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The Study on the Uniformity, Deposition Rate of PECVD SiO_2 Deposition

Eun Hyeong Kim[*,**], **Yoon Hee Choi**[*,**], **Hyeon Ji Jeon**[*,**], **Woo Hyeok Jang**[*,**] **and Garam Kim**[*†]
[*†] Department of Electronics Engineering, Myongji University,
[**] Semiconductor Equipment Engineering Program, Myongji University

ABSTRACT

SiO_2, renowned for its excellent insulating properties, has been used in the semiconductor industry as a valuable dielectric material. High-quality SiO_2 films find applications in gate spacers and interlayer insulation gap-fill oxides, among other uses. One of the prevalent methods for depositing these SiO_2 films is plasma enhanced chemical vapor deposition (PECVD) favored for its relatively low processing costs and ability to operate at low temperatures. However, compared to the increasingly utilized atomic layer deposition (ALD) method, PECVD exhibits inferior film characteristics such as uniformity. This study aims to produce SiO_2 films with uniformity as close as possible to those achieved by ALD through the adjustment of PECVD process parameters. we conducted a total of nine PECVD processes, varying the process time and gas flow rates, which were identified as the most influential factors on the PECVD process. Furthermore, ellipsometry analysis was employed to examine the uniformity variations of each process. The experimental results enabled us to elucidate the relationship between uniformity and deposition rate, as well as the impact of gas flow rate and deposition time on the process outcomes. Additionally, thickness measurements obtained through ellipsometer facilitate the identification of optimal process parameters for PECVD.

Key Words : PECVD(Plasma Enhanced Chemical Vapor Deposition), SiO_2, Uniformity, Deposition Rate

1. Introduction

Silicon dioxide (SiO_2) has been widely used as a dielectric material in the semiconductor industry due to its excellent insulating properties such as wide bandgap, low leakage current, and good thermal stability [1]. It is particularly widely used in memory device applications [2,3]. For example, high-quality SiO_2 films have been used as gate spacers or have been examined as gap-fill oxides for interlayer insulation. It is also used as a tunneling layer for insulating layers into paths through silicon and electron charging trap layers in memory devices [4]. The most common method of depositing SiO_2 is to grow thermally through the oxidation of silicon or to use plasma enhanced chemical vapor deposition (PECVD). PECVD is relatively inexpensive, well-controlled [5,6], and can avoid defect formation, doping diffusion, and metal layer collapse by processing at low temperatures between 60℃ and about 300℃ [7]. These PECVDs have advantages in terms of applicability and economics, making them a promising technology for depositing films and playing a key role in the semiconductor and display manufacturing industries [8]. Uniformity and roughness are important factors that directly affect the quality of the film. The uniformity and roughness of the SiO_2 film are determined by process variables such as chamber pressure, substrate temperature, RF power, gas flow, deposition time, etc. [9]. Therefore, it is important to understand and optimize the relationship between the properties of the thin film and the process variables in order to improve the quality of the thin film [10,11].

[†] E-mail: garamkim@mju.ac.kr

One of the main disadvantages of PECVD is its failure to match the excellent uniformity achieved by atomic layer deposition (ALD) technology. ALD technology is of high interest as a technology that can form uniform thin films even in complex structures with precise thickness control [1]. However, ALD provides excellent uniformity but is limited to large-scale industrial applications due to its high cost. Therefore, the motivation for this study stems from the need to enhance the uniformity of SiO_2 films deposited by PECVD to levels comparable with ALD. By investigating and optimizing key PECVD process parameters such as deposition time and gas flow rates, this research aims to identify the conditions that yield the best uniformity for SiO_2 films. This optimization not only improves the PECVD process but also makes it a more attractive alternative to ALD in terms of cost and practicality for industrial applications.

Accordingly, this study aims to investigate the effect of the deposition time on the uniformity of SiO_2 thin film deposited through PECVD and the ratio of N_2O/SiH_4 gas. By analyzing the relationship between these parameters, we aim to identify the optimal process recipe in which the SiO_2 thin film deposited with PECVD has a high level of uniformity.

In this study, the relationship between the change of deposition rate and uniformity according to the N_2O/SiH_4 gas ratio and deposition time was investigated. In this study, the deposition process was carried out by setting the ratio of N_2O/SiH_4 gas to 2.778, 3.889 and 5 to obtain good uniformity with gases with low N content. In addition, in order to observe the change of uniformity over time, the deposition was carried out by setting it to 5 min, 10 min, and 15 min. In order to investigate the effect of the ratio of N_2O/SiH_4 gas and the deposition time on the uniformity of the SiO_2 thin film deposited on the wafer after the deposition process, it was observed using ellipsometry by dividing it into five parts: center, top, bottom, left, and right. The correlation between the changes and the optimal process recipe were studied by investigating the N_2O/SiH_4 gas flow rate ratio and the change of the uniformity and deposition rate of the SiO_2 thin film according to the deposition time.

2. Experiment

In this experiment, SiO_2 films were deposited using equipment from Plasmart, specifically a capacitively coupled plasma (CCP) type 6-inch chamber with a 13.56 MHz RF power supply capable of delivering up to 600 W, and a 13.56 MHz single RF matcher. A p-type Si(100) wafer was used as a substrate to deposit the SiO_2 film, and a total of runs were performed according to the N_2O/SiH_4 gas flow ratio and deposition time. The recipe for SiO_2 deposition is as follows; $SiH_4 + 2N_2O \rightarrow SiO_2 + 2H_2 + 2N_2$ [12]. Table 1 shows the SiO_2 process recipe. Ellipsometry was used to measure the thickness of films. Fig. 1 shows the locations of these 5 measurement points. Equation 1 was used for the uniformity considered in this study. Where t_{max} is the maximum thin film thickness, t_{min} is the minimum thin film thickness, and avg is the average thin film thickness.

Table 1. SiO_2 Deposition Process Recipe

Experiment	Unit	Value
Temperature	°C	300
Power(W)	Watt	350
Pressure	mTorr	1000

Run	N_2O (sccm)	SiH_4 (sccm)	time (min)
1	25	9	5
2	35		
3	45		
4	25		10
5	35		
6	45		
7	25		15
8	35		
9	45		

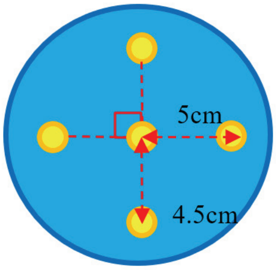

Fig. 1. Mapping measurement point information.

Equation 1. Uniformity calculation

$$uniformity = \frac{(t_{max} - t_{min})}{2 \times avg} \times 100$$

3. Results and Discussion

The experimental conditions yield the results shown in Table 2. Using ellipsometry measurements, we determined both the uniformity and deposition rate. Most of the uniformity values were below 10%, except for the condition where the N_2O gas flow rate was 25 sccm and the process time was 5 minutes, which resulted in the worst uniformity at 17.162%.

Table 2. Uniformity percentage and deposition rate of the oxide according to deposition time and gas flow rate

N_2O (sccm)	SiH_4 (sccm)	time (min)	Uniformity (%)	Dep rate (Å/sec)
25	9	5	17.162	1.318
35			7.402	1.177
45			11.061	0.988
25		10	10.456	1.580
35			7.499	1.532
45			8.276	1.484
25		15	8.924	1.509
35			8.579	1.336
45			9.099	1.224

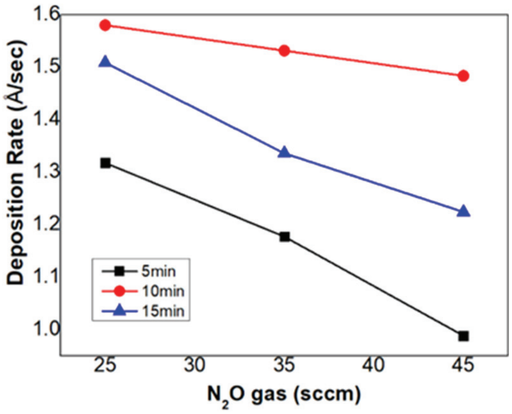

Fig. 2. Effects of gas flow rate on deposition rate.

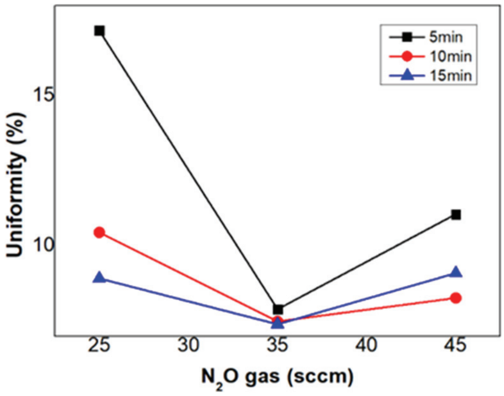

Fig. 3. Effects of gas flow rate on uniformity.

Fig. 2 illustrates the deposition results of SiO_2 using PECVD with varying process times of 5, 10, and 15 minutes, each under different N_2O gas flow rates. This study investigates the impact of the gas flow ratio of N_2O to SiH_4 and process time on the deposition rate. As observed from the Fig. 2, the deposition rate decreases with increasing N_2O gas flow, irrespective of the process time. Fig. 3, derived from ellipsometer measurements, presents the uniformity of each wafer and examines the influence of gas flow ratio and process time on uniformity. The uniformity improves with increasing N_2O gas flow, reaching its peak at 35 sccm, beyond which the uniformity deteriorates.

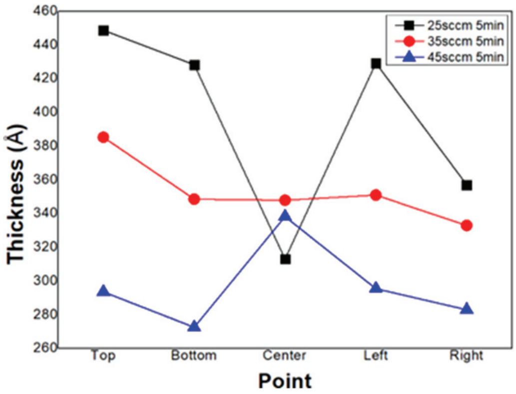

Fig. 4. Thickness variation at 5 minutes deposition time.

Fig. 4 presents the thickness profile of three wafers deposited for 5 minutes at various points. The wafer with the best uniformity was deposited with an N_2O gas flow rate of 35 sccm. This wafer demonstrated a relatively uniform thickness of deposited SiO_2 across all 5 measured points, regardless of position. Unlike the wafer deposited at an N_2O flow rate of 35 sccm, wafers deposited at N_2O flow rates of 25 sccm or 45 sccm exhibited significant variations in SiO_2 thickness depending on the position. The wafer deposited at 25 sccm showed a rapid deposition rate at the top, bottom, and left positions, while the wafer deposited at 45 sccm exhibited a slower deposition rate at all positions except the center.

In the case of a high deposition rate in PECVD, excessive surface reactions and subsequent deposition may occur only in specific areas where the reactive gas is supplied, resulting in decreased uniformity. In contrast, when the deposition rate is low, the reactive gas may be diluted by byproducts or expelled from the chamber before surface reactions can occur across the entire wafer, which can also lead to decreased uniformity [1]. Therefore, to achieve high uniformity in PECVD, it is necessary to optimize the gas flow rate and deposition rate. In this process, the optimal conditions for achieving the best uniformity are found to be at a SiH_4flow of 9 sccm and N_2O flow of 35 sccm.

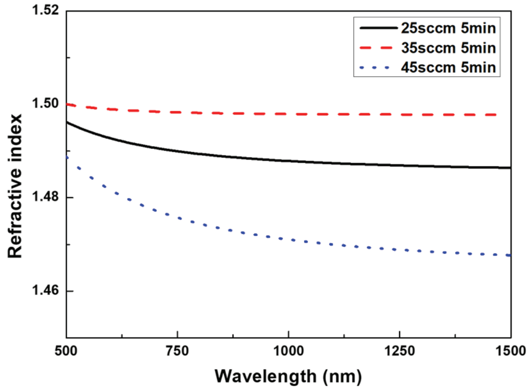

Fig. 5. Refractive index at 5 minutes deposition time.

In order to analyze the characteristics of the deposited SiO_2 film, the refractive index was measured using spectroscopic ellipsometry. It is well-known that SiO_2 films with lower density exhibit a lower refractive index [13]. As shown in Fig. 5, the comparison of the refractive index for SiO_2 films deposited for 5 minutes indicates that wafers with poor uniformity also display lower refractive indices. This correlation suggests that improving the uniformity of the PECVD process can also enhance the density and the quality of the SiO_2 films.

4. Conclusion

In this study, SiO_2 thin films were deposited using plasma-enhanced chemical vapor deposition (PECVD). The effects of the N_2O/SiH_4 gas ratio and deposition time on the deposition rate and uniformity of SiO_2 thin films were analyzed by dividing these PECVD process variables into various levels.

Experimental results showed that as the gas ratio increased, the deposition rate tended to decrease, while uniformity exhibited an increasing trend within a specific range. Decreases in uniformity were observed both at high and low deposition rates. Consequently, the maximum uniformity of the films was achieved within a specific range where the deposition rate based on the N_2O/SiH_4 gas ratio was neither too high nor too low.

Based on the measured data, the N_2O/SiH_4 gas ratio and deposition time were statistically proved to be the main variables in securing the uniformity of the SiO_2 film deposited with PECVD, and the optimal process conditions contributing to the improvement of uniformity were derived by identifying the relationship between the major variables.

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