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Improvement in Characteristics of Polycrystalline Silicon Thin-Film Transistors by Heating with High-Pressure H_2O Vapor

Toshiyuki SAMESHIMA, Mitsuru SATOH, Keiji SAKAMOTO, Kentaro OZAKI and Keiko SAITOH
Tokyo University of Agriculture and Technology, 2-24-16 Nakamachi, Koganei, Tokyo 184-8588, Japan

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A heat treatment with high-pressure H_2O vapor at temperatures of 190 °C to 270 °C was applied to improve the characteristics of n-channel polycrystalline silicon thin-film transistors. The heating at 190 °C with 3.6×10^5 Pa H_2O vapor increased the carrier mobility from 50 $cm^2V^{-1}\cdot s^{-1}$ (as fabricated) to 412 $cm^2V^{-1}\cdot s^{-1}$ and reduced the threshold voltage from 2.2 V to 1.1 V. The drain current at negative gate voltages caused by the heating with high-pressure H_2O vapor was reduced by additional heating at 300 °C as well as at 350 °C with H_2O vapor at one atmospheric pressure. This annealing process resulted in an on/off drain current ratio of 10^7.

KEYWORDS: LPCVD, laser crystallization, remote plasma CVD, fixed oxide charge, SiO_2/Si interfaces

The fabrication of polycrystalline silicon thin-film transistors (poly-Si TFTs) at low temperatures is attractive for many device applications because it enables fabrication of electronic devices at a low cost on a large substrate. There have been many reports on the technologies for the low temperature fabrication of high-performance poly-Si TFTs.[1–7] We reported that heat treatment at temperatures around 300 °C with high-pressure H_2O vapor improves SiO_2 bulk properties and SiO_2/Single-crystalline Si interfaces.[8] The heat treatment markedly reduces the density of the fixed oxide charges in SiO_2 films as well as the density of trap states of SiO_2/Si. Moreover, we recently revealed that the densities of defect states in amorphous silicon films as well as poly-Si films are reduced by heat treatment with high-pressure H_2O vapor at temperature above 190 °C.[9]

In this study, we demonstrate a possibility of improving the characteristics of poly-Si TFTs by heat treatment at low temperatures with high-pressure H_2O vapor. An increase in the carrier mobility by the heat treatment is observed. Heating with high-pressure H_2O vapor followed by that with one atmospheric pressure H_2O vapor realizes a high on/off drain current ratio.

Top-gate-type n-channel poly-Si TFTs were fabricated by pulsed laser crystallization using 30 ns pulsed XeCl excimer laser. Islands of 20-nm-thick hydrogenated amorphous silicon films doped with 2 atomic% phosphorus were first formed on a glass substrate at 250 °C using conventional plasma-enhanced chemical vapor deposition (PECVD) and an etching method as dopant sources for the formation of source and drain regions. Undoped a-Si:H films 20 nm thick were then deposited using PECVD over the entire substrate. Island patterning was conducted by etching the amorphous layers. The silicon layers were crystallized by laser irradiation in vacuum to form undoped and doped poly-Si regions. In order to realize a smooth surface by slowly desorbing hydrogen from a film, irradiation with multiple energy steps was performed.[10] The laser energy was controlled up to 210 mJ/cm^2, which was below the amorphization threshold (240 mJ/cm^2) for 20-nm-thick films. Laser heating induced the diffusion of dopant atoms from the underlying doped region vertically through the entire thickness of the Si layers so that doped poly-Si regions as well as undoped poly-Si regions were formed. A triode-type remote plasma CVD was used to form 160-nm-thick SiO_2 films.[7] Through the decomposition of SiH_4 gas by oxygen and helium radicals, SiO_2 films were formed on a substrate heated at 250 °C. Then, Al gate, source and drain electrodes were formed.

The TFT samples were placed into a pressure-proof stainless-steel chamber with a volume of 60 cm^3 using a metal seal. Pure water of 0.1 cm^3 was also introduced into the chamber. The chamber was then placed on a resistive heater plate for heating the sample at 190 °C, 230 °C and 270 °C for 1 h with H_2O as well as air inside the chamber. H_2O was evaporated during the heating process and the gas pressure was increased to 3.6×10^5 Pa, 3.9×10^5 Pa and 4.2×10^5 Pa for the above-mentioned temperatures, respectively. These conditions were determined from the changes in electrical and optical properties of poly-Si films caused by heating with high-pressure H_2O vapor reported elsewhere.[9] Heat treatment was also carried out at 300 °C and at 350 °C in a quartz belljar filled with H_2O vapor of almost one atmospheric pressure ($\sim1.0\times10^5$ Pa).

Figure 1 shows the transfer characteristics of the TFTs as fabricated (curve a) and annealed at 190 °C with 3.6×10^5 Pa H_2O vapor (curve b). The high-pressure H_2O vapor heating increased the drain current at positive gate voltages. This means that the carrier mobility was increased by the heat treatment. However, the drain current also increased at negative gate voltages. The drain current at negative gate voltage was effectively reduced by additional heating with H_2O vapor of one atmospheric pressure at 300 °C for1 h followed by a second heating at 350 °C for1 h, as shown respectively by curves (c) and (d) in Fig. 1. The on-state drain current showed almost the same output characteristics as the high drain current immediately after the high-pressure H_2O vapor heating and after the additional heat treatments with H_2O vapor of one atmospheric pressure.

The same heating process with high-pressure H_2O vapor and one atmospheric pressure H_2O vapor was applied to TFTs at different heating temperatures of 230 °C and 270 °C. We observed an increase in drain current at positive and negative gate voltages, which is induced by heat treatment with high-pressure H_2O vapor at each heating temperature and is similar to the case of the 190 °C heating treatment, as shown in Fig. 1. The reduction of the drain current at negative gate voltages was also achieved by subsequent heating with H_2O vapor of one atmospheric pressure at 300 °C and then at 350 °C.

Figure 2 shows changes in the carrier mobility (a) and the threshold voltage (b) with heat treatment with high-pressure H_2O vapor at 190 °C, 230 °C and 270 °C, and the subsequent

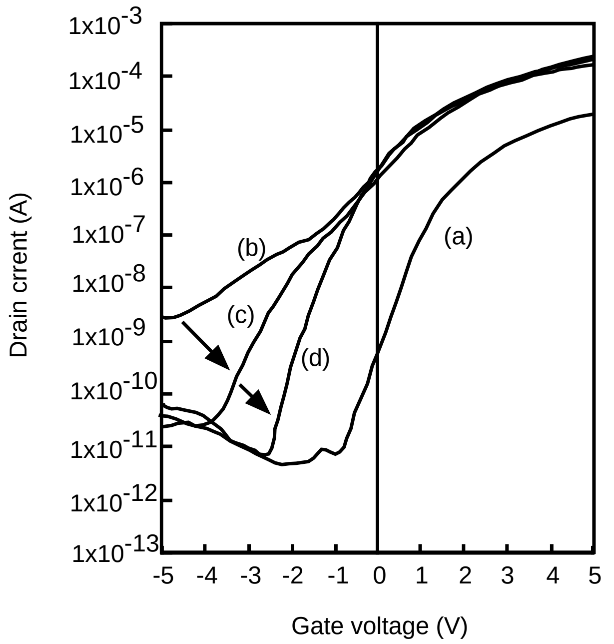

Fig. 1. Transfer characteristics of the TFTs as fabricated (curve a), annealed at 190 °C with 3.6×10^5 Pa H_2O vapor (curve b), additional heating at 300 °C for1 h with H_2O vapor of one atmospheric pressure (curve c), followed by heating at 350 °C for 1 h in H_2O vapor of one atmospheric pressure (curve d). The drain voltage was 1 V. The ratio of channel width to channel length (W/L) was 5. The thickness of the gate SiO_2 insulator was 160 nm.

heat treatment with H_2O vapor of one atmospheric pressure at 300 °C and then 350 °C. The carrier mobility and the threshold voltage were estimated using the relationship between drain current (I_d) and the gate voltage (V_g) in the linear region, which is given by

$$I_d = \frac{W}{L} C_{ox} \mu \left(V_g - V_t - \frac{V_d}{2} \right) V_d, \tag{1}$$

where W is the channel width, L is the channel length, C_{ox} is the gate capacitance per unit area, μ is the carrier mobility, V_t is the threshold voltage and V_d is the drain voltage. From the experimental data, the threshold voltage was determined to have a maximum value of

$$V_g - \frac{V_d}{2} - I_d \left(\frac{\partial I_d}{\partial V_g} \right)^{-1}.$$

The carrier mobility was determined to have a value of

$$\left(\frac{W}{L} C_{ox} V_d \right)^{-1} \frac{\partial I_d}{\partial V_g}$$

at a gate voltage of 2 V above the threshold voltage.

The carrier mobility increased with the high-pressure H_2O vapor heating treatment for all each heating temperatures, as shown in Fig. 2(a). The highest mobility of 412 $cm^2V^{-1}{\cdot}s^{-1}$ was obtained for the case of 190 °C-heat treatment. The mobility remained almost constant even after heating at 300 °C and at 350 °C with H_2O vapor of one atmospheric pressure. We believe that the density of defects located around the grain boundaries at poly-Si and SiO_2/poly-Si interfaces was effectively reduced by the heat treatment. However, the high-temperature heat treatments at 230 and 270 °C resulted in a smaller increase in carrier mobility compared with the 190 °C heat treatment case. In particular, the mobility decreased to 120 $cm^2V^{-1}{\cdot}s^{-1}$ by the heat treatment at 300 °C and at 350 °C with H_2O vapor of one atmospheric pressure for the case of the initial 270 °C heat treatment with high-pressure H_2O vapor. Although the reason for this is unclear, we hypothesize that oxygen incorporation in silicon films or oxidation of silicon films would proceed especially at grain boundaries during the heat treatment at a high temperature because the high-pressure H_2O vapor heating at 300 °C has a strong oxidation effect.[8] Moreover, the additional heat treatment might enhance the oxidation of silicon films by the incorporated oxygen atoms. Because the degree of oxygen incorporation was probably serious for the 270 °C heat treatment case, the ef-

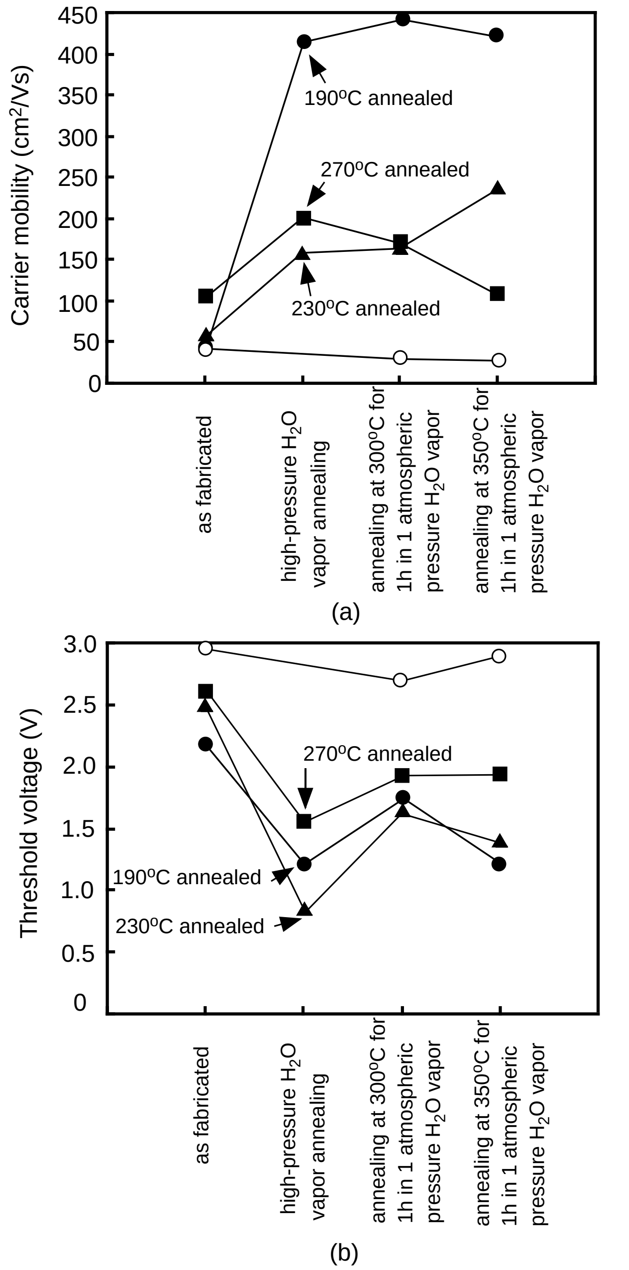

Fig. 2. Changes in the carrier mobility (a) and the threshold voltage (b) with heat treatment with high-pressure H_2O vapor at 190 °C, 230 °C and 270 °C and the additional heat treatments with H_2O vapor of one atmospheric pressure at 300 °C and at 350 °C. Changes in the carrier mobility and the threshold voltage with no heat treatment with the high-pressure H_2O vapor are also shown by open circles.

fective mobility could only have a low value even if defect density reduction were achieved. For the 230 °C heat treatment case, an increase in carrier mobility was observed after heat treatment with H_2O vapor of one atmospheric pressure. We assume that the electrical properties at the SiO_2/poly-Si interface were further improved by the additional heat treatment in that case. On the other hand, the carrier mobility did not increase from the initial value when TFTs were subjected only to heatings with H_2O vapor of one atmospheric pressure, as shown by the open circles in Fig. 2(a).

The threshold voltage was reduced by the heat treatment with high-pressure H_2O vapor as shown in Fig. 2(b). In particular, it was lower than 1.5 V for the case of heating with high-pressure H_2O vapor at 190 °C and 230 °C. An increase in drain current at negative gate voltages, which was caused by the high-pressure H_2O vapor heat treatment, was observed. This may have resulted from the local and partial generation of fixed charges in the SiO_2 gate oxide layer for the SiO_2/poly-Si layered structure. The characteristics of the depletion mode, therefore, would have appeared in addition to the enhancement transfer characteristics such that the drain current at negative gate voltages increased. Thus, the reduction of the threshold voltage caused by the high-pressure H_2O vapor heating probably resulted from the reduction of the density of the interface trap states and an increase in the density of fixed charges. The heat treatments at 300 °C and 350 °C in H_2O vapor of one atmospheric pressure effectively reduced the density of the fixed charges in SiO_2. The characteristic of the depletion mode was therefore reduced and consequently, the threshold voltage was increased slightly. The heating process with H_2O vapor of one atmospheric pressure resulted in a low off drain current. The highest on/off drain current ratio of $\sim 10^7$ was obtained for the heat treatments at 190 °C and 230 °C with the high-pressure H_2O vapor and the subsequent heat treatment at 300 °C and 350 °C with H_2O vapor of one atmospheric pressure.

Heat treatment with high-pressure H_2O vapor at temperatures ranging from 190 °C to 270 °C was investigated to improve n-channel poly-Si TFTs characteristics. The heating at 190 °C with 3.6×10^5 Pa H_2O vapor increased the carrier mobility from 50 $cm^2V^{-1}\cdot s^{-1}$ (as fabricated) to 412 $cm^2V^{-1}\cdot s^{-1}$ and reduced the threshold voltage from 2.2 V to 1.1 V. The carrier mobility increased by the heat treatment decreased from 412 $cm^2V^{-1}\cdot s^{-1}$ to 200 $cm^2V^{-1}\cdot s^{-1}$ as the heating temperature increased from 190 °C to 270 °C. The drain current at negative gate voltages was increased by heating with high-pressure H_2O vapor at those heating temperatures. Its increase was probably caused by the parasitic depletion mode characteristic. The additional heating at 300 °C as well as at 350 °C with H_2O vapor of one atmospheric pressure reduced the drain current at negative gate voltages. This annealing process resulted in an on/off drain current ratio of 10^7.

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