High mobility transparent thin-film transistors with amorphous zinc tin oxide channel layer

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Transparent thin-film transistors (TTFTs) with an amorphous zinc tin oxide channel layer formed via rf magnetron sputter deposition are demonstrated. Field-effect mobilities of 5–15 and 20–50 cm² V⁻¹ s⁻¹ are obtained for devices post-deposition annealed at 300 and 600 °C, respectively. TTFTs processed at 300 and 600 °C yield devices with turn-on voltage of 0–15 and −5–5 V, respectively. Under both processing conditions, a drain current on-to-off ratio greater than 10⁷ is obtained. Zinc tin oxide is one example of a new class of high performance TTFT channel materials involving amorphous oxides composed of heavy-metal cations with (n−1)d¹⁰ ns⁰ (n ≥ 4) electronic configurations. © 2005 American Institute of Physics. [DOI: 10.1063/1.1843286]
so it is not possible to explicitly identify the phase(s) present in the film. Moreover, the breadth of the diffraction peaks indicates that crystallites within the film do not exceed a diameter of ~5 nm. Thus, the exact description of the zinc tin oxide film as multiphase nanocrystalline or amorphous is difficult to discern. In contrast, above an annealing temperature near 650 °C, a multiplicity of sharp XRD peaks appear, indicating a dramatic increase in the crystalline nature of the zinc tin oxide films.

The scanning electron microscope (SEM) image shown in the inset of Fig. 2 is a cross-sectional view of a zinc tin oxide film. This image is obtained at a magnification of 100 000× and provides qualitative information regarding the morphology of these zinc tin oxide thin films. In agreement with XRD results, the image does not indicate any grain formation in the sample. Similar to the XRD results, there is little, if any, observable difference in the SEM cross-sectional view of unannealed samples and those samples that are annealed up to 600 °C.

The optical transmittance versus wavelength through the source/drain region of a zinc tin oxide TTFT is shown in Fig. 1. The average transmittance in the visible portion of the electromagnetic spectrum (400–700 nm) is ~84% for this device. The data represent raw transmission through the entire structure, including the substrate, i.e., the measured transmission is reduced by both absorption and reflection.

The electrical parameters used to characterize a thin-film transistor are typically threshold voltage, drain current on-to-off ratio, and channel mobility. The threshold voltage (extracted from an \( I_D - V_{GS} \) measurement with a small \( V_{DS} = 40 \) V) for device operation in the linear region is typically 0–10 V for zinc tin oxide channel TTFTs. However, precise identification of the threshold voltage for a given device is somewhat ambiguous. A less ambiguous device parameter, although not explicitly quoted as often in the literature, is the turn-on voltage \( (V_{on}) \). This parameter is the gate voltage at the onset of channel current flow.
conduction, i.e., the gate voltage at the onset of the initial sharp increase in current in a \( \log(I_D)-V_{GS} \) characteristic.\(^{22}\) \( V_{on} \) is equal to \(-5 \) V in Fig. 3, and it is typically \(-5 \) to \(5 \) V for \(0\)–\(50 \) zinc tin oxide channel devices with a \(600 ^\circ C \) post-deposition anneal.

The typical \( I_D \) on-to-off ratio is \(\sim 10^2 \)–\(10^4 \). As shown in Fig. 3, the transistor “off” current is established by gate leakage, which is typically \(\sim 10^{-10} \) A for the ATO gate dielectric employed here.

Channel mobility is arguably the most important TFT electrical parameter, as it quantifies the semiconductor channel layer performance, specifically with respect to current drive capability and maximum switching frequency. The channel mobility is assessed by differentiating the drain current characteristic in the linear (or triode) region of device operation, with respect to \( V_{GS} \), i.e., the field-effect mobility (\( \mu_{FE} \)).\(^{21,22}\) \( \mu_{FE} \) is typically \(20 \)–\(50 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\) for our zinc tin oxide TFTs. This compares to \(\sim 25 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\) for the best polycrystalline ZnO TFTT reported to date,\(^{2,22}\) and \(\sim 80 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\) for an engineered superlattice single-crystal TFT prepared by pulsed laser deposition and a high-temperature anneal of \(1400 ^\circ C \).\(^{5}\) Finally, note for comparison that opaque Si:H and polycrystalline-Si TFTs typically have channel mobilities on the order of \(1.5 \)–\(2.0 \) and \(100 \)–\(200 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\), respectively.\(^{23,25}\)

The zinc tin oxide channel layer has been deposited from sputter targets with two different stoichiometries, \( (\text{ZnO})_x(\text{SnO}_2)_{1-x} \) (\( x=1/2 \) and \( x=2/3 \)), corresponding to the compositions of the ilmenite and spinel structures, respectively. Device performance, specifically in terms of channel mobility, exhibits little variation between these two stoichiometries, indicating the possibility of a surprising degree of insensitivity to stoichiometry (specifically the Zn:Sn ratio).

Finally, we should point out that relatively low processing temperatures, i.e., a \(300 ^\circ C \) channel layer anneal (in place of the \(600 ^\circ C \) anneal as discussed above), have been employed to yield devices with channel mobilities of \(5 \)–\(15 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\), a modest performance reduction in light of the substantial decrease in processing temperature. Typical \( \mu_{FE}-V_{GS} \) characteristics for devices annealed at \(300 \) and \(600 ^\circ C \) are illustrated in Fig. 4. This mobility trend (i.e., increasing mobility with increased annealing temperature) is tentatively attributed to modification of the semiconductor–insulator interface with annealing or improved local atomic rearrangement at higher temperature rather than to enhanced long-range crystallinity, since zinc tin oxide films annealed at \(300 \) and \(600 ^\circ C \) have virtually identical XRD patterns.

The results presented in this letter identify zinc tin oxide as a viable TTFT channel layer material with respect to electrical performance and processing requirements. Furthermore, other types of amorphous oxides composed of heavy-metal cations with \((n-1)d^{10}\) ns\(^2\) (\(n \geq 4\)) electronic configurations may provide opportunities for identification of TTFT channel materials with further improved electron transport and optical transparency.

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