Multimodal LTPS and Oxide TFTs

Radu A. Sporea

r.a.sporea@surrey.ac.uk
Advanced Technology Institute, School of Computer Science and Electronic Engineering,
University of Surrey, Guildford, GU2 7XH, UK

Keywords: LTPS, oxide, off-state, source-gated transistor, multimodal transistor

ABSTRACT

Thin-film transistors (TFTs) have enabled many applications, with displays being the most pervasive. Yet, shortcomings exist that Ohmic-contact TFTs cannot address, such as off-state leakage in low-temperature polysilicon. Multimodal transistors are new contact-controlled devices with superior off-state operation and versatile behavior that enables compact circuit design.

1 Introduction

Conventional Ohmic-contact thin-film transistors (TFTs) still dominate display technology, irrespective of the technology of choice. Ranging from legacy hydrogenated amorphous Si (a-Si:H) to emerging organic semiconductors [1], TFTs have been implemented in a variety of architectures (coplanar, staggered-electrode, bottom/top gate), including dual gate implementations [2]. Although oxide semiconductors (e.g. InGaZnO (IGZO)) receive significant attention in the research community [3] because of reduced leakage and low-cost manufacturing methods, low temperature polysilicon (LTPS) is still highly favored [2], [4], [5]. Its superior mobility and ability to develop complementary circuit design are still desirable, even though its off-state performance is poor [6]. LTPO (LTPS and oxide) does indeed solve the off-state performance issues [7], but this comes at considerable expense.

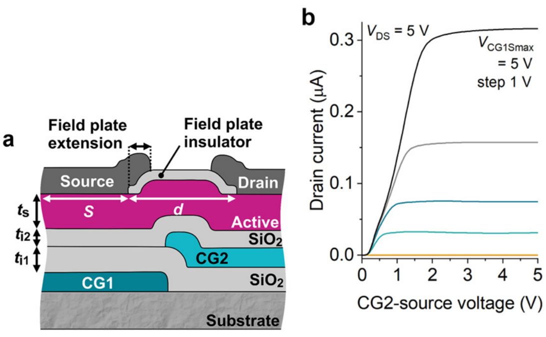

Fig. 1. a) Cross-sections of a) LTPS MMT in bottom gate, top contact configuration. b) transfer characteristic indicating independence of drain current on channel control gate (CG2) voltage. Adapted from [12] under Creative Commons CC-BY 4.0 license.

The multimodal transistor (MMT, Fig. 1) [8] is an alternative architecture that does not suffer the same shortcomings as Ohmic-contact TFTs. It uses source energy barriers to mitigate leakage currents in the off-state, as well as separate gating of the channel to reduce hot carrier effects in the on-state [9]. Thus, it is a more suitable candidate device for LTPS, but also for oxides, particularly as hot-carrier effects are being encountered as higher mobilities are achieved [10]. Thus, there are performance advantages of the MMT architecture at device level. Yet, due to its unique mixed-signal operation, the MMT has important benefits at circuit level. Specifically, it allows for the design of highly compact circuits [11]–[13], meaning cost saving for manufacturers and improved picture quality for users.

Here, we look at key considerations of LTPS and IGZO MMTs, with respect to device geometry and barrier design, as well as highlight recent developments in compact circuit design.

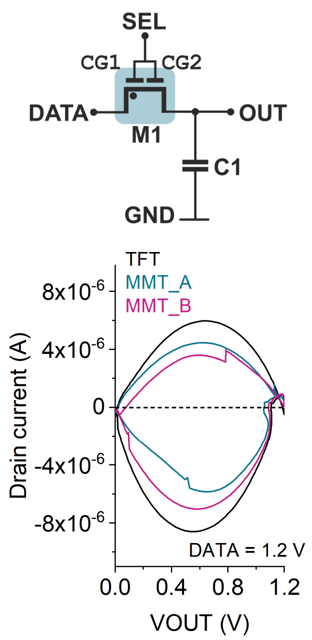

Fig. 2. Top: simple 1T1C test circuit; bottom: current-voltage plot showing the that contact-controlled transistors attain comparable charging and discharging current as ohmic-contact TFTs [12].

ISSN-L 1883-2490/32/0154 © 2025 ITE and SID

2 MMTs in Low Temperature Polycrystalline Silicon (LTPS)

The typical MMT cross section illustrated in Fig. 1a can be adapted to take advantage of process specifics [11], [12]. The transistor exhibits all the features of source-gated transistors (SGTs) [14], and additionally allows the drain current to be set to a desired value independently of the conduction state of the channel [8]. This is exhibited in the transfer characteristic of Fig. 1b, which demonstrates independence of drain current on CG2 voltage, as long as the channel is sufficiently conductive. This ability to independently control the presence of the drain current and its magnitude provides useful functionality for a variety of applications, the most mature of which is in active-matrix display backplanes.

A long-standing concern in LTPS pixel circuits is the relatively poor off-state performance [6], in particular of the N-channel transistor. Contact controlled transistors can attain exceptionally low of currents due to the band bending at the source [15] and may find value as switches in active matrix pixel circuits [13], [16]. A complication is developed by the fact that these switches require a high on current to be able to charge or discharge the storage capacitor in a short time, and contact control transistors typically have substantially lower on current than equivalent TFTs. Nevertheless, as Fig. 2 shows, the biasing conditions under which these switches operate mean that their transfer characteristics are quite similar, whether they are implemented as TFTs or contact controlled transistors. As such, the TFT only has a marginal advantage in terms of drive current and programming time. This finding is central to the future adoption of contact controlled transistors, not only as voltage-controlled current sources (drivers) [17], [18] but also as switches in pixel circuits [16].

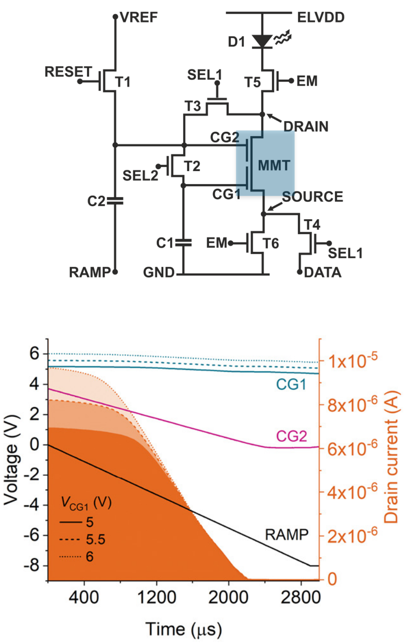

Fig. 3. Top 1M6T2C PWM + PWM circuit schematic using the MMT as driver. Bottom: waveforms showing amplitude modulation by programming CG1 potential. Adapted from [12] under Creative Commons CC-BY 4.0 license.

The main advantage of contact-controlled transistors is their saturation behavior, which is ideal for current sources as found within emissive pixels [17]. Additionally, the MMT configuration allows added functionality in a compact layout [8]. Fig. 3 demonstrates a remarkably compact circuit in which the MMT controls both the pulse width and the pulse amplitude modulation required for driving a micro-LED pixel with a built-in scheme for threshold compensation for both functions [12].

The additional complexity of the MMT is offset by the superior saturation performance even in the absence of low drain doping, resulting in a net reduction of fabrication process complexity. Moreover, the additional functionality of the MMT structure allows a compact layout for the transistor itself and the reduction of overall circuit complexity [12], which translates in simpler signal routing and a potential reduction of the number of masks required for interconnect.

3 MMTs in oxide semiconductors, e.g. IGZO

MMTs retain their specific functionality in IGZO, but here, the material intrinsically allows for reduced off current. The main advantage could be in improved stability, but in reality, barrier inhomogeneities result in significant variations in performance [19]. In the extreme, this unwanted effect can be exploited by designing hybrid contacts with two work functions to create a high energy barrier at the edge of the source closest to the drain and a low energy barrier within the bulk of the source contact [20], [21]. This preserves the contact-controlled behavior, while drastically increasing on-state current, as demonstrated by two independent groups. The processing practicalities, as well as the requirements for alignment between the two contact

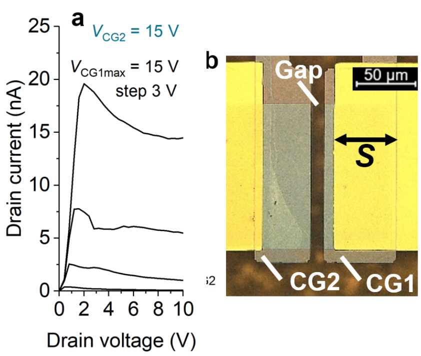

Fig. 4. a) Output characteristics showing time dependent current decay in IGZO bottom gate MMTs; b) micrograph of the IGZO MMTs [22].

Table I: Current state of understanding of contact-controlled superiority and inferiority in various thin-film technologies and for typical applications

Application or function	LTPS	Organic	IGZO	LTPO	HPO
Emissive pixel drive transistor	○	○	△	△	○
Pixel switch transistor (LED or LCD) - speed	△	△	△	△	△
Pixel switch transistor (LED or LCD) – leakage	○	△	△	△	△
Current source	○	○	○	○	○
Current mirror / active load	○	△	△	○	○
Gain stage	○	△	△	△	○
Logic – noise margin	○	○	○	○	○
Logic - speed	△	△	△	△	△
Transducer input	○	×	×	△	△
Temperature sensor	○	△	○	○	○
Strain and bending effects	Yet to be thoroughly investigated				

metals, are a topic of active investigation.

Separately, interesting behavior has been observed in some contact-controlled transistors in which the drain current reduces drastically after saturation. IGZO transistors have shown the most profound effect, and present investigations are confirming that the behavior is induced not by drain voltage variations but rather by continued biasing. While such characteristics, as shown in Fig. 4 [22], may offer little to display applications, they may prove valuable in neuromorphic (e.g. spiking neural network, SNN) applications [23].

4 Conclusion and outlook

The contact-controlled architecture coupled with the independent control of the injection and channel regions makes multimodal transistors (MMTs) highly versatile tools for display and other analog applications. Encouragingly, these devices can be implemented across a large range of material systems, with numerous advantages available if the application is co-designed to take advantage of the transistor's advanced functionality. Table 1 presents the suitability of contact-controlled transistors implemented in various technologies for different applications. The LTPS variant has enormous potential across the application spectrum, even though there are several investigations yet to be performed regarding bending and mechanical strain behavior across all semiconductor systems.

References

[1] L. Han *et al.*, "Wafer-scale organic-on-III-V monolithic heterogeneous integration for active-matrix micro-LED displays," *Nat. Commun.*, vol. 14, no. 1, pp. 1–9, 2023, doi: 10.1038/s41467-023-42443-8.

[2] D. Y. Jeong, M. M. Billah, A. B. Siddik, B. Han, Y. Chang, and J. Jang, "High performance dual gate blue laser annealed poly-Si thin-film transistor for high-resolution displays," *IEEE Trans. Electron Devices*, vol. 68, no. 8, pp. 3863–3869, 2021, doi: 10.1109/TED.2021.3091965.

[3] T. Kim *et al.*, "Progress, Challenges, and Opportunities in Oxide Semiconductor Devices: A Key Building Block for Applications Ranging from Display Backplanes to 3D Integrated Semiconductor Chips," *Adv. Mater.*, vol. 35, no. 43, pp. 1–50, 2023, doi: 10.1002/adma.202204663.

[4] Y. X. Wang *et al.*, "A Novel Structure to Reduce Degradation under Mechanical Bending in Foldable Low Temperature Polysilicon TFTs Fabricated on Polyimide," *IEEE Electron Device Lett.*, vol. 41, no. 5, pp. 725–728, 2020, doi: 10.1109/LED.2020.2979276.

[5] J. Oh *et al.*, "Pixel circuit with P-type low-temperature polycrystalline silicon thin-film transistor for micro light-emitting diode displays using pulse width modulation," *IEEE Electron Device Lett.*, vol. 42, no. 10, pp. 1496–1499, 2021, doi: 10.1109/LED.2021.3107152.

[6] K. C. Moon, J. H. Jeon, and K. C. Park, "A Study of Device Parameters Affecting the Current Error Rate in a Low-Temperature Polycrystalline Silicon Thin-Film Transistor Pixel Circuit for Active-Matrix Organic Light-Emitting Diode Display Applications," *Electron.*, vol. 13, no. 23, 2024, doi: 10.3390/electronics13234810.

[7] T. K. Chang, C. W. Lin, and S. Chang, "LTPO TFT technology for amoleds," *Dig. Tech. Pap. - SID Int. Symp.*, vol. 50, no. 1, pp. 545–548, 2019, doi: 10.1002/sdtp.12978.

[8] E. Bestelink, O. de Sagazan, L. Motte, B. Schultes, S. R. P. Silva, and R. A. Sporea, "Versatile thin-film transistor with independent control of charge injection and transport for mixed signal and analog computation," *Adv. Intell. Syst.*, vol. 3, p. 2000199, 2020, doi: 10.1002/aisy.202000199.

[9] E. Bestelink, O. De Sagazan, L. Motte, and R. A. Sporea, "Suppression of hot-carrier effects facilitated by the multimodal thin-film transistor architecture," *Adv. Electron. Mater.*, vol. 7, p.

2100533, 2021, doi: 10.1002/aelm.202100533.
[10] N. On, B. K. Kim, S. Lee, E. H. Kim, J. H. Lim, and J. K. Jeong, "Hot carrier effect in self-aligned In-Ga-Zn-O thin-film transistors with short channel length," *IEEE Trans. Electron Devices*, vol. 67, no. 12, pp. 5544–5550, Nov. 2020, doi: 10.1109/ted.2020.3032383.
[11] E. Bestelink and R. A. Sporea, "A compact 4T1M2C AMOLED pixel circuit with multimodal drive transistor," *J. Inf. Disp.*, 2024, doi: 10.1080/15980316.2024.2442965.
[12] E. Bestelink and R. A. Sporea, "Simultaneous pulse amplitude and pulse width modulation in a 6T1M2C pixel circuit enabled by the separate timing control for charge injection and transport in the multimodal transistor," *J. Soc. Inf. Disp.*, pp. 1–11, 2025, doi: 10.1002/jsid.2035.
[13] E. Bestelink and R. A. Sporea, "(Invited) 95-3: Pixel Design Techniques for 1 Hz Refresh Rate LTPS Emissive Displays Leveraging Multimodal Transistor On- and Off-State Current Characteristics," in *Dig. Tech. Pap. - SID Int. Symp.,* 2025.
[14] G. Wang *et al.*, "New opportunities for high-performance source-gated transistors using unconventional materials," *Adv. Sci.*, p. 2101473, 2021, doi: 10.1002/advs.202101473.
[15] E. Bestelink, T. Landers, and R. A. Sporea, "Turn-off mechanisms in thin-film source-gated transistors with applications to power devices and rectification," *Appl. Phys. Lett.*, vol. 114, p. 182103, May 2019, doi: 10.1063/1.5088681.
[16] E. Bestelink and R. A. Sporea, "62-4: Contact-controlled transistors as sufficiently fast switches for active-matrix pixel circuits," in *Dig. Tech. Pap. - SID Int. Symp.,* 2025.
[17] X. Xu, R. A. Sporea, and X. Guo, "Source-gated transistors for power-and area-efficient AMOLED pixel circuits," in *IEEE/OSA Journal of Display Technology*, 2014, vol. 10, no. 11, pp. 928–933, doi: 10.1109/JDT.2013.2293181.
[18] S. Huang, J. Jin, J. Kim, W. Wu, A. Song, and J. Zhang, "IGZO Source-Gated Transistor for AMOLED Pixel Circuit," *IEEE Trans. Electron Devices*, vol. 70, no. 7, pp. 3637–3642, 2023, doi: 10.1109/TED.2023.3274501.
[19] J. Zhang *et al.*, "Extremely high-gain source-gated transistors," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 116, no. 11, pp. 4843–4848, 2019, doi: 10.1073/pnas.1820756116.
[20] P. Sihapitak, J. P. S. Bermundo, and Y. Uraoka, "22-2: Significant Improvement of a-IGZO Source-Gated Transistor Current over Traditional Design through Architecture Modification," in *Dig. Tech. Pap. - SID Int. Symp.*, 2024, pp. 276–279, doi: 10.1002/sdtp.17508.
[21] G. Sheleg and N. Tessler, "Double injection function InGaZnO transistor—computational analysis of the patterned doping method," *Appl. Phys. Lett.*, vol. 120, no. 25, p. 253504, 2022, doi: 10.1063/5.0094334.
[22] E. Bestelink, D. C. Corsino, F. Catania, G. Cantarella, N. Munzenrieder, and R. A. Sporea, "Amorphous InGaZnO Multimodal Transistors with a Simplified Gate Stack Design," in *IEEE CAS*, 2024.
[23] K. Kim, M. S. Song, H. Hwang, S. Hwang, and H. Kim, "A comprehensive review of advanced trends: from artificial synapses to neuromorphic systems with consideration of non-ideal effects," *Front. Neurosci.*, vol. 18, p. 1279708, 2024, doi: 10.3389/fnins.2024.1279708.