XVI International School and Symposium
on Synchrotron Radiation in Natural Science
Poland, 25-30 May 2025

Ultrafast x-rays reveal new opportunities in nanostructured quantum materials

M. Lorenc[1,5]*, E. Janod[2], S. Iwai[3], H. Tokoro[4], H. Cailleau[5], E. Pastor[5], C. Mariette[6], P. Rabiller[5], E. Trzop[5], D. Lea[5], R. Mandal[2,5] and J. Guzman[2,5]

[1]*CNRS, Univ Rennes, DYNACOM—IRL2015, The University of Tokyo, Tokyo, Japan*
[2]*Nantes Université, CNRS, Institut des Matériaux de Nantes Jean Rouxel, IMN, Nantes, France*
[3]*Department of Physics, Tohoku University, Sendai, Japan*
[4]*Department of Materials Science, Institute of Pure and Applied Sciences, University of Tsukuba, Japan*
[5]*Univ Rennes, CNRS, IPR (Institut de Physique de Rennes)—UMR 6251, Rennes, France*
[6]*European Synchrotron Radiation Facility, B.P.220, F-38043 Grenoble Cedex, France*

*e-mail: maciej.lorenc@univ-rennes.fr

The ultrafast light pulses can induce new functionality in quantum materials [1] not accessible via the application of conventional thermodynamic parameters like temperature or pressure [2]. The non-equilibrium pathways hold great technological potential [3] and topical examples include insulator to metal transitions (IMT) for optical memories [4] or neural networks for AI [5]. From fundamental standpoint, several degrees of freedom couple during such transformations, which gives rise to multiscale dynamics in time and space. While structural reorganizations often play an important role in the stabilization of the newly formed electronic state, the establishment of a new macroscopic structural order requires long-range crystalline deformations, involving the propagation of acoustic waves. In a recent work, we evidenced a macroscopic transformation pathway from semiconductor to metal in nanocrystals of trititanium pentaoxide (Ti_3O_5) [6], that involved generation and propagation of volumic strain waves. In another example, we studied a prototypical Mott insulator V_2O_3, a widely considered test bed for quantum materials. While V_2O_3 is metallic at room temperature (PI), below 150 K it transitions to insulating phase (AFI) involving antiferromagnetic and ferroelastic symmetry breaking. In addition, AFI to PI transition also involves a non-symmetry-breaking volume contraction. Transient reflectivity studies of V_2O_3 in the AFI phase unveiled a transformation within time consistent with the acoustic propagation of strain waves. Astoundingly, transformation yield of up to 100% can be achieved above a threshold laser fluence. The granular morphology of V_2O_3 films favours complete transformation to the metallic phase, unlike a single crystal where in-plane clamping takes place and hinders photoinduced IMT [7]. The ultrafast x-ray diffraction on thin films revealed volume contraction and confirmed the quasi-complete transformation to metallic phase on the acoustic time-scale of strain waves, also observed in the optical studies.

In brief, we discuss how photoinduced strain and material morphology can provide with control knobs [6,8] in the fast-growing field of non-equilibrium material science, largely driven by progress in femtosecond x-ray techniques. The grand objective is to develop efficient stimuli and frugal functional materials operating either at ultrafast timescales or permanently switchable, with functionality on demand.

Acknowledgements: M. Lorenc and E.J. acknowledge the Agence Nationale de la Recherche for financial support under grant nos. ANR-16-CE30-0018 ('Elastica'), ANR-19-CE29-0018 ('Multicross') and ANR-23-CE30-0027 ('FASTRAIN'). S.I. acknoledges JST CREST (JPMJCR1901) and MEXT Q-LEAP (JPMXS0118067426) for their financial support. E.P. acknowledges support from the CNRS and the French Agence Nationale de la Recherche (ANR), under grant no. ANR-22-CPJ2-0053-01. This study is co-funded by the European Union (ERC, PhotoDefect, 101076203).

References

1. A. de la Torre et al., Rev. Mod. Phys. 93, 041002 (2021). D. N. Basov et al., Nature Materials 16 (2017) 1077.
2. Y. Tokura et al., Nature Physics 13(2017) 11.
3. A. Sood et al., Science 373 (2021) 352.
4. S.-i. Ohkoshi, et al., Nature Chem. 2 (2010) 539.
5. V. Guiot et al., Nature Commun. 4, 1 (2013). D. Babich et al., PRAppl. 17 (2022) 014040.
6. C. Mariette, et al., Nature Communications 12 (2021) 1-11.
7. A. von Reppert et al., Appl. Phys. Lett. 113 (2018) 123101.
8. T. Amano et al., Nature Phys. (2025)., DOI:10.1038/s41567-024-02628-4