**Review**

**Recent Advances of Solution-Processed Heterojunction Oxide Thin-Film Transistors**

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**Abstract:** Thin-film transistors (TFTs) made of metal oxide semiconductors are now increasingly used in flat-panel displays. Metal oxides are mainly fabricated via vacuum-based technologies, but solution approaches are of great interest due to the advantages of low-cost and high-throughput manufacturing. Unfortunately, solution-processed oxide TFTs suffer from relatively poor electrical performance, hindering further development. Recent studies suggest that this issue could be solved by introducing a novel heterojunction strategy. This article reviews the recent advances in solution-processed heterojunction oxide TFTs, with a specific focus on the latest developments over the past five years. Two of the most prominent advantages of heterostructure oxide TFTs are discussed, namely electrical-property modulation and mobility enhancement by forming 2D electron gas. It is expected that this review will manifest the strong potential of solution-based heterojunction oxide TFTs towards high performance and large-scale electronics.

**Keywords:** heterojunction; metal oxide semiconductor; thin-film transistors; solution-processed

1. Introduction

Today, there is a growing demand for flat-panel displays with higher resolution, larger screen sizes, better viewing, and lower power consumption, pushing traditional amorphous silicon thin-film transistor (TFT) technology to its limits [1–3]. TFTs made of metal oxide semiconductors hold great promise in future display technology, owing to their high mobility, good transparency, and scalability [4–7]. Commercial metal oxides are grown via physical vapor deposition technologies, but solution-based approaches have been attracting particular attention recently [5,8–11]. Compared with conventional vacuum-based technologies, the solution approaches have additional advantages, including cost effectiveness, atmospheric fabrication, higher throughput, and material composition that is easy to tune [12–15]. Ways to reduce defect states and improve electrical performance and stability are an urgent challenge for solution-based metal oxide TFTs [16,17]. Various approaches have been taken to solve the above challenge, such as doping, modification of components, addition of additives, and novel post-treatments [9,18–20]. However, electron transport properties are still hindered by these defect-prone oxides [21–25].

A notable strategy has been recently developed to enhance the electrical performance of solution-derived oxide TFTs by utilizing heterojunction channels [26]. The schematic of the heterojunction oxide TFTs is demonstrated in Figure 1. It is revealed that heterostructures could
modulate electrical performance by taking advantage of both the front channel (providing high mobility) and the back channel (maintaining low off current) [27,28]. More importantly, some recent studies argue that the presence of a 2D electron gas system formed at the carefully engineered oxide heterointerface can greatly improve device mobility [24,29–33]. In this review, we summarize the recent progress of solution-processed heterostructure oxide TFTs. The heterojunction channel strategy could address the shortcomings of single-layer devices, providing a new route for future TFT technology development [34–36].

![Figure 1. Cross-sectional view of the heterojunction oxide thin-film transistors (TFTs).](image)

2. Heterojunction Oxide TFTs

2.1. Vacuum-Processed Heterojunction Oxide TFTs

Before reviewing solution-processed heterojunction oxide TFTs, we would like to make a short introduction on vacuum-based heterojunction oxide devices. In 2008, Kim et al. produced InSnO/GaInZnO (ITO/GIZO) heterojunction TFTs by magnetron sputtering, with a high mobility of 104 cm$^2$/Vs, a suitable threshold voltage ($V_{th}$) of 0.5 V, and a low $V_{th}$ shift of 0.75 V for 4 h under 10 V bias voltage [37]. They found that the lower layer of highly conductive oxides could provide high mobility for the TFTs, while the upper layer of oxides with lower carrier concentration could adjust the threshold voltage. This new structure provides a new way to adjust the performance of TFTs. Subsequently, a number of scientists have studied and produced various excellent heterojunction oxide TFTs. In 2014, Chen et al. prepared InSnO/SnZnO (ITO/TZO) TFT on a glass substrate by taking advantage of ITO’s higher carrier concentration and TZO’s ability to control the charge conductance, and they obtained a high mobility of 105 cm$^2$/Vs [38]. In 2016, Cong et al. built quasi-double-channel (QDC) AlSnZnO (ATZO) TFTs with a superior mobility of 108 cm$^2$/Vs and an on/off ratio of $10^7$ [36]. In 2019, He et al. prepared InGaZnO/In$_2$O$_3$ (IGZO/In$_2$O$_3$) TFTs by magnetron sputtering at room temperature, exhibiting high mobility (64.4 cm$^2$/Vs) and high on/off ratio ($10^7$), with large enhancement compared with single-layer IGZO and In$_2$O$_3$ TFTs [39]. They attributed this improvement to the defect self-compensation mechanism between the two layers. In 2019, Furuta et al. prepared IGZO/IGZO TFTs with a mobility of 24.7 cm$^2$/Vs and an on/off ratio of $10^7$ [40]. Table 1 summarizes the recent progress in vacuum-processed heterojunction oxide TFTs. It can be observed that heterojunction oxide TFTs show excellent electrical properties, which are much better than those of the traditional single-layer device.
electrical-property modulation and mobility enhancement by forming 2D electron gas. For heterojunction oxide TFTs, we discuss two of the most prominent advantages, namely oxygen and processing (such as spin-coating, spraying, and printing) allows for the design and fabrication of novel oxide TFTs in a low-cost and straightforward fashion [43–45]. Many researchers have begun to study solution-grown heterojunction oxide TFTs. Table 2 and Figure 2 summarize the recent advances in solution-processed heterojunction oxide TFTs and representative single-layer devices.

### Table 1. Recent advances in vacuum-processed heterojunction oxide TFTs and representative single-layer devices.

| Channel     | Mobility (cm²/V·s⁻¹) | Ion/Ioff | Subthreshold Swing | Dielectric | Year | Reference |
|-------------|----------------------|----------|--------------------|------------|------|-----------|
| ITO/GIZO    | 104                  | 10⁶      | 0.25               | PECVD SiO₂ | 2008 | [37]     |
| ZTO/ITO     | 52                   | 10⁶      | -                  | PECVD SiO₂ | 2010 | [7]      |
| IZO/IGZO    | 30                   | 10⁶      | -                  | PECVD SiO₂ | 2010 | [11]     |
| H₂O/IGZO/IZO| 15                   | 10⁻⁶     | -                  | Thermal SiO₂| 2010 | [3]      |
| IGZO/GZO    | 10                   | 10⁻⁷     | 0.93               | Thermal SiO₂| 2011 | [6]      |
| ZTO/ITO     | 43                   | 10⁻⁷     | 0.18               | PECVD SiO₂ | 2011 | [41]     |
| HIZO/IZO    | 41.4                 | 10⁻⁷     | 1.45               | Thermal SiO₂| 2011 | [42]     |
| IZO/GIZO    | 48                   | 10⁻⁸     | -                  | PECVD SiO₂ | 2012 | [27]     |
| HIZO/IZO    | 48                   | 10⁻⁸     | 0.28               | PECVD SiO₂ | 2012 | [13]     |
| IGZO/IGZO:Ti| 63                   | 10⁻⁸     | 0.73               | HfO₂       | 2014 | [22]     |
| ZTO/ITO     | 32                   | 10⁻⁸     | 0.20               | PECVD SiO₂ | 2014 | [23]     |
| ITO/ITO     | 105                  | 10⁻⁸     | 0.33               | PECVD SiO₂ | 2014 | [38]     |
| In₂O₃/GZO  | 38                   | 10⁻⁸     | 0.12               | ZrO₂       | 2014 | [24]     |
| High-O-IGZO/Low-O-IGZO | 60       | 10⁻⁸     | 0.2                | Thermal SiO₂| 2014 | [34]     |
| IZO/AZTO    | 53.2                 | 10⁻¹⁰    | 0.15               | PECVD SiO₂ | 2016 | [12]     |
| ZnO-H/ZnO   | 43                   | 10⁻⁸     | 0.13               | Thermal SiO₂| 2016 | [35]     |
| L-AZTO/H-AZTO| 108                 | 10⁻⁸     | 0.15               | PECVD SiO₂ | 2016 | [36]     |
| InGZO/In₂O₃| 53.2                 | 10⁻⁸     | 0.19               | PECVD SiO₂ | 2017 | [25]     |
| Al₂O/ITO    | 53                   | 10⁻⁸     | 0.15               | PECVD SiO₂ | 2018 | [32]     |
| In₂O₃/IGZO  | 64.4                 | 10⁻⁷     | 0.20               | Thermal SiO₂| 2019 | [39]     |
| In₂O₃/IGZO  | 67.5                 | 10⁻⁷     | 0.08               | HfO₂       | 2019 | [39]     |
| In₂O₃/GZO   | 79.1                 | 10⁻⁷     | 0.09               | Si₃N₄      | 2019 | [39]     |
| ZnO(DEZ+O)/ZnO/(DEZ+H₂O) | 31.1         | 10⁻⁷     | 0.21               | Al₂O₃      | 2019 | [33]     |
| IGZO/IGZO   | 24.7                 | 10⁻⁷     | 0.1                | Thermal SiO₂| 2019 | [40]     |
| SnO₂        | 35.4                 | 10⁻⁷     | -                  | Thermal SiO₂| 2015 | [43]     |
| ZnO         | 20                   | 10⁻⁸     | 0.38               | TiO₂/Al₂O₃| 2015 | [44]     |

2.2. Solution-Processed Heterojunction Oxide TFTs

Compared with conventional vapor-based techniques, solution processing (such as spin-coating, spraying, and printing) allows for the design and fabrication of novel oxide TFTs in a low-cost and straightforward fashion [43–45]. Many researchers have begun to study solution-grown heterojunction oxide TFTs. For heterojunction oxide TFTs, we discuss two of the most prominent advantages, namely electrical-property modulation and mobility enhancement by forming 2D electron gas.

### Table 2. Recent advances in solution-processed heterojunction oxide TFTs and representative single-layer devices.

| Channel     | Processing Temperature (°C) | Mobility (cm²/V·s⁻¹) | Ion/Ioff | Subthreshold Swing | Dielectric | Year | Reference |
|-------------|-----------------------------|----------------------|----------|--------------------|------------|------|-----------|
| AI₂O/ITO    | 350                         | 1.57                 | 10⁶      | 0.59               | SiO₂       | 2011 | [26]     |
| AI₂O/ITO    | 350                         | 5.62                 | 10⁶      | 0.53               | SiO₂       | 2012 | [46]     |
| InGZO/In₂O₃| 450                         | 2.4                  | 10⁵      | 0.69               | SiO₂       | 2013 | [47]     |
| ZTO/ITO     | 450                         | 2.09                 | 10⁷      | 0.49               | SiO₂       | 2013 | [48]     |
| In₂O₃/IGZO  | 250                         | 2.6                  | 10⁵      | -                  | SiO₂       | 2013 | [49]     |
| Al₂O/ITO    | 350                         | 23.4                 | 10⁵      | 0.27               | SiO₂       | 2014 | [50]     |
| ITO/IGZO    | 450                         | 22.16                | 10⁵      | 0.51               | SiO₂       | 2014 | [51]     |
| ITO/IGZO    | 450                         | 40.03                | 10⁵      | 0.12               | ZrO₂       | 2014 | [51]     |
| Q5H-III⁻     | 200                         | 40                   | 10⁵      | 0.27               | Al₂O₃/ZrO₂ | 2015 | [52]     |
| ZnO/SnO₂    | 300                         | 15.4                 | 10⁵      | -                  | SiO₂       | 2016 | [53]     |
Due to the existence of an energy barrier, the back-channel layer can only provide higher carrier concentration, thus forming maximum charge accumulation and finally reducing interface current ($I_{on}$) and adjusting threshold voltage ($V_{th}$) [46]. A series of materials and technological means could be applied to enhance the electrical properties of the back-channel layer. Table 2. Cont.

| Channel         | Processing Temperature (°C) | Mobility ($cm^2 \cdot V^{-1} \cdot s^{-1}$) | $I_{on}/I_{off}$ | Subthreshold Swing | Dielectric | Year | Reference |
|-----------------|-----------------------------|------------------------------------------|------------------|--------------------|------------|------|-----------|
| $In_2O_3/ZnO$   | 400                         | 48                                       | $10^4$           | -                  | SiO$_2$    | 2016 [54] |
| $In_2O_3/ZnO$   | 250                         | 45                                       | $10^7$           | -                  | SiO$_2$    | 2017 [55] |
| $In_2O_3/Li-ZnO$| 350                         | 11.4                                     | $10^5$           | -                  | SiO$_2$    | 2017 [29] |
| $ITZO/IGZO$     | 350                         | 3.8                                      | $10^5$           | 0.41               | SiO$_2$    | 2018 [30] |
| $In_2O_3/PEI-In_2O_3$ | 350 | 10                           | $10^5$           | -                  | SiO$_2$    | 2018 [56] |
| $In_2O_3/PEI-In_2O_3$ | 250 | 30                           | $10^5$           | -                  | ZrO$_2$    | 2018 [56] |
| $In_2O_3/IGZO$  | 400                         | 14.5                                     | $10^6$           | -                  | SiO$_2$    | 2019 [17] |
| $In_2O_3/ZnO-NPS/PS/ZnO$ | 200 | 50.7                         | $10^6$           | 2.71               | SiO$_2$    | 2019 [31] |
| QSL-III         | 200                         | 11.4                                     | $10^7$           | -                  | SiO$_2$    | 2019 [57] |
| Li-IZIZ         | 200                         | 25                                       | $10^4$           | -                  | AlO$_x$/ZrO$_2$ | 2019 [57] |
| AlInO/In$_2$O$_3$ | 300                         | 40                                       | $10^7$           | 0.7                | SiO$_2$    | 2019 [58] |
| $In_2O_3/In_2$O$_3$ | 250                         | 50                                       | $10^7$           | -                  | SiO$_2$    | 2019 [58] |
| ITZO            | 150                         | 14                                       | $10^6$           | 0.17               | Al$_2$O$_3$ | 2012 [14] |
| $In_{3}SmO$     | 350                         | 21.5                                     | $10^6$           | 0.66               | SiO$_2$    | 2020 [15] |

1 In$_2$O$_3$/Ga$_2$O$_3$/ZnO/Ga$_2$O$_3$/In$_2$O$_3$ (QSL-III). 2 Polyethylenimine-doped In$_2$O$_3$ (PEI-In$_2$O$_3$). 3 In$_2$O$_3$/ZnO/In$_2$O$_3$/ZnO (IZIZ). 4 In$_2$O$_3$/ZnO-Li/In$_2$O$_3$/ZnO-Li (Li-IZIZ).

Figure 2. Mobility vs. processing temperature for solution-processed heterojunction oxide TFTs from Table 2 or high-k dielectrics. (QSL-III denotes In$_2$O$_3$/Ga$_2$O$_3$/ZnO/Ga$_2$O$_3$/In$_2$O$_3$; PEI-In$_2$O$_3$ denotes polyethylenimine-doped In$_2$O$_3$; IZIZ denotes In$_2$O$_3$/ZnO/In$_2$O$_3$/ZnO; Li-IZIZ denotes In$_2$O$_3$/ZnO-Li/In$_2$O$_3$/ZnO-Li.)

2.2.1. Electrical-Property Modulation

As a product of structural engineering technology, heterojunction oxide TFTs can take advantage of the excellent electrical properties of each layer [30,37]. As the front-channel layer has good conductivity, it can provide higher carrier concentration, thus forming maximum charge accumulation and finally achieving high mobility [10,41,42]. The carrier concentration in the back-channel layer is much lower than that of the front-channel layer, which leads to the difference in electron activation energy between the conduction band minimum and the Fermi energy level, forming an energy barrier at the interface [51]. Due to the existence of an energy barrier, the back-channel layer can effectively control the electron flow, thus reducing off current ($I_{off}$) and adjusting threshold voltage ($V_{th}$) [46]. A series...
of representative papers show that heterojunction TFTs can achieve both high mobility and \( I_{\text{off}} \) by selecting suitable front- and back-channel materials.

In 2012, Jeong et al. adjusted the carrier concentration of the AlInZnO/InZnO (AIZO/IZO) interface and barrier height by changing the ratio of In/Zn in the IZO layer and the thickness of the IZO layer. The IZO layer could provide an enhanced mobility for the device due to its high electron concentration. Compared with the IZO layer, the AIZO layer had a larger \( E_C - E_F \) due to its lower carrier concentration, forming an energy barrier at the interface and reducing \( I_{\text{off}} \). As the thickness of the conductive IZO layer decreased, the AIZO/IZO TFTs \( V_{\text{th}} \) shifted positive, and \( I_{\text{off}} \) decreased from \( 10^{-8} \) to \( 10^{-11} \) A. With a 12-nm-thick IZO layer, they obtained a device mobility of 5.63 cm\(^2\)/Vs and an on/off ratio of \( 10^6 \) [46]. For similar reports, refer to Kim et al. ZnSnO/InGaZnO (ZTO/IGZO), Yu et al. In\(_2\)O\(_3\)/InGaO (In\(_2\)O\(_3\)/IGO), Kim et al. InGaZnO/InGaZnO (IGZO/IGZO), Seo et al. AIZO/IZO, and Lee et al. In\(_2\)O\(_3\)/In\(_2\)O\(_3\) (amorphous In\(_2\)O\(_3\) and polycrystalline In\(_2\)O\(_3\)) [47–50].

Rim et al. boosted up the mobility of solution-processed oxide TFTs using an extremely thin layer of conductive InSnZnO (ITZO) inserted between the dielectric layer and the InGaZnO (IGZO) active layer [51]. The ITZO/IGZO TFTs have a high mobility (22.16 cm\(^2\)/Vs) and an excellent on/off current ratio (\( 10^7 \)). As shown in Figure 3a, the mobility of ITZO/IGZO is over ten times higher than that of single-layer IGZO (from 1.56 to 22.16 cm\(^2\)/Vs). At the front channel of ITZO, Sn\(^{4+} \) replaced In\(^{3+} \) to provide additional electrons to increase electron concentration, forming a highly conductive channel and providing high mobility for devices. Moreover, a barrier height (0.15 eV) between IGZO and ITZO (Figure 3b) could effectively modulate off current and threshold voltage. Nadarajah et al. (2015) also tried solution-processed ITZO/IGZO TFTs, showing a mobility of ~30 cm\(^2\)/Vs and an \( I_{\text{on}}/I_{\text{off}} \) of \( 10^6 \) [59].

![Figure 3. (a) Transfer characteristics of InGaZnO (IGZO), InSnZnO (ITZO), and ITZO/IGZO TFTs. (b) Energy band diagram of ITZO/IGZO. Reproduced with permission [51]. Copyright 2014, Wiley-VCH.](image)

Nam et al. prepared high-performance solution-processed indium-free ZnO/SnO\(_2\) TFTs at 300 °C by UV annealing [53]. The ZnO/SnO\(_2\) TFTs exhibited a mobility of 15.4 cm\(^2\)/Vs, an outstanding on/off ratio of \( 10^8 \), and superior bias stability. As shown in Figure 4a, ZnO/SnO\(_2\) bilayers are composed of a Zn-rich layer, a Zn-Sn mixed zone, and an Sn-rich layer. The Sn-rich channel has high conductivity and provides a path for rapid electronic transport. Meanwhile, Zn atoms can diffuse into the Zn-Sn mixing zone to reduce \( I_{\text{off}} \) by control carrier concentration. Furthermore, due to the suppression of oxygen vacancy (\( V_o \)) defects in the bilayer film, the ZnO/SnO\(_2\) TFTs exhibited remarkable bias-stress stability (Figure 4b).

2.2.2. Mobility Enhancement by Forming 2D Electron Gas

In addition to electrical-performance modulation, some recent studies suggest that well-designed heterojunction oxides could greatly boost mobility by forming 2D electron gas at the interface [52]. Through careful interface engineering, electron transfer and confinement at the heterointerface can occur because of a large conduction band offset between the two layers, resulting in the formation of 2D...
electron gas in the interface [55]. The formation of 2D electron gas enables the realization of TFTs with mobilities close to the theoretical limit set by phonon scattering in the absence of impurity scattering [30]. In this situation, the mobility of the heterojunction device is often several times or even ten times higher than that of the single-layer device. Additionally, the enhanced electron mobility is accompanied by a marked change in the charge transport mechanism. Through fitting the transfer curves and analyzing the temperature dependence of mobility, it was revealed that heterojunction TFTs exhibited band-like electron transport, while the single-layer device showed trap-limited conduction [55]. It should be mentioned that the transfer curve of the heterojunction TFTs shifted to the negative direction compared with the single-layer device, due to the formation of 2D electron gas.

Faber et al. demonstrated In$_2$O$_3$/ZnO TFTs with unprecedented electron mobility grown from the solution [55]. The mobility of In$_2$O$_3$/ZnO TFTs (45 cm$^2$/Vs) was 2 to 100 times greater than that of single-layer In$_2$O$_3$ and ZnO devices. According to X-ray photoelectron spectroscopy, optical absorption, and Kelvin probe measurements, the In$_2$O$_3$/ZnO interface has a large conduction band offset (0.36 eV), which makes the electron transfer from the ZnO layer to In$_2$O$_3$ and forms 2D electron gas. 2D electron gas greatly increases the concentration of free electrons in the In$_2$O$_3$ layer of the crystal. The electron transport mechanism of In$_2$O$_3$/ZnO TFTs was changed from trap-limited conduction to percolation conduction. This marked improvement originated from the presence of 2D electron gas formed at the atomically sharp heterointerface induced by the large conduction band offset between In$_2$O$_3$ and ZnO. The In$_2$O$_3$/ZnO TFTs developed in this work not only surpassed the performance of single-layer In$_2$O$_3$ and ZnO TFTs but also compared favorably to state-of-the-art vacuum-processed devices. Lin et al. used solution-grown In$_2$O$_3$, Ga$_2$O$_3$, and ZnO to construct heterojunction and quasi-superlattice (QSL) TFTs (Figure 5a) [52]. By carefully optimizing the structure, QSLs with smooth interfaces and surfaces could be realized (Figure 5b). As shown in Figure 5c, it was proved that single-layer metal oxide TFTs were dominated by trap-limited conduction (TLC), while QSL-I/III were dominated by percolation conduction (PC). The change of electron transport mode led to a great increase in electron mobility (from 4 to 30 cm$^2$/Vs).
Later studies showed that layer configuration and annealing temperature greatly affect heterojunction device performance. Khim explored the effect of layer configuration on electron transport in heterojunction transistors composed of ZnO and In$_2$O$_3$ [57]. They found that depositing In$_2$O$_3$ first followed by ZnO resulted in a smooth interface, while reversing the layer order yielded poor interface roughness. Tetzner et al. studied the influence of annealing temperature on morphology, chemical state, and electrical performance of solution-based heterostructure In$_2$O$_3$/ZnO TFTs [54]. It was found that the annealing temperature changed surface roughness and atomic diffusion at the interface of In$_2$O$_3$/ZnO. At the annealing temperature of 400 °C, the In$_2$O$_3$/ZnO TFTs showed an optimized mobility of 48 cm$^2$/Vs and an on/off current ratio of $\sim 10^4$.

The large conduction band offset between the two layers is one of the key points to induce 2D electron gas for mobility improvement. A doping strategy has been adopted to enlarge the conduction band offset between the two layers. Khim and co-workers reported the controlled growth of In$_2$O$_3$/Li-ZnO TFTs by modulation doping [29]. It was revealed that Li addition in ZnO led to n-type doping and allowed for the accurate tuning of its Fermi energy. Therefore, doping of Li could precisely regulate $\Delta E_F$ between In$_2$O$_3$ and Li-ZnO and change the conduction band offset between the two layers (Figure 6). When the doping amount of Li was 20%, the mobility of In$_2$O$_3$/Li-ZnO heterojunction TFTs reached the maximum value of 11.4 cm$^2$/Vs and the on/off current ratio of $\sim 10^5$. Chen et al. demonstrated high performance In$_2$O$_3$/In$_2$O$_3$-polyethylenimine (PEI) heterostructure TFTs [56]. The 2D electron gas was achieved by creating a band offset between In$_2$O$_3$ and In$_2$O$_3$:PEI via work function tuning of the PEI-doping ratio. The resulting device exhibited a mobility of 10 cm$^2$/Vs on SiO$_2$ gate dielectric. Similarly, Liu et al. took In$_2$O$_3$ as the front channel and combined it with the back-channel AlInO to construct heterojunction transistors. By adjusting the thickness of AlInO and the doping amount of Al, AlInO (30%)/In$_2$O$_3$ heterostructure TFTs with a high mobility of 40 cm$^2$/Vs, a threshold slope of 0.7 V/dec, and an on/off ratio of $10^7$ could be realized [58].
We believe that by addressing the issues presented above, solution-processed heterojunction oxide TFTs will show great promise in future large-area and high-performance electronics. A detailed review of this topic has been presented, with special attention on the latest developments. The polystyrene interlayer could passivate electron traps in the channel, leading to high mobility and excellent operational stability. However, continued work should be carried out. It should be mentioned that well-optimized single-layer vacuum-based metal oxide TFTs show high performance and stability. Unfortunately, this could increase the complexity of the process. In terms of future research directions, several key issues need to be addressed. First, the reported high mobility heterojunction oxide TFTs often suffered from negative threshold voltages, high off-state currents, or poor stability, which have a negative impact on commercial applications. The negative threshold voltage and high off-state current of heterojunction oxide TFTs are closely related to the formation of 2D electron gas. Lee et al. constructed corrugated structure ITZO/IGZO TFTs with both high mobility (51 cm²/Vs) and low off-state current [30]. The thick ITZO/IGZO portion increased the overall resistivity of the current path, effectively reducing the off-state current. The thick ITZO/IGZO could provide free electrons to form a high-speed electronic channel, highly improving the electron mobility. By using this new corrugated heterojunction, solution-based oxide transistors with high mobility and low off current could be realized. Unfortunately, this could increase the complexity of the process. Lin et al. reported solution-processed ZnO/ZnO-NP/PS/In₂O₃ multilayer TFTs with high electron mobility (50 cm²/Vs) and prolonged operational stability [31]. Insertion of the ozone-treated polystyrene interlayer could passivate electron traps in the channel, leading to high mobility and excellent operational stability. However, continued work should be carried out. It should be mentioned that well-optimized single-layer vacuum-based metal oxide TFTs show high performance and stability. Secondly, previous studies argued that the mobility enhancement is attributed to the 2D electron gas that formed at the heterogeneous interface. However, the traditional 2D electron gas usually exists in high-quality epitaxial heterojunction systems (such as AlGaAs/GaAs heterojunctions). The oxide thin films prepared by the solution method are usually polycrystalline or amorphous, and the 2D electron gas formation mechanism is still unclear. Thirdly, the carrier transport properties in heterojunction oxide need further investigation. A deep understanding of the heterojunction electron transport can promote better design of high-performance heterojunction oxide devices. Fourthly, the previous research mainly focused on the In₂O₃/ZnO system; it is necessary to extend this to other multicomponent oxide semiconductor heterostructures (such as the IGZO system) for further device performance improvement. We believe that by addressing the issues presented above, solution-processed heterojunction oxide TFTs will show great promise in future large-area and high-performance electronics.

![Figure 6](image_url)

**Figure 6.** (a) Evolution of the Fermi energy level in In₂O₃ and ZnO layers as a function of Li concentration. (b) Schematic energy band diagram illustrating the shift of $E_{F(Zn)}$ to higher energies with increasing Li concentration in relation to $E_{F(In)}$. Reproduced with permission [29]. Copyright 2017, Wiley-VCH.

### 3. Conclusions and Outlooks

Great progress has been made in the past few years in solution-processed heterojunction oxide TFTs. A detailed review of this topic has been presented, with special attention on the latest developments over the past 5 years. It was revealed that heterojunction channels could overcome the disadvantages of single-layer structures. By using this novel strategy, solution-based oxide transistors with high mobility (~50 cm²/Vs) and operational stability could be realized, competing with or even surpassing vacuum-grown counterparts.

In terms of future research directions, several key issues need to be addressed. First, the reported high mobility heterojunction oxide TFTs often suffered from negative threshold voltages, high off-state currents, or poor stability, which have a negative impact on commercial applications. The negative threshold voltage and high off-state current of heterojunction oxide TFTs are closely related to the formation of 2D electron gas. Lee et al. constructed corrugated structure ITZO/IGZO TFTs with both high mobility (51 cm²/Vs) and low off-state current [30]. The thick ITZO/IGZO portion increased the overall resistivity of the current path, effectively reducing the off-state current. The thick ITZO/IGZO could provide free electrons to form a high-speed electronic channel, highly improving the electron mobility. By using this new corrugated heterojunction, solution-based oxide transistors with high mobility and low off current could be realized. Unfortunately, this could increase the complexity of the process. Lin et al. reported solution-processed ZnO/ZnO-NP/PS/In₂O₃ multilayer TFTs with high electron mobility (50 cm²/Vs) and prolonged operational stability [31]. Insertion of the ozone-treated polystyrene interlayer could passivate electron traps in the channel, leading to high mobility and excellent operational stability. However, continued work should be carried out. It should be mentioned that well-optimized single-layer vacuum-based metal oxide TFTs show high performance and stability.
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References
1. Yu, X.; Marks, T.J.; Facchetti, A. Metal oxides for optoelectronic applications. Nat. Mater. 2016, 15, 383. [CrossRef]
2. Fortunato, E.; Barquinha, P.; Martins, R. Oxide semiconductor thin-film transistors: A review of recent advances. Adv. Mater. 2012, 24, 2945–2986. [CrossRef] [PubMed]
3. Park, J.C.; Kim, S.; Kim, S.; Kim, C.; Song, I.; Park, Y.; Jung, U.I.; Kim, D.H.; Lee, J.S. Highly stable transparent amorphous oxide semiconductor thin-film transistors having double-stacked active layers. Adv. Mater. 2010, 22, 5512–5516. [CrossRef] [PubMed]
4. Pasquarelli, R.M.; Ginley, D.S.; Ryan, O.H. Solution processing of transparent conductors: From flask to film. Chem. Soc. Rev. 2015, 43, 5406–5441. [CrossRef] [PubMed]
5. Xu, W.; Li, H.; Xu, J.-B.; Wang, L. Recent Advances of Solution-Processed Metal Oxide Thin-Film Transistors. ACS Appl. Mater. Interfaces 2018, 10, 25878–25901. [CrossRef]
6. Chong, E.; Jeon, Y.W.; Chun, Y.S.; Kim, D.H.; Lee, S.Y. Localization effect of a current-path in amorphous In–Ga–Zn–O thin film transistors with a highly doped buried-layer. Thin Solid Films. 2011, 519, 4347–4350. [CrossRef]
7. Wakana, H.; Kawamura, T.; Fujii, K.; Uchiyama, H.; Hatano, M. P-17: Amorphous ZTO/ITO Stacked-Channel TFTs with Field Effect Mobility over 50 cm²/Vs and Resistant to Channel Thickness Dispersion. Sid Symp. Dig. Tech. Pap. 2010, 41, 1287–1290. [CrossRef]
8. Liu, G.; Ao, L.; Zhu, H.; Shin, B.; Shan, F. Low-Temperature, Nontoxic Water-Induced Metal-Oxide Thin Films and Their Application in Thin-Film Transistors. Adv. Funct. Mater. 2015, 25, 2564–2572. [CrossRef]
9. Han, S.Y.; Herman, G.S.; Chang, C.H. Low-Temperature, High-Performance, Solution-Processed Indium Oxide Thin-Film Transistors. J. Am. Chem. Soc. 2011, 133, 5166. [CrossRef]
10. Marrs, M.A.; Moyer, C.D.; Bawolek, E.J.; Cordova, R.J.; Trujillo, J.; Raupp, G.B.; Vogt, B.D. Control of Threshold Voltage and Saturation Mobility Using Dual-Active-Layer Device Based on Amorphous Mixed Metal–Oxide–Semiconductor on Flexible Plastic Substrates. IEEE Trans. Electron Devices 2011, 58, 3428–3434. [CrossRef]
11. Jeon, S.; Sun, I.K.; Park, S.; Song, I.; Kim, C. Low-Frequency Noise Performance of a Bilayer InZnO–InGaZnO Thin-Film Transistor for Analog Device Applications. IEEE Electron Device Lett. 2010, 31, 1128–1130. [CrossRef]
12. Yang, J.H.; Choi, J.H.; Pi, J.E.; Kim, H.O.; Park, E.S.; Kwon, O.S.; Nam, S.; Cho, S.H.; Yoo, S.; Hwang, C.S. High Performance Back Channel Etch Metal Oxide Thin-film Transistor with Double Active Layers. Sid Int. Symp. Dig. Technol. Pap. 2016, 47, 1151–1154. [CrossRef]
13. Kim, H.S.; Park, J.S.; Jeong, H.K.; Son, K.S.; Kim, T.S.; Seon, J.B.; Lee, E.; Chung, J.G.; Kim, D.H.; Ryu, M.; et al. Density of states-based design of metal oxide thin-film transistors for high mobility and superior photostability. ACS Appl. Mater. Interfaces 2012, 4, 5416–5421. [CrossRef] [PubMed]
14. Kim, Y.H.; Heo, J.S.; Kim, T.H.; Park, S.; Yoon, M.H.; Kim, J.; Oh, M.S.; Yi, G.R.; Noh, Y.Y.; Park, S.K. Flexible metal-oxide devices made by room-temperature photochemical activation of sol-gel films. Nature 2012, 489, 128–132. [CrossRef] [PubMed]
15. Li, Y.; Zhu, D.; Xu, W.; Han, S.; Fang, M.; Liu, W.; Cao, P.; Lu, Y. High-mobility nanometer-thick crystalline In–Sm–O thin-film transistors via aqueous solution processing. J. Mater. Chem. C 2020, 8, 310–318. [CrossRef]
16. Jeong, S.; Ha, Y.G.; Moon, J.; Facchetti, A.; Marks, T.J. Role of gallium doping in dramatically lowering amorphous-oxide processing temperatures for solution-derived indium oxide thin-film transistors. Adv. Mater. 2010, 22, 1346. [CrossRef] [PubMed]
17. Liang, K.; Wang, Y.; Shao, S.; Luo, M.; Pecunia, V.; Shao, L.; Zhao, J.; Chen, Z.; Mo, L.; Cui, Z. High-performance metal-oxide thin-film transistors based on inkjet-printed self-confined bilayer heterojunction channels. *J. Mater. Chem. C* 2019, 7, 6169–6177. [CrossRef]

18. Hennek, J.W.; Jeremy, S.; Aiming, Y.; Myung-Gil, K.; Wei, Z.; Dravid, V.P.; Antonio, F.; Marks, T.J. Oxygen “getter” effects on microstructure and carrier transport in low temperature combustion-processed a-InXZnO (X = Ga, Sc, Y, La) transistors. *J. Am. Chem. Soc.* 2013, 135, 10729–10741. [CrossRef]

19. Glynn, C.; O’Dwyer, C. Solution Processable Metal Oxide Thin Film Deposition and Material Growth for Electronic and Photonic Devices. *Adv. Mater. Interfaces* 2017, 4, 1600610. [CrossRef]

20. Garlapati, S.K.; Divyaa, M.; Breitung, B.; Kruk, R.; Dasgupta, S. Printed Electronics Based on Inorganic Semiconductors: From Processes and Materials to Devices. *Adv. Mater.* 2018, 30, 1707600. [CrossRef]

21. Seo, J.S.; Jeon, J.H.; Hwang, Y.H.; Park, H.; Ryu, M.; Park, S.H.; Bae, B.S. Solution-processed flexible fluorine-doped indium oxide thin-film transistors fabricated on plastic film at low temperature. *Sci. Rep.* 2013, 3, 2085. [CrossRef] [PubMed]

22. Hsu, H.-H.; Chang, C.-Y.; Cheng, C.-H.; Chiu, S.-H.; Huang, C.-H. High Mobility Bilayer Metal–Oxide Thin Film Transistors Using Titanium-Doped InGaZnO. *IEEE Electron Device Lett.* 2014, 35, 87–89. [CrossRef]

23. Jung, H.Y.; Kang, Y.; Hwang, A.Y.; Lee, C.K.; Han, S.; Kim, D.H.; Bae, J.U.; Shin, W.S.; Jeong, J.K. Origin of the improved mobility and photo-bias stability in a double-channel metal oxide transistor. *Sci. Rep.* 2014, 4, 3765. [CrossRef] [PubMed]

24. Liu, G.X.; Liu, A.; Shan, F.K.; Meng, Y.; Shin, B.C.; Fortunato, E.; Martins, R. High-performance fully amorphous bilayer metal-oxide thin film transistors using ultra-thin solution-processed ZrOx dielectric. *Appl. Phys. Lett.* 2014, 105, 113509. [CrossRef]

25. Yang, C.P.; Chang, S.J.; Chang, T.H.; Wei, C.Y.; Juan, Y.M.; Chu, C.J.; Weng, W.Y. Thin-Film Transistors With Amorphous Indium–Gallium–Oxide Bilayer Channel. *IEEE Electron Device Lett.* 2017, 38, 572–575. [CrossRef]

26. Kim, K.M.; Jeong, W.H.; Kim, D.L.; Rim, Y.S.; Choi, Y.; Ryu, M.-K.; Park, K.-B.; Kim, H.J. Low-Temperature Solution Processing of AlInZnO/InZnO Dual-Channel Thin-Film Transistors. *IEEE Electron Device Lett.* 2011, 32, 1242–1244. [CrossRef]

27. Park, J.C.; Lee, H.-N. Improvement of the Performance and Stability of Oxide Semiconductor Thin-Film Transistors Using Double-Stacked Active Layers. *IEEE Electron Device Lett.* 2012, 33, 818–820. [CrossRef]

28. Lee, J.; Lee, J.; Park, J.; Lee, S.E.; Lee, E.G.; Im, C.; Lim, K.H.; Kim, Y.S. Solution-Grown Homojunction Oxide Thin-Film Transistors. *ACS Appl. Mater. Interfaces* 2019, 11, 4103–4110. [CrossRef]

29. Khim, D.; Lin, Y.H.; Nam, S.; Faber, H.; Tetzner, K.; Li, R.; Zhang, Q.; Li, J.; Zhang, X.; Anthropoulos, T.D. Modulation-Doped InOx/InO Heterojunction Transistors Processed from Solution. *Adv. Mater.* 2017, 29. [CrossRef]

30. Lee, M.; Jo, J.W.; Kim, Y.J.; Choi, S.; Kwon, S.M.; Jeon, S.P.; Facchetti, A.; Kim, Y.H.; Park, S.K. Corrugated Heterojunction Metal-Oxide Thin-Film Transistors with High Electron Mobility via Vertical Interface Manipulation. *Adv. Mater.* 2018, e1804120. [CrossRef]

31. Lin, Y.-H.; Li, W.; Faber, H.; Seithkan, A.; Hastas, N.A.; Khim, D.; Zhang, Q.; Zhang, X.; Pliatsikas, N.; Tsetseris, L.; et al. Hybrid organic–metal oxide multilayer channel transistors with high operational stability. *Nat. Electron.* 2019, 2, 587–595. [CrossRef]

32. Yang, J.-H.; Choi, J.H.; Cho, S.H.; Pi, J.-E.; Kim, H.-O.; Hwang, C.-S.; Park, K.; Yoo, S. Highly Stable AlInZnSnO and InZnO Double-Layer Oxide Thin-Film Transistors With Mobility Over 50 cm^2/Vs for High-Speed Operation. *IEEE Electron Device Lett.* 2018, 39, 508–511. [CrossRef]

33. Chen, X.; Wan, J.; Wu, H.; Liu, C. ZnO bilayer thin film transistors using H2O and O3 as oxidants by atomic layer deposition. *Acta Mater.* 2020, 202, 204–210. [CrossRef]

34. Tian, Y.; Han, D.; Zhang, S.; Huang, F.; Shan, D.; Cong, Y.; Cai, J.; Wang, L.; Zhang, S.; Zhang, X.; et al. High-performance dual-layer channel indium gallium zinc oxide thin-film transistors fabricated in different oxygen contents at low temperature. *Ipn. J. Appl. Phys.* 2014, 53, 04EF07. [CrossRef]

35. Abliz, A.; Huang, C.W.; Wang, J.; Xu, L.; Liao, I.; Xiao, X.; Wu, W.W.; Fan, Z.; Jiang, C.; Li, J.; et al. Rational Design of ZnO:H/ZnO Bilayer Structure for High-Performance Thin-Film Transistors. *ACS Appl. Mater. Interfaces* 2016, 8, 7862–7868. [CrossRef]

36. Cong, Y.; Han, D.; Zhou, X.; Hu, P.; Yu, W.; Zhang, Y.; Zhang, S.; Zhang, X.; Wang, Y. High-Performance Al–Sn–Zn–O Thin-Film Transistor With a Quasi-Double-Channel Structure. *IEEE Electron Device Lett.* 2016, 37, 53–56. [CrossRef]
37. Sun Il, K.; Jung, K.C.; Chul, P.J.; Ihun, S.; Wook, K.S.; Huaxiang, Y.; Eunha, L.; Chul, L.J.; Youngsoo, P. High performance oxide thin film transistors with double active layers. In Proceedings of the 2008 IEEE International Electron Devices Meeting, San Francisco, CA, USA, 15–17 December 2008; pp. 1–4.

38. Chen, Z.; Han, D.; Zhao, N.; Cong, Y.; Jing, W.; Dong, J.; Zhao, F.; Liu, L.; Zhang, S.; Xing, Z. High-performance dual-layer channel ITO/TZO/TFTs fabricated on glass substrate. Electron. Lett. 2014, 50, 633–635. [CrossRef]

39. He, J.; Li, G.; Lv, Y.; Wang, C.; Liu, C.; Li, J.; Flandre, D.; Chen, H.; Guo, T.; Liao, L. Defect Self-Compensation for High-Mobility Bilayer InGaZnO/In2O3 Thin-Film Transistor. Adv. Electron. Mater. 2019, 5, 1900125. [CrossRef]

40. Furuta, M.; Koretomo, D.; Magari, Y.; Aman, S.G.M.; Higashi, R.; Hamada, S. Heterojunction channel engineering to enhance performance and reliability of amorphous In–Ga–Zn–O thin-film transistors. Jpn. J. Appl. Phys. 2019, 58, 090604. [CrossRef]

41. Kim, J.-I.; Hwan Ji, K.; Yoon Jung, H.; Yeob Park, S.; Choi, R.; Jang, M.; Yang, H.; Kim, D.-H.; Bae, J.-U.; Dong Kim, C.; et al. Improvement in both mobility and bias stability of ZnSnO transistors by inserting ultra-thin InSnO layer at the gate insulator/channel interface. Appl. Phys. Lett. 2011, 99, 121102. [CrossRef]

42. Chong, E.; Lee, S.Y. Influence of a highly doped buried layer for HfInZnO thin-film transistors. Semicond. Sci. Technol. 2012, 27, 012001. [CrossRef]

43. Jo, K.-W.; Moon, S.-W.; Cho, W.-J. Fabrication of high-performance ultra-thin-body SnO2 thin-film transistors using microwave-irradiation post-deposition annealing. Appl. Phys. Lett. 2015, 106, 043501. [CrossRef]

44. Lin, Y.Y.; Hsu, C.C.; Tseng, M.H.; Shyue, J.J.; Tsai, F.Y. Stable and High-Performance Flexible ZnO Thin-Film Transistors by Atomic Layer Deposition. ACS Appl. Mater. Interfaces 2015, 7, 22610–22617. [CrossRef]

45. Park, J.W.; Kang, B.H.; Kim, H.J. A Review of Low-Temperature Solution-Processed Metal Oxide Thin-Film Transistors for Flexible Electronics. Adv. Funct. Mater. 2019, 1904632. [CrossRef]

46. Jeong, W.H.; Kim, K.M.; Kim, D.L.; Rim, Y.S.; Kim, H.J. The Effects of Dual-Active-Layer Modulation on a Low-Temperature Solution-Processed Oxide Thin-Film Transistor. IEEE Trans. Electron Devices 2012, 59, 2149–2152. [CrossRef]

47. Kim, D.J.; Rim, Y.S.; Kim, H.J. Enhanced electrical properties of thin-film transistor with self-passivated multistacked active layers. ACS Appl. Mater. Interfaces 2013, 5, 4190–4194. [CrossRef]

48. Kim, C.H.; Rim, Y.S.; Kim, H.J. Chemical stability and electrical performance of dual-active-layered zinc-tin-oxide/indium-gallium-zinc-oxide thin-film transistors using a solution process. ACS Appl. Mater. Interfaces 2013, 5, 6108–6112. [CrossRef]

49. Yu, X.; Zhou, N.; Smith, J.; Lin, H.; Stallings, K.; Yu, J.; Marks, T.J.; Facchetti, A. Synergistic approach to high-performance oxide thin film transistors using a bilayer channel architecture. ACS Appl. Mater. Interfaces 2013, 5, 7983–7988. [CrossRef]

50. Seo, J.S.; Bae, B.S. Improved electrical performance and bias stability of solution-processed active bilayer structure of indium zinc oxide based TFT. ACS Appl. Mater. Interfaces 2014, 6, 15335–15343. [CrossRef]

51. Rim, Y.S.; Chen, H.; Kou, X.; Duan, H.S.; Zhou, H.; Cai, M.; Kim, H.J.; Yang, Y. Boost up mobility of solution-processed metal oxide thin-film transistors via confining structure on electron pathways. Adv. Mater. 2014, 26, 4273–4278. [CrossRef]

52. Lin, Y.H.; Faber, H.; Labram, J.G.; Stratakis, E.; Sygellou, L.; Kymakis, E.; Hastas, N.A.; Li, R.; Zhao, K.; Amassian, A.; et al. High Electron Mobility Thin-Film Transistors Based on Solution-Processed Semiconducting Metal Oxide Heterojunctions and Quasi-Superlattices. Adv. Sci. 2015, 2, 1500058. [CrossRef] [PubMed]

53. Nam, S.; Yang, J.-H.; Cho, S.H.; Choi, J.H.; Kwon, O.-S.; Park, E-S.; Lee, S-J.; Cho, K-I.; Jiang, J.; Hwang, C.-S. Solution-processed indium-free ZnO/SnO2 bilayer heterostructures as a low-temperature route to high-performance metal oxide thin-film transistors with excellent stabilities. J. Mater. Chem. C 2016, 4, 11298–11304. [CrossRef]

54. Tetzner, K.; Isakov, I.; Regoutz, A.; Payne, D.J.; Anthopoulos, T.D. The impact of post-deposition annealing on the performance of solution-processed single layer In2O3 and isotype In2O3/ZnO heterojunction transistors. J. Mater. Chem. C 2017, 5, 59–64. [CrossRef]

55. Faber, H.; Das, S.; Lin, Y.H.; Platsikas, N.; Zhao, K.; Kehagias, T.; Dimitrakopulos, G.; Amassian, A.; Patsalas, P.A.; Anthopoulos, T.D. Heterojunction oxide thin-film transistors with unprecedented electron mobility grown from solution. Sci. Adv. 2017, 3, e1602640. [CrossRef] [PubMed]
56. Chen, Y.; Huang, W.; Sangwan, V.K.; Wang, B.; Zeng, L.; Wang, G.; Huang, Y.; Lu, Z.; Bedzyk, M.J.; Hersam, M.C.; et al. Polymer Doping Enables a Two-Dimensional Electron Gas for High-Performance Homo junction Oxide Thin-Film Transistors. Adv. Mater. 2019, 31, e1805082. [CrossRef] [PubMed]

57. Khim, D.; Lin, Y.H.; Anthopoulos, T.D. Impact of Layer Configuration and Doping on Electron Transport and Bias Stability in Heterojunction and Superlattice Metal Oxide Transistors. Adv. Funct. Mater. 2019, 29, 1902591. [CrossRef]

58. Liu, L.; Chen, S.; Liang, X.; Pei, Y. Solution Processed AlInO/In2O3 Heterostructure Channel Thin Film Transistor with Enhanced Performance. Adv. Electron. Mater. 2019, 5, 1900550. [CrossRef]

59. Nadarajah, A.; Wu, M.Z.B.; Archila, K.; Kast, M.G.; Smith, A.M.; Chiang, T.H.; Keszler, D.A.; Wager, J.F.; Boettcher, S.W. Amorphous In–Ga–Zn Oxide Semiconducting Thin Films with High Mobility from Electrochemically Generated Aqueous Nanocluster Inks. Chem. Mater. 2015, 27, 5587–5596. [CrossRef]