ZnO TFTs for giga-Hertz wireless systems without sub-micron lithography: Maximizing f_T, f_{MAX}, and $|Z_{OFF}/Z_{ON}|$

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We describe the key structure and material approaches towards recently demonstrated giga-Hertz large-area electronics (LAE) wireless systems using zinc-oxide (ZnO) thin-film transistors (TFTs) [1-4], and the resulting performance parameters. Today's LAE, including solar panels and flat-panel displays, operate at frequencies up to ~100 MHz. The next target is wireless applications [Internet of Things (IoT), 5/6G], where bringing LAE to the giga-Hertz regime opens new capabilities, enabling meter-scale radiative apertures for enhanced spatial resolution and power efficiency.

The two central performance goals that guide TFT design, fabrication, and in-circuit use, are: (1) for active device operation, achieving gain at high frequency, especially recognizing the potential for power gain (bound by f_{MAX}) rather than current gain (bound by f_T), and exploiting f_{MAX}-limited circuit operation to generate power at giga-Hertz frequencies; (2) for passive switch operation, achieving high off-to-on impedance ratio to reconfigure antenna elements. In terms of physical electronics, these goals are met in the following ways:

- f_T, the frequency up to which the TFT provides current gain, is determined by the electron transit time τ between source and drain, and electron shunting by parasitic capacitances. τ depends on electron mobility, channel length, and source/drain (S/D) contact resistance; while the shunting capacitances depend on the gate-source/drain (G-S/D) overlap regions. These are the knobs to turn for high f_T: the electron mobility is primarily set by the choice of semiconductor; minimal S/D contact resistance is achieved by selective etching; and channel length and G-S/D overlaps are minimized by self-aligning S/D to gate electrode. The f_T thus achieved is 0.4 GHz, for a typical ZnO TFT with channel length of 1um, biased at V_{GS}=V_{DS}=6 V with V_T=2 V.
- f_{MAX}, the frequency up to which the TFT provides power gain, depends on f_T, but can be made larger than f_T by reducing the sources of loss within the TFT. In practice, a factor that limits f_{MAX} is the power loss due to the gate resistance. This loss can be readily reduced by using a thick and highly conductive gate metal stack and multi-finger layout (putting fingers in parallel to reduce the resistance along gate width). The f_{MAX} thus achieved is 2.0 GHz for the typical

ZnO TFT and biasing. The higher achievable f_{MAX}, compared to f_T, motivates f_{MAX}-limited circuit architectures for LAE systems.

- $|Z_{OFF}/Z_{ON}|$, the off-to-on impedance ratio of a TFT switch at a particular frequency, depends on the conductance around an off channel, through G-S/D parasitic capacitances (which sets $|Z_{OFF}|$), as well as the τ through the ZnO channel (which sets $|Z_{ON}|$). Conduction through the parasitic capacitances can be minimized via: (1) small G-S/D overlaps; and (2) the use of resonant inductors, which can be formed with high quality factor thanks to the sq. mm dimensions and low-loss substrates available in LAE. One important approach to minimizing $|Z_{ON}|$ is to operate at high V_{GS} but low V_{DS}. This ensures high channel conductance while reducing TFT power dissipation to avoid thermal-induced breakdown [3]. The $|Z_{OFF}/Z_{ON}|$ thus achieved is ~48 at 2.4 GHz, at the half-bandwidth (the frequency range over which $|Z_{OFF}/Z_{ON}|$ drops to half of its maximum) of ~350 MHz.

Based on these advanced ZnO TFTs, we demonstrated a cross-coupled LC oscillator operating at 1.25 GHz [1] and an LAE-based phased array system operating at 1 GHz with beamforming capability [2]. In a reconfigurable antenna with tunable directionality and operating frequency, ZnO TFT switches operate in the 2.4 GHz frequency band [3]. These giga-Hertz system performance results suggest that LAE is a promising candidate for wireless applications in IoT and 5/6G.

[1] Y. Mehlman et al., IEEE 2019 DRC pp. 63-64.

[2] C. Wu et al., Nat. Electron., in press.

[3] C. Wu et al., IEEE 2020 IEDM, paper 33-6.

[4] C. Wu et al., IEEE 2021 28th AM-FPD, pp. 51-54.

This work was supported by grants from Semiconductor Research Corporation (SRC), DARPA, and Princeton Program in Plasma Science and Technology (PPST). This work also utilized the Princeton PRISM cleanroom facilities.