**Direct observation of the density of in-gap states of In2O3:H thin films and the origin of instability of thin film transistors**

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Nowadays, displays are essential devices in the information society. Their performance largely depends on the properties of the thin-film transistors (TFTs) in the displays. In recent years, the advancement of display technologies such as OLED and µLED has required the demand for TFTs with high field-effect mobility (*μ*FE ~100 cm2 V−1 s−1). *n-*type transparent oxide semiconductors (TOSs) are commonly used as channel layers in TFTs, and hydrogen-doped indium oxide (In2O3:H) has attracted significant attention due to its high *μ*FE (~100 cm2 V−1 s−1) [1].

However, the electron transport properties of In2O3:H are highly sensitive to the deposition and post-annealing conditions. Furthermore, the TFT characteristics are easily degraded under applying electric field and/or UV irradiation stress. The possible origin of such instability is the small electronic states in the bandgap, known as in-gap states. Despite their importance, in-gap states are extremely difficult to measure because their density is extremely low. Hard X-ray photoelectron spectroscopy (HAXPES) has been utilized to probe the in-gap states in the bulk directly. Previously, we demonstrated that high-energy excitation sources in HAXPES can induce sample damage in amorphous InGaZnO4 which is commercially used as a channel layer of TFTs [2]. In this study, we investigate the density of in-gap states of In2O3:H thin film by high-sensitivity ultraviolet photoelectron spectroscopy (HS-UPS) using low-energy photons. Low-energy photons minimize sample damage and achieve a long probing depth. We reveal the origin of the instability of TFTs based on the in-gap states observed directly.

In2O3:H films were fabricated by pulsed laser deposition at room temperature [3] and post-annealed in air at 300 °C for one hour. Figure 1 shows the HS-UPS spectrum in the gap region as a function of binding energy. The valence band maximum is set at the binding energy of 0 eV. The arrows show the Fermi level (*E*F). The excitation source was Xe I (*hν* = 8.4 eV). The HS-UPS measurements clarified the line shape of the density of in-gap states over nearly four orders of magnitude. After performing He I HS-UPS (*hν* = 21.2 eV) and XPS (*hv* = 1253 eV), we observed the generation of photo-induced in-gap states near the *E*F and the shift of the *E*F. These results indicate that Xe I HS-UPS is more suitable for probing the in-gap states of non-damaged In2O3:H. We will also discuss the origin of the photo-induced in-gap states and the relationship between in-gap states and instability of TFTs at the meeting.



Figure 1 High-sensitivity ultraviolet photoemission spectra in the band gap region. The excitation source is Xe I (*hv* = 8.4 eV).

[1] Y. Magari *et al.,* Nat. Commun., 13, 1078 (2022).

[2] R. Nakazawa *et al.,* J. Appl. Phys., 135, 085301 (2024).

[3] P. R. Ghediya et al., Small Methods 9, 2400578 (2025).