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EDITORIAL

Preface to the Special Topic on *In-Situ* and *in-operando* Characterization of Semiconductor Materials and Devices

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Characterization of materials and devices is fundamental to the understanding of structure-property relationship and improving device performance. Driven by the rapid progress achieved in semiconductors research, advanced characterization techniques at high spatial resolution are being developed, with the capability to reveal microstructures down to atomic or sub-atomic scale. Coupled with *in-situ* and *in-operando* techniques, responses of materials and devices under multiple external stimuli can be investigated at both high spatial resolution and high time resolution, providing in-depth understanding of the growth, reaction, defects evolution and degradation mechanism etc. with unprecedented details.

This special issue assembles 6 review articles providing a timely summary of advanced *in-situ* and *in-operando* characterization techniques, covering areas of traditional semiconductor devices, organic semiconductor devices, metal oxide semiconductors, photocatalysts, and halide perovskites.

Jiang *et al.* dedicate the review to the up-to-date developments in the *in-situ/operando* optical, scanning probe microscopy, and spectroscopy techniques specifically for organic semiconducting films and devices[1]. Simultaneous probes of film morphological evolution, crystal structures, semiconductor-electrolyte interface properties, and charge carrier dynamics, as revealed by advanced *in-situ/operando* characterization, effectively facilitate the exploration of the intrinsic structure-property relationship of organic materials and the optimization of organic devices for advanced applications.

Zhang *et al.* introduce a comprehensive approach of defect study, i.e., a series mode, to address the issues of traditional parallel mode where defects investigated by structural characterization techniques were not the same defect that affected the device[2]. As demonstrated by the *in-operando* study of individual dislocation type defects in GaAs solar cells, this novel approach is able to offer answers to questions like: (i) how do individual defects affect device performance? (ii) how does the impact depend on the device operation conditions? (iii) how does the impact vary from one defect to another?

Li *et al.* deliverer a comprehensive review on quantitative transmission electron microscopy (TEM) characterization where off-axis electron holography is introduced in detail[3]. This unique method is illustrated by applications in various semiconductor nanomaterials including group IV, compound and two-dimensional semiconductor nanostructures, both in static states and under various stimuli. Particularly, the challenges facing the *in-situ* electron holographic study of semiconductor devices at working conditions are presented.

Fang *et al.* summarize the recent progress of *in-situ* characterization techniques on exploring the dynamic behavior of catalyst materials and reaction intermediates[4]. Semiconductor photocatalytic processes revealed by microscopic imaging and spectroscopic characterization are discussed. Challenges in *in-situ* characterization are highlighted, geared toward the development of more advanced *in-situ* techniques to guide the design of advanced photocatalysts.

Zhao *et al.* review the recent progress regarding the mechanical deformation mechanisms in metal oxide semiconductors, such as CuO and ZnO nanowires (NWs), using *in-situ* TEM[5]. Enabled by *in-situ* mechanical testing, the phase transformation of CuO NWs under compressive stress and phase transition in ZnO NWs under tensile strain is revealed down to atomic scale.

Wu *et al.* provide a timely review on recent studies of the halide perovskites using advanced TEM characterization[6]. Due to the extreme beam-sensitivity of the halide perovskites, the irradiation damages caused by the interaction between the electron beam and perovskite sample under the imaging conditions are discussed in detail. Emerging TEM techniques such as cryo-TEM, ptychography etc. are then discussed, where recent achievements on atomic-resolution imaging, defects identification and chemical mapping on halide perovskites are reviewed. Particularly, the developments of *in-situ* TEM in the degradation study of the perovskites under different environmental conditions such as heating, biasing, light illumination, and humidity are reviewed.

We sincerely hope this special issue could provide timely review and perspective on the development of emerging *in-situ/operando* characterization techniques and their contributions to unveil the structure-property relationship in semiconductor materials and devices, and ultimately improve the device performance. We also hope this special issue could not only benefit the on-going research in lab and industry by introducing cutting-edge characterization techniques, but also inspire more creative approaches to be developed for semiconductors research in the coming future.

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