Oxide electronics: Translating materials science from lab-to-fab

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Advances in the science and technology of thin-film materials have fueled a myriad of developments in large area electronics. This is particularly true for amorphous oxide semiconductors. Oxides have underpinned a number of technologically significant innovations in displays, sensors, and photovoltaics. Now they are setting the stage for exciting new applications related to flexible electronics and three-dimensional (3D) integration for post-complementary metal oxide semiconductor (CMOS) back-end-of-line processing in the quest for more-than-Moore solutions. This article reviews the development of oxide semiconductors and associated integration processes that have translated materials science fiction to commercial reality on a large scale. These advances have been driven by a host of advantages such as low cost, prudent manufacturing and large area scalability. What makes oxide semiconductors so attractive? These materials have a wide bandgap, which provides for high transparency; a cool feature for seamless embedding of electronics, particularly displays and imagers, for the immersive ambient. The OFF-current in oxide thin-film transistors is ultralow, thanks to the very low density of states in the bandgap. Indeed, this attribute is indispensable to minimize charge leakage in switching transistors and for low power, low-voltage, high-resolution sensor interfaces. More importantly, oxide thin-film transistors can be processed at relatively low temperatures thus making them amenable for 3D integration on post-processed CMOS silicon. This article provides the current status of the oxide semiconductor technology. We review the evolution of oxides based on their functional properties, along with deposition and solution processing techniques for heterostructure thin-film transistors, phototransistors, nanowire image sensors, ultralow power Schottky-barrier transistors, and 3D integration for back-end-of-line CMOS. These devices constitute fundamental building blocks for a new generation of applications ranging from interactive displays and imaging to future 3D electronic systems that are not constrained by form factor.

Evolution of oxides for electronics

Our general understanding of the materials science of oxides has surpassed the research and development phase in laboratories and has reached large-scale commercial adoption, at the same time opening new opportunities in emerging application areas. In particular, new functional semiconducting oxides and associated fabrication processing techniques continue to play a key role where cost and performance have become key factors for scalable, large-scale integration.¹

Metal oxides can be classified based on their electrically functional properties, and can come in various forms such as bulk or thin-film microstructures, one-dimensional (1D)/two-dimensional (2D) nanostructures, and multilayer heterostructures.^{2,3} They are useful in a myriad of applications widely ranging from electronics (encompassing transparent

optoelectronics, magnetoelectronics, photonics, spintronics, thermoelectrics, and piezoelectrics) to energy harvesting and hydrogen storage.^{2–5} Notable examples of use of oxides for electronics include transparent conductors, flat-panel displays, photovoltaics, and solid-state fuel cells, and more recently, neuromorphic computing and oxide microelectromechanical systems.^{3,6}

High-quality oxide materials have been demonstrated using advanced film growth techniques such as molecular beam epitaxy, pulsed laser deposition, and atomic layer deposition.³ Despite advances in deposition, challenges remain in the quest to push device performance to new limits. Achieving high mobility in the semiconducting oxide is a key performance attribute in electronic devices, in which transport is determined by the overlap of the cationic and anionic orbitals. However,

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this overlap can be tuned by doping or strain.^{7,8} In flat-panel applications, maintaining uniformity of the oxide layer over large area surfaces, without compromising functionality or electronic properties, is a critical requirement in commercial applications. Compatibility with silicon technology has become an attractive requirement for three-dimensional (3D) heterogeneous integration in the quest for more-than-Moore solutions. Maintaining this compatibility stems the need for deposition of high-quality functional oxides with minimal native oxide barriers on the surface of silicon. Last, but not least, integration of small-scale, complex device structures requires high aspect ratio patterning techniques reminiscent of reactive ion etching.²

In early sensing applications, sintered oxides (e.g., ZnO powders) were used. Subsequently a new generation of sensors based on nanostructured (e.g., 1D nanowire/nanorod/nanotube, and 2D nanosheet) materials emerged by virtue of the increased surface area to volume ratio.⁹ Oxides have also become a key enabler for flexible electronics as demonstrated by the introduction of foldable display screens in cellphones. A key advantage of the oxide material system is its relatively large bandgap energy, which provides for transparency; an attractive feature of display and imaging systems.^{10,11}

As shown in **Figure 1**, the indium-gallium-zinc-oxide (IGZO) in active-matrix pixelated arrays has pronounced advantages over its conventional amorphous silicon (a-Si)

counterpart, such as high mobility, low leakage current and very high ON/OFF ratio. As a result, IGZO thin-film transistors (TFTs) yield higher display resolution (more pixels/area) and faster addressing, thereby making IGZO-based backplanes a great market choice for both small- and large-screen displays.¹²

While device and systems integration at present requires high vacuum physical and chemical vapor deposition routes coupled with relatively expensive photolithography processes,¹³ solution-processed fabrication techniques such as spin coating, spray pyrolysis, or printing are gaining considerable traction as possible alternatives for large area, scalable electronics.^{14–18} Therefore, attention is increasingly being drawn to solution-processed transparent semiconducting oxides such as ZnO, In₂O₃, and IGZO, in order to develop high-performance TFTs.^{19–21} Another noteworthy change in solution processing is the annealing temperature, which has decreased by nearly 500°C in the last decade.^{22–26} Most TFTs developed to-date are based on *n*-type semiconducting oxides, while future focus may turn to high-performance *p*-type TFTs using low cost solution processes for CMOS system-on-panel (SoC) integration.²

With transparent conducting oxides (TCOs), much of the early work in the last twenty to thirty years was empirical and focused on ZnO and variants of In_xSn_{1-x}O₂. A detailed account of TCO development can be found in the following excellent

reviews.^{4,27,28} The United States led the development of TCOs with market demand and rapid growth during the late 1990s to early 2000, driven by the need to scale-up flat-screen high-definition televisions and portable computer screens. Adding to this demand has been low emissivity (“low-e”) and electrochromic window glass, thin-film photovoltaics (PV), and a plethora of new handheld, smart devices.^{4,10}

It is quite remarkable to see how this field has since exploded, and is now mainly dominated by Asia, thanks in part to the drive for low cost manufacturing and need for higher performance TCOs. In particular,

with the growing importance of transition-metal-based oxides in electro-optical devices, the last few years are witnessing new entrants such as F- or Al-doped ZnO, fluorine-doped tin oxide and pyrolytic tin oxide in the TCO market. Recently, ternary oxide materials such as Cd_2SnO_4 , Zn_2SnO_4 , MgIn_2O_4 , CdSb_2O_6 , Y , ZnSnO_3 , GaInO_3 , $\text{Zn}_2\text{In}_2\text{O}_5$, and $\text{In}_4\text{Sn}_3\text{O}_{12}$ have come under investigation.^{10,24} However, indium tin oxide (ITO) still remains the most commonly used TCO in flat-panel applications. For example, in liquid crystal displays, the basic function of the ITO is to serve as a transparent electrode, while in organic light-emitting diode displays, it can serve as an anode due to its high work function to enhance hole injection. Often, it can also have additional functions where it performs as an antistatic electromagnetic interference shield or an electric heater. Despite this, doped ZnO is currently becoming a strong contender to replace ITO in flat-panel displays, solar cells and LEDs. It is abundant, cheaper, less toxic, easier to process, and can be fabricated at lower temperatures.^{5,29} Moreover, the conductivities attainable with degenerately doped ZnO (typically with Al, Ga, or Si) are becoming comparable to ITO; high conductivity being crucial to cope with the demand for bigger, faster displays while maintaining transparency.⁴ The main challenge faced by industry, however, is the market risk of displacing the well-established production base of ITO.

Oxides for newly emerging applications

The previous section described the various proven applications of oxide materials. Here, we present selected illustrative examples of newly emerging applications drawn from the literature. These include (1) heterostructure photo-TFT and nanowire image sensors, (2) touch-free optically interactive displays, (3) ultralow power Schottky TFTs, (4) flexible electronics, and (5) 3D integration for back-end-of-line CMOS.

Heterostructure photo-TFT and nanowire image sensors

While the oxide semiconductor has great attributes such as high mobility ($30 \text{ cm}^2 \text{ s}^{-1} \text{ V}^{-1}$), low subthreshold slope (0.1 V/dec), high bias stability, and low thermal budget deposition with large area uniformity, it suffers from persistent photo-conductivity (PPC) when subject to illumination by virtue of oxygen defects located within the bandgap. As a result, the material remains conductive for extended time periods, ruling out use of two-terminal optical sensors. This is because of the large response time, hence limiting the frame rate when deployed in active-matrix pixelated imaging arrays. To overcome the PPC issue, a three-terminal image sensor (or photo-TFT) was demonstrated,³⁵ in which the gated photo-TFT array consists of a high mobility gallium-indium-zinc-oxide (GIZO)/indium-zinc-oxide (IZO)/gallium-indium-zinc-oxide (GIZO) heterostructure channel layer as shown in **Figure 2**. Here, the sandwiched IZO layer is rich in O-defects, hence providing high sub-gap absorption in the visible spectrum, while the optically transparent GIZO layers serve to transport the photo-generated carriers to the terminals. A positive, gate

voltage pulse (of duration $\sim 10 \text{ ns}$) drives the Fermi level to the band edge to sweep out the photo-generated carriers, thereby accelerating recombination with the ionized oxygen defect states. The pulsing scheme applied to an active-matrix photo-TFT based imaging array yields a response time of $25 \mu\text{s}$ with a frame rate of 150 Hz . Besides its application as a contact-free interactive display,³⁵ as further described in the next example, the as-fabricated photo-TFT image sensor array can serve as a transparent camera.

A critical requirement for in-cell, dual-mode co-integrated TFT and photosensor for interactive displays and imaging arrays, is high aperture ratio. Besides scaling down TFTs in the active-matrix to minimum size, the photosensor must be scaled without compromising its optoelectronic performance. Here, 1D nanostructures such as nanowires (NWs), nanorods and nanotubes constitute a possible route due to their often-enhanced physical and electrical properties. While significant progress has been made with semiconducting ZnO, V_2O_5 , Sb_2Se_3 , InAs, CdS, and carbon nanotubes and graphene for display applications,^{36–43} challenges remain with doping and controllability, uniformity, and repeatability of the nanostructure and its dimensionality.

High-performance NW-based photo-TFTs have been reported for image sensing and interactive display applications.⁴⁴ A schematic of the NW photo-TFT is depicted in **Figure 3a–c**, in which its surface morphology (top view) is shown along with a photograph of the fabricated fully transparent oxide imager. High photocurrent gain of 10^4 – 10^6 was reported at wavelengths smaller than 550 nm with a dependence on incident photon flux as Φ^β where $1 \leq \beta \leq 1.5$. As mentioned earlier, a key requirement in oxide nanostructure pixelated arrays is a high frame rate. Excellent endurance during repeated

Figure 2. Cross-sectional HAADF-STEM image for the trilayer GIZO/IZO/GIZO photo-TFT channel. Indicated are positions 1, 2, and 3 confirming the uniformity in thickness of the active channel via the zoomed-in images.

illumination cycles was demonstrated using the aforementioned gate-pulse reset to overcome PPC. Apart from applications in high-resolution imaging, the NW photo-TFT can be employed in photosensitive scanning probe tips and optical biosensors.⁴⁴

Touch-free optically interactive displays

Most interactive displays rely on touch functionality realized based on infrared, resistive, capacitive, or surface acoustic wave architectures. Use of photosensors is attractive as it enables remote touch-free interaction on any screen-type, and can be fabricated using a variety of active semiconductors, including organics and metal oxides material systems. The latter is advantageous in view of the superior electrical and optical properties and long-term stability.

High-performance, display-compatible, photo-TFT sensors have been demonstrated using semiconducting oxides as the active channel material in conventional bottom-gate TFT configuration. The photo-TFT channel comprises a bilayer of GaInZnO and InZnO suitably optimized for enhanced photoreponse and stability. **Figure 4a** depicts sub-pixels of display and sensor regions, in which the TFTs of the in-cell touch layout are partitioned for switching, photosensing, and display. When compared to the conventional amorphous silicon-based photo-TFT, the bilayer oxide photo-TFT yields higher photocurrent and responsivity for a broad range of illumination intensities, in addition to its higher dark-state ON- and lower dark-state OFF-current. This is because of its higher carrier mobility and larger bandgap, respectively. Despite the simplicity in pixel architecture and intrinsic PPC property, these arrays are useful in large area interactive displays and provide a unique sensing scheme for high-speed array operations.⁴⁵

Ultralow power Schottky TFTs

Low-voltage, low-current operation is essential for wearable and implantable devices, especially in sensor interfaces to cope with the limited battery lifetime. At present, there are

only few TFT technologies that can operate at low power and the oxide semiconductor TFT is a prime example because its wide bandgap, and hence, ultralow OFF-current. Moreover, the ability to integrate oxide electronics at lower temperatures makes it compatible to flexible substrates.

Schottky-barrier IGZO TFTs functioning at ultralow power (<1 nW) and low supply voltages (<1 V) were reported⁴⁶ because of device operation in the deep subthreshold regime (i.e., near the OFF state) as depicted in **Figure 5a**. By modulating the degree of O-compensation in IGZO film during the sputtering process, Schottky contacts at source and drain of the TFT were formed as shown in **Figure 5b**. This yields a saturation drain current (I_{DS}) that is independent of drain voltage (V_{DS}) giving rise to an infinite output resistance. Basically the operating principle of the Schottky-barrier IGZO TFT in deep subthreshold regime brings together the best of the bipolar and field-effect transistor families. The high intrinsic gain (>400) with this device architecture constitutes a new design paradigm for near-OFF state operation of sensor interfaces and analog front-end circuits. These are vital building blocks for wearables and implantable devices.⁴⁶

Flexible electronics

The IZO-based photo-TFT presented earlier shows excellent photoresponse due to its exceptional sub-gap optical absorption in the 400–550 nm (2.2–3.1 eV) range. However, the materials used for the TFT's gate insulator and active channel layers are of limited stretchability, and research on more resilient materials for TFT integration continues to be ongoing.

The example considered here on flexible/stretchable oxide transistors is an IZO-based TFT with amorphous FeZr metal electrodes on a flexible substrate (PDMS). The as-fabricated IZO photosensor with FeZr electrodes yields a saturation mobility of 3.12 cm²/V-s, threshold voltage 4 V,

Figure 3. (a) Schematic inverted staggered NW oxide photo-TFT, (b) SEM image (top view) of NW oxide photo-TFT, and (c) photograph of the fabricated fully transparent imager.

and subthreshold swing 810 mV/decade at a drain voltage of 10 V. When the amorphous FeZr metal electrodes were bent or stretched to 15%, the TFT retained its ON-current at 1.4 μ A. This clearly points to the possible choice of amorphous FeZr as a core material in stretchable electronics. It relies on conventional semiconductor processing routes, without necessarily resorting to alternative structural patterns such as zig-zag, horseshoe, or wrinkling. The TFT photosensors integrated on electronic skin (Figure 6) are promising for a new generation of applications, including human-machine interactive interfaces, healthcare-monitoring systems, and medical diagnostic devices.⁴⁷

Three-dimensional integration for back-end-of-line CMOS

Oxide semiconductors are very promising for monolithic 3D integration in view of their low processing temperature and thermodynamic stability. There are a growing number of 3D integration examples for various applications ranging from high power to post-CMOS more-than-Moore functions, including possible DRAM integration. Recently an *n*-AOS/*p*⁺-NiO heterojunction diode fabricated at a process temperature of 300°C was demonstrated for 3D power integration⁴⁸ by utilizing a BEOL process. These examples are illustrated in Figure 7. Other emerging applications of this technology

Figure 6. (a) Stretchable oxide TFT with amorphous FeZr metal electrodes. (b) stretchable active-matrix organic light-emitting diode display.

include wearable energy harvesting, integrated photovoltaics, and soft robotics.

Three-dimensional integration of oxide TFTs augmenting power electronics have also been reported,⁴⁹ in which various oxide hafnium-indium-zinc-oxide (HIZO), IZO, and bilayer HIZO-IZO transistors were fabricated at sub-300°C maintaining BEOL compatibility. Along similar lines a novel hybrid CMOS image sensor architecture has been reported comprising nanometer-scale IGZO TFTs fabricated at sub-200°C on conventional Si photodiodes. This offers a new integration route for image sensors in micro-/nanosystems.⁵⁰

The quest for high performance continues to fuel research into highly scaled down devices with performance comparable to that of 2D materials. Short-channel transistors have been recently reported³⁸ based on ultrathin 4-nm ITO channel layer

with a lanthanum-doped hafnium oxide dielectric. Here, short-channel immunity was observed for a 40 nm device with subthreshold slope 66 mV per decade, OFF-state current $< 100 \text{ fA}/\mu\text{m}$ and ON/OFF ratio up to 5.5×10^9 , with overall characteristics that are very promising for ultralow power applications.⁵¹

In this issue

This issue of *MRS Bulletin* deals with recent developments and progress in oxide electronics with topics ranging from the materials science of oxides to device applications. There are six contributions that address aspects related to doping of oxide semiconductors and emerging magnetic oxide material systems in skyrmionics, thin-film transistors and integration architectures for displays, imaging, and neuromorphic computing, and 2D oxides for sensing.

Robertson and Zhang discuss doping limits in *p*-type oxide semiconductors.⁵² Development of electronically active oxide systems with both *n*- and *p*-type characteristics has been actively pursued in the device community. While high-speed, high-stability *n*-type oxide semiconductors have been routinely reported, the

problem remains with achieving a stable *p*-type oxide. The limit on how far the Fermi energy in the semiconductor can be adjusted by doping depends on the band edges. The authors notice that some possible *p*-type oxide materials have cation *s*-like lone-pair states, and present computational results on *p*-type oxides, representatively SnTa_2O_6 together with a perovskite structure. Complementary *n*- and *p*-integration is of significant interest for low power circuit functions particularly in monolithic 3D post-CMOS BEOL integration.

The article by Kawai et al. reviews high thermal stability

Figure 7. (a) Illustration of monolithic 3D integration for highly compact power electronic systems, (b) thermal budget flow for 3D integration where required power reduces going from bottom to top, (c) example of a 1T-1C DRAM cell schematic for implementation using oxide TFTs in a post-CMOS back-end-of-line process. In its OFF-state, the TFT's ultralow leakage current maximizes charge retention in the storage capacitor, C_{mbit} .

requirements of oxide semiconductors and present fluorine-doped IGZO field-effect transistors for BEOL 3D integration.⁵³ Despite the low process temperature needed for back-end-of-line integration, the IGZO should overcome thermal stability issues especially under a forming gas ambient, which tends to impose thermal budget constraints for 3D integration. The atomistic impact of F doping to amorphous IGZO by means of first-principles calculations suggest that the reduction of atomic coordination number in F-doped a-IGZO is a key factor to adjust oxygen vacancy formation. Authors discuss the effect of fluorine on the carrier diffusion path, conduction-band minimum and carrier mobility, and present back-end-of-line integration of stackable devices, including TFTs for DRAM and other applications.

Lim et al. provide insight on emerging magnetic oxide material systems and their topological textures in the field of skyrmionics.⁵⁴ They review special functionalities of magnetic oxide materials such as coupled ferroic order-parameters and correlation between the various internal degrees of freedom, which appear highly favorable as compared to bulk topological textures. Starting with an assessment of ferromagnetic oxides whereby stabilization of topological textures is discussed, it goes on to highlight the limitations of ferromagnetic oxide materials and brings into exploration ferrimagnetic and anti-ferromagnetic textures. The article concludes with a highlight of recent advances in electric field control of textures and provides an insight to realize electrically controlled, nonvolatile, low power skyrmionic devices.

Amorphous oxide TFTs have been becoming a key back-plane technology for flat-panel displays and x-ray imagers. Striakhilev, Park, and Tang review the various merits of amorphous oxides for TFTs and related manufacturing technologies.⁵⁵ Electronic properties and TFT characteristics, organized in terms of various applications, are discussed along with integration architectures for pixelated AMOLED displays, phototransistor image sensors and x-ray imagers. Stability issues associated with TFT materials are presented, and ways to mitigate this in the manufacturing process are discussed. The authors review architectural aspects of TFT and pixelated arrays with emphasis on circuits, particularly, device–circuit interactions for overall system compensation.

The penultimate article by Park et al. reviews binary ferroelectric oxides for a new computing paradigm built around neuromorphic and logic-in-memory devices as a promising alternative to the classical von Neumann architecture.⁵⁶ Since the discovery of ferroelectricity in doped thin-film hafnia, the ferroelectric nonvolatile field-effect transistor, compatible with the complementary metal–oxide–semiconductor transistor, has become a core building block, thanks to its high-speed, high-reliability, and multilevel device functionality. This article presents a comprehensive review from materials to devices with a focus on ferroelectric transistors, and introduces binary ferroelectric oxides for memory applications discussing current state-of-the-art and issues pertinent to ferroelectric memories for future computing.

The final article by Shin et al. reviews rational and synthesis strategies of various 2D semiconducting oxides optimized for chemiresistive gas sensors.⁵⁷ It presents not only representative synthesis approaches, but also rich insights to their fundamental design principles, discussing exfoliation of layered oxide semiconductors and templating routes using sacrificial means. Template-free synthesis routes to clarify the basic design principles of oxide nanosheets are also discussed along with assembly approaches to high-performance gas sensors. Here, hierarchical and hybrid nanostructures in terms of morphology and composition are presented. The authors conclude with an outlook of developments in 2D metal oxides.

Outlook

Oxide semiconductors have been responsible for a number of significant innovations in electronics and are setting the stage for newly emerging application areas. The evolution and the present status of oxide semiconductor materials and technologies are reviewed along with TFT design and integration strategies for the next-generation flat-panel, including flexible, electronics. There are several factors that act in strong favor of semiconducting oxides for future applications.

The wide bandgap of oxides, unlike a-Si and low-temperature polycrystalline silicon (LTPS), provides for optical transparency. The band-to-band transitions in deep blue or near-UV wavelengths paves the way for transparent displays. However, light sensitivity can be designed by introducing deep sub-gap defects (i.e., oxygen vacancies). This gives rise to sub-gap absorption at green and lower wavelengths making it potentially useful for imaging applications. When compared to the conventional a-Si based photo-TFT, the oxide counterpart yields higher photocurrent and responsivity for a broad range of illumination intensities. This is in addition to its higher dark-state ON- and lower dark-state OFF-current due to its higher carrier mobility and larger bandgap, respectively. However, PPC effects set in whereby the material remains conductive for extended time periods. PPC can be overcome by use of a photo-TFT image sensor comprising a GIZO/IZO/GIZO heterostructure channel layer. A positive voltage pulse of about 10 ns duration sweeps out the photo-generated carriers and overcomes frame rate constraints when deployed in active-matrix architectures. To meet the requirements of high aperture ratio in interactive displays and imaging arrays, the 1D nanostructured photo-TFT constitutes a possible route due to its enhanced physical and electrical properties. High photocurrent gain can be achieved at wavelengths smaller than 550 nm with excellent endurance during repeated illumination cycles using the gate-pulse reset scheme to overcome PPC.

The low density of states in oxide semiconductors implies a relatively high mobility compared with amorphous silicon that is achievable at practically low gate voltages. For wearable and implantable devices, low voltage, low current operation is essential especially in sensor interfaces to cope with the limited battery lifetime. There are very few TFT technologies if any that can operate at low power and the oxide semiconductor

TFT is a prime example by virtue of its wide bandgap and low density of states. Schottky-barrier IGZO TFTs functioning at ultralow power and low supply voltages can be realized by modulating the degree of O-compensation in the IGZO film during the sputtering process. Here, the saturation drain current is independent of drain voltage giving rise to an infinite output resistance and thus a high intrinsic gain. Such an architecture with oxide TFTs constitutes a new design paradigm for near-OFF state operation of sensor interfaces and analog front-end circuits, particularly considering the eight-to-nine orders wide dynamic range in the low current, near OFF-state regime.

The ability to integrate oxide electronics at lower temperatures makes it compatible to flexible substrates. Stretchable IZO-based TFTs with amorphous FeZr metal electrodes are able to retain their electrical characteristics when bent or stretched to 15 percent. The amorphous FeZr appears to be a possible choice as a core metallization material for a new generation of stretchable electronics applications using conventional semiconductor processing routes, without need for alternative strain-absorbing structural patterns.

The extremely low OFF-current, of the order of zepto amperes (zA), is indispensable for switching TFTs in view of very low charge leakage, making them ideal for 3D stacking of circuits. Driven by the need for more-than-Moore solutions, an interesting recent development is 3D integration for layering of new functionality circuits on post-processed CMOS silicon integrated circuit wafers. What makes this possible is the relatively low thermal deposition budget. The zA OFF-current makes oxide TFTs highly attractive, for example, for DRAM implementation in back-end-of-line CMOS. The pursuit for high performance continues with early reports of highly scaled down, ultrathin channel layer oxide TFTs of comparable performance to that of 2D materials showing excellent short-channel immunity, steep subthreshold characteristics, and high ON/OFF ratio.

Device and systems integration at present requires vacuum-based deposition and photolithographic patterning. Alternative routes based on solution processing are emerging, whereby spin coating, spray pyrolysis, and printing are gaining considerable traction. Here, particular attention is increasingly being drawn to solution-processed oxides such as ZnO, In₂O₃ and IGZO to develop high-performance TFTs with much lower annealing temperature.

While there is a myriad of *n*-type semiconducting oxides that have translated to high-performance TFTs, the development of thermodynamically stable *p*-type oxides continues to be a near-impossible technical problem.^{12,58,59} The challenge lies in development of *p*-type oxides of a similar materials structure to that of the *n*-type and which is compatible to the IGZO TFT to facilitate low cost CMOS implementation.

Epitaxially grown semiconducting oxides are opening up new horizons in electronics. They are attractive in view of their potentially high mobilities. Films grown on crystalline substrates yield mobility values comparable to that obtained in the single crystal with values in excess of 100 cm²/V-s. While

significant efforts have been placed on high mobility oxides, growth temperatures have been above 500°C, which makes it incompatible with the thermal budget of the well-established fabrication processes in the display industry, particularly for flexible electronics integration. Additionally, the best mobilities reported have been with oxides grown using molecular beam epitaxy with low growth rates and requiring high-temperature processing.^{60,61} Future efforts on epitaxial growth should be directed at lowering the process temperatures and on growth of films on wider range of substrates, including amorphous substrates such as glass and plastics. Solution to both these challenges will lend use of epitaxial oxides in displays and flexible electronics technologies, and 3D integration on post-CMOS silicon for logic and memory applications.

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Data availability

Data sharing not applicable to this article as no data sets were generated or analyzed during the current study.

Conflict of interest

The authors state that there is no conflict of interest.

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