The Effects of H_2–O_2-Plasma Treatment on the Characteristics of Polysilicon Thin-Film Transistors

Horng Nan Chern, Chung Len Lee, and Tan Fu Lei

***Abstract*—The effects of H_2-plasma followed by O_2-plasma treatment on n-channel polysilicon TFT's were investigated. It was found that the H_2–O_2-plasma treatment is more effective in passivating the trap states of polysilicon films than do the H_2-plasma treatment only or the O_2-plasma treatment only. Hence, it is more effective in improving the device performance on the subthreshold swing, carrier mobility and the current ON/OFF ratio. It is also found that thermal annealing on plasma-treated devices increases the deep states but has no effect on the tail states of the devices.**

I. Introduction

POLYSILICON thin film transistors have been widely used in large-area electronic devices [1]. Recently, they have been studied for applying to higher density SRAM [2]. However, due to the high density of defect states at grain boundaries, polysilicon TFT's exhibit a poor performance such as a low mobility, a large subthreshold swing, a large threshold voltage and a large leakage current. Many techniques have been investigated to improve the performance of polysilicon TFT's. One of methods is to reduce the defect states of polysilicon by using the H_2-plasma treatment [3], [4] to passivate the grain boundaries. It had been found that the characteristics of polysilicon TFTs improves after the H_2-plasma treatment but the improvement reaches saturation [4], which limits the practical application of the H_2-plasma treatment because the performance of hydrogenated polysilicon TFT's is still much poorer than that of single-crystal Si MOSFET's. It had also been used to apply the O_2-plasma treatment to polysilicon resistors, but this treatment increased grain boundary trap-states and decreased the conductance of polysilicon [5]. However, it was reported that the treatment of O_2-plasma improved the performance of the P-channel polysilicon TFT when the device was succeedingly annealed in an H_2/N_2 ambient [6]. It had also been reported that a thermal annealing in the O_2 or $H_2 + O_2$ ambient after a passivation layer capping on polysilicon TFT improved the devices performance [6], [7]. Hence, the real role of oxygen in the improvement of polysilicon TFT's is not understood. It is suspected that the formation of the intergranular oxide within grain boundaries is the main reason to improve the performance since the device with a thermal gate-oxide exhibited a better performance than those with a deposited gate-oxide [9].

In this paper, the effects of H_2-plasma followed by O_2-plasma treatment (H_2–O_2-plasma) on polysilicon TFT's have been studied. It is found that by jointly applying the H_2-plasma and O_2-plasma treatments to polysilicon TFT's, the device performance is better than that with the H_2-plasma or the O_2-plasma treatment only. Experimental results also show that the treatment of the O_2-plasma did not exhibit the saturation phenomenon as observed in H_2-plasma-treated devices. Using the method of field effect conductance [8], it is found that the trap-state density can be effectively reduced by the H_2–O_2-plasma treatment, especially for the midgap deep-state. The thermal stability of plasma-treated devices was also studied. It is found that the degradation of the device performance after thermal annealing is due to the generation of the deep states.

II. Experiments

The polysilicon TFT's studied in this work were prepared as follows: Amorphous silicon films of a thickness approximately 1100 Å were deposited at 550°C by a low-pressure chemical vapor deposition (LPCVD) system on thermally oxidized silicon wafers. The wafers were then annealed at 550°C for 48 h to transform the deposited amorphous films to polysilicon. The grain size of the recrystallized polysilicon was about 0.25 μm as observed by using a transmission electron microscope (TEM). After defining the active islands, a 690 Å gate oxide was grown in dry O_2 at 1000°C. Another 3500 Å polysilicon film was then deposited at 625°C by the LPCVD system to be the gate electrode. After defining the gate geometry, a self-aligned phosphorus implantation of a dose of 5×10^{15} cm^{-2} was performed to form the source, drain and gate electrodes. The dopants were activated at 900°C for 30 min in an N_2 atmosphere. Some samples were subjected to the H_2/N_2 or/and the O_2 plasma treatment. This was done in a commercial 13.5 M Hz parallel-plate plasma reactor at 300°C with a power density of 0.7 W/cm^2.

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Then, all devices were covered with a 5000 Å plasma-enhanced chemical vapor deposition (PECVD) SiO_2 for passivation. Contact holes were opened, and Al was deposited and then patterned. In order to study the thermal stability of plasma-treated devices, some of the devices were annealed at 400°C for 30 min in an N_2 ambient.

The I–V characteristics of fabricated devices were measured by an HP4145B semiconductor parameter analyzer, and the device parameters: the threshold voltage (V_{th}), the subthreshold swing (S) and the field effect mobility (μ), were measured at $V_d = 0.1$ V. The threshold voltage is defined from the intercept on the voltage axis of the straight line in the drain current I_d versus the gate voltage V_g plot. The leakage current I_{off} is the minimum value of the drain current at $V_d = 5$ V. Using the linearly fitting of the ln (I_d) versus the $1/k \cdot T$ plot, where k is the Boltzmann constant and T is the temperature, the activation energy E_a of the drain current at different gate bias was deduced.

III. Results and Discussions

The I–V characteristics of n-channel polysilicon TFTs with a 60 min H_2-plasma, a 50 min H_2-plasma followed by a 10 min O_2-plasma, a 20 min H_2-plasma followed by a 40 min O_2-plasma and 60 min O_2-plasma treatments are shown in Fig. 1. The I-V curve of the device without the plasma treatment is also shown for comparison. It is seen that the Ho_2–O_2-plasma treatment had a better improvement effect on the devices than did the H_2-plasma treatment only or the O_2-plasma treatment only. It was performed on experiment by applying TFT devices the H_2–O_2-plasma for a total 60 min but varying the H_2-plasma exposure time from 0 to 60 min and measuring the change of the threshold voltage, the subthreshold, and the electron mobility of the devices. The results are shown in Fig. 2 in terms of the H_2-plasma exposure time. The experimental result revealed that all the devices with the H_2-plasma treatment followed by O_2-plasma treatment exhibited a better performance than those with the H_2-plasma treatment only or the O_2-plasma treatment only, and the device treated with a 20 min H_2-plasma followed by a 40 min O_2-plasma exhibited the best performance.

In order to obtain a clearer picture on the passivation effect of the H_2–O_2-plasma treatment, devices with the H_2-plasma treatment only and the O_2-plasma treatment only were also studied systematically. Fig. 3(a) and (b) show the change of the subthreshold swing and the electron mobility respectively of the devices with H_2-plasma treatment only and O_2-plasma treatment only as a function of the plasma-exposure time. It is found that the improvement of the H_2-plasma treatment on the devices saturates after a 50 min plasma treatment and further increasing the H_2-plasma-exposure time does not significantly improve the device. For O_2-plasma-treated devices, the performance improves with the plasma-exposure time up to 120 min. The mechanism for the saturated passivation phenomenon of H_2-plasma treatment might be due to that the grain boundaries act as hydrogen traps rather than diffusion paths [10]. After hydrogen atoms are trapped at the grain boundary, further H diffusions are impeded. Hence, the hydrogen passivation of grain boundaries in polysili-

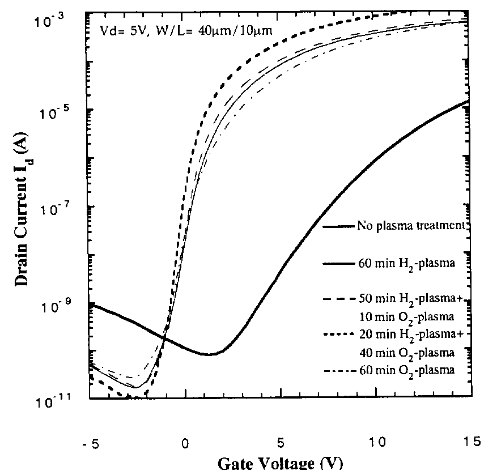


Fig. 1. I_d–V_g characteristics at $V_d = 5$ V of polysilicon TFT's with a 60 min H_2-plasma, a 50 min H_2-plasma followed by a 10 min O_2-plasma, a 20 min H_2-plasma followed by a 40 min O_2-plasma and a 60 min O_2-plasma treatment respectively. The I–V curve of the device without plasma treatment is also shown for comparison. All devices had a $W/L = 40$ μm/10 μm.

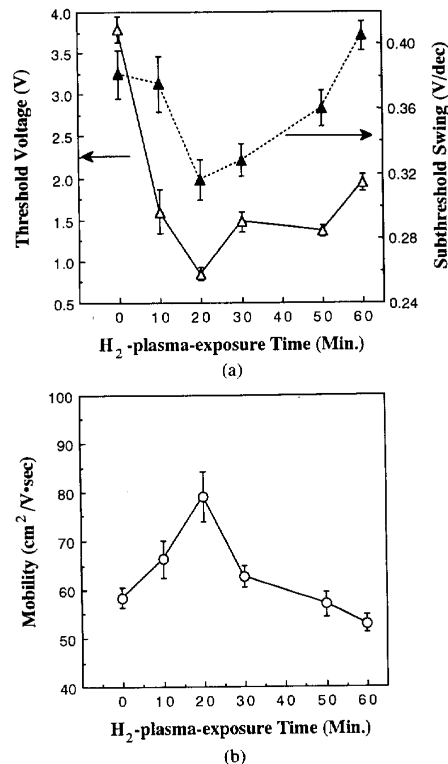


Fig. 2. (a) The threshold voltage and the subthreshold swing; and (b) the electron mobility for the H_2–O_2-plasma-treated devices as a function of the H_2-plasma-exposure time. The total plasma-exposure time was 60 min.

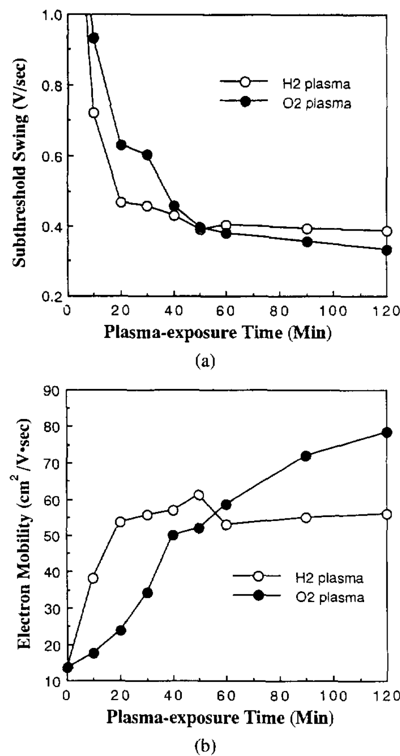


Fig. 3. (a) The subthreshold voltage; and (b) the electron mobility for the H_2-plasma-treated and the O_2-plasma-treated devices as a function of the plasma-exposure time.

con TFT's is saturated after a period of H_2-plasma treatment. From Fig. 3, the initial passivation rate is higher for the H_2-plasma treatment, while for the long plasma-exposure time (>60 min), the O_2-plasma-treated devices exhibit higher electron mobility than do the H_2-plasma-treated devices. In a previous work [6], it was report that O_2-plasma treatment can enhance the hydrogen effect to reduce the dangling bonds in the succeeding H_2/N_2 annealing step. However, our O_2-plasma-treated devices which were not annealed in an H_2/N_2 ambient also show the passivation effect. Hence, the passivation effect of the O_2-plasma treatment is caused by oxygen atoms themselves. It is believed that oxygen in polysilicon tends to segregate to grain boundaries and forms silicon-oxygen bondings [11]. If the concentration of oxygen in polysilicon is not high, the formation of silicon-oxygen bonding reduces the density of Si dangling bond, thereby reduces the density of trap states and the barrier potential [9]. The slower passivation rate of the O_2-plasma may be due to that the diffusivity of oxygen atoms in polysilicon is smaller than that of hydrogen atoms at 300°C.

From the above study, two possible mechanisms can be used to explain the further passivation effect of the O_2-plasma treatment following the H_2-plasma treatment. The first mechanism is the passivation effect of oxygen atoms themselves. The oxygen can form the bond Si–O–Si. This causes a different passivation effect from Si–H bonding

TABLE I

THE VALUES OF THE SUBTHRESHOLD SWING, THE ELECTRON MOBILITY, AND THE I_{on}/I_{off} RATIO OF POLYSILICON TFT'S WITH A 60 MIN H_2-PLASMA TREATMENT, A 120 MIN H_2-PLASMA TREATMENT AND A 60 MIN H_2-PLASMA FOLLOWED BY A 60 MIN O_2-PLASMA TREATMENT, RESPECTIVELY

Condition \ Parameters	S (V/dec)	Mobility (cm^2/V sec)	Ion/Ioff
60 min H_2 plasma	0.405	53	2.9×10^7
120 min H_2 plasma	0.387	56	1.2×10^8
60 min H_2 plasma+ 60 min O_2 plasma	0.290	111	6.7×10^8

on defects. The second mechanism is that it is suspected that the O_2-plasma further drive in the residual hydrogen, which was originally at the gate oxide, the source end, the drain end and the bottom oxide after the H_2-plasma, into the active channel region, and the O_2-plasma process could crack the residually inactive hydrogen (e.g., molecular hydrogen) to become active. The passivation effect is thus enhanced [13]. The improvement of H_2–O_2-plasma treatment over the H_2-plasma treatment is more apparent as the plasma-exposure time is increased. Table I complies the values of the device parameters after the devices had been subjected to a 60 min H_2-plasma, a 60 min H_2-plasma followed by another 60 min H_2-plasma, and a 60 min H_2-plasma followed by a 60 min O_2-plasma. The characteristics of the 60 min H_2-plasma-treated device with a further 60 min H_2-plasma treatment improved only slightly. The 60 min H_2-plasma followed by 60 min O_2-plasma-treated was the most effective in improving the device performance than a succeeding 60 min H_2-plasma treatment. A further 60 min O_2-plasma caused significant improvements, especially, on the electron mobility, and the drain current ON/OFF ratio.

It is generally recognized that the density of defect states in polysilicon is continuous across the forbidden band gap [12]. Many investigations have shown that the midgap deep-states and the exponentially distributed band tail-states affect the characteristics of polysilicon TFTs in different ways [4], [14], [15]. In this work, the method of field effect conductance [8] was used to determine the density of trap states in polysilicon. The results are shown in Fig. 4 for the 60 min H_2-plasma, the 60 min O_2-plasma, the 20 min H_2-plasma followed by 40 min O_2-plasma and without plasma-treated devices. It is clearly seen that all the plasma treatment reduce the tail-state and the deep-state density significantly. The H_2-plasma is more effective in reducing the tail-state density and the O_2-plasma is more effective in reducing the deep-state density, and the H_2–O_2-plasma treatment is the most effective in reducing the tail-state density. It is also found that the exponential slopes of the tail-state distribution curves become steeper after the plasma treatment. The extracted values of the exponential slope are 44 meV for the unpassivated devices, 30 meV for the H_2- or the O_2-plasma-treated devices and 23 meV for the H_2–O_2-plasma-treated devices. These values are close to values reported in the literature [8], [12]. The temperature dependence of the

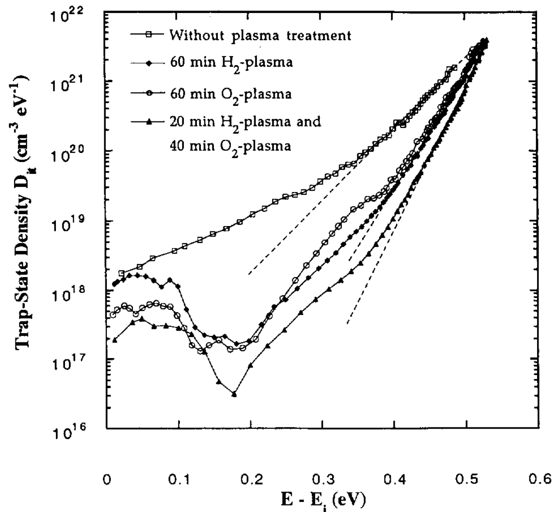


Fig. 4. The distributions of the trap-state densities measured by the field-effect-conductance method for the 60 min H_2-plasma- , the 60 min O_2-plasma- and the 20 min H_2-plasma followed by 40 min O_2-plasma-treated devices.

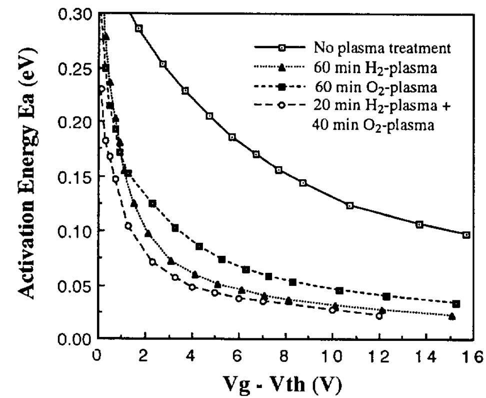
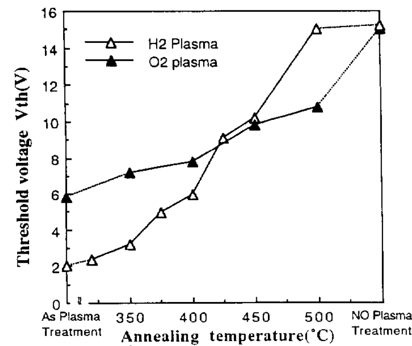


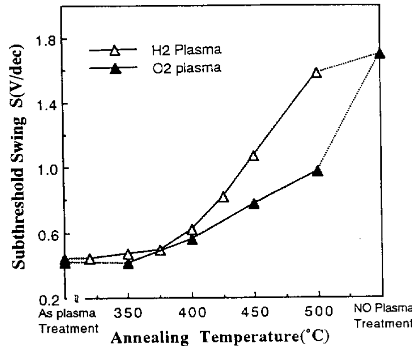
Fig. 5. The activation energies of the drain currents for the devices of Fig. 4 plotted in terms of V_g–V_{th}. Data were measured at V_d = 0.1 V in the temperature range from 20°C to 150°C.

drain currents of the H_2-plasma, the O_2-plasma- and the H_2–O_2-plasma-treat devices were also measured in the temperature range from 20°C to 150°C. The activation energies of the drain currents were derived and plotted in Fig. 5 in terms of V_g–V_{th}. The value of the activation energy reflects the carrier transport barrier of the grain boundary in the polysilicon channel. A smaller trap-state density gives smaller grain-boundary potential barrier and hence, a smaller activation energy of the drain current. It is seen that the H_2-plasma-treated device also has a smaller activation energy than that of the O_2-plasma-treated device while the H_2–O_2-plasma-treated device has the lowest activation energy.

The thermal stability of the devices after they were subjected to different plasma-treatments was also studied. Fig. 6(a) and (b) show the threshold voltage and the subthreshold swing of the H_2-plasma-treated and O_2-plasma-treated devices respectively, after they were subjected to annealings of temperature of 320°C to 500°C in an N_2 ambient. The H_2-plasma-treated devices exhibited a higher degradation rate than that of the O_2-plasma-treated devices. This may be due to that hydrogen has a weaker Si–H bond than the Si–O bond and a smaller effective mass than oxygen [16]. Table II lists the changes of the threshold voltage, the subthreshold swing, and the I_{off} of the H_2-plasma (60 min)-treated device, O_2-plasma (60 min)-treated device, and the H_2-plasma (20 min) followed by the O_2-plasma (40 min)-treated device, after they were annealed at 400°C for 30 min in N_2. In this table, the O_2-plasma-treated device has the best thermal stability, and the H_2–O_2-plasma-treated device and the H_2-plasma-treated device have the comparable stability. The $+\Delta V_{th}$ shift means that the V_{th} has increased by, for example, 1.38 V for the 60 min H_2-plasma-treated device after annealing. This increase in V_{th} is due to the dehy-



(a)



(b)

Fig. 6. Variations of (a) the threshold voltage and (b) the subthreshold swing of the 30 min H_2-plasma and the 30 min O_2-plasma-treated devices as a function of the annealing temperature. The annealing time was 30 min.

drogenation effect that the hydrogen released from the defect sites and caused the generation of trap states. The slight V_{th} decrease for O_2-plasma-treated devices after annealing may be due to the annealing-out of the plasma-induced damages [13]. For all the devices, thermal annealing decreased the I_{off}. This also may be due to that the thermal treatment had annealed the plasma-induced surface damage [13]. The degradation of the device perfor-

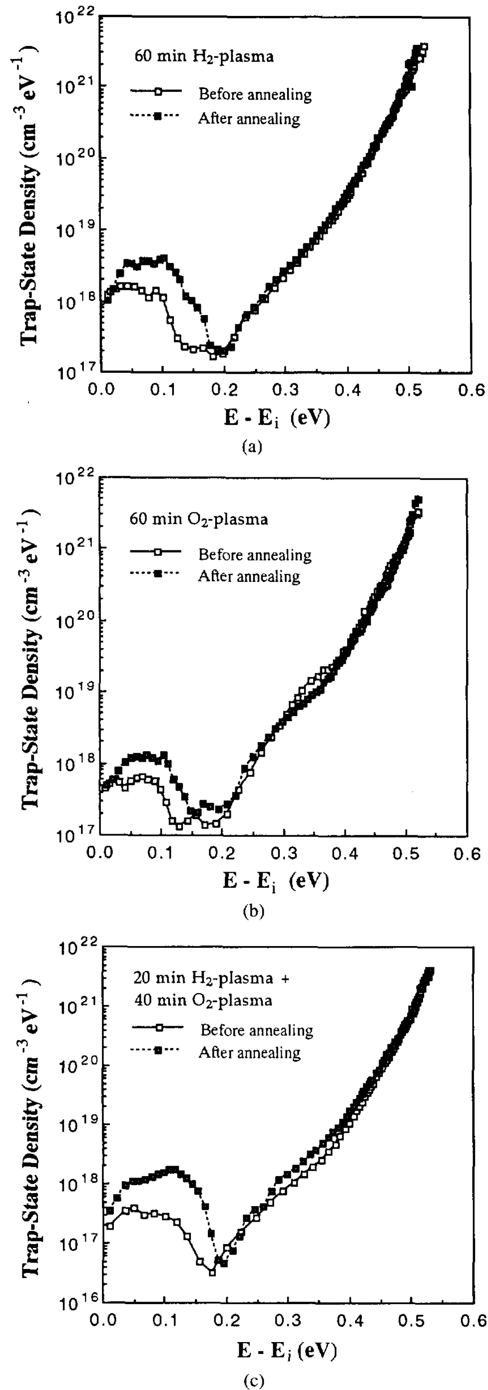


Fig. 7. The distributions of the trap-state densities before and after annealing at 400°C for 30 min for the devices with (a) a 60 min H_2-plasma treatment; (b) a 60 min O_2-plasma treatment; and (c) a 20 min H_2-plasma followed by a 40 min O_2-plasma treatment.

mance after annealing was found to be due to the generation of the deep state. Fig. 7(a)–(c) show the trap-state density distribution before and after annealing for the 60 min H_2-plasma-treated, the 60 min O_2-plasma-treated and the 20 min H_2-plasma followed by 40 min O_2-plasma-treated devices respectively. It is seen that after annealing, the deep states in the energy gap between the range of E_i + 0.05 eV and E_i + 0.15 eV increased for all plasma-treated devices, where E_i is the intrinsic Fermi-level of the polysilicon film. The tail-state density changed only slightly. Also in this figure, the O_2-plasma-treated device exhibited the least increment in the deep states. This is consistent with the result of Table II, where the O_2-plasma-treated device has the best thermal stability. It is also noted that, the deep states of the H_2–O_2-plasma-treated device were still lower than that of the H_2-plasma-treated device after the annealing.

TABLE II
THE INCREMENT OF THE THRESHOLD VOLTAGE, THE SUBTHRESHOLD VOLTAGE, AND THE LEAKAGE CURRENT AFTER ANNEALING AT 400°C FOR 30 MIN IN AN N_2 AMBIENT FOR THE DEVICES WITH A 60 MIN H_2-PLASMA TREATMENT, A 60 MIN O_2-PLASMA TREATMENT AND A 20 MIN H_2-PLASMA FOLLOWED BY A 40 MIN O_2-PLASMA TREATMENT, RESPECTIVELY. THE Δ IS DEFINED AS THE VALUE AFTER ANNEALING—THE VALUE BEFORE ANNEALING

Conduction / Parameter	60 min H2-plasma	60 min O2-plasma	20 min H2- and 40 min O2-plasma
ΔVth (V)	1.38	-0.28	1.11
ΔS (V/dec)	0.131	0.103	0.221
ΔIoff (pA)	-10.4	-25.6	-5.0

IV. CONCLUSION

In this paper, the effects of the H_2–O_2-plasma as well as the H_2- and O_2-plasma on the electrical characteristics of polysilicon TFT's have been studied. The H_2-plasma treatment followed by O_2-plasma treatment is much more effective to passivate grain-boundary trap-states in polysilicon films. The polysilicon TFT's with the H_2-O_2-plasma treatment exhibit consistently a superior performance than those with the H_2-plasma treatment only or the O_2-plasma treatment only. Two mechanisms are used to explain the passivation effect of the H_2–O_2-plasma treatment. One is the passivation effect by oxygen atoms themselves and the other is the enhanced passivation effect of existing hydrogen atoms to the polysilicon by the O_2-plasma. On the thermal stability, it is found that O_2-plasma-treated devices has the best thermal stability but the H_2-O_2-plasma-treated device exhibits a comparable thermal stability as the H_2-plasma-treated device. The thermal annealing on the plasma-treated devices increase the deep states, but has no effect on the tail states of the devices.

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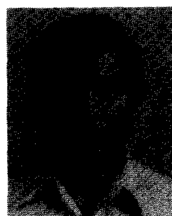

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