

Data Supporting Literature

for

Sub-threshold Schottky-barrier thin film transistors with ultralow power and high intrinsic gain

Sungsik Lee and Arokia Nathan*

Electrical Engineering Division, Department of Engineering, University of Cambridge, 9
JJ Thomson Avenue, Cambridge CB3 0FA, UK

*Corresponding author. Email: an299@cam.ac.uk

This file includes:

References with DOI links

References

1. K. Nomura, H. Ohta, K. Ueda, T. Kamiya, M. Hirano, H. Hosono, Thin-film transistor fabricated in single-crystalline transparent oxide semiconductor. *Science* **300**, 1269–1272 (2003). [doi:10.1126/science.1083212](https://doi.org/10.1126/science.1083212) [Medline](#)
2. J. F. Wager, Applied physics. Transparent electronics. *Science* **300**, 1245–1246 (2003). [doi:10.1126/science.1085276](https://doi.org/10.1126/science.1085276) [Medline](#)
3. K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, H. Hosono, Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors. *Nature* **432**, 488–492 (2004). [doi:10.1038/nature03090](https://doi.org/10.1038/nature03090) [Medline](#)
4. R. Martins, A. Nathan, R. Barros, L. Pereira, P. Barquinha, N. Correia, R. Costa, A. Ahnood, I. Ferreira, E. Fortunato, Complementary metal oxide semiconductor technology with and on paper. *Adv. Mater.* **23**, 4491–4496 (2011). [doi:10.1002/adma.201102232](https://doi.org/10.1002/adma.201102232) [Medline](#)
5. S. Lee, S. Jeon, R. Chaji, A. Nathan, Transparent semiconducting oxide technology for touch free interactive flexible displays. *Proc. IEEE* **103**, 644–664 (2015). [doi:10.1109/JPROC.2015.2405767](https://doi.org/10.1109/JPROC.2015.2405767)
6. E. Fortunato, P. Barquinha, R. Martins, Oxide semiconductor thin-film transistors: A review of recent advances. *Adv. Mater.* **24**, 2945–2986 (2012). [doi:10.1002/adma.201103228](https://doi.org/10.1002/adma.201103228) [Medline](#)
7. Y. J. Tak, B. D. Ahn, S. P. Park, S. J. Kim, A. R. Song, K.-B. Chung, H. J. Kim, Activation of sputter-processed indium-gallium-zinc oxide films by simultaneous ultraviolet and thermal treatments. *Sci. Rep.* **6**, 21869 (2016). [doi:10.1038/srep21869](https://doi.org/10.1038/srep21869) [Medline](#)
8. J. F. Wager, B. Yeh, R. L. Hoffman, D. A. Keszler, An amorphous oxide semiconductor thin-film transistor route to oxide electronics. *Curr. Opin. Solid State Mater. Sci.* **18**, 53–61 (2014). [doi:10.1016/j.cossms.2013.07.002](https://doi.org/10.1016/j.cossms.2013.07.002)
9. H. Nishide, K. Oyaizu, Toward flexible batteries. *Science* **319**, 737–738 (2008). [doi:10.1126/science.1151831](https://doi.org/10.1126/science.1151831) [Medline](#)
10. P. D. Mitcheson, E. M. Yeatman, G. K. Rao, A. S. Holmes, T. C. Green, Energy harvesting from human and machine motion for wireless electronic devices. *Proc. IEEE* **96**, 1457–1486 (2008). [doi:10.1109/JPROC.2008.927494](https://doi.org/10.1109/JPROC.2008.927494)
11. J. M. Donelan, Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, A. D. Kuo, Biomechanical energy harvesting: Generating electricity during walking with minimal user effort. *Science* **319**, 807–810 (2008). [doi:10.1126/science.1149860](https://doi.org/10.1126/science.1149860) [Medline](#)
12. R. J. M. Vullers, R. van Schaijk, I. Doms, C. Van Hoof, R. Mertens, Micropower energy harvesting. *Solid-State Electron.* **53**, 684–693 (2009). [doi:10.1016/j.sse.2008.12.011](https://doi.org/10.1016/j.sse.2008.12.011)

13. T. Kodaira, S. Hirabayashi, Y. Komatsu, M. Miyasaka, H. Kawai, S. Nebashi, S. Inoue, T. Shimoda, A flexible 2.1-in. active-matrix electrophoretic display with high resolution and a thickness of 100 μm . *J. Soc. Inf. Disp.* **16**, 107 (2008). [doi:10.1889/1.2835015](https://doi.org/10.1889/1.2835015)
14. H. Gleskova, S. Wagner, W. Soboyejo, Z. Suo, Electrical response of amorphous silicon thin-film transistors under mechanical strain. *J. Appl. Phys.* **92**, 6224 (2002). [doi:10.1063/1.1513187](https://doi.org/10.1063/1.1513187)
15. T. Sekitani, U. Zschieschang, H. Klauk, T. Someya, Flexible organic transistors and circuits with extreme bending stability. *Nat. Mater.* **9**, 1015–1022 (2010). [doi:10.1038/nmat2896](https://doi.org/10.1038/nmat2896) [Medline](#)
16. R. Chaji, A. Nathan, *Thin Film Transistor Circuits and Systems* (Cambridge Univ. Press, Cambridge, UK, 2013).
17. B. Razavi, *Design of Analog CMOS Integrated Circuits* (McGraw-Hill, New York, 2001).
18. A. S. Sedra, K. C. Smith, *Microelectronic Circuits* (Oxford Univ. Press, New York, USA, 2007).
19. A. Janotti, C. G. Van de Walle, Oxygen vacancies in ZnO. *Appl. Phys. Lett.* **87**, 122102 (2005). [doi:10.1063/1.2053360](https://doi.org/10.1063/1.2053360)
20. S. Lany, A. Zunger, Anion vacancies as a source of persistent photoconductivity in II-VI and chalcopyrite semiconductors. *Phys. Rev. B* **72**, 035215 (2005). [doi:10.1103/PhysRevB.72.035215](https://doi.org/10.1103/PhysRevB.72.035215)
21. S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, Hoboken, NJ, ed. 2, 1981).
22. S. Lee, S. Jeon, A. Nathan, “Modeling sub-threshold current–voltage characteristics in thin film transistors,” *J. Disp. Technol.* **9**, 833 (2013). [doi:10.1109/JDT.2013.2256878](https://doi.org/10.1109/JDT.2013.2256878)
23. Y. Umemoto, W. J. Schaff, H. Park, L. F. Eastman, Effect of thermionic-field emission on effective barrier height lowering in $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ Schottky diodes. *Appl. Phys. Lett.* **62**, 1964 (1993). [doi:10.1063/1.109638](https://doi.org/10.1063/1.109638)
24. S. Lee, A. Nathan, S. Jeon, J. Robertson, Oxygen defect-induced metastability in oxide semiconductors probed by gate pulse spectroscopy. *Sci. Rep.* **5**, 14902 (2015). [doi:10.1038/srep14902](https://doi.org/10.1038/srep14902) [Medline](#)
25. P. Ranade, H. Takeuchi, T.-J. King, C. Hu, *Electrochem. Solid-State Lett.* **4**, G85 (2001). [doi:10.1149/1.1402497](https://doi.org/10.1149/1.1402497)
26. W. Hu, R. L. Peterson, Molybdenum as a contact material in zinc tin oxide thin film transistors. *Appl. Phys. Lett.* **104**, 192105 (2014). [doi:10.1063/1.4875958](https://doi.org/10.1063/1.4875958)

27. T. Kamiya, H. Hosono, Material characteristics and applications of transparent amorphous oxide semiconductors. *NPG Asia Mater.* **2**, 15–22 (2010). [doi:10.1038/asiamat.2010.5](https://doi.org/10.1038/asiamat.2010.5)
28. Y.-S. Lee, Z.-M. Dai, C.-I. Lin, H.-C. Lin, “Relationships between the crystalline phase of an IGZO target and electrical properties of a-IGZO channel film,” *Ceramics International* **38S**, S859 (2012). [doi: dx.doi.org/10.1016/j.ceramint.2011.05.105](https://doi.org/10.1016/j.ceramint.2011.05.105)
29. C.-C. Lo, T.-E. Hsieh, Preparation of IGZO sputtering target and its applications to thin-film transistor devices. *Ceram. Int.* **38**, 3977–3983 (2012). [doi:10.1016/j.ceramint.2012.01.052](https://doi.org/10.1016/j.ceramint.2012.01.052)
30. S. Park, S. Bang, S. Lee, J. Park, Y. Ko, H. Jeon, The effect of annealing ambient on the characteristics of an indium-gallium-zinc oxide thin film transistor. *J. Nanosci. Nanotechnol.* **11**, 6029–6033 (2011). [doi:10.1166/jnn.2011.4360](https://doi.org/10.1166/jnn.2011.4360) [Medline](#)
31. S. Kim, Y. Gil, Y. Choi, K.-K. Kim, H. J. Yun, B. Son, C.-J. Choi, H. Kim, Carrier transport at metal/amorphous hafnium-indium-zinc oxide interfaces. *ACS Appl. Mater. Interfaces* **7**, 22385–22393 (2015). [doi:10.1021/acsami.5b06223](https://doi.org/10.1021/acsami.5b06223) [Medline](#)
32. A. Ortiz-Conde, F. J. García Sánchez, J. J. Liou, A. Cerdeira, M. Estrada, Y. Yue, A review of recent MOSFET threshold voltage extraction methods. *Microelectron. Reliab.* **42**, 583–596 (2002). [doi:10.1016/S0026-2714\(02\)00027-6](https://doi.org/10.1016/S0026-2714(02)00027-6)
33. S.-H. Kuk, D. W. Kang, J. S. Lee, S. J. Kim, J. Y. Kwon, M. K. Han, “Short channel effect of indium-gallium-zinc-oxide thin film transistors,” *Proc. of Int. Conf. on Soli. Stat. Device and Mater.* **2010**, pp. 363-364, Sep 21, 2010 - Sep 24, 2010, the University of Tokyo, Tokyo, Japan. [doi: dx.doi.org/10.7567/ssdm.2010.p-6-5](https://doi.org/10.7567/ssdm.2010.p-6-5)
34. D. H. Kang, J. Ung Han, M. Mativenga, S. Hwa Ha, J. Jang, Threshold voltage dependence on channel length in amorphous-indium-gallium-zinc-oxide thin-film transistors. *Appl. Phys. Lett.* **102**, 083508 (2013). [doi:10.1063/1.4793996](https://doi.org/10.1063/1.4793996)
35. F. A. Padovani, R. Stratton, Field and thermionic-field emission in Schottky barriers. *Solid-State Electron.* **9**, 695–707 (1966). [doi:10.1016/0038-1101\(66\)90097-9](https://doi.org/10.1016/0038-1101(66)90097-9)
36. A. Schenk, *Advanced Physical Models for Silicon Device Simulation* (Springer, Berlin, Germany, 1998).
37. M. J. Powell, The physics of amorphous-silicon thin-film transistors. *IEEE Trans. Electron Dev.* **36**, 2753–2763 (1989). [doi:10.1109/16.40933](https://doi.org/10.1109/16.40933)
38. M. J. Powell, S. C. Deane, Improved defect-pool model for charged defects in amorphous silicon. *Phys. Rev. B* **48**, 10815–10827 (1993). [doi:10.1103/PhysRevB.48.10815](https://doi.org/10.1103/PhysRevB.48.10815) [Medline](#)