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Effective phase control of silicon films during high-rate deposition in atmospheric-pressure very high-frequency plasma: Impacts of gas residence time on the performance of bottom-gate thin film transistors

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ABSTRACT

Hydrogenated amorphous silicon (*a*-Si) and microcrystalline silicon (*μc*-Si) films were grown in atmospheric-pressure (AP) He/H_2/SiH_4 plasma excited by a 150-MHz very high-frequency (VHF) power at a temperature of 220 °C. The variations in thickness and crystallinity of the deposited Si films along the gas flow direction were studied as functions of gas residence time in the plasma, VHF power density and H_2 flow rate. Furthermore, the electrical characteristics of bottom-gate thin film transistors (TFTs) were investigated to evaluate the film quality. The results revealed that the chemical reactions both in gas phase and on the growing film surface were significantly enhanced in AP-VHF plasma, promoting phase transition from amorphous to microcrystalline in a time of the order of 0.1 ms. The performance of the TFTs showed that *a*-Si layers formed in the upstream portion of the plasma zone had reasonably good electrical property (field-effect mobility of approximately 2 cm^2/V s) despite very high deposition rates around 20 nm/s. While *μc*-Si layers deposited in the downstream portion were very defective, which might come from the insufficient passivation of grain boundaries with *a*-Si tissues due to a too long gas residence time in the plasma. The precise control of gas residence time by adjusting the length of plasma will be effective for the phase control of Si films with desired quality.

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1. Introduction

There has been a considerable interest in the low-temperature and high-rate deposition processes of hydrogenated amorphous silicon (*a*-Si) and microcrystalline silicon (*μc*-Si) films, which are widely used in large-area electronic devices including thin film transistors (TFTs) and thin film solar cells. Especially, *a*-Si and *μc*-Si films deposited on polymer materials can realize flexible TFT-based devices and solar cells. A promising method for fabricating *a*-Si and *μc*-Si films is plasma-enhanced chemical vapor deposition (PECVD) using silane (SiH_4) and hydrogen (H_2) as the source gasses. However, in conventional PECVD processes, reactive plasma is excited at low pressures by a 13.56-MHz radio frequency power [1–5], resulting in low deposition rates. In addition, since substrate heating in the range of 200–400 °C is needed in order to obtain good-quality Si films, thermosensitive flexible substrates can hardly be used as far as conventional radio-frequency PECVD processes are used.

Recently, there has been a steady increase in the utilization of reactive plasma excited at atmospheric pressure (AP) for PECVD processes. Since AP plasma can serve as an efficient source of atomic and molecular active species, it can be a viable approach to realize a highly efficient thin film formation process at low temperatures. Although a number of investigations have been reported on the depositions of oxide materials using AP corona, glow and dielectric barrier discharges and also using AP plasma jets [6–19], few works have been published on the deposition of Si thin films using AP plasma.

We have developed an AP plasma technology in order to fabricate Si and related thin films with high rates at low temperatures. In this technology, a 150-MHz very high-frequency (VHF) power is effectively used to excite stable plasma under AP [20–26], the properties of which are considered to be different from other AP plasma sources [27]. In our previous study [21], we demonstrated high-rate depositions of reasonably good-quality *a*-Si films at a substrate temperature of 220 °C by using a cylindrical rotary electrode. In high H_2/SiH_4 ratio conditions (H_2/SiH_4 > 50), *μc*-Si films could also be obtained. The high-speed electrode rotation (~5000 rev./min) enabled us to form a one-dimensional high-speed gas flow in the plasma region of less than 0.5 mm spacing. However, the deposition process using the cylindrical rotary electrode suffered some problems. One of the problems was that the length of plasma in the gas flow direction varied depending on the plasma operating conditions, such as electrode rotation speed (gas flow rate) and reactive gas concentration. In addition, because of the cylindrical shape of the electrode, the gap spacing varied along the gas flow that caused the non-homogeneities of electric field and gas flow velocity in the plasma region. Moreover, the turbulence of gas flow existing behind the electrode promoted the gas-phase condensation of precursor molecules, leading to the contamination of substrate surface by dusty particles in a

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certain condition [26]. These problems limited us to study the growth process of device-quality *a*-Si and *μc*-Si films in AP-VHF plasma.

The goal of the present study is to achieve a highly efficient formation of device-quality *a*-Si and *μc*-Si layers on flexible polymer substrates using AP-VHF plasma on the basis of the results described above. In this paper, as a first step to the deposition at temperatures lower than 100 °C, we discuss the growth processes of Si films in AP-VHF plasma at a temperature of 220 °C, focusing on exploring the effects of gas residence time in the plasma on the growth of Si films under a condition of well-regulated gas flow. For this purpose, we propose the use of a parallel-plate-type electrode system that can define the length of plasma and gap spacing and can also avoid a turbulent gas flow around the plasma region. To check the film quality, we evaluate the performance of bottom-gate TFTs, the channel layers of which have been prepared in AP-VHF plasma.

2. Experimental details

The experiments were conducted in an AP plasma CVD system that equipped a load lock chamber. A parallel-plate-type electrode of 16 mm length and 80 mm width was placed in the reaction chamber. Fig. 1a schematically shows the experimental setup. The electrode surface was coated with alumina of ~0.1 mm thickness in order to restrain the emission of secondary electrons. Quartz guide blocks were used to define the gas flow path, achieving a laminar flow of gasses in the plasma zone. Corning EAGLE XG glass plates of 0.7 mm thickness (100×100 mm^2) were mainly used as substrates. The substrates were fixed on a TiN-coated copper susceptor of the substrate heating stage by a vacuum chuck system that ensured an efficient heat transfer across the substrate/susceptor interface at AP [24]. By virtue of the vacuum chuck system, the temperature of the

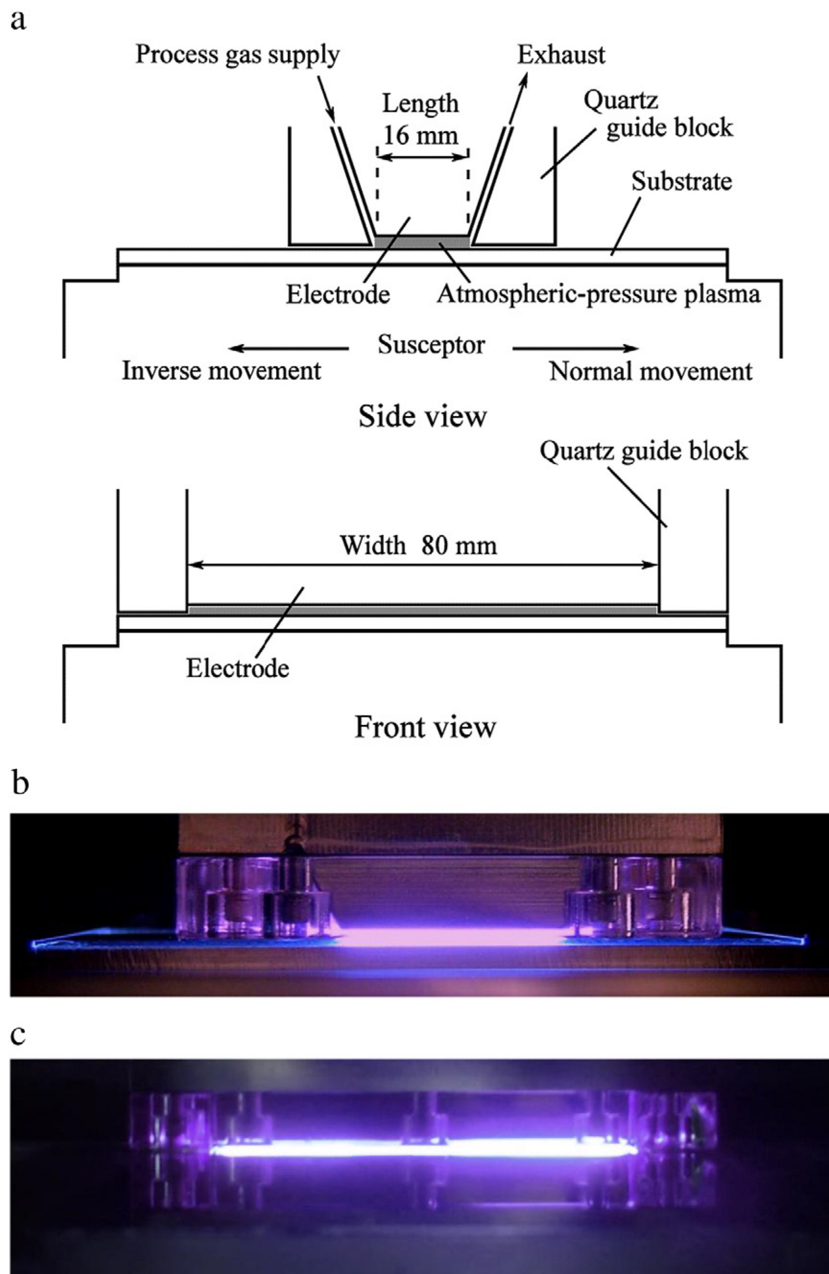

Fig. 1. (a) Schematic illustration of the experimental setup. (b) Side and (c) front view photographs of AP-VHF plasma excited using a glass substrate in a deposition condition ($H_2 = 0.5$ slm, $P_{VHF} = 16$ W/cm^2).

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