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Low Temperature Annealing with Solid-State Laser or UV Lamp Irradiation on Amorphous IGZO Thin-Film Transistors

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Instead of the conventional furnace annealing process with a temperature higher than 300°C, two low temperature annealing methods are successfully demonstrated to suppress the instability problem of amorphous indium gallium zinc oxide (IGZO) thin film transistors (TFTs). With adequate Nd:YAG laser and xenon lamp, annealing energy density or Xe excimer UV lamp irradiation time, the on voltage shift is greatly suppressed from over 10 to 0.1 V. The influence of laser energy density and UV lamp irradiation time on the performance of IGZO TFTs is also investigated and explained. The proposed methods are promising for the development of amorphous IGZO TFTs on flexible substrates.

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Recently, transparent amorphous InGaZnO₄ (IGZO) thin-film transistors (TFTs) have become promising candidates to realize flexible display on plastic substrates because they can be deposited at a temperature lower than 150°C. ¹ Compared to amorphous silicon TFT, IGZO TFT exhibits a higher mobility (3–30 cm²/V s) even in the amorphous phase. ² However, in many articles, low temperature deposited IGZO TFT suffers from significant instability problems. ³,⁴ Its current–voltage (I–V) characteristics shift during electrical measurement. To suppress the characteristics’ shift, furnace annealing higher than 300°C is usually used. It was reported that the annealing process reduces the tan δ defects, rearranges the amorphous structure, and improves oxygen compensation in the nonstoichiometric film. ⁵,⁶ However, an annealing temperature higher than 300°C makes the process unsuitable for flexible substrates. A low temperature annealing process is essential for the development of stable IGZO TFTs on flexible substrates.

One method utilizing excimer laser annealing (ELA) to improve IGZO TFT characteristics was proposed recently. ⁷ Although the authors did not mention stability issues, they successfully demonstrated the feasibility of using ELA on IGZO TFTs. In our study, two low temperature annealing methods are proposed to effectively solve the stability problem. One method is the solid-state Nd:YAG laser aluminum garnet (YAG) laser annealing method; the other method is a simple UV lamp irradiation method. The Nd:YAG solid-state laser operates at a wavelength of 266 nm, annealing the IGZO TFT at a low laser energy density of 10.7 mJ/cm². This low energy density enables the future design of a large laser beam size with a low production cost. To further reduce the production cost, another annealing process is proposed. This annealing process uses a low power (50 mW/cm²) Xe excimer lamp with a wavelength of 172 nm (UV light). The UV lamp irradiation effectively anneals the devices. The proposed method is a promising candidate to realize large-area, low cost UV lamp annealing for IGZO TFTs. In this article, the influences of laser energy density and UV lamp irradiation time on the performance and stability of IGZO TFTs are investigated. The bias-stress effects of an unannealed device, a laser-annealed device, and a UV-annealed device are also analyzed and compared.

Experimental

A bottom-gate top-contact structure was used in this study. Heavily doped p-type Si(100) was used as a substrate and as a gate electrode. 100 nm thick silicon nitride (SiN) deposited by low pressure chemical vapor deposition at 780°C was used as the gate dielectric. Then, a 35 nm thick amorphous InGaZnO₄ (a-IGZO) channel layer (3 in. circular target, In:Ga:Zn = 1:1:1 atom %) was deposited at room temperature by using a radio-frequency sputtering system with a power of 100 W, a working pressure of 0.5 Torr, and an Ar flow rate of 20 sccm. The active layer was patterned by using a shadow mask. Then, 100 nm thick Ti pads were deposited through a shadow mask to form the source and drain contacts. All devices exhibited a channel length (L) of 400 μm and a channel width (W) of 1000 μm. Finally, the samples were subjected to low temperature annealing. For Nd:YAG laser annealing, the laser beam passed through two frequency-doubling crystals to generate a laser beam at a wavelength (λ) of 266 nm. The pulse duration was 4 ns, the pulse frequency was 10 Hz, and the average energy density ranged from 10 to 25 mJ/cm². For UV lamp annealing, the wavelength and power density of the Xe excimer lamp are 172 and 50 mW/cm², respectively. Because UV light is easily absorbed by oxygen, the samples were annealed in an isolated chamber filled with nitrogen (N₂) to maintain the radiation intensity on samples. Based on the absorption coefficient spectrum of the a-IGZO film determined by a spectrometer (JASCO V-750, ranging from 200 to 1100 nm), the penetration depths for the 266 nm laser and for the 172 nm UV lamp were approximately 60 and 30 nm, respectively. The penetration depths were comparable to the active layer thickness (35 nm), indicating that the channel region near the dielectric/channel interface can possibly be directly treated by incident photons.

All electrical characteristics were measured by an Agilent 4156. The threshold voltage and mobility were extracted from the slope, and the x-axis intercept of the Iₓ versus Vᵧ curve was measured under saturation condition (Vₓ = 20 V, Vᵧ = 0 V, and Vᵧ was scanned from −15 to 20 V).

Results and Discussion

The transfer characteristics measured seven times in immediate succession for as-deposited a-IGZO TFTs are shown in Fig. 1a, while those for laser-annealed devices with annealing energy density of 10.7 mJ/cm² are shown in Fig. 1b. For the as-deposited a-IGZO TFTs, as shown in Fig. 1a, a significant deviation in the transfer characteristics is observed. For the laser-annealed devices (Fig. 1b) and for the UV-lamp-annealed devices (not shown), the deviation can be greatly suppressed. We define the threshold voltage Vᵧₐ as the gate voltage where the drain current starts to increase exponentially, ⁸ the deviation can be expressed by the shift of the on voltage (ΔVᵧₐ) between the first and the seventh measurements. The suppression of deviation by using laser annealing or UV lamp annealing is then investigated in Fig. 2 by plotting ΔVᵧₐ as a function of laser energy density (the bottom x-axis) or UV lamp irradiation time (the top x-axis). When laser energy density is higher than 10.7 mJ/cm² or when UV irradiation time is longer than 30 min, both annealing methods are effective in suppressing the deviation. It was reported that annealing helps relax the a-IGZO phase as well as introduce a new equilibrium by oxygen incorporation or by removal.

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of weakly bonded oxygen atoms from the film. The variation in oxygen content of a-IGZO significantly influences film conductivity. The conductivity obtained by four-point probe measurement as a function of laser energy density or UV lamp irradiation time is shown by triangles or circles in Fig. 2, respectively. When laser energy density is larger than 10.7 mJ/cm$^2$ or when UV lamp irradiation time is longer than 30 min, the conductivity of the IGZO film increases rapidly. A drastic variation from low conductivity to high conductivity occurs at a critical laser energy density (10.7 mJ/cm$^2$) or at a critical UV irradiation time. The influence of laser energy density on IGZO conductivity was also reported by Nakata et al. when they used a XeCl excimer laser to treat an IGZO film. In their article, increasing laser energy density also significantly increases IGZO conductivity, and a critical laser energy density such as 90 mJ/cm$^2$ is observed. The critical laser energy in their article is much larger than that in our experiment because a XeCl excimer laser (308 nm) has much poorer absorption in an IGZO film than a solid-state Nd:YAG laser (266 nm).

The transfer characteristics in the seventh measurements for the IGZO TFTs annealed at different laser energy densities are compared in Fig. 3a. For devices annealed at a laser energy density of as low as 10 mJ/cm$^2$, a large on voltage is observed because the laser energy density is not sufficient to stabilize the IGZO film. When the laser energy density increases to 10.7 mJ/cm$^2$, device stability is greatly improved while the leakage current remains low. The device exhibits a mobility of 8 cm$^2$/Vs, a threshold voltage of 0 V, a subthreshold swing of 0.3 V/dec, and an on/off current ratio larger than 7 orders. For devices annealed at a laser energy density of 14.2 mJ/cm$^2$, threshold voltage becomes negative and the leakage current increases. For a laser energy density higher than 19.9 mJ/cm$^2$, a conductive IGZO film shorts source and drain electrodes. The drastic change in device performance when laser energy density changes from 10 to 20 mJ/cm$^2$ reveals a narrow process window and a potential uniformity problem. Oxygen content is sensitive to laser energy density and causes a large difference in device characteristics even when the IGZO film remains as an amorphous thin film. The overlapping of a laser beam scan over a large-area thin film may further degrade uniformity.

A low cost, large-area UV lamp ($\lambda = 172$ nm), however, may avoid the uniformity issue raised by beam scanning in the laser annealing process. As shown in Fig. 3b, we successfully demonstrated that with a low power (50 mW/cm$^2$) UV lamp, IGZO TFT changed from an unstable transistor to a normal one, then to a conductive IGZO resistance by changing UV irradiation time from 10 to 180 min. The IGZO TFT annealed by 30 min UV-lamp irradiation exhibits a mobility of 3 cm$^2$/Vs, a threshold voltage of 0 V, a subthreshold swing of 0.55 V/dec, and an on/off current ratio larger than 6 orders. The device performance in this study is better than that of amorphous silicon TFTs and is good enough for display pixel design.

Finally, the bias-stress effect of the unannealed device, laser-annealed device, and UV-annealed device is studied. During stress, a 10 V gate bias is applied while source and drain are grounded. A threshold voltage shift with stress time is shown in Fig. 4. Data are analyzed by a standard fitting based on the stretched exponential
The very low relaxation time of the unannealed device represents a severe threshold voltage shift due to bias stress. To increase relaxation time without using any annealing process, an optimal deposition condition is usually required. However, the process window for the optimal deposition condition is usually very narrow. Moreover, along with time, the optimal deposition condition varies when the target composition varies due to the different sputtering rates of indium, gallium, and zinc.

It is therefore beneficial to develop an annealing process to control device stability and reliability regardless of the initial condition of the device. In this study, the initial device exhibits a very poor stability and reliability. After annealing, both laser-annealed device and UV-annealed device exhibit a relaxation time longer than 60,000 s, which is comparable to those reported (2 × 10^5–3 × 10^5 s) for a-IGZO TFTs.

The reliability of laser-annealed or UV-annealed a-IGZO TFT is expected to be further improved by employing suitable passivation together with annealing.

Conclusions

Absorbing high energy photons from a Nd:YAG pulse laser (266 nm) or a UV lamp (172 nm) is an effective approach to relax an a-IGZO structure, reduce defects, and suppress the instability in a-IGZO TFTs. The energy transferred from high energy photons, however, also helps to remove weakly bonded oxygen atoms from the film. Increased oxygen vacancies enlarge thin-film conductivity and increase bulk leakage current. With a proper process control, stable a-IGZO TFTs with good performances are successfully demonstrated.

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References