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Complementary inverter circuits based on $p$-SnO$_2$ and $n$-In$_2$O$_3$ thin film transistors

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Thin film transistors (TFTs) of indium oxide (In$_2$O$_3$) and tin oxide (SnO$_2$) were fabricated on SiO$_2$ gate dielectric using reactive evaporation process. Structural investigation of the films revealed that In$_2$O$_3$ films were polycrystalline in nature with preferred (222) orientation and SnO$_2$ films exhibited amorphous nature. The x-ray photoelectric spectroscopy measurements suggest that SnO$_2$ films were oxygen rich and presume mixed oxidation states of Sn, namely Sn$^{2+}$ and Sn$^{4+}$. While the In$_2$O$_3$ based TFTs possess $n$-type channel conduction, SnO$_2$ based TFTs exhibited anomalous $p$-type conductivity. Integration of these $n$- and $p$-type devices resulted in complementary inverter with a gain of 11. © 2008 American Institute of Physics. [DOI: 10.1063/1.2936275]

Inorganic oxide semiconductors are the basis of most of the high performance microelectronic devices. For example, metal oxides such as indium oxide (In$_2$O$_3$), tin oxide (SnO$_2$), and their alloys have been widely used for a variety of applications such as transparent electrodes,¹ thin film solar cells,² gas sensors,³ etc. Recently, they were also explored in the area of thin film transistors (TFTs). For instance, In$_2$O$_3$ has been found to be a promising material for the active channel layer in TFTs and has been published in literature.⁴ They exhibit high optical transparency⁵ and high mobility at room temperature, and they can be grown by a simple process such as reactive evaporation and has been previously reported by the authors.⁶ Thin films of SnO$_2$ have also been utilized for the TFT fabrication and the majority of reports found in the literature claim that they exhibit $n$-type conduction.⁷ Interestingly, it is also possible to achieve $p$-type conduction in SnO$_2$ by the careful doping of either monovalent Li or trivalent Al. Such reports are also available in literature.⁸ The recent advances in optoelectronic devices demand for the $p$-type transparent oxide films and great attention has been paid to the $p$-type oxide semiconductors. The materials such as CuAlO$_2$,⁷ Zn$_{1-x}$Li$_x$O, Zn$_{1-x}$Mg$_x$O,¹⁰ and indium doped tin oxide¹¹ thin films exhibited $p$-type conduction.

Extensive research has been accomplished in the area of amorphous oxide semiconductors and exploration of $p$-type amorphous semiconductors has been a key issue for the development of giant microelectronics such as solar cells and TFTs for flat panel displays. Realization of such a $p$-type oxide semiconductor is very much essential in the transparent electronics, wherein integration of $p$- and $n$-oxide semiconductors could lead to the devices such as ambipolar TFTs and complementary inverter circuits. Progressing in this direction, we investigated that oxygen rich binary oxide, namely SnO$_2$, was found to exhibit $p$-type behavior. In this article, we report the appearance of $p$-type electrical conduction in amorphous SnO$_2$ thin films by utilizing them as active channel layers for the fabrication of TFTs. The integration of $p$-SnO$_2$/n-In$_2$O$_3$ TFTs for the complementary inverter circuits is also demonstrated. The fabrication process utilizes a simple reactive evaporation technique and the subsequent heat treatments.

Bottom gated In$_2$O$_3$ and SnO$_2$ TFTs were fabricated using conventional reactive evaporation process. Silicon dioxide of thickness ~300 nm and silicon were used as a gate oxide and gate electrode, respectively. The deposition condition for the In$_2$O$_3$ TFT is published previously,⁶ and the growth of SnO$_2$ active layer is as follows: Preceding the routine substrate cleaning, they were transferred to a vacuum chamber and the chamber was pumped down to a base vacuum of $\sim 2 \times 10^{-6}$ Torr. High purity oxygen was introduced into the chamber and the deposition was carried out at a pressure of $1 \times 10^{-4}$ Torr. Pure Sn was used as an evapo-
ration source and oxygen was used as the reactive gas for the deposition of SnO₂ thin films. The substrate temperature was maintained at 100 °C during the metal oxide deposition. The thickness of the channel layer used was 7.5 nm. The as-deposited films were subjected to postdeposition annealing treatments at various temperatures to suppress the background electron concentration. The optimized annealing temperature and the time for the realization of the p-channel TFT were 100 °C and 1 h, respectively. All the films were subjected to structural characterization to reveal the crystalline phase. X-ray diffraction (XRD) was used as a tool to measure the crystal structure and atomic force microscopy was used to evaluate the surface morphology and roughness of the channel layers. Subsequently, the TFT fabrication was completed with the silver deposition, which served as source and drain electrodes. The length and width of the active channel layer was 100 and 2000 μm, respectively. Device characterization was performed using an Agilent 4156C semiconductor parameter analyzer and a Keithley 4200 semiconductor parameter analyzer. All the measurements were carried out in dark at room temperature.

XRD confirms that the In₂O₃ thin films were crystalline in nature with preferred (222) orientation. However, the SnO₂ thin films grown under similar conditions were found to be amorphous in nature. Figure 1 shows the XRD pattern of In₂O₃ and SnO₂ thin films grown under similar conditions. In the case of In₂O₃ thin films, it was found that the as-deposited films were amorphous in nature and they tend to become polycrystalline after the completion of the air annealing process. It has been previously observed that the optimum temperature for the complete crystalline process is around 200 °C. In order to ensure the crystallinity of the films, this temperature was selected for the annealing process. On the other hand, the films grown under similar conditions in the case of the SnO₂ were found to be amorphous in nature. As a result of the amorphous behavior of the films, the observed mobility of the SnO₂ TFT was quite low because of the carrier scattering as explained in the subsequent sections.

X-ray photoelectron spectroscopy (XPS) was used as a tool to explain the p-type behavior in the SnO₂ thin films. Chemical analysis of SnO₂ thin films done by XPS helped in the estimation of Sn and O in the samples and it was found that there was a considerable increase in the oxygen concentration upon annealing. The ratio of O/Sn present in the films before and after the annealing was 2.5 and 3.11. These results suggest that the annealed films were oxygen rich. In an oxygen rich environment, there is a possibility of transformation of fraction of Sn²⁺ to Sn⁴⁺ in order to maintain the charge neutrality. During the process, hole creation takes place, and hence, results in p-type behavior. Moreover, the phase diagram of SnO₂ suggests coexistence of mixed phases, namely SnO and SnO₂, when the heat treatment is near 100 °C. Such a phase diagram is reported in the literature. Hence annealing temperature of 100 °C was selected and the XPS results shown in Fig. 2 suggest the existence of the mixed valance states for Sn, i.e., Sn²⁺ and Sn⁴⁺. The mixed oxidation states together with the acceptorlike intrinsic defect states such as VSn and Oi are the plausible contributors toward hole creation in SnO₂ systems. No external impurity atoms were doped in the present work. There-

![FIG. 2. (Color online) XPS spectra (Sn 3d and O 1s) of SnO₂ films.](image-url)

![FIG. 3. (Color online) Variation of drain current (I_D) as a function of drain-to-source voltage (V_DS) at different gate-source voltages (V GS) and variation of (a) In₂O₃ and (b) SnO₂ TFTs.](image-url)
fore, the origin of hole creation is intrinsic in nature, with
probable explanation being the excess oxygen. It is well
known in the binary oxides such as ZnO that the films grown
under oxygen rich conditions result in p-type behavior due to
annihilation of the metal ion interstitials.\textsuperscript{14} Such mixed val-
ce states together with the enriched oxygen composition of
the films are mainly responsible for the p-type behavior in
the films. Intentional doping and elucidation of the origin of
p-type conductivity are the topic of further research and the
progressive efforts are underway in that direction.

Figures 3(a) and 3(b) show the static output characteristics
of In\textsubscript{2}O\textsubscript{3} and SnO\textsubscript{2} TFTs measured at room temperature,
respectively. Drain-source voltage was continuously varied
from 0 to ±80 V. The output curve is marked by a well
defined saturation both in n- and p-channel devices. The car-
errier mobility and the threshold voltage (\(V_{th}\)) were
obtained from the plot of \(I_D\) versus \(V_{GS}\) (Fig. 4) using the following
relation: \(I_D = W C_i \mu_{FE} 2L (V_{GS} - V_T)^2\), where \(C_i\) is the capac-
tance per unit area of the gate dielectric, \(V_T\) is the threshold
voltage, and \(\mu_{FE}\) is the field-effect mobility. The field-effect
mobility of 0.054 and 0.0047 cm\(^2\)V\(^{-1}\)s\(^{-1}\) was obtained for the
In\textsubscript{2}O\textsubscript{3} and SnO\textsubscript{2} TFTs, respectively. The threshold voltages
of the In\textsubscript{2}O\textsubscript{3} and SnO\textsubscript{2} devices were 10 and 30 V, respec-
tively. The lower mobility observed in the case of SnO\textsubscript{2} TFT
could be due to the increased disorder because of the amor-
phous behavior of the films and greater surface roughness at
the interface between the semiconductor and the gate dielec-
tric. Moreover, the threshold voltage obtained in the case of
p-SnO\textsubscript{2} TFT was relatively larger. Such a large threshold
voltage was also been observed by the earlier researchers in
the case of SnO\textsubscript{2} TFTs. The large threshold voltage ob-
served in the case of SnO\textsubscript{2} TFT suggests the significant trap
states at the semiconductor/gate dielectrics. Surface treat-
ment of the gate oxide plays a major role in shifting the
threshold voltage toward near zero and present research is
focused in that direction.

An inverter circuit based on p-SnO\textsubscript{2} and n-In\textsubscript{2}O\textsubscript{3} TFTs
was constructed. The static behavior of the inverter was
tested using a Keithley 4200 semiconductor parameter ana-
lyzer. The Si complementary metal-oxide semiconductor
technology normally utilizes a slower p-channel field-effect
transistor (FET) as the load transistor and a higher n channel

\[ V_G = \frac{V_D}{2} \]

are used as driver FETs. Similarly, we demonstrated the in-
verter circuit using the slower p channel as load and the
higher n channel as the driver in the present investigation.

}\textsuperscript{11}\textsuperscript{The static inverter behavior of the all-oxide TFTs suggests that In\textsubscript{2}O\textsubscript{3}
and SnO\textsubscript{2} could be promising candidates for the microelectronic
circuits.

In conclusion, the current research opens up a way for
the fabrication of a low-cost and simple process for the fea-
sibility of the microelectronic devices such as TFTs and in-
verters. Appearance of p-type conductivity in SnO\textsubscript{2} would
widen its applications for the optoelectronic devices. The
origin of p-type conduction in SnO\textsubscript{2} is intrinsic in nature,
with acceptor-like defects such as V\textsubscript{Sn} and O\textsubscript{2} contributing to
such phenomena.

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