

Atmospheric-Pressure Plasma-Enhanced Chemical Vapor Deposition of Silicon and Silicon Oxide Layers for Low-Temperature Thin Film Transistors

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Abstract

The goal of the present study is to develop a highly efficient deposition technology for good-quality amorphous Si (*a*-Si), microcrystalline Si (μ c-Si) and SiO_x films on flexible polymer substrates. For this purpose, we have been using atmospheric-pressure (AP) plasma excited by a 150-MHz very high-frequency (VHF) power. The changes of thickness and microstructure of the films in the gas flow direction were studied as a function of distance from the plasma entrance, VHF power density, gas flow rates and substrate temperature. The results showed that the chemical reactions both in gas phase and on the growing film surface were significantly enhanced in the AP-VHF plasma, promoting phase transitions from *a*-Si to μ c-Si and from organic to inorganic SiO_x on a time scale of the order of less than 0.1 ms. In both cases, the precise control of gas residence time was shown very important to improve the film quality.

1. Introduction

Low-temperature silicon (Si) thin film transistors (TFTs) are a promising electronic device for the use in large-area flat panel displays and sensors. Generally, plasma-enhanced chemical vapor deposition (PECVD) operated under vacuum conditions is used for depositing hydrogenated amorphous Si (*a*-Si) and microcrystalline Si (μ c-Si) films, as well as for preparing silicon oxide (SiO_x) and silicon nitride films. On the other hand, PECVD under atmospheric pressure (AP) has nowadays been the focus of much research. However, according to the commented researches in the review papers [1–3], the main body of the AP-PECVD researches has been related to organic polymers and oxide films, probably because these materials are favorable for the first realization of industrial needs. As far as we know, few works have been published on the deposition of *a*-Si and/or μ c-Si films by using AP-PECVD.

By using homogeneous AP plasma excited by 150-MHz very high-frequency (VHF) powers, we have demonstrated high-rate and low-temperature depositions of *a*-Si and μ c-Si films [4–6] and Si-related compound films, such as SiN_x and SiO_x. The aim of this study is to examine the growth behaviors of Si and SiO_x films in AP-VHF plasma and to test their applicability to actual TFTs.

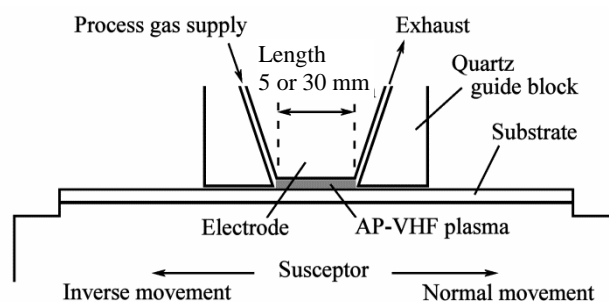


Fig. 1. Schematic diagram of the parallel-plate-type electrode system (side view). The electrode width was 80 mm.

2. Experiments

The depositions of Si and SiO_x films were carried out separately using two AP-PECVD systems. Each system was equipped with a parallel-plate-type electrode in the reaction chamber (Fig. 1). The electrode surface (area = 5×80 and 30×80 mm² for Si and SiO_x depositions, respectively) was coated with sprayed alumina of 0.1 mm thickness.

Si films were deposited from gas mixtures of helium (He), hydrogen (H₂) and silane (SiH₄) at a constant pressure of 1×10⁵ Pa. 0.7 mm-thick Corning EAGLE XG glass plates (10×10 cm²) and six-inch thermally oxidized p-type Si wafers of 0.002–0.004 Ω cm resistivity were used as the substrates. VHF power density (P_{VHF}), and H₂ and SiH₄ flow rates were varied as parameters at substrate temperatures (T_{sub}) of 220 and 120 °C. On the other hand, SiO_x films were prepared using gas mixtures of He, oxygen (O₂) and hexamethyldisiloxane (HMDSO) at T_{sub} of ≤120 °C. P_{VHF} and flow rates of O₂ and HMDSO were varied as parameters.

Bottom-gate TFTs were fabricated to evaluate the bulk quality of the Si films. The Si channel layers were deposited on thermally oxidized Si wafers with substrate movement at a speed of 1 or 0.5 mm/s. Aluminum source-drain electrodes of 100 nm thicknesses were directly formed on the Si channel layers by vacuum evaporation at room temperature. The length and width of the channel were 50 and 100 μm, respectively. Drain current–gate voltage transfer characteristics of the TFTs were measured using a Keithley 4200 semiconductor characterization system at room temperature. Threshold voltage and electron field-effect mobility were derived from the linear region of TFT operation.

3. Results and discussion

Si depositions

Deposition rate and crystalline volume fraction (I_C^{RS}) of the Si films deposited at $P_{VHF} = 16 \text{ W/cm}^2$ and $T_{sub} = 220^\circ\text{C}$ are shown in Fig. 2. It is suggested that the source SiH_4 gas is immediately decomposed after being introduced into the plasma region, contributing to the film growth. As a result, it is worth to note that the H_2/SiH_4 ratio (H/SiH_x ratio) substantially increases in the gas flow direction, which leads to the crystallization of the growing film within only 0.3 ms.

The influences of T_{sub} and P_{VHF} on the film crystallinity investigated in the same gas flow condition as that used in Fig. 2 are shown in Fig. 3. From the data in Figs. 2 and 3, inactivation of the film-forming reactions by lowering T_{sub} is obvious. However, increasing P_{VHF} enhances the gas-phase and/or the surface reactions, causing the film crystallization occurring in a shorter gas residence time. The initial H_2/SiH_4 ratio also had a significant effect on the gas residence time necessary for the phase transition. By increasing H_2/SiH_4 ratio by decreasing SiH_4 flow rate under fixed P_{VHF} and H_2 flow rate, a $\mu\text{c-Si}$ film could be grown at $T_{sub} = 120^\circ\text{C}$ even in the vicinity of the plasma entrance.

If the substrate is horizontally moved during deposition for TFT fabrications, Si films with uniform thickness is obtained in the area that the plasma passes over, whereas the film structure remains inhomogeneous in the thickness direction. Namely, if the substrate is moved in the same direction as the gas flow, $a\text{-Si}$ bottom surface is formed, while $\mu\text{c-Si}$ bottom surface is likely to be obtained by moving substrate in the inverse direction. Thus, both $a\text{-Si}$ and $\mu\text{c-Si}$ channels of bottom-gate TFTs can be formed under the same condition only by changing the substrate moving direction.

SiO_x depositions

The thickness and the microstructure of SiO_x films also varied along the gas flow, which resulted from the change in plasma chemistry accompanied with the HMDSO consumption [5]. Both increasing P_{VHF} and O_2/HMDSO ratio led to the higher fragmentation and oxidation of HMDSO, leading to the organic-inorganic transition occurring in a shorter gas residence time in the plasma. When a SiO_x film is deposited

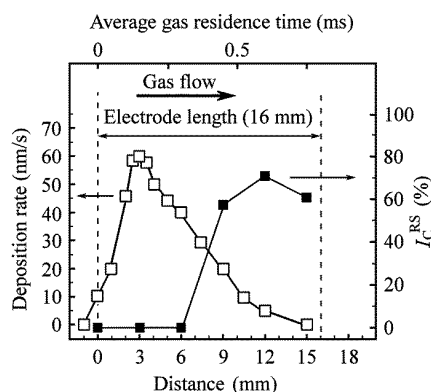


Fig. 2. Variations of deposition rate and crystalline volume fraction of the Si films deposited at $T_{sub} = 220^\circ\text{C}$ on stationary glass substrates with $P_{VHF} = 16 \text{ W/cm}^2$. The flow rates of He, H_2 and SiH_4 were 50 slm, 500 sccm and 50 sccm, respectively.

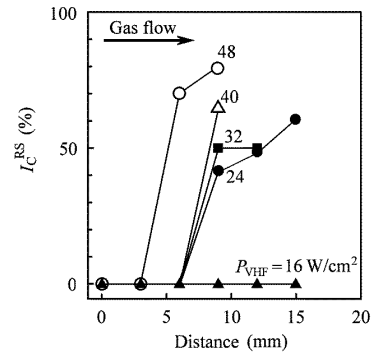


Fig. 3. Effects of P_{VHF} on the phase transition behavior of the Si films deposited at $T_{sub} = 120^\circ\text{C}$ on stationary glass substrates. He, H_2 and SiH_4 flow rates were the same as those used in Fig. 2.

with moving substrate, a certain layer having some organic character may be incorporated into the film. However, we consider that, if the quality of the inorganic layer is high enough, the film is usable as the gate dielectrics of TFTs.

TFT fabrications

The characterization of the bottom-gate TFTs showed that the $a\text{-Si}$ channel layers formed at $T_{sub} = 220^\circ\text{C}$ had sufficiently good electrical property (field effect mobility of $1\text{--}1.5 \text{ cm}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1}$) despite the high deposition rates of several tens of nm/s. Meanwhile, $\mu\text{c-Si}$ layers did not acquire their original superiority over $a\text{-Si}$, probably due to the shortage of passivation of defects at grain boundaries [6]. The precise control of gas residence time in the AP-VHF plasma was considered to be primarily important for the formation of good-quality $\mu\text{c-Si}$. In this sense, the use of pulse modulation of input electric power that can control the plasma chemistry independently of electrode length is an effective means to improve the film quality. The pulse modulation was also shown effective on improving film quality at the lower T_{sub} . The results will be presented in the conference.

3. Conclusions

The fabrication of high-performance TFTs on polymers awaits further detailed researches on the improvement of quality of both Si and SiO_x films.

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