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Editorial: Wide-bandgap oxide semiconductors: unveiling excitonic potential

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Editorial on the Research Topic
Wide-bandgap oxide semiconductors: unveiling excitonic potential

Excitons, bound states of electrons and holes via Coulomb attraction, are usually short-lived and weakly bound in semiconductors like silicon, primarily because of the strong dielectric screening effects. On the other hand, in the case of wide band semiconductors, exciton binding energies are significantly enhanced, ranging from approximately 60 meV in ZnO to more than 100 meV in β-Ga_2O_3, which often exceeds the thermal energy at room temperature (kT ~ 25 meV) (Das et al., 2022; Sikdar et al., 2020). This makes excitonic transitions stable and spectroscopically resolvable even at ambient conditions. Consequently, sharp excitonic absorption and emission features can be observed in photoluminescence (PL), reflectance, or ellipsometric spectra, often dominating the optical response near the band edge. The presence of the excitonic properties provides a platform for various optoelectronic applications of such materials. The various applications of excitons observed in a wide band gap oxide semiconductor is shown in the schematic of Figure 1.

ZnO, one of the most extensively studied wide band gap oxide semiconductors, shows three clear excitonic peaks. It has perhaps served as a model system for room-temperature excitonic lasing, and the development of polariton condensates in ZnO microcavities has propelled research into solid-state Bose–Einstein condensation. In contrast, β-Ga_2O_3, a fourth-generation semiconductor with a relatively broad bandgap of about 4.8 eV, has much larger exciton binding energies and anisotropic excitonic behaviour, much due to its low-symmetric monoclinic crystal structure. These characteristics, along with its high breakdown field, render Ga_2O_3 a highly promising material for numerous possible applications, including deep-ultraviolet photonics and high-power electronics devices (Shi and Qiao, 2022).

Despite their potential characteristics, retaining their excitonic properties can be challenging. This is due to the material issues, such as the presence of grain boundaries, native vacancies, and structural flaws. These material defects can act as nonradiative recombination sites that suppress excitonic emission. Excitons are typically more localised (Frenkel-type) and have a low radiative

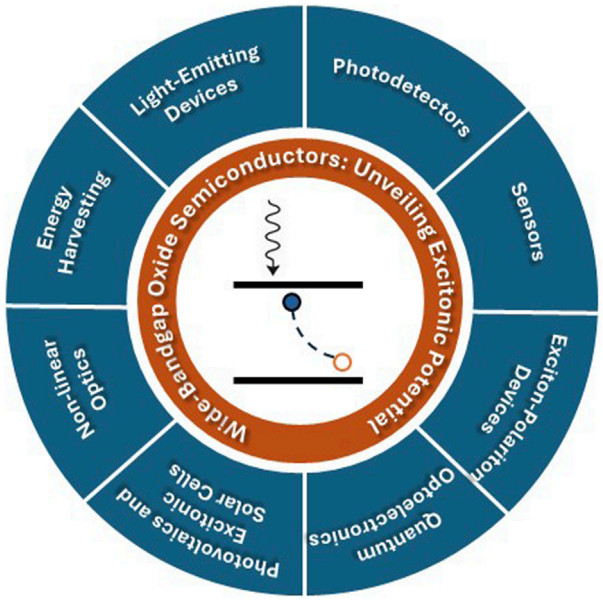

FIGURE 1
A schematic showing various applications of excitons present in a wide band gap oxide semiconductor.

recombination efficiency in materials such as TiO_2. This affects their utility in light-emitting applications but plays a crucial role in photocatalytic activity and charge separation processes (Olvera-Neria et al., 2024). Nevertheless, controlling crystallinity, surface states, and doping levels is essential for harnessing excitonic effects in a device.

Characterising excitonic properties in wide band gap materials has also been important for effectively understanding and designing functioning optoelectronic (excitonic) devices. Exciton lifetimes and recombination pathways can be directly measured using time-resolved photoluminescence (TRPL). High-resolution techniques such as cathodoluminescence (CL) spectroscopy and hyperspectral imaging can, on the other hand, image the exciton distribution, particularly in the vicinity of defects or interfaces.

Theoretical modelling has also been key in understanding the physics of the exciton, its origin, decay, and its engineering. State-of-the-art many-body perturbation theory, combined with the Bethe–Salpeter equation (BSE), has enabled quantitative predictions of exciton binding energies, wavefunctions, and optical spectra in excitonic wide band gap materials (Onida et al., 2002; Sun et al., 2020). These models are critical for the absolute understanding of excitonic behaviour and for guiding the design of heterostructures and quantum-confined systems.

Currently, the focus is mostly on excitonic engineering, which manipulates exciton formation, transport, and recombination through nano-structuring, strain modulation, and a dielectric environment. Quantum confinement of excitons, as provided by nanowires, quantum wells, and 2D oxides, can further improve excitonic binding and charge recombination dynamics. Integrated systems of 2D materials and oxide semiconductors can offer new opportunities for ultrafast charge separation and energy transfers. These systems are key to the fields of photovoltaics and excitonic transistors.

In summary, wide-bandgap oxide semiconductors' excitonic characteristics are essential to a variety of cutting-edge technologies and are no longer only an academic curiosity. The future of light-matter interaction will be shaped by the accurate control of excitonic dynamics as growth techniques advance and theoretical-experimental integration becomes more profound.

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