Polycrystalline Silicon Thin-Film Transistors Fabricated by Defect Reduction Methods

H. Watakabe and T. Sameshima

***Abstract*—Fabrication of n-channel polycrystalline silicon thin-film transistors (poly-Si TFTs) at a low temperature is reported. 13.56 MHz-oxygen plasma at a 100 W, 130 Pa at 250 °C for 5 min, and heat treatment at 260 °C with 1.3×10^6-Pa-H_2O vapor for 3 h were applied to reduction of the density of defect states in 25-nm-thick silicon films crystallized by irradiation of a 30 ns-pulsed XeCl excimer laser. Defect reduction was numerically analyzed. Those treatments resulted in a high carrier mobility of 830 cm^2/Vs and a low threshold voltage of 1.5 V at a laser crystallization energy density of 285 mJ/cm^2.**

***Index Terms*—Carrier density, carrier mobility, defect, interface, H_2O vapor, laser crystallization, oxygen plasma.**

I. Introduction

POLYCRYSTALLINE silicon thin-film transistors (poly-Si TFTs) have been widely applied to fabrication of electronic devices. Low-temperature fabrication is attractive for introducing poly-Si TFTs to a device application, such as liquid crystal flat-panel display or organic electroluminescence display [1]–[3]. Pulsed laser crystallization and plasma enhancement chemical vapor deposition (PECVD) have been used for fabrication of poly-Si TFTs at low temperatures [4]–[9]. Inevitable grain boundaries among crystalline silicon grains can have electrically active defect states because of lattice disordering and dangling bonds. The defects reduce electrical current due to trapping carriers. One of most important problems on low-temperature fabrication of poly-Si TFTs is reduction of densities of those defect states. We have recently reported improvement of electrical properties of laser crystallized silicon films by oxygen plasma treatment as well as heat treatment with high-pressure H_2O vapor [10]–[14]. Those treatments effectively make defect states electrically inactive. Oxygen plasma treatment especially reduces the density of deep level states in the band gap due to oxidation of dangling bonds. High-pressure H_2O vapor heat treatment effectively reduces tail states. We have also reported that the combination of oxygen plasma treatment with H_2O vapor heat treatment reduces tail state as well as deep level states to low level at temperature below 300 °C [15].

In this paper, we report fabrication of poly-Si TFTs using defect reduction of heat treatments of oxygen plasma and high-pressure H_2O vapor. We apply those methods to polycrystalline silicon films formed by pulsed laser crystallization. We show that the defect reduction treatments are essential for a low threshold voltage and a high drain current with a high carrier mobility. We also analyze defect reduction behavior using an numerical calculation program to discuss the relation between the density of defects and the characteristics of poly-Si TFTs.

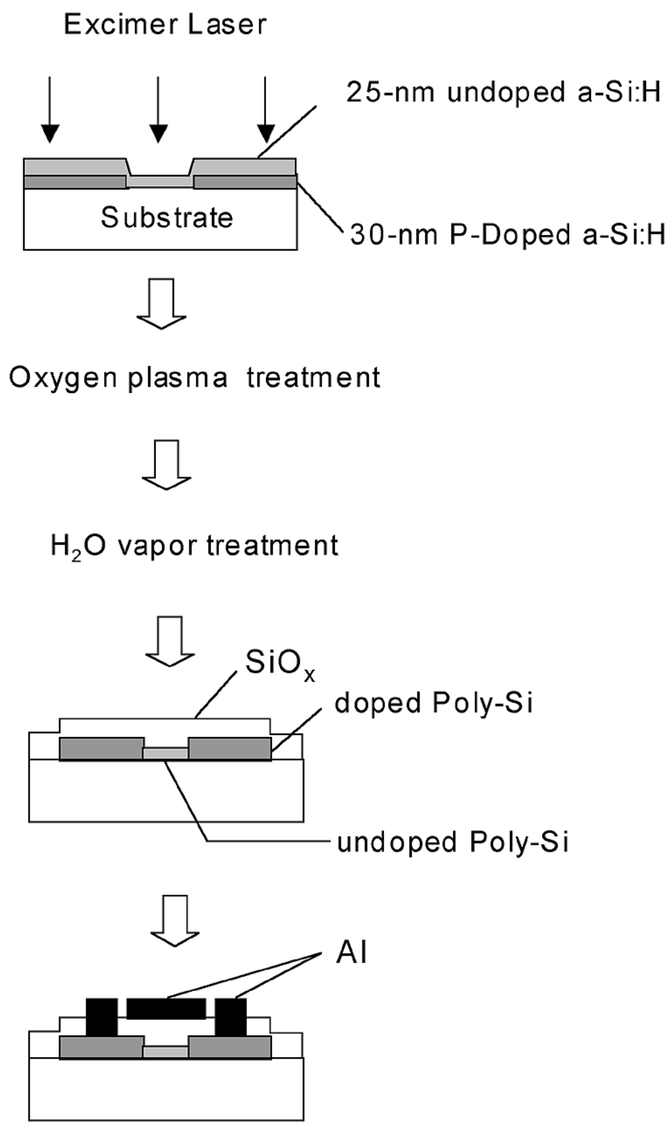

Fig. 1. Schematic process steps for fabrication of poly-Si TFTs.

II. Experimental

Fig. 1 shows fabrication process steps for present poly-Si TFTs. Hydrogenated amorphous silicon (a-Si:H) films doped with 7×10^{20} cm^{-3}-phosphorus and with a thickness of 30 nm

Manuscript received May 29, 2002; revised August 27, 2002. The review of this paper was arranged by Editor J. M. Vasi.

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Digital Object Identifier 10.1109/TED.2002.805234

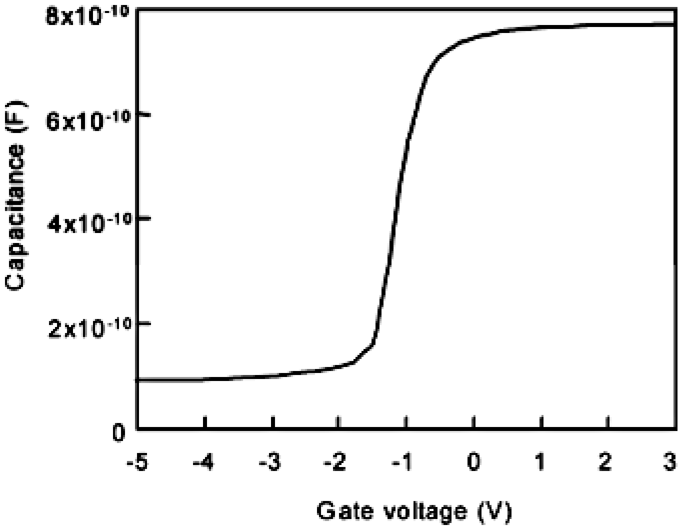


Fig. 2. Capacitance vs voltage characteristics with high frequency at 1 MHz for Al-gate MOS capacitors with 120-nm-thick SiO_x films for n-type substrates fabricated by thermal evaporation of SiO powders at room temperature in oxygen radical. The area of the Al electrodes is 0.01 cm^2.

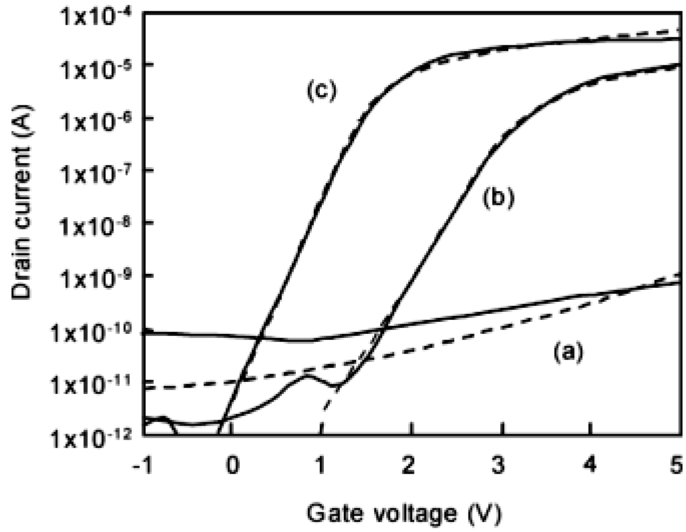


Fig. 3. Transfer characteristics for TFTs fabricated with (a) no oxygen plasma or no H_2O vapor heat treatments, (b) oxygen plasma treatment, and (c) additional H_2O vapor heat treatment. Dashed curves were calculated transfer characteristics which were obtained by a numerical calculation program.

were first formed on glass substrates at 330 °C using plasma enhanced chemical vapor deposition (PECVD). The doped films were removed at channel region with a length of 25 μm by etching and they were used as dopant sources for forming source and drain regions. A 25-nm-thick undoped a-Si:H films were then deposited using PECVD over the whole area. The silicon layers were crystallized at 250 °C in vacuum at 3×10^{-4} Pa by 30 ns-pulsed XeCl excimer laser. Multiple-step-laser energy irradiation was conducted in order to release hydrogen atoms from the films. The laser energy density was increased from 160 mJ/cm^2 (crystallization threshold) to 300 mJ/cm^2 with 50 shots. Undoped crystallized regions were used as the channel region. Source and drain regions were simultaneously formed through diffusion of phosphorus atoms into the overlaying silicon layer during the laser crystallization. The melt duration of silicon during laser crystallization was shorter than 100 ns so that the diffusion distance of the dopant atom was at most 60 nm in liquid silicon [15] and the 25-μm channel length hardly changed. Immediately after laser crystallization, the silicon films were treated with oxygen plasma at 250 °C for 5 min at a 13.56-MHz-RF power of 100 W at a gas pressure of 130 Pa in order to reduce defect density in polycrystalline silicon films. The oxygen plasma condition was determined by our investigation of the electrical conductivity with 7.4×10^{17}-cm^{-3}-phosphorus doped laser crystallized silicon with oxygen plasma treatment giving the highest electrical conductivity of 10 S/cm. Some samples were also annealed at 260 °C with 1.3×10^6 Pa H_2O vapor for 3 h for further defect reduction. The silicon films were then patterned by etching for isolation. The molecular beam deposition method was used for formation of the gate insulator. A 115–135-nm-thick SiO_x layers were deposited at room temperature as the gate insulator by thermal evaporation of SiO powders using Knudsen cell in oxygen radical at 1×10^{-2} Pa, which was generated by 300 W induction coupled remote plasma equipment [17]. Fig. 2 shows capacitance responses with the gate voltage with frequencies of 1 MHz for Al gate metal-oxide-semiconductor (MOS) capacitors with the present SiO_x. A sharp capacitance transition was observed. From the curve of capacitance versus gate voltage, the specific dielectric constant of the SiO_x layer, the densities of interface traps and fixed oxide charges were estimated to be 8.7, 3.9×10^{11} $cm^{-2}eV^{-1}$ and 4.5×10^{11} cm^{-2}, respectively, for MOS capacitors when the work function of Al gate metal was 4.3 eV. The high specific dielectric constant of 8.7 results from high dielectric-dispersion characteristic at low-frequency regime compared with that of thermally grown SiO_2, 3.9, while the specific dielectric constant was 2.16 in the visible wavelength range, which was almost the same as that of thermally grown SiO_2. The high dielectric-dispersion characteristic was probably caused by bonding distortion of Si-O associated with lack of oxygen atoms in the SiO_x films [13]. In the TFT fabrication process, contact holes were then opened in the SiO_x layer on the source and drain regions. Gate, drain, and source electrodes were formed with Al metals. No additional heat treatment was carried out after TFT fabrication. Room temperature fabrication of gate oxide layers and metal electrodes made it possible to investigate the relation between the quality of polycrystalline silicon films and TFT characteristics.

III. Results and Discussion

Fig. 3 shows transfer characteristics of TFTs fabricated at 285 mJ/cm^2-laser crystallization with (a) no oxygen plasma or no H_2O vapor heat treatments, (b) oxygen plasma treatment, and (c) additional H_2O vapor heat treatment TFTs had a gate width of 80 μm and a gate length of 25 μm. The transfer characteristics were measured at a drain voltage 0.1 V. Very low drain current with a high threshold voltage was measured for TFT with no defect reduction treatment, as shown by curve (a) in Fig. 3. This means that highly dense defect states in the channel region of polycrystalline silicon made the density of free electron low because of carrier trap under the gate voltage application ranging from 0 to 5 V. On the other hand, sharp increase in the drain current was observed for TFT with oxygen plasma treatment, as shown by curve (b) in Fig. 3. The threshold voltage V_t and the effective carrier mobility μ were estimated from the linear relation between gate voltage and drain current, as follows:

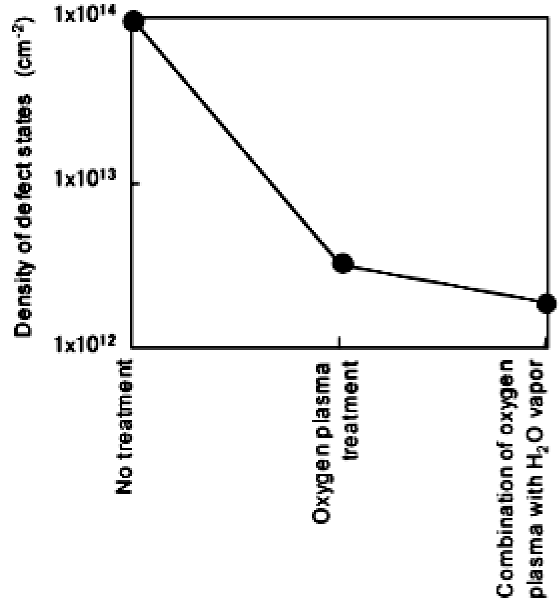
$$V_t = V_g - \frac{V_d}{2} - I_d \left(\frac{\partial I_d}{\partial V_g}\right)^{-1}$$
$$\mu = \left(\frac{W}{L} C_{\mathrm{ox}} V_d\right)^{-1} \frac{\partial I_d}{\partial V_g} \qquad (1)$$

where

V_g and V_d gate voltage and the drain voltage, respectively;
I_d drain current;
W and L gate width and the gate length, respectively;
C_{ox} gate capacitance, which was obtained by C-V measurements.

The threshold voltage and the effective carrier mobility were 3.2 V and 251 cm^2/Vs at maximum, respectively. According to our previous study [11], defect states associated with dangling bonds are localized at grain boundaries. They are reacted by oxygen atoms diffused into silicon films. The dangling bonds are terminated and SiO bondings are probably formed. Consequently defect states are changed electrically inactive. The additional high-pressure H_2O vapor heat treatment to polycrystalline silicon films further improved characteristics of TFTs, as shown by curve (c) in Fig. 3. The drain current increased at low gate voltage. The threshold voltage decreased to 1.5 V. The peak effective carrier mobility increased to 830 cm^2/Vs. This result indicates that electrical properties were further improved by the high-pressure H_2O vapor heat treatment. Defect states localized at grain boundaries for laser crystallized silicon films are reacted with H_2O molecules incorporated into silicon films. H_2O molecules at defect sates would be chemically dissociated with the help of heating energy. The dangling and weak bonds of silicon atoms were probably eliminated through the formation of Si-O, Si-OH, or Si-H bonds.

In order to estimate the density of defect states in polycrystalline silicon films as well as SiO_2/Si interfaces, transfer characteristics were analyzed using a numerical calculation program used with finite-element method combined with statistical thermodynamical conditions with defect states localized at SiO_2/Si interfaces as well as silicon films [18], [19]. We introduced the deep-level defect states localized at the mid gap, which had a Gaussian-type energy distribution was assumed. Tail-state-type defect states were also introduced. The density exponentially decreased from the conduction band as well as valence band edges to deep energy level symmetrically in the band gap. The defect states were placed spatial-uniformly in the silicon films. The density of defect states at SiO_2/Si interfaces was determined by C-V measurements of MOS capacitors. The best agreement of calculated transfer characteristics to experimental ones resulted in the defect states. Dashed curves shown in Fig. 3 are calculated transfer characteristics best fitted to experimental curves. The numerical analysis gave the density of defect states in silicon films, as shown in Fig. 4(a),



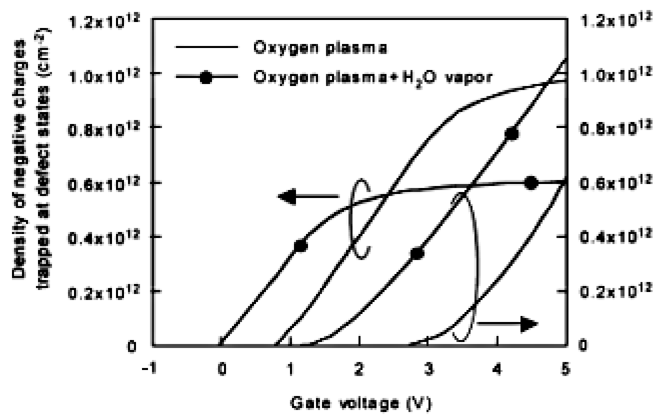


Fig. 4. (a) Change in the density of unoccupied defect states in the flat-band condition with defect reduction steps. (b) Calculated electron carrier density and the density of the negative charges trapped at defect states for TFTs fabricated with oxygen plasma treatment and combination of oxygen plasma with high-pressure H_2O vapor heat treatment.

which was defined as the density of unoccupied-acceptor type defect states in the flat-band condition. A high density of defect states of 1.0×10^{14} cm^{-2} was estimated for TFTs fabricated with no defect reduction treatments. The defect density was reduced to 3.1×10^{12} cm^{-2} by the oxygen plasma treatment after laser crystallization at 285 mJ/cm^2. It further decreased to 1.9×10^{12} cm^{-2} after the high-pressure H_2O vapor heat treatment. Oxygen plasma treatment effectively reduces the high density of defect states at 1×10^{14} cm^{-2} to 3.1×10^{12} cm^{-2} because of effective oxidation of dangling bonds. On the other hand, the high-pressure H_2O vapor heat treatment further reduced the density of defect states. Oxygen plasma would cause plasma damage especially at surface region during plasma treatment. We believe the high-pressure H_2O vapor heat treatment after oxygen plasma would reduce defects caused by oxygen plasma as well as residual defects in the silicon films. Oxygen plasma followed by H_2O vapor treatments will be therefore effective to reduce the density of defect states. Fig. 4(b) shows the calculated density of the negative charges trapped at defect states, N_t, and the calculated electron carrier density, N_e, in the silicon films, which are caused by the gate voltage application, as functions of the gate voltage for TFTs fabricated with oxygen plasma treatment and combination of oxygen plasma with high-pressure H_2O vapor heat treatment. In the case of the oxygen plasma treatment, N_t proportionally increased as the gate voltage increase up to the threshold voltage of 3.2 V. On the other hand, N_e was very low. Most of charges caused by gate voltage application were trapped at the defect states for the low gate voltage regime. N_e significantly increased when the gate voltage was above 3.2 V. Free carriers appear when the defects are filled with negative charges near the SiO_2/Si interface for the gate voltage above the threshold. N_t almost leveled off at 9.6×10^{11} cm^{-2} at a gate voltage above 5.0 V. It was lower that that of the density of defect states shown in Fig. 4(a). Band bending caused by gate voltage application allowed defect states occupied near the SiO_2/Si interface. This result clearly shows the drain current is governed by the density of defect states. Reduction of the density of defect states is essential to improve TFT performances. N_t saturated at 6.0×10^{11} cm^{-2} and N_e increased for gate voltage above 1.5 V in the case of the combination of oxygen plasma with high-pressure H_2O vapor heat treatment, as shown in Fig. 4(b) because the treatments effectively reduced the density of defect states in silicon films.

Fig. 5 shows (a) the carrier mobility and (b) the threshold voltage as a function of laser energy density. The effective carrier mobility increased and the threshold voltage decreased by the defect reduction treatments applied to silicon films for every laser energy condition. TFTs fabricated with oxygen plasma treatment had a carrier mobility of 251 cm^2/Vs at maximum and a threshold voltage of 2.8 V at minimum. On the other hand, the combination of oxygen plasma with high-pressure H_2O vapor heat treatment resulted in a high carrier mobility of 200 cm^2/Vs was achieved at the low laser energy density of 250 mJ/cm^2 although the average grain size was as small as 40 nm. The carrier mobility gradually increased to 830 cm^2/Vs as the laser energy density increased to 285 mJ/cm^2, as shown in Fig. 5(a). The increase in the effective carrier mobility is interpreted as increase of the crystalline volume ratio with increasing the laser energy density [20] because increase of the crystalline volume ratio results in increase of the electrical conductance in the channel region. The grain size also increased as the laser energy increased, but it was smaller than 100 nm according to our previous study [21]. The high carrier mobility of 830 cm^2/Vs probably resulted from the mobility-enhancement effect due to reduction of the effective mass in tensile-strained silicon. Mizuno *et al.* demonstrated an 40% enhancement of the electron carrier mobility for n-channel metal-oxide-semiconductor-field-effect transistors (MOSFETs) fabricated in strained silicon layers grown on silicon germanium layers. They determined that the strain silicon had tensile stress at 4.6×10^8 Pa [22]. On the other hand, the laser crystallized silicon thin films formed on glass substrates have a high tensile stress $\sim 10^9$ Pa [23], [24], which would be high enough to increase the bulk drift mobility. We believe that the mobility enhancement was achieved for poly-Si TFTs fabricated in the strained polycrystalline silicon fillms. The threshold voltage ranged between 1.4 and 1.8 V, as shown in Fig. 5(b). It did not seriously depend on the laser energy density. For laser energy density above 290 mJ/cm^2, microcrystallization occurs because of rapid solidification associated with super-cooled liquid state. In microcrystallziation sates, grain size is smaller than 10 nm and disordered amorphous states are seriously formed. Crystalline volume ratio is very small. Electrical conductance is not increased by defect reduction under this states. Those experimental results shows the possibility of fabrication of TFTs with a high carrier mobility and a low threshold voltage in polycrystalline silicon films with small crystalline grains when the density of defect states are reduced low enough.

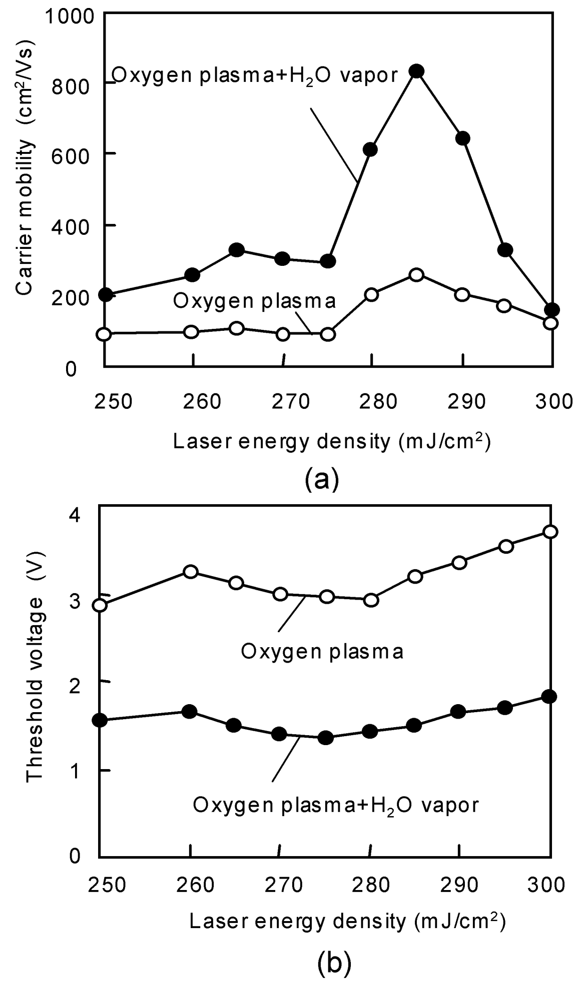


Fig. 5. (a) Effective carrier mobility and (b) threshold voltage as a function of laser energy density for TFTs fabricated with oxygen plasma treatment and combination of oxygen plasma with high-pressure H_2O vapor heat treatment.

IV. Conclusion

The defect reduction treatment was investigated for fabrication of n-channel poly-Si TFTs at low temperatures. 13.56 MHz-oxygen plasma at a 100 W, 130 Pa at 250 °C for 5 min, and heat treatment at 260 °C with 1.3×10^6-Pa-H_2O vapor for 3 h were applied to reduction of the density of defect states in 25-nm-thick silicon films crystallized by irradiation of a 30 ns-pulsed

XeCl excimer laser. The SiO_x layers formed at room temperature by molecular beam deposition in oxygen radical was used as gate insulator. The density of unoccupied defect states was reduced to 1.9×10^{12} cm^{-2} and the density of negative charges trapped at defects caused by the gate voltage application 6×10^{11} cm^{-2} when the oxygen plasma treatment followed by high-pressure H_2O vapor were applied to silicon films crystallized at 285 mJ/cm^2.

The combination of the oxygen plasma treatment with the high-pressure H_2O vapor heat treatment resulted in the high carrier mobility and the low threshold voltage. It was 200 cm^2/Vs for TFTs with silicon films crystallized at 250 mJ/cm^2. It increased to 830 cm^2/Vs as the laser energy density increased to 285 mJ/cm^2. The threshold voltage ranged from 1.4 V to 1.8 V, which did not seriously depend on the laser energy density. These results indicate that defect reduction is essential for fabrication of poly-Si TFTs with high performance.

ACKNOWLEDGMENT

The authors thank T. Sturutz, T. Oitome, S. Higashi, M. Kimura, T. Mohri, and T. Saitoh for their support.

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