Magnetic characterization of exfoliated Fe_5GeTe_2 flakes by in-situ TEM

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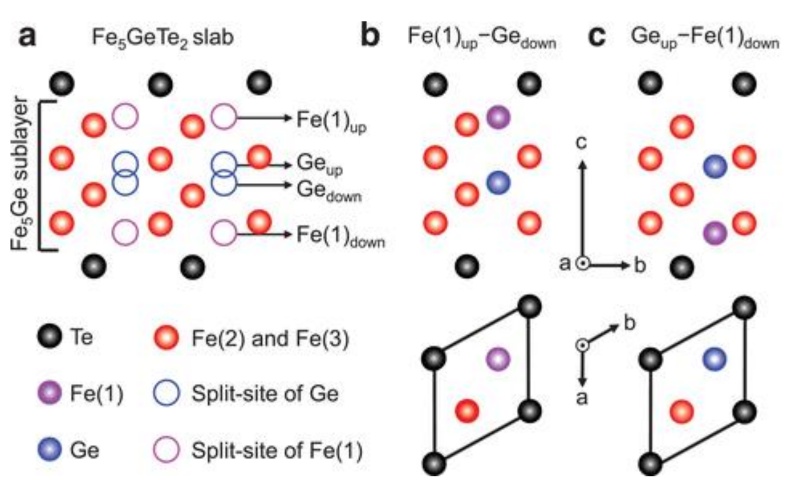
Introduction

- **Ferromagnetism:** Tc=270 K- 300 K [1]
- **Anisotropy:** Out of plane anisotropy
- **Layer-Dependent Magnetism**: Magnetic properties vary with layer thickness



Crystal structure of FGT [1]

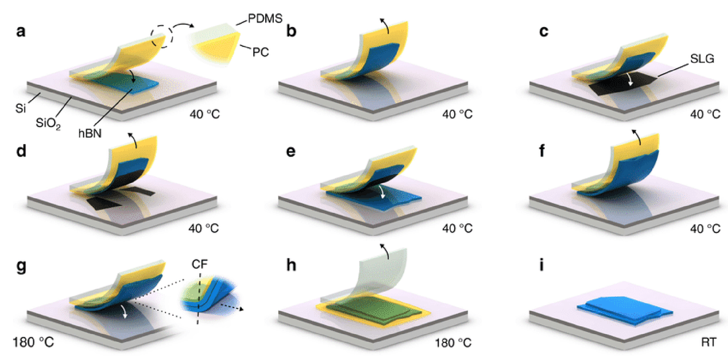
- Current research utilizes FIB (Focused Ion Beam) sample preparation to study 2D magnetic material.
- The goal is to investigate whether the sample preparation method affects the magnetic properties of 2D magnetic materials.
- In-situ transmission electron microscope to gain a comprehensive understanding of the magnetic properties.

Sample preparation & thickness characterization

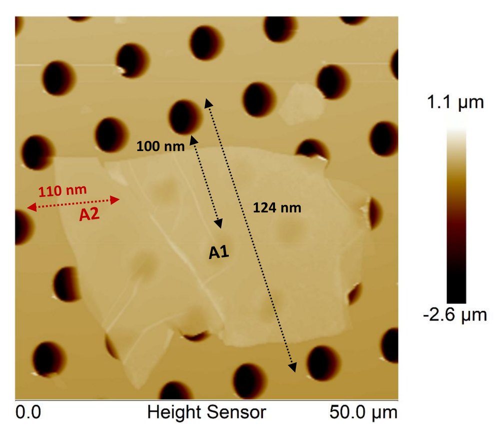
Mechanical exfoliation method

- Layer-by –layer exfoliation
- Clean Transfer
- Thickness Control
- Stacking feasibility
- TEM Suitability

Wet transfer method



[2]

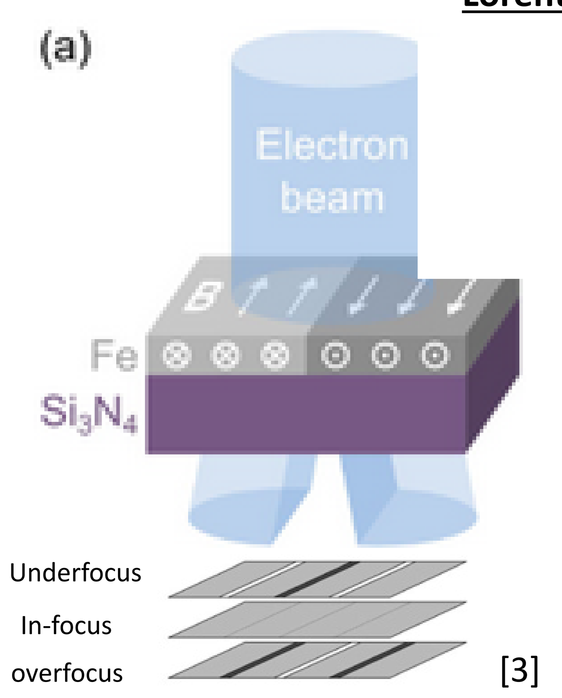


- Flakes studied have thicknesses between 50 and 300 nm.
- Some flake has areas with different thicknesses.
- Some areas have wrinkles or layers stacked on top of each other.

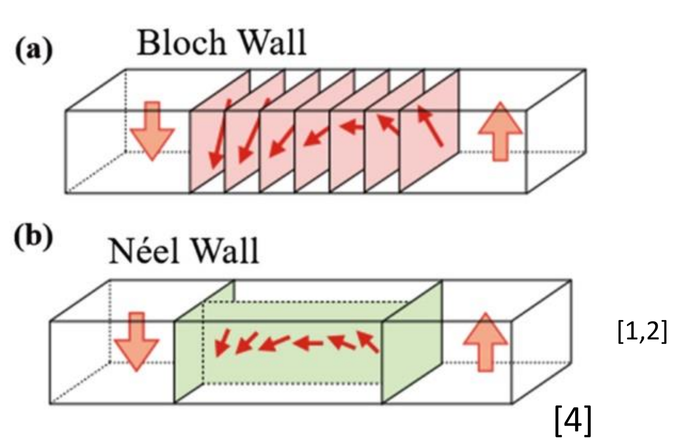
Flake	Thickness
1	100- 158 nm
2	100- 140 nm
3	~ 50 nm
4	100- 150 nm
5	60-300 nm

Magnetic characterization using lorentz transmission electron microscope

Lorentz transmission electron microscope (LTEM)

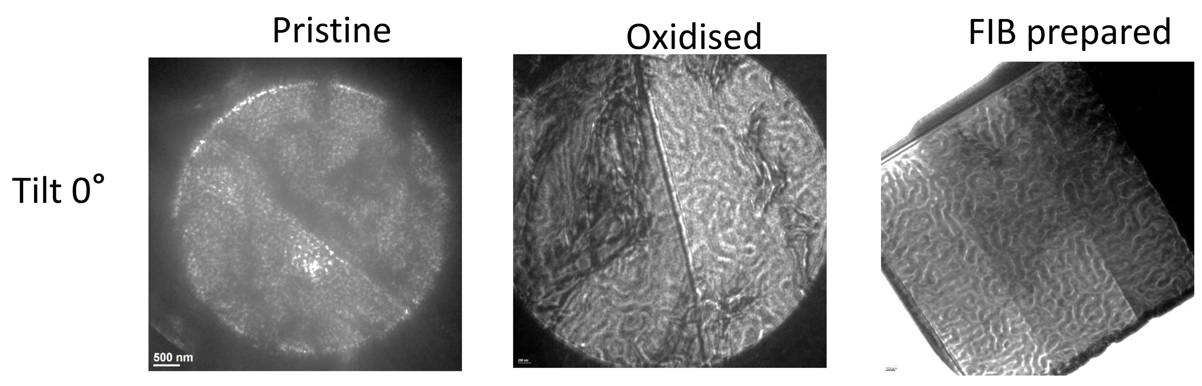


[3]



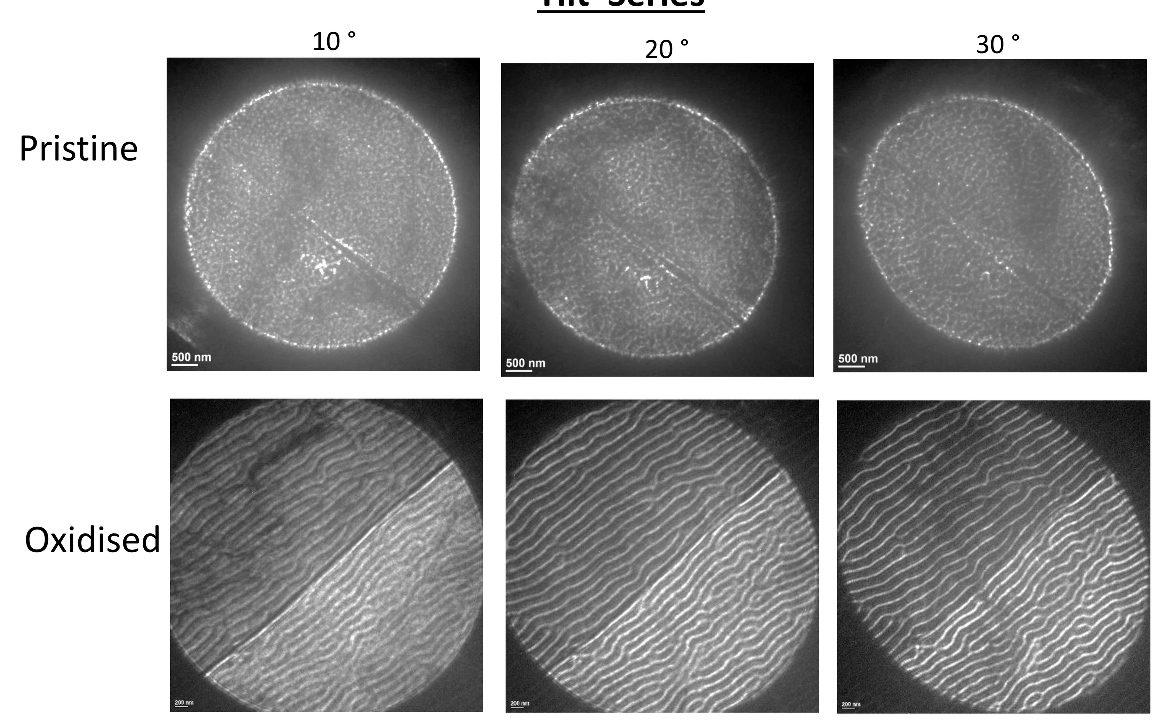
[4]

Magnetic domain structure : Neel vs Bloch!



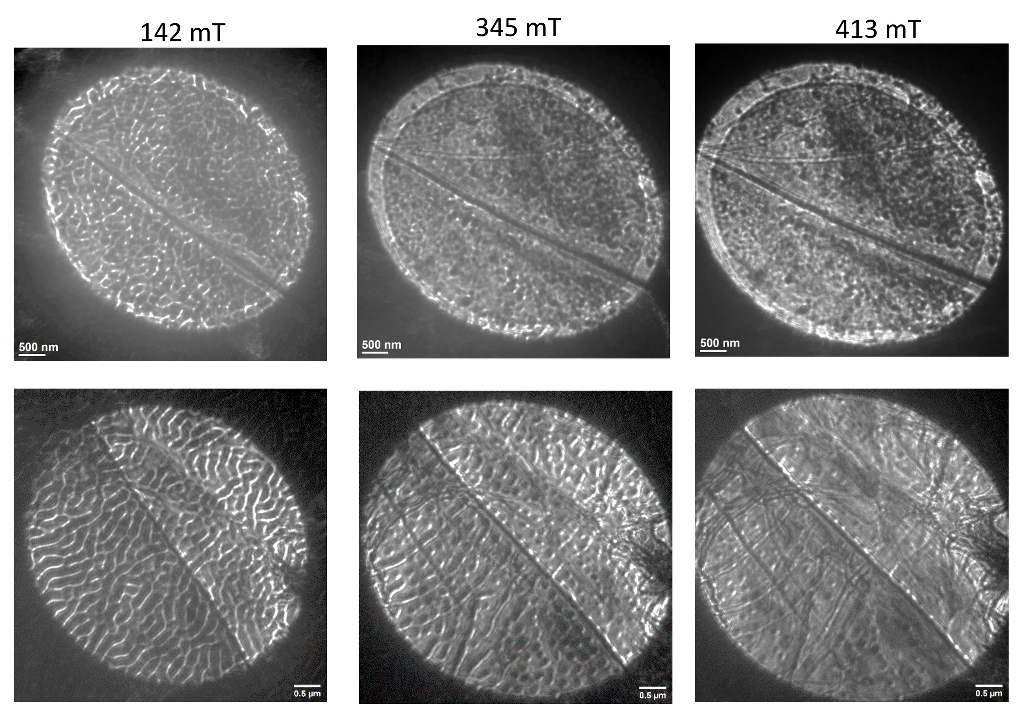
- LTEM images of pristine and oxidised samples were taken at a tilt of 0°, at 100K, with no magnetic field (0 mT), and a defocus of -2.5 mm.
- The pristine sample shows no features, while the oxidised sample shows magnetic features, suggesting a Néel domain structure in the pristine sample and a Bloch-type domain in the oxidised and FIB-prepared sample.

Tilt Series



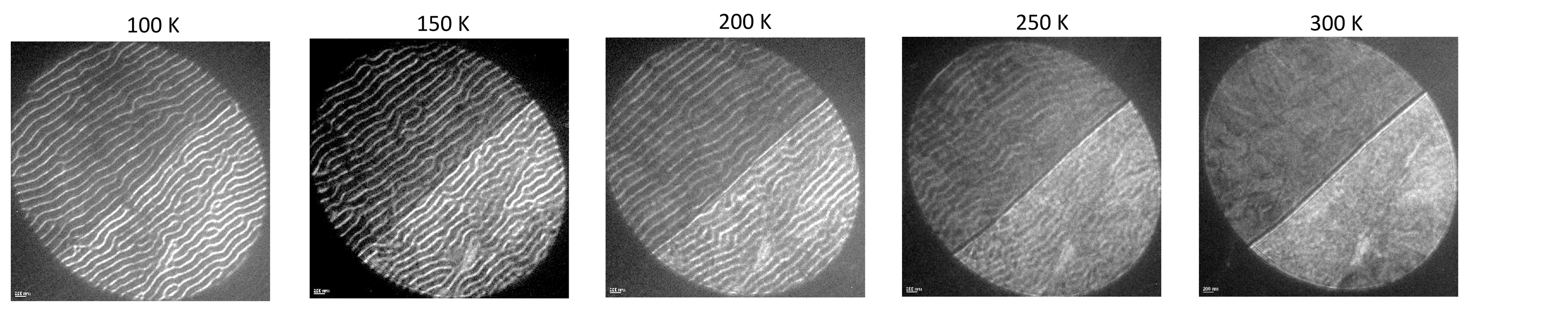
- Images were taken at 100K, with no magnetic field (0 mT) and a defocus of -2.5 mm.
- The evolution of magnetic features in both samples was observed as the tilt angle increased from 0° to 30°.

Field Series



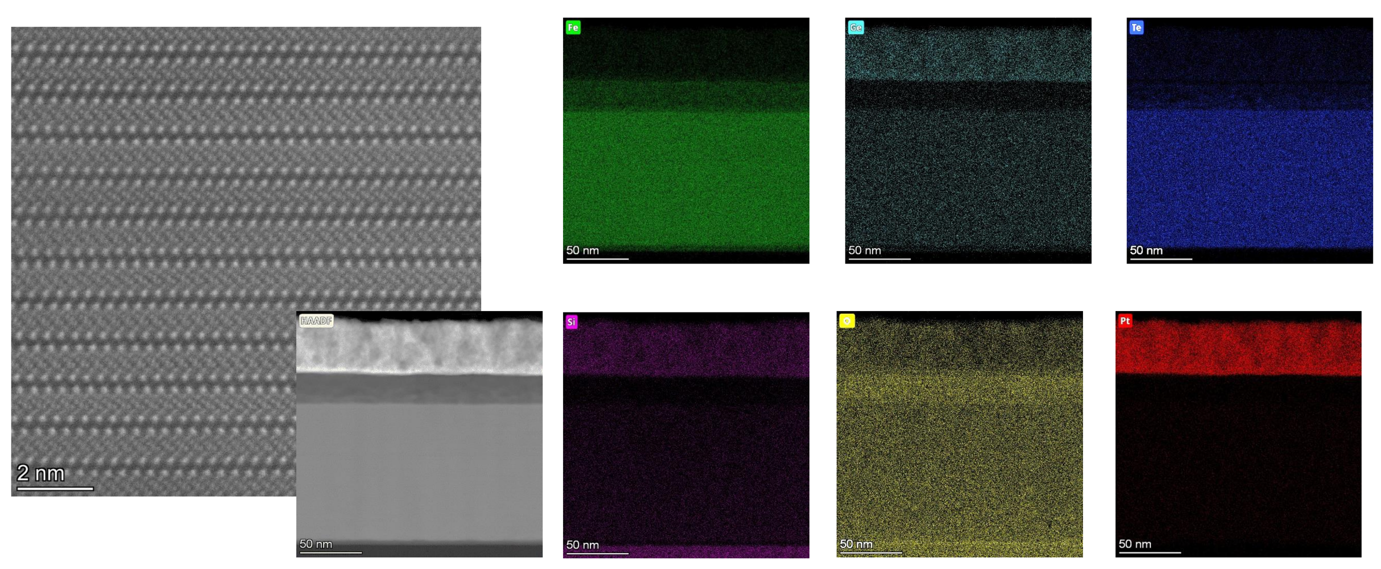
- Images were taken at 100K, 30 ° & defocus of -2.5 mm.
- Bubble formation appeared at around 345 mT.
- The magnetic saturation fields for the pristine and oxidised are 413 mT and 480 mT..

Temperature Series



- images of the oxidised sample were taken at a tilt of 30°, with no magnetic field (0 mT) and a defocus of -2.5 mm.
- The magnetic domain structure remains stable up to 250 K.

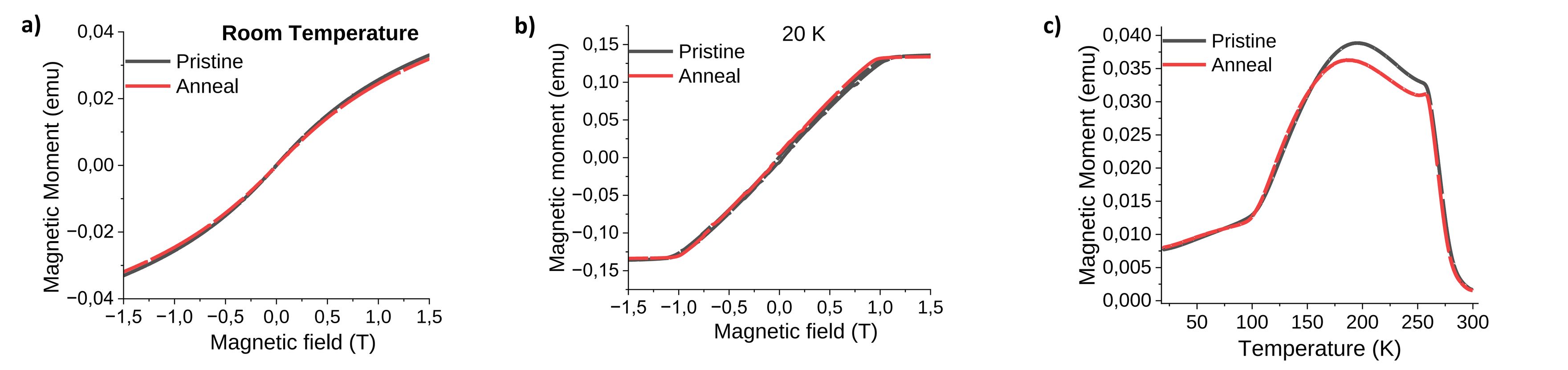
Intrinsic magnetic structure



- High-resolution TEM image shows the crystal structure with the c-axis aligned vertically.
- Energy-dispersive X-ray (EDX) composition map of cross-sectional FGT displays the distribution of elements, including an oxidation layer about 20 nm thick.

Magnetization characteristics

Magnetization Vs Magnetic field **Magnetization Vs Temperature at 50 mT**



- **Figures 1a and 1b** display the magnetization of FGT bulk crystals in pristine and oxidised (anneal at 80 °C for 5 hours) forms at room temperature and 20 K, showing no significant differences in magnetization curves between the two forms.
- Temperature-dependent magnetization measurements with an external field parallel to the ab-plane (50 mT) reveal noticeable changes in magnetization between 150 K and 220 K.

Summary

- LTEM study shows the exfoliated pristine and oxidised sample exhibit distinct magnetic behavior, where pristine shows Neel type domain whereas oxidised sample exhibit bloch type domain.
- The oxidised exfoliated FGT sample exhibits similar characteristics to the one prepared using the FIB method.
- Spectra analysis of cross-sectional FGT shows that keeping sample 100 hr leads to oxidisation of top layers of 20 nm of sample.
- Magnetization under varying temperature also evident changes in magnetic property in oxidised crystal .
- It suggests that the 2D magnetic material prepared via the FIB process likely reflects the properties of the oxidised material, rather than those of the pristine (unoxidised) form.

References

1) Ly, T.T., Park, J., Kim, K., Ahn, H.B., Lee, N.J., Kim, K., Park, T.E., Duvjir, G., Lam, N.H., Jang, K. and You, C.Y., 2021. Direct observation of Fe-Ge ordering in Fe5− xGeTe2 crystals and resultant helimagnetism. *Advanced Functional Materials*, *31*(17), p.2009758.
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3) Seki S Mochizuki M 2016 Skyrmions in Magnetic Materials New York Springer.
4) Eggebrecht, T., Möller, M., Gatzmann, J.G., Rubiano da Silva, N., Feist, A., Martens, U., Ulrichs, H., Münzenberg, M., Ropers, C. and Schäfer, S., 2017. Light-induced metastable magnetic texture uncovered by in situ Lorentz microscopy. *Physical review letters*, *118*(9), p.097203.