A Two-Mask Process for Fabrication of Bottom-Gate IGZO-Based Tens

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Abstract—A simple process is presented with which a bottom-gate-type oxide thin-film transistor (TFT) can be fabricated by using two photomasks. The active channel, the source–drain electrode, and the pixel electrode layers were simultaneously formed via a single photolithography using a gray-tone mask (GTM). In particular, the gray-tone profiles of the photoresist were carefully observed to ensure process feasibility with the GTM. From the transparent-oxide TFTs fabricated in this letter, functional indices, such as threshold voltage $V_T = 4.13 \text{V}$ (at $V_{DS} = 10 \text{V}$), subthreshold swing $S = 0.59 \text{V/dec}$, field-effect mobility $\mu_{FE} = 12.41 \text{cm}^2/\text{V} \cdot \text{s}$, on-off current ratio lesser than $8 \times 10^6$, and transmittance higher than $85\%$, were obtained.

Index Terms—Gray-tone mask (GTM), transparent-oxide thin-film transistor (TFT), two-mask process.

I. INTRODUCTION

RECENTLY, oxide semiconductors, such as zinc oxide (ZnO) [1], indium–zinc oxide (IZO) [2], and indium–galium–zinc oxide (IGZO) [3], have come to be regarded of late as materials that may replace the Si-based active channel layers of TFTs for active matrix of a flat-panel display. The Si-based TFT technology has limitation such as low carrier mobilities (0.5–1 cm$^2$/V · s) for amorphous silicon (a-Si:H) due to its structural deficiency or high cost for polycrystalline silicon (poly-Si) due to a high-temperature process or laser annealing [4]. The high field-effect mobility of these oxide semiconductors when used as active channel layers of TFTs can allow the rapid switching required for driving a flat-panel display such as active matrix liquid crystal display (AMLCD) and active matrix organic light-emitting diode (AMOLED) [5], [6]. In addition, most oxide semiconductors can be used for making transparent TFTs at visible-light wavelengths because of their wide-band-gap energy of 3–4 eV, and these materials will not undergo degradation even when exposed to visible light.

For many TFT-LCD manufacturers, achieving high field-effect mobility for the TFT and lowering cost along with increasing productivity by simplifying the process are the top priorities [7], [8]. A gray-tone mask (GTM) makes semiexposure possible by shielding part of the light with slit patterns that are finer than the resolution provided by conventional exposure equipment. Therefore, three levels of exposure intensity on TFT glass substrates in one round of exposure can be created using a GTM: fully exposed, semiexposed, and nonexposed areas. As a result, the photoresist (PR) can be left on glass substrates in two kinds of thicknesses. Using the difference between these thicknesses, a smaller number of photomasks can transfer patterns to glass substrates and thus increase the production efficiency of TFT-LCDs. In general, the Si-based semiconductor materials such as a-Si:H and poly-Si should undergo a complex process involving the use of four to five photomasks because of their opacity at visible-light wavelength, and their device and pixel electrode areas should be separated so that a TFT could be made. In contrast, an oxide semiconductor with higher transmittance at a visible-light wavelength even with semiconductor layers under the pixel electrodes makes it possible to come up with a display panel by allowing a sufficient amount of light from the LCD backlight to pass through.

In this letter, how to make a bottom-gate-type transparent-oxide TFT that allows construction of a TFT with only two photomasks using IGZO as an active channel layer and IZO as source–drain and pixel electrodes was looked into. The two-mask process was achieved by simultaneously forming all layers, including the active channel and source–drain, and pixel electrode layers via a single photolithography process using a GTM. For this, a new GTM was suggested, in which the PR on glass substrates in one round of exposure can be created using a GTM: fully exposed, semiexposed, and nonexposed areas. As a result, the photoresist (PR) can be left on glass substrates in two kinds of thicknesses. Using the difference between these thicknesses, a smaller number of photomasks can transfer patterns to glass substrates and thus increase the production efficiency of TFT-LCDs. In general, the Si-based semiconductor materials such as a-Si:H and poly-Si should undergo a complex process involving the use of four to five photomasks because of their opacity at visible-light wavelength, and their device and pixel electrode areas should be separated so that a TFT could be made. In contrast, an oxide semiconductor with higher transmittance at a visible-light wavelength even with semiconductor layers under the pixel electrodes makes it possible to come up with a display panel by allowing a sufficient amount of light from the LCD backlight to pass through.

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II. EXPERIMENTAL DETAILS

Fig. 1 shows the schematic diagrams representing the transparent-oxide TFTs suggested in this letter. In the a-Si:H...
TFT-LCD, the a-Si:H active channel layer is opaque, not allowing the light from the backlight to pass through. As such, a separate pixel electrode should be formed using transparent electrodes, such as indium tin oxide. As shown in Fig. 1, on the other hand, an oxide semiconductor with high transmittance, such as IGZO, makes it possible to construct a TFT-LCD without being influenced by the operation of the TFT, even when a semiconductor layer exists under the pixel electrode.

For the fabrication of the transparent-oxide TFTs, 100-nm-thick chromium (Cr) was deposited on a Corning 1737 glass plate using a dc magnetron sputter; then, the first masking process was then performed using a GTM designed as 0–3.5 µm. A 200-nm-thick silicon dioxide (SiO2), as a gate-insulating layer, was deposited by plasma-enhanced chemical vapor deposition system at 300 ºC. For the active channel layer and the source–drain/pixel electrodes, 70-nm-thick IGZO and 100-nm-thick IZO were deposited using an RF magnetron sputter at room temperature, respectively. The process conditions for IGZO and IZO were as follows: a 4-inch diameter sputter target of IGZO (In2O3 : Ga2O3 : ZnO = 1 : 1 : 1 wt.%) and IZO (In2O3 : ZnO = 9 : 1 wt.%), RF power of 30 and 80 W, a working pressure of 3 and 20 mTorr, and an Ar flow rate of 30 and 12 sccm, respectively. The second masking process was then performed using a GTM designed according to the requirements of this letter. The IZO, IGZO, and SiO2 thin films were serially removed by buffered oxide etchant for the area where no PR existed due to the GTM process; then, the PR formed in gray tone was selectively removed from the inductively coupled plasma dry etcher using O2 plasma under the following process conditions: RF power of 100 W, a working pressure of 20 mTorr, and an O2 flow rate of 20 sccm, respectively (Ash rate: 55 nm/min). In this process, all the PRs that were formed in gray tone on the active channel layer due to the difference in thickness were removed, but the PRs on the source–drain/pixel electrodes were retained. Finally, only the IZO layer exposed in the previous phase was selectively removed, but the IGZO active channel layer that was in the lower part of the IZO remained. In this process, a diluted acid solution (formic acid: DI = 1:50) was used as an etchant. The etch rate for the IZO layer was about 2.5 nm/s, whereas the IGZO layers were not attacked by these solutions. It is believed that the etch selectivity between the IZO and IGZO layers was very high. As a result, the construction of the bottom-gate-type transparent-oxide TFTs was completed.

To examine the appropriateness of the GTM process, the shape and thickness of the PR in gray tone were monitored at each phase of the process, using an optical microscope and a surface profiler (DEKTAK-3, Veeco). Moreover, to analyze the electrical and optical characteristics of the transparent-oxide TFTs, the output and transfer current–voltage characteristics were measured using a semiconductor parameter analyzer (4200-SCS, Keithley), and transmittance was measured at the UV and visible-light wavelength of 300–1000 nm using a UV/visible spectrometer (S-3100, SCINCO).

III. RESULTS AND DISCUSSION

For the TFTs fabricated in this letter, the size of the slit that forms the gray tone of the PR inside the channel was separately designed as 0–3.5 µm (0.5-µm step). The slit inside the channel area between the source and the drain partially blocks the light energy of the exposure system used in the photo process and forms a PR gray tone. For O2 plasma ashing, the thickness of the PR gray tone should be 480–540-nm thick (corresponding to approximately 40%–45% of the initial coating thickness of 1200 nm on the active channel). In this case, the optimum gray tone should be formed at the slit sizes of 2 µm.

Fig. 2 shows each phase of the process of making a transparent-oxide TFT using GTM. The optical microscopic image of each processing phase, the measured surface profile, and the relevant cross-sectional image for the active channel layer of the TFT designed with a channel length of 6 µm and a slit size of 2 µm are shown. In particular, the thickness of the cross section at each phase was used as a basis for determining the appropriateness of the process. As shown in Fig. 2(a), an approximately 480-nm PR gray tone was properly formed on
transparent-oxide TFTs consisted of IZO, IGZO, and SiO.
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The active channel layer after the GTM process. Moreover, the 100-nm IZO, 70-nm IGZO, and 200-nm SiO thin films in the area not covered by the PR were all removed via the etching process. Fig. 2(b) shows that the PR gray tone in the active channel layer was completely removed via O₂ plasma ashing, whereas the PRs in the other area remained, maintaining a certain thickness. Finally, Fig. 2(c) shows that the devices were completely formed by defining the active channel layer via IZO (a source–drain electrode) etching.

Fig. 3 shows the measured electrical characteristics of the transparent-oxide TFTs fabricated in this letter, with a channel width and length of 100 and 6 μm, respectively. Fig. 3(a) shows the characteristics of the TFT elements at the enhancement mode based on the output characteristics. Functional indices such as threshold voltage \( V_T = 4.13 \) V (at \( V_{DS} = 10 \) V), subthreshold swing \( S = 0.59 \) V/decade, field-effect mobility \( \mu_{FE} = 12.41 \) cm²/V·s, and on-off current ratio \( > 8 \times 10^6 \) were obtained from the transfer characteristics shown in Fig. 3(b). These results showed that the transparent-oxide TFTs fabricated using only two photomasks functionally worked, with favorable levels of device indices.

Fig. 4 compares the transmittance of a case where only a SiO₂ thin film existed on the glass plate and a case where the transparent-oxide TFTs consisted of IZO, IGZO, and SiO₂ thin films, with a bare glass as a reference. Transmittance values of 97.7% through the SiO₂ layer and 85.6% through the full TFT layer of IZO/IGZO/SiO₂ were observed at the 400–700-nm visible-light wavelengths. In particular, the difference in transmittance between the positions \( P_1 \), \( P_2 \), and \( P_3 \) for the transparent-oxide TFTs was less than 0.9%, indicating that the devices were formed very uniformly. An actual image of the transparent-oxide TFTs constructed on a 20 × 30-mm glass plate is also shown in the inset in Fig. 4. The transparent-oxide TFTs were sufficiently transparent for the background letters under the surface of the plate to be identified.

IV. CONCLUSION

A novel mask reduction method where only two masks are needed to produce a bottom-gate transparent-oxide TFT has been proposed in this letter. The major aim of such two-mask process was to simultaneously form active layers, source–drain layers, and pixel electrodes via a single photolithography process by applying the GTM technique. The measured electrical characteristics of the transparent-oxide TFTs fabricated in this letter showed that they have functionally worked, with favorable levels of device indices.

REFERENCES