

Comparative Study of Electron Mobility Response in Flexible Thin Film Transistors under Mechanical Bending

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Abstract

In this paper, the change in the performance characteristics with various mechanical bending conditions for different flexible Thin-Film Transistors (TFTs) is compared. Bending strains induce modifications of the localized density of states (DOS) which in turn cause changes in the electrical characteristics of the TFTs. The change in the characteristics is estimated as a function of curvature radius of the channel. For amorphous silicon, field-effect mobility decreases by bending, e.g., ~11% with a radius at $R = 30$ mm and a knee voltage increases, while a threshold voltage remains the same. While the mobility, threshold voltage, and sub threshold slope of IGZO TFTs remained essentially unchanged over the entire bending range, the electrical performance parameters of ZnO TFTs were strongly degraded by bending. For ZnO TFTs bent to a radius of 10 mm, the mobility decreased by more than two orders of magnitude.

Keywords: - Thin film transistors, bending radius, field-effect mobility

INTRODUCTION

FLEXIBLE thin-film transistors (TFTs) are the most important device in the flexible electronics and display systems. Many flexible TFTs have been developed using different materials including amorphous silicon (Si), amorphous

semiconducting oxides, and organic materials. However, the mobility values of the TFTs with a channel made of those materials are very low in the range of ~0.1–20 cm²/Vs, which are significantly lower than the typical values of single-crystalline Si, e.g., $\mu > 500$ cm²/Vs. The

low mobility of those transistors imposes the limitations in their use mainly in switches of display. For display switches, threshold voltage, V_T and on/off ratio of the transistor are the important characteristics, which are not affected by the bending of the devices [1]. All flexible or conformal display applications require some degree of bending. Bending or draping will induce strain in the electronic circuits [2]. Therefore, understanding the electrical performance of thin-film transistors (TFTs) during and after mechanical strain becomes essential. The flexible devices for the extended applications will require systematic studies on the other characteristics that are changed by the bending. Especially, the characteristics of high-quality transistor channels such as drain current, I_{ds} were reported to be sensitive to the degree of bending of the structure, due to their high mobility of charged carriers in the channel [3], [4].

Recently, both zinc-oxide (ZnO) and amorphous indium-gallium-ZnO (IGZO) have been investigated as materials to replace the a-Si:H active layer in flexible TFTs due to the low deposition temperatures and high electron motilities of these materials. However, flexible display backplanes also require TFTs that

are insensitive to applied bending. Various groups have also investigated ZnO and IGZO TFTs and circuits bent to a specific radius [5]. The impact of bending on the electronic properties of ZnO and IGZO TFTs has not been studied over a continuous range of bending radii or at radii smaller than 20 mm. Amorphous indium-gallium-zinc-oxide (a-IGZO) TFTs have received significant attention for the realization of desirable driving devices for flexible displays owing to their high mobility, low-temperature processing, and low-cost manufacturing on flexible substrates [6].

The characteristics of the flexible transistors were measured under various bending conditions [7]. Many reports, however, lack in the discussion on the physical origins of the changes with different bending conditions. Current and saturation-current change in bent field-effect transistors could originate from the change in the effective mass of the carriers by strain, modulation in the carrier density by external strain, and effective mobility change by the curved channel [8], [9]. For the study on the physical origin of the changes in characteristics, theoretical studies as well as experimental measurement need to be conducted. There are only limited number of publications

related to the modelling of amorphous and polycrystalline TFTs. However, they are based on flat rigid structures; hence, only consider the effects of crystallinity but not the effects from the bending of the structures. The purpose of this study is to establish a model for the performance of high-mobility TFTs in various bending conditions [10].

DEVICE STRUCTURE AND SIMULATION

Fig. 1 shows a schematic cross-sectional structure of a bent TFT device. The flexible substrate can be any flexible material as long as the integrity of the interfaces is maintained and can be integrated with a semiconductor channel via layer-transfer or direct-growth

technique. Oxide (SiO_2) buffer was included between the substrate and channel for the isolation of the channel. For the modeling, Silvaco's process simulator Athena and its associated module Atlas are used to form the bottom gate layered structure of a TFT along with its current-voltage characteristics. Origin Pro is used to extract the points from the graph using the Digitizer tool, extrapolate the bending effects on current with voltage variations and plot the same. The channel has a thickness of 50 nm with a carrier concentration of $n \sim 5 \times 10^{18} \text{ cm}^{-3}$. The mobility of carriers in the channel for an unbent device was set at $200 \text{ cm}^2/\text{Vs}$ to simulate the case of flexible single-crystal-like TFTs [11].

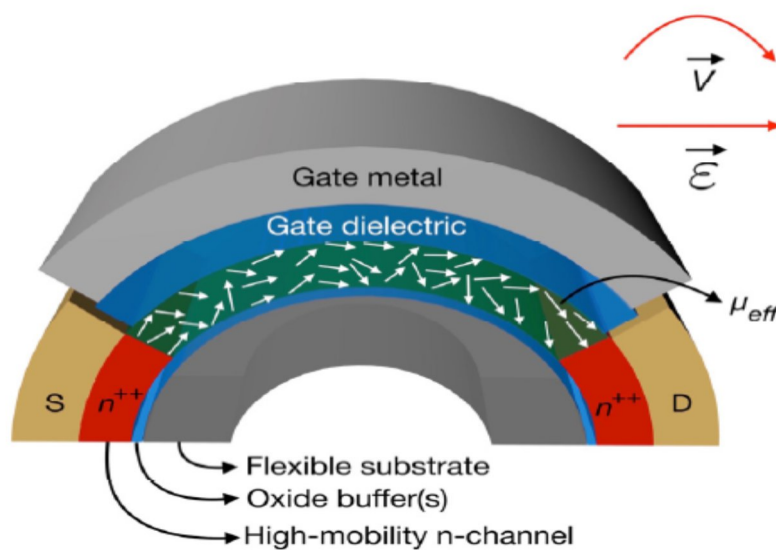


Fig. 1: Schematic illustration of a thin-film transistor (TFT) device with bending effective velocity vector, electric field, curvature-dependent effective mobility (μ_{eff}).

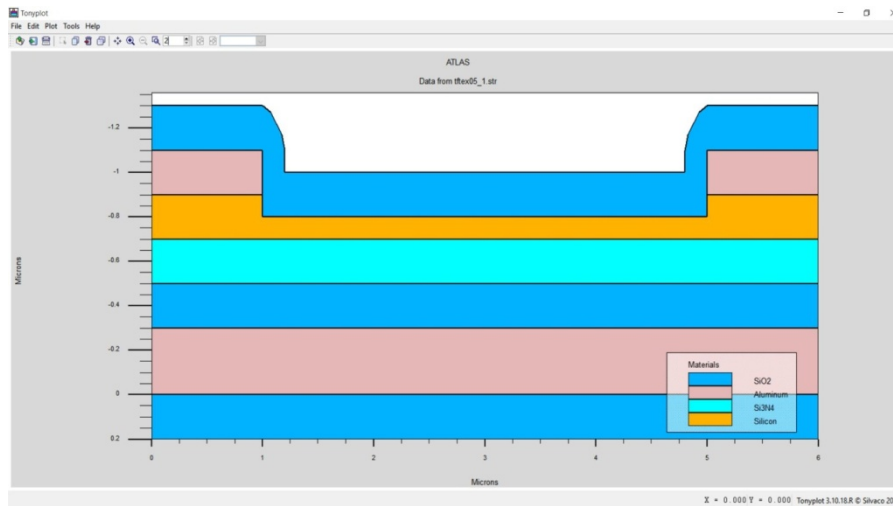


Fig. 2: Bottom gate staggered TFT layers

In fig. 2, the basic structure of a bottom gate staggered TFT is shown. The semiconductor layer can be either a:Si or IGZO or ZnO. The saturation mobility is calculated from the I_{ds} - V_{ds} family curves in a saturation region using the following equation:

$$I_{ds} = \frac{W}{2L} \times C_{ox} \times \mu_{sat} \times (V_{gs} - V_T)^2 \dots\dots (1)$$

where C_{ox} , V_T , W and L are the gate capacitance, threshold voltage, channel width and length, respectively. Since the simulation is performed using the same structure and normalized to W/L for all the bent and unbent conditions, the reduction in I_{ds} only depends on the changes in saturation mobility and V_T at the same gate bias (V_{gs}). The V_T extracted from the I_{ds} - V_{gs} plot (Fig. 2(d)) shows no changes at different bending radii ($R = 4, 8, 15, 30$ mm and ∞), as expected. Therefore, the effective saturation mobility during bending is expressed by:

$$\mu_{sat}^{bent} = \frac{I_{ds}^{bent}}{I_{ds}^{unbent}} \times \mu_{sat}^{unbent} \dots\dots (2)$$

The above equation can be used to extract the effective saturation mobility of the bent TFT at different R operated in saturation region. Similarly, the effective field-effect mobility is calculated from the g_m - V_{gs} transconductance curves at the maximum point in the linear region (i.e., low V_{ds}) by the following equations:

$$\mu_{FE} = \frac{g_{max}}{W/L \times C_{ox} \times V_{ds}} \dots\dots\dots (3)$$

$$\mu_{FE}^{bent} = \frac{g_{max}^{bent}}{g_{max}^{unbent}} \times \mu_{FE}^{unbent} \dots\dots\dots (4)$$

where g_{max} and V_{ds} are the maximum transconductance and drain-to-source voltage, respectively. The reduction in I_{ds} in the bent TFT is a result of reduced effective mobility. The effective field-

effect mobility as a function of the bending radius, $\mu_{\text{eff}}(R)$ is:

$$\mu_{\text{eff}}(R) = \theta \times \mu_{\text{Hall}} \dots \dots (5)$$

θ is dependent on bending radius, surface states, and other structural defects. When the semiconductor contains many traps or surface states, the large fraction of trapped electrons may cause the effective drift mobility to be smaller than the Hall mobility by the factor θ , which is less than one. Because the effects from the defects are fixed by using the same material and device structure, we consider the variable θ as a function of R only in this study.

The bending setup with a loaded carrier substrate and flexible TFT sample is depicted in Fig. 3. Fig. 4 shows 2D cross sectional view of the simulated electron concentration and electric field distribution, when the bent TFT is operated in a saturation region at $V_{\text{ds}} = 10$ V and $V_{\text{gs}} = 20$ V. Free electron concentration (n) is shown as a contour plot in Fig. 4(a). High concentrations of free electrons ($n > 10^{19} \text{ cm}^{-3}$) are accumulated near the curved gate insulator/ n -Si interface, as shown in Fig. 4(c), similar to the case of the unbent channel. This region carries the majority of the drain current.

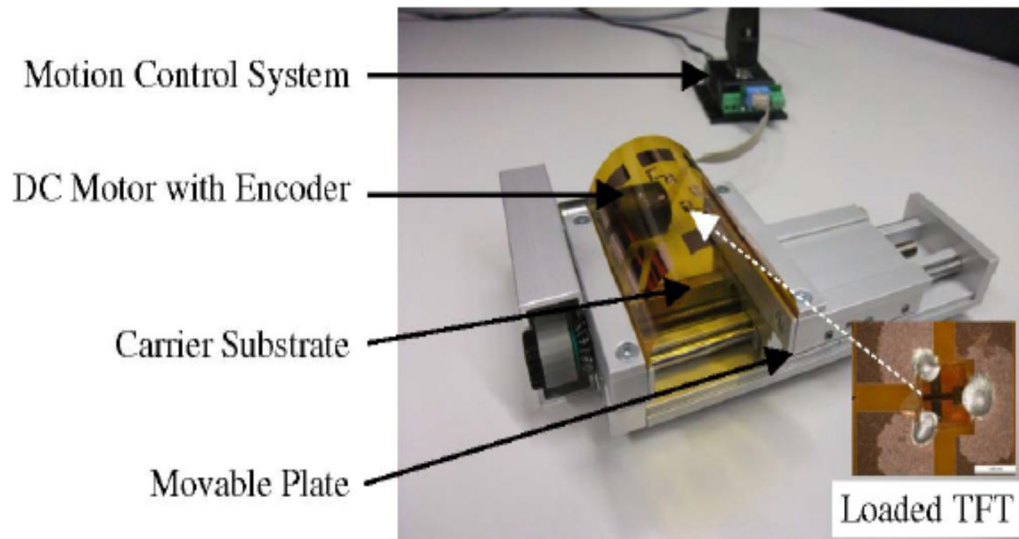


Fig. 3: Photograph of the bending tester with a loaded carrier substrate and an attached flexible TFT sample.

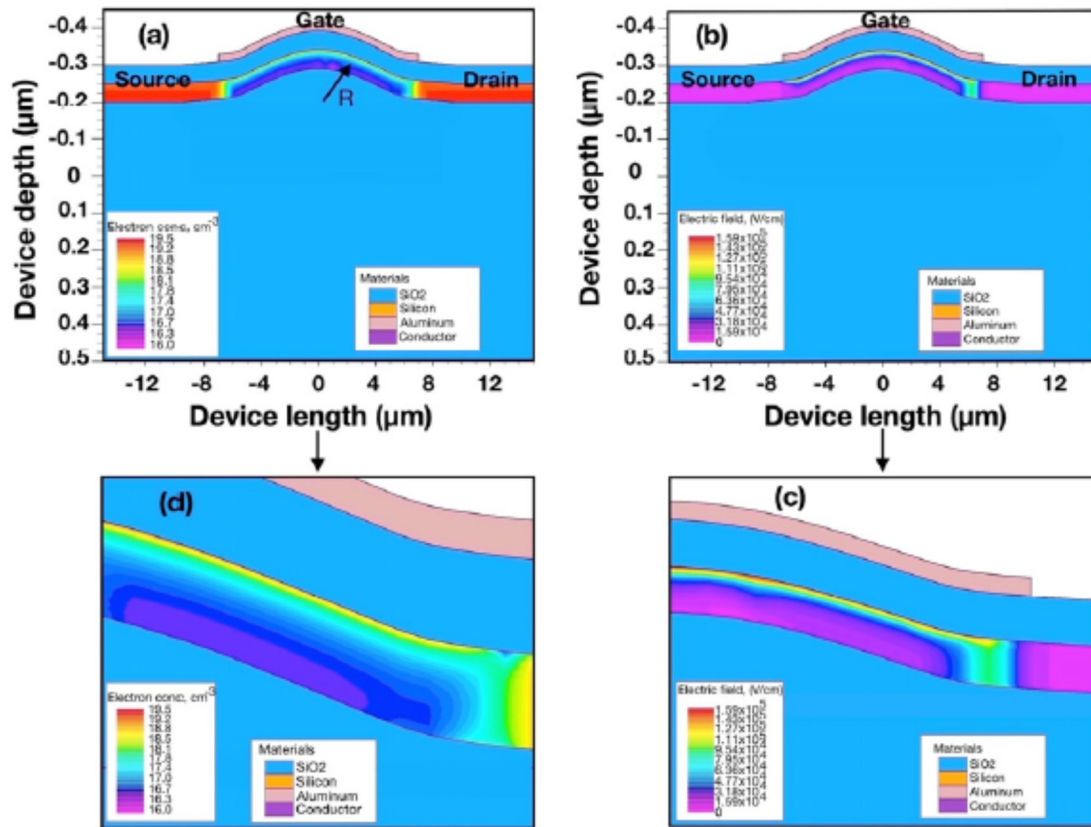


Fig. 4: (a) TFT device operation during bending showing 2D profile of electron concentration and (b) electric field using contour plot. (c) Magnified bent channel showing electron concentration and pinch-off point and (d) electric field distribution during bending.

RESULTS AND DISCUSSION

Fig. 5 shows the simulation results for the change of the effective saturation mobility values and Fig. 6 shows the simulation results for the change of the effective field-effect mobility values by bending for the same flexible device. Both the field-effect mobility and saturation mobility decrease with increasing bending. For instance, the bent TFT with $R = 30$ mm shows $\mu_{FE} = 178$ cm²/Vs which is $\sim 11\%$ lower than the initial mobility of the unbent TFT (200

cm²/Vs). The effective mobility is degraded as low as ~ 120 cm²/Vs with large bending ($R = 4$ mm). The simulation results are in a good agreement with experimental measurement using a single-crystal-like Si TFT where lower saturation current was observed during the bending [11]. Measured field-effect mobility values at $R = 15$ and 30 mm are compared. The device characteristics do not change before and after bending for unbent TFTs. In addition, we do not observe cracks after

bending. Therefore, we believe that the fracture or plastic deformation of the channel does not occur for the bent TFT up to the curvature with $R = 15$ mm. Fig. 6 also shows lower saturation mobility than

field-effect mobility (~ 6 -7% reduction) for high-quality channel materials which is expected from the electron velocity vs. field diagram.

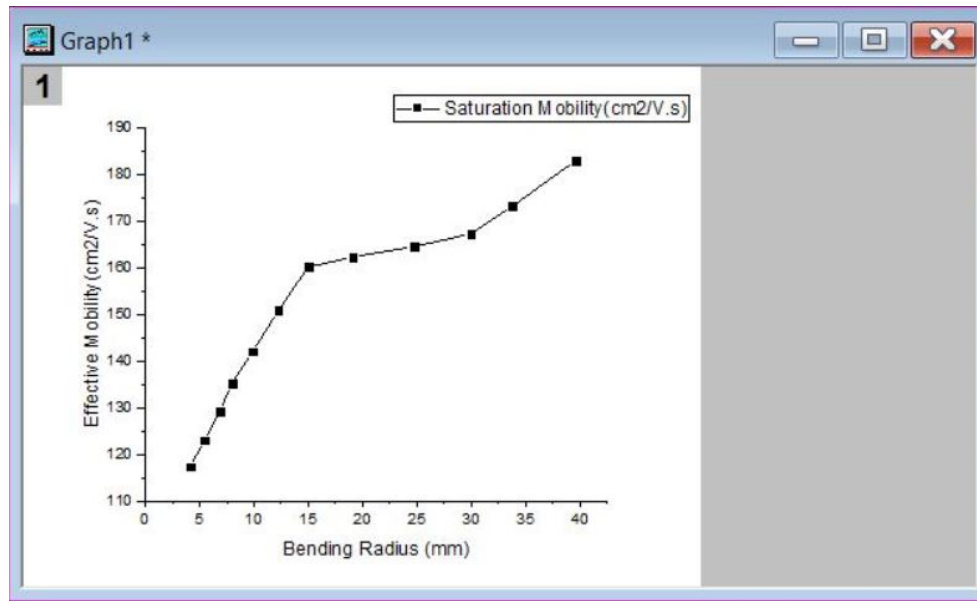


Fig. 5: Saturation mobility as a function of bending radius for flexible Si-TFT

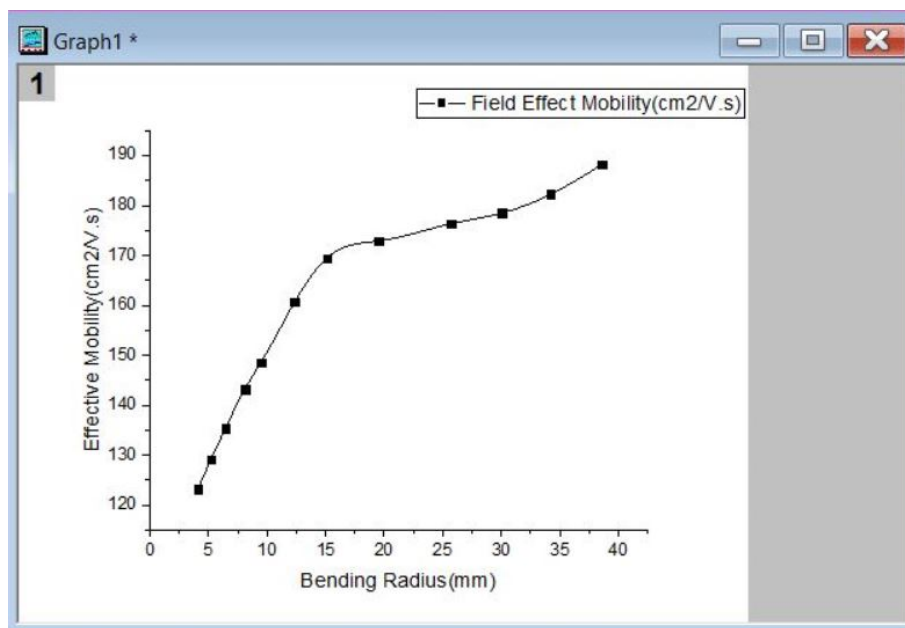


Fig. 6: Field-effect mobility as a function of bending radius for flexible Si-TFT

Fig. 7 shows the current-voltage (I_d - V_g) characteristic curve for an unbent a: Si TFT.

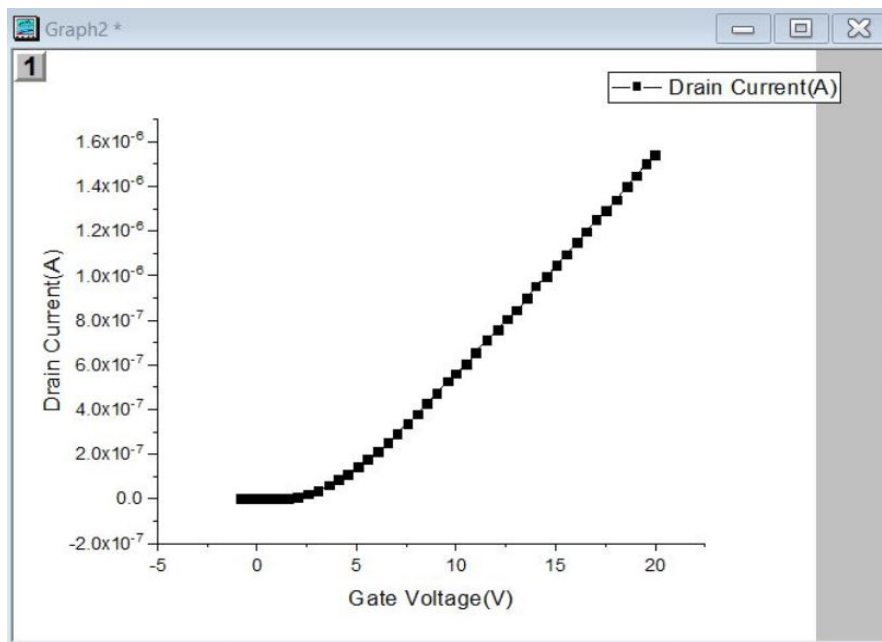


Fig. 7: Current-Voltage (I_d - V_g) characteristic of an unbent flexible Si-TFT.

The effects of bending on current at different radius $R=5$ mm, 10 mm, 15 mm, 20 mm, 30 mm and 40 mm calculated using the OriginPro software whose values are shown in Fig. 8 and are plotted subsequently in Fig. 9.

	A(X)	B(Y)	C(Y)	E(Y)	F(Y)	G(Y)	H(Y)	I(Y)
Long Name	Gate Voltage	Drain Current	R=5mm	R=10mm	R=15mm	R=20mm	R=30mm	R=40mm
Units								
Comments								
F(x)=								
Scale Type	Linear Scale	Linear Scale		Linear Scale	Linear Scale	Linear Scale	Linear Scale	Linear Scale
14	5.55634	1.76379E-7	1.08438E-7	1.25229E-7	1.41103E-7	1.42867E-7	1.47277E-7	1.51686E-7
15	6.06109	2.10729E-7	1.29556E-7	1.49618E-7	1.68583E-7	1.70691E-7	1.75959E-7	1.81227E-7
16	6.56059	2.50544E-7	1.54034E-7	1.77886E-7	2.00435E-7	2.0294E-7	2.09204E-7	2.15468E-7
17	7.01802	2.91139E-7	1.78992E-7	2.06709E-7	2.32911E-7	2.35823E-7	2.43101E-7	2.5038E-7
18	7.55958	3.38761E-7	2.0827E-7	2.4052E-7	2.71008E-7	2.74396E-7	2.82865E-7	2.91334E-7
19	8.06434	3.79356E-7	2.33228E-7	2.69343E-7	3.03485E-7	3.07278E-7	3.16762E-7	3.26246E-7
20	8.51652	4.26197E-7	2.62026E-7	3.026E-7	3.40957E-7	3.45219E-7	3.55874E-7	3.66529E-7
21	9.02127	4.73818E-7	2.91303E-7	3.36411E-7	3.79054E-7	3.83793E-7	3.95638E-7	4.07484E-7
22	9.56809	5.27685E-7	3.24421E-7	3.74656E-7	4.22148E-7	4.27425E-7	4.40617E-7	4.53809E-7
23	9.9782	5.62035E-7	3.45539E-7	3.99045E-7	4.49628E-7	4.55248E-7	4.69299E-7	4.8335E-7
24	10.51976	6.0185E-7	3.70017E-7	4.27313E-7	4.8148E-7	4.87498E-7	5.02544E-7	5.17591E-7
25	10.9772	6.56497E-7	4.03614E-7	4.66113E-7	5.25198E-7	5.31763E-7	5.48175E-7	5.64588E-7
26	11.52402	7.10364E-7	4.36732E-7	5.04358E-7	5.68291E-7	5.75395E-7	5.93154E-7	6.10913E-7
27	12.07083	7.57205E-7	4.6553E-7	5.37615E-7	6.05764E-7	6.13336E-7	6.32266E-7	6.51196E-7
28	12.57033	8.04826E-7	4.94807E-7	5.71427E-7	6.43861E-7	6.51909E-7	6.7203E-7	6.92151E-7
29	13.02777	8.45422E-7	5.19765E-7	6.00249E-7	6.76337E-7	6.84792E-7	7.05927E-7	7.27063E-7
30	13.57458	8.99289E-7	5.52883E-7	6.38495E-7	7.19431E-7	7.28424E-7	7.50906E-7	7.73388E-7
31	13.9847	9.53155E-7	5.86E-7	6.7674E-7	7.62524E-7	7.72056E-7	7.95885E-7	8.19714E-7

Fig. 8: Current-voltage (I_d - V_g) variation with bending radius $R=5$ mm, 10mm, 15mm, 20mm, 30mm and 40mm.

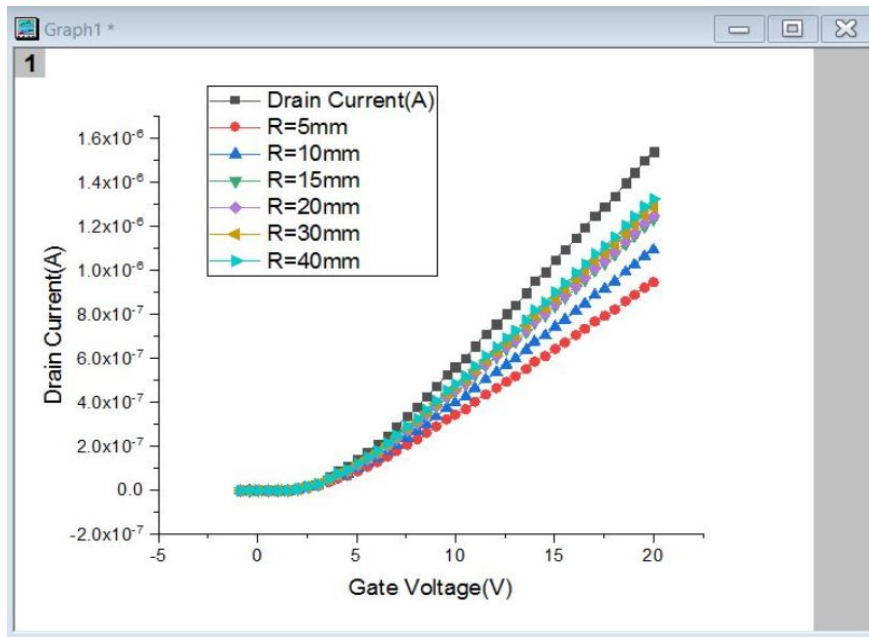


Fig. 9: Curve of current-voltage (I_d - V_g) with bending radius variation at $R=5$ mm, 10 mm, 15 mm, 20 mm, 30 mm and 40 mm.

Fig. 10 shows the current-voltage (I_d - V_d) characteristic curve for an unbent a: Si TFT. The effects of bending on current at different radius $R=5$ mm, 10 mm, 15 mm, 20 mm, 30 mm and 40 mm calculated using the OriginPro software whose values are shown in Fig. 11 and are plotted subsequently in Fig. 12.

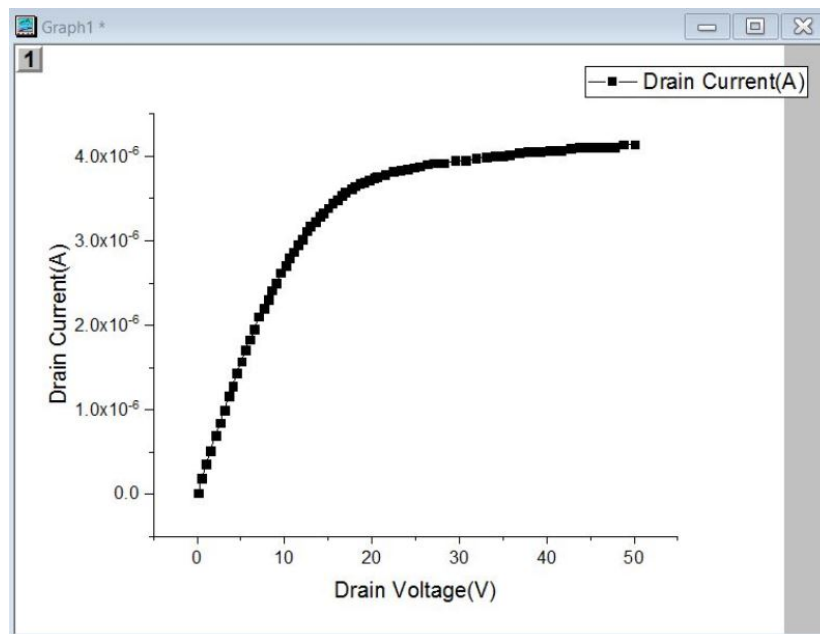


Fig. 10: Current-Voltage (I_d - V_d) characteristic of an unbent flexible Si-TFT.

	A(X)	B(Y)	C(Y)	D(Y)	E(Y)	F(Y)	G(Y)	H(Y)
Long Name	Drain Voltag	Drain Curre	R=5mm	R=10mm	R=15mm	R=20mm	R=30mm	R=40mm
Units								
Comments								
F(x)=								
Scale Type	Linear Scale	Linear Scale	Linear Scale	Linear Scale	Linear Scale	Linear Scale	Linear Scale	Linear Scale
43	21.51256	3.78285E-6	2.32569E-6	2.68582E-6	3.02628E-6	3.06411E-6	3.15868E-6	3.25325E-6
44	22.4161	3.82438E-6	2.35123E-6	2.71531E-6	3.05951E-6	3.09775E-6	3.19336E-6	3.28897E-6
45	23.24435	3.83892E-6	2.36017E-6	2.72563E-6	3.07114E-6	3.10953E-6	3.2055E-6	3.30147E-6
46	24.0726	3.85138E-6	2.36783E-6	2.73448E-6	3.08111E-6	3.11962E-6	3.21591E-6	3.31219E-6
47	24.813	3.86592E-6	2.37677E-6	2.7448E-6	3.09274E-6	3.1314E-6	3.22804E-6	3.32469E-6
48	25.47811	3.87838E-6	2.38443E-6	2.75365E-6	3.10271E-6	3.14149E-6	3.23845E-6	3.33541E-6
49	26.29381	3.90538E-6	2.40103E-6	2.77282E-6	3.12431E-6	3.16336E-6	3.26099E-6	3.35863E-6
50	27.04676	3.91992E-6	2.40997E-6	2.78314E-6	3.13594E-6	3.17514E-6	3.27313E-6	3.37113E-6
51	27.78717	3.91992E-6	2.40997E-6	2.78314E-6	3.13594E-6	3.17514E-6	3.27313E-6	3.37113E-6
52	28.27659	3.91992E-6	2.40997E-6	2.78314E-6	3.13594E-6	3.17514E-6	3.27313E-6	3.37113E-6
53	29.51896	3.94692E-6	2.42657E-6	2.80231E-6	3.15754E-6	3.19701E-6	3.29568E-6	3.39435E-6
54	30.67349	3.94692E-6	2.42657E-6	2.80231E-6	3.15754E-6	3.19701E-6	3.29568E-6	3.39435E-6
55	31.91586	3.97392E-6	2.44317E-6	2.82148E-6	3.17914E-6	3.21887E-6	3.31822E-6	3.41757E-6
56	33.07039	3.98846E-6	2.4521E-6	2.83181E-6	3.19077E-6	3.23065E-6	3.33036E-6	3.43007E-6
57	34.13707	4.00092E-6	2.45977E-6	2.84065E-6	3.20074E-6	3.24074E-6	3.34077E-6	3.44079E-6
58	34.97787	4.00092E-6	2.45977E-6	2.84065E-6	3.20074E-6	3.24074E-6	3.34077E-6	3.44079E-6
59	35.71827	4.01546E-6	2.4687E-6	2.85097E-6	3.21237E-6	3.25252E-6	3.35291E-6	3.45329E-6
60	36.8728	4.04246E-6	2.4853E-6	2.87014E-6	3.23397E-6	3.27439E-6	3.37545E-6	3.47651E-6
61	37.86419	4.05699E-6	2.49424E-6	2.88047E-6	3.2456E-6	3.28617E-6	3.38759E-6	3.48902E-6
62	38.60459	4.05699E-6	2.49424E-6	2.88047E-6	3.2456E-6	3.28617E-6	3.38759E-6	3.48902E-6
63	39.2697	4.05699E-6	2.49424E-6	2.88047E-6	3.2456E-6	3.28617E-6	3.38759E-6	3.48902E-6
64	40.33638	4.06946E-6	2.5019E-6	2.88931E-6	3.25556E-6	3.29626E-6	3.398E-6	3.49973E-6
65	40.75051	4.06946E-6	2.5019E-6	2.88931E-6	3.25556E-6	3.29626E-6	3.398E-6	3.49973E-6
66	41.57876	4.06946E-6	2.5019E-6	2.88931E-6	3.25556E-6	3.29626E-6	3.398E-6	3.49973E-6
67	42.73328	4.09853E-6	2.51978E-6	2.90996E-6	3.27883E-6	3.31981E-6	3.42227E-6	3.52474E-6
68	43.72467	4.11099E-6	2.52744E-6	2.91881E-6	3.2888E-6	3.32991E-6	3.43268E-6	3.53545E-6
69	44.37723	4.11099E-6	2.52744E-6	2.91881E-6	3.2888E-6	3.32991E-6	3.43268E-6	3.53545E-6
70	45.36862	4.11099E-6	2.52744E-6	2.91881E-6	3.2888E-6	3.32991E-6	3.43268E-6	3.53545E-6
71	46.10902	4.11099E-6	2.52744E-6	2.91881E-6	3.2888E-6	3.32991E-6	3.43268E-6	3.53545E-6
72	46.86198	4.11099E-6	2.52744E-6	2.91881E-6	3.2888E-6	3.32991E-6	3.43268E-6	3.53545E-6
73	47.76552	4.11099E-6	2.52744E-6	2.91881E-6	3.2888E-6	3.32991E-6	3.43268E-6	3.53545E-6
74	48.75691	4.13799E-6	2.54404E-6	2.93798E-6	3.31039E-6	3.35177E-6	3.45522E-6	3.55867E-6
75	50.07458	4.13799E-6	2.54404E-6	2.93798E-6	3.31039E-6	3.35177E-6	3.45522E-6	3.55867E-6

Fig. 11: Current-voltage (I_d - V_g) variation with bending radius $R=5\text{mm}$, 10mm , 15mm , 20mm , 30mm and 40mm .

For all the bent devices, the saturation currents decrease with increasing curvature (decreasing R). When the TFT structure is bent, scattering events for the moving carriers in the bent channel become significant in addition to those from lattice vibrations and crystalline and interfacial imperfections. Unlike the unbent channel, electron velocity vector (V) and the electric field (E) are not parallel during the bending, resulting

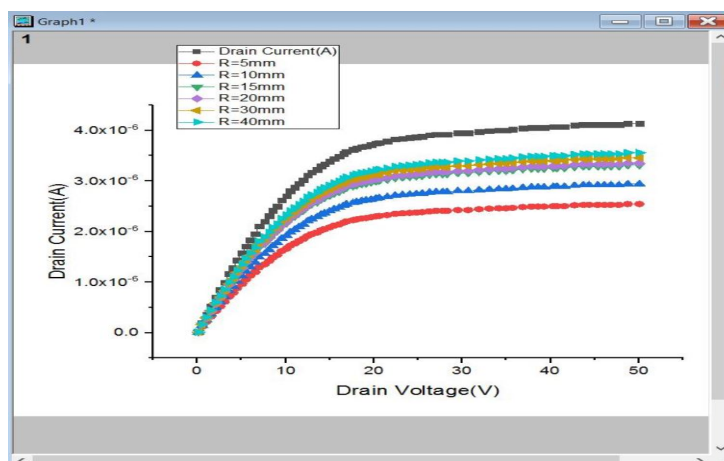


Fig. 12: Curve of current-voltage (I_d - V_g) with bending radius variation at $R=5\text{ mm}$, 10 mm , 15 mm , 20mm , 30 mm and 40mm .

in lower effective velocity; hence, effective mobility (μ_{eff}) of the bent device decreases. In addition, as the curvature increases, the knee voltage is shifted to higher values and the saturation occurs at higher drain voltages: $V_{d,sat}(\text{bent}) > V_{d,sat}(\text{unbent})$. Therefore, triode region is extended to higher drain voltages during the bending. This phenomenon is due to delayed pinch-off for the bent devices. The

change in transfer characteristics of a flexible TFT with different bending conditions is shown in Fig. 7. The device with the highest degree of bending ($R = 4 \text{ mm}$) show the lowest current. Nevertheless, the on/off ratio remains nearly the same for all the bending conditions. The threshold voltage does not change regardless of the bending condition, as shown in Fig. 9.

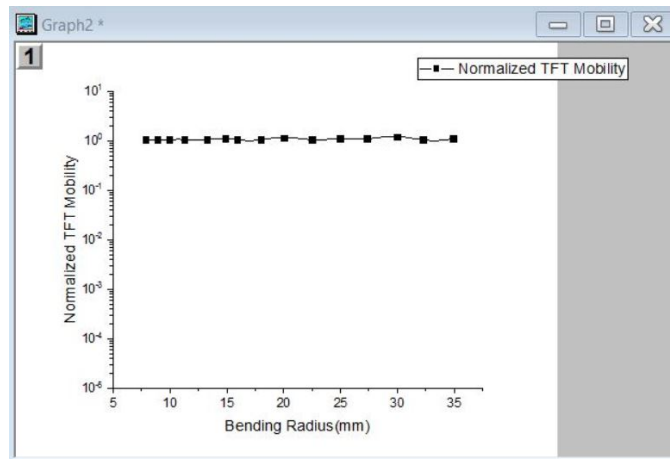


Fig. 13: Plot showing the effect of bending on IGZO TFTs normalized saturation mobility.

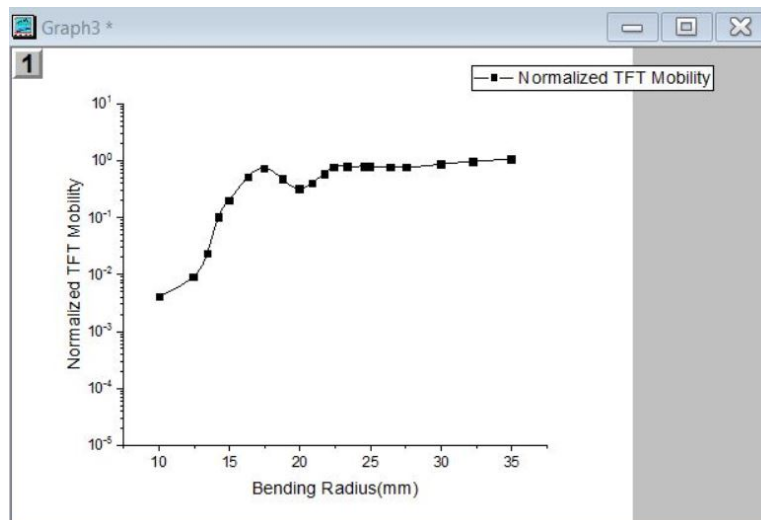


Fig. 14: Plot showing the effect of bending on ZnO TFTs normalized saturation mobility.

Fig. 13 and Fig. 14 show typical normalized saturation motilities for an IGZO and ZnO TFT versus bending radius respectively. All electrical parameters are normalized by their values measured for the flat TFT prior to bending. The extracted parameters for flat ZnO and IGZO TFTs are μSAT_0 , ZnO = 2.04 $\text{cm}^2/\text{V} \cdot \text{s}$, μSAT_0 , IGZO = 10.5 cm^2/Vs . Here, μSAT is the saturation mobility. The “0” in the subscript indicates values measured for flat TFTs. Fig. 13 shows that the electrical parameters of the IGZO TFT remain essentially unchanged over the entire bending range. The plot of the flat and bent transfer characteristic of an IGZO TFT in [5] also shows that bending has little impact on the transfer characteristic of IGZO TFTs. In contrast μSAT of the ZnO TFT decreased by more than two orders of magnitude during bending.

CONCLUSION

The characteristics of the bent TFTs by the simulation are in good agreement with those of experimental measurements of TFTs based on single-crystal-like Si thin films. This paper has shown that ZnO TFTs are sensitive to applied mechanical bending, while IGZO TFTs are resistant to bending. Therefore, of these two materials, IGZO is the best choice for development

of robust flexible TFTs and flexible electronic circuits.

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