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Focused ion beam milling for the fabrication of 160 nm channel length IGZO TFTs on flexible polymer substrates

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Abstract. The quest for short channel length transistors is an important challenge in semiconductor industry. A similar trend is observed in the field of flexible electronics where sensor conditioning circuits and transceivers have to be realized on plastic foils. Here the use of a focused Ga⁺ ion beam (FIB) to structure the channel of a flexible InGaZnO based thin-film transistor (TFT) is presented. The resulting flexible TFT exhibits a channel length of 160 nm and an effective field effect mobility of 4 cm²V⁻¹s⁻¹. Furthermore, the optimized Ga⁺ beam milling does not damage the underneath Al₂O₃ gate insulator leading to a gate leakage current of <200 pA. The extreme channel length demonstrates that focused ion beams can complement conventional fabrication approaches, overcoming current limitations imposed by flexible substrates. While the dimensions result in short channel effects and a drain conductance of 25 μS limiting the DC applicability of the FIB TFT, the device also exhibits a high internal gain of 3.4 dB. Consequently, a transit frequency of ≈6 MHz and a maximum frequency of oscillation of ≈19 MHz is measured for supply voltages ≤0.5 V. This shows that highly scaled flexible TFTs for analog circuits can be fabricated by ion beam milling.

Keywords: Fabrication technology, Flexible electronics, Thin-film transistors, InGaZnO, AC performance, Focused ion beam

1. Introduction

Flexible and light-weight sensor systems integrated into everyday objects, or fabricated on cheap polymer substrates are one of the next major milestones for consumer and healthcare products [1]. Besides sensors itself, flexible and fast analog circuits capable of handling signals at radio frequencies are of paramount importance to realize unobtrusive data transceivers [2]. These are needed to convert stand-alone flexible sensors into useful sensor nodes for various applications [3, 4]. In this context, flexible thin-film transistors (TFTs) utilizing high mobility semiconductors such as MoS₂ [5], silicon nano-membranes [6], black phosphorus [7], or graphene [8] exhibited transit frequencies (f_T) of 5.6 GHz, 12 GHz, 17.5 GHz, and 95 GHz, respectively. While these values are impressive, the employed materials exhibit limited compatibility with large area fabrication processes. Alternatives are novel semiconductors, such as organic materials, amorphous silicon, and oxides. In particular, InGaZnO (IGZO) [9] combines good electrical performance, with low temperature processability, and extreme bendability [10]. However, the carrier mobility of amorphous IGZO is lower than the values provided by crystalline materials. Consequently, the channel length of flexible IGZO TFTs has to be minimized to achieve fast transistors. Moreover, the mechanical properties of polymer foils complicate the fabrication of small features on flexible substrates. The main fabrication challenges include thermal expansion, swelling due to the absorption of water and solvents, as well as high surface roughness when compared to standard Si substrates. To date, self-alignment [11], vertical structures [12] and direct laser writing [13] were used to structure flexible TFTs with channel lengths down to 280 nm.

Here, we present the use of a focused ion beam (FIB) to fabricate IGZO TFTs with channel length down to 160 nm on a flexible polyimide substrate. The FIB TFTs are fully compatible with established UV lithographic fabrication methods, which enables the integration of FIB and conventional devices. This in turn opens an alternative way towards to fabrication of fast flexible circuits. To our best knowledge these are the shortest flexible IGZO TFTs, they exhibit a measured transit frequency and a maximum frequency of oscillation of ≈ 6 MHz and ≈ 19 MHz.

2. Device structure and fabrication

The structure of the developed inverted staggered bottom-gate FIB TFTs on a polymer foil is shown in Fig. 1a. The TFT manufacturing process (Fig. 1b) is divided into two semi-independent parts. First, the TFT stack is fabricated using standard UV lithography. Afterwards, a focused ion beam is used to separate the source and drain contacts.

2.1. Device stack fabrication

UV lithography, employing a Karl Süss MA6 mask aligner, was used to manufacture the TFT stack on a free standing 50 μm thick polyimide foil. The substrate was

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Figure 1. a) Schematic and layer thicknesses of a flexible bottom gate inverted staggered FIB TFT. b) Focused ion beam assisted fabrication process flow to manufacture short channel TFTs on a polyimide substrate.

encapsulated with 50 nm SiN (PECVD, Oxford Instruments PECVD 80+). A 35 nm thick Ti bottom gate was e-beam evaporated and structured by lift-off. The gate was electrically insulated by the atomic layer deposition of 50 nm Al₂O₃ (Picosun Sunale R-150B) exhibiting a dielectric constant of 9.5. This deposition was done at 150 °C, which is the highest temperature involved in the fabrication process. Next, a 45 nm thick amorphous IGZO semiconductor layer was RF sputtered in a pure Ar atmosphere at a pressure of 2 mTorr. This was done using a ceramic InGaZnO₄ target and a magnetron sputtering tool from PVD Products. The gate insulator and semiconductor were structured using wet etching. Finally, a 10 nm Ti adhesion layer, and a 75 nm Au layer were deposited and structured by lift-off. All metal layers were evaporated using a Plassys electron beam evaporator. A lift-off process was used to structure these layers into source/drain electrodes and contact pads. However, the TFT channel was not defined in this step, i.e. the 5 μ m wide source and drain contacts were short circuited as illustrated in Fig. 1b (3). The thicknesses of all metal, Al₂O₃, and IGZO layers were monitored using a quartz crystal monitor, an ellipsometer, and a surface profilometer, respectively. Furthermore, all source contacts were connected with each other on the substrate, to create a single conductive structure on the insulating polyimide substrate, drastically reducing charging effects during SEM/FIB processing.

2.2. FIB structuring

The TFT channel was created using a FEI Strata 235 equipped with a Raith ELPHY MultiBeam SEM/FIB patterning unit. FIB assisted structuring of gold with different adhesion layers using Ga⁺ ion milling is a standard technique [14, 15]. However, for this TFT application it is important to adjust the process to fully separate the Ti/Au source and drain contacts without removing too much ($\gtrsim 30$ nm) of the underlying IGZO semiconductor or damaging the Al₂O₃ gate insulator. At this aim, preliminary experiments were performed with the Ga⁺ current beam, used to raster across the sample surface, set to 30 kV and 10 pA. The FIB used a dwell time of 1 μ s and a step size of 5 nm. The milling time per unit area, and hence the number of times the

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Figure 2. a) Ga⁺ beam (top) and e-beam (bottom) micrographs of the same 0.5 μm × 2 μm test structures (red boxes) milled for different times. The test structures partially overlap the Ti/Au metallization. A Ga⁺ current of 10 pA was used. b) and c) Milling test structures with high aspect ratio showing and incomplete and complete separation of metal contacts.

Ga⁺ beam rastered across the surface, was adjusted to vary the total dose. 0.5 μm × 2 μm rectangular test structures were placed on the Ti/Al₂O₃/IGZO stack partial overlapping the additional Ti/Au metallization. Alignment was done using SEM images. Fig. 2a displays micrographs of the sample surface acquired using a Ga⁺ beam and an e-beam. Four test structures milled using different times are shown. It is visible that a milling time of 5.7 s/μm² is not sufficient to completely remove the Ti/Au layer (bottom right image Fig. 2a). At the same time, higher milling times (e.g. 11.4 s/μm², center images Fig. 2a) damage the underlying IGZO: in particular, a milling time of 22.8 s/μm² completely removed the semiconductor (top left image Fig. 2a). These results are also confirmed by Fig. 2b, showing a trench milled for 5.7 s/μm². Again, this dose is not sufficient to separate the 85 nm thick Ti/Au layer. The images show that the optimal milling time has to be above 5.7 s/μm² but below 11.4 s/μm². Furthermore, we theoretically calculated the Ti/Au sputter yield of the employed Ga⁺ beam [16]. Our exposure doses correspond well to the calculated ones, which confirms the validity of the experimentally determined exposure times. The information combined from literature, calculations and the presented experiments showed that a milling time of 10.9 s/μm², in combination with the chosen FIB settings, yields the best results. The resulting trench, milled for 10.9 s/μm² (Fig. 2c), fully cuts through the metal but not the underlying IGZO layer. Finally, this optimized setting was used to conclude the flexible TFT fabrication by milling a rectangular structure into the Ti/Au layer on top of the previously prepared gate stack. The software defined dimensions of this structure were 8 μm × 200 nm. The difference in dimension between the 5 μm wide contacts and the 8 μm long milling area is to simplify the alignment of the two structures relative to each other.

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Figure 3. a) Flexible polyimide substrate with IGZO TFTs, and comparison of a TFT structure before and after FIB milling. b) Optical micrograph of the fully processed TFT channel region. c) Topographic representation of the channel region. The inset shows the corresponding height map. The transistor channel has a length over width ratio of 160 nm / 5 μm.

3. Results and Discussion

The TFT dimensions were characterized using SEM images. Fig. 3a shows a flexible TFT before FIB milling and after the fabrication process is finished. The FIB defined TFT has a channel width of 5 μm. An optical micrograph of the TFT is shown in Fig. 3b, although the feature size is close to the resolution limit, the milled channel is visible. A topographic characterization of the same transistor was done by a contact mode AFM measurement (CoreAFM with a Tap150Al-G cantilever). The resulting 3D visualization and height map conforming the layer thicknesses and the dimensions of the FIB milled channel are given in Fig. 3c. In contrast to the lateral dimension of the milled area (200 nm), the exact dimension of the resulting trench and hence the channel length is 160 nm. Electrical characterization was performed under ambient conditions.

3.1. DC transistor performance

The FIB TFT was measured using a Keysight B1500A parameter analyzer, and performance parameters were extracted using the Shichman-Hodges model [17]. Fig. 4

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Figure 4. DC performance of the flexible FIB TFT. a) Transfer characteristic measured for two different drain source voltages. b) Output characteristic.

shows that the TFT operates as depletion mode device. Most importantly, Fig. 4a confirms that the Ga^+ beam did not damage the gate insulator layer. The measured gate leakage current is < 0.2 nA, which is in line with other flexible IGZO bottom gate TFTs [10]. At the same time, the other DC parameters are not comparable to state-of-the-art long channel IGZO TFTs. The FIB TFT exhibits a field effect mobility of $4 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, a threshold voltage V_{TH} of -22 V, an on/off current ratio of $\approx 10^1$, and a specific gate capacitance of 170 nF/cm^2 . The relatively low performance is mainly caused by the dimensions of the channel, especially the ratio between the channel length (160 nm) and the total thickness of the gate insulator, semiconductor and source/drain contacts (170 nm). The low aspect ratio leads to poor electrostatic control of the channel and causes short channel effects (visible in Fig. 4). This behavior is also illustrated by the output characteristic in Fig. 4b showing weak saturation resulting in a drain conductance g_{ds} up to $25 \mu\text{S}$. In particular the on/off current ratio is not comparable with long channel IGZO TFTs [13]. However, this is not predominately caused by short channel effects, as additional fabricated FIB TFTs with channel length up to 300 nm exhibited similar performance. In contrast, the off current is influenced by Ga^+ ions, which are implanted during the FIB milling process. This implantation typically happens within 50 nm from the sample surface, and hence mostly in the 45 nm thick IGZO layer. The increased Ga concentration increases the conductivity of the IGZO [18], and the off current of the TFTs. At the same time it has to be mentioned that the demonstrated on/off ratio it is similar to several other flexible transistors aiming at high speed operation such as graphene based devices [19]. Furthermore, as transistors in analog circuits are nearly always biased above threshold the on/off current ratio is not relevant for such applications. Since the maximum measured transconductance g_m is $37 \mu\text{S}$, the TFT exhibits an internal gain of 3.4 dB which makes the device suitable for analog applications.

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Figure 5. a) Micrograph of the FIB TFT with GSG contacts optimized for S-parameter measurements. b) Magnitude and c) imaginary part of the measured current gain. d) Maximum stable gain versus frequency.

3.2. AC transistor performance

The AC performance characterization was done using a HP 8753E two port vector network analyzer. To ensure reliable measurements, the layout of the FIB TFT exhibits Ground-Signal-Ground (GSG) contact pads as shown in Fig. 5a. Scattering parameters were measured using an AC voltage of 100 mV, and DC bias voltages of $V_{DS} = 0.5 \text{ V}$, and $V_{GS} = 0 \text{ V}$. The measured Scattering parameters were subsequently used to calculate the transistor current gain h_{21} . Figures 5b and 5c display the magnitude and imaginary part of h_{21} . As shown, at low frequencies the short channel length of the FIB TFT leads to a current gain of $5.5 \text{ dB}/\mu\text{m}$, which is significantly larger than for previously published flexible IGZO TFTs [20]. The TFTs transit frequency f_T is extracted using two complimentary methods, namely the unity current gain frequency and the slope of $\Im\{h_{21}\}$ [21]. Both methods result in similar results of 5.9 MHz, and 6.1 MHz. Additionally, the maximum stable gain was calculated (Fig. 5d). Here the 19.2 MHz unity gain frequency of the maximum stable gain equals the maximum frequency of oscillation f_{MAX} which is the highest frequency at which the TFT can provide a power gain. These values are in line with the TFT's transconductance and gate capacitance. This illustrates that the frequency is currently limited by a parasitic capacitance of $\approx 250 \text{ fF}$. This capacitance is dominated by the width of the semiconductor island, which

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is wider than the actual channel (compare Fig. 5a). Consequently, future improvements could include minimizing the layer thicknesses and lateral semiconductor island size to reduce short channel effects as well as drain leakage currents and gate capacitance. Additionally, a passivation of the device using e.g. Al_2O_3 could neutralize trap states at the IGZO surface and further improve the device performance [10].

4. Conclusion

Ga^+ beam assisted fabrication of flexible IGZO TFTs enables very short channel lengths of only 160 nm, without damaging the TFT stack. While the extremely scaled dimensions cause short channel effects, which limit the DC performance and suitability for DC applications, the FIB TFT exhibits an exceptional AC current gain. Additionally, transit frequencies and maximum frequencies of oscillation in the Megahertz range were demonstrated using bias voltages ≤ 0.5 V. Besides Ga based focused ion beams, FIBs can also employ e.g. Helium, Neon or Xenon ions. While such tools are less common, the use of noble gases could be an interesting future alternative for the fabrication of FIB TFTs. This is mostly because such elements are expected to not dope the semiconductor material. Although no significant effect of the Ga implanted into the InGaZnO semiconductor was observed, the use of e.g. He could help to reduce the off current of the TFTs, and more importantly enable the use of not Ga based semiconductors.

Although FIB milling is traditionally used for sample preparation and prototyping, it is also employed in the commercial production of miniaturized magnetic field sensors for hard drives [22, 23], which indicates its potential for the fabrication of specialized active devices. Furthermore, the fabrication of radio frequency circuits generally requires only a very small number of fast TFTs along with additional long channel devices e.g. for biasing purposes [24]. Consequently, FIB TFTs combined with conventional transistors provides new opportunities for the fabrication of aggressively scaled flexible TFTs and analog circuits.

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References

- [1] A. Nathan, A. Ahnood, M. T. Cole, S. Lee, Y. Suzuki, P. Hiralal, F. Bonaccorso, T. Hasan, L. Garcia-Gancedo, A. Dyadyusha, S. Haque, P. Andrew, S. Hofmann, J. Moultrie, D. Chu, A. J. Flewitt, A. C. Ferrari, M. J. Kelly, J. Robertson, G. A. J. Amaratunga, and W. I. Milne, "Flexible electronics: The next ubiquitous platform," *Proc. of the IEEE*, vol. 100, no. 13, pp. 1486–1517, 2012. [Online]. Available: <http://dx.doi.org/10.1109/JPROC.2012.2190168>

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- [2] K. Myny, "The development of flexible integrated circuits based on thin-film transistors," *Nature Electronics*, vol. 1, no. 1, p. 30, 2018. [Online]. Available: <http://dx.doi.org/10.1038/s41928-017-0008-6>
- [3] F. Ellinger, C. Tzschoppe, D. Fritsche, P. Stärke, K. Ishida, and T. Meister, "Review of fast, efficient and bendable radio-frequency integrated receivers for the wireless communication systems of the future," in *2018 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*. IEEE, 2018, pp. 766–768. [Online]. Available: <https://doi.org/10.1109/APWC.2018.8503759>
- [4] J. C. Costa, F. Spina, P. Lugoda, L. Garcia-Garcia, D. Roggen, and N. Münzenrieder, "Flexible sensors—from materials to applications," *Technologies*, vol. 7, no. 2, p. 35, 2019. [Online]. Available: <https://doi.org/10.3390/technologies7020035>
- [5] H.-Y. Chang, M. N. Yogeesh, R. Ghosh, A. Rai, A. Sanne, S. Yang, N. Lu, S. K. Banerjee, and D. Akinwande, "Large-area monolayer mos2 for flexible low-power rf nanoelectronics in the ghz regime," *Advanced Materials*, vol. 28, no. 9, pp. 1818–1823, 2016. [Online]. Available: <https://doi.org/10.1002/adma.201504309>
- [6] L. Sun, G. Qin, J.-H. Seo, G. K. Celler, W. Zhou, and Z. Ma, "12-ghz thin-film transistors on transferrable silicon nanomembranes for high-performance flexible electronics," *Small*, vol. 6, no. 22, pp. 2553–2557, 2010. [Online]. Available: <https://doi.org/10.1002/sml.201000522>
- [7] W. Zhu, S. Park, M. N. Yogeesh, K. M. McNicholas, S. R. Bank, and D. Akinwande, "Black phosphorus flexible thin film transistors at gighertz frequencies," *Nano letters*, vol. 16, no. 4, pp. 2301–2306, 2016. [Online]. Available: <https://doi.org/10.1021/acs.nanolett.5b04768>
- [8] S. Park, S. H. Shin, M. N. Yogeesh, A. L. Lee, S. Rahimi, and D. Akinwande, "Extremely high-frequency flexible graphene thin-film transistors," *IEEE Electron Device Letters*, vol. 37, no. 4, pp. 512–515, 2016. [Online]. Available: <https://doi.org/10.1109/LED.2016.2535484>
- [9] K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, "Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors," *Nature*, vol. 432, no. 7016, pp. 488–492, 2004. [Online]. Available: <http://dx.doi.org/10.1038/nature03090>
- [10] L. Petti, N. Münzenrieder, C. Vogt, H. Faber, L. Büthe, G. Cantarella, F. Bottacchi, T. D. Anthopoulos, and G. Tröster, "Metal oxide semiconductor thin-film transistors for flexible electronics," *Applied Physics Reviews*, vol. 3, no. 2, p. 021303, 2016. [Online]. Available: <http://dx.doi.org/10.1063/1.4953034>
- [11] N. Münzenrieder, K. Ishida, T. Meister, G. Cantarella, L. Petti, C. Carta, F. Ellinger, and G. Tröster, "Flexible ingazno tfts with fmax above 300 mhz," *IEEE Electron Device Letters*, vol. 39, no. 9, pp. 1310–1313, 2018. [Online]. Available: <https://doi.org/10.1109/LED.2018.2854362>
- [12] L. Petti, A. Frutiger, N. Münzenrieder, G. A. Salvatore, L. Büthe, C. Vogt, G. Cantarella, and G. Tröster, "Flexible quasi-vertical in-ga-zn-o thin-film transistor with 300-nm channel length," *IEEE Electron Device Letters*, vol. 36, no. 5, pp. 475–477, 2015. [Online]. Available: <https://doi.org/10.1109/LED.2015.2418295>
- [13] L. Petti, E. Greco, G. Cantarella, N. Münzenrieder, C. Vogt, and G. Tröster, "Flexible in-ga-zn-o thin-film transistors with sub-300-nm channel lengths defined by two-photon direct laser writing," *IEEE Transactions on Electron Devices*, vol. 65, no. 9, pp. 3796–3802, 2018. [Online]. Available: <https://doi.org/10.1109/TED.2018.2851926>
- [14] T. Blom, K. Welch, M. Strömme, E. Coronel, and K. Leifer, "Fabrication and characterization of highly reproducible, high resistance nanogaps made by focused ion beam milling," *Nanotechnology*, vol. 18, no. 28, p. 285301, 2007. [Online]. Available: <https://doi.org/10.1088/0957-4484/18/28/285301>
- [15] T. Nagase, K. Gamo, T. Kubota, and S. Mashiko, "Direct fabrication of nano-gap electrodes by focused ion beam etching," *Thin Solid Films*, vol. 499, no. 1-2, pp. 279–284, 2006. [Online]. Available: <https://doi.org/10.1016/j.tsf.2005.07.031>

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- [16] N. Matsunami, Y. Yamamura, Y. Itikawa, N. Itoh, Y. Kazumata, S. Miyagawa, K. Morita, R. Shimizu, and H. Tawara, "Energy dependence of the yields of ion-induced sputtering of monatomic solids," *Technical Report IPPJ-AM-32 Institute of Plasma Physics, Nagoya University*, 1983.
- [17] H. Shichman and D. A. Hodges, "Modeling and simulation of insulated-gate field-effect transistor switching circuits," *IEEE Journal of Solid-State Circuits*, vol. 3, no. 3, pp. 285–289, 1968. [Online]. Available: <http://doi.org/10.1109/JSSC.1968.1049902>
- [18] P. Barquinha, L. Pereira, G. Goncalves, R. Martins, and E. Fortunato, "Toward high-performance amorphous gizo tfts," *Journal of the Electrochemical Society*, vol. 156, no. 3, pp. H161–H168, 2009. [Online]. Available: <https://doi.org/10.1149/1.3049819>
- [19] H. Jang, Y. J. Park, X. Chen, T. Das, M.-S. Kim, and J.-H. Ahn, "Graphene-based flexible and stretchable electronics," *Advanced Materials*, vol. 28, no. 22, pp. 4184–4202, 2016. [Online]. Available: <https://doi.org/10.1002/adma.201504245>
- [20] N. Münzenrieder, G. A. Salvatore, L. Petti, C. Zysset, L. Büthe, C. Vogt, G. Cantarella, and G. Tröster, "Contact resistance and overlapping capacitance in flexible sub-micron long oxide thin-film transistors for above 100 mhz operation," *Applied Physics Letters*, vol. 105, no. 26, p. 263504, 2014. [Online]. Available: <https://doi.org/10.1063/1.4905015>
- [21] H. Gummel, "On the definition of the cutoff frequency f_t ," *Proceedings of the IEEE*, vol. 57, no. 12, pp. 2159–2159, 1969. [Online]. Available: <https://doi.org/10.1109/PROC.1969.7509>
- [22] M. Madison, T. Arnoldussen, M. Pinarbasi, T. Chang, M. Parker, J. Li, S. Duan, X. Bian, M. Mirzamaani, R. Payne *et al.*, "Beyond 10 gb/in²: Using a merged notched head (fib-defined writer and gmr reader) on advanced low noise media," *IEEE transactions on magnetics*, vol. 35, no. 2, pp. 695–699, 1999. [Online]. Available: <https://doi.org/10.1109/20.750630>
- [23] K. Kant and D. Losic, "Focused ion beam (fib) technology for micro-and nanoscale fabrications," in *FIB Nanostructures*. Springer, 2013, pp. 1–22. [Online]. Available: <https://doi.org/10.1007/978-3-319-02874-3-1>
- [24] F. Ellinger, *Radio frequency integrated circuits and technologies*. Springer Science & Business Media, 2008.