TOPICAL REVIEW — Stephen J. Pennycook: A research life in atomic-resolution STEM and EELS

Editorial: Stephen J. Pennycook — A research life in atomic-resolution STEM and EELS

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(Received 13 December 2024; accepted manuscript online 13 December 2024)

DOI: 10.1088/1674-1056/ad9e9f

The interplay between advanced microscopy techniques and fundamental scientific discovery has always been a cornerstone of physics. Among the many tools that have reshaped our understanding of condensed matter and materials physics, **scanning transmission electron microscopy (STEM)** stands out as a transformative technique. By enabling direct atomic-scale imaging and advanced spectroscopic analysis, STEM has illuminated the complex atomic structures and dynamics that underpin material properties. In this spirit of innovation and discovery, we dedicate this special issue to celebrate the illustrious contributions of **Prof. Stephen J. Pennycook**, a pioneer whose work has defined the field of STEM and its applications.

STEM is much more than a powerful imaging tool; it is a gateway to the quantum world. Its ability to achieve atomic-resolution imaging while simultaneously providing chemical and electronic structural information through electron energy loss spectroscopy (EELS) has reshaped research paradigms in condensed matter physics and materials sciences. From elucidating atomic-scale defect structures to uncovering the interplay of lattice, charge, orbit, and spin in advanced functional materials, STEM has provided insights that would otherwise remain inaccessible. It has allowed us to probe not only where atoms are but also what they are doing and how they interact with their environment. Today, the technique is indispensable in the study of systems as diverse as quantum materials, energy materials, structural materials, and electronic devices.

Prof. Stephen Pennycook's contributions to STEM and EELS have been monumental. His pioneering work in ***Z*-contrast imaging** fundamentally changed how we visualize materials, enabling a direct correlation between atomic number and image intensity. This breakthrough provided unparalleled clarity and interpretability, laying the foundation for modern atomic-resolution imaging. Moreover, his advancements in STEM-EELS analysis have opened new avenues for understanding material properties, offering deep insights into elemental composition, chemical bonding, and electronic structure at atomic-resolution.

Beyond his technical contributions, Prof. Pennycook's work has profound impact in the fields of condensed matter physics, materials sciences and chemistry. His studies on grain boundary structures, high-temperature superconductors, and catalytic materials exemplify the power of STEM to unravel the atomic-scale mechanisms governing material behaviors. Equally remarkable is his impact as a mentor: over the years, Prof. Pennycook has trained more than 70 visiting scientists, postdocs and graduate students from across the world during his tenure at Oak Ridge National Laboratory (ORNL), the National University of Singapore, and most recently, as a Distinguished Visiting Professor at the University of Chinese Academy of Sciences. Many of these researchers have returned to their home countries and continue to contribute to STEM research, further amplifying his legacy.

This special issue brings together a rich collection of 19 articles, contributed by authors from China, the USA, the UK, Singapore, Japan, and Korea, reflecting the depth and breadth of STEM's impact on physical sciences.

We are particularly honored to feature two perspective articles:

(i) Prof. Stephen Pennycook's Perspective In this insightful piece, Pennycook discusses the physical insights gained from STEM and EELS that have advanced our understanding of materials physics. He also provides a visionary outlook on the future of electron microscopy, emphasizing the potential of atomic-resolution three-dimensional imaging and the integration of artificial intelligence (AI) in driving new discoveries.

(ii) Prof. Sokrates Pantelides' Perspective This article illustrates via a few examples how combining atomic-resolution STEM imaging and spectroscopy with density functional theory (DFT) calculations can provide a comprehensive understanding of material properties at the atomic scale. Pantelides also discusses the promising future synergy between emerging electron microscopy techniques and theoretical modeling.

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The special issue also includes a series of review articles that highlight the diverse applications and technical advancements of STEM: including progress in 3D imaging via STEM depth sectioning, and the applications of STEM in studying a wide range of materials, including electronic materials, beam-sensitive materials, superconducting nickelates, electrocatalysts, and metal halide perovskite thin films.

Additionally, the issue features a broad array of research articles focused on both STEM technique developments — such as 4D STEM and imaging quantification via Zernike moments — and STEM applications in fields of superconductors, multiferroics and two-dimensional materials. Collectively, these contributions exemplify the versatility and power of STEM as a tool for discovery.

As we look to the future, STEM continues to hold immense promise for advancing condensed matter physics and materials sciences. The integration of AI and machine learning is poised to revolutionize data acquisition and interpretation, enabling real-time analysis and the discovery of subtle correlations in complex datasets. Advances in three-dimensional imaging techniques, such as tomography, depth sectioning, and multi-slice ptychography, will allow researchers to explore materials in their full structural complexity. Emerging imaging and spectroscopy techniques will enable direct measurement of materials properties at the atomic scale. Furthermore, as environmental and *in-situ* capabilities improve, STEM will provide unparalleled insights into dynamic processes, such as chemical reactions and phase transitions. The ongoing microscopy technique development, coupled with innovative computational tools, will further expand the horizons of STEM, deepening our understanding of fundamental material properties.

This special issue is both a celebration of Prof. Stephen Pennycook's extraordinary contributions and a showcase of the transformative power of STEM in condensed matter and materials physics. We hope that the insights, perspectives, and discoveries presented here will inspire the community to push the boundaries of what is possible with electron microscopy. On behalf of the editorial team, we extend our gratitude to all the authors and reviewers who have contributed to this tribute, and to Prof. Stephen Pennycook for a lifetime of pioneering achievements that continue to shape the field.