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High-Temperature Optical Properties of Indium Tin Oxide Thin-Films

Jiwoong Kim

University of Kentucky, jiwoong.kim@uky.edu

Sujan Shrestha

University of Kentucky, Sujan.Shrestha@uky.edu

Maryam Sourì

University of Kentucky, souri.maryam@gmail.com

John G. Connell

University of Kentucky, johnconnell@uky.edu

Sungkyun Park

Pusan National University, South Korea

See next page for additional authors

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Authors

Jiwoong Kim, Sujan Shrestha, Maryam Souri, John G. Connell, Sungkyun Park, and Ambrose Seo



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High-temperature optical properties of indium tin oxide thin-films

Jiwoong Kim^{1,2}, Sujan Shrestha¹, Maryam Souri¹, John G. Connell¹, Sungkyun Park² & Ambrose Seo¹✉

Indium tin oxide (ITO) is one of the most widely used transparent conductors in optoelectronic device applications. We investigated the optical properties of ITO thin films at high temperatures up to 800 °C using spectroscopic ellipsometry. As temperature increases, amorphous ITO thin films undergo a phase transition at ~200 °C and develop polycrystalline phases with increased optical gap energies. The optical gap energies of both polycrystalline and epitaxial ITO thin films decrease with increasing temperature due to electron–phonon interactions. Depending on the background oxygen partial pressure, however, we observed that the optical gap energies exhibit reversible changes, implying that the oxidation and reduction processes occur vigorously due to the low oxidation and reduction potential energies of the ITO thin films at high temperatures. This result suggests that the electronic structure of ITO thin films strongly depends on temperature and oxygen partial pressure while they remain optically transparent, i.e., optical gap energies > 3.6 eV.

Tin-doped indium oxide or indium tin oxide (ITO) is a transparent conductor, which is widely used in modern optoelectronic devices such as thin-film transistors, resistive switching memories, and solar cells^{1–5}. However, it is mostly unexplored if its high electrical conductivity and optical transparency will remain intact at extreme conditions such as high temperature or pressure. The question concerning the high-temperature property of materials is particularly important as modern technology evolves to device applications and operations in harsh environments above 500 °C^{6–8}. Since the bandgap energies of semiconductors usually decrease with increasing temperature^{9,10}, we may expect that ITO will also lose its optical transparency at high temperatures. Indeed, indium oxide (In₂O₃) single crystals have been reported to show a more significant reduction of its optical gap at high temperatures than semiconductor crystals such as Si and GaAs¹¹. This somewhat pessimistic result is understood by a strong interaction between electrons and lattice vibrations (i.e., electron–phonon interaction), affecting the bandgap energy of In₂O₃¹². However, it is essential to note that high concentrations of doped Sn ions and oxygen vacancies play a crucial role in the electronic band structure of ITO and its optical properties. For example, the optical gap energy of ITO is larger than that of undoped In₂O₃ because of the existence of free electron carriers¹³, according to the Burstein–Moss effect¹⁴, and the temperature dependence of free carrier concentration is nearly constant¹⁵. Hence, investigating the high-temperature optical properties of ITO requires systematic measurements and understanding of the role of dopants and defects as well as electron–phonon interactions.

In this paper, we report the high-temperature optical properties of ITO thin films up to 800 °C. We studied ITO thin films of amorphous (*a*-ITO), polycrystalline (*poly*-ITO), and epitaxial (*epi*-ITO) phases rather than ITO bulk crystals because these thin-film forms are the ones used in various optoelectronic device applications. While *a*-ITO thin films show an abrupt increase of optical gap energies due to crystallization at ~200 °C, the optical gap energies of *poly*-ITO and *epi*-ITO thin films decrease gradually as temperature increases. Nevertheless, the optical gap energies (E_g) remain higher than the visible photon energies (i.e., $E_g > 3$ eV), meaning that their optical transparency is unaffected. We also found that background oxygen partial pressure at high temperatures alters the optical gap energies of ITO thin films *reversibly* by oxidation and reduction processes. Our results demonstrate that an unintentional oxygen annealing effect at high temperatures can result in different optical and transport properties of ITO thin films.

¹Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA. ²Department of Physics, Pusan National University, Busan 46241, Korea. ✉email: a.seo@uky.edu

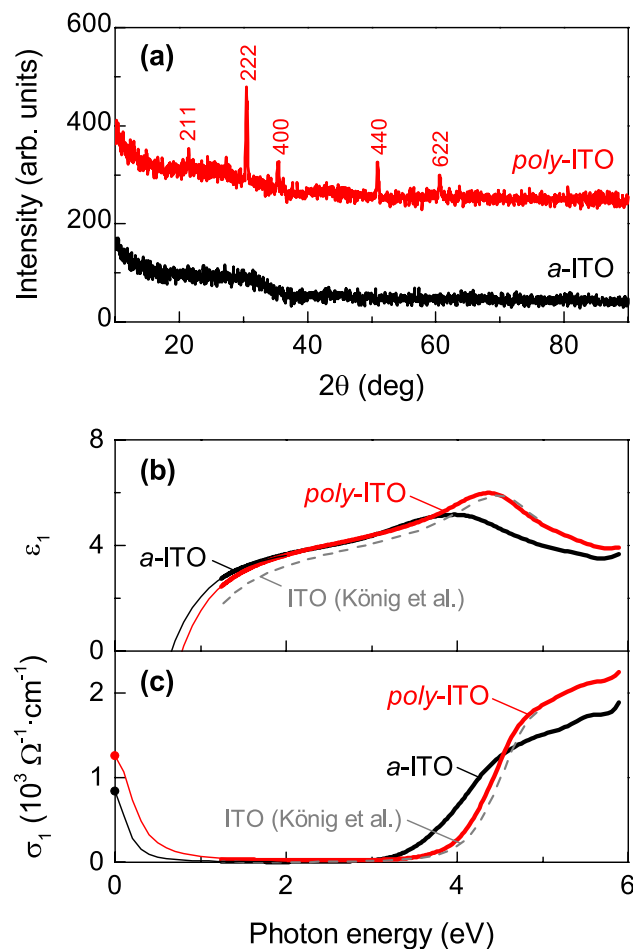


Figure 1. Structural and optical characterization of *a*-ITO and *poly*-ITO thin films. **(a)** XRD θ – 2θ scans of *a*-ITO (black) and *poly*-ITO (red) thin films. According to the diffraction indices of *poly*-ITO, it is a cubic bixbyite structure (ICSD #50848). **(b)** Dielectric constant (ϵ_1) and **(c)** optical conductivity (σ_1) spectra of *a*-ITO (black) and *poly*-ITO (red) thin films measured at room temperature. The grey dashed lines are the spectra from Ref.³³ for comparison. The dots at zero photon energy are from *dc*-conductivity measurements. The solid thin lines between 0 and 1.2 eV are interpolated using the Drude model.

Results and discussion

Amorphous and polycrystalline ITO thin films. We observed that *a*-ITO thin films undergo a phase transition in the annealing process and develop a polycrystalline phase with increased E_g at high temperatures. Figure 1a shows X-ray diffraction (XRD) θ – 2θ scans of both as-grown *a*-ITO and *poly*-ITO, which are ITO thin films on glass substrates before and after post-annealing at 500 °C, respectively. While the *a*-ITO thin film shows no visible peak, which verifies that the thin film is amorphous, clear diffraction peaks appear in the annealed sample. The diffraction peaks of the *poly*-ITO thin film match well with the cubic bixbyite ITO structure (ICSD #50848). Note that *poly*-ITO thin films exhibit a larger E_g (i.e., 4.25 ± 0.01 eV) than *a*-ITO thin films (i.e., 3.85 ± 0.01 eV) at room temperature, as shown in Fig. 1b,c. The relation between the complex dielectric function ($\tilde{\epsilon} = \tilde{n}^2 = \epsilon_1 + i\epsilon_2$), and the optical conductivity (σ_1) is $\sigma_1 = \frac{\epsilon_2\omega}{4\pi}$, where ω is the photon energy. The spectral shapes of ϵ_1 and σ_1 and the change of E_g are consistent with each other according to the Kramers–Kronig relation. We extrapolated the spectra below 1.2 eV using the Drude model¹⁶ to match with the *dc* conductivities (i.e., σ_1 at 0 eV) of these samples. The estimated plasma frequencies, where the dielectric constant crosses zero, increase from 0.7 ± 0.1 eV (*a*-ITO) to 0.8 ± 0.1 eV (*poly*-ITO). Since the plasma frequency (ω_p) is proportional to the carrier concentration (n_e) ($\omega_p^2 = 4\pi n_e e^2 / m$, where e and m are the elementary charge and the effective mass of electron, respectively), the enhanced E_g in *poly*-ITO thin films is presumably due to increased free carriers (i.e., the Burstein–Moss effect¹⁴) and reduced disorder¹⁷.

To determine high-temperature E_g of *a*-ITO and *poly*-ITO thin films, we calculated the absorption coefficient (α) from the extinction coefficient (k) using $\alpha = 4\pi k / \lambda$, where λ is the wavelength of the photon. Since the direct E_g has the relation: $\alpha \approx (\omega - E_g)^{1/2}$ (Ref.¹⁴), Figure 2a,b shows α^2 vs. photon energy plots of *a*-ITO and *poly*-ITO thin films above room temperature, respectively. E_g is estimated by linear extrapolation at each temperature. Figure 2c shows E_g as a function of temperature for both *a*-ITO and *poly*-ITO thin films. Note that E_g of *a*-ITO thin films shows an abrupt change above 200 °C, where polycrystalline ITO starts forming, as reported in

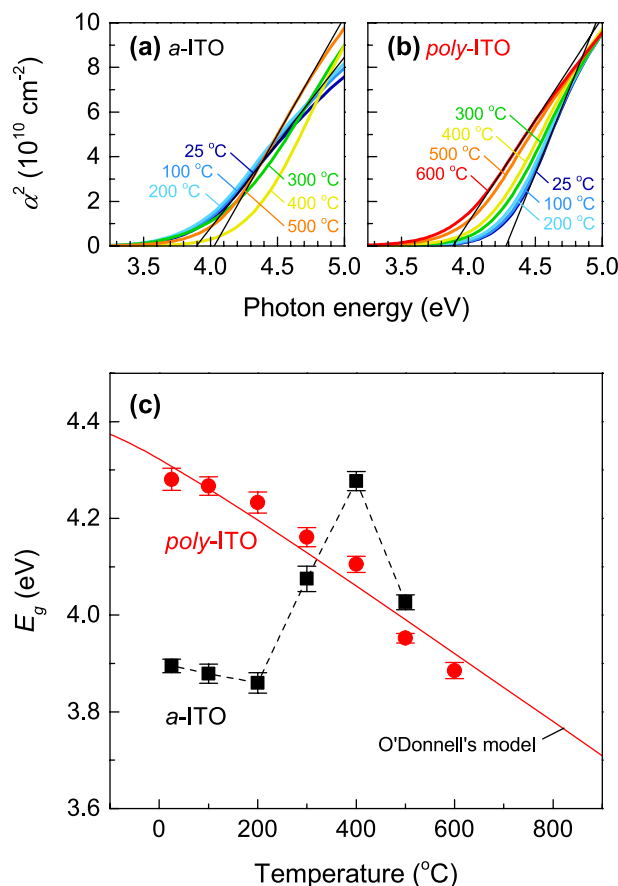


Figure 2. High-temperature optical properties of *a*-ITO and *poly*-ITO thin films. Absorption coefficient squared (α^2) vs. photon energy plots for (a) *a*-ITO and (b) *poly*-ITO thin films obtained from ellipsometry spectra at high temperatures up to 500 °C and 600 °C, respectively. The black lines are the linear extrapolation of α^2 spectra at 25 °C and 500 °C (600 °C) for the *a*-ITO (*poly*-ITO) thin film. (c) Optical gap energies of *a*-ITO and *poly*-ITO thin films as a function of temperature. The solid red line is a curve fit from O'Donnell's model¹⁰.

Refs.^{18,19}. On the other hand, E_g of *poly*-ITO thin films decreases gradually with increasing temperature, as also shown in Fig. 2c. We suggest that strong electron–phonon interaction of *poly*-ITO thin films is responsible for the temperature dependence of E_g . According to O'Donnell's model¹⁰, E_g at absolute temperature T is described by

$$E_g(T) = E_g(0) - S\langle\hbar\omega_{ph}\rangle \left[\coth\left(\frac{\langle\hbar\omega_{ph}\rangle}{2k_B T}\right) - 1 \right], \quad (1)$$

where S is a dimensionless coupling constant, $\langle\hbar\omega_{ph}\rangle$ is the average phonon energy, and k_B is the Boltzmann constant. Using the average phonon energy of In_2O_3 (38.6 meV)¹¹, we can obtain $E_g(0) = 4.40 \pm 0.04$ eV and $S = 4.2 \pm 0.5$, as shown in Fig. 2c (red line). Note that the coupling constant S is smaller than that of undoped In_2O_3 ($S = 8.24$)¹¹, implying that lattice imperfections such as substitutional Sn ions, oxygen vacancies, and grain boundaries, at which phonons are scattered²⁰, suppress the electron–phonon interactions in *poly*-ITO thin films.

Epitaxial ITO thin films. To explore intrinsic high-temperature optical properties, we measured *epi*-ITO thin films prepared in two different annealing conditions, i.e., $p(\text{O}_2) = 10$ mTorr (O_2 -annealed) and $p(\text{O}_2) < 1.0 \times 10^{-6}$ Torr (vacuum-annealed). Figure 3a,b shows XRD θ - 2θ scans and reciprocal space mappings, respectively. Both *epi*-ITO thin films are coherently grown without any notable secondary phases. It is noteworthy that these samples show identical in-plane (10.25 ± 0.01 Å) and out-of-plane lattice constants (10.07 ± 0.01 Å) regardless of the annealing conditions. The *epi*-ITO thin films are under tensile strain ($\sim 1.3\%$) due to the lattice mismatch with YSZ substrates²¹. However, the room-temperature optical spectra of *epi*-ITO thin films strongly depend on the annealing conditions presumably due to different concentrations of oxygen vacancies. It was found that the carrier concentration of In_2O_3 thin films decreased as increasing the O_2 pressure during growth^{22,23}. DFT calculations suggested that the oxygen vacancies are shallow donors in In_2O_3 , contributing to the carrier concentration^{24,25}. Figure 3c shows ϵ_1 and σ_1 spectra of *epi*-ITO thin films, respectively. The vacuum-annealed *epi*-ITO thin film shows both increased ω_p (0.8 ± 0.1 eV) and E_g (i.e., 4.26 ± 0.03 eV) compared to the O_2 -annealed *epi*-ITO thin film ($\omega_p = 0.5 \pm 0.1$ eV and $E_g = 4.00 \pm 0.05$ eV). This observation is consistent with the Burstein–Moss effect¹⁴ since larger free carrier concentrations result in higher E_g values. Therefore, the annealing

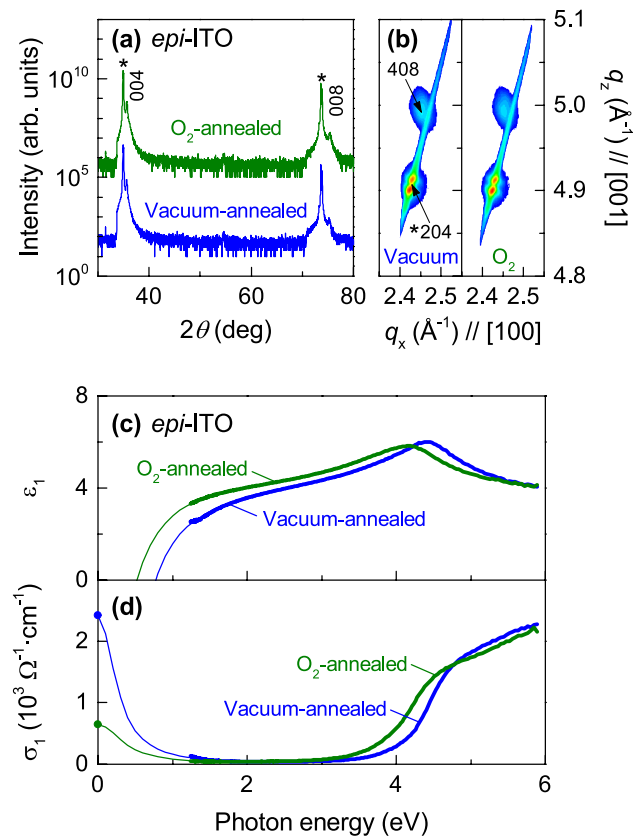


Figure 3. Structural and optical characterization of *epi*-ITO thin films. (a) XRD θ - 2θ scans of *epi*-ITO thin films annealed in O₂ (green) and vacuum (blue) conditions. The asterisks (*) and the indices denote the peaks from the YSZ substrate and cubic bixbyite ITO thin films, respectively. (b) X-ray reciprocal space maps near the 204-reflection of YSZ. Both samples show clear 408-reflections from *epi*-ITO thin films. (c) ϵ_1 and (d) σ_1 spectra of vacuum-annealed and O₂-annealed *epi*-ITO thin films at room temperature. The dots at zero photon energy are from *dc*-conductivity measurements. The solid thin lines between 0 and 1.2 eV are interpolated using the Drude model.

conditions influence the number of oxygen vacancies, which are electrons donors¹³, and increase (decrease) the carrier concentrations by reducing (oxidizing) *epi*-ITO thin films and change their optical properties without any noticeable difference in the crystal structure.

We measured E_g of *epi*-ITO thin films at high temperatures while maintaining the same environmental conditions as the post-annealing process. Figure 4a,b shows α^2 vs. photon energy plots for vacuum-annealed and O₂-annealed *epi*-ITO thin films, respectively. Figure 4c shows E_g of *epi*-ITO thin films as a function of temperature obtained from the spectra. Note that both samples show systematically decreasing E_g with increasing temperature. Based on the average phonon energy of In₂O₃ (38.6 meV)¹¹, we find $E_g(0) = 4.33 \pm 0.01$ eV and $S = 3.0 \pm 0.1$ for the vacuum-annealed *epi*-ITO thin film and $E_g(0) = 4.10 \pm 0.02$ eV and $S = 3.6 \pm 0.3$ for the O₂-annealed *epi*-ITO thin film. Interestingly, the O₂-annealed *epi*-ITO shows an almost constant E_g above 600 °C. We speculate that these steady E_g values above 600 °C are related to the phase transition of In₂O₃ from a cubic bixbyite structure to a rhombohedral corundum structure²⁶ because the E_g of corundum phase (3.8 eV)²⁷ is higher than bixbyite phase (2.7 eV)¹¹ at room temperature. However, it should be checked by high-temperature structural characterizations in future studies.

Oxidation and reduction of ITO thin films at high temperatures. We observed that *reversible* oxidation and reduction processes affect E_g of *epi*-ITO thin films at high temperatures. Figure 5 shows temperature-dependent E_g of vacuum-annealed or O₂-annealed *epi*-ITO thin films measured under the conditions of vacuum ($p(\text{O}_2) < 1.0 \times 10^{-6}$ Torr) or oxygen ($p(\text{O}_2) = 10$ mTorr). When the vacuum-annealed *epi*-ITO thin film is placed under the vacuum environment (Fig. 5a), its E_g shows identical temperature-dependence during the heating and cooling cycles. However, when the sample is under the oxygen environment (Fig. 5b), its E_g decreases significantly at around 300 °C during the heating process, and its E_g becomes about 0.23 eV smaller than the initial E_g after cooling down to room temperature. This observation indicates that exposure to high temperatures above 300 °C oxidizes *epi*-ITO thin films and reduces free electron carriers.

In contrast, when the O₂-annealed *epi*-ITO thin film is located under the vacuum condition, its E_g at room temperature increases about 0.24 eV after the heating and cooling cycle (Fig. 5c) whereas its E_g does not change

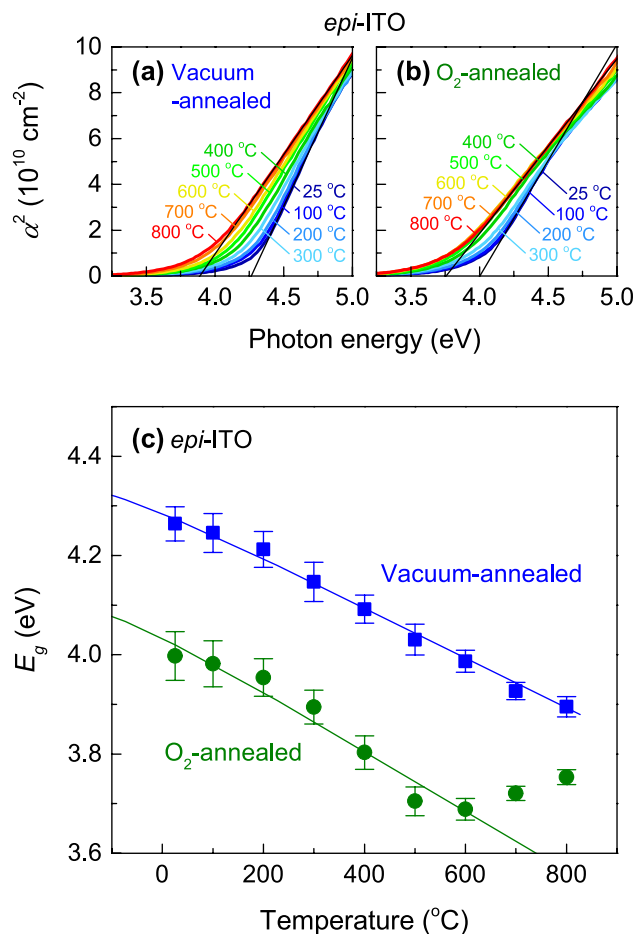


Figure 4. High-temperature optical properties of *epi*-ITO thin films. α^2 vs. photon energy plots for (a) vacuum-annealed and (b) O_2 -annealed *epi*-ITO thin films obtained from ellipsometry spectra at high temperatures up to 800 °C. The black lines show the linear extrapolation of α^2 spectra at 25 °C and 800 °C. (c) Optical gap energies of vacuum-annealed and O_2 -annealed *epi*-ITO thin films as a function of temperature. The blue and green lines are curve fits of vacuum-annealed and O_2 -annealed *epi*-ITO thin films, respectively, using O'Donnell's model¹⁰.

after the thermal cycling under the O_2 environment (Fig. 5d). The increased E_g under the vacuum condition reveals that oxygen vacancies and free-electron carriers are generated at high temperatures. Therefore, we can see that the background oxygen partial pressure at high temperatures affect the number of oxygen vacancies, which alters E_g of *epi*-ITO thin films. Note that the change of E_g is reversible (compare Fig. 5b with Fig. 5c), meaning that the oxidation and reduction potential energies of the ITO thin films are so low that oxidation and reduction processes occur vigorously at high temperatures.

Conclusion

We have investigated the optical properties of ITO thin films at high temperatures using SE. The *a*-ITO thin films undergo a phase transition from amorphous to polycrystalline above 200 °C, and its E_g increases during the transition due to increased free carriers and reduced disorder. The *poly*-ITO and *epi*-ITO thin films exhibit a decrease in E_g with increasing temperature due to electron–phonon interactions. By monitoring E_g of *epi*-ITO thin films, we have observed that the oxidation and reduction processes occur reversibly at high temperatures depending on background oxygen partial pressure. All ITO thin films exhibit E_g higher than 3.5 eV up to 800 °C despite various changes in their electronic structures, suggesting that ITO thin films possess robust optical transparency for high-temperature device applications.

Methods

We synthesized *a*-ITO and *poly*-ITO thin films grown on glass substrates. The *a*-ITO thin films were grown by using the *dc*-magnetron sputtering technique with a mixture gas of Ar and O_2 . The as-grown *a*-ITO thin films were crystallized into *poly*-ITO thin films after annealing at 500 °C under O_2 environment ($p(\text{O}_2) = 10$ mTorr). We fabricated the *epi*-ITO thin films on yttria-stabilized zirconia (YSZ) Y:ZrO_2 (001) substrates using pulsed laser deposition (PLD). The PLD conditions were the oxygen partial pressure ($p(\text{O}_2)$) of 10 mTorr, and the laser (KrF excimer laser ($\lambda = 248$ nm)) influence of 1.5 J/cm² with the repetition rate of 10 Hz. The substrate temperature

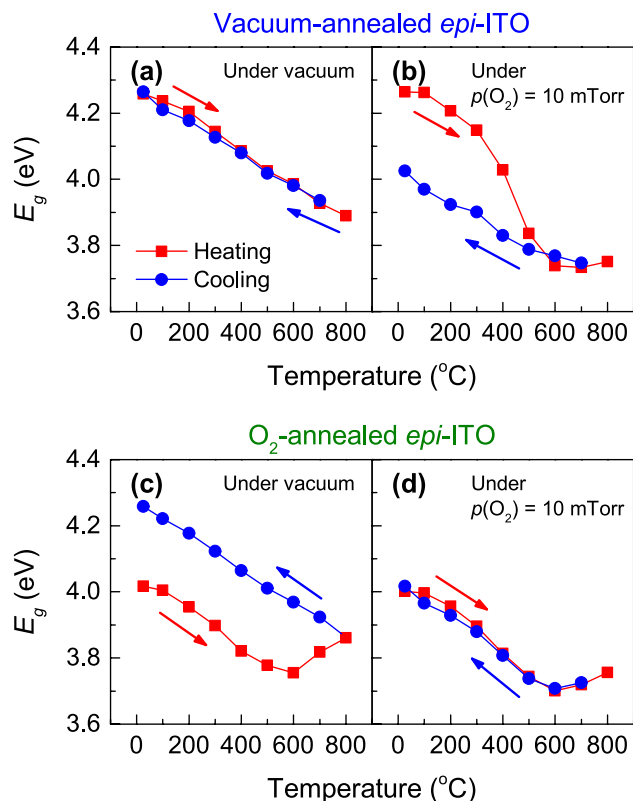


Figure 5. Optical gap energies of *epi*-ITO thin films during oxidation and reduction processes. The vacuum-annealed *epi*-ITO thin film is exposed to (a) vacuum and (b) $p(\text{O}_2) = 10$ mTorr during the thermal cycle. The O_2 -annealed *epi*-ITO thin film is exposed to (c) vacuum and (d) $p(\text{O}_2) = 10$ mTorr during the thermal cycle. The red and blue arrows indicate the directions of heating and cooling processes, respectively.

was 600 °C to grow high crystalline *epi*-ITO thin film²⁸. After the *epi*-ITO thin film growth, the samples were annealed under vacuum ($p(\text{O}_2) < 1.0 \times 10^{-6}$ Torr) and O_2 ($p(\text{O}_2) = 10$ mTorr) environments, respectively, to control oxygen vacancies inside the thin films. Table S1 summarizes the growth condition of various ITO thin films in this study. We performed optical spectroscopic measurements with photon energies from 1.2 to 6.0 eV using a spectroscopic ellipsometer (Woollam M-2000) equipped with a custom-built vacuum chamber²⁹ with an incident angle of 65° at high temperatures. We measured *a*-ITO (*poly*-ITO) thin films at $p(\text{O}_2) = 10$ mTorr up to 500 °C (600 °C) before the glass substrate is deformed³⁰. For *epi*-ITO thin films, we measured up to 800 °C under vacuum ($p(\text{O}_2) < 1.0 \times 10^{-6}$ Torr) and oxygen ($p(\text{O}_2) = 10$ mTorr) environments. We extracted the complex refractive index, $\tilde{n} = n + ik$, where n and k are the refractive index and the extinction coefficient, respectively, from the measured spectroscopic ellipsometry parameters, Ψ and Δ , which are the amplitude ratio and phase difference³¹, using numerical interaction process based on the Fresnel equation³². (See the Supplementary material for details.) We used a single slab model, i.e., air/ITO/YSZ, without any correction of surface roughness.

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References

- Qian, K., Han, X., Li, H., Chen, T. & Lee, P. S. Uncovering the indium filament revolution in transparent bipolar ITO/SiO_x/ITO resistive switching memories. *ACS Appl. Mater. Interfaces* **12**, 4579–4585 (2020).
- Lin, Y. *et al.* 17% Efficient organic solar cells based on liquid exfoliated WS₂ as a replacement for PEDOT:PSS. *Adv. Mater.* **31**, 1902965 (2019).
- Liu, Z. *et al.* Flexible indium-tin-oxide homojunction thin-film transistors with two in-plane gates on cellulose-nanofiber-soaked papers. *Adv. Electron. Mater.* **5**, 1900235 (2019).
- Kim, J.-H. *et al.* Flexible ITO films with atomically flat surfaces for high performance flexible perovskite solar cells. *Nanoscale* **10**, 20587–20598 (2018).
- Delahoy, A. E. & Guo, S. In *Handbook of Photovoltaic Science and Engineering* (eds Luque, A. & Hegedus, S.) 716–796 (Wiley, New York, 2011).
- Watson, J. & Castro, G. A review of high-temperature electronics technology and applications. *J. Mater. Sci. Mater. Electron.* **26**, 9226–9235 (2015).
- Medina, D. F. In *Handbook of Cosmic Hazards and Planetary Defense* (eds Pelton, J. N. & Allahdadi, F.) 295–314 (Springer International Publishing, Cham, 2015).
- National Research Council *Materials for High-Temperature Semiconductor Devices* (The National Academies Press, 1995).

9. Varshni, Y. P. Temperature dependence of the energy gap in semiconductors. *Physica* **34**, 149–154 (1967).
10. O'Donnell, K. P. & Chen, X. Temperature dependence of semiconductor band gaps. *Appl. Phys. Lett.* **58**, 2924–2926 (1991).
11. Irmscher, K. *et al.* On the nature and temperature dependence of the fundamental band gap of In_2O_3 . *Phys. Status Solidi A* **211**, 54–58 (2014).
12. Morris, A. J. & Monserrat, B. Optical absorption driven by dynamical symmetry breaking in indium oxide. *Phys. Rev. B* **98**, 161203 (2018).
13. Fan, J. C. C. & Goodenough, J. B. X-ray photoemission spectroscopy studies of Sn-doped indium-oxide films. *J. Appl. Phys.* **48**, 3524–3531 (1977).
14. Hamberg, I. & Granqvist, C. G. Evaporated Sn-doped In_2O_3 films: Basic optical properties and applications to energy-efficient windows. *J. Appl. Phys.* **60**, R123–R160 (1986).
15. Müller, H. K. Electrical and optical properties of sputtered In_2O_3 films. I. Electrical properties and intrinsic absorption. *Phys. Status Solidi B* **27**, 723–731 (1968).
16. Ginley, D. S., Hosono, H. & Paine, D. C. *Handbook of Transparent Conductors* (Springer, New York, 2010).
17. Madan, A. & Shaw, M. P. In *The Physics and Applications of Amorphous Semiconductors* (eds Madan, A. & Shaw, M. P.) 1–10 (Academic Press, London, 1988).
18. Kim, J.-W. *et al.* Atomistic aspects of carrier concentration variation in post-annealed indium tin oxide films. *J. Phys. D Appl. Phys.* **48**, 395307 (2015).
19. Paine, D. C. *et al.* A study of low temperature crystallization of amorphous thin film indium–tin–oxide. *J. Appl. Phys.* **85**, 8445–8450 (1999).
20. Ziman, J. M. *Electrons and Phonons: The Theory of Transport Phenomena in Solids* (Oxford University Press, Oxford, 2001).
21. Taga, N. *et al.* Electrical properties of heteroepitaxial grown tin-doped indium oxide films. *J. Appl. Phys.* **80**, 978–984 (1996).
22. Nistor, M., Gherendi, F. & Perrière, J. Degenerate and non-degenerate In_2O_3 thin films by pulsed electron beam deposition. *Mater. Sci. Semicond. Process.* **88**, 45–50 (2018).
23. Nistor, M., Seiler, W., Hebert, C., Matei, E. & Perrière, J. Effects of substrate and ambient gas on epitaxial growth indium oxide thin films. *Appl. Surf. Sci.* **307**, 455–460 (2014).
24. Chatratin, I. *et al.* Role of point defects in the electrical and optical properties of In_2O_3 . *Phys. Rev. Mater.* **3**, 074604 (2019).
25. Buckeridge, J. *et al.* Deep vs shallow nature of oxygen vacancies and consequent *n*-type carrier concentrations in transparent conducting oxides. *Phys. Rev. Mater.* **2**, 054604 (2018).
26. Jiang, X. B., Jiang, M. & Zhao, M. Thermodynamic understanding of phase transitions of In_2O_3 nanocrystals. *Chem. Phys. Lett.* **563**, 76–79 (2013).
27. Fujita, S. & Kaneko, K. Epitaxial growth of corundum-structured wide band gap III-oxide semiconductor thin films. *J. Cryst. Growth* **401**, 588–592 (2014).
28. Ohta, H. *et al.* Highly electrically conductive indium–tin–oxide thin films epitaxially grown on yttria-stabilized zirconia (100) by pulsed-laser deposition. *Appl. Phys. Lett.* **76**, 2740–2742 (2000).
29. Gruenewald, J. H., Nichols, J. & Seo, S. S. A. Pulsed laser deposition with simultaneous in situ real-time monitoring of optical spectroscopic ellipsometry and reflection high-energy electron diffraction. *Rev. Sci. Instrum.* **84**, 043902 (2013).
30. Guerette, M. & Huang, L. In-situ Raman and Brillouin light scattering study of the international simple glass in response to temperature and pressure. *J. Non-Cryst. Solids* **411**, 101–105 (2015).
31. Azzam, R. M. A. & Bashara, N. M. *Ellipsometry and Polarized Light* (North-Holland, Amsterdam, 1987).
32. Maulana, L. Z. *et al.* Inexpensive home-made single wavelength ellipsometer ($\lambda = 633 \text{ nm}$) for measuring the optical constant of nanostructured materials. *IOP Conf. Ser. Mater. Sci. Eng.* **202**, 012031 (2017).
33. König, T. A. F. *et al.* Electrically tunable plasmonic behavior of nanocube-polymer nanomaterials induced by a redox-active electrochromic polymer. *ACS Nano* **8**, 6182–6192 (2014).

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Author contributions

J.K. and J.G.C. synthesized the samples. J.K. carried out the X-ray diffraction and optical spectroscopic ellipsometry measurements. S.S., M.S. and S.P. provided technical assistance and scientific advice. J.K. and A.S. analyzed the experimental data, wrote the manuscript, and all authors reviewed it. A.S. conceived the project and supervised its progress for this manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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