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Device Process and Circuit Application Interaction for Harsh Electronics: Hf-In-Zn-O Thin Film Transistors as an Example

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***Abstract* – The effects of Hf content on the radiation hardness of Hf-In-Zn-O thin-film transistors (HIZO TFTs) and HIZO TFT-based circuits are systemically examined. The evaluated circuits, including current-starved ring oscillator, energy harvesting and RF circuits are essential for space electronic systems. It is shown that HIZO TFTs with low Hf concentration have better initial performance while TFTs with high Hf concentration are more stable against radiation. On the other hand, for circuit application, the stable HIZO TFTs are not necessarily preferred for all circuits. The work demonstrates that understanding the device-circuit interactions is necessary for device optimization and circuit reliability improvements for harsh electronic systems.**

***Index Terms*— Hf-In-Zn-O (HIZO), thin film transistor (TFT), harsh electronics.**

I. Introduction

Due to the increasing demand for circuits to operate in extreme environment from the industries, such as oil, gas, aerospace, military companies, harsh electronics have drawn more and more attention [1-7]. While much insight on device physics of harsh electronics has been gained in recent years, understanding of the relation between device process and circuit performance has been rather limited [8-9]. In particular, it is expected that the requirements for device characteristics for better circuit reliability may vary depending on the circuit structure.

Therefore, in this work, using HIZO TFTs (which show better stability and performance as compared to other oxide-TFT counterparts) in space electronic system as an example, we systemically examined the effects of Hf content on the radiation hardness of HIZO TFTs [10-12]. Further, the dependence of circuit performance on the Hf content of HIZO TFT are also explored. The evaluated HIZO TFT-based circuits, including current-starved ring oscillator, energy harvesting and RF circuits are essential for space electronic systems [13-14]. Our results indicate that HIZO TFTs with low Hf concentration feature a better initial performance while HIZO TFTs with higher Hf concentration shows high stability under proton exposure. In circuit level, the device stability is proven to be critical for oscillator application. On the contrary, for RF and power convertor circuits, the weak radiation resistance of low Hf concentration HIZO TFTs is preferred.

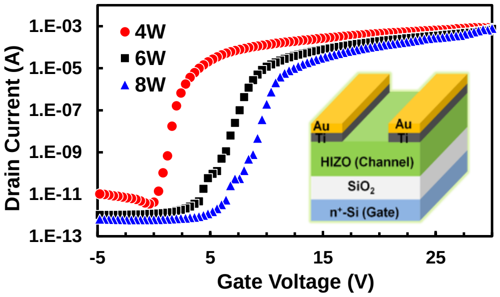

Fig. 1 The transfer characteristics of HIZO TFTs with DX Hf target sputtering power from 4W to 8W. The inset is the schematic diagram of HIZO TFT.

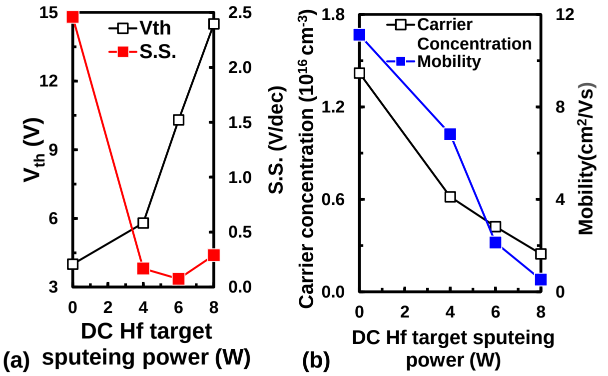

Fig. 2 (a) Threshold voltage (V_{th}), Subthreshold slope (S.S.), (b) carrier concentration and Mobility as a function of DC Hf target sputtering power.

II. Fabrication & Device Characteristics

Fig. 1 shows the schematic of the HIZO TFTs. Thermally grown 90-nm-thick SiO2 on n+-Si (~0.01Ωcm) substrates is adopted for a gate dielectric/electrode. Prior to the deposition of HIZO thin films, the substrate was cleaned with acetone, IPA and de-ionized water. A 35-nm-thick HIZO thin film was grown by radio-frequency. To investigate the influence of Hf concentration on the radiation hardness of HIZO TFTs, a range of DC Hf target sputtering power (4W-8W) was applied in the fabrication process. After the deposition of channel material, the patterning of source and drain electrodes was defined using photolithography. Then, 20-nm-thick Ti and 80-nm-thick Au with 5 μm wide and 200 μm long were deposited for source/drain electrodes by e-gun, followed by photolithography/lifted off processes. The channel length (*L*) is 5 μm, and channel width (*W*) is 200 μm. Finally, the fabricated TFTs were annealed at 150 °C for 1 hour in N2 ambient. After the fabrication process of HIZO TFTs, the electrical characteristics of devices were measured by a Keithley 4200 semiconductor parameter analyzer at room temperature in the dark. Moreover, for radiation resistance testing, HIZO TFTs were irradiated with a 2-MeV proton with the fluences ranging from 10^{13} to 10^{15} cm^{-2} from a 3-MV

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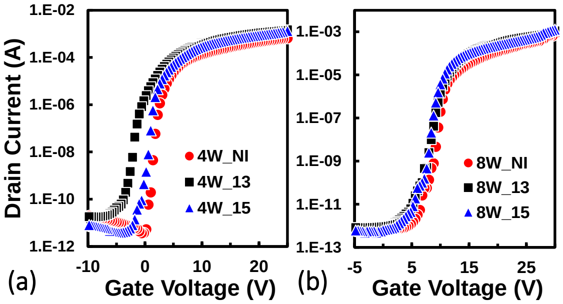

Fig. 3 V_{GS}–I_{DS} curves of HIZO TFTs under (a) 4W and (b) 8W DC Hf target sputtering power with three irradiation fluence conditions (*i.e.* no irradiation, 10^{13} cm^{-2} and 10^{15} cm^{-2} proton irradiation fluence). The V_{GS}–I_{DS} is measured in the dark box at room temperature.

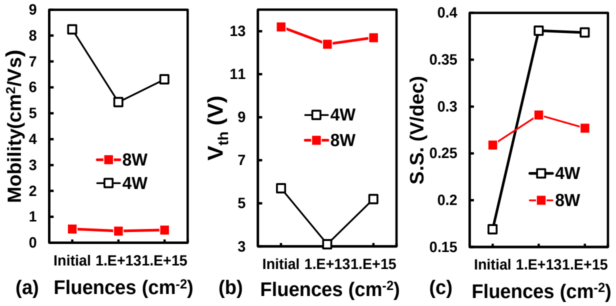

Fig. 4 (a) μ_{FE}, (b) V_{th} and (c) *S.S* as a function of 2-MeV proton irradiation fluence with two different DX Hf target sputtering power (4W and 8W). The results are extracted from the *I*–*V* curves of HIZO TFTs in Fig. 3.

tandem accelerator (NEC 9SDH-2, National Electrostatics Corporation). Fig. 1 shows the transfer characteristics of HIZO TFTs with DC Hf target sputtering power from 4W to 8W, while the inset of Fig.1 illustrates the schematic of the as-fabricated HIZO TFTs. It is clearly shown in Fig. 2 that when DC Hf target sputtering power increases (*i.e.*, the Hf concentration increases), the threshold voltage (V_{th}) shifts positively while subthreshold slope (*S.S.*), carrier concentration (N_c), mobility (μ_{FE}) and on-current level decreases. The observed decrease in *S.S.* with the increase in Hf concentration is attributed to the reduction in interface and deep trap states. Furthermore, the Hf content-dependent carrier concentration indicates that Hf ions may act as charge-carrier suppressors due to its high oxygen binding energy. Moreover, the decreased μ_{FE} can be attributed to the heavy weight of Hf content that suppresses the carrier diffusion. These results demonstrate the strong dependence of HIZO TFT characteristics on the Hf concentration.

III. Device-level Radiation Resistance Test

For radiation resistance testing, HIZO TFTs were irradiated with a 2-MeV proton beam with the fluences ranging from 10^{13} to 10^{15} cm^{-2} from a 3-MV tandem accelerator. The V_{GS}–I_{DS} curves of HIZO TFTs with 4 W and 8 W DC target sputtering power under different proton fluences are shown in Fig. 3. The results demonstrate narrow distribution for the case of 8W. The device characteristics of HIZO including, μ_{FE}, V_{th} and *S.S.* are extracted and shown in Fig.4. It is clear in Fig. 4(a) that after

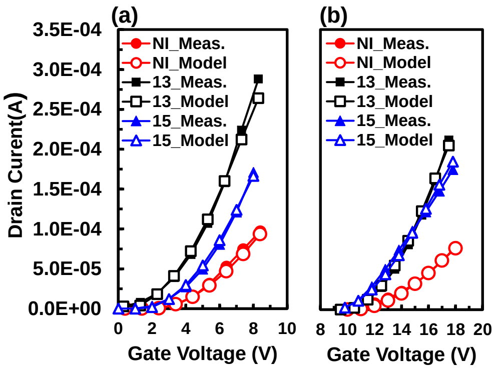

Fig. 5 Comparison of *I*–*V* curves from Level 62 RPI SPICE model and experimental results for HIZO TFTs under (a) 4W and (b) 8W DC Hf target sputtering power with three irradiation fluence conditions (*i.e.* no irradiation, 10^{13} cm^{-2} and 10^{15} cm^{-2} proton irradiation fluence).

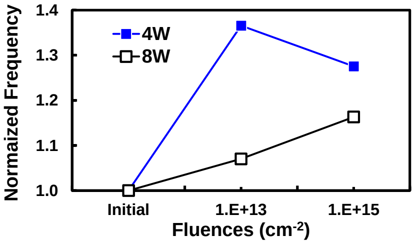

Fig. 6 The output frequency of a three-stage current-starved ring oscillator [13] as a function of proton irradiation fluence for 4W and 8W Hf target sputtering power conditions.

proton exposure at a fluence of 10^{13} cm^{-2}, a reduction in μ_{FE} was observed. The reduction is due to the increase in lattice and Coulomb scattering causing from the rise of proton-induced trap density in the channel/gate oxide interface and/or in the channel region. Moreover, the increased trap density leads to the negative directional shift of V_{th} and the increased *S.S* as shown in Fig. 4(b) and 4(c). It is worth noting that, as the proton irradiation fluence increases to 10^{15} cm^{-2}, the drain current of HIZO TFTs is recovered. These results suggest that recrystallization occurs due to the high substrate temperature during the ultra-high fluence proton radiation process (*i.e.*, self-annealing effects). On the other hand, as shown in Fig. 3(b), the transfer characteristics of 8W TFTs are insensitive to the proton irradiation fluences. Clearly, the high Hf concentration makes the device more stable under proton irradiation. It can be attributed to the fact that the strong chemical bond in HIZO compounds due to the high oxygen binding energy of Hf, leads to the superior stability of HIZO TFTs under proton irradiation.

IV. Device Process and Circuit Application Interaction

To study the effect of radiation on HIZO TFT-based circuits, HSPICE models were extracted and verified with measured device V_{GS}–I_{DS} data for circuit simulation. As shown in Fig. 5, the V_{GS}–I_{DS} results from Level 62 RPI SPICE model match well with measurement data.

Having the HSPICE model, we are able to examine and compare the radiation hardness of the HIZO TFT-based

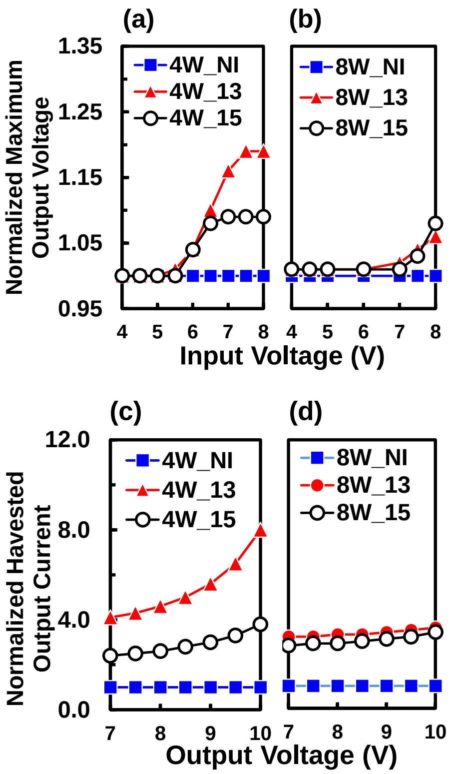

Fig. 7 Normalized maximum output voltage of a power converter circuit [14] as a function of input voltage with HIZO TFTs under (a) 4W and (b) 8W DC Hf target sputtering power and three irradiation fluence conditions. Normalized harvested output current of a power converter circuit as a function of output voltage with HIZO TFTs under (c) 4W and (d) 8W DC Hf target sputtering power and three irradiation fluence conditions.

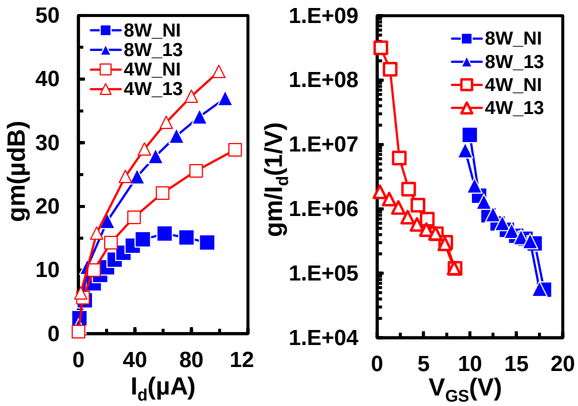

Fig. 8 Comparison of (a) cutoff frequency (f_T) (b) normalized trans-conductance (g_m/I_{DS}) for HIZO TFT-based RF circuit under 4W and 8W DC Hf target sputtering power with two irradiation fluence conditions (*i.e.* no irradiation and 10^{13} cm^{-2} proton irradiation fluence).

circuits including current-starved ring oscillator, energy harvesting and RF circuits [13-14]. Fig. 6 plots one of the most important characteristics of a three-stage current-starved ring oscillator, the oscillation frequency. Ring oscillators with 4W TFTs exhibit a larger variation (37%) on oscillation frequency than 8W TFTs (16%) after irradiation which is attributed to the larger V_{th} variation of 4W TFTs. This observation suggests that 8W TFT is preferred in this application since a stable output frequency is essential for oscillator circuits.

In a charge pump circuit, the most important characteristics, voltage boosting capability (i.e., maximum output voltage) and power transfer capability (i.e., harvested output current) are mainly determined by on-resistance of a transistor. As shown in Fig. 7, the maximum output voltage and harvested output current of charge pump increase after irradiation for both cases (4W & 8W). Thus, power converter circuit benefits from proton radiation since V_{th} (as well as on-resistance) becomes smaller after irradiation. Note that, similar to device results, the maximum output voltage and harvested output current of charge pump restore back towards no irradiation case when exposing to 10^{15} cm^{-2} irradiation due to self-annealing effects, as shown in Fig. 3. Overall, in contrast to oscillator circuit, energy harvesting systems favor 4W HIZO TFTs. These results stress the importance in understanding device-circuit interactions for developing harsh electronic systems.

Finally, to evaluate the impacts of radiation on RF performances of a HIZO TFT, cutoff frequency (f_T) and device normalized trans-conductance (g_m/I_{DS}) extracted from the measured V_{GS}–I_{DS} data in Fig. 3. As shown in Fig. 8(a) and 8(b), although f_T and gm/I_{DS} of 4W TFTs are higher than those of 8W TFTs due to the higher mobility, the 4W TFTs clearly show larger variation with different irradiation fluence conditions on f_T and gm/I_{DS} than 8W TFTs. It should be noted that the variation of device metrics (such as V_{th}, f_T and gm/I_{DS}) in analog and RF circuits require increased guard-banding at the design phase, resulting in the higher power consumption.

V. Conclusion

For the first time, the interaction between HIZO TFT process and HIZO TFT-based circuits were examined for harsh applications. We validated that HIZO TFTs with low Hf concentration can achieve better device performance while HIZO TFTs with higher Hf concentration exhibit high stability under proton exposure. On the other hand, for circuits, the stability is shown to be crucial for oscillator application. The weak radiation resistance of low Hf concentration HIZO TFTs, however, is preferred for RF and power convertor circuits. The device-circuit interaction results in this work give insights not only on process optimization for harsh electronic devices, but also in developing high performance and robust harsh electronic circuits.

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