Flexible IGZO TFT Spice model and design of active strain-compensation circuits for bendable active matrix arrays

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Flexible IGZO TFT SPICE model and design of active strain-compensation circuits for bendable active matrix arrays

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***Abstract*—The detailed measurement and characterization of strain induced performance variations in flexible InGaZnO thin-film transistors (TFTs) resulted in a Spice TFT model able to simulate tensile and compressive bending. This model was used to evaluate a new concept, namely the active compensation of strain induced performance variations in pixel driving circuits for bendable active matrix arrays. The designed circuits can compensate the mobility and threshold voltage shifts in IGZO TFTs induced by bending. In a single TFT, a drain current of 1 mA varies by 83 µA per percent of mechanical strain. The most effective compensation circuit design, comprising one additional TFT and two resistors, reduces the driving current variation to 1.1 µA per percent of strain. The compensation circuit requires no additional control signals, and increases the power consumption by only 235 µW (corresponds to 4.7 %). Finally, switching operation is possible for frequencies up to 200 kHz. This opens a way towards the fabrication of flexible displays with constant brightness even when bent.**

***Index Terms*—Thin-film transistors, Flexible electronics, IGZO, Strain, Spice-simulation.**

I. INTRODUCTION

BENDABLE electronics are a major next step for consumer electronics [1]. In this respect, new semiconductors, including Indium-Gallium-Zinc-Oxide (IGZO) attracted attention [2], [3], and have been used to demonstrate applications such as flexible sensor arrays or displays [4], [5], [6].

It is known that IGZO TFTs suffer from instabilities caused by aging, water absorption or bias stress [7]. These instabilities cause drain current variations. At the same time, flexible transistors are affected by mechanical strain [8], [9]. This issue was addressed by measures such as the relative alignment of TFTs within circuits [10], [11], or attempts to optimize the yield of circuits made from flexible TFTs suffering from parameter variations and degradation effects [12]. Here, we propose an alternative approach, and present circuits with active strain compensation. To evaluate this concept, different pixel driving circuits are simulated. These circuits enable new applications, in particular driving of pixels in sensing arrays such as flexible Hall sensors [13], or LEDs in deformable active matrix displays [14].

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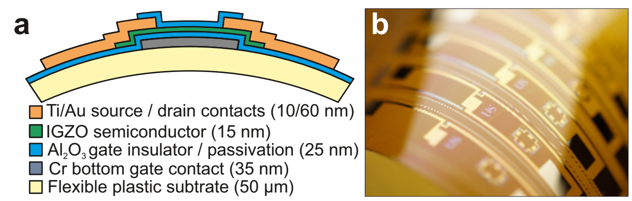

Fig. 1. a) Schematic cross-section and layer thicknesses of the characterized and simulated flexible IGZO TFTs. b) Flexible TFTs used for bending tests.

Numerous published circuits compensate for parameter shifts caused by long term aging or bias stress [15], [16], [17], [18]. Additionally, the influence of bending on the gate bias stability of amorphous Si TFTs and a corresponding pixel driving circuit able to compensate the resulting threshold voltage shift were presented [19]. At the same time, no circuit to compensate the parameter variations caused by mechanical strain has been developed. Here, the presented simulated circuits can counteract strain by adjusting the transistor bias voltage. This was achieved by enabling a level 61 IGZO TFT HSpice simulation model, to simulate the performance parameter variation caused by bending of the flexible substrate.

II. STRAIN ENABLED TFT SIMULATION

A HSpice model to simulate flexible IGZO based circuits under strain was developed by characterizing bent TFTs.

A. Bendable thin-film transistors

The structure of the passivated, bottom-gate TFTs is shown in Fig. 1a. The TFTs were fabricated on a 50 µm thick polyimide using UV lithography. Thin-film depositions were done using e-beam evaporation (metallic contacts), RF sputtering (IGZO), and atomic layer deposition (Al_2O_3). The maximum fabrication temperature was 150 °C. The manufacturing process and materials are optimized for high bendability. A detailed description of the fabrication process can be found elsewhere [20]. The TFT contact pads are located ≈1 cm away from the TFT channel to ensure the mechanical properties of the TFTs are not influenced by connected characterization equipment. A photograph of the devices (Fig. 1b) illustrates their geometry. Figure 2a shows a typical transfer characteristic of the fabricated TFTs measured using a Keysight

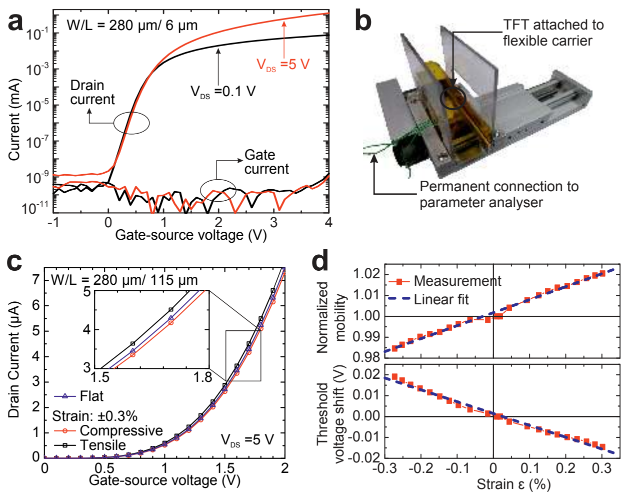

Fig. 2. a) Transfer characteristic of a flexible IGZO TFT. b) Automated bending tester used to characterize the TFT under strain. c) Influence of strain on the TFT transfer characteristic. d) Variation of the threshold voltage (bottom) and effective mobility (top) under tensile and compressive strain.

B1500A parameter analyzer. We used the standard Shichman-Hodges model [21] to extract the TFT performance parameters. In average, our TFTs exhibit a field effect mobility of $14\,\text{cm}^2\text{V}^{-1}\text{s}^{-1}$, a threshold voltage of 0.7 V, a subthreshold swing of 140 mV/dec, and an On/Off current ratio of $> 10^9$.

To fabricate resistors, we used the 35 nm thick Cr gate layer with a resistance of $1.16 \times 10^{-6}\,\Omega\,\text{m}$ [22]. Using meander structures and a conservative minimum feature size of 5 µm a 1 kΩ resistor consumes an area of ≈1300 µm^2.

To evaluate the influence of bending, an automated bending tester shown in Fig. 2b was used. This setup enables the measurement of flexible TFTs under tensile and compressive strain without parasitic effects related to unintentional re-flattening, or changing contact resistances [20]. The TFT characteristics were measured under ambient conditions without illumination, while the device was bent to tensile and compressive radii ≥8 mm [20]. Strain was applied parallel to the channel since such strain has a larger influence than perpendicular strain [11]. To minimize the influence of the contact resistance which becomes significant for TFTs shorter than 2 µm [23], 115 µm long TFTs were used. The measured variation of the TFT characteristics is shown in Fig. 2c. The maximum strain these TFTs can withstand, varies between 0.7 % and 1.55 % [24], [25]. The measurements show that bending influences IGZO TFTs in multiple ways. Tensile strain increases the subthreshold swing by 3.5 %/%, the gate capacitance by 1 %/%, and the transit frequency by ≈4 %/% (compressive strain has the opposite effect), while the On/Off current ratio is not significantly influenced [20], [23]. However, the most important effect is that tensile strain increases the drain current by ≈8.5 %/%. This current variation is mainly caused by a change of the threshold voltage V_{TH}, and the mobility μ. Fig. 2d shows the strain dependency of these two parameters. Linear fits can be used to quantify the influence of strain on μ and V_{TH}, the resulting equations are [20]:

$$\mu(\epsilon) = \mu_0 \times (1.005 + 0.062 \times \epsilon) \quad (1)$$

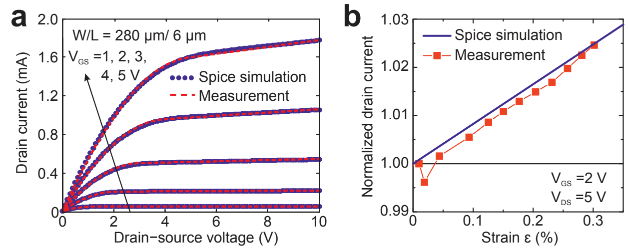

Fig. 3. a) Measured and simulated (using the developed level 61 HSpice simulation model) TFT output characteristics b) Comparison of the measured and simulated influence of strain on the TFT drain current.

$$V_{TH}(\epsilon) = V_{TH,0} - 57mV \times \epsilon \quad (2)$$

Where, ϵ is the strain, and μ_0 and $V_{TH,0}$ are the mobility and the threshold voltage of the unstrained TFT. These shifts result in an effective gauge factor of -8.2. These variations are reversible, and in-line with other published reports. They are caused by modifications of the IGZO band structure and are described elsewhere [3], [20]. TFTs shorter than 2 µm would require modified equations since the larger relative impact of the contact resistance changes the bending behavior [23].

B. Spice model

A customized HSpice level 61 model was used to simulate the electrical performance of the presented IGZO TFTs [10], [26]. Fig. 3a shows the simulated and measured TFT characteristics and verifies the model. The influence of tensile and compressive bending was considered by implementing equations 1 and 2 into the VTO (Zero-bias threshold voltage), and MUBAND (Conduction band mobility) parameters of the Spice model [27]. These equations are not derivations from basic physics formulas, instead they parametrize the bending behavior of fabricated and characterized TFTs. A comparison of the simulated and measured drain current variation caused by tensile strain (Fig. 3b) validates this approach. In average, the simulated drain currents vary by <0.2 % when compared to the measurement. This enables the simulation of flexible circuits bent to arbitrary radii. The circuit simulations also consider the gauge factor of the Cr resistors (equal to +1.3) [28], [29]. However, strain cannot simply be compensated by connecting Cr resistors in series with IGZO TFTs, as they would limit the current. Also, the gauge factor of IGZO TFTs is significantly larger than the Cr gauge factor.

III. Results and Discussion

Initially, the performance of a single driver TFT connected to a transducer consuming 1 mA was simulated as a reference (Fig. 4a). As an example, a diode transducer simulating a light emitting element was chosen, but the same circuit can be used to power sensors [13]. The supply and high control voltages were 5 V, the low control voltage was 0 V. These voltages are compatible with mobile applications and IGZO TFTs. The current was tuned by adjusting the W/L ratio of the driver TFT M1 (240 µm / 10 µm). The variation of the output current caused by mechanical strain is shown in Fig. 5a. Strain causes the current to vary by 83 µA%$^{-1}$, this in turn causes undesirable brightness fluctuations of the LED. The simplest approach to compensate for such current variations is to adjust the gate-source voltage (V_{GS}) of the driver TFT accordingly. For tensile/compressive strain V_{GS} has to be reduced/increased to counteract the transconductance variations. The following paragraphs present two active compensation circuits designed and simulated using the developed simulation model.

The first approach to implement a compensation circuit is shown in Fig. 4b. Here, a voltage divider employing a resistor (R1) and an IGZO TFT (M2), acting as strain sensor and switch, are used to adjust the gate voltage of M1. Since the voltage divider is an inverting structure, a second inverter is needed to ensure the circuit can be turned on using a high control signal. The second inverter is made from a driver TFT (M3), and an active load TFT in diode configuration (M4). Since strain changes the transconductance of M3 and M4 by the same factor the output voltage of the second inverter (similar to a voltage divider) is not influenced by strain, hence M3/M4 do not counteract the effect of R1/M2. This was also verified experimentally [11]. The resistances and W/L ratios of the components are as follows: R1: 1 kΩ, M2: 400 µm / 10 µm, M3: 400 µm / 10 µm, and M4: 100 µm / 10 µm, here the W/L ratio of M1 was adjusted to maintain an output current of 1 mA. The resulting strain induced output current variation is shown in Fig. 5a. This inverter based circuit reduces the current variation to 12 µA$\%^{-1}$. This is a significant improvement but the circuit complexity is comparably high and the result is still not optimal. For this reason, we developed a second approach. Fig. 4c shows how active strain compensation can be achieved using only one additional strain sensitive TFT. This push-pull design employs M2 as a variable attenuator, and two resistors as bias elements. If tensile strain is applied, the TFT transconductances of M1 and M2 increase by the same relative amount. Hence the voltage drop across M2 reduces and its drain voltage is pulled down. This reduces the gate voltage of M1 and counteracts the strain induced drain current increase. Simultaneously, compressive strain has the opposite effect. The resistances and W/L ratios of the components are as follows: R1: 10 kΩ, R2: 30 kΩ, M1: 900 µm / 10 µm, and M2: 100 µm / 100 µm. This configuration has multiple advantages. First, the effects of strain are counteracted efficiently (Fig. 5a), as the output current variation is only 1.1 µA$\%^{-1}$. Second, due to the low transconductance of M2 the active strain compensation consumes only 47 µA, which corresponds to a power consumption increase of <235 µW. Furthermore, independent of the strain, the active compensation circuits never exhibit an output current larger than the value of the flat circuit. This can be considered a security feature which avoids damage or fast aging of the transducers.

Since the push-pull compensator is the most suitable approach, we show a possible circuit layout employing a minimum feature size of 5 µm in Fig. 4c. The circuit consumes an area of ≈0.092 mm^2. The area consumption of the additional components, in particular the resistors, has to be considered, however it is possible to reduce the circuit area using materials with higher specific resistance than Cr [30].

Fig. 5b shows the strain dependent transient response of the single TFT and the push-pull compensator while the control

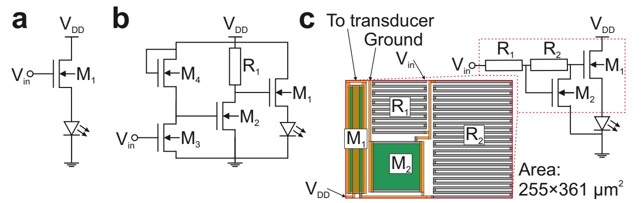

Fig. 4. Driving circuits: a) Single reference TFT, b) Inverter compensation, c) Push-pull compensation (with circuit layout optimized for 5 µm technology), and using the same color scheme as Fig. 1a.

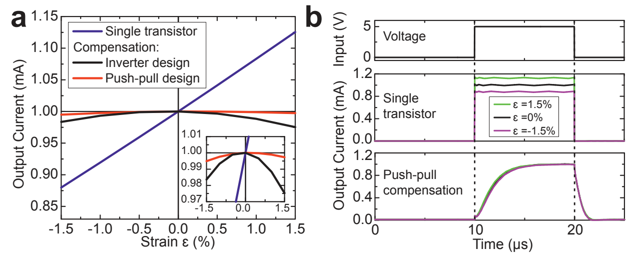

Fig. 5. a) Strain dependent current of a single TFT and the compensation circuits. b) Transient response of a single TFT and the push-pull compensator.

signal switches from low (0 V) to high (5 V) and back to low. In case of the push-pull circuit, the simulation shows the strain independency of the output current. At the same time, the rise time of the output current is increased to 5 µs (while the fall time is virtually unchanged). This is because the gate is controlled using high impedance elements. The resulting maximum operation frequency is 200 kHz. Consequently this circuit can be used to realize sensor arrays with high temporal resolution, or to drive an LED display, controlled by switching the control and power lines [14].

Finally, positive gate bias stress was simulated using measured data from single TFTs. A stress field of 2×10^8 V/m, applied for 600 s causes a V_{TH} shift of +42 µV, this decreases the drain current by 1.9 %. The push-pull compensation reduces this drain current reduction to 1.5 %. This shift is smaller than the value obtained from the bias stress compensation circuit presented in [19]. However this is mainly due to the beneficial stability of our IGZO TFTs [3].

IV. Conclusion

We presented the quantitative characterization of the influence of bending on flexible IGZO TFTs, and a corresponding HSpice level 61 TFT model able to simulate the influence of mechanical strain. This model was used to design circuits able to actively compensate strain induced transconductance variations. This is important for rollable sensor arrays requiring a constant bias current [31], and shows new approaches of designing flexible display driving circuits. These circuits are optimized for the presented IGZO TFTs, however, the described methods and principles can be applied to any other flexible TFT technology.

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