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変革を駆動する先端物理・数学プログラム（FoPM）

国外連携機関長期研修　報告書

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Background

The orbital Edelstein effect (OEE) is a quantum phenomenon where an applied electric current in a noncentrosymmetric material induces a non-equilibrium orbital angular momentum polarization, resulting in an orbital current [1-2]. Unlike the conventional Edelstein effect, which relies on spin polarization via spin-momentum locking, OEE originates from an asymmetric distribution and flow of orbital degrees of freedom in electronic states. This orbital current can interact with spins through spin-orbit coupling, offering an efficient way to control magnetization and spin currents in materials with strong orbital character. Such unique properties provide promising opportunities for developing advanced spintronic and orbitronic devices.

Activities during the International Collaboration

Soft X-ray Magneto-optic Kerr Effect (SXMOKE) Measurements in Japan

From May 21st to 25th, we performed SXMOKE measurements at SACLA, the advanced X-ray free-electron laser facility at SPring-8 in Japan. These measurements targeted the orbital angular momentum properties at the CuO/Cu interface, which served as a reference system for understanding the orbital Edelstein effect. The experimental setup took advantage of SACLA's high spatial resolution and ultrafast pulsed X-ray capabilities, enabling us to probe the orbital magnetization dynamics with exceptional precision.

The SXMOKE experiments successfully provided detailed spectral data revealing the generation and redistribution of orbital angular momentum specifically at the CuO/Cu interface. By analyzing differences between the bulk and interface spectral features, we were able to isolate and characterize the interface-specific modifications of orbital-driven magnetic order. The data were analyzed in close collaboration with the French team, with regular discussions ensuring that interpretations were consistent with theoretical models and complementary experimental insights.

These SXMOKE results not only validated theoretical predictions but also established a solid foundation for extending similar measurements to the CuB/Cu interface. Such comparative studies are critical to discerning how subtle changes in atomic arrangement and local symmetry influence orbital magnetization and related phenomena, ultimately expanding the range of materials suitable for orbitronic applications.

Sample Preparation and STM Measurement Coordination with France

A major challenge for this project was the preparation of high-quality CuB/Cu samples suitable for STM measurements. As the French team lacked the necessary equipment, before the main

measurement starts in French, sample synthesis was undertaken in Japan using molecular beam epitaxy (MBE) within an ultra-high vacuum chamber, in collaboration with the French group online.

Intensive focus has been targeted on optimizing the synthesis parameters. These included fine-tuning the substrate temperature, cleaning protocols, and deposition conditions to produce samples with the desired quality and cleanliness required for atomic-scale STM analysis. Over several months, iterative refinements were made based on characterization results.

Throughout the sample preparation process, frequent and detailed communication with Prof. D'angelo's team were maintained. Regular online meetings and remote support sessions ensured that both groups shared progress, challenges, and insights, enabling efficient problem-solving and mutual learning despite geographical separation. This collaborative approach was essential to synchronize the Japanese synthesis efforts with the experimental plans of the French STM team.

The STM measurements themselves are planned for Autumn in France, where the prepared CuB/Cu samples and established protocols will be used to directly visualize the atomic-scale orbital textures and magnetic order linked to the OEE. These measurements will complement and extend the SXMOKE findings, providing a more comprehensive picture of orbital dynamics and their role in magnetism at the interface.

Outcome for Myself

Participating in this international collaboration has been an invaluable opportunity for my professional and scientific development. Direct engagement with experts in physics and chemistry has broadened my understanding of cutting-edge research in orbitronics and related fields. The frequent and in-depth discussions have significantly influenced my perspective on interdisciplinary research, emphasizing the importance of integrating theoretical, spectroscopic, and microscopic approaches to tackle complex quantum phenomena.

The SXMOKE measurements at SACLA not only enriched my knowledge in orbital angular momentum dynamics at interfaces, but also strengthened my data analysis capabilities. This experience offered insights into the organizational and research culture of world-leading scientific facilities, enriching my ability to collaborate effectively within high-caliber international teams.

Furthermore, coordinating sample synthesis and preparation for STM measurements cultivated my ability to lead cross-border experimental planning and remote collaboration effectively. Navigating the technical challenges of molecular beam epitaxy and maintaining continuous communication with the French collaborators have enhanced my ability to conduct remote collaboration and experimental support effectively.

Working closely with Prof. D'angelo's group has broadened my understanding of techniques, underscoring the critical role of multidisciplinary collaboration in advancing frontier research. The integration of STM results with theoretical and spectroscopic data will provide a holistic understanding of the orbital Edelstein effect, which I plan to leverage in my future research directions.

Looking ahead, I intend to incorporate the insights and skills gained from this collaboration into my ongoing projects and actively pursue further international partnerships. This experience has motivated me to explore novel scientific fields and concepts, contributing to the broader development of next-generation technologies and materials.

References

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