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

Hiroaki Kakiuchi<sup>1</sup>, Hiromasa Ohmi<sup>1,2</sup> and Kiyoshi Yasutake<sup>1</sup>

<sup>1</sup> Department of Precision Science and Technology, Graduate School of Engineering, Osaka University

2-1 Yamada-oka, Suita,

Osaka 565–0871, Japan

Phone: +81-6-6879-7269 E-mail: kakiuchi@prec.eng.osaka-u.ac.jp

<sup>2</sup> Research Center for Ultra-Precision Science and Technology, Osaka University

2-1 Yamada-oka, Suita,

Osaka 565-0871, Japan

#### Abstract

The goal of the present study is to develop a highly efficient deposition technology for good-quality amorphous Si (a-Si), microcrystalline Si ( $\mu$ c-Si) and SiO<sub>x</sub> 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  $\mu c$ -Si and from organic to inorganic SiO<sub>x</sub> 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 ( $\mu$ 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  $\mu c$ -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  $\mu c$ -Si films [4–6] and Si-related compound films, such as SiN<sub>x</sub> and SiO<sub>x</sub>. The aim of this study is to examine the growth behaviors of Si and SiO<sub>x</sub> films in AP-VHF plasma and to test their applicability to actual TFTs.

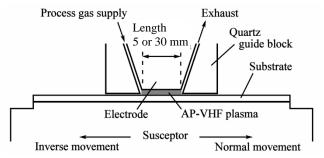


Fig. 1. Schematic diagram of the parallel-plate-type electrode system (side view). The electrode width was 80 mm.

#### 2. Experiments

The depositions of Si and SiO<sub>x</sub> 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 =  $5 \times 80$  and  $30 \times 80$  mm<sup>2</sup> for Si and SiO<sub>x</sub> depositions, respectively) was coated with sprayed alumina of 0.1 mm thickness.

Si films were deposited from gas mixtures of helium (He), hydrogen (H<sub>2</sub>) and silane (SiH<sub>4</sub>) at a constant pressure of  $1 \times 10^5$  Pa. 0.7 mm-thick Corning EAGLE XG glass plates ( $10 \times 10$  cm<sup>2</sup>) and six-inch thermally oxidized p-type Si wafers of 0.002–0.004  $\Omega$  cm resistivity were used as the substrates. VHF power density ( $P_{VHF}$ ), and H<sub>2</sub> and SiH<sub>4</sub> flow rates were varied as parameters at substrate temperatures ( $T_{sub}$ ) of 220 and 120 °C. On the other hand, SiO<sub>x</sub> films were prepared using gas mixtures of He, oxygen (O<sub>2</sub>) and hexamethyldisiloxane (HMDSO) at  $T_{sub}$  of  $\leq 120$  °C.  $P_{VHF}$  and flow rates of O<sub>2</sub> 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  $\mu$ m, 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  $T_{sub} = 220 \text{ }^{\circ}\text{C}$  are shown in Fig. 2. It is suggested that the source SiH<sub>4</sub> 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<sub>2</sub>/SiH<sub>4</sub> ratio (H/SiH<sub>x</sub> 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<sub>2</sub>/SiH<sub>4</sub> ratio also had a significant effect on the gas residence time necessary for the phase transition. By increasing H<sub>2</sub>/SiH<sub>4</sub> ratio by decreasing SiH<sub>4</sub> flow rate under fixed  $P_{VHF}$  and H<sub>2</sub> flow rate, a  $\mu c$ -Si film could be grown at  $T_{sub} = 120$  °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*-Si bottom surface is formed, while  $\mu c$ -Si bottom surface is likely to be obtained by moving substrate in the inverse direction. Thus, both *a*-Si and  $\mu c$ -Si channels of bottom-gate TFTs can be formed under the same condition only by changing the substrate moving direction.

#### SiO<sub>x</sub> 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<sub>x</sub> film is deposited

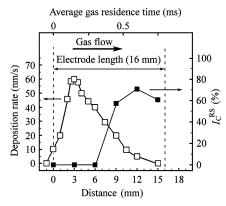


Fig. 2. Variations of deposition rate and crystalline volume fraction of the Si films deposited at  $T_{sub} = 220$  °C on stationary glass substrates with  $P_{VHF} = 16$  W/cm<sup>2</sup>. The flow rates of He, H<sub>2</sub> and SiH<sub>4</sub> were 50 slm, 500 sccm and 50 sccm, respectively.

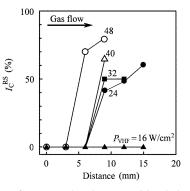


Fig. 3. Effects of  $P_{\text{VHF}}$  on the phase transition behavior of the Si films deposited at  $T_{\text{sub}} = 120$  °C on stationary glass substrates. He, H<sub>2</sub> and SiH<sub>4</sub> flow rates were the same as those used in Fig. 2.

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*-Si channel layers formed at  $T_{sub} = 220$  °C had sufficiently good electrical property (filed effect mobility of 1–  $1.5 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ ) despite the high deposition rates of several tens of nm/s. Meanwhile,  $\mu c$ -Si layers did not acquire their original superiority over *a*-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  $\mu c$ -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.

#### Acknowledgements

The experiments were supported by KAKENHI (20676003 and 26249010) from the Ministry of Education, Culture, Sports, Science and Technology.

## References

- [1] L. Bardos and H. Barankova, Thin Solid Films **518** (2010) 6705.
- [2] D. Pappas, J. Vac. Sci. Technol. A 29 (2011) 020801.
- [3] F. Massines, C. S.-Bournet, F. Fanelli, N. Naudé, and N. Gherardi, Plasma Process. Polym. 9 (2012) 1041.
- [4] H. Kakiuchi, H. Ohmi, and K. Yasutake, J. Vac. Sci. Technol. A 32 (2014) 030801.
- [5] H. Kakiuchi, H. Ohmi, T. Yamada, S. Tamaki, T. Sakaguchi, W. Lin, and K. Yasutake, Phys. Stat. Sol. A 212 (2015) 1571.
- [6] H. Kakiuchi, H. Ohmi, and K. Yasutake, J. Phys. D: Appl. Phys. 51 (2018) 355203.