A thin-film transistor with no apparent channel for simplified, high aperture ratio pixel architectures

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Abstract
Advances in practical electronics often result from the quest to improve the scalability of fundamental components, but improvements in the scalability of thin-film transistors (TFTs) have been frustrated by performance degradation at reduced dimensions. In particular, many of these scaling issues are tied to a common feature of all transistors, the semiconductor channel. Here, we introduce TFTs with source and drain materials in direct contact. In the absence of a channel, these TFTs maintain excellent performance including high effective mobility and low voltage saturation. Central to our design is the combination of the depleting properties of a Schottky source electrode with a quasi-metallic drain material, in this case indium-tin-oxide. As an example application, we propose a simpler, more compact pixel architecture for realizing high-resolution displays, which reduces transistor area by two thirds and can reduce pixel power consumption by almost 80% when compared to conventional TFT structures.

KEYWORDS
display technology, oxide semiconductors, short-channel effects, source-gated transistor, thin-film transistor
1 INTRODUCTION

A unique combination of properties provided by oxide semiconductors and conductors, including high transparency in the visible spectrum, mechanical flexibility, and low-temperature deposition, has allowed for a reimagining of transistor applications, especially in flexible displays, wearable electronics, and medical devices.1–3 The most promising of these oxide semiconductors, indium-gallium-zinc-oxide (IGZO), has started to replace amorphous silicon and poly-crystalline silicon due to its amorphous structure, high stability, and relatively high mobility.4 Since the pioneering work by the Hosono group in 2003, IGZO-based thin-film transistors (TFTs) have become an important component in display industries.5 During this period, the potential applications of IGZO have been broadened with significant developments including IGZO TFTs operating beyond 1 GHz,6 IGZO TFTs with significantly enhanced mobility,7 IGZO Schottky diodes operating beyond 2.45 GHz,8 IGZO-based RFID tags,9 IGZO/carbon nanotube-based macro-electronics,10 and large-area complementary circuits using IGZO and SnO.11 These advances have paved the road towards fully oxide-based flexible electronics.

A separate but widely used oxide material, indium-tin-oxide (ITO), was discovered in the 1950s12 and has long been used as a transparent conductor/electrode13,14 for organic light emitting diodes,15 solar cells,16 and window heating elements.17 Due to a high concentration of In2O3, the carrier mobility of ITO is much higher than IGZO.18 However, the very high electron concentration of ITO (attributed to its oxygen deficiency and tin dopants) pins its Fermi level to the conduction band edge and makes ITO TFTs nearly impossible to switch off.19 A few recent studies have focused on using ITO as a semiconductor.18–21 Techniques proposed to reduce the carrier concentration include decreasing the ITO thickness,18 increasing the oxygen content,20 and introducing other dopants.21 However, these approaches still adopt conventional TFT structures, which may sacrifice the high mobility of ITO to meet the requirement for a low carrier concentration, particularly for devices on temperature sensitive substrates such as polymers.22 As a result, how to design a transistor to maximize the potential of oxide materials, as well as other thin-film electronic materials, remains an open question.

Currently, the most important industrial application of ITO and IGZO is the back-panel drive unit of displays. Here, the size of the transistor directly affects the quality of the display as each pixel requires at least one TFT (two or more for OLED displays). In conventional pixel designs, in order to optimize energy efficiency, it is important to maximize the so-called aperture ratio between the light-emitting active area and the opaque area taken up by the TFTs. However, as higher resolution demands smaller pixels, i.e., a higher number of pixels per inch (PPI), difficulties in scaling down the size of TFTs mean that the opaque area occupied by TFTs may be similar to the area of the active region.23 The degradation of TFT characteristics, such as the quality of saturation and threshold voltage stability,24,25 at reduced device dimensions occurs for a variety of reasons including channel-length modulation, impact ionization,26 and contact resistance.27,28 Such issues, which are persistent problems with conventional TFT designs, are collectively known as short-channel effects. Thus, the desire to increase resolution has led to the implementation of increasingly complex pixel architectures to compensate for the shortcomings of conventional TFTs.23 It would be highly desirable to design a new transistor structure which allows for both aggressive scaling and simple pixel architectures.

Independent of oxide semiconductor research, a thin-film transistor with a unique operating mechanism was invented by Shannon and Gerstner29 at the University of Surrey using amorphous silicon. The device, known as a source-gated transistor (SGT), has now been demonstrated using several semiconductor channel materials including oxide semiconductors,30 organic semiconductors,31 and poly-crystalline silicon32 but always requires a Schottky source electrode instead of an Ohmic one. The use of a Schottky source leads to a major departure from the usual TFT operating mechanism. Indeed, the behavior of the Schottky source is the main determinant of the current in an SGT as opposed to the properties of the semiconductor channel layer. For example, the extremely flat saturation current and the low-voltage operation which make SGTs an excellent current source are caused by depletion from the Schottky source and cannot be achieved by ordinary TFTs which use the drain pinch-off mechanism and are limited by short-channel effects.29,33

One unique advantage of the SGT design is that it allows for a highly conductive channel material, as the resistive source region controls the current through the device. In this work, we apply well-established techniques of Schottky contact formation on oxide semiconductors34,35 to ITO, which has high mobility, high carrier concentration, and high transparency. As a result, we demonstrate SGTs which can be considered to have their source and drain materials in direct contact. This is in stark contrast to conventional transistors where a semiconducting channel is a necessity and the dimensions of the channel largely determine the transistor performance. First, we present a comparison of IGZO TFTs and ITO SGTs and investigate the effects of varying
oxygen content at the Schottky source electrode on the threshold voltages of the latter. Then, we examine the scalability of the ITO SGTs, and, having obviated the need for a metallized drain contact, we propose an ITO SGT with no channel. Finally, as an example application, we create a compact pixel design and consider the resulting improvements in image quality, brightness and power consumption of displays.

2 RESULTS AND DISCUSSION

2.1 Replacing semiconductors in thin-film transistors

Figure 1A–C illustrates the differences between the conventional TFT, conventional SGT, and the SGT using a conductor as the channel material. In a conventional TFT, drain current modulation is made possible by capacitive coupling between the gate electrode and the semiconductor channel. The drain current also varies linearly with drain voltage until the drain voltage is high enough to compensate for the gate voltage at the drain end of the channel, at which point the current saturates (drain pinch-off).36 In an SGT, the drain current is still modulated by the gate voltage, but the area close to the Schottky source forms the main current limiting region, and the channel only acts as a parasitic resistance.33 The Schottky junction at the source leads to the formation of a depletion region beneath the source, which extends as drain voltage is increased. When the depletion region extends to the semiconductor/insulator interface, the drain current saturates (source pinch-off). Source pinch-off occurs at lower drain voltages than drain pinch-off; thus, the SGT saturates at a significantly lower drain voltage than the ordinary TFT.29 Moreover, as the saturation no longer depends on the channel, short-channel effects have little influence on the saturation current of SGTs, resulting a much higher output impedance and intrinsic gain compared with conventional TFTs.37 Figure 1C demonstrates how the SGT can operate using a quasi-conductor as the channel material. The high carrier concentration of the channel material creates a high electric field in the region of the source which reduces the effective barrier height of the Schottky source, resulting in a higher on-current than a conventional SGT (roughly 50 times greater than our results with IGZO for the same device dimensions and bias).33 In the source region the carrier concentration decreases due to the depletion caused by the Schottky barrier, making it possible for the...

![Figure 1](https://via.placeholder.com/150)

**FIGURE 1** Replacing semiconductors in thin-film transistors. (A–C) Cross-sectional schematics of a typical TFT, a conventional SGT, and an SGT using an oxide conductor. (D–F) Cross-sectional schematics and (G–I) output curves of an IGZO TFT, an ITO TFT, and an ITO SGT. (J) Transfer characteristics of a typical IGZO TFT and an ITO SGT. (K) Transfer characteristics of ITO transistors with different source and drain contacts including Al, Pt sputtered in Ar, and Pt sputtered in Ar balanced O₂ from 0.05% to 20%.
gate to modulate the carrier concentration under the source contact. Thus, the device can also achieve the excellent saturation associated with conventional SGTs. Another advantage of using a quasi-conductor is that the parasitic resistance in the channel is much lower, which can further improve the on-current.

In order to demonstrate the proposed device concept, three different devices were fabricated with the same dimensions: an IGZO TFT, an ITO TFT, and an ITO SGT. Cross-section schematics and output curves of these devices are shown in Figure 1D–I. In Figure 1G, the IGZO TFT demonstrates standard TFT output curves, saturating when \( V_D = V_G - V_{TH} \), where \( V_D \) is the drain voltage, \( V_G \) is the gate voltage, and \( V_{TH} \) is the threshold voltage of the TFT. For example, when \( V_G = 40 \) V, the IGZO TFT saturates when \( V_D > 20 \) V. The ITO TFT composes Al source/drain contacts deposited on a 10 nm-thick ITO layer, whose resistivity is found to be around \( 1.6 \times 10^{-3} \) \( \Omega \) cm from 4-probe measurement, which is similar to other reported values and that of commercially available ITO-coated conductive glass at such thickness.\(^{38} \) The ITO TFT demonstrates a far higher current than the IGZO TFT, but almost no gate modulation as shown in Figure 1H,K. However, by replacing the Al source contact with a Pt contact sputtered in Ar and 3\% Ar, the ITO SGT is formed, as shown in Figure 1F,I. Here, to save a processing step, we also replace the drain with a Pt contact sputtered in Ar and 3\% Ar; this has no effect on the device performance because the drain is forward biased and therefore orders of magnitude less resistive than the reverse biased source.

A comparison of the output curves in Figure 1G,I shows that the ITO SGT has much lower drain saturation voltages than the IGZO TFT. At low drain voltages, when the ITO SGT is saturated, the drain current is also higher than in the IGZO TFT. For example, when \( V_G = 40 \) V, the ITO SGT saturates around 7 V and provides a drain current of around 1.8 mA, while the IGZO TFT is still in the linear regime, and the current is around 1.2 mA. The substantially lower voltage saturation and stable saturation current make the ITO SGT a more appropriate choice for low-voltage current sources.

As discussed previously, the high carrier concentration of ITO can lower the effective barrier height of the Schottky source contact. Indeed, where semiconductor-based SGTs have suffered from a low current,\(^{33,37} \) the ITO SGT also has the added advantage of a similar saturation current to the IGZO TFT. The transfer curves of the IGZO TFT and the ITO SGT are compared in Figure 1J, further demonstrating that the ITO SGT can achieve higher currents than the IGZO TFT at low drain biases. Figure 1K demonstrates that the drain current of the ITO devices only has a strong gate dependence when the source contact is a high work function metal such as Pt. This is due to the depletion caused by the formation of a Schottky source contact. Our previous studies have shown that for oxide Schottky contacts, the barrier height is highly dependent upon the oxygen content at the interface.\(^{33} \) Introducing oxygen during the deposition of Pt causes a positive shift in the SGT threshold voltage and higher oxygen concentrations yield more positive threshold voltages. The subthreshold swing remains almost the same when increasing the oxygen content to 3\%. However, when sputtering Pt in 20\% O\(_2\), the subthreshold swing increases, suggesting the excess oxygen starts to diffuse into ITO and form interface traps. Thus, controlling the source/channel interfacial oxygen concentration provides a method to tune the threshold voltage by changing the barrier height of the Schottky contact.

### 2.2 Analysis of ITO SGT performance

In industrial manufacturing, the size of the transistor directly determines the integration density, cost, and power consumption. As the source area is the main determinant of SGT behavior, the area of the Schottky source contact directly affects the drain current. As a result, investigating and understanding the area dependence of the ITO SGT is necessary. ITO SGTs with a fixed source width and source lengths from 5.2 to 14.5 \( \mu \)m were fabricated on an SiO\(_2\)/Si substrate. Figure 2A shows an ITO SGT with a source length, \( L_S \), of 5.2 \( \mu \)m and a source width of 8.4 \( \mu \)m. The transfer curves and output curves of the device are shown in Figure 2B,C. The saturation voltages are around 1 V in the output curves, again demonstrating the excellent saturation of SGTs compared to TFTs. As the SGT is a contact controlled device, it is not strictly correct to discuss an overall device mobility. However, to get an insight into the performance of the ITO SGT, the effective field-effect mobility can be extracted using the conventional TFT equation. In this case, the channel length of the device is assumed to be 5 \( \mu \)m, which is similar to the true critical dimension of the SGT, the source length. It is found that the effective mobility peaks at 34 cm\(^2\)/Vs, as shown in Figure 2D, which is higher than that of the IGZO TFT in Figure 1G.

Figure 2E shows the drain current with different source lengths at different gate voltages. The results suggest that the current of the device has a linear dependence upon source length. This agrees with SGT theory,\(^{33} \) which states that the significant current can
be injected from areas of the source far from the edge nearest the drain electrode. The current density distribution in the source region is dictated by the effective length of the source contact, $L_{\text{eff}}$ (otherwise known as the transfer length). In the case of Figure 2E, when $V_G = 30\, \text{V}$, the current is limited by the source length, $L_S$, (as defined by lithography) suggesting that $L_{\text{eff}}$ is longer than $L_S$ and that significant current is being injected from all areas of the source. The effective mobility of the ITO SGT increases when increasing the source length as shown in Figure 2F. When the source length increases to 14.5 $\mu\text{m}$, the effective field-effect mobility is higher than 45 cm$^2$/Vs. The results discussed thus far suggest that for the TFT dimensions used in display back panels, ITO SGTs can outperform IGZO TFTs in terms of effective mobility, output impedance, and operating voltage.

According to SGT theory, the saturation current can be described by

$$I_{\text{sat}} = WL_{\text{eff}}J_V$$

$$= W \sqrt{\frac{qNC_G(V_G - V_T)e^{\frac{\phi_0}{k_BT}}}{H} \left[ \frac{\phi_0}{q} + \frac{C_G}{C_G + C_S}(V_G - V_T) \right] \left( 1 - e^{\frac{-\phi_0}{k_BT}} \right)}$$

where $W$ is the channel width, $L_{\text{eff}}$ is the effective length of the source contact, $J_V$ is the current density passing vertically down from the source contact, $N_C = 5 \times 10^{18} \, \text{cm}^{-3}$ is effective density of states in the conduction band (based on effective masses of conducting electrons in ITO), $V_T$ is the threshold voltage of the SGT, $H$ is the thickness of the semiconductor, $\mu$ is the field-effect mobility, $q$ is the electron charge, $\phi_0$ is the mean barrier height, $C_G$ and $C_S$ are the capacitance per unit area of the gate insulator and the semiconductor, $V_T$ is the threshold voltage of the SGT, $k_B$ is the Boltzmann constant, and $T$
is the temperature. The effective barrier height, $\phi_{\text{eff}}$, can be expressed as $(\phi_0 - \alpha E)$, where $E$ is the electric field in the semiconductor and $\alpha$ is the effective tunneling constant. The effective tunneling is induced by image-force lowering at high electrical fields. However, when the source is much shorter than the effective source length, as suggested by the linear dependence of the saturation current upon the source length, the saturation current can be described by

$$I_{\text{sat}} = W L_S J_V = q W L_S \mu N_C \left( \frac{\phi_0}{q} + \frac{C_G}{C_G + C_S} (V_G - V_T) \right) e^{-\frac{\phi_{\text{eff}}}{kT}},$$

(2)

where $L_S$ is the source length. From the transfer curve of the ITO TFT with Al contacts shown in Figure 1K, the ITO mobility is found to be 33.4 cm$^2$/Vs (Figure S1). Using Equation 2, the barrier height, threshold voltage, and the effective tunneling constant of the ITO SGT with the source length of 5.2 $\mu$m are found to be 0.43 eV, 2.70 V, and 0.30 nm, respectively, and the subthreshold swing is 2.75 V/dec (Figure S2).

FIGURE 2G,H shows the atomic force microscope (AFM) and Kelvin probe force microscope (KPFM) images of the ITO SGT. The potential map in Figure 2H illustrates that the surface of the ITO is quite inhomogeneous, with a surface potential roughness of around 0.06 eV. The surface potential difference between the Pt and ITO is around 0.36 eV as shown in Figure 2I and almost matches the source barrier height (0.43 eV) calculated from Equation 2.

2.3 | High-density pixel architecture using ITO SGTs

By using an SGT with a highly doped semiconductor, or even a degenerate semiconductor, as a channel, it is possible to dramatically improve upon the standard TFT design. First, the gate voltage will be shielded by the high carrier concentration in the channel area making it unnecessary to have the gate extending beyond the source edge. Second, ITO is widely used as the transparent conductive electrode for the liquid crystal in LCDs or OLEDs in OLED displays. Consequently, we can use ITO as the channel as well as the drain contact. Thus, the

FIGURE 3 Thin-film transistors with no apparent channel. (A) Schematics of a simplified pixel using an IGZO TFT and a pixel using the ITO SGT with no apparent channel. (B) Microscope image of the ITO SGT matrix using the new design. The dashed line highlights the ITO transparent electrode. (C) Output characteristics of the ITO SGTs in the matrix. (D) Comparison of the designs for pixels using IGZO TFT and ITO SGT. The active areas are highlighted using the red dashed lines. (E) Aperture ratios (transparent active area: total pixel area) of the pixels using IGZO TFT and ITO SGTs.
total (opaque) device area is just the area of the source, which is around one third the area of a conventional TFT, as shown in Figure 3A. Such a device is more like a vertical device rather than the conventional lateral device. The drain current flows from the conductive sidewall into the active region of the transistor beneath the source, where it is driven upwards to the source contact.

Figure 3B shows an ITO SGT matrix with the novel design. Normally, the pixel area comprises the transparent electrode area (i.e., the active area) and the opaque area occupied by circuitry. The ratio between the transparent active area and the total pixel area is called the aperture ratio and is a key figure of merit in display technology. For example, as the display of a smartphone uses a significant percentage of its total power, and displays with smaller aperture ratios require more power to achieve the same overall brightness, the aperture ratio directly affects the energy efficiency. In the case of the ITO SGT matrix, the gate line overlaps with the data line, and the ITO is used as both channel material and transparent area. This design is highly preferable in displays as it enables a major improvement in aperture ratio, while simultaneously simplifying the fabrication process.

The output curves in Figure 3C display the excellent characteristics which are typical of the ITO SGT design, including a saturation voltage lower than 1 V. A rudimentary comparison of the pixel designs using a TFT and an SGT is shown in Figure 3D. As the ITO, source contact and gate electrode are overlapped and hide under the data line; for the same line width, the active area of the SGT pixel is larger than the TFT one. This becomes more significant when increasing the pixel density (reducing the pixel area). If assuming the line width is 3 μm, the aperture ratio as a function of pixel density is shown in Figure 3E. It shows that when the pixels per inch (PPI) is around 400, the aperture ratio of the SGT pixel is similar to that of the TFT pixel. However, when increasing the PPI to 1,000, the aperture ratio of an SGT pixel is almost five times higher than that of a TFT pixel. Thus, to maintain the same overall illumination for LCDs, the TFT pixel must be five times brighter than the SGT pixel. As a result, implementing the SGT pixel design can reduce pixel power consumption by almost 80% when compared to conventional TFT structures. For smartphones, the display always consumes a significant percentage of power, though the exact percentage fluctuates dependent upon various factors such as use case, display size, and mitigation techniques. In extreme cases, the backlight of an LCD can consume as much as 60% of the smartphone power, thus by implementing an SGT-based architecture the total power consumption could be reduced by 48%, leading to significant gains in battery operation time.

ITO SGTs are also suitable for use as the driver TFT in OLED pixels, but not only because of their high scalability and potential for reduced power consumption. The output current in ITO SGTs is pinned off by the depletion under the Schottky source, leading to lower saturation voltages and high output impedances. The source contact current control also allows immunity from channel length variation down to hundreds of nm (directly measured) and is further evidenced, though indirectly, in Figure 21 where the influence of Schottky source on the ITO (a typical depletion region of a reversed biased Schottky contact) only extends ~20 nm beyond the source edge. Thus, ITO SGTs are a preferable to conventional TFTs because they can provide very stable current with a low voltage drop across the device.

As the fabrication process of ITO SGTs is compatible with the current commercialized production line of IGZO TFTs, the new design can be easily utilized by industrial manufacturers. Besides, the simplified structure of the new design can reduce the number of manufacturing steps as the transparent electrode, drain contact, and the active material of the transistor are the same material and can be deposited in one step. Hence, ITO SGTs are suitable to be used in the back panels of liquid crystal, OLED, and e-ink displays.

3 | CONCLUSIONS

By using a new SGT design for conductive channel materials, several inadequacies of oxide semiconductor TFTs and their related pixel architectures are overcome. The threshold voltage of the SGT can be modulated by the properties of the source contact: in the case of the ITO SGT, by varying the oxygen content at the source/channel interface. For an ITO SGT with a source length of 5.2 μm, the effective mobility is more than 30 cm²/Vs, which is higher than that of an IGZO TFT with the same dimensions. Moreover, the structure and the operating mechanism of the ITO SGT make it more like a vertical device rather than a lateral one. The result is a transistor with no apparent channel, which can tolerate far more aggressive scaling than an ordinary oxide TFT. Indeed, the area of the ITO SGT with the new design, which uses the ITO as both the active material and drain contact, is only 1/3 of that of a conventional TFT. Using the new design in display pixels substantially improves the aperture ratio, eases manufacturing, and lowers the cost. This work not only provides an insight into the theory of SGTs but also offers a practical device with a simple architecture for industrial application.
4 | MATERIALS AND METHODS

4.1 | Device fabrication

In this work, two types of substrates are used: 300 nm thick SiO2/Si wafers and Corning 7059 Glass. For the ITO SGTs on SiO2/Si substrates, a 10 nm thick ITO film was deposited using RF sputtering from a 3" target in Ar at 5 × 10⁻³ mbar. The source and drain contacts were deposited using the same method with a 3" Pt target in Ar and O₂ mixed gas. For devices on glass substrates, a 200 nm thick Al gate was deposited via thermal evaporation, and a 10 nm thick AlOₓ dielectric layer was subsequently anodized in 1 mM citric acid in water. The ITO, IGZO, and Pt layers were deposited using the same sputtering method as mentioned above. Al source-drain contacts were deposited via thermal evaporation. All devices were patterned using shadow masks or a laser writer.

4.2 | Device characterization

The current–voltage (IV) characterization was performed at room temperature in the dark using a Keysight E5270B semiconductor analyzer. The AFM/KPFM images were taken using Bruker ICON AFM.

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AUTHOR CONTRIBUTIONS

J. W., J. Z., and A. S. conceived the project, planned experiments, and contributed towards the manuscript during its preparation. J. W. and J. Z. carried out experiments and analyzed the data. A. S. supervised the project.

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