Advanced electron microscopy of emerging data storage devices and energy materials

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Introduction

Modern society is constantly searching for innovative solutions to address critical issues such as energy and information technology, driving the study of the next generation of functional materials. Advanced electron microscopy techniques can provide fundamental insight into the nano-scale properties of modern magnetic, thermoelectric and topologically-insulated materials, leading to emerging energy materials technology and realising novel data storage devices. Here we present the research of a selection of graduate students, including imaging of synthetic antiferromagnetic skyrmions, nanopatterning of complex 3D magnetic structures using electrons, probing plasmonic properties of fullerenes and diffuse electron scattering in Half-Heuslers for heat waste recovery.

Electron Beam Deposition of Functional 3D Magnetic Nanowires

The field of nanomagnetism is beginning to move into the **third dimension** [1]. Made possible through new nano-prototyping methods like **Focused Electron Beam Induced Deposition (FEBID)**.

FEBID can be used as a nano 3D printer.

Microscopic structures can be created from **computer designed images** (*e.g.,* fig 1b).

Geometry of deposits can **control the magnetisation** e.g., left and right-handed double helices produce left and right-handed domain walls (*e.g.,* fig 1c).

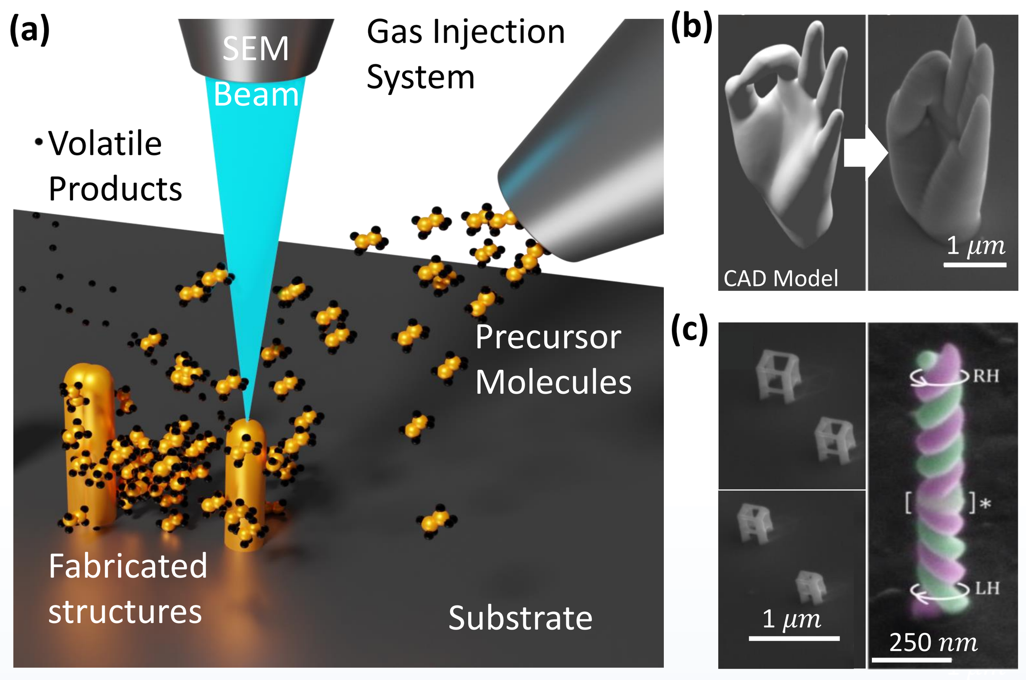


Figure 1: (a) FEBID process, electron beam breaks down precursor molecules into magnetic deposits. (b) Left - computer model of hand, right – FEBID fabricated hand [2]. (c) Other examples of FEBID structures [3].

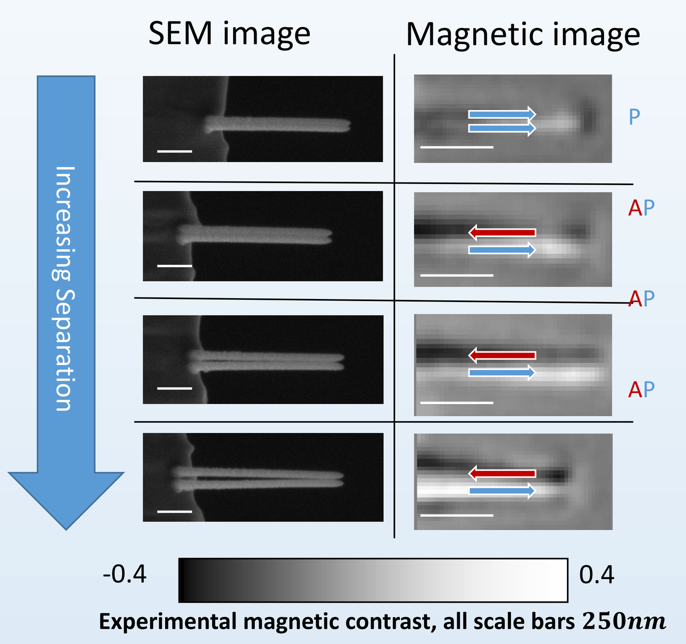


Figure 2: Fabricated nanowire pairs with increasing separation from top to bottom. Left – SEM images of structure, right– magnetic images.

The precision of FEBID can be used to **create coupled nanowire structures** (left of fig 2) where the magnetic competition between wires can be tuned by varying the separation between wires.

The magnetisation can be imaged in synchrotrons (right of fig 2). And illustrates the varying of coupling with a transition from the parallel (P) state to the anti-parallel state (AP).

FEBID can create **highly pure, well-defined 3D structures** and play a key role in the development of **low-power computing and data storage devices.**

1. A. Fernández-Pacheco, et. al., Three-dimensional nanomagnetism, *Nat. Comm.*, **8**, 15756 (2017).
2. L. Skoric, et. al., Layer-by-layer growth of complex-shaped three-dimensional nanostructures with focused electron beams, *Nano Lett.*, **20**, 184 (2020).
3. D. Sanz-Hernández, et al., Artificial double-helix for geometrical control of magnetic chirality, *ASC Nano.*, **14**, 8084 (2020).

Skyrmions in Synthetic Antiferromagnetic Multilayers

Skyrmions are **topologically protected** nanomagnetic structures which are stable in applied fields and resistant to annihilation.

These properties can be enhanced using a synthetic antiferromagnetic (SAF) multilayer and have led to potential applications in logic devices and **next generation data storage** devices.

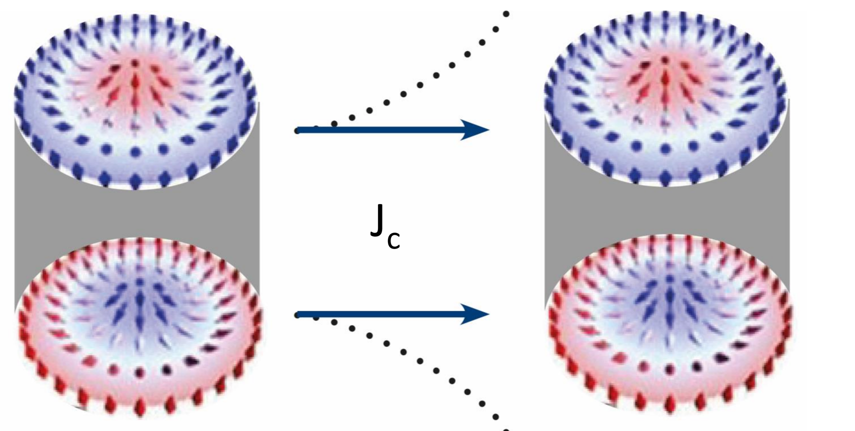


Figure 3: Schematic of SAF coupled skyrmion motion under applied current (J_c). SAF coupling cancels the Skyrmion Hall Effect and prevents circular motion (dotted lines)

MAIN CHALLENGES

1. Need **high current density** for skyrmion motion
2. Nucleation is **unpredictable**

FRESNEL IMAGING uses a defocussed electron beam to generate contrast from magnetic structures in a TEM.

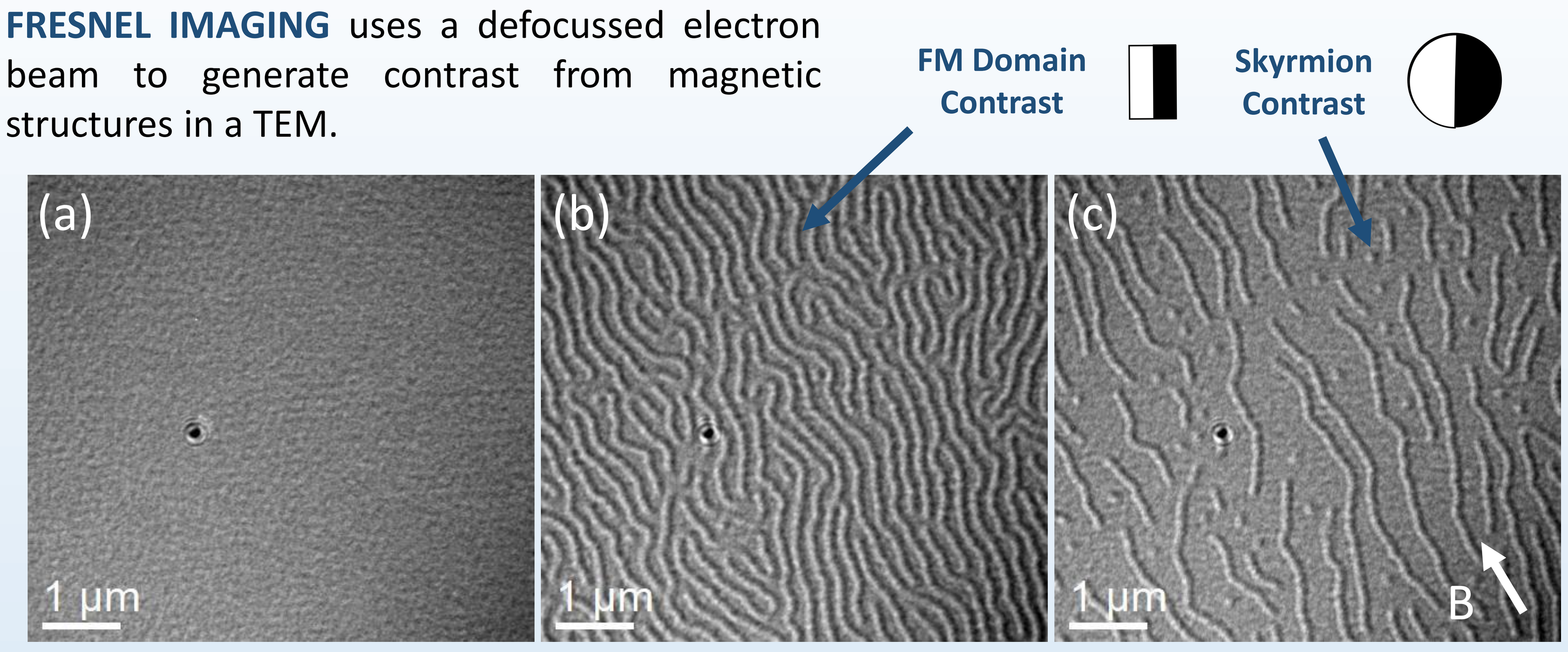


Figure 4: Fresnel imaging of a SAF multilayer with magnetic layers of CoB and CoFeB. (a) SAF coupled phase (OOP = -63 mT) (b) ferromagnetic domain phase (OOP = -86 mT) and (c) ferromagnetic skyrmion phase (OOP = -97 mT). All images at 25° tilt in direction of applied field.

We can use this to analyse the magnetic phases of SAF multilayers and investigate new **methods of controlling nucleation** (eg: using C_{60} pinning and local magnetic field control).

1. Zhou, S. et al. Manipulating skyrmions in synthetic antiferromagnetic nanowires by magnetic field gradients', *J. Mag. and Mag. Mat.*, **493**, p.165740 (2020).

Plasmons in Topological Insulators

Topological insulators (TIs) such as Bi_2Se_3 have a topologically protected surface state (TSS), due to spin orbit coupling, that can support Dirac plasmons [1,2]. These could be used in **low-loss, THz communication for high speed computing**.

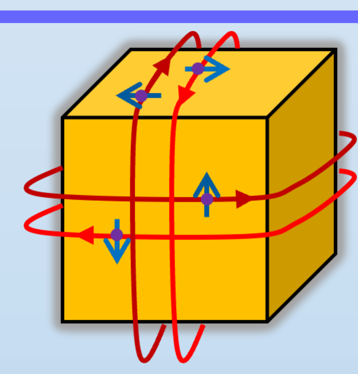


Figure 5: Topological surface states confined to 2D surfaces on a 3D topological insulator.

We can develop plasmonic circuits by **actively controlling the surface states**. For example using layers of organic molecules, such as fullerenes, to alter the TSS.

Plasmons can be observed by electron energy loss spectroscopy (EELS) which records both bulk (fig 2c) and surface modes (fig 2d) [3].

In Bi_2Se_3 we observe two Bi edges (26.5 eV and 28.4 eV) and two volume plasmons (7.2 eV and 17.3 eV).

At the interface with Al_2O_3 we observe a **localised surface plasmon (5eV)** as well as features from the bulk of each material.

Mapping the surface plasmon energy vs momentum to obtain the plasmon dispersion relation will give **insight into if this surface plasmon is the Dirac plasmon [4]**.

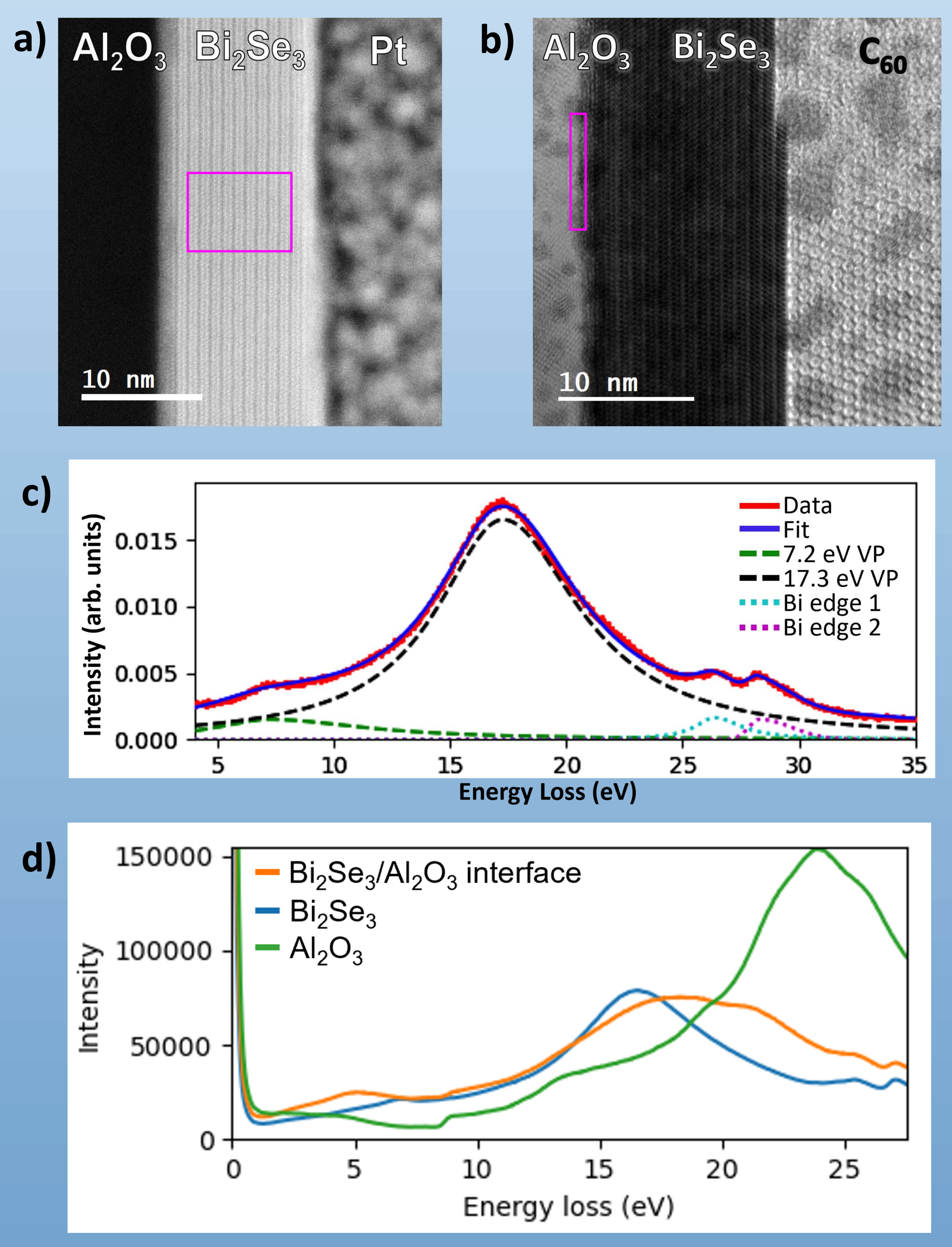


Figure 6: a) HAADF STEM image of Bi_2Se_3, b) BF STEM image of Bi_2Se_3/C_{60}, c) deconvolved EELS spectrum of Bi_2Se_3 from enclosed area in a), with two volume plasmons (VP) and two Bi edges fitted by asymmetric pseudo Voigt functions, c) EELS spectra at the Al_2O_3/Bi_2Se_3 interface in b) and in the bulk Bi_2Se_3 and Al_2O_3.

1. M Bianchi et al, *Nature Communications,* **1** (2010)
2. J E Moore, *Nature,* **464,** 194–8 (2010)
3. S C Liou et al, *Physical Review B - Condensed Matter and Materials Physics,* **87** (2013)
4. F S Hage et al, *Physical Review B - Condensed Matter and Materials Physics,* **88** (2013)

Characterisation of vacancy clusters in thermoelectric half-Heusler alloys

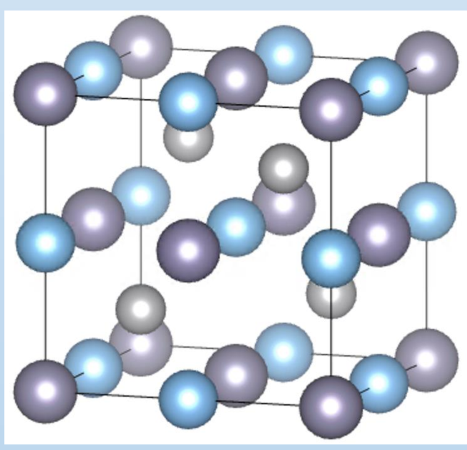


Figure 7: Half-Heusler unit cell

- **Aperiodic defects improve performance** of thermoelectric half-Heuslers.
- **Diffuse bands and rings of intensity** exist around and between the fundamental spots in electron diffraction patterns.
- Diffuse intensity arises from **presence of vacancy clusters.**

- Diffuse scattering can be described as the **intersection of Ewald sphere with diffuse scattering surfaces** in reciprocal space.
- Structure factor for **octahedral cluster** agrees with shape/periodicity of diffuse bands:

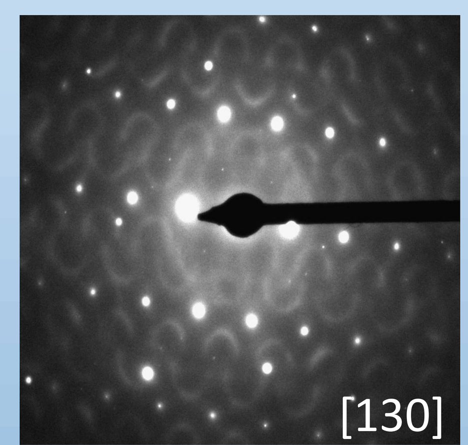
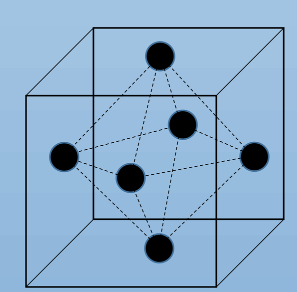


Figure 8: Electron diffraction pattern of VCoSb



$$f(\boldsymbol{g}) = \sum_{j=1}^{n} \exp\left[i2\pi\left(h_j + k_j + l_j\right)\right] = 0$$

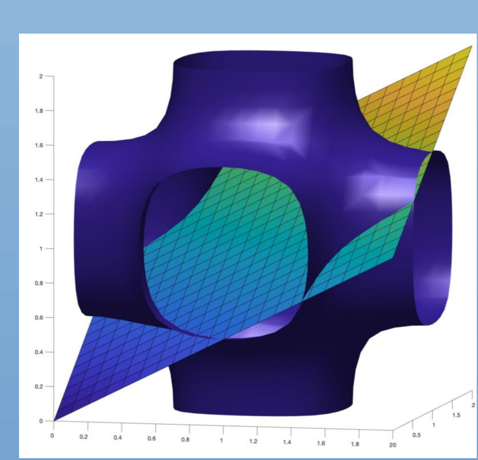


Figure 8: Scattering surface with intersecting plane

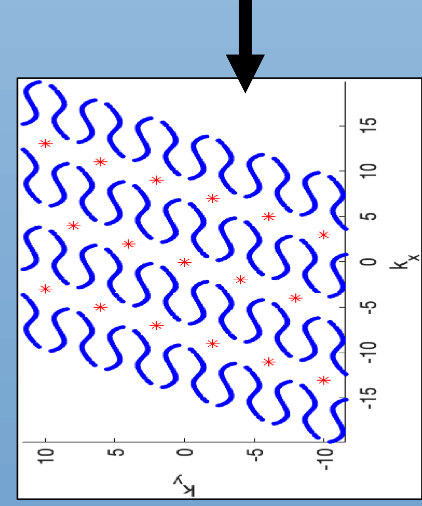


Figure 9: Intersection of scattering surfaces and [130] plane

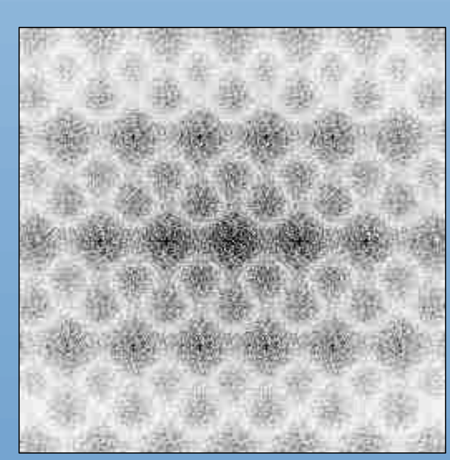


Figure 10: Simulated DP from aperiodic **octahedral clusters**

- Knowing that **aperiodic defects exist** as octahedral vacancy clusters gives greater insight into **thermoelectric performance of half-Heuslers** and how it could be **improved further**.

1. A. I. Gusev, *Physics-Uspekhi*, (2006)
2. N. Roth, T. J. Zhu and B. B. Iversen, *Iucrj*, **7**, 673-680 (2020)