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Effect of the Nitrogen Environment On Indium Gallium Zinc Oxide Thin Film Transistors with Low Temperature Ultraviolet Annealing

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Abstract: This study explores the influence of nitrogen gas flow rate on the electrical characteristics of indium-gallium-zinc-oxide (IGZO) thin-film transistors (TFTs) annealed under heat-assisted UV illumination. The aim is to understand how nitrogen flow rates impact the performance of solution-processed IGZO TFTs annealed at low temperatures, which is crucial for developing high-performance devices for next-generation electronics and temperature-sensitive applications. The IGZO TFTs were fabricated on glass substrates using a bottom-gate top-contact configuration, with the IGZO thin film deposited by inkjet printing and annealed in a chamber with varying nitrogen gas flow rates (0.5, 1, 2, and 5 L/min) at 250°C for 2 hours under UV illumination. The electrical characteristics were extracted from transfer characteristics measurements. The results show that a nitrogen flow rate of 1 L/min enhances the electrical properties of IGZO TFTs, likely due to a suitable concentration of oxygen vacancies. Excessive N2 flow rates (>1 L/min) negatively impact on the TFT characteristics, while lower flow rates (<1 L/min) result in more negative threshold voltages and lower on/off current ratios. The study concludes that optimizing the nitrogen gas flow rate is critical for achieving desired TFT properties, offering a valuable tool for fine-tuning IGZO TFTs to meet specific application requirements.

Keywords: MEC; IGZO TFTs; Low temperature; Nitrogen Annealing Effect; Oxide Semiconductor; Thin Film Transistor

Vpliv dušikovega okolja na tankoplastne tranzistorje iz indij-galij-cinkovega oksida z nizkotemperaturnim ultravijoličnim žarjenjem

Izvleček: Študija raziskuje vpliv pretoka dušikovega plina na električne lastnosti tankoplastnih tranzistorjev (TFT) iz indij-galij-cink-oksida (IGZO), žarjenih pod toplotno podprto UV-osvetlitvijo. Cilj je razumeti, kako pretok dušika vpliva na delovanje IGZO TFT, obdelanih s tekočino in žarjenih pri nizkih temperaturah, kar je ključnega pomena za razvoj visoko zmogljivih naprav za elektroniko naslednje generacije in temperature občutljive aplikacije. IGZO TFT so bili izdelani na steklenih podlagah z uporabo konfiguracije spodnjih vrat in zgornjega kontakta, pri čemer je bil IGZO tanek film nanesen s tiskanjem z inkjet tiskalnikom in žarjen v komori z različnimi pretoki dušika (0,5, 1, 2 in 5 l/min) pri 250 °C 2 uri pod UV-osvetlitvijo. Električne lastnosti so bile izmerjene iz meritev prenosnih lastnosti. Rezultati kažejo, da pretok dušika 1 l/min izboljša električne lastnosti IGZO TFT, verjetno zaradi ustrezne koncentracije kisikovih praznin. Prekomerni pretoki N2 (>1 l/min) negativno vplivajo na lastnosti TFT, medtem ko nižji pretoki (<1 l/min) povzročajo bolj negativne pragovne napetosti in nižja razmerja med vklopnim in izklopnim tokom. Študija zaključuje, da je optimizacija pretoka dušika ključna za doseganje želenih lastnosti TFT, kar ponuja dragoceno orodje za natančno nastavitev IGZO TFT, da izpolnjujejo specifične zahteve aplikacij.

Ključne besede: IGZO TFTs; nizka temperatura; učinek dušikovega žarjenja; oksidni polprevodnik; tankoplastni tranzistor

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1 Introduction

In recent years, solution processed IGZO TFTs have emerged as potential technology for a wide range of applications, including displays, sensors, and wearable devices, due to their elevated mobility, elevated transparency, and small power consumption characteristics [1]–[5]. The performance of IGZO TFTs is significantly influenced by the fabrication process, particularly the annealing process, which is vital for enhancing the electrical transport properties and stability of the transistors. Traditionally, thermal annealing has been generally applied in the fabrication of IGZO TFTs to enhance the thin film quality and carrier mobility. Heat annealing typically involves annealing the IGZO thin films at elevated temperatures classically above 300°C for an extended period [6]. During heat annealing, the high temperature can help to remove the defects and impurities in the thin film, decreased oxygen vacancies, resulting in improved carrier mobility of the IGZO TFTs [7]. However, there are several disadvantages associated with heat annealing. Firstly, the high temperature may cause thermal damage to the substrate, leading to substrate warping or degradation of other components in the device structure. Secondly, temperature control during the annealing process can be challenging, as it requires precise control to avoid over-annealing or under-annealing, which can affect the uniformity and reproducibility of the TFT performance[8]. Lastly, the long annealing times required for heat annealing may not be conducive to high throughput manufacturing processes, resulting in reduced productivity and increased fabrication costs) [9], [10].

To overcome the limitations of traditional heat annealing, UV annealing has been studied as an alternative approach for the construction of IGZO TFTs. UV annealing has several advantages, including shorter annealing times, reduced substrate damage, and improved uniformity of the TFT performance [9], [11]–[14]. UV annealing has also been reported to decrease the defects and enhance the electrical properties of IGZO TFTs [15]. Additionally, UV annealing has been found to be compatible with low-temperature substrates, making it suitable for flexible electronics and other temperature-sensitive applications[16]. However, this annealing method alone may not be sufficient to fully optimize the performance of IGZO TFTs, as it may not effectively remove all the defects and impurities in the thin film, resulting in suboptimal electrical characteristics [17]–[19].

A combination of heat and UV annealing has been studied as a new method for the fabrication of IGZO TFTs, aiming to synergistically leverage the benefits of both approaches and overcome their constraints [3], [20]. For example, Zhang et al. demonstrated that the combination of heat and UV annealing led to a meaningful improvement in the carrier mobility of IGZO TFTs compared to heat annealing or UV annealing alone [21]. They attributed enhanced performance to the synergistic effects of heat and UV annealing, which led to improved crystallinity and reduced defect density in the IGZO films.

Among the backdrop of exploring various annealing techniques to enhance IGZO TFT performance, including the novel approach of combining heat and UV annealing, there is a mounting interest in the role of annealing environments, particularly the use of high-pressure gases[22]. Research has shown that high-pressure annealing with gases like nitrogen[23]and hydrogen [24] can significantly enhance the electrical characteristics of IGZO based TFTs by promoting carrier mobility and reducing oxygen vacancies [24]– [27].

This investigation focuses on describing the role of N2 flow rate at low pressure during heat-assisted UV annealing process, indicating the electrical attributes of IGZO TFTs. By precisely altering the N2 flow rates, we have observed consequential shifts in the transistors electrical behavior which pinpoint the profound impact of annealing environment on defect dynamics within the IGZO films. Our results demonstrate that a carefully calibrated nitrogen environment at low pressure is key to modulating defect-related phenomena, thereby refining the electrical performance of IGZO TFTs. This work not only advances the methodologies for defect control in low-temperature at low pressure, solution- processed semiconductors but also enriches the fundamental understanding of defect behavior under low pressure annealing environment, aligning with the ongoing discourse on defect engineering in semiconductor technology.

2 Materials and methods

IGZO TFTs were fabricated on glass substrates utilizing a bottom-gate top-contact (BGTC) configuration as presented in Fig.1. The TFT channel length and the width were 10 µm and 150 µm, respectively. The gate electrode was made of platinum Pt, and the gate dielectric consisted of a SiO2/Si3N4 layer. A 2.5M IGZO solution was prepared using nitrate salts of In:Ga:Zn in a ratio of 6.8:1:2.2, dissolved in a blend of 2-Methoxyethanol, Propanediol, and Glycerol in a ratio of 7:2:1. The IGZO solution was deposited onto the substrate using an inkjet printing method with a drop spacing of 60 µm and 3 drops. The deposited IGZO thin film was then annealed inside a chamber with a nitrogen gas flow. The annealing was performed using a hot plate set at 250°C and a UV lamp with a power density of 33 mW/cm2 and a wavelength of 184 nm, respectively. Four different N2 gas flow rates: 0.5 L/min, 1 L/min, 2 L/min, and 5 L/min were used at the same annealing temperature, with each condition being annealed for a duration of 2 hours. The annealing process is illustrated in Fig. 2. Aluminum was deposited onto the IGZO thin film by physical vapor deposition to create the source/drain electrodes. The transfer characteristics of the fabricated devices were recorded by utilizing a semiconductor parameter analyzer. The electrical characteristics of the TFTs, Subthreshold swing, on/off current ratio, threshold voltage, and off current were extracted from the transfer characteristics measurements.

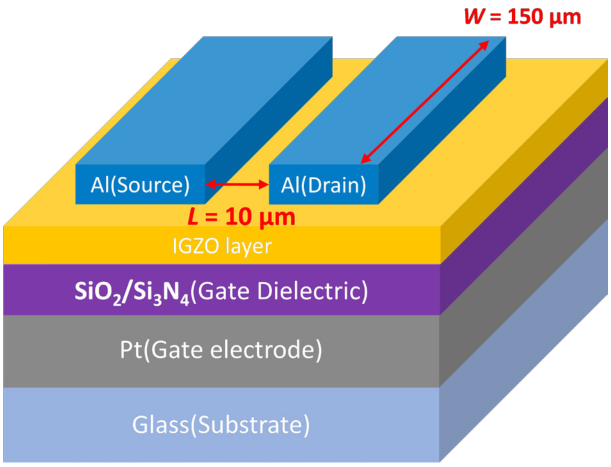

Figure 1: Cross-sectional representation of a bottom-gate IGZO TFT with a SiNx/SiO2 gate dielectric layer, constructed on a glass substrate.

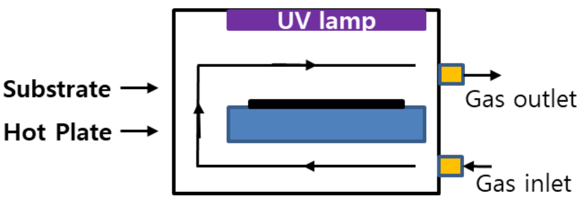

Figure 2: Annealing chamber with UV lamp and hot plate.

3 Results and discussions

Figure 3 illustrates the transfer characteristics of the TFTs annealed at 250°C for 2h with varying nitrogen flow rates. Specifically, Figs.3(a), Figs.3(b), Figs.3(c) and Figs.3(d) display transfer curves for flow rates of 0.5, 1, 2, and 5 L/min, respectively. The on-current slightly increases as the gas flow rate changes from 0.5 L/min to 1 L/min, which reveals an improvement in the electrical behavior of the device. This could be ascribed to the moderate presence of oxygen vacancies from the IGZO film surface due to the exposure to UV and heat under the following nitrogen, which enhances the carrier concentration. 1 L/min to 2 L/min, the on-current slightly decreases, Furthermore, as the N2 flow rate increases to 5 L/min the on-current decreases dramatically.

The electrical characteristics of the devices based on the N2 gas flow are summarized in Table I. The V_{TH} was determined by extrapolating the ID square root against the V_G curve in the saturation region. The threshold voltage of the devices varies between –8.3 V and –12.5 V as the N2 flow changed from 0.5 L/min to 5 L/min.

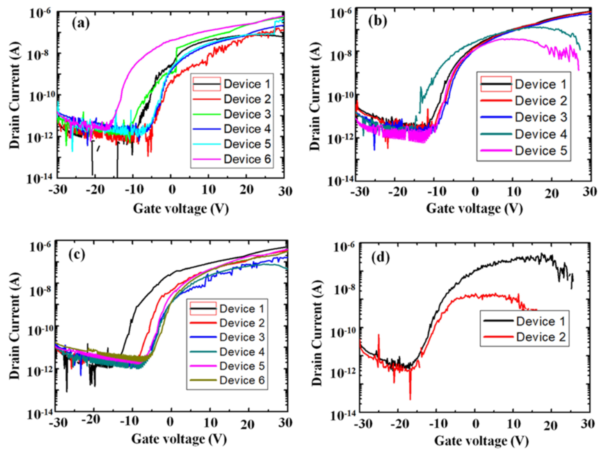

Figure 3: The transfer characteristics of TFTs annealed at varied Nitrogen gas flow rate a) 0.5 L/min, b) 1 L/min, c) 2 L/min and d) 5 L/min

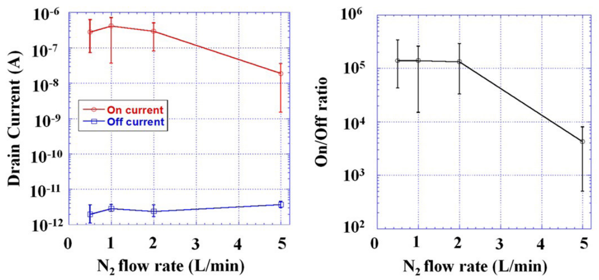

Figure 4: a) On-current(red) and off-current (blue) b) On/Off current ratio.

For a broader perspective, Table 1 also includes data for IGZO TFTs annealed in a stable nitrogen environment (0.0 L/min), as reported by Huang et al. [28] Under these conditions, the device exhibited a threshold voltage of -14.77 V, an on/off current ratio of 2.22×10^4, and a subthreshold swing of 7.37 V/dec. These values are significantly inferior to those achieved in this work at an optimized flow rate of 1 L/min, which yielded a less negative threshold voltage (–2.6 V), a much higher on/off ratio (5.13×10^5), and a lower subthreshold swing (1.84 V/dec). This comparison demonstrates that a

Table 1: Summary of transistor characteristics corresponding to the N2 flow rate.

N_2 flow rate(L/min)	Vth(V)	I_{off}(A)	I(On)/I(off)	Subthreshold. Swing (V/dec)	References
0.0 (stable N2)	-14.77	N/A	2.22×10^4	7.37	[28]
0.5	-8.3	1.16×10^{-12}	5.90×10^4	1.87	This work
1	-2.6	1.25×10^{-12}	5.13×10^5	1.84	
2	-4.8	2.71×10^{-12}	1.21×10^5	2.17	
5	-12.5	2.17×10^{-6}	9.80×10^2	5.31	

static nitrogen environment (no flow) results in poorer device performance compared to controlled nitrogen flow during annealing.

A negative V_{TH} indicates more electron carriers making the transistor operate in depletion mode. The increase in the negative direction of V_{TH} at higher flow rate is ascribed to an increase of deficiencies, specifically oxygen vacancies. However, as the nitrogen flow rate increases from 1 L/min, the primary source of free electrons in oxide semiconductors based on Zinc Oxide (ZnO) is largely associated with the creation of oxygen vacancies[29]–[31] whereas the current ratio slightly increases and significantly decreases as the gas flower changes from 2 to 5 L/min. Furthermore, the increase in the gas flow rate results in higher off current. Consequently, it is anticipated that annealing at an elevated N2 flow rate improves the creation of oxygen vacancy defects[32]. Thus, an elevated N2 flow rate results in more electron carriers which leads to negative V_{TH} shifts with higher off current as nitrogen flow rate increases. The occurrence of oxygen deficiencies similarly negatively impacts the subthreshold swing (S.S.) value resulting in higher S. S [33]. On the other hand, lowering the nitrogen flow rate leads to lower off-current level and lower threshold voltage value, and lower subthreshold swing. While a very low nitrogen flow level gives a more negative V_{TH} and lower ratio of on/off current. This indicates that annealing in nitrogen environment is beneficial to regulate the electrical properties of the TFTs based on IGZO simply by altering the nitrogen quantity.

4 Conclusions

We have demonstrated the effects of annealing process in flowing N2 ambient on IGZO TFTs with low Temperature Ultraviolet Annealing. Our research shows that nitrogen gas flow rate is a critical parameter influencing the electrical characteristics of IGZO based TFTs. Improving electrical properties, a reasonable flow rate of 1 L/min suggests the creation of suitable oxygen vacancies in the IGZO film. In contrast, elevated flow rates lead to an increased carrier concentration, which results in a higher off current, implying the formation of detrimental defects. This study highlights the delicate optimization required in nitrogen-assisted annealing processes for refining the performance of IGZO TFTs. The findings offer a pathway for enhancing low-temperature solution-processed semiconductors, a step forward in semiconductor defect engineering. Further investigations are warranted to deepen the understanding of nitrogen's role in adjusting the defect landscape of IGZO thin films.

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6 Conflict of interest

The authors affirm that they have no known financial conflicts of interest or personal connections that could have potentially influenced the research presented in this paper.

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