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BEOL-Transistor Technology with InGaZnO channel for High/Low Voltage Bridging I/Os

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Abstract

We have proposed a new concept of BEOL Transistor (BEOL-Tr) integrated into Cu interconnects with only one additional mask using a wide-band-gap InGaZnO (IGZO) as the channel and cap-SiN/Cu interconnect as the gate dielectric/ bottom-gate electrode. Thickness control of both the IGZO channel and gate insulator SiN is a key for high I_{on} and normally-off characteristics. Setting the gate-to-drain offset design to just 0.1um realizes +20V enhancement in breakdown voltage. Oxygen concentration control in IGZO channel, suppressing deep donor states, achieves stable I_{on} for wide temperature range (RT-125^{o}C) and highly-reliable operation under high V_g stress. Successful operation of high-V_{DD} inverter and comb-type high-current switch enable on-chip bridging I/Os between high/low voltage on MCUs.

Introduction

As CMOS technology scales down, driving voltage drops down to about 1V for low-power consumption. On the other hand, control of a variety of loads with high voltage swings is needed for car, displays, home-electronics etc. Thus, the voltage gap between Si-CMOS and controlled devices is growing. This requires on-chip bridging I/Os to cover the voltage conversion. [1]. We proposed BEOL-Tr integrated into Cu interconnects by using a wide band-gap IGZO channel with high mobility [2] and highV_{BD} for on-chip bridging I/Os. This paper discusses about the integrated BEOL-Tr characteristics, reliabilities and applications .

Transistor characteristics

The BEOL-Tr is characterized as a unique reverse-type TFT structure with Cu/SiN gate stack, which was formed as underlying interconnect/cap-dielectrics. The BEOL-Tr was fabricated with only one additional mask to the conventional BEOL process for the IGZO channel [2]. The source and drain (S/D) contacts were made by Al pad metals with Ti barrier. As discussed later, BEOL-Transistors with different Gate/Drain (G/D) offset designs were integrated into the Cu interconnects (Figs. 2). As shown in Figs. 3, difference in the work function between Cu (4.68eV) and IGZO (4.1eV) [3] bends the band diagram at the interface to deplete the channel at V_g=0V, resulting in off-state with low I_{off}. By increasing V_g, the IGZO channel turns into bulk conduction state at V_{FB}. Further enhancement of I_{on} at V_g>V_{th} makes the transistor on-state. The thin SiN gate-dielectrics enhanced drivability to increase I_{on}, and the thin IGZO channel suppressed $I_{off,}$ due to channel-depletion (Fig. 4). The IGZO thinning drastically reduces I_{off} without any penalty of I_{on}. A 10nm-thick IGZO with the 20nm-thick SiN achieved high on-current of 18uA/um at V_g=V_d=3.3V, high I_{on}/I_{off} ratio of 10^7, low SS of 0.19V/decade and high carrier mobility of 13.5 cm^2/Vs (Fig. 5). Gate-to-drain offset enhances V_{BD} significantly and a V_{BD} increase of >20V with a 0.1um offset increase is obtained (Fig.6).

Reliability improvement

We have fabricated two kinds of BEOL-Tr with (a) conventional IGZO film [2] and (b) an oxygen-controlled IGZO film [3]. Oxygen-controlled IGZO achieves a highly stable I_d-V_g performance at temperatures between 25^{o}C and 125^{o}C, compared with the conventional one which shows varying V_{th} with temperature (Fig. 7). Fig. 8 shows temperature dependence of channel resistivity at V_{FB}~V_{th}. V_{th} trend is of a single activation mode of ~70meV for the oxygen-controlled IGZO, whereas the trend in V_{th} drastically changes above 85^{o}C (to 210meV) for the conventional IGZO. In the case of oxygen-controlled IGZO, the I_{on} (V_g=5V, V_d=1V) stability is drastically improved, showing less than 3 % drop after 1000 seconds stress and predicting only 10% drop after 10 years, while I_{on} dropped 43% in the conventional IGZO only after 1000s (Fig. 9). The oxygen control of IGZO channel effectively suppresses the deep-level donor generation related with the excess oxygen in IGZO, improving the temperature and long-term bias duration stability

Applications

We integrated n-type inverters with a static resistor (R) of an IGZO film or an active resistor of IGZO BEOL-Tr. Inverter cut-off is achieved with V_{out} =0V for V_{in} >1.5V, demonstrating logic-level input control of the high-V_{DD} inverter (Fig.10). Figure 11 shows I_{on} plot of a single channel device and the comb-type devices with varied device area, from 28 to 3300 um^2. I_{on} increases with increased area and a 2.2 x10^3-fold enhancement is obtained for the largest device, compared to the single channel device. I_{on} (@V_g=10V) is linearly dependent on area and I_{on}=0.1A (@V_g=10V) is achieved under V_d=10V (Fig. 11).

Finally, optimized characteristics and related key technologies of BEOL-Tr. are summarized in Table.1.

Conclusion

BEOL-Transistors with IGZO channel were successfully integrated into the Cu interconnects with only one additional mask. Structural design such as thicknesses of the IGZO and SiN gate dielectric achieved high I_{on} and normally-off characteristics. Just 0.1um offset realized 20V enhancement of the breakdown voltage. The oxygen control of IGZO channel effectively suppressed the deep donor states, achieving temperature and long-term bias duration stability. High-V_{DD} inverter and high-current switches built on BEOL-Tr technology are strong candidates for high-performance bridging I/Os between high-voltage loads and low-voltage CMOS core logics for a next-generation add-on system LSIs and MCU applications.

References [1] S. Jeon et al., VLSI. Tech. Symp., p125 (2012). [2] K. Nomura et al., Nature, 432, p488 (2004). [3] K.Kaneko *et al.*, VLSI. Tech. Symp., p120 (2011). [4] K.Kaneko et al., IEDM Tech Dig p150 (2011). [5] K.Kaneko et al., VLSI. Tech. Symp., p123 (2012).

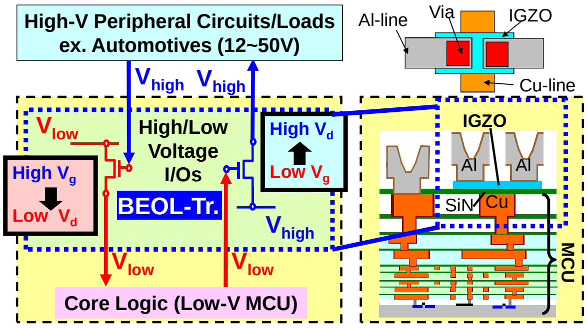

Fig. 1 Concept of bridging I/Os between high-voltage peripheral devices and low-voltage MCU cores. BEOL-Transistor (BEOL-Tr) with InGaZnO (IGZO) channel is integrated into LSI interconnects with only one additional mask[1].

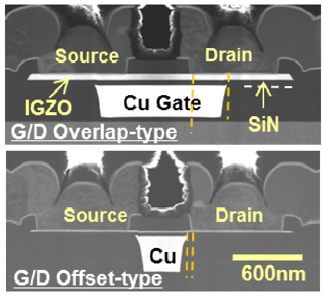

Fig. 2 Cross-sectional TEM images of the integrated BEOL-Tr with overlap G/D and offset G/D.

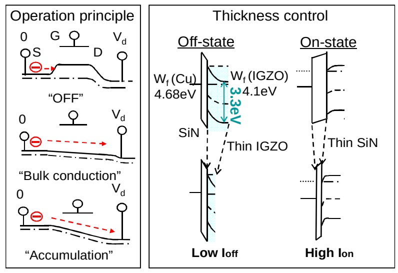

Fig.3 Operation principle with band diagram and thickness control strategy for both Ioff and Ion improvement.

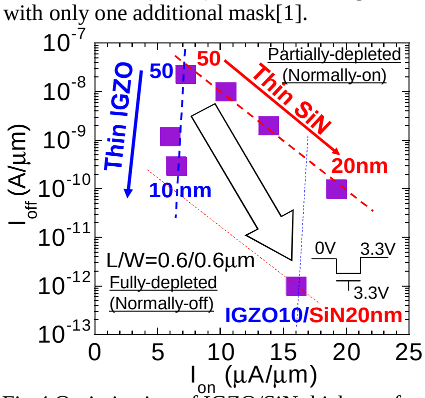

Fig.4 Optimization of IGZO/SiN thickness for both low I_{off} and high I_{on}.IGZO 10nm/SiN 20nm achieves high I_{on} with normally-off characteristics.

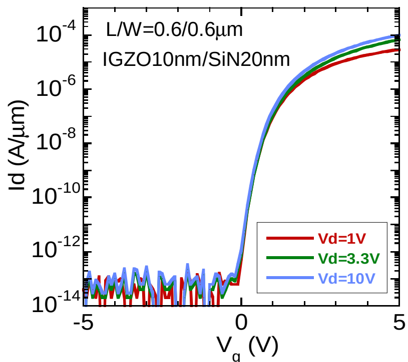

Fig.5 Normally-off Id-Vg characteristics, showing Ion = 18µA/µm at 3.3V, on-off ratio of 10^7 and SS=0.19 V/decade.

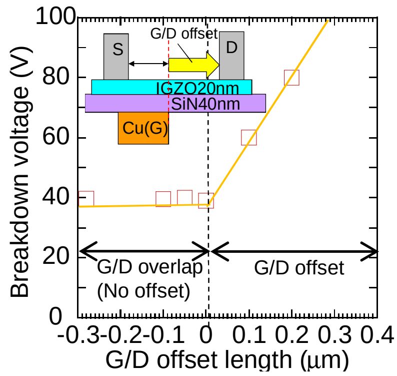

Fig.6 Breakdown voltage versus G/D offset. Breakdown increases by 20V per 0.1 µm offset.

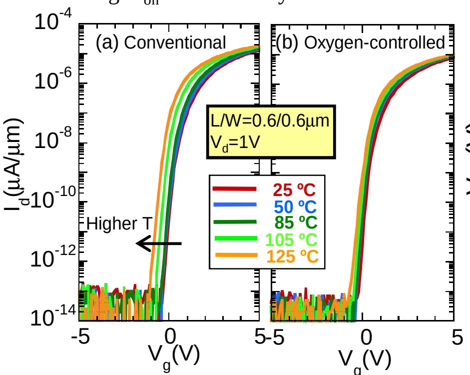

Fig.7 I_d-V_g characteristics at various temperatures of BEOL-Tr with (a) conventional and (b) oxygen-controlled IGZO. Oxygen control suppresses the temperature instability.

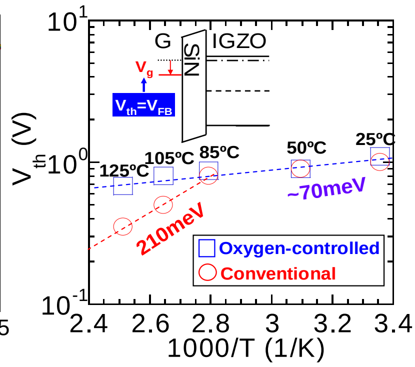

Fig.8 Arrhenius plot of Vth with different IGZO bulk qualities. Suppressing deep donor by oxygen control is a key to realize the temperature stability.

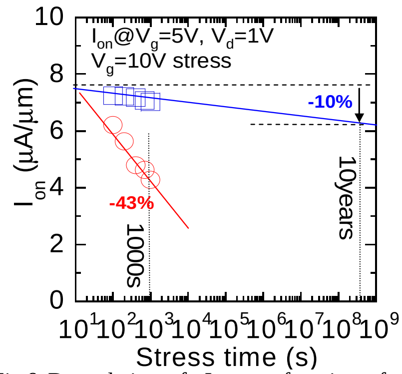

Fig.9 Degradation of I_{on} as a function of gate stress duration in the PBTI test. In the case of oxygen-controlled IGZO, I_{on} degradation was limited to be less than 10 % after 10 years.

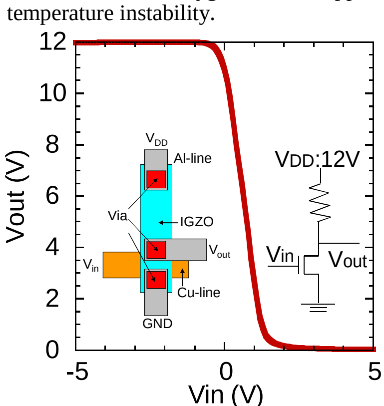

Fig.10 Demonstration of inverter with IGZO-Tr and IGZO-load resistance. Full-swing Vdd output can be cut off by a low V_{in} input.

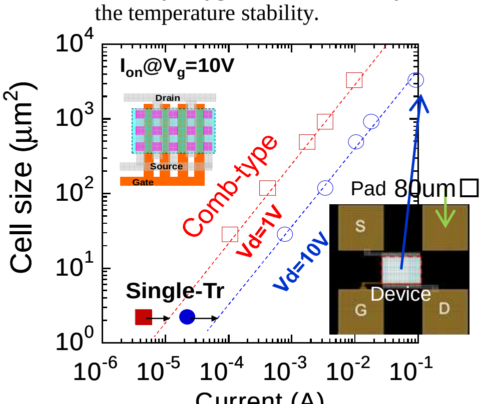

Fig.11 Current versus cell size showing comb type device can achieve I_{on}~100mA with cell size ~ 60µm□.

Table.1 Summary of optimized characteristics and key technologies of BEOL-Tr.

	Optimized	Key technologies
Channel length (µm)	0.6	-Fine patterning -High-mobility IGZO -Thickness control to IGZO10/SiN20nm
I_{off} at 0V (A/um)	< 10^{-12}	
I_{on} at 3.3V (uA/um)	18	
Mobility (cm^2/Vs)	13	
On-off ratio	10^7	
SS (V/decade)	0.18	
ΔIon (%) after 10year	<10	Oxygen content control in IGZO
ΔV_{BD} (by 0.1um G/D offset)	20V	Wide band-gap IGZO Gate/Drain offset