Supporting Information

Indium Oxide Thin-Film Transistors Processed at Low Temperature via Ultrasonic Spray Pyrolysis

Hendrik Faber, Yen-Hung Lin, Stuart R. Thomas, Kui Zhao, Nikos Pliatsikas, Martyn A. McLachlan, Aram Amassian, Panos A. Patsalas and Thomas D. Anthopoulos*

Prof. T. D. Anthopoulos, Mr. Y.-H. Lin, Dr. S. R. Thomas, Dr. H. Faber
Department of Physics and Centre for Plastic Electronics
Blackett Laboratory, Imperial College London
London SW7 2AZ (United Kingdom)
E-mail: t.anthopoulos@ic.ac.uk; h.faber@imperial.ac.uk

Dr. M. McLachlan
Department of Materials and Centre for Plastic Electronics
Imperial College London
London Royal School of Mines
London SW7 2AZ (United Kingdom)

Dr. Kui Zhao, Prof. Aram Amassian
Materials Science and Engineering
Division of Physical Sciences and Engineering
King Abdullah University of Science and Technology
Thuwal 23955-6900, Saudi Arabia

Prof. P. A. Patsalas, Mr. Nikos Pliatsikas
Department of Physics, Laboratory of Applied Physics
Aristotle University of Thessaloniki
GR-54124 Thessaloniki, Greece

S1. Tauc analysis.

The intercept of extrapolated plots of $(\alpha h\nu)^2$ vs. hν (Tauc plots) was used to evaluate the optical band gap of spray deposited indium oxide films. For deposition temperatures of 200 °C, 250 °C and 300 °C, the optical band gap values were found to be 3.81 eV, 3.77 eV and 3.78 eV, respectively (**Fig. S1**).

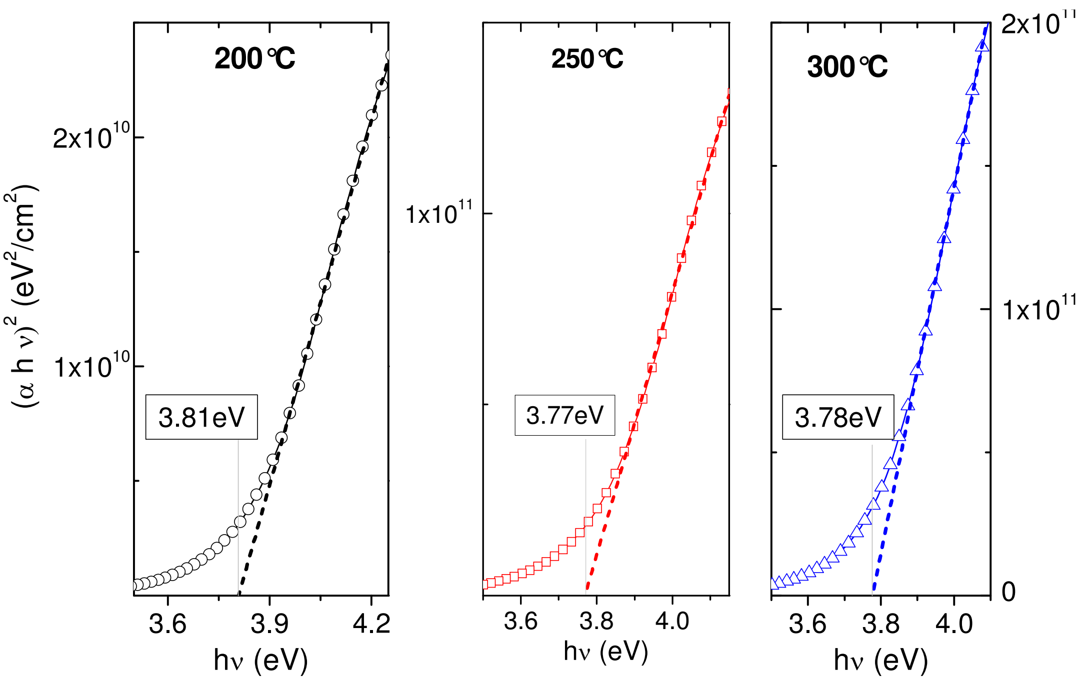

Figure S1. Tauc ($(\alpha h\nu)^2$ vs. hν) plots used for determining the optical band gap of indium oxide layers grown at three different deposition temperatures namely 200 °C, 250 °C, and 300 °C.

S2. XRD survey scan

The XRD patterns of all investigated indium oxide films deposited at temperatures between 200 °C and 300 °C indicate a good match to the cubic In_2O_3 powder diffraction reference (see **Fig. S2**). The determination of the mean grain size was carried out using the Scherrer method and the (222) peak at ~30.5 ° (see **Fig. 3a**).

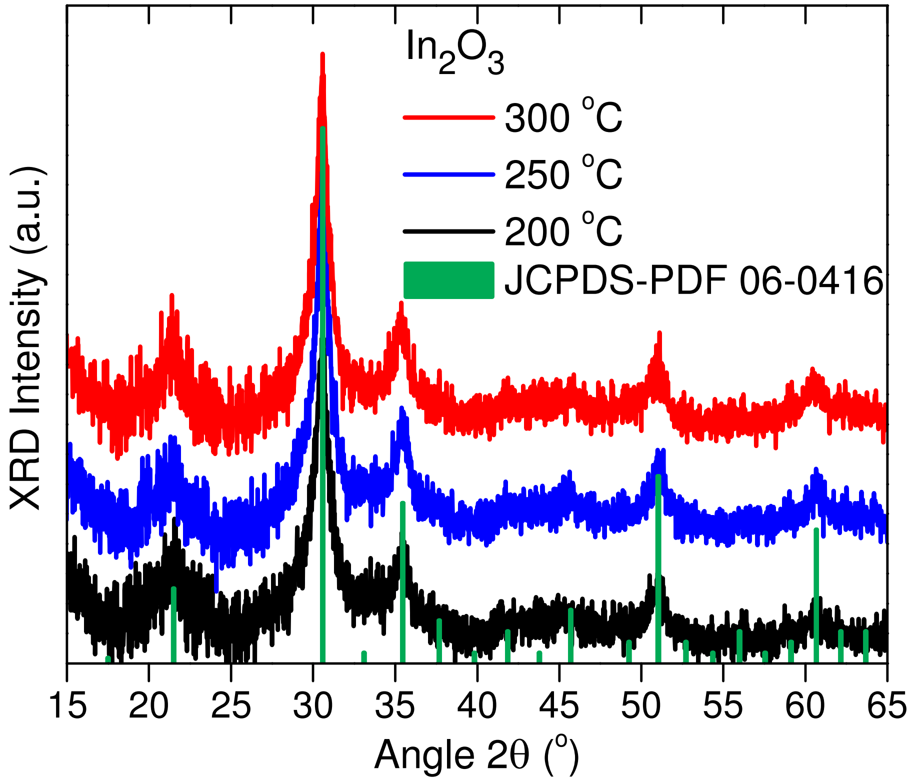

Figure S2. XRD wide angle scans measured for indium oxide films deposited at T_D = 200 °C, 250 °C, and 300 °C. The patterns are vertically moved for better visibility and represent data after subtraction of substrate contributions.

S3. Comparison with In_2O_3 Powder Reference

The resemblance of XRD and GIXRD patterns indicate that there is no preferred growth orientation and the growth of In_2O_3 crystals is random, as in a powder sample. In order to evaluate quantitatively this feature, all the peaks observed in the GIXRD were fitted by Lorentzians from which the peak strength (i.e. integral area) was determined. The result of this analysis for a film deposited at $T_D = 250°C$ is compared to the reference powder diffraction file (JCPDS-PDF 06-0416) and both are listed in Table SI. The results listed in **Table S1** are visualized in **Figure S1**; the observed differences between experiment and reference are minor and within the experimental error limits. Therefore, there is a strong quantitative proof for the random orientation of the grown In_2O_3 grains.

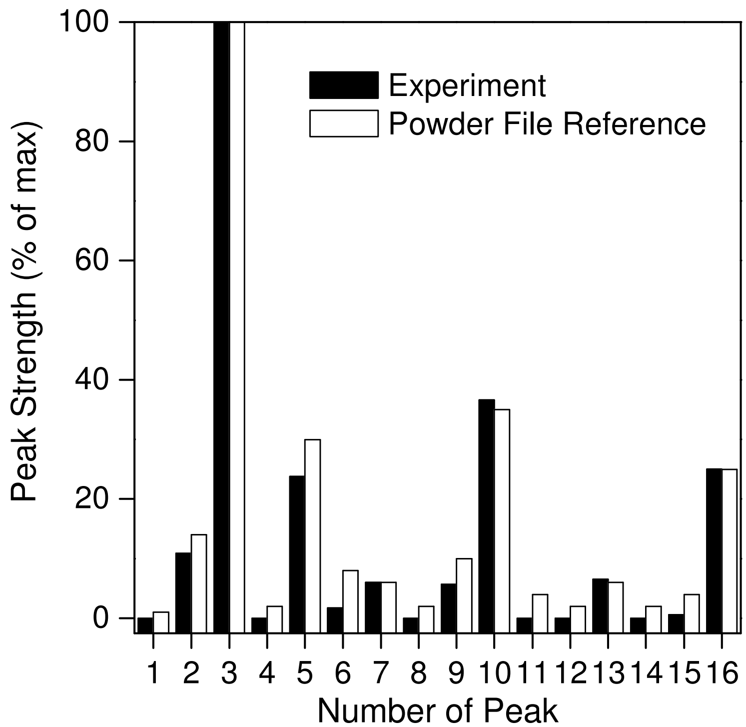

Figure S3. Histogram of comparison of the experimental (Experiment) and powder reference (Powder File Reference) strengths of the first 16 diffraction peaks of In_2O_3 grown at $T_D = 250$ °C.

Table S1. Comparison of the relative strength (%) of the diffraction peaks observed in experiment and in the reference file.

Peak	Angle 2θ (°)	*hkl*	Peak strength (% of max.) Experiment	Powder file reference
1	17.5	200	0.00	1.01
2	21.38	211	10.92	13.99
3	30.49	222	100.00	100.00
4	33.11	321	0.00	2.01
5	35.39	400	23.75	29.99
6	37.55	411	1.68	7.98
7	41.62	332	6.00	6.00
8	43.79	422	0.00	2.01
9	45.53	431	5.71	10.00
10	50.91	440	36.61	34.99
11	52.72	433	0.00	4.00
12	54.37	600	0.00	2.01
13	56.36	611	6.56	6.00
14	57.56	620	0.00	2.01
15	59.14	541	0.58	4.00
16	60.32	622	25.02	24.99

S4. X-Ray Diffused Scattering Measurements

X-ray diffused scattering (XDS) measurements were performed in order to determine the density of the as-deposited indium oxide films. **Figure S4** displays a representative XDS measurements for two films grown at 250 °C and 300 °C. In XDS the surface density ρ can be calculated from the critical angle θ_c:

$$\theta_c^2 = \left(\frac{e^2\lambda^2}{\pi m c^2}\right)\left(\mathrm{N}_0\frac{\mathrm{Z}}{\mathrm{A}}\right)\rho \tag{3}$$

Here, *m* and *e* are the electron mass and charge, respectively, λ is the X-ray wavelength, N_0 is the Avogadro's number, and Z and A are the atomic number and atomic weight of the studied element, respectively. θ_c is manifested in XDS as two distinct peaks (**Figure S4**), called Yoneda wings, that appear for $\theta_i=\theta_c$ and $\theta_d=\theta_c$, where θ_i and θ_d are the angle of incidence and the angle of detector, respectively.

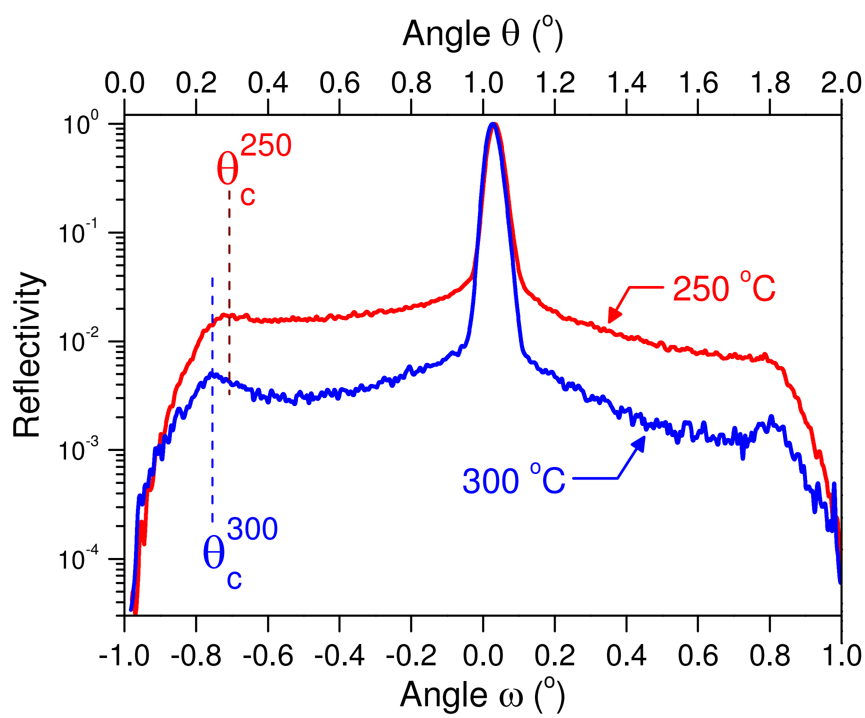

Figure S4. Representative XDS measurements for two indium oxide films grown at 250 °C and 300 °C. Measurements performed on indium oxide films grown a T_D = 200 °C did not yield sufficient signal and similar analysis could not be performed. Analysis of the data reveal that films grown at 250 °C are denser (ρ = 4.75 g cm^{-3}) as compared to film grown at 300 °C (ρ = 3.25 g cm^{-3}). However, both film densities is well below that od crystalline In_2O_3 (ρ = 7.179 g cm^{-3}).

S5. Transistor Transfer and Output Characteristics

A set of representative transfer and output characteristics of In_2O_3 transistors processed at different temperatures in the range 200-300 °C is shown in **Figure S5**. A summary of the transistor operating characteristics is provided in **Table S2**.

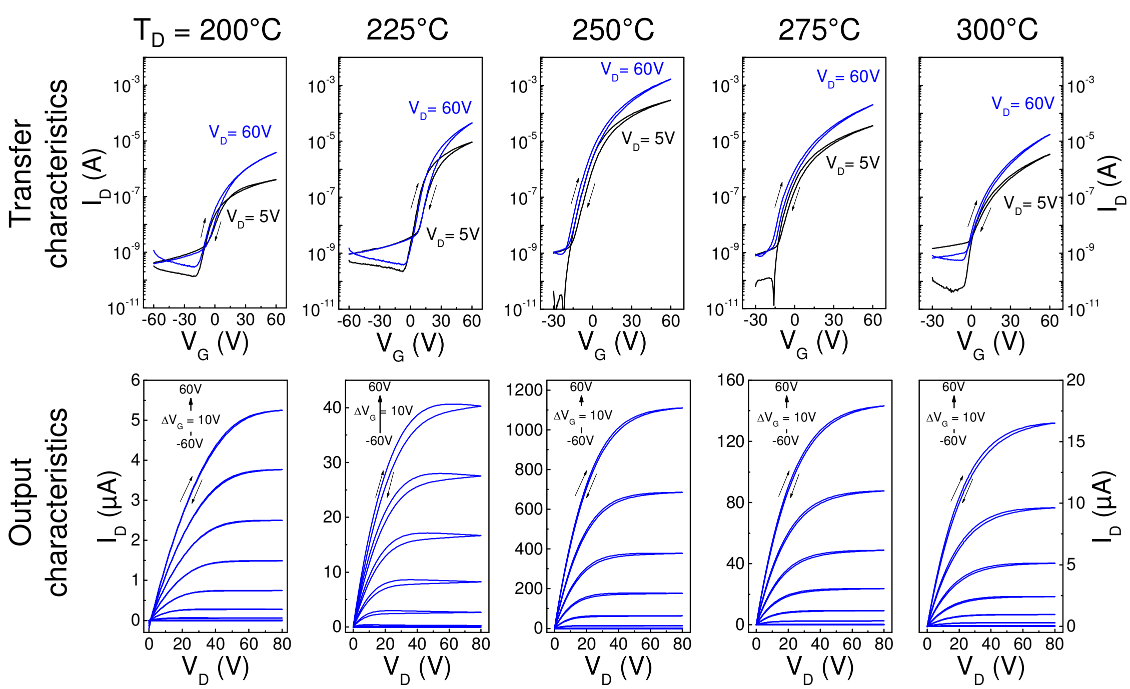

Figure S5. Representative transfer (top row) and output (bottom row) characteristics of In_2O_3 bottom-gate top-contact transistors with channel length (L) and width (W) of 100 μm and 1000 μm, respectively. Transistors were fabricated at temperatures between 200-300 °C employing SiO_2 as the gate dielectric.

Table S2: Summary of the transistor operating characteristics shown in **Fig. S3**. Electron mobility values were calculated in the linear (V_D = 5 V) and saturation (V_D = 60 V) regimes using the standard gradual channel approximation model. Specifically the linear mobility was calculated using $\mu_{lin} = \frac{L}{WC_i V_{D,lin}} \frac{\partial I_{D,lin}}{\partial V_G}$, while the saturation mobility employing $\mu_{sat} = \frac{L}{W\,C_i} \frac{\partial^2 I_{D,sat}}{\partial V_G^2}$, where L and W are the channel length and width respectively, I_D is the drain current and C_i the geometrical capacitance of the gate dielectric (i.e. SiO_2) used.

Deposition temperature (°C)	Mobility (cm^2/Vs)		V_{TH} (V)	Current on/off
	Linear	Saturation		
200	0.02 ± 0.006	0.03 ± 0.002	1.5 ± 2.0	2.2×10^4
225	0.5 ± 0.03	0.6 ± 0.03	19.7 ± 4.0	4.3×10^5
250	17.7 ± 1.8	16.2 ± 1.3	9.6 ± 1.6	7.5×10^6
275	3.2 ± 1.4	3.8 ± 1.6	12.4 ± 3.0	3.4×10^5
300	0.32 ± 0.15	0.37 ± 0.16	19.3 ± 3.7	2.4×10^4