Determining Electronic and Thermal Properties of -Ga2O3 Based Devices Using In Situ STEM Combined with Spectroscopic Methods

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Meeting-report

Determining Electronic and Thermal Properties of β-Ga_2O_3 Based Devices Using In Situ STEM Combined with Spectroscopic Methods

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We present our recent study on atomic scale defects and interfaces in gallium oxide devices using scanning transmission electron microscopy (STEM) combined with various in situ and spectroscopic methods that provides insights on how atomic structure and defects correlate to the material's electronic and thermal properties. Beta gallium oxide (β-Ga_2O_3) shows unique advantages, such as the large bandgap (~ 4.8 eV), high breakdown voltage, and availability as inexpensive bulk substrates, that attracted significant attention for its potential applications in high power devices essential for efficient usage and transfer of energies, for example, for electrical grids for the wide adaptation of next-generation electric vehicles and high speed rails in the next decade.

Like in many other wide band gap semiconductors, the intrinsic n-type behavior and doping properties of β-Ga_2O_3 greatly depend on point defects. We first show the discovery of interstitial-divacancy complex in β-Ga_2O_3 (Fig. 1a and 1b) using quantitative STEM analysis combined with deep-level optical spectroscopy (DLOS) [1]. This complex is essential to understand because they form spontaneously as the impurity (or doping) concentration increases through an unusual self-relaxation mechanism, which results in the increased amount of Ga vacancies responsible for intrinsic n-type behavior related to a defect energy state that we detected using DLOS (Fig. 1c). Furthermore, we discovered that the complex can go through secondary relaxation assisted by local atomic jumping (i.e. diffusion) which eventually leads to γ-Ga_2O_3 that has been prevalently observed in heavily doped β-Ga_2O_3 (Fig. 2a) [2]. Such structural evolution and transformation were also observed in ion-implanted β-Ga_2O_3 devices, which we studied using in situ STEM as well as secondary ion mass spectrometry (SIMS) (Fig. 2b) [3]. In this case however, the strain from implanted ions induces martensitic-like transformation to γ-Ga_2O_3 (Fig. 2c), as opposed to the diffusional transformation. These results provide critical guidance to the doping and tuning of the β-Ga_2O_3 devices for their optimal performance.

Meanwhile, one drawback of β-Ga_2O_3 is low intrinsic thermal conductivity. Several approaches have been explored to mitigate this issue, such as by wafer bonding, for which we studied the impact of the interface quality to the thermal transport across the bonded interface [4]. To understand the thermal transport across the interface, or inversely the thermal interface resistance (TIR) that is critical for thermal management of the device, we introduce the STEM-based Debye-Waller thermometry [5], which measures the Debye-Waller factor from the electron scattering at the atomic resolution. This allows us to measure the temperature variation at the atomic to nanometer scale, which ideally enable the measurement of the temperature drop at the interface which can be directly related to TIR (Fig. 3a). A careful study of the sensitivity of the electron scattering to the detection angles was performed, which revealed the optimal scattering angles for the STEM Debye-Waller thermometry (Fig. 3b). TIR measurement using this method requires an in situ thermal gradient across the interface (Fig. 3c). We will discuss the details of the in situ settings for this measurement and our ongoing effort to determine the TIR at various oxide interfaces including the ones in β-Ga_2O_3 devices [6].

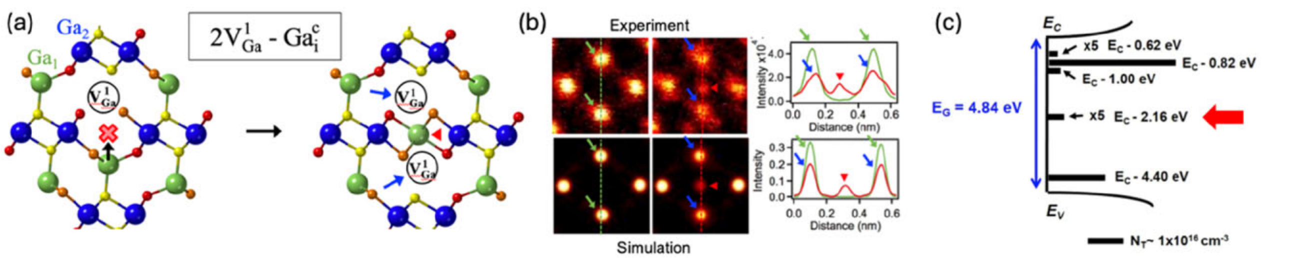

Fig. 1. (a) Schematic showing the formation of interstitial-divacancy complex (b) Experimental confirmation of the complex in experimental STEM images. (c) DLOS shows the defect state at E_c-2.16 eV that corresponds to the complex.

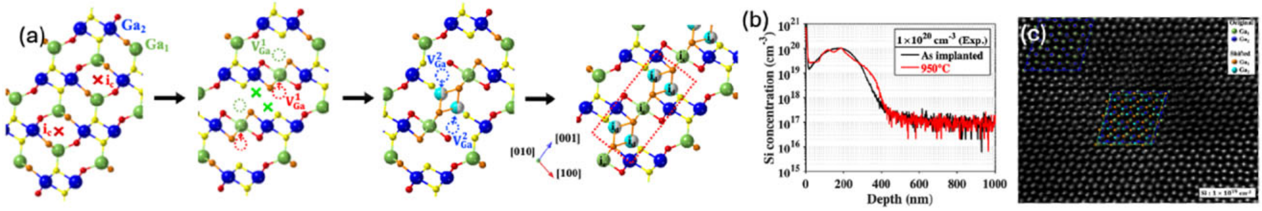

Fig. 2. (a) Secondary relaxation process of interstitial-divacancy complexes leading to γ-Ga_2O_3. (b) SIMS of ion-implanted β-Ga_2O_3 showing irregular distribution of Si implants that corresponds to the formation of point and extended defects shown in (c).

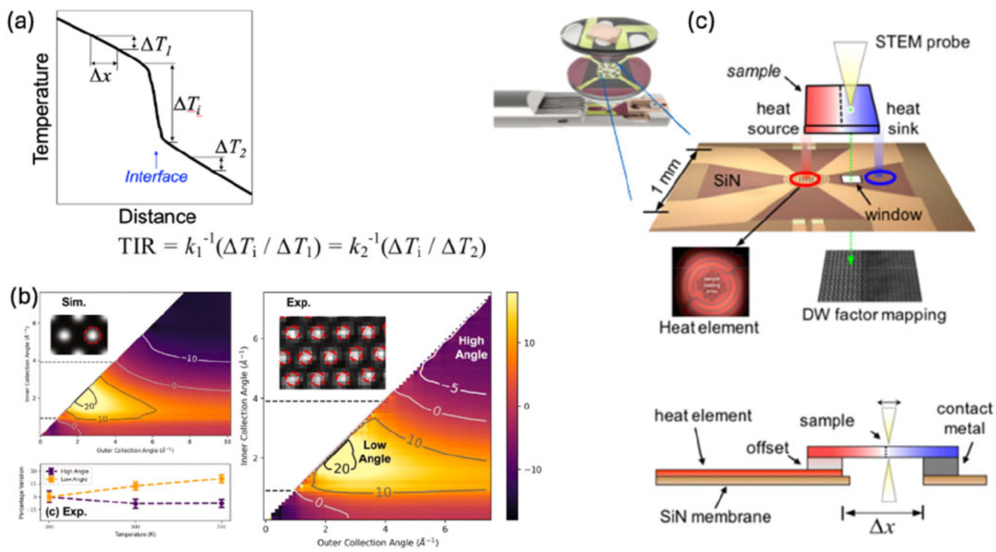

Fig. 3. (a) Determining TIR using the temperature change at the interface. (b) Sensitivity of atomic scale STEM image intensity as a function of low and high angle detection limit, simulation (left) vs. experiment (right). (c) In situ thermal gradient setup using a customized MEMS-type TEM heating holder.

Referenes

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