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High-Density Hollow Cathode Plasma Etching for Field Emission Display Applications

Joon Hoi Lee[a], Wook Jae Lee[a], Man Sub Choi[b], and Joon Sin Yi[a*]

Abstract

This paper investigates the characteristics of a newly developed high density hollow cathode plasma(HCP) system and its application for the etching of silicon wafers. We used SF_6 and O_2 gases in the HCP dry etch process. This paper demonstrates very high plasma density of 2×10^{12} cm^{-3} at a discharge current of 20 mA. Silicon etch rate of 1.3 μm/min was achieved with SF_6/O_2 plasma conditions of total gas pressure of 50 mTorr, gas flow rate of 40 sccm, and RF power of 200W. This paper presents surface etching characteristics on a crystalline silicon wafer and large area cast type multicrystlline silicon wafer. We obtained field emitter tips size of less than 0.1 μm without any photomask step as well as with a conventional photolithography. Our experimental results can be applied to various display systems such as thin film growth and etching for TFT-LCDs, emitter tip formations for FEDs, and bright plasma discharge for PDP applications. In this research, we studied silicon etching properties by using the hollow cathode plasma system.

Keywords : HCP(Hollow cathode plasma), etch rate, optogalvanic(OG) signal, plasma ion density

1. Introduction

High density plasma system has so far been considered as a key instrument for display system applications. High density plasma illustrates high deposition rate, better film crystal structure and improved etching characteristics[1,2]. Dry etching techniques have become an essential part in the manufacturing of microelectronic devices[3]. Conventional high density plasma source like inductively coupled plasma (ICP) was generated by the application of RF power of greater than 500 W[4-7]. Because of the application of high power during reactive ion etching (RIE) the semiconductor surface is exposed to bombardment by the energetic ions, which greatly enhances the reaction rate of the etching process[8]. However, bombardment results in surface contamination, and can also produce substantial damage in the semiconductor layer, which in turn degrades the material quality.

To overcome these problems, we investigated the HCP system that permits high density plasma source, while keeping a low RF input power. The hollow cathode discharge has been studied over a number of years because of its applicability to spectroscopy source, laser and other diverse devices. This design allows operation with the negative glow region trapped within the cathode cavity, reduces maintenance voltage, and enhances electron multiplication. The hollow cathode discharge is based on the oscillations of electron between repelling potential drop of cathode at the opposite wall of the cathode and hence, the electron density increases in the hollow cathode. Fig. 1 shows the schematic illustration

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[*] Member, KIDS.

Corresponding Author : Joo Hoi Lee

a. School of Electrical and Computer Engineering, Sungkyunkwan Univerwity 300 Chunchun-dong, Jangan-gu, Suwon, Kyunggi-do 440-746, korea.

b. Photon Semiconductor and Energy Co. 300 Chunchun-dong, Jangan-gu, Suwon, Kyunggi-do 440-746, Korea.

E-mail : 1jh8774@hanimail.com **Tel** : +31 290-7139 **Fax** : +31 290-7179

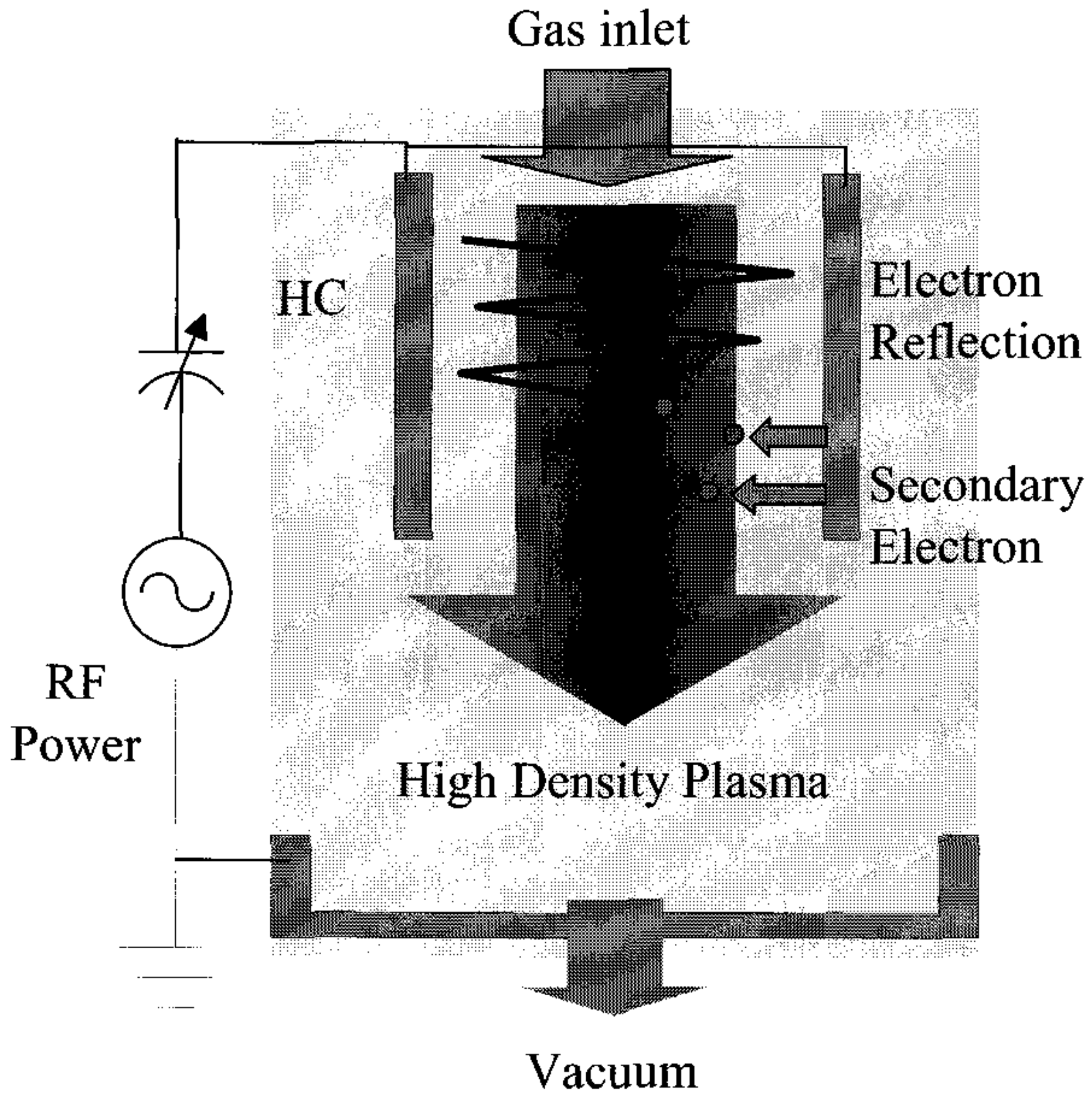

Fig. 1. Schematic illustration of vertical- and circular-type hollow cathode plasma system.

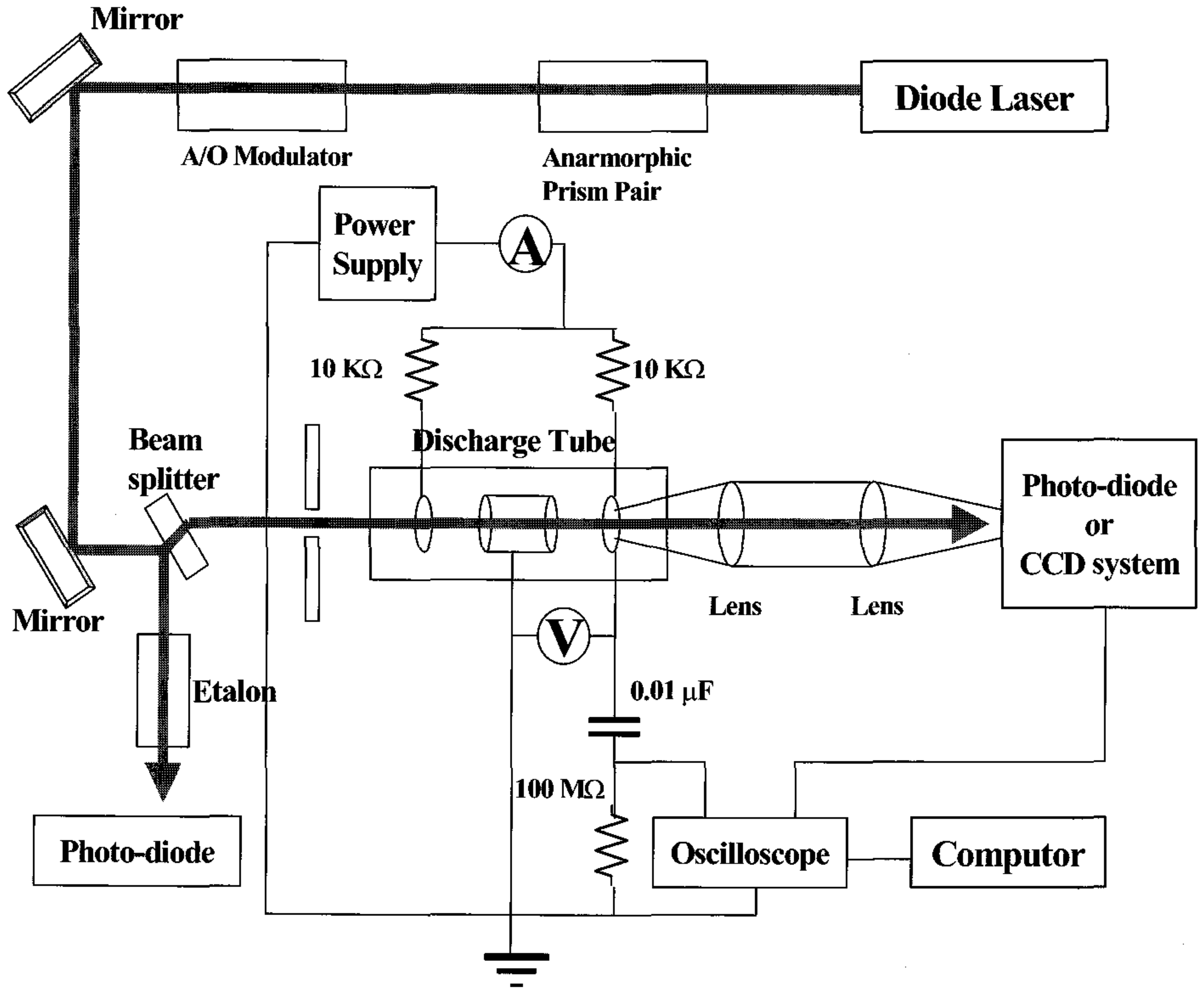

Fig. 2. Experimental setups for the characterization of high density hollow cathode plasma system.

of how the electron density is increased in a HCP system.

We report a successful attempt to form silicon emitter tips by employing a new hollow cathode discharge in a reactive RF sputtering system. Before the start of the plasma etching, we focused on the plasma characteristics of the hollow cathode plasma system. After obtaining a plasma ion density of up to 2×10^{12} cm^{-3}, the HCP system was applied to surface etching studies on a crystalline silicon(c-Si) wafer and large area multicrystlline silicon(mc-Si) wafer.

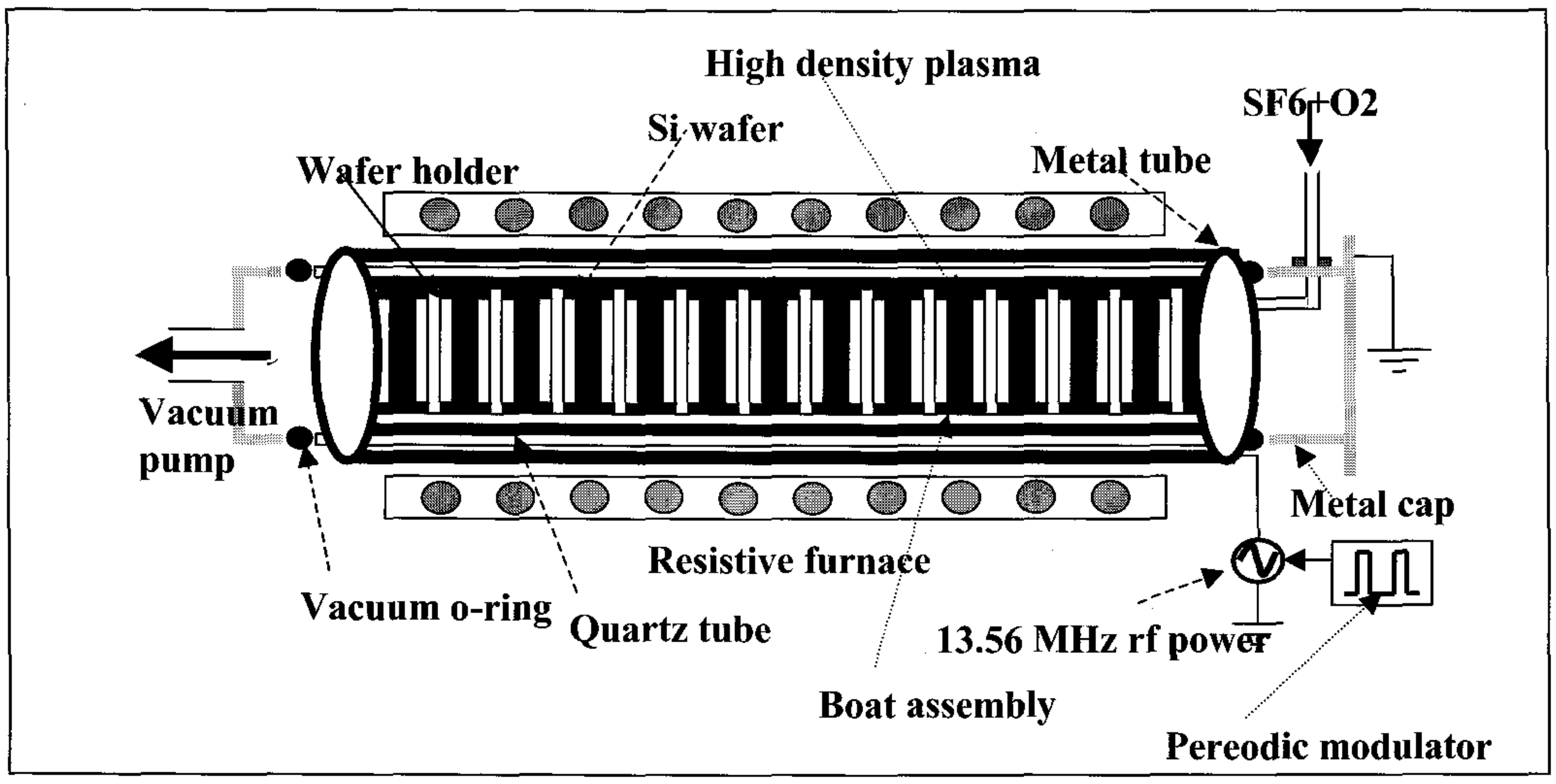

Fig. 3. Schematic Employed HCP system for a single crystal and multicrystal silicon etching study.

2. Experiment

We carried out a characterization of a HCP system, first and then, applied the system in the silicon surface etching study. During the experiment, the optogalvanic (OG) signal was monitoring the plasma conductivity variation caused by the absorption of radiation at a certain spectral transition of the plasma medium. The OG effect technique was developed for the purpose of laser spectroscopy and has been used in plasma diagnosis; such as that, ionization rate, atomic density, and translational temperature of the plasma[9]. The experimental setup for the measurement of the emission and OG signal is shown schematically in Fig. 2. For the OG signal measurement, the laser beam from a CW single-frequency diode laser(Environmental Optical Sensor, Inc., Model ECU-2010) was directed axially along the bore of the hollow cathode. The emission signal has been obtained from a low-noise photo-diode (New Focus Inc., model 1801) while it has been placed along the axis at detected the spatially averaged intensity with the help of two identical biconvex lenses(f = 120 nm, diameter of 50.8 mm). The absorption signal has been obtained in the same configuration and an iris diaphragm of 2 mm in diameter was placed in front of the discharge tube to remove the emission intensity. The emission intensity passing through the iris diaphragm was negligible when the transmitted laser beam intensity was detected.

Fig. 3 shows the schematic illustration of the hollow cathode plasma system used in this study for silicon etching. Hollow cathode array with parallel-type disks (diameter of 50 mm and thickness of 5 mm) was placed inside a 1400 mm long quartz tube. Each cathode disk is separated by about 20 mm. The hollow cathode plasma produced in this design has only two distinctive regions; the cathode dark space and the negative glow of the normal glow discharge regions. This paper investigates the characteristics of this newly developed high density hollow cathode plasma system and the application of this system to Si surface etching study. We used SF_6 and O_2 gases for the dry etch of silicon wafer surface. In our experiment, the inductive power was 200 W at 13.56 MHz. The total pressure(SF_6+O_2) was 50 mTorr and etching time was varied from 5 to 30 minutes. The oxygen partial pressure was maintained at less than 50 % of the total chamber pressure. Surface morphology was observed using an atomic force microscope(AFM) and a scanning electron microscope(SEM, philips, XL30FEG).

3. Results

Fig. 4 shows the emission intensity of a hollow cathode plasma system as a function of position in the plasma discharge. The emission intensity is distributed almost uniformly in the discharge space except in the vicinity of the cathode surface where it has a minimum. Since the buffer gas fills the discharge space uniformly, the spatial emission distributions of buffer gas atoms approximately show the characteristic of the spatial distribution of electrons in the discharge. Therefore, the electron density is quite uniform at the center and linearly decreases as it approaches the cathode wall. Hence, the hollow cathode represents a unique source of dense and stable plasma in the negative glow region. At the same power, the hollow-cathode exhibits plasma density one- or two-orders of magnitude higher than of conventional planar electrodes.

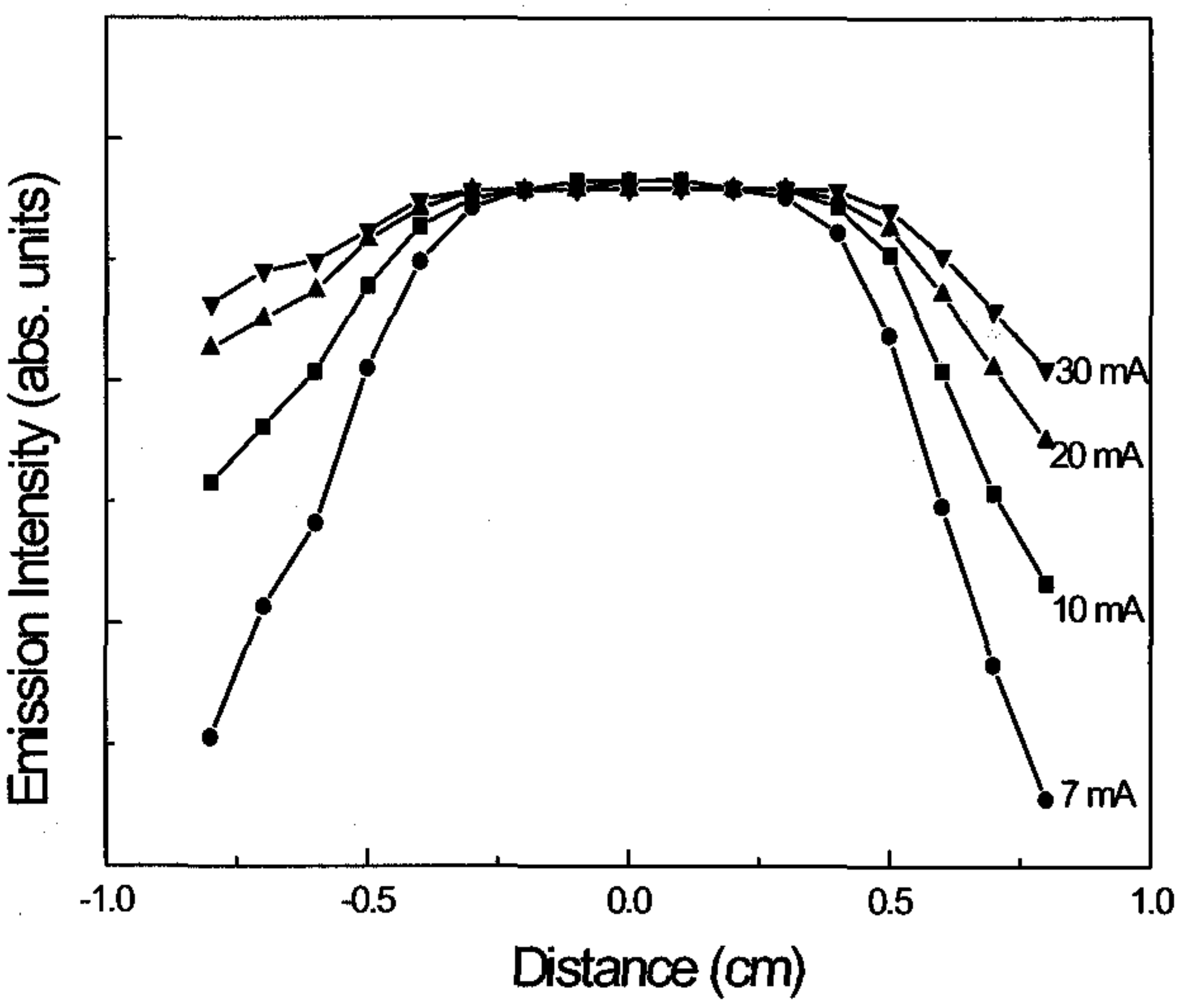

Fig. 4. The radial profile of the emission intensity of a hollow cathode system. The decrease of this signal corresponds to the decrease of electron density.

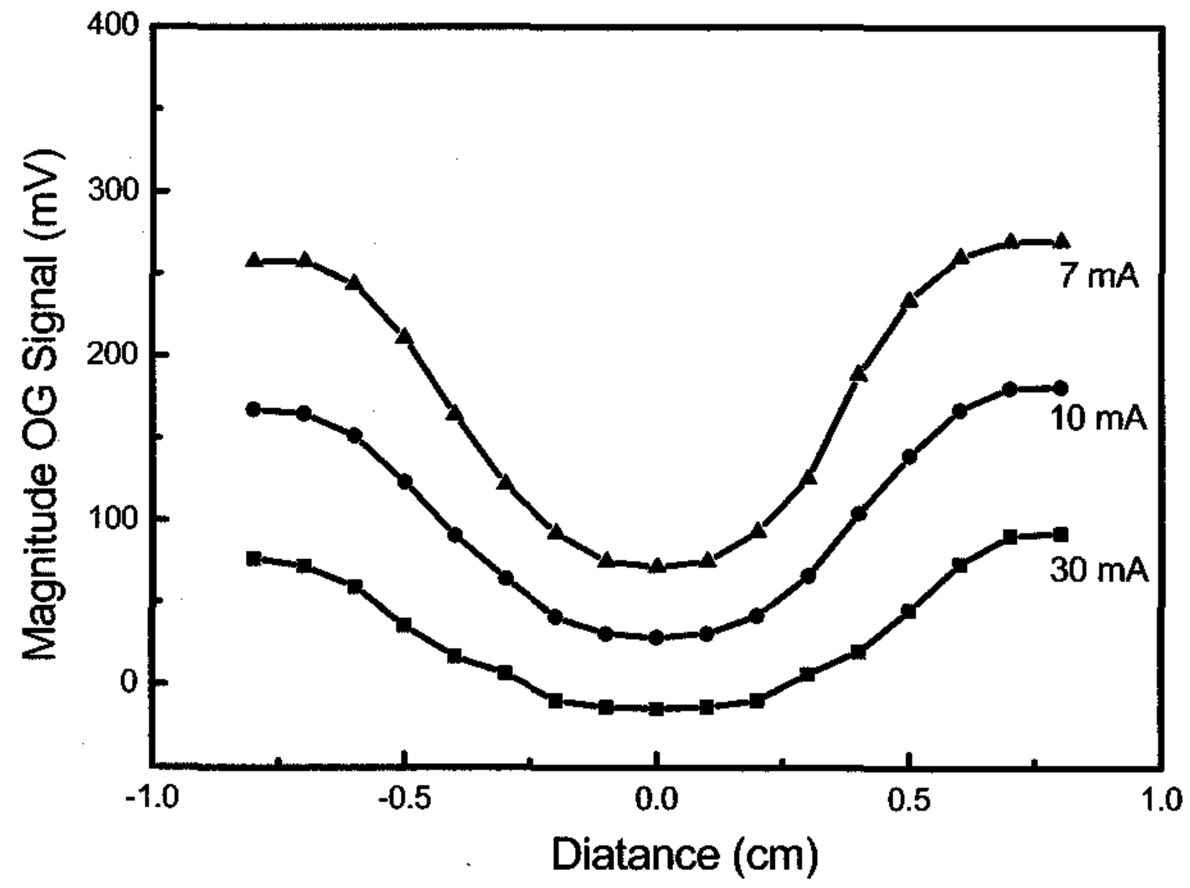

Fig. 5. The magnitude of OG signal at various positions of hollow cathode in the radial direction.

The magnitude of the OG signal exhibited a certain dependence on positions of hollow cathode discharge tube. The spatial distributions of magnitude of the OG signal across a hollow cathode are shown in Fig. 5. To explain the higher OG signal magnitude near the cathode wall than at the center, we need to consider the electron density distribution. The electron density is higher and uniform at the center than near the cathode wall, as seen in Fig. 4. In the vicinity of cathode wall region, where the electron density is lower, the ionization rate due to electron impact is negligible. Therefore, the OG signal has a maximum amplitude near the cathode wall and decreases by one order of magnitude at the center. The OG signal has a minimum and constant value at the center. This is due to the effect of the increased collision ionization rate at the center of the tube, which causes a uniform and high electron density at the center of a HCP system. From this result we predict that a unique source of dense and uniform plasma can be obtained by using a HCP system.

To estimate the plasma density, the absorption spectra have been measured. The ionic charge density can be obtained by the equation[10], where λ is the center wavelength, g_1 and g_2 are the statistical weights of the upper and lower level, respectively, A is the transition probability, and α_υ is the absorption coefficient, The g_2A

$$N = (8\,\pi/\lambda^2)\,(g_1/g_2\,A) \int \alpha_\upsilon\, d\upsilon$$

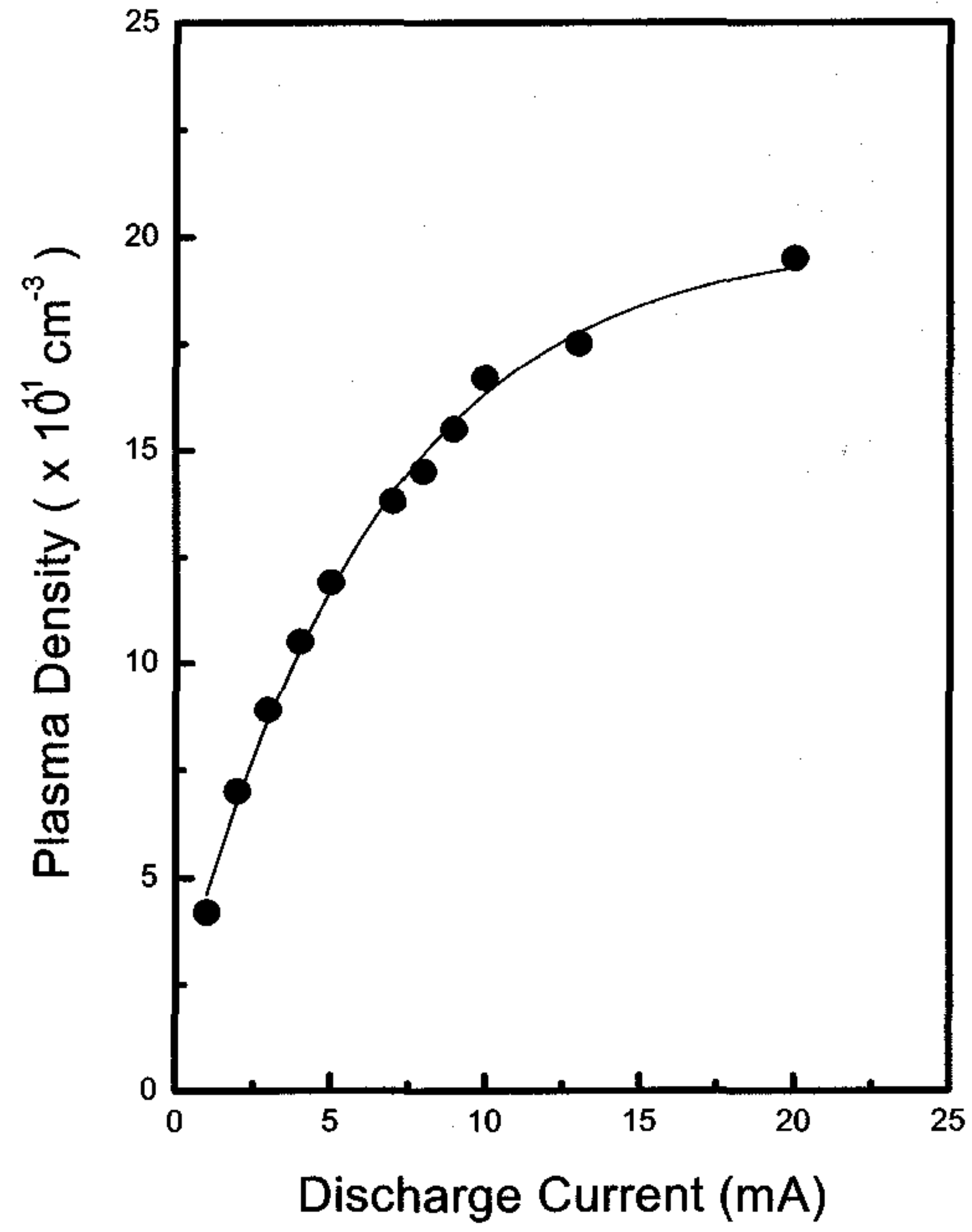

Fig. 6. Plasma density variations as a function of discharge current. The result was estimated from absorption spectra measurement.

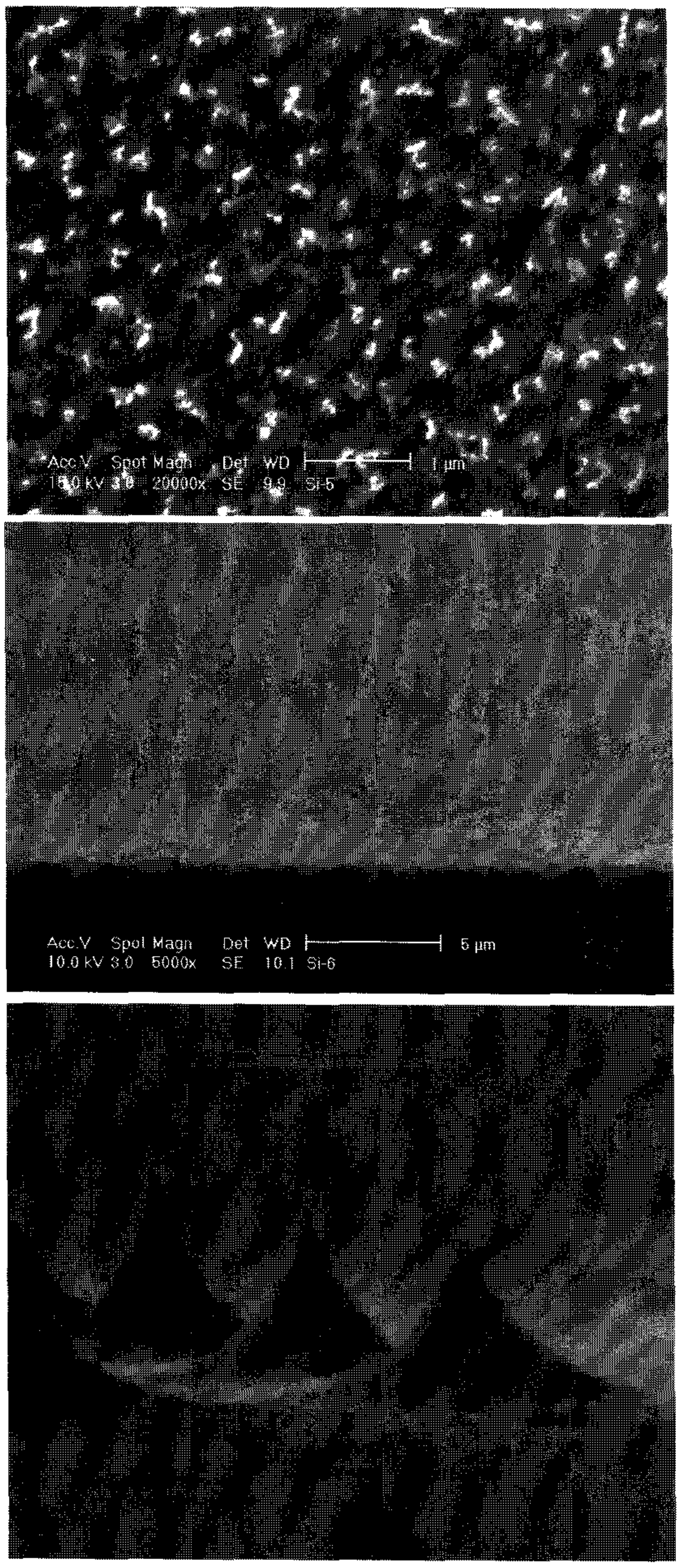

Fig. 7. Surface structure of a single crystal silicon wafer after the various conditions; for top two samples without photolithographic work and for the bottom sample with a conventional field emitter tips generated by PR works (Top: SF_6 =50 mTorr, RF power=100 W, etch time=5 min., middle: SF_6=45 mTorr, O_2=45 mTorr RF power=100 W, etch time=30 min., bottom: SiO_2 mask thickness 200 nm, SF_6=350 mTorr RF power=300 W, etch time=3 min.).

value was taken from the work of Wiese et al.[11]. The estimated atomic density is about 7×10^{11} cm^{-3} for the integrated absorption coefficient($\int \alpha_\upsilon \, d\upsilon$) of about 0.57 GHz·$cm^{-1}$ at the discharge current 2 mA. Fig. 6 shows the plasma density as a function of the discharge current. The calculated plasma density of our HCP system was varied from 10^{11} to 10^{12} cm^{-3}. Such values for the investigated hollow cathode plasma system was considered to be one to two orders of magnitude higher than the capacitively coupled plasma(CCP) system. Our result indicates that the HCP system plasma density is comparable with other high density plasma systems such as ICP and ECR plasma sources. The HCP system generated plasma ion density of up to 2×10^{12} cm^{-3}. This high ion concentrations are expected to yield high deposition rates or give high etch rates in various display system fabrication processes.

The HCP system of the present study was used in the etching study of silicon surface. Surface morphology study after the HCP etch process showed a strong dependence on process conditions such as plasma power, process temperature, SF_6 and O_2 gas ratio and flow rates. Fig. 7 shows the SEM photograph images of a single crystalline silicon wafer surface after HCD plasma etching. For the first two samples shown in the figure were bare silicon wafers exposed to the HCP plasma system. An etch rate of 1.3 µm/min was achieved with SF_6/O_2 plasma conditions of total gas pressure=50 mTorr, gas flow rate=40 sccm, and RF power=200 W. The first sample was etched in SF_6 =50 mTorr, RF power=100 Watt, etch time=5 min and the second sample was prepared with SF_6=45 mTorr, O_2=45 mTorr RF power=100 W, etch time=30 min. Our surface morphology study showed a tip formation with and without photolithographic work. From the second sample, we were able to generate needle-like field emitter tips less than 0.1 µm size even without any photolithographic work. Similar results of needle-like tips were obtained by generating a black silicon surface[12]. Etch product like SiO:F increased the anisotropy of the etched silicon surface. Our result can be applied to form a filed emitter array by first forming the gas and then defining field emitter.

Motivated by the etching characteristics on a single crystaline silicon wafer, we directed our research work to a multicrystalline silicon wafer because mc-Si wafers can be prepared with larger area upto 800 mm by 800 mm. Fig. 8 displays the AFM images for the multicrystal silicon wafer before and after the HCP etch process. Surface structure of as-cut mc-Si wafer[Fig. 8(a)] exhibited saw damaged roughness less than 30 µm. This rough surface was greatly improved after chemical

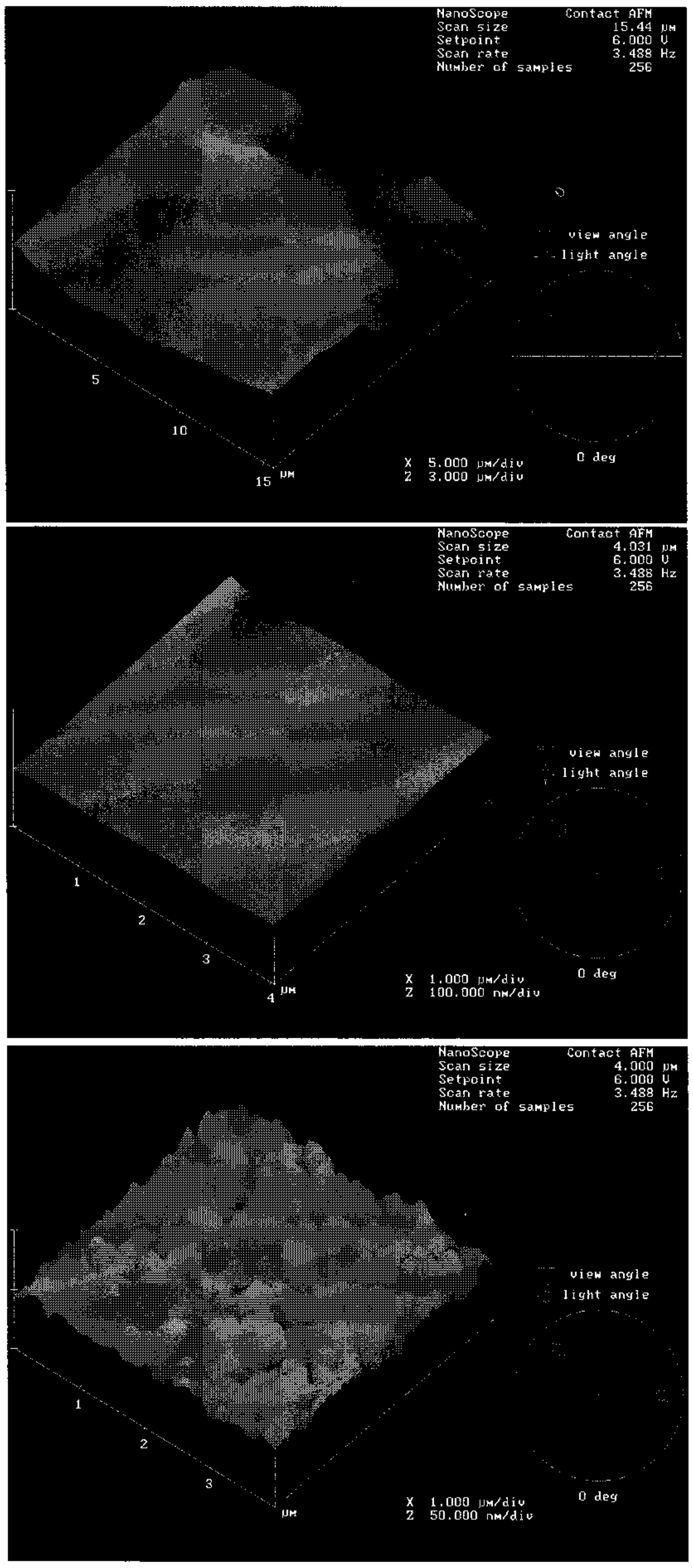

Fig. 8. Surface structure of a multicrystal Si wafer i) top: s-cut mc-Si, ii) middle: chemically polished and without HCP etch iii) bottom: chemically polished and with HCP etch SF_6=45 mTorr, O_2=45 mTorr RF power=100 W, etch time=10 min.

polishing steps[Fig. 8(b)]. We achieved the pyramid-type emitter tips for the sample after chemical polishing and then exposing it to the HCP system under the process conditions of SF_6=45 mTorr, O_2=45 mTorr, RF power=100 W, and etch time=10 min. Our newly developed etch system and etch process are very promising in various display systems such as thin film growth and etching for TFT-LCDs, emitter tip formations for FEDs, and bright plasma discharge for PDP applications.

4. Conclusion

In this paper, we investigated the characteristics of a newly developed HCP system and then directed the system application to mono- and multi-crystal silicon wafer surface etching. The HCP system generated plasma ion density up to 10^{12} cm^{-3}. We obtained silicon etch rate of 1.3 µm/min. at a low input power of 200 W. This paper presented the HCP system application in FED emitter tip generation. Our experimental results are expected to be used in a wide range of display systems because of the HCP capability of high plasma generation at a low discharge power of less than 200 W.

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