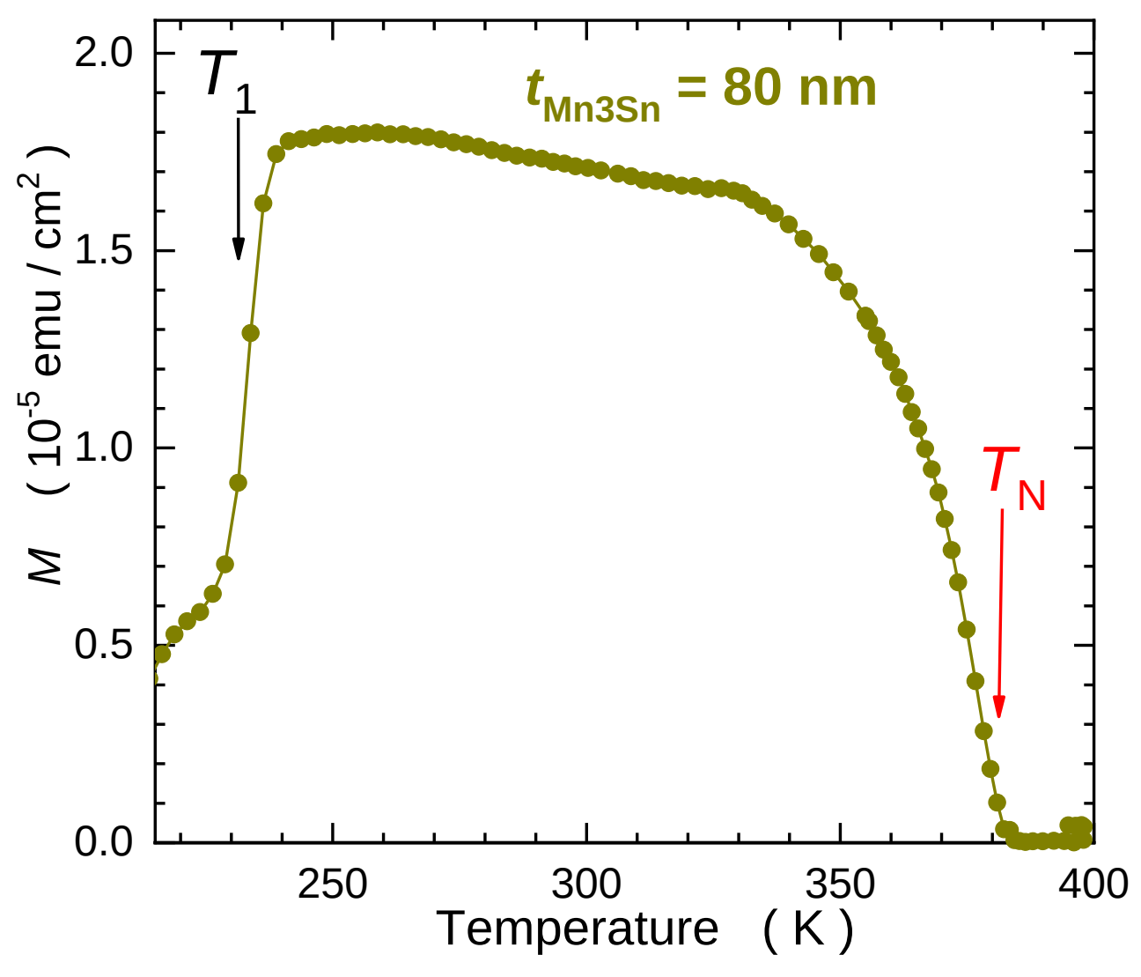




- ✓ Strong variations of the values of the basal plane *a* lattice parameter is observed presumably due to epitaxial strain.
- ✓ Spontaneous magnetization, M_{SP}, at 300 K correlates with the inverse of the basal plane *a* lattice parameter. (M_{SP} of bulk $Mn_3Sn \approx 10$ mμ_B/f.u. [1])
- ✓ A decrease of FWHM for thicker layers indicates improved crystalline quality .



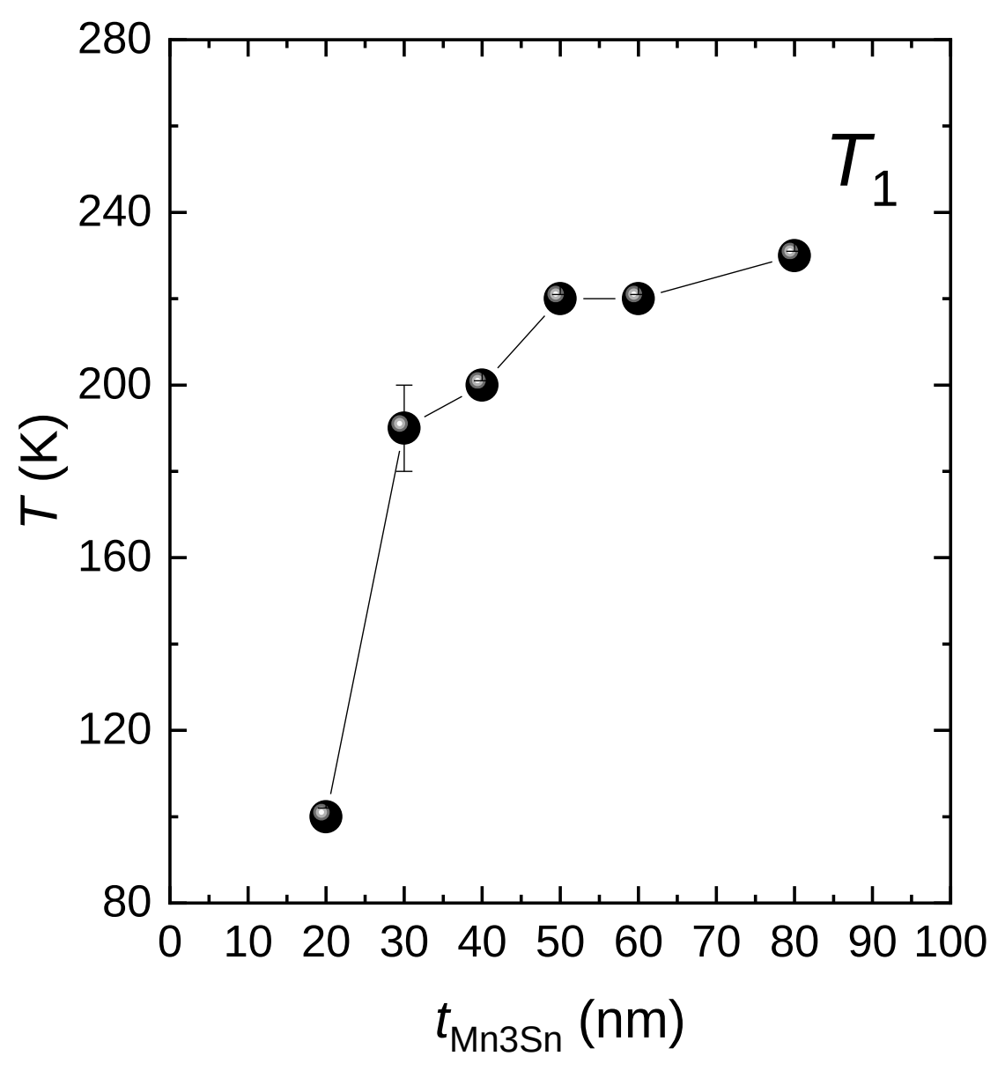
Temperature dependent studies

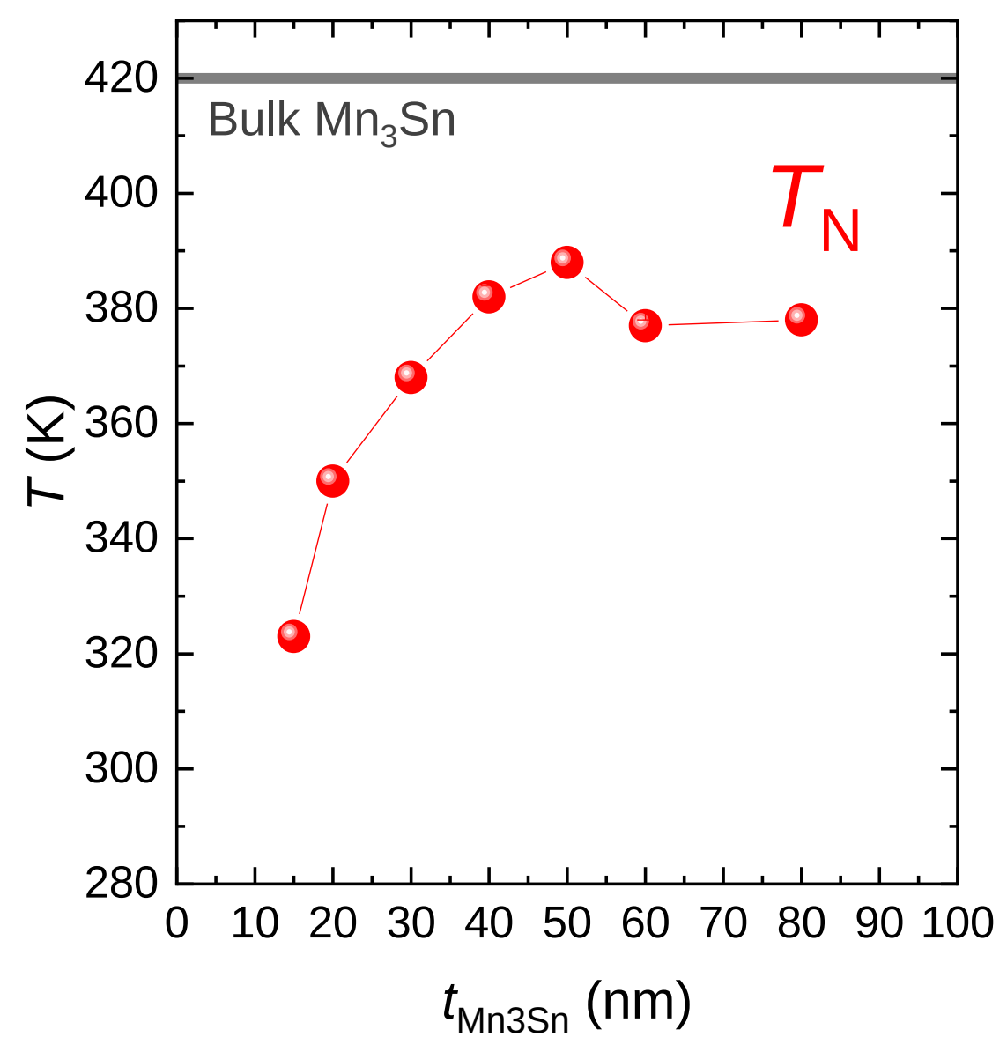


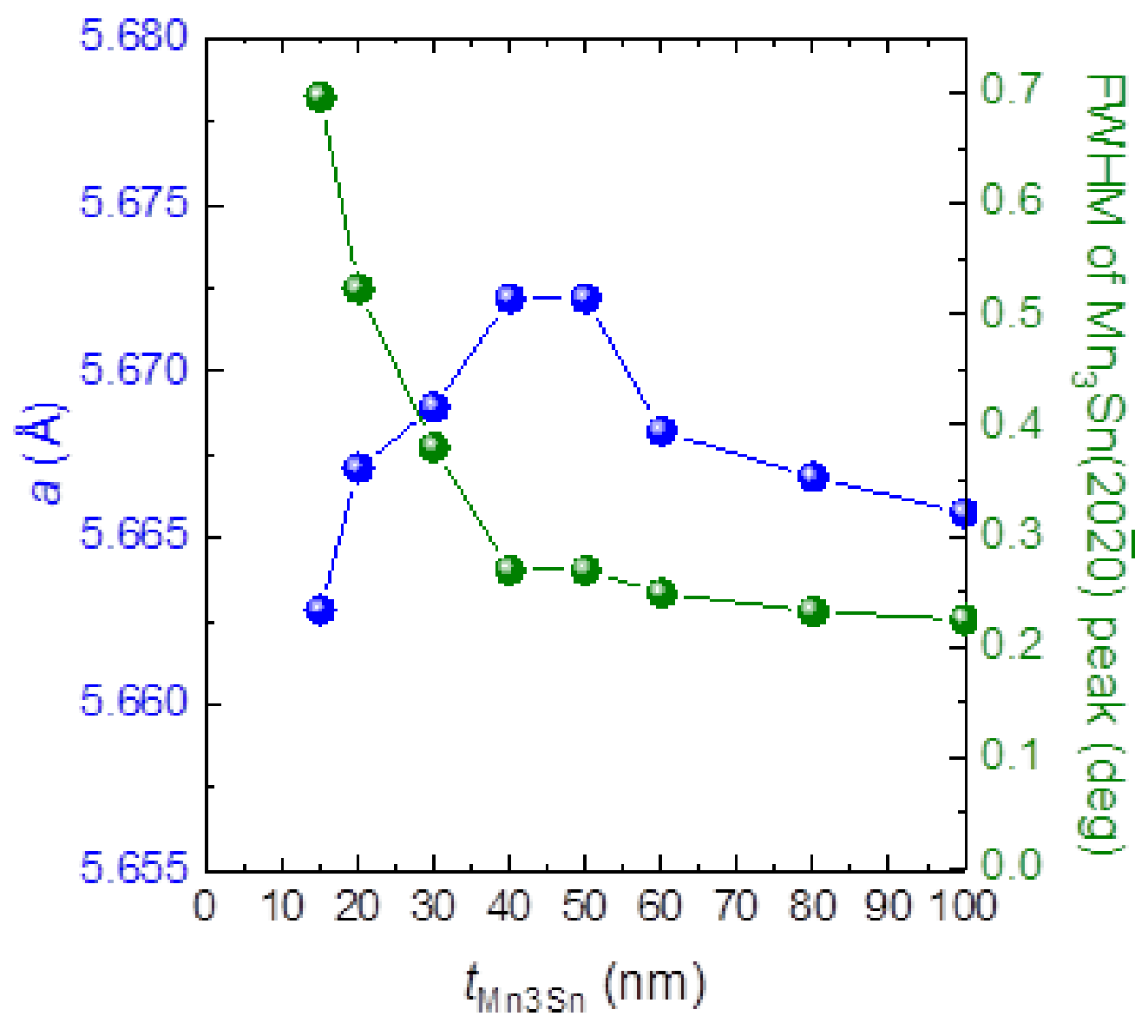
Exemplary temperature dependent magnetization showing two transition temperatures:

T_N – Néel temperature, transition from paramagnetic to inverse triangular AFM spin state (canted spins yield FM response).

T_1 – transition from inverse triangular state to an incommensurate magnetic structure.







- ✓ The Néel temperature, T_N, in thin Mn_3Sn layers is consistently lower than in bulk Mn_3Sn.
- ✓ T_N and T_1 increase with the layer thickness due to improvement of the crystal quality and relaxation of epitaxial strain.

References

[1] S. Nakatsuji *et al.*, Nature **527**, 212 (2015) .
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