Ultra-thin Indium Oxide Thin-film Transistors with Gigahertz Operation Frequency

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Keywords: indium oxide, oxide semiconductor, thin-film transistor, BEOL compatible, atomic layer deposition, RF, high-frequency

Abstract—The remarkable DC performance of ultra-thin indium oxide transistors offers a path towards high-performance back-end-of-line (BEOL) and monolithically integrated logic and memory devices for next-generation computing. Its low thermal budget, high reliability, scalability, and 3D conformality are additional factors that make these devices well-suited for these applications. Here, the radio frequency (RF) performance of indium oxide transistors with a high working frequency is characterized for the first time. A new record high transit frequency (f_T) among amorphous metal oxide semiconductor transistors is reported with simultaneously high maximum frequency of power gain (f_{max}). Detailed statistical measurements across a wide variety of channel lengths and overlaps provide insight into optimization of the parasitics and future scaling trends. Even at relatively long channel lengths of 1 µm the operation frequency is sufficient for these devices to function alongside traditional silicon complementary metal oxide semiconductor (CMOS) devices which are generally clocked at less than 5 GHz.

I. Introduction

The last several years have seen amorphous metal oxide thin-film transistors (TFTs) break past the barrier of 1 GHz operation frequency due to significant efforts in materials growth, contact optimization, device geometry, and scaling. These developments enable a host of new applications including high-speed logic and analog signal modulation in the ultra-high frequency (UHF) band and beyond. The disorder-resistant high mobility and low thermal budget processing of amorphous metal oxides make them well-suited for back-end-of-line (BEOL) devices for monolithic 3D (M3D) integration, which is an important emerging area of research as the silicon complementary metal-oxide-semiconductor (CMOS) industry scales to single-digit nanometer nodes and chip area for peripheral circuitry becomes ever more precious. Simultaneously, the last several years have revealed that extremely thin metal oxide channels can give extraordinary DC performance. This is especially true for pure indium oxide (In_2O_3) [1-6], which has the highest mobility among the family of metal oxides. Indium oxide has been historically ignored in favor of indium gallium zinc oxide (IGZO) and other doped relatives due to its degenerate carrier concentration and tendency to grow polycrystalline. Both of these challenges are resolved by using atomic-layer- deposited (ALD) atomically thin layers. The ALD In_2O_3 channel gives atomically precise thickness control and is highly uniform across arbitrary areas and conformal on 3D structures. The typical fabrication process has a thermal budget of 225 °C, which is fully BEOL compatible. Despite the very low thermal budget relative to traditional CMOS processing, these devices can achieve excellent on current as high as 3 A/mm [3], near-ideal room-temperature subthreshold swing (SS) below 70 mV/dec, high mobility up to 113 $cm^2/V\cdot s$ despite being amorphous, I_{on}/I_{off} ratio potentially as high as 10^{17} [4] and transconductance up to 1.5 S/mm [3] in deeply scaled devices. Furthermore, the devices are immune to hydrogen exposure issues which are common in BEOL materials, appear to be comparably stable to traditional devices under bias stress, have engineerable V_T allowing for enhancement- and depletion-mode operation, and much like 2D materials are resistant to short-channel effects (SCEs) due to the thin body of the channel.

II. Experiments

Devices were fabricated by a process similar to previously published work [1-4] with a few notable exceptions. Here, the substrate was highly resistive intrinsic silicon (>10 kΩ/□) with a coating of 35 nm Al_2O_3 grown by ALD at 175 °C with trimethylaluminum (TMA) and H_2O as the precursors. The intrinsic silicon is used to minimize substrate parasitics at high frequencies. A bilayer lift-off process is used to define the buried gate contacts by electron beam lithography (EBL). A Jeol JBX-8100FS EBL system is used to achieve high resolution and precise alignment of the contacts. SF9 (PMGI) is used as the underlayer with AR-P 6200.13 electron beam resist as the top layer. In this way, high resolution is achieved without jagged metal edges while retaining the processing simplicity of lift-off. 60 nm e-beam evaporated Ni is used for the buried gate contacts. Then, 5 nm HfO_2 grown by ALD at 200 °C using tetrakis(dimethylamido)hafnium (TDMAHf) and H_2O as the Hf and O precursors was used for the gate dielectric layer. A relatively thick approximately 2 nm layer of In_2O_3 was grown by ALD at 225 ºC using trimethylindium (TMIn) and H_2O as the In and O precursors as the channel layer. Channel regions of indium oxide were defined by photolithography and isolated by wet etching in concentrated HCl. The source and drain contacts were defined by EBL, e-beam evaporation of 60 nm Ni, and lift-off. Gate contact windows were then photolithographically defined and the exposed HfO_2 was dry etched in an inductively coupled plasma reactive ion etching (ICP-RIE) system with BCl_3/Ar plasma. Finally, large contact pads consisting of a further 100 nm Ni/200 nm Au were photolithographically defined and deposited by e-beam evaporation. No plasma treatment or annealing was performed in this work.

III. Results

DC measurements of some of the In_2O_3 TFTs were collected

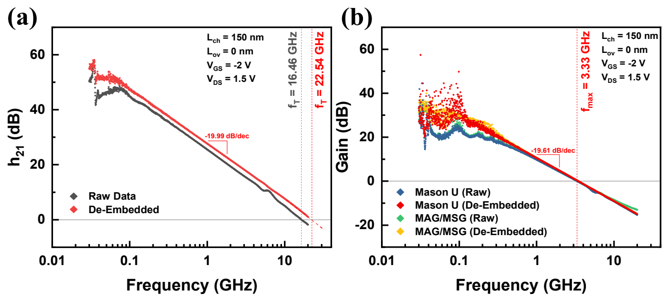

Fig. 1. Extraction of (a) f_T and (b) f_{max} for the device with the highest f_T among the measured devices. A new record f_T among amorphous metal oxide devices of 22.54 GHz is found.

to verify function and identify bias points. Device transfer and output characteristics for a typical device with the shortest channel length in this study of 150 nm show high g_m around 370 mS/mm and effective mobility around 47 cm^2/V·s extracted in this device. Detailed statistical thickness-dependent DC characterization has been reported on previously [5]. Due to the thicker In_2O_3 layer without annealing or plasma treatment, compared to some of the previous work V_T is quite negative in these RF devices and they are difficult to fully turn off. Broadly, scaling to shorter channel lengths significantly improves f_T and gives moderate improvements to f_{max} indicating that the performance does not become dominated by the contacts, consistent with our DC data. Nickel contacts to In_2O_3 have very low contact resistance typically less than 10^{-1} Ω·mm [3]. Increasing the drain bias further improves both figures of merit by increasing transconductance, which results in the highest f_T shown in Fig. 1. The measured h_{21} and U roll-off are very near to the ideal -20 dB/dec. To the best of the authors' knowledge this is a new record among RF amorphous metal oxide transistors [5]. Furthermore, the previous record was achieved at an aggressively scaled channel length of 30 nm [5], whereas the minimum channel length in this study is 150 nm.

Figure 2 shows a comparison to the metal oxide RF transistor literature. Most doped indium oxides such as IGZO have lower mobilities which limit their g_m. Indium tin oxide (ITO) is an exception, but in general still has lower mobility than pure indium oxide. Hence, in this work comparable performance is achieved with pure indium oxide channels even with significantly longer gate and channel length devices. ZnO is included since it has similarities as a metal oxide channel and is noteworthy for outperforming at a given channel length. However, its strong tendency to become nanocrystalline even in very thin layers may limit its practical usefulness due to reliability issues. The previous record 20 GHz f_T on ITO with 30 nm channel length is surpassed by an un-optimized indium oxide device with 150 nm channel length. The best $\sqrt{f_T \cdot f_{max}}$ achieved is around 10 GHz.

IV. Conclusion

High-frequency measurements of ultra-thin indium oxide RF transistors have been presented from gate lengths of approximately 2 μm down to 150 nm. Record-high f_T among amorphous metal oxide transistors above 20 GHz was achieved

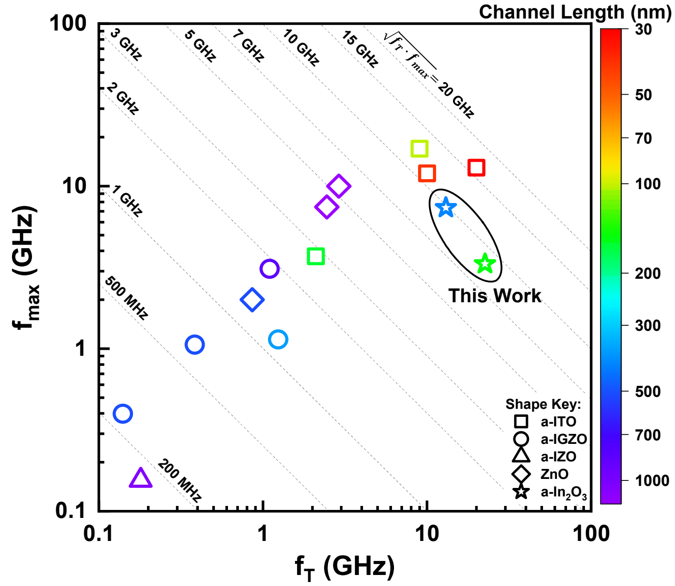

Fig. 2. Comparison to the metal oxide transistor device literature. Only wafer-scale-compatible and BEOL-compatible processes are included. Shapes correspond to channel material. Color corresponds to channel length (source to drain distance).

with simultaneously high f_{max}. The operation speed of the devices is sufficient for them to be clocked at silicon CMOS speeds (*i.e.* <5 GHz) for BEOL integration. The operation frequency could be improved by deeper channel length scaling and geometry refinement.

References

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