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Thin Solid Films 475 (2005) 318–322
thin solid films
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Fabrication of SiC micro-lens by plasma etching

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Available online 15 January 2005

Abstract

SiC micro-lenses were fabricated by a plasma etching method by controlling the etch selectivities between photoresist and SiC. To etch SiC, inductively coupled plasmas were used with CF_4, HCl, and HCl/HBr as the etch gases. When CF_4 and HCl were used to etch SiC, the etch selectivities of SiC over photoresist were remained near 0.4 and 0.6, respectively. However, by using HCl/HBr, the selectivity was changed from 0.6 to 1.1. The SiC etch rates for HCl/HBr were in the range from 345 to 500 nm/min. The curvature radius of SiC micro-lenses fabricated with HCl/HBr was in the range from 20 to 27.54 μm and the roughness of the fabricated lenses was in the range from 1.7 to 2.65 nm.

Keywords: SiC; Plasma etching; Micro-lens

1. Introduction

Micro-lenses are applied to optoelectronic devices such as emitters and detectors to enhance optical efficiency by reducing the scattered lights and converging the incident lights, respectively. Also, in the case of microelectromechanical systems (MEMS), it is used to convert the optical path or used for the optical interconnections.

SiC is used as the substrate for optoelectronic devices such as light-emitting diodes (LEDs) and laser diodes (LDs) and also for microelectromechanical systems (MEMS). Micro-lenses that are required for collecting lights emitted from the devices have been generally formed by a reflowed photoresist having a lens shape [1–3]. However, if the micro-lenses are directly fabricated on the substrates by etching the reflowed lens-shape photoresist, higher optical efficiency can be obtained [4]. Therefore, the formation of micro-lenses by plasma etchings has been studied recently by etching the reflowed photoresist all the way to the substrate with the etch selectivity of 1.0 for GaN and SiO_2 [4–6]. However, no study has been reported on the formation of SiC micro-lenses that are also used for LED and LD devices. To fabricate micro-lenses on the substrates, not only the SiC etch rates but also the curvature and roughness of the micro-lens should be considered. Therefore, in this study, SiC micro-lenses have been fabricated with a reflowed photoresist and the possibility to form micro-lenses having various curvature radius with minimal roughness has been investigated using an inductively coupled plasma etching equipment with CF_4, HCl, and HCl/HBr gases.

2. Experimental

Fig. 1 shows the schematic diagram of the inductively coupled plasma etching system used in the formation of SiC micro-lenses. 13.56 MHz rf power (0–2 kW) was applied to the center of the gold-coated 3-turn square coil to generate inductively coupled plasmas. Also, a separate 13.56-MHz rf power (0–2 kW) was used to generate dc-bias voltage to the wafers.

6H-SiC wafers were used as the etch samples and reflowed photoresist (AZ 9260) having a lens shape was used as the etch mask. To investigate SiC etch rates and the etch selectivities over photoresist, inductive power was varied from 700 to 1400 W using 50 sccm of HCl or CF_4 while keeping dc-bias voltage and working pressure at −150 V and 10 mTorr, respectively. Also, mixtures of HCl and HBr

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0040-6090/$ - see front matter © 2004 Published by Elsevier B.V.
doi:10.1016/j.tsf.2004.08.056

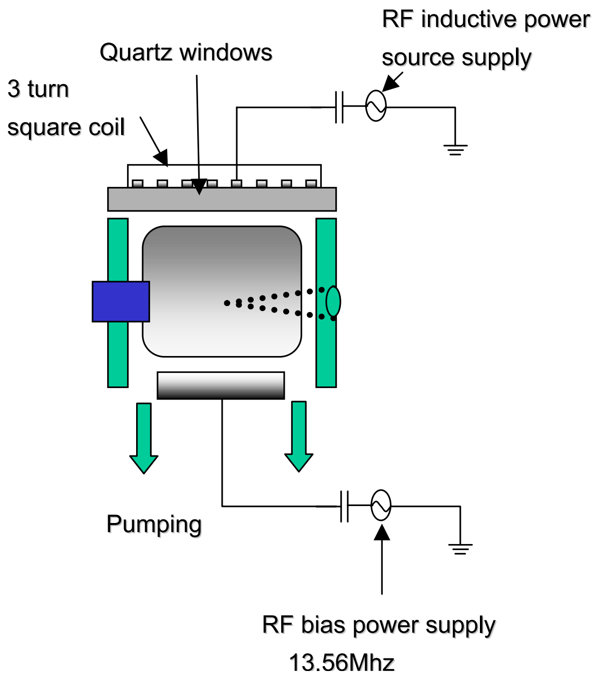


Fig. 1. Schematic diagram of the inductively coupled plasma etch system used in this study.

were used to improve the etch selectivity of SiC over photoresist. The substrate temperature was kept at 273 K.

The etch rates of SiC and photoresist were measured using a depth profilometer (Alpha-step 500, Tencor). Etch profiles and surface roughness were measured using a scanning electron microscope (SEM; S-4700, Hitachi) and an atomic force microscope (AFM: AP0100, TM), respectively.

3. Results and discussion

Fig. 2 shows the effect of gas and inductive power on the etch rates of SiC and the etch selectivities of SiC over photoresist. The etch gases, HCl and CF_4, were used while keeping other etch parameters such as gas flow rate, working pressure, and dc-bias voltage at 50 sccm, 10 mTorr, and −150 V, respectively. As shown in Fig. 2, the increase of inductive power increased SiC etch rates for both HCl and CF_4; however, the etch rates with HCl were higher than those with CF_4. The etch rates of photoresist were higher than those of SiC and also increased with inductive power. Therefore, the etch selectivities of SiC to photoresist were lower than 1 and remained similar with inductive power. In Fig. 2, the etch selectivities were about 0.4 and about 0.6 for CF_4 and HCl, respectively.

The increase of SiC etch rates with inductive power is related to the increase of reactive ions and radicals in the plasma, which is required to form volatile etch products with SiC at high powers. The possible etch products formed by H and Cl in HCl are SiH_4 (m.p: −88 K), $SiCl_4$ (m.p: −204 K), CH_4 (m.p: 90.3 K), and CCl_4 (m.p: 250 K) and these etch products are volatile at room temperature. In the case of CF_4, only F in CF_4 forms volatile SiF_4 (m.p: 183 K) and C in CF_4 does not form volatile etch products with SiC; therefore, the etch rates of SiC with CF_4 appear to be lower than those with HCl in the experiment. The etch selectivities to photoresist lower than 1 appear to be from the formation of easier and more volatile etch products with reactive ions and radicals by HCl and CF_4 for photoresist compared to SiC. Negligible change of etch selectivity of SiC to photoresist with inductive power appears to be from the increased reaction of photoresist by increased reactive ions and radicals similar to SiC at higher powers. In Fig. 2, the highest SiC etch rate for the investigated experimental conditions was 345 nm/min with HCl at 1400 W inductive power.

To change the etch selectivity to photoresist, HBr was added to 50 sccm HCl while other etch conditions such as inductive power, dc bias voltage, and working pressure are maintained at 1400 W, −150 V, and 10 mTorr, respectively. The measured SiC etch rates and etch selectivities to photoresist are shown in Fig. 3. As shown in Fig. 3, the addition of HBr up to 60 sccm increased the SiC etch rate and etch selectivity and the further increase of HBr decreased the etch rate and etch selectivity. The highest etch rate was 503 nm/min and the etch selectivity was 1.1. The increase of SiC etch rate with the addition and increase of HBr to HCl appears related to the increased ion bombardment effect by heavier Br ions because the vapor pressures of etch products such as CBr_4 (m.p: 363 K) and $SiBr_4$ (m.p: 278 K) formed by HBr are lower than those by HCl. The increase of etch selectivity to photoresist is due to the negligible change of photoresist etch rate with the addition and increase of HBr; therefore, Br ion bombardment by HBr appears not to significantly affect the photoresist etch rate compared to the chemical reaction of photoresist with Cl and Br. The decrease of SiC etch rate at

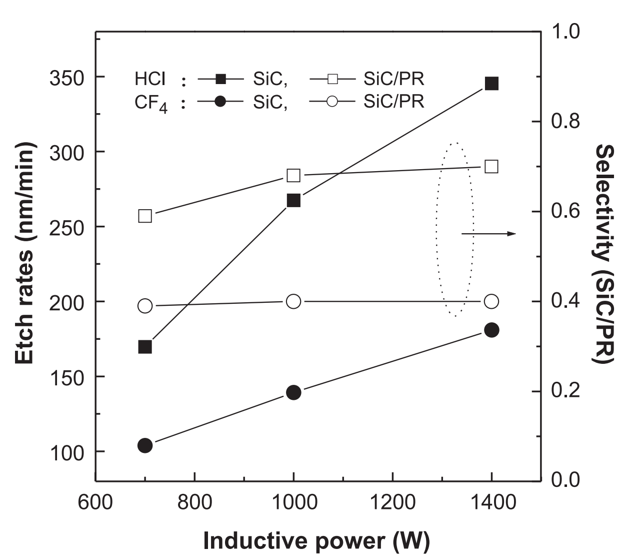


Fig. 2. Measured SiC etch rates and PR selectivity as a function of inductive power for HCl and CF_4 (inductive power: 700–1400 W; bias voltage: −150 V; total gas flow rates: 50 sccm; working pressure: 10 mTorr).

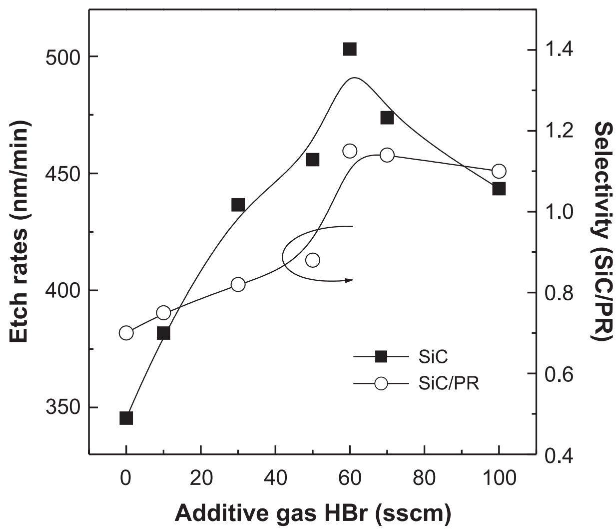


Fig. 3. Measured SiC etch rates and PR selectivity as a function of additive HBr (inductive power: 1400 W; bias voltage: −150 V; HCl: 50 sccm; working pressure: 10 mTorr).

high HBr addition appears related to significant formation of CBr_4 on the SiC surface, which has lower vapor pressure than CCl_4.

The etch selectivity by the addition of HBr to HCl changed from 0.6 at HCl only to 1.1 by the addition of 60 sccm HBr. Using some of the etch conditions in Fig. 3, photoresist having a lens shape was etched and its change of curvature was investigated. Fig. 4 shows the SEM photographs of photoresist having a lens shape and various SiC lenses formed by various etch conditions. To form a micro-lens-shaped photoresist, the photoresist was baked at 110 °C for 30 min followed by baking at 200 °C for 30 s at a hot plate. The diameter and height of the photoresist micro-lens were 26 and 4.3 μm, respectively. The calculated curvature radius of the photoresist micro-lens was 21.8 μm. The SiC with the photoresist was etched at 50 sccm HCl (b), 50 sccm HCl+50 sccm HBr (c), and 50 sccm HCl+60 sccm HBr (c), which has the etch selectivity of SiC to photoresist, 0.6, 0.9, and 1.1, respectively, until all of the photoresist is etched away. As shown in Fig. 4, by varying the etch selectivity, various SiC micro-lenses having different curvatures could be obtained. The curvature radiuses with 50 sccm HCl, 50 sccm HCl+50 sccm HBr, and 50 sccm HCl+60 sccm HBr were 27.5, 25.2, and 20.0 μm, respectively. Therefore, by varying the etch selectivity, the SiC micro-lens having curvature radius from lower to higher than that of photoresist micro-lens could be obtained. It is believed that these SiC micro-lenses having various curvatures could be used for the fabrication of various SiC-based optical devices.

In the case of conventional LEDs and LDs, the size of the device is about 200–300 μm. To collect the light emitted

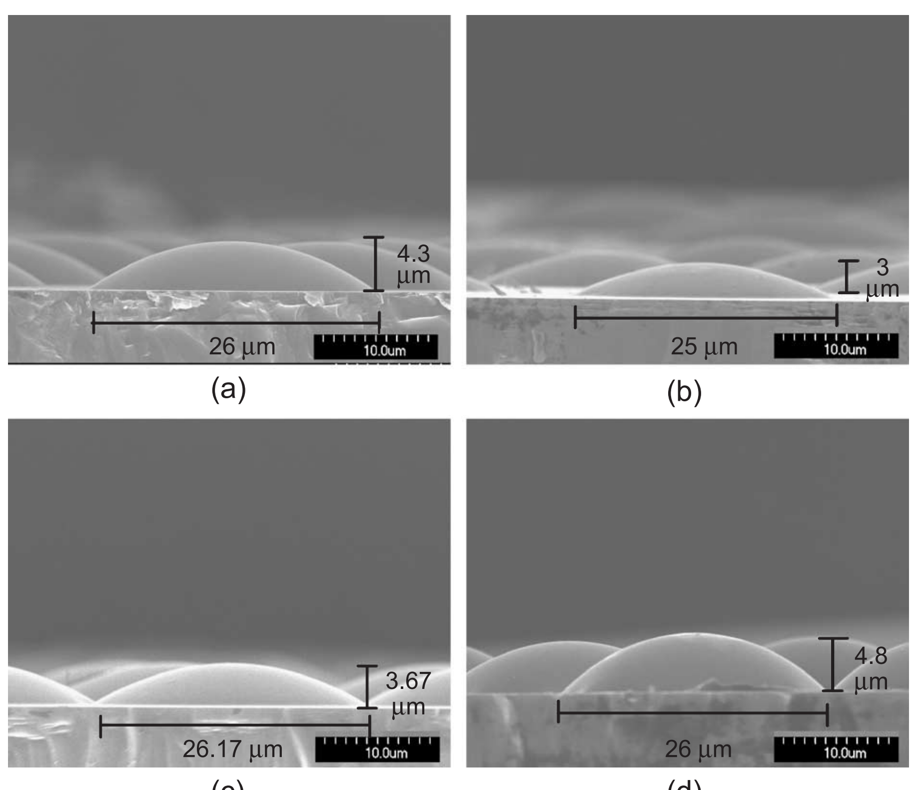
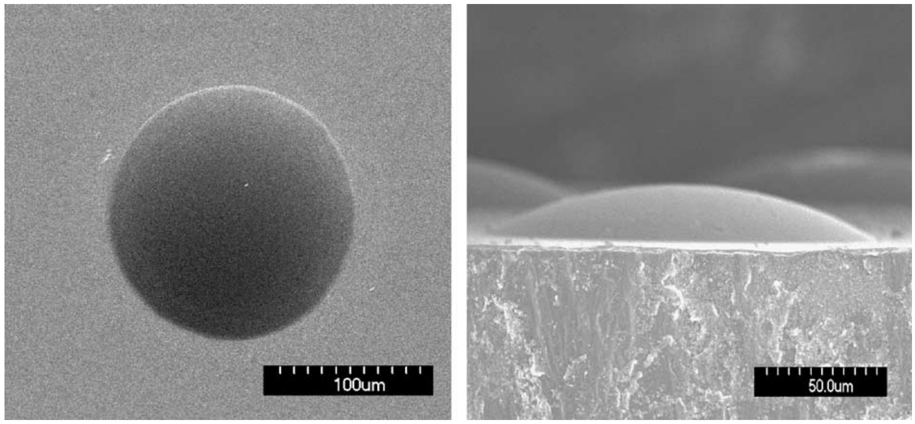


Fig. 4. SEM micrographs of the etched SiC micro-lens structures. (a) reflowed PR micro-lens, (b) HBr 0 sccm, (c) HBr 50 sccm, and (d) HBr 60 sccm (inductive power: 1400 W; bias voltage: −150 V; HCl: 50 sccm; working pressure: 10 mTorr).



(a) (b)

Fig. 5. SEM micrographs of the etched SiC micro-lens having about 200-μm diameter (inductive power: 1400 W; bias voltage: −150 V; gas composition: HCl 50 sccm+HBr 60 sccm; working pressure: 10 mTorr).

from the devices, a micro-lens having the size of 200–300 μm should be fabricated on the device. Using 21-μm-thick photoresist, a photoresist micro-lens having 200-μm diameter was formed and etched using 50 sccm HCl+60 sccm HBr. The other etch conditions such as inductive power, dc bias voltage, and working pressure were also kept at 1400 W, −150 V, and 10 mTorr. Fig. 5(a),(b) shows the top and side view, respectively, of the fabricated SiC micro-lens having 200 μm diameter. The curvature radius of the SiC micro-lens is 218 μm and it is applicable to current optical devices.

To apply SiC micro-lenses to current optical devices, the surface of the lenses should be smooth to increase optical collection efficiency. To figure out the degree of smoothness of the fabricated SiC micro-lenses, the roughness of the etched SiC surfaces for various etch conditions were investigated. Fig. 6 shows the roughness data of the received and etched SiC surfaces measured by AFM. The flow rate of HBr added to HCl was from 0 to 60 sccm at 1400-W inductive power, −150 V dc bias voltage, and 10 mTorr working pressure, and which are the same as the conditions used in Fig. 3. As shown in Fig. 6, the roughness before the etching was 1.43 nm; after the etching, the roughness was changed from 1.7 to 2.65 nm. However, the increase of the roughness after the etching was not significant. Therefore, it is believed that the SiC micro-lens fabricated by the etching can be used for the SiC-based optical devices without loss of optical efficiency.

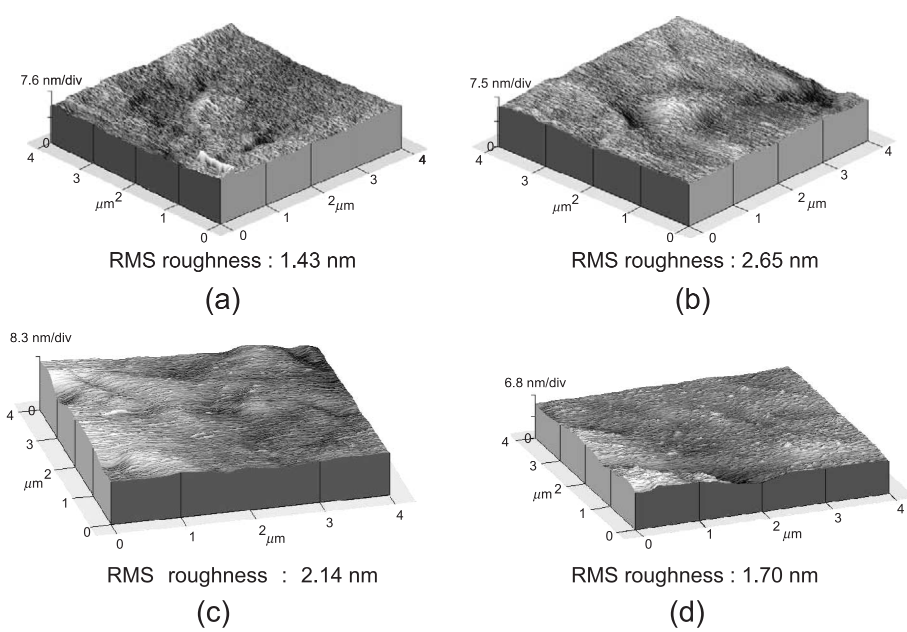


Fig. 6. AFM micrographs of the etched SiC surfaces. (a) SiC before etching, (b) HBr 0 sccm, (c) HBr 50 sccm, and (d) HBr 60 sccm (inductive power: 1400 W; bias voltage: −150 V; HCl 50 sccm; working pressure: 10 mTorr).

4. Conclusions

In this study, the etch rates of SiC and etch selectivities to photoresist were investigated as a function of inductive power for HCl and CF_4 and as a function of gas mixture of HCl and HBr. The various etch selectivities obtained using HCl and HCl/HBr were used to fabricate SiC micro-lenses as the application to the SiC-based optical devices.

When HCl and CF_4 were used to etch SiC, the etch rates and etch selectivities obtained by HCl were higher than those by CF_4 possibly due to the differences in the volatility of various etch products formed by HCl and CF_4. The increase of inductive power increased the SiC etch rates for both for HCl and CF_4; however, the etch selectivities with inductive power remained similar due to the increase of photoresist etch rates with inductive power. The addition of HBr to HCl up to 60 sccm increased the SiC etch rates and the etch selectivities possibly by the increased Br ion bombardment effect on the SiC etching.

The etch selectivities of SiC to photoresist from 0.6 to 1.1 obtained by adding HBr to HCl were applied to the formation of SiC micro-lenses having various curvatures. By varying the HBr to HCl, various micro-lenses having various curvature radiuses could be obtained, and the increase of the roughness of SiC after the etching was insignificant. Therefore, it is believed that SiC micro-lenses formed by the etching could be applicable to the SiC-based optical devices.

Acknowledgments

This work was supported by a National Research Laboratory program by the Ministry of Science and Technology in Korea.

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