Recent progress of oxide-TFT-based inverter technology

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Developing a cost-effective oxide-thin-film transistor (oxide-TFT)-based inverter circuit is an important step to advance oxide TFT technology to a variety of next-generation device applications including wearable/flexible electronics and system-on-glass (SOG) technology. Therefore, numerous efforts on the development of oxide-TFT-based inverter including n-channel MOS (NMOS) and complementary MOS (CMOS) have been made with the intense development of high-performance oxide-TFT. This paper presents the reviews of the recent progress of oxide-TFT-based inverter technology and discusses the challenges to further advance oxide-TFT electronics to the next level of device applications.

1. Introduction

Oxide semiconductors are becoming the mainstream of thin-film transistor (TFT) technology for flat-panel display applications because of the low-temperature processability that is compatible with a plastic substrate, excellent electron carrier transport property, good long-term device stability, and reliability. [1] Additionally, by taking the advantages such as high manufacturability and process compatibility including low-cost solution/printing, oxide-TFT technology is rapidly expanding to a wide area of device applications such as energy-harvesting, Internet-on thing, system on glass technology, etc.

Transistor is well-known as one of the fundamental building blocks in modern electronics composed of analog/digital circuits. The inverter circuit, which is composed of two transistors, is also an essential component that inverts the input signal level to the opposite level is indispensable for the digital/analog circuit. Practically, complementary metal-oxide-semiconductor (CMOS) technology, which comprises of n-MOS and p-MOS transistor, is critical for the most modern electronics because of several advantages such as low noise immunity, low power consumption, low heat dissipation, small device foot-print area, etc. CMOS technology allows the development of more simple circuit architectures with high packing density on integration circuit applications.

Therefore, developing an oxide-CMOS circuit is vital to advance oxide-TFT technology to the next stages of device applications. [2] However, the absence of p-channel oxide-TFT that operates in the comparable device performances as an n-channel oxide-TFT, which is mainly originating from the non-dispersive valence band structure nature of oxides, hinders the development of high-performance oxide-CMOS inverters. [3]

In this paper, we review the recent progress and challenges in oxide-TFT-based-inverter technology. After we review the recent progress of oxide-TFT-based inverter technology for NMOS and CMOS, the challenges on the development of oxide-TFT-based inverter are discussed. We also discuss the origin of insufficient device performances of p-channel oxide-TFT and how to improve the TFT characteristics.

2. The development of oxide-NMOS inverter

Figure 1 (a) summarizes the number of publications for oxide-TFT-based inverters by year. Here oxide-NMOS includes all types of drive/load TFT configurations and oxide-CMOS only takes an account alloxide-CMOS only made by both n and p-channel oxide-TFTs. The other devices such as inorganic/organic hybrid-CMOS and CMOS-like inverters are not included.

![Figure 1](image.png)

Figure 1. (a) Summary of the number of publications for oxide inverters including NMOS and CMOS inverters by year. (b) Progress of voltage gain for the reported oxide-NMOS and all-oxide-CMOS inverters.
Compared with numerous publications regarding oxide-TFT including channel material exploration, process development, and TFT instability studies have been reported, oxide-inverter is still a developing. Due to simple fabrication of high-performance $n$-channel oxide-TFTs, oxide-NMOS inverter, which is implemented only by $n$-channel oxide-TFTs, has been developing since the early stage of oxide-TFT technology. The performances of oxide NMOS inverters are remarkably advanced in these years with the development of high-performance $n$-channel oxide-TFT. Several high-performance oxide-NMOS inverter exhibiting a high voltage gain over 400 have been already demonstrated. [4] (Fig.1 (b))

The key technology for oxide-NMOS lies in how to control threshold voltage ($V_{th}$) of $n$-channel oxide-TFTs at high reproducibility and reliability because depletion-load NMOS inverter, fabricating by enhancement (E)-mode-driver and depletion (D)-mode-load oxide-TFTs, is preferable for the most applications. Since a-IGZO is intrinsically $n$-type semiconductor, fabricating D-mode oxide-TFTs is relatively easier than E-mode-TFT. Therefore, D-mode load-TFT is fabricated by transforming from E-mode device in most cases. As well-known currently, substitutional doping is not established yet for ionic amorphous oxide semiconductor due to the nature of structure flexibility. Thus, the electron density of the $n$-channel layer is mainly controlled by changing anion stoichiometry (oxygen vacancy) and hydrogen doping. However, the control of anion stoichiometry is often unstable, and it is vital to develop the stable method of electron density of $n$-type oxides.

In contrast, oxide-TFT-based PMOS inverter is largely behind form NMOS inverter. The absence of good $p$-channel oxide-TFTs is the main reason. Since $n$-channel device usually shows higher carrier mobility, moreover, NMOS-inverter offers several advantages such as higher density, and higher speed operations. Therefore, NMOS inverter is generally preferable in most circuit applications.

3. Oxide-CMOS technology

Oxide-CMOS inverter technology, configured by both $n$-channel and $p$-channel-oxide TFTs, are highly demanded because it exhibits significant advantages for most digital and analog circuit applications. However, the number of publications of all-oxide-CMOS is still low due to the difficulty of fabrication of high-performance $p$-channel oxide-TFT.

Since good oxide-TFT are almost $n$-channel, adapting $p$-channel organic-TFT is the one of solutions, and the device is named an inorganic/organic hybrid CMOS. Moreover, both organic and oxide have good compatibility of solution-process and the type is promising for low-cost printing inkjet process. Several excellent $p$-type materials exhibiting high hole mobility are available and CNT-TFT are highly promising counterpart for the $n$-channel oxide-TFT for hybrid-CMOS inverter. [5]

Currently, oxide semiconductors cannot control $p$ and $n$ polarity at device-quality levels, and all-oxide CMOS fabricated by a single oxide material has not been realized yet. Therefore, all the current oxide-CMOS is constructed by different channel materials for $n$ and $p$-channel oxide-TFTs. In contrast to $n$-type oxides in which several channel materials are available, including ZnO, a-IGZO, In$_2$O$_3$, etc., SnO, and Cu$_2$O are the only options for $p$-channel oxide-TFTs.

The recent improvement of device performance of all-oxide-CMOS inverter is remarkable, and high voltage gain over 300 was achieved so far. [6] However, the device performances are still not satisfactory yet. This is mainly due to the unbalanced device performances of $n$ and $p$-channel oxide-TFTs and developing a high-performance $p$-channel device is the key for all-oxide-CMOS inverter. The reason for the poor device performances for these $p$-oxide TFTs is due to the presence of high-density subgap defects including bulk channel and front-interface/back-channel surfaces. Therefore, eliminating these channel subgap defects is indispensable to improve the device performances of the $p$-channel oxide.

3.1 Oxide-CMOS technology with $p$-SnO-TFT

$P$-type SnO is well-known as a promising material for $p$-channel oxide-TFT because of the low-temperature processability and reasonably high mobility of 1-3 cm$^2$/Vs. Already many demonstrations of $p$-channel SnO-TFT have been reported, but their device performances such as high-off current level of nA, and high operation voltage are not satisfactory due to the existence of high-density channel defects. Oxygen vacancy (Vo) defect is considered as a hole trap defect and is the root cause for insufficient TFT characteristics. Therefore, the terminating Vo defect is vital to improve the TFT performances of SnO-TFTs. [7] So far, several approaches including hydrogen annealing, passivation formation, high-temperature deposition have been proposed to reduce subgap defects for SnO. Since the SnO-TFT operated in fully depletion-mode due to high acceptor level of the
SnO channel, moreover, atomically ultra-thin channel technology is promising to improve the device characteristics. Figure 2 shows the typical TFT characteristics of $p$-channel SnO-TFT with ~1 nm-thick. SnO channel prepared by vacuum- and solvent-free liquid-metal route. (Fig. 2 (a)) The presented device operates in the improved characteristic such as the low off-current of pA levels and a large on/off current ratio of ~10^6. [8]

Figure 2 (a) AFM image of the ultra-thin (~1nm) SnO channel. (b) The transfer characteristics for the $p$-channel SnO-TFT with the 1-nm-thick SnO channel.

Figure 3 also shows the voltage transfer characteristics (VTC) for the all oxide-CMOS with the ultra-thin $p$-channel SnO-TFT and conventional $n$-channel a-IGZO-TFT. With full-voltage swing inverter action from high to low, significant improvement of the oxide-CMOS inverter was achieved with the voltage gain of >270 by using the ultrathin $p$-channel SnO-TFT with the improved TFT characteristics.

Figure 3. All-oxide-CMOS inverter with the ultra-thin $p$-SnO-TFT and $n$-a-IGZO-TFT. (a) The equivalent circuit diagram of oxide-CMOS and (b) typical voltage transfer characteristics with the voltage gain of >250.

3.2 Oxide-CMOS technology with $p$-Cu$_2$O-TFT

$P$-type Cu$_2$O is also famous for $p$-channel oxide-TFT from way before. The excellent electrical property such as high hole mobility of ~100 cm$^2$/Vs with the low-hole density of $10^{12}$-$10^{15}$ cm$^{-3}$ expects the development of high-performance $p$-channel oxide-TFT. The high hole mobility is easily obtained in Cu$_2$O thin-film sample by Hall-effect measurement, but the device performance is quite poor, and the most of reported Cu$_2$O-TFT shows the lower device performances than conventional $p$-SnO-TFT.

This is obvious that subgap defect control the TFT characteristics of Cu$_2$O-TFTs. Vo is also an energetically stable point defect but electrically inactive defect for Cu$_2$O. Amphoteric Cu interstitial defect (Cui) is the defect that should be eliminated for Cu$_2$O. Recent studies clarified that Cui defect concentrated the back-channel region and found eliminating the back-channel Cui was the key to improving the device performances. [9]

Figure 4 (a) shows the improvement of TFT performances of the back-channel terminated Cu$_2$O-TFT. By reducing the back-channel Cui defect, significant improvement of the off-current down to as low as ~1 pA is observed. The device exhibits the improved performances such as the TFT mobility of ~1.81 cm$^2$/Vs, s-values of ~1.3 V/dec., and the on/off current ratio of ~6.0 x 10^6.

Figure 4. (a) The improved transfer characteristics for the back-channel defect-terminated $p$-Cu$_2$O-TFTs. (b) Typical VTC with voltage gain over 230 for the $p$-Cu$_2$O-TFT-based all-oxide-CMOS inverter with $n$-a-IGZO-TFT.

Figure 4 (d) also shows the VTC and the corresponding voltage gains for the oxide-CMOS inverter fabricated by the back-channel defect terminated $p$-channel Cu$_2$O-TFT with $n$-channel a-IGZO-TFTs. The inverters exhibited a sharp and full signal switching with rail-to-rail output swings, and the maximum gain of 232.

4. Conclusions

A review for oxide-TFT-based NMOS and CMOS inverter was presented. Since excellent $n$-channel oxide-TFT is available, the oxide-NMOS-inverter is advanced and move forward to next stages such as large-scale circuit level currently. It is clear that the absence of high-performance $p$-channel oxide TFTs hinders the
high potential of oxide-TFT technology. It still highly requires significant breakthroughs at the levels of material and device level developments for p-channel oxide-TFTs to realize high-level integrated circuits using oxide-TFTs. Developing high-performance stable p-channel oxide-TFT is critical for next-generation oxide-TFT electronics.

References
1) K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, H. Hosono, Nature 432 (2004) 488.
2) K. Nomura, J. Infor. Display 22 (2021) 211.
3) K. Nomura, Chapter 24 in Amorphous Oxide Semiconductors: IGZO and Related Materials for Display and Memory (H. Hosono and H. Kumomi Eds), Wiley (In press).
4) H. Fwzah H. Alshammari, M. K. Hota, H. N. Alsharee, Small 16 (2018) 1803969.
5) M. Luo, H. Xie, M. Wei, K. Liang, S. Shao, J. Zhao, T. Gao, L. Mo, Y. Chen, S. Chen, C. Lee, Z. Cui, Adv. Electron. Mater. 5 (2019) 1900034.
6) Shu-Ming Hsu, Dong-Yue Su, Feng-Yu Tsai; Jian-Zhang Chen; I-Chun Cheng, IEEE Trans. Electron Devices 68 (2021) 1070.
7) A. W Lee, D. Le, K. Matsuzaki, K. Nomura, ACS Appl. Electron. Mater. 2 (2020)1162.
8) Chi-Hsin Huang, Yalan Tang, Tzu-Yi Yang, Yu-Lun Chueh, Kenji Nomura, ACS Appl. Mater. Interface 13 (2021) 52783.
9) H. Chang, C.-H. Huang, K. Matsuzaki, K. Nomura, ACS Applied Materials & Interfaces 46 (2020) 51581.