The Effects of H₂–O₂-Plasma Treatment on the Characteristics of Polysilicon Thin-Film Transistors

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

Abstract—The effects of H₂-plasma followed by O₂-plasma treatment on n-channel polysilicon TFT's were investigated. It was found that the H₂–O₂-plasma treatment is more effective in passivating the trap states of polysilicon films that do the H₂-plasma treatment only or the O₂-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 the methods is to reduce the defect states of polysilicon by using the H₂-plasma treatment [3], [4] to passivate the grain boundaries. It had been found that the characteristics of polysilicon TFT's improves after the H₂-plasma treatment but the improvement reaches saturation [4], which limits the practical application of the H₂-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 O₂-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 O₂-plasma improved the performance of the P-channel polysilicon TFT when the device was successively annealed in an H₂/N₂ ambient [6]. It had also been reported that a thermal annealing in the O₂ or H₂ + O₂ 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 H₂-plasma followed by O₂-plasma treatment (H₂–O₂-plasma) on polysilicon TFT's have been studied. It is found that by jointly applying the H₂-plasma and O₂-plasma treatments to polysilicon TFT's, the device performance is better than that with the H₂-plasma or the O₂-plasma treatment only. Experimental results also show that the treatment of the O₂-plasma did not exhibit the saturation phenomenon as observed in H₂-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 H₂–O₂-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 of 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 690Å gate oxide was grown in dry O₂ 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 x 10¹⁵ cm⁻² was performed to form the source, drain and gate electrodes. The dopants were activated at 900°C for 30 min in an N₂ atmosphere. Some samples were subjected to the H₂/N₂ or the O₂ 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/cm².
Then, all devices were covered with a 5000 Å plasma-enhanced chemical vapor deposition (PECVD) SiO2 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 N2 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 ($\mu$), 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 $I_{leak}$ 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 H2-plasma, a 50 min H2-plasma followed by a 10 min O2-plasma, a 20 min H2-plasma followed by a 40 min O2-plasma and 60 min O2-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 H2–O2-plasma treatment had a better improvement effect on the devices than did the H2-plasma treatment only or the O2-plasma treatment only. It was performed on experiment by applying TFT devices the H2–O2-plasma for a total 60 min but varying the H2-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 H2-plasma exposure time. The experimental result revealed that all the devices with the H2-plasma treatment followed by O2-plasma treatment exhibited a better performance than those with the H2-plasma treatment only or the O2-plasma treatment only, and the device treated with a 20 min H2-plasma followed by a 40 min O2-plasma exhibited the best performance.

In order to obtain a clearer picture on the passivation effect of the H2–O2-plasma treatment, devices with the H2-plasma treatment only and the O2-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 H2-plasma treatment only and O2-plasma treatment only as a function of the plasma-exposure time. It is found that the improvement of the H2-plasma treatment on the devices saturates after a 50 min plasma treatment and further increasing the H2-plasma-exposure time does not significantly improve the device. For O2-plasma-treated devices, the performance improves with the plasma-exposure time up to 120 min. The mechanism for the saturated passivation phenomenon of H2-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 polysilico-
From the above study, two possible mechanisms can be used to explain the further passivation effect of the O₂-plasma treatment following the H₂-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 on defects. The second mechanism is that it is suspected that the O₂-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 H₂-plasma, into the active channel region, and the O₂-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 H₂–O₂-plasma treatment over the H₂-plasma treatment is more apparent as the plasma-exposure time is increased. Table I compiles the values of the device parameters after the devices had been subjected to a 60 min H₂-plasma, a 60 min H₂-plasma followed by another 60 min H₂-plasma, and a 60 min H₂-plasma followed by a 60 min O₂-plasma. The characteristics of the 60 min H₂-plasma-treated device with a further 60 min H₂-plasma treatment improved only slightly. The 60 min H₂-plasma followed by 60 min O₂-plasma-treated was the most effective in improving the device performance than a succeeding 60 min H₂-plasma treatment. A further 60 min O₂-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 H₂-plasma, the 60 min O₂-plasma, the 20 min H₂-plasma followed by 40 min O₂-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 H₂-plasma is more effective in reducing the tail-state density and the O₂-plasma is more effective in reducing the deep-state density, and the H₂–O₂-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 unpasivated devices, 30 meV for the H₂- or the O₂-plasma-treated devices and 23 meV for the H₂–O₂-plasma-treated devices. These values are close to values reported in the literature [8], [12]. The temperature dependence of the
drain currents of the H₂-plasma, the O₂-plasma- and the H₂-O₂-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 H₂-plasma-treated device also has a smaller activation energy than that of the O₂-plasma-treated device while the H₂-O₂-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 H₂-plasma-treated and O₂-plasma-treated devices respectively, after they were subjected to annealings of temperature of 320°C to 500°C in an N₂ ambient. The H₂-plasma-treated devices exhibited a higher degradation rate than that of the O₂-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 H₂-plasma (60 min)-treated device, O₂-plasma (60 min)-treated device, and the H₂-plasma (20 min) followed by the O₂-plasma (40 min)-treated device, after they were annealed at 400°C for 30 min in N₂. In this table, the O₂-plasma-treated device has the best thermal stability, and the H₂-O₂-plasma-treated device and the H₂-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 H₂-plasma-treated device after annealing. This increase in $V_{th}$ is due to the dehydrogenation effect that the hydrogen released from the defect sites and caused the generation of trap states. The slight $V_{th}$ decrease for O₂-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 H₂-plasma treatment; (b) a 60 min O₂-plasma treatment; and (c) a 20 min H₂-plasma followed by a 40 min O₂-plasma treatment.

Performance 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 H₂-plasma-treated, the 60 min O₂-plasma-treated and the 20 min H₂-plasma followed by 40 min O₂-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 O₂-plasma-treated device exhibited the least increment in the deep states. This is consistent with the result of Table II, where the O₂-plasma-treated device has the best thermal stability. It is also noted that, the deep states of the H₂-O₂-plasma-treated device were still lower than that of the H₂-plasma-treated device after the annealing.

IV. Conclusion

In this paper, the effects of the H₂-O₂-plasma as well as the H₂- and O₂-plasma on the electrical characteristics of polysilicon TFT's have been studied. The H₂-plasma treatment followed by O₂-plasma treatment is much more effective to passivate grain-boundary trap-states in polysilicon films. The polysilicon TFT's with the H₂-O₂-plasma treatment exhibit consistently a superior performance than those with the H₂-plasma treatment only or the O₂-plasma treatment only. Two mechanisms are used to explain the passivation effect of the H₂-O₂-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 O₂-plasma. On the thermal stability, it is found that O₂-plasma-treated devices has the best thermal stability but the H₂-O₂-plasma-treated device exhibits a comparable thermal stability as the H₂-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.

REFERENCES


Horng Nan Chern was born in Tainan, Taiwan, Republic of China, on February 9, 1967. He received the B.S. degree in electrical engineering from National Cheng Kung University, Taiwan, in 1989. He is currently working towards the Ph.D. degree in the Department of Electronics Engineering at National Chiao Tung University. His research focuses on the fabrication and modeling of polysilicon thin-film transistors.

Chung Len Lee received the B.S. degree from National Taiwan University, Taiwan, R.O.C., and the M.S. and Ph.D. degrees from Carnegie-Mellon University, Philadelphia, PA, all in electrical engineering, in 1968, 1971, and 1975, respectively. He joined the Department of Electronic Engineering, National Chiao Tung University as a faculty member in 1975 and presently he is a Professor. His teaching and research have been in the areas of optoelectronics, integrated circuits and computer-aided-design. He was the director of Semiconductor Research Center of the university in 1980-1983 and has been the director of Submicron Professionals Training Center since 1989. He has supervised more than 120 papers in journals and conferences in the above areas.

Tan Fu Lei was born in Keelung, Taiwan, Republic of China, on September 17, 1944. He received the B.S. degree in the electrical engineering from National Cheng Kung University, Taiwan, in 1967 and the M.S. and Ph.D. degree in electronics engineering from National Chiao Tung University, Hsinchu, Taiwan, in 1970 and 1979, respectively. From 1970 to 1979, he was with the Fine Products Microelectronics Corporation, Taiwan, as an Engineer working on the fabrication of small-signal transistors. From 1980 to 1982, he was the Plant Manager of Photronic Corporation, Taiwan. In 1983, he joined the faculty at National Chiao Tung University as an Associate Professor in the Department of Electronics Engineering and the Institute of Electronics. From 1984 to 1986, he was the Director of the Semiconductor Research Center. Presently, he is a Professor of that department and the Associate Director of National Nano Device Laboratory. His research interests are semiconductor devices and optoelectronics.