Characterization of Si films deposited at 220 °C in atmospheric-pressure very high-frequency plasma and their application to thin film transistors


Department of Precision Science and Technology, Graduate School of Engineering, Osaka University, 2–1 Yamada-Oka, Suita, Osaka 565-0871, Japan

Abstract: Low-temperature amorphous silicon (a-Si) and microcrystalline silicon (µc-Si) are promising thin film materials for use in large-area electronic devices including thin film transistors (TFTs) and thin film solar cells. In this study, atmospheric-pressure (AP) plasma excited by a 150-MHz very-high-frequency (VHF) power was used to prepare a-Si and µc-Si films at a substrate temperature of 220 °C. The variations of thickness and crystallinity of the Si films in the gas flow direction were studied as functions of gas residence time in the plasma, VHF power density and H2/SiH4 ratio. Furthermore, the performance of bottom-gate TFTs, the channel Si layers of which were deposited using AP He/H2/SiH4 plasma, were examined to test the applicability of the Si films to actual TFTs. The detailed results will be presented in the symposium.

Keywords: silicon, atmospheric-pressure plasma, thin film transistors

1. Introduction

Hydrogenated amorphous silicon (a-Si) and microcrystalline silicon (µc-Si) films prepared at low temperatures are promising for use in large-area electronic devices such as thin film transistors (TFTs) and thin film solar cells. Plasma-enhanced chemical vapour deposition (PECVD) operated under vacuum conditions is a common technique for depositing a-Si and µc-Si films at low temperatures, as well as for depositing Si-based compound films including SiC, SiNx and SiOx. On the other hand, PECVD under atmospheric pressure (AP) has recently been the focus of much research [1-4]. Since AP plasma can serve as an efficient source of active species, it is useful in increasing deposition rate and also in lowering substrate temperature for preparing good-quality functional thin films.

By using AP plasma excited by a 150-MHz very-high-frequency (VHF) power, we have demonstrated high-rate and low-temperature depositions of a-Si and µc-Si films, in addition to SiC, SiNx and SiOx films [5, 6]. The aim of the present study is to fabricate TFTs on flexible polymer substrates by attaining a highly efficient deposition process for good-quality a-Si and µc-Si films using the AP plasma technology. As a step to the goal, we discuss the growths of Si films in AP-VHF plasma at a temperature of 220 °C.

2. Experimental

The experiments were carried out in an AP-PECVD system, which had a parallel-plate-type electrode in the reaction chamber (Fig. 1). The electrode surface (area = 16×80 mm²) was covered with sprayed alumina of ~0.1 mm thickness. Quartz guide blocks were used to form a one-dimensional laminar gas flow in the narrow gap spacing (0.5 mm) between the electrode and a substrate that was vacuum-chucked on the susceptor of a horizon-tally movable stage at the ground potential. By supplying a 150 MHz VHF power through an impedance matching unit, AP He/H2/SiH4 plasma was confined in the gap region. Under a constant process pressure of 1×10⁵ Pa, VHF power density (P_{VHF}) and flow rates of H2 and SiH4, were varied as parameters. For all the deposition conditions used in this study, the electrode surface was entirely covered with the homogeneous emissions from the AP-VHF plasma as observed in Fig. 2. Dusty Si particles formed by the gas-phase condensation in the outside of the plasma region were completely removed by sucking the gas flow before their adhering to the substrate surface.

Fig. 1. Schematic illustration of the experimental setup (side view). The electrode width is 80 mm.

Fig. 2. Side-view photograph of AP-VHF plasma.
3. Results and discussion

Fig. 3 shows the dependences of (a) thickness and (b) crystalline volume fraction ($I_c$) of the Si films on the position from the plasma entrance after 20 s deposition in stationary conditions at $P_{VHF} = 16$ and 32 W/cm² ($H_2$ and $SiH_4 = 500$ and 50 sccm, respectively). $I_c$ was deduced from the Raman spectra of the Si films. The data suggest that the $SiH_4$ gas is immediately decomposed after being introduced into the plasma region, contributing to the film growth. As a result, it is noteworthy that the $H_2/SiH_4$ ratio (H/SiH$_4$ ratio) increases along the gas flow direction. This results in the crystallization of the growing film in $\leq 0.3$ ms. Increasing $P_{VHF}$ enhances the gas-phase and/or the surface reactions, causing the shift of the thickness peak position to the upstream side and the film crystallization occurring in a shorter gas residence time.

![Average gas residence time (ms)](image)

The initial $H_2/SiH_4$ ratio also had a significant effect on the gas residence time necessary for the phase transition of the Si films (data not shown here). When the $H_2/SiH_4$ ratio was increased by increasing $H_2$ flow rate under fixed $P_{VHF}$ and $SiH_4$ flow rate, the formation of crystalline Si phases took place more slowly [6]. This was considered to be due to the shortage of $P_{VHF}$ necessary for the adequate dissociation of $H_2$, which led to the insufficient generation of atomic hydrogen in the upstream portion. In contrast, in the case of increasing $H_2/SiH_4$ ratio by decreasing $SiH_4$ flow rate under fixed $P_{VHF}$ and $H_2$ flow rate, a $\mu$c-Si film could be grown even at the plasma entrance.

It is clear from the above results that the thickness and structure of Si films are inevitably inhomogeneous in the gas flow direction as far as the Si films are deposited by AP-PECVD processes. When the substrate is horizontally moved at a constant speed during the plasma operation, such inhomogeneities along the gas flow are integrated in the direction perpendicular to the substrate surface; then, Si films with uniform thickness can be obtained, while the film structure remains inhomogeneous in the thickness direction. We, however, consider that such inhomogeneous Si films with gradient microstructures can be accepted for TFTs, because the electrical property of very thin channel layers is especially important. Considering the data shown in Fig. 3b, if the substrate is moved in the same direction as the gas flow (normal movement), $a$-Si bottom surface is obtained, while $\mu$c-Si bottom surface can be formed by moving substrate inversely (inverse movement).

In order to test the applicability of the Si films to TFTs, we fabricated bottom-gate TFTs using thermally oxidized p-type Si(001) wafers of 0.002 - 0.004 Ω cm resistivity [6]. Si channel layers were formed with a substrate movement at a constant speed of 1 mm/s on the thermal oxide of 300 nm thickness. Aluminium layers of 300 nm thickness (200 µm length and 100 µm width) were vacuum-evaporated on the Si channel layers at room temperature using a mask pattern for the source-drain electrodes. When the channel Si layers were prepared with normal substrate movement, the TFTs exhibited field-effect mobilities in the range of 0.5–2 cm²/Vs, indicating that reasonably good-quality $a$-Si layers were grown near the plasma entrance. However, in the case of TFTs with the inverse substrate movement, the data suggested that the $\mu$c-Si channel layers formed in the vicinity of the plasma exit had poor electrical properties, which might result from the sparse film structure without enough passivation of the grain boundaries by amorphous Si tissues. Thus, the precise control of gas residence time is needed for the growth of good-quality $a$-Si and $\mu$c-Si, together with the optimization of $P_{VHF}$ and $H_2/SiH_4$ ratio.

Based on the above results, we have been focussing on the impact of gas residence time on the TFT performance by using shorter electrodes and/or changing the gas flow velocity in the plasma. The effect of substrate temperature on the film-forming behaviour is also under investigation at present. The results will be reported in the symposium.

4. References


