Laser diode floating zone growth of ultrahigh-purity crystals for Skyrmion Qubits

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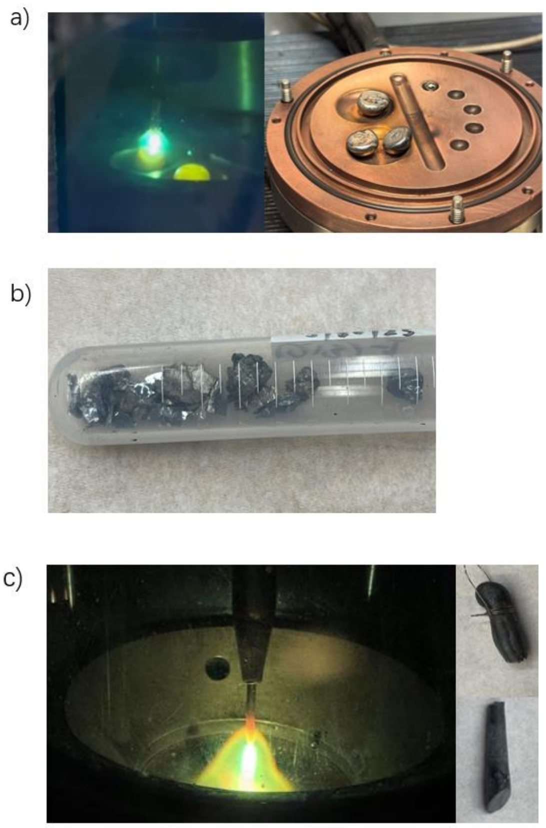
A quantum bit, or qubit, is the core entity of quantum computing. Recently, theoreticians have proposed magnetic skyrmions, topologically protected swirling spin textures, as a promising candidate for macroscopic qubits due to their topological stability, nanoscale size, and helicity-based characteristics. In this summer's research, Laser Diode Floating Zone (LDFZ) technique was applied to grow the bulk single crystals: $Gd_3Ru_4Al_{12}$, which is identified by modeling group as hosting nanoskyrmions, to develop potential materials for skyrmion qubits. After crystal growth, X-Ray Diffraction (XRD) methods were used to characterize the crystal's structure properties. Additionally, the magnetic and magneto-transport properties of the grown crystals were investigated by using Physical Property Measurement System (PPMS) and Magnetic Property Measurement System (MPMS).

Introduction

The rapidly growing field of quantum computing offers a promising solution to overcome the limitations of traditional semiconductor-transistor based information technologies. At the core of quantum computing lies the quantum bit (qubit), which can be realized through various physical systems such as ultracold atoms, trapped ions, superconducting circuits, and nitrogen-vacancy (NV) centers in diamond [1]. Recently, magnetic skyrmions, a topologically protected swirling spin textures [2], have emerged as a compelling macroscopic qubit candidate due to their inherent topological stability and nanosize [3,4]. Unlike conventional skyrmions stabilized by strong Dzyaloshinskii–Moriya interactions (DMI), helicity-based skyrmion qubits [5] require skyrmions formed in material systems with negligible or zero DMI, enabling an additional internal degree of freedom associated with helicity rotation [3]. For the quantum nature of skyrmions to manifest, their size must be below 10 nm, and the host material should exhibit ultralow Gilbert damping ($\alpha \approx 10^{-5}$–10^{-4}) to ensure long coherence times [4]. In this work, I synthesized and characterized $Gd_3Ru_4Al_{12}$ single crystals, a candidate material system that fulfills key criteria for helicity-based skyrmion qubits: (1) the capability to host nanoskyrmions, (2) negligible DMI to preserve the helicity degree of freedom, and (3) ultralow Gilbert damping to enable long qubit lifetimes, thereby contributing to the development of skyrmion-based quantum information platforms.

Experimental Setup

For preparing before the crystal growth, the elements Gd, Ru, and Al were arc-melted in specific stoichiometric ratios to synthesis $Gd_3Ru_4Al_{12}$ buttons. After getting the buttons, the buttons were broken to pieces to repeat arc-melting several times and the $Gd_3Ru_4Al_{12}$ were casted into dense and uniformed polycrystalline rods for subsequent floating zone crystal growth. After that, two long-rod shaped $Gd_3Ru_4Al_{12}$ were mounted into the Laser Diode Floating Zone Furnace (LDFZ) and the argon gas was purged to the system to make the crystal growth occur in a stable environment.



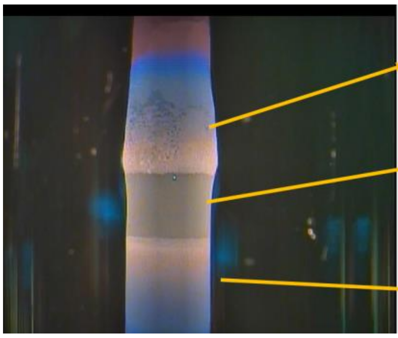


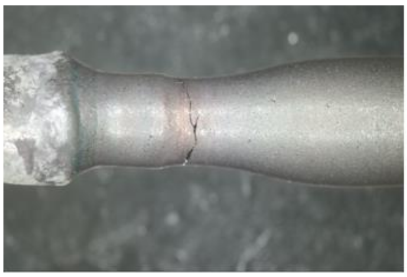
Figure 1: the process of crystal growth preparation (a) arc-melted different elements into buttons; (b)broke the button into pieces; (c) repeat arc-melting and cast the uniform polycrystalline rod; (d) a picture taken during the crystal growth in LDFZ furnace

The crystal growth was conducted with laser diode floating zone (LDFZ) method. The LDFZ method uses high-power laser diodes to locally melt a region of a feed rod while keeping the rest solid. A seed rod is placed below the feed rod, and the molten zone is slowly moved along the rod by vertical translation, allowing the material to resolidify with the seed's crystallographic orientation. During the growth, by actively adjusting the rotation and control laser power and growth rate, LDFZ enables the production of high-purity single crystals.

Results

The structural properties of grown single crystal $Gd_3Ru_4Al_{12}$ were characterized by Laue backscatter diffraction and X-ray powder diffraction method. For the detected Laue diffraction pattern, the alignment of the six-fold lattice points' direction between the detected pattern and simulated lattice points indicated the desired hexagonal single crystal in space group P63/mmc were formed. By comparing with the simulated data, the (001) axis direction were found and the crystal slices were cut along the 001 plane to prepare sample for further characterization.

a)



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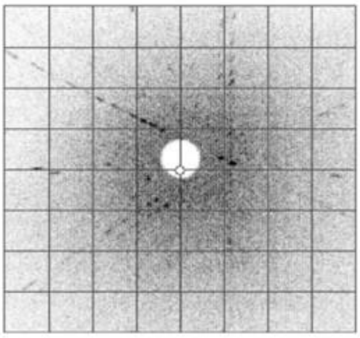

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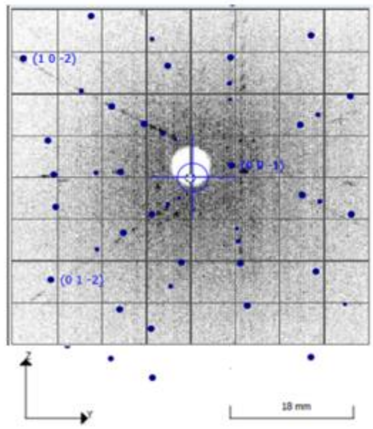


Figure 2: the Laue backscatter diffraction result of grown $Gd_3Ru_4Al_{12}$ crystal at <001> plane. (a) grown $Gd_3Ru_4Al_{12}$ crystal picture taken by microscope; (b) detected Laue diffraction pattern; (c) detected result was aligned with simulated lattice points (blue dots), confirming the single crystal $Gd_3Ru_4Al_{12}$ were grown as designed.

Additionally, the grown single crystal was characterized by X-ray powder diffraction. The alignment of the diffraction peaks' position with the data provided by ICSD data file helped confirm that we grew the single crystal $Gd_3Ru_4Al_{12}$ as designed. The lattice constant were confirmed as a = 8.8142Å, b= 8.8142Å, c= 9.5692Å.

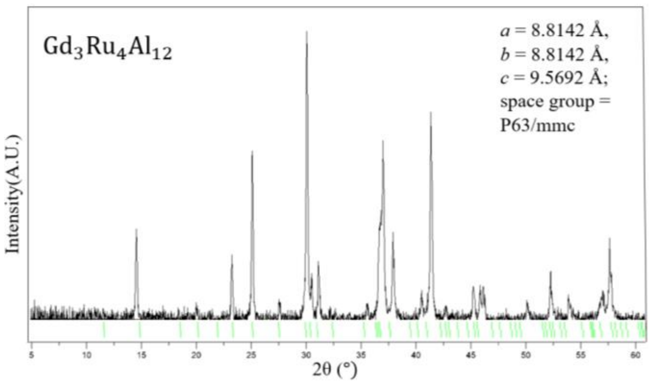
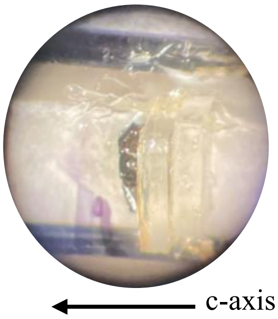


Figure 3: the powder X-ray diffraction pattern of grown $Gd_3Ru_4Al_{12}$ single crystal, aligning with the peak position of ICSD file.

The magnetic properties of grown single crystal $Gd_3Ru_4Al_{12}$ were characterized by Magnetic Property Measurement System (MPMS). 4.6mg of bulk grown crystal sample was placed with c-axis parallel to the applied field direction and was applied with 100 Oe magnetic field. Under this condition, the DC magnetic moment of the crystal was measured from 2K to 300K.

a)



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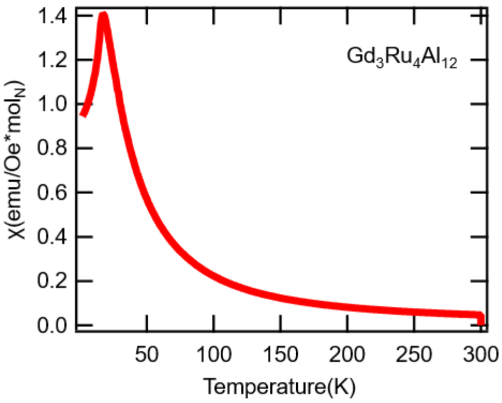

Figure 4: the MPMS result of grown $Gd_3Ru_4Al_{12}$ single crystal. (a) the picture taken when mounting the crystal (b) the X vs. T result of $Gd_3Ru_4Al_{12}$ with 100 Oe applied field, shown that the grown $Gd_3Ru_4Al_{12}$ single crystal is an antiferromagnet and the Neel temperature is around 20K.

Conclusion & future plan

In this summer's work, we successfully synthesized the $Gd_3Ru_4Al_{12}$ single crystal as designed, using the arc-melting and laser diode floating zone (LDFZ) methods. The LDFZ method offers the advantage of growing large-volume, high-purity crystals because it allows active adjustment of the growth environment during the process.

The quality and structural properties of the grown crystal were characterized by X-ray diffraction methods. The measured data matched well with the reference data from the ICSD database.

The magnetic properties were characterized successfully with MPMS and the X vs. T result suggested that the grown $Gd_3Ru_4Al_{12}$ single crystal was an antiferromagnet and follow the result measured by previous work [6].

In the future, we aim to continue characterizing the magnetic and magneto-transport properties of the grown $Gd_3Ru_4Al_{12}$ crystal to further exploring their skyrmion phases and Gillbert damping constant with Brillouin Light Scattering spectroscopy (BLS). In the long run, these crystals will be processed to fabricate nanoscale isolate skyrmion qubits.

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