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<th>Fluorinated InGaZnO Thin-Film Transistor With HfLaO Gate Dielectric</th>
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Abstract—Fluorinated amorphous InGaZnO thin-film transistor with HfLaO gate dielectric has been studied by treating InGaZnO film in a CHF3/O2 plasma. The saturation carrier mobility can be improved from 29.6 cm²/V·s to as high as 39.8 cm²/V·s. In addition, the passivation effect of the fluorination on the dominant donor-like traps at the InGaZnO/HfLaO interface is observed, as reflected by suppression of hysteresis phenomenon and smaller subthreshold swing. Measurement result of low-frequency noise further supports the improvement in electrical properties by the plasma treatment.

Index Terms—Amorphous InGaZnO (a-IGZO), thin-film transistor (TFT), HfLaO, fluorine, plasma.

I. INTRODUCTION

In the field of flat-panel displays (FPDs), thin-film transistors (TFTs) with high field-effect mobility (μFE) are required [1]. Accordingly, ZnO-based TFTs have been intensively explored to replace conventional amorphous silicon TFTs. Compared to polycrystalline ZnO (poly-ZnO) TFTs, amorphous InGaZnO (a-IGZO) TFTs exhibit better spatial uniformity of device performance. In addition, the incorporation of Ga ions, which act as carrier suppressors and network stabilizers in InZnO (IZO), is beneficial to achieving high carrier mobility and excellent uniformity [2]. Hence, a-IGZO TFT has been regarded as one of the most promising candidates for the application in FPDs. Lee et al. reported a-IGZO TFT with a high μFE of 28 cm²/V·s using ZrO₂ gate dielectric [3]. However, it had large subthreshold swing (SS, 0.56 V/dec) and large threshold-voltage (VT) hysteresis (∆VT, 3 V), which could slow down the switching and deteriorate the reliability properties of the device respectively. In addition, Zan et al. used nanometer dot doping to improve μFE to an average value of 67.5 cm²/V·s [4]. Nevertheless, if considering the effective intrinsic channel length, the average intrinsic μFE is 33.8 cm²/V·s. However, the SS of this device is as large as 0.92 V/dec, and a negative VT of −2.94 V was achieved, making the device unsuitable for switching applications. a-IGZO TFT with TiO₂ gate dielectric achieved a high μFE of 61.5 cm²/V·s, but also had a large SS (0.61 V/dec) [5]. It was reported that the electrical characteristics of poly-ZnO TFTs could be improved by fluorine implantation [6]. Unfortunately, the improvements in mobility and SS were accompanied by a change of operation mode from accumulation to depletion.

Furthermore, fluorine doping by spin coating of metal-fluoride (ZnF₂ and InF₃) precursor aqueous solution was also adopted to improve both the carrier mobility and stability of IZO TFTs [7].

In this letter, the effects of fluorine incorporation in a-IGZO on the characteristics of a-IGZO TFTs are studied for the first time. Fluorine is introduced in a-IGZO by means of plasma treatment, which is more compatible with device processing on large-area substrate and also induces less damage to thin film than implantation. Due to its superior properties, including high dielectric constant, good thermal stability and low trap density [8], high-k material HfLaO is selected as the gate dielectric for the samples in this letter. Consequently, both high saturation carrier mobility (μsat, 39.8 cm²/V·s) and small SS (0.21 V/dec) can simultaneously be obtained by the sample with the plasma treatment. Moreover, this sample can operate in enhancement mode with a small ∆VT of −0.5 V.

II. EXPERIMENTAL DETAILS

The schematic diagrams of the device cross section during the CHF₃/O₂ plasma treatment and after all the fabrication processes are shown in Fig. 1. P-type (100) silicon acts as both substrate and gate electrode. Firstly, deposition of a 40-nm HfLaO film was done by a sputtering system. An annealing treatment at 400 °C in N₂ for 10 min followed. Subsequently, the sample received a deposition of a 60-nm a-IGZO active layer through radio-frequency (RF) sputtering in an Ar/O₂ mixed ambient. Then, the sample received the CHF₃/O₂ plasma treatment with the flow rate of 10 sccm/1 sccm at a RF power of 20 W for 3 min. The addition of O₂ was to remove carbon and increase fluorine concentration by suppressing CFₓ radicals [9], [10]. The control sample without plasma treatment was also fabricated. After that, a lift-off process was utilized to form the source/drain electrodes, which were composed of 20-nm Ti and 80-nm Au. The channel width (W) and length (L) were 100 μm and 20 μm respectively. Finally, both samples were annealed in a forming-gas (N₂ : H₂ = 95 : 5) ambient at 350 °C for 20 min. In addition, metal-insulator-semiconductor (MIS) capacitor was prepared beside the transistor to monitor the gate-oxide capacitance per unit area (Cox, equal to 0.202 μF/cm² in this letter). For each condition, 12 devices were measured, and the device with the median value of μsat was selected to represent the condition.
III. RESULTS AND DISCUSSION

Fig. 2 exhibits the secondary ion-mass spectrometry (SIMS) depth profile in the stack of IGZO/HfLaO/Si thin films. The ordinate refers to the atom counts in an analysis area of $56.6 \mu m \times 56.6 \mu m$ while the abscissa is about the acquisition time which reflects the depth from the surface of a-IGZO. For the plasma-treated sample before the forming-gas annealing, it is apparent that fluorine has been successfully introduced into a-IGZO by the plasma treatment, and majority of fluorine atoms piles up near the surface of a-IGZO. The fluorine peak at the IGZO/HfLaO interface should be due to its blocking effect on the fluorine incorporation. After the forming-gas annealing, fluorine atoms have diffused towards the a-IGZO/HfLaO interface, and a fraction of them has spread into HfLaO.

Fig. 3(a) shows the transfer characteristics of the a-IGZO TFTs with or without CHF$_3$/O$_2$ plasma treatment for a-IGZO: drain current ($I_D$) vs. $V_{GS}$, and $I_D^{1/2}$ vs. $V_{GS}$ at a drain-to-source voltage ($V_{DS}$) of 5 V. The important electrical parameters are extracted from Fig. 3 and listed in Table I. Among them, $\mu_{sat}$ and $V_{TH}$ are calculated from a linear fitting to the plot of $I_D^{1/2}$ vs. $V_{GS}$ (using a $V_{GS}$ range of 1 V), which is based on the I–V equation of field-effect transistor operating in the saturation region:

$$I_D = (\mu_{sat}C_{ox}W/2L)(V_{GS}-V_{TH})^2$$

(1)

The inset of Fig. 3(a) reveals $\mu_{sat}$ is gate-bias dependent, which is consistent with the result reported in [11], and accordingly the maximum value of $\mu_{sat}$ during the $V_{GS}$ sweeping is selected for comparison purpose [6], [11]. Compared to the control sample ($\mu_{sat} = 29.6 \text{ cm}^2/\text{V} \cdot \text{s}$), the plasma-treated sample possesses a steeper slope of $I_D^{1/2}$ vs. $V_{GS}$ and accordingly a higher $\mu_{sat}$ (39.8 cm$^2$/V·s). It is well known that fluorine and oxygen have similar ionic radius, and the Zn–F bonding is more stable than the Zn–O one. Therefore, it is easy to cause the substitution of the oxygen atoms in the lattice ($O^2_0$) of a-IGZO by the fluorine atoms derived from the CHF$_3$/O$_2$ plasma. Moreover, the difference in electronegativity between oxygen ion ($O^{2-}$) and fluorine ion ($F^{-}$) can induce the substitution of an oxygen ion by a fluorine ion to generate a free electron [7]:

$$O^2_0 + F^- \rightarrow F^+_0 + e^-$$

(2)

Therefore, the electron concentration in a-IGZO is increased, resulting in a shift of the zero-gate-bias Femi level towards the conduction band. Accordingly, a larger fraction of the acceptor-like traps in a-IGZO and/or at the a-IGZO/HfLaO interface can be filled by the generated free electrons. As a result of the filling of acceptor-like traps at/near the a-IGZO/HfLaO interface, trap-induced scattering on channel electrons is suppressed, and thus carrier mobility is increased [12]. However, even with an increased electron concentration in a-IGZO, $V_{TH}$ is slightly increased from 2.5 V to 2.8 V by the plasma treatment, possibly due to the introduction of negative fluorine ions in the gate oxide. As a result of the filling of acceptor-like traps at/near the a-IGZO/HfLaO interface, trap-induced scattering on channel electrons is suppressed, and thus carrier mobility is increased [12]. However, even with an increased electron concentration in a-IGZO, $V_{TH}$ is slightly increased from 2.5 V to 2.8 V by the plasma treatment, possibly due to the introduction of negative fluorine ions in the gate oxide. As a result of the filling of acceptor-like traps at/near the a-IGZO/HfLaO interface, trap-induced scattering on channel electrons is suppressed, and thus carrier mobility is increased [12]. However, even with an increased electron concentration in a-IGZO, $V_{TH}$ is slightly increased from 2.5 V to 2.8 V by the plasma treatment, possibly due to the introduction of negative fluorine ions in the gate oxide.

As a result of the filling of acceptor-like traps at/near the a-IGZO/HfLaO interface, trap-induced scattering on channel electrons is suppressed, and thus carrier mobility is increased [12]. However, even with an increased electron concentration in a-IGZO, $V_{TH}$ is slightly increased from 2.5 V to 2.8 V by the plasma treatment, possibly due to the introduction of negative fluorine ions in the gate oxide. As a whole, a slight improvement of $I_{on}/I_{off}$ (from $9.0 \times 10^5$ to $9.2 \times 10^5$) can still be achieved by the plasma treatment.

As shown in Fig. 4, both samples present a hysteresis phenomenon in the counter-clockwise direction, which reveals the dominant role of donor-like traps at the a-IGZO/HfLaO interface. Nevertheless, the reduction of $\Delta V_{TH}$ from $-1.3 \text{ V}$ to...
It is found that $\mu_{\text{sat}}$ can be increased from 29.6 cm$^2$/V·s to as high as 39.8 cm$^2$/V·s by the plasma treatment. Accordingly, $I_{\text{on}}$ is increased by over 20%. In addition, the passivation effect of plasma treatment on the dominant donor-like traps at the a-IGZO/HfLaO interface is also observed. As a result, the hysteresis phenomenon is suppressed while SS is reduced. Accordingly, both high saturation carrier mobility and small SS (0.21 V/dec) can simultaneously be achieved by the plasma-treated sample, which can also operate in enhancement mode with a small $\Delta V_H$ of $-0.5$ V. The LFN measurement further supports the improvement in electrical properties.

In summary, fluorinated a-IGZO is a promising material for making high-performance TFT used in the field of FPDs.

**REFERENCES**


