Effect of capacitive to inductive coupling transition in multiple linear U-type antenna on silicon thin film deposition from pure SiH_4 discharges

Hong Bum Kim
Advanced Institute of Nano Technology, Sungkyunkwan University, Suwon 440-746, Korea

Hyoung Cheol Lee, Kyong Nam Kim, and Geun Young Yeom[a]
Department of Advanced Materials Science and Engineering, Sungkyunkwan University, Suwon 440-746, Korea

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Using a large area internal-type inductively coupled plasma (ICP) source called "multiple U-type ICP source" having the size of 1020×830 mm^2, the electrical properties of the antennas and the dissociation characteristics were investigated as a function of rf power using pure SiH_4 and their influence on the deposited silicon films was studied. With increasing rf power, the plasma mode has changed from capacitively coupled plasma (*E* mode) to inductively coupled plasma (*H* mode), and the change of plasma mode increased the ratios of $H^*_{\text{Fulcher}}/SiH^*$ and Si^*/SiH^* by changing the electron energy distribution function. In addition, the increase in $H^*_{\text{Fulcher}}/SiH^*$ changed the microstructure of a silicon thin film deposited on glass substrates from amorphous to microcrystalline. At the high rf power regime of 4000 W, a silicon films having the crystalline volume fraction of 53% with optical band gap (Tauc') of about 2.1 eV and dark conductivity of $2.4 \times 10^{-5}\ \Omega^{-1}\,\text{cm}^{-1}$ could be obtained at 20 mTorr of SiH_4 [70 SCCM (SCCM denotes cubic centimeter per minute at STP)]. © *2008 American Vacuum Society.* [DOI: 10.1116/1.2924340]

I. INTRODUCTION

Microcrystalline silicon films are attracting much attention because of their potential in improving the performance of amorphous silicon-based devices such as thin film transistors or solar cells. In particular, for solar cells, microcrystalline silicon is intensively studied to overcome the light-induced degradation observed for hydrogenated amorphous silicon (a-Si:H) films, to improve the efficiency by increasing the light absorption wavelength range, and to improve carrier transport and collection.[1–3]

Various high density plasma sources such as electron cyclotron resonance plasma, helicon wave plasma, or inductively coupled plasma (ICP) have been applied for the plasma enhanced chemical vapor deposition (PECVD) of numerous silicon-based materials at low substrate temperature.[4–6] Among these, ICP-PECVD has advantages in the growth of microcrystalline silicon uniformly on a large substrate area because of its scalability to large area without external magnets.[7] As ICP-PECVD, conventional ICP sources with external spiral-type antennas are generally studied. However, these ICP sources show problems in the application to the processing of the extremely large substrate size of thin film transistor liquid crystal display and solar cells due to the cost and thickness of the dielectric material required to transmit electromagnetic field from the antennas and the large impedance of the antennas when scaling up to larger areas. The large impedance of the antenna causes a high radio-frequency (rf) voltage on the antenna, and it can lead a low efficient power transfer to the plasmas by the increased capacitive coupling. One of the solutions resolving the above problems is to use internal-type ICPs, which could effectively exclude the problems related to the thickness of the dielectric material when scaling to large areas. One of the promising internal-type sources is the ICP source having multiple internal linear antennas with U-type parallel connection called "multiple U-type internal ICP source." It is known to exhibit excellent plasma uniformity over the large area substrate by avoiding the standing wave effect that causes a nonuniform power distribution along the antennas.[8]

In this study, using the multiple U-type internal ICP source, silicon thin films were deposited on the glass substrate using pure SiH_4. The electric and plasma characteristics and their relation to the characteristics of microcrystalline silicon films were investigated as the application tool for the deposition of microcrystalline silicon. They were deposited on the glass substrate on a large area substrate and at a low temperature.

II. EXPERIMENT

Figure 1 shows the schematic drawing of the multiple U-type ICP source for the deposition of silicon films installed in a rectangular process chamber having the inner size of 1020×830 mm^2. The ICP antenna was consisted of four U-type antennas connected in parallel and each antenna was located to have an equal spacing of 7.6 cm. Each antenna was made of copper tube enclosed by quartz tube. The 13.56 MHz rf power supply of 5 kW was connected to one end of each U-type antenna through the L-type matching network and the other end of the antenna was connected to the ground, as shown in Fig. 1. The details of the multiple U-type ICP source can be found elsewhere.[9]

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[a] Electronic mail: gyyeom@skku.edu

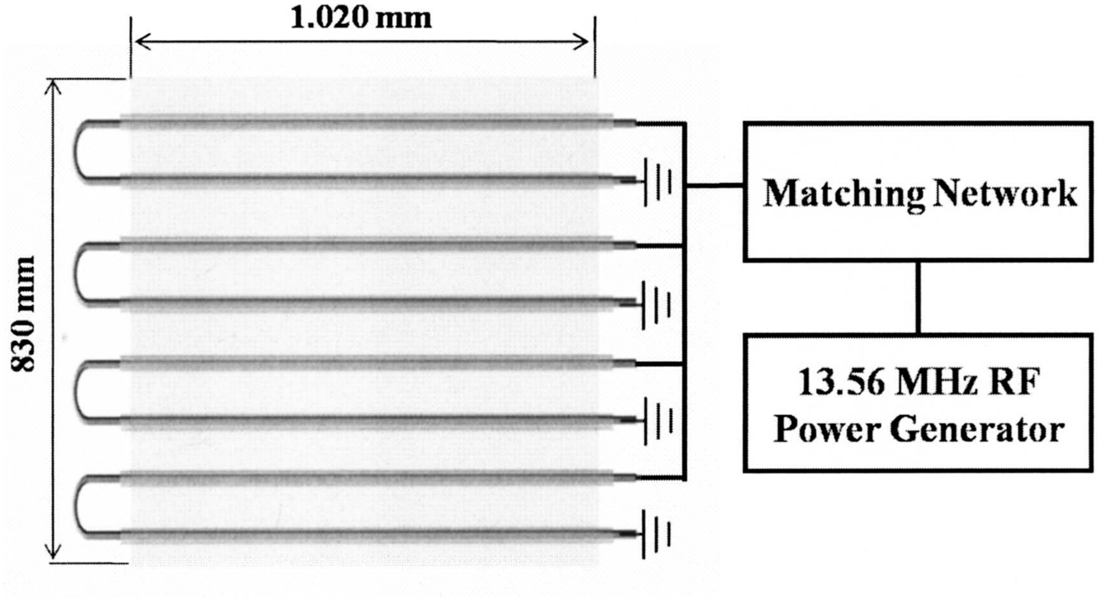

FIG. 1. Schematic diagram of the multiple U-type ICP source used in the experiment for deposition of silicon film.

Corning 1737 glass was used as the substrate and, to grow silicon films, 70 SCCM (SCCM denotes cubic centimeter per minute at STP) of pure SiH_4 was fed to the chamber and the operating pressure was maintained at 20 mTorr. rf power to the ICP source was varied from 200 to 4000 W while keeping the substrate temperature at 240 °C. During the operation of the SiH_4 plasma, the electrical characteristics of the antennas such as root-mean-square (rms) current and resistance were measured by using an impedance analyzer (MKS Inc.) located between the matching network and the antenna. Optical emission spectroscopy (OES) (PCM 420 SC-Technology) was used to measure the ratio of excited species such as Si^*/SiH^* and $H^*_{Fulcher}/SiH^*$ in the plasma during the deposition process. Raman spectroscopy (Kaiser optical system Inc.) was used to evaluate the crystalline volume fraction of the films at the deposition thickness of 3000 Å (±200 Å). Optical band gap and dark conductivity of the 3000 Å thick films deposited as a function of rf power were investigated by an ultraviolet-visible (UV-vis) spectrometer (Scinco S-1000) and by a semiconductor characterization system (Keithley 4200) after the formation of Al coplanar electrodes on the deposited silicon films, respectively.

III. RESULTS AND DISCUSSION

Figure 2 shows the rms current induced on the multiple U-type ICP antenna and the power transfer efficiency of the plasma measured using the impedance probe as a function of rf power. The rf power transfer efficiency was calculated by using the following equation after the measurement of Joule loss by matching network, rf cable, and antenna using the impedance probe;

$$\begin{aligned}\text{Power transfer efficiency} &= \text{true rf power/input rf power}\\ &= 1 - I_{rf}^2 R/\text{input rf power},\end{aligned}$$

where true power is the actual power transferred to the plasma, input power is the power generated by the rf power supply, I_{rf} is the rms current measured at the output side of the matching network, and R is the resistance of the antenna. The rf power was varied from 200 to 4000 W while the operating pressure was maintained at 20 mTorr by using 70 SCCM of SiH_4. As shown in Fig. 2, the increase in rf power from 200 to 2000 W increased the rms current from 8 to 19 A; however, the further increase in rf power to 4000 W did not increase the rms current rapidly. In the case of power transfer efficiency, it was increased with increasing

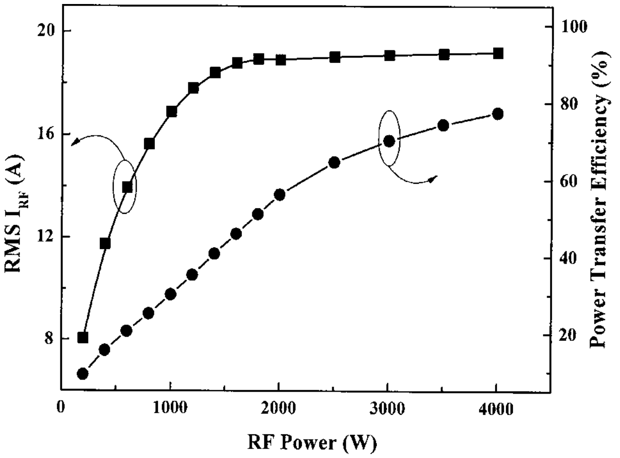

FIG. 2. rms current measured between the matching network and the antenna, and the calculated power transfer efficiency as a function of rf power at 20 mTorr of SiH_4 (70 SCCM) using an impedance analyzer.

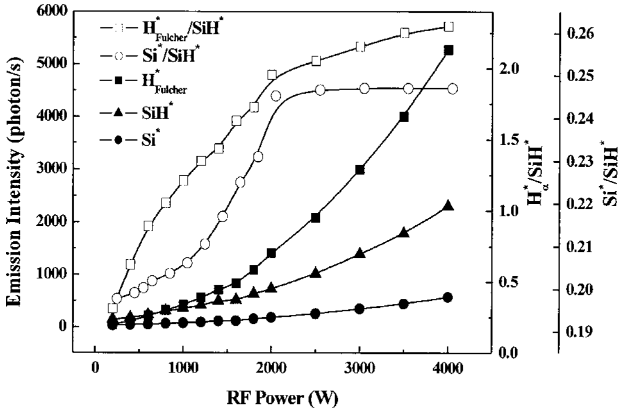

FIG. 3. OES for I_{SiH*}, I_{SiH*}, and $I_{HFulcher*}$, and the ratios of Si^*/SiH^* and $H^*_{Fulcher}/SiH^*$ as a function of rf power at 20 mTorr of SiH_4.

the rf power and, at 4000 W, the highest rf power transfer efficiency of about 80% could be obtained. In addition, similar to the rms current, the rf power transfer efficiency was increased significantly when the rf power was increased from 200 to 2000 W, and the further increase of rf power to 4000 W increased the rf power transfer efficiency slowly. Therefore, it is believed that the power range from 200 to 2000 W is the transition range from capacitively coupled plasma (*E* mode) to inductively coupled plasma (*H* mode) of SiH_4 plasma generated by the multiple U-type ICP source. Therefore, it is believed that the plasma generated at a low rf power such as 300 W is close to *E* mode and the plasma generated at a high rf power such as 4000 W is close to *H* mode.

In general, during the operation of the ICP source, the plasma is generated not only by the inductive mode (*H* mode) originated from the current passing through the antenna but also by the capacitive mode (*E* mode) originated from the electrostatic field induced on the antenna. When the rf power is low, due to the low plasma density, the electric field on the electrode is more important in the operation of the plasma, therefore, the plasma is close to *E* mode. Generally, the discharge mode transition from *E* mode to *H* mode is followed by an intense increase in n_e where the plasma conductivity (σ) is proportional to the plasma density ($\sigma \propto n_e$). The plasma impedance, where the real part of the plasma impedance is proportional to $1/\sigma$, is directly related to the power transfer to the plasma and the mutual coupling between the antenna and the plasma. Therefore, the change in plasma operation mode can be also observed through the investigation of the impedance variation ($Z=Z_r+i\,Z_i$, Z_r:plasma resistance, Z_i:plasma reactance). Therefore, during the operation of ICP source, the transition from *E* mode to *H* mode is observed with increasing the rf power and, at this transition region, both plasma density and plasma conductance are significantly increased. Also, by calculating the power transfer efficiency which is proportional to the plasma density and the plasma conductance, the transition of *E-H* mode can be estimated.[10,11]

Figure 3 shows the OES spectra of Si^*, SiH^*, and $H^*_{Fulcher}$ and their ratios of Si^*/SiH^* and $H^*_{Fulcher}/SiH^*$ measured as a function of rf power for the condition in Fig. 2. The emission intensities of Si^*, SiH^*, and $H^*_{Fulcher}$ were observed at 288, 414, and 656 nm, respectively. As shown in Fig. 3, the increase in rf power increased the excitation of the gas molecules, therefore, the increase in the excited species from SiH_4 such as Si, SiH, and H could be observed with increasing the rf power at a fixed SiH_4 flow rate of 70 SCCM. However, as shown in the figure, when the ratios of Si^*/SiH^* and $H^*_{Fulcher}/SiH^*$ were taken, they were increased rapidly with increasing rf power from 200 to 2000 W, and when the rf power was further increased from 2000 to 4000 W, the ratio of Si^*/SiH^* was almost saturated and the ratio of $H^*_{Fulcher}/SiH^*$ was increased slowly. Due to the similar cross-sectional shape of Si^* and SiH^*, the ratio of Si^*/SiH^* is known to give the information on the high energy tail of the electron energy distribution function of the plasma and, if the ratio of Si^*/SiH^* is small, it means that the high energy tail of the electron energy distribution function is steeper.[12–14] It has been reported that, during the operation of an ICP source, electron tends to have a bi-Maxwellian distribution mostly composed of low energy electrons at a low rf power of *E* mode and, after the *E-H* mode transition, the electron tends to have a Maxellian distribution composed of high energy electrons at the high rf power of *H* mode.[15,16] The rapid increase in the ratio of Si^*/SiH^* observed from 200 to 2000 W appears to be from the transition from *E* mode to *H* mode and the saturation of the ratio of Si^*/SiH^* appears to show that the plasma is in *H* mode.

The rapid change in the ratio of $H^*_{Fulcher}/SiH^*$ shown with increasing the rf power from 200 to 2000 W also appears to be related to the transition of the plasma mode from *E* mode to *H* mode.[17–19] In addition, the change in the ratio of $H^*_{Fulcher}/SiH^*$ in a SiH_4 plasmas is known to change the structural properties of the silicon deposited on the glass substrate.[20,21] With increasing the rf power from 200 to 4000 W, the ratio of $H^*_{Fulcher}/SiH^*$ was increased considerably from 0.3 to 2.3, therefore, a significant change of the structure can be expected for the microcrystalline silicon deposited as a function of rf power.

Figure 4 shows the Raman spectra of the microcrystalline silicon thin films deposited as a function of rf power using 70 SCCM SiH_4 to investigate the change in the film structure by changing from *E* mode to *H* mode for the multiple U-type ICP. The substrate temperature was kept at 240 °C. The peaks (A_{510} and A_{520}) located at 510 and 520 cm^{-1} were originated from the crystalline silicon peak and the peak (A_{480}) located at 480 cm^{-1} was from the amorphous silicon peak.[22] The Raman crystallinity (X_c) was calculated by $X_c = (A_{510}+A_{520})/(A_{480}+A_{520}+A_{510})$. As shown in the figure, when the rf power was 300 and 1000 W, *E* mode is stronger and amorphous silicon film was obtained possibly due to the low ratio of $H^*_{Fulcher}/SiH^*$ observed in Fig. 3. The crystalline peak could be observed when the rf power was higher than 2000 W (where the ratio of $H^*_{Fulcher}/SiH^* > 2.0$), and the further increase in rf power decreased A_{480} while increasing

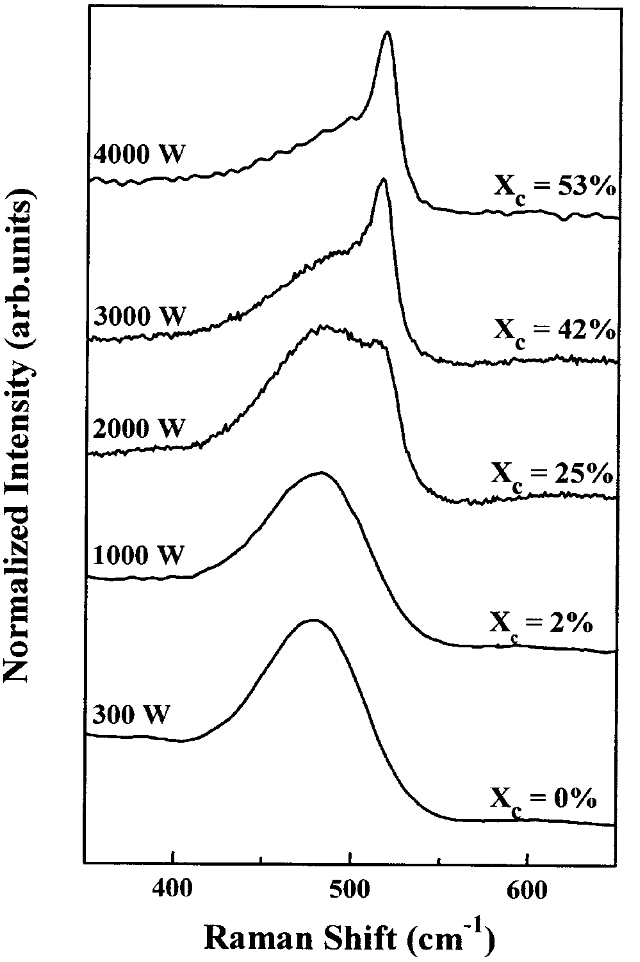

FIG. 4. Raman intensities of silicon films deposited as a function of rf power at 20 mTorr of SiH_4 (70 SCCM) and at the substrate temperature of 240 °C.

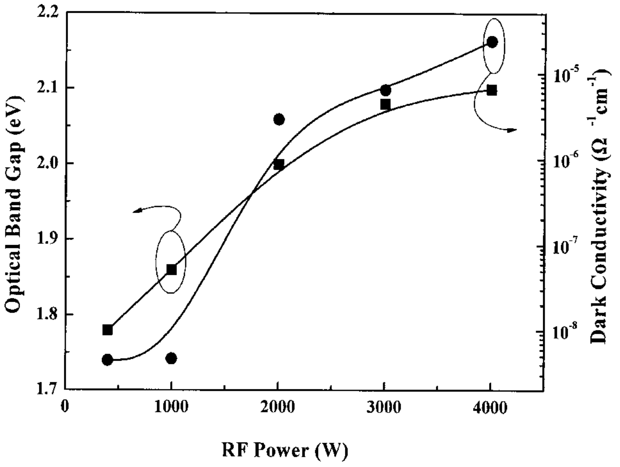

FIG. 5. Dark conductivity and optical band gap (Tauc') of the silicon thin films deposited as a function of rf power at 20 mTorr of SiH_4 (70 SCCM) and at the substrate temperature of 240 °C.

A_{510} and A_{520}, therefore, the further increase in rf power increased the Raman crystallinity. At the rf power of 4000 W, where the plasma is in *H* mode, the Raman crystallinity of the deposited thin film was estimated to be 53%.

The characteristics of the deposited silicon films such as dark conductivity (σ_D) and optical band gap estimated by Tauc' plot after the measurement by a UV-vis spectrometer were investigated and the results are shown in Fig. 5 as a function of rf power. The deposition condition is the same as Fig. 2. It is reported that σ_D of silicon thin films is increased with increasing the Raman crystallinity and with decreasing the disorder in the thin film through the etching of disordered atoms by atomic hydrogen during the deposition process.[23] As shown in the Fig. 5, at the rf power of 300 W, where *E* mode is stronger, σ_D was 4.5×10^{-9} Ω^{-1} cm^{-1} and, with increasing rf power to 4000 W, where *H* mode is stronger, σ_D was increased to 2.4×10^{-5} Ω^{-1} cm^{-1}. Especially, at the region of rf power from 1000 to 2000 W, where $H^*_{\text{Fulcher}}/SiH^*$ is increased significantly from 1.2 to 2.0 and the crystallization volume fraction is drastically increased from 2% to 25%, σ_D was also increased about three order magnitude.

As shown in Fig. 5, the optical band gap energy was also increased with increasing rf power, as shown in the figure, and, at the rf power range from 300 to 2000 W, more significant increase in optical band gap energy from 1.8 to 2 eV compared to the increase from 2.0 to 2.1 eV at the rf power range from 2000 to 4000 W could be obtained. It is known that microcrystalline silicon has higher optical band gap energy compared to amorphous silicon and the optical band gap energy is increased with increasing crystalline volume fraction.[23,24] Therefore, from the above results on σ_D and optical band gap (Tauc') data, it can be concluded that the increase in rf power in the multiple U-type ICP changed the ratio of $H^*_{\text{Fulcher}}/SiH^*$ by changing the plasma mode from *E* mode to *H* mode, and finally, the structure of the deposited film change from amorphous to silicon having more microcrystalline silicon volume fraction.

IV. CONCLUSIONS

The antenna and plasma characteristics of the multiple U-type ICP source and their relationship to the characteristics of the deposited silicon films were investigated as a function of rf power by using pure SiH_4. By increasing rf power to the multiple U-type ICP source, the transition of plasma mode from *E* mode to *H* mode could be observed through the rapid increase in rms antenna current and power transfer efficiency from 200 to 2000 W. The transition of *E* mode to *H* mode increased the high energy tail of the electron energy distribution function, therefore, the significant increase in the ratios of Si^*/SiH^* and $H^*_{\text{Fulcher}}/SiH^*$ could be observed by OES at the transition power range. The significant change in the ratio of $H^*_{\text{Fulcher}}/SiH^*$ measured as a function of rf power changed microstructure of the silicon film deposited on the glass substrate at the temperature of 240 °C. When the silicon was deposited at a low rf power of 300 W which has strong *E* mode, the deposited film showed amorphous structure and the dark conductivity (σ_D) and optical band gap estimated by Tauc' plot were 4×10^{-9} Ω^{-1} cm^{-1} and 1.8 eV, respectively, indicating the characteristics of amorphous silicon. However, when the silicon was deposited at a high power of 4000 W having strong *H* mode, the deposited film showed a microcrystalline structure having 53% of Raman crystallinity. The dark conductivity (σ_D) and optical band gap estimated by Tauc' plot were $2.4 \times 10^{-5}\ \Omega^{-1}\,\mathrm{cm}^{-1}$ and 2.1 eV, respectively, indicating the characteristics of microcrystalline siliconlike structure. Therefore, it is believed that, for the operation of the multiple U-type ICP, by using high rf power which is beneficial in operating at H mode, a silicon film having higher crystallization volume fraction could be obtained. Therefore, the operation at high rf power of the multiple U-type ICP, which is beneficial in operating at H mode, is able to grow silicon films having higher crystalline fraction.

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