ORIGINAL ARTICLES

Taguchi’s Method of Statistical Design to Form an Ultra Thin Silicon Dioxide

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ABSTRACT

Taguchi method was performed on a series of ultra thin SiO₂ films in order to study the parameter affecting the oxide growth. The samples of ultra thin SiO₂ were prepared through a dry oxidation method using a high temperature furnace. There are three level of temperature used, that are 750, 800 and 850°C. The samples were grown in 0.333 litre/min, 0.667liter/min and 1liter/min oxygen flow rate and with variation in time, that is 1, 2 and 3 minutes. The thickness characterization was done by ellipsometer. The thickness of the oxide was obtained and is ranging from 1 to 5 nm. All the data has been interpreted using Taguchi’s method to analyze the most significant factors in producing an ultra thin silicon dioxide using a high temperature furnace.

Key words: Ultra-thin silicon dioxide, Taguchi’s method, CVD, Microfabrication, Clean room.

Introduction

Thermally grown films of silicon dioxide serve various key roles in the fabrication and operation of integrated circuits. The most critical role of silicon dioxide is its use as a MOSFET gate dielectric (M. Bryant, 2004; Salehuddin et al, 2011). One demand is that the oxide thickness must be controlled to the desired thickness that matches the design specifications of the MOSFET. Considering the application of ultra thin silicon dioxide film with the thickness of a few atomic layers to stacked gate dielectrics in MOS devices, even single atomic steps at the interface or small roughness on the surface should be eliminated (Hasunuma et al, 2008; A. Marras et al,2004 ; P. V. Zant, 20000). The thickness of the oxide must be less than 3 nm to be considered as an ultra thin film. This is in a very small scale so any different in thickness even if 1 nm would give a different characteristic (H. Xiao, 2007) Therefore uniformity of the oxide is a must for achieving a good thin film oxide. The thickness must be sufficiently uniform across the wafer, wafer to wafer and from run to run. Even though oxidation at higher temperature, has been reported as effective to reduce the surface roughness, but still it is insufficient and yet should be improved.

In this experiment, Taguchi method is used to find and examine the interactions between factors. The equilibrium between levels of different factors, robust tolerance design, and costs is based on two main concepts proposed by Taguchi: quality loss function and signal/noise ratio. According to Taguchi’s quality engineering philosophy and methodology, there are three important steps in designing a product or process: system design, parameter design and tolerance design (P. Mur, et al 2001; R.P.S. Thakur et al, 1999; B.E. Weir et al. 1999; Datta S. et al, 2009a; Datta S. et al, 2009b). The aim of system design is to create a product that indeed possesses the properties intended for it at the planning stage to do so, it has be monitored, the influence of significant parameter at different stages of the processes, the line up of the processes are done in order to have stage investigation of effect of the significant parameter at the early stage of the product to avoid what is mostly happening in most cases (O. Martin et al, 2009; Sanjit Moshat et al, 2010) study of the product is being done after passing through all the production processes. This approach is cost and time consuming and increase monetary loss caused by deviate specification production. This involves the development of a prototype, choice of materials, parts, components, assembly system and manufacturing processes, so that the product fulfills the specified conditions and tolerances at the lowest costs (K. ROY et al, 2001; Paul et al, 2004).

The thickness of the oxide must be less than 3 nm to be considered as an ultra thin film. With the Taguchi methods perform on a series of oxide, the thicknesses of all possible combination of parameters were able to be predicted. This will reduce the cost and time of the actual experiment.

There are few methods of producing ultra thin gate oxide but silicon dioxide is usually thermally grown and not deposited by CVD (chemical vapour deposition). Thermal oxide has high integrity than most CVD oxide film and so far has demonstrated high uniformities, less defect and high dielectric strength than deposited Oxide thin film [5]. Thermal oxide is normally grown in a diffusion furnace at a high temperature using either wet or
dry growth method. Dry oxide growth rate is much slower than wet, for this reason dry oxidation are primarily used for thin oxide where high uniformity and high dielectric strength are needed [6].

**Materials and Methods**

Details of the experimental setup are summarized as follows. The substrate is <100> silicon wafers. The pre-oxidation cleaning sequence consist of H2O2-based solutions of NH4OH and HCl with appropriate DI water rinsed, followed by a dip in dilute HF and a final DI water rinse. The wafers were then dried using nitrogen and immediately loaded in the oxidation furnace with nitrogen flowing. The silicon dioxide are grown by dry oxidation method using a high-temperature furnace. The silicon dioxide layers had being grown from the range of 1 to 3 minutes with temperatures at 750, 800 and 950°C and with the differences in oxygen flow rate. The oxygen flow rates used are 0.333, 0.667 and 1 litre/minute. Upon reaching the target oxidation temperature, the furnace ambient was then switched to dry oxygen. The parameters are arrange in an standard L9 orthogonal array[14,15] which means for any pair of columns, all combinations of factor level occur an equal number of times. Detail of the parameters is shown in table 1. The thicknesses were then measured using ellipsometer.

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Temperature (°C)</th>
<th>Time (min)</th>
<th>Oxygen Flowrate (l/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750</td>
<td>1</td>
<td>0.333</td>
</tr>
<tr>
<td>2</td>
<td>750</td>
<td>2</td>
<td>0.667</td>
</tr>
<tr>
<td>3</td>
<td>750</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>800</td>
<td>1</td>
<td>0.667</td>
</tr>
<tr>
<td>5</td>
<td>800</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>800</td>
<td>3</td>
<td>0.333</td>
</tr>
<tr>
<td>7</td>
<td>850</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>850</td>
<td>2</td>
<td>0.333</td>
</tr>
<tr>
<td>9</td>
<td>850</td>
<td>3</td>
<td>0.667</td>
</tr>
</tbody>
</table>

All the thickness data obtained was interpreted using Taguchi’s method to achieve the best parameter of acquiring the thickness below 3 nm.

**Results and Discussion**

The thickness of each sample was obtained at five different points using an ellipsometer. Using the five thickness datas, S/N ratio for each sample is calculated using the formula [1] given:

\[
S/N \text{ Ration} = -10 \log_{10} \left[ \frac{1}{n} \sum_{j=1}^{n} x^2 \right] \tag{1}
\]

Which \(n = 5\) (the number of times, thickness is measured) and \(x\) is the thickness value.

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>S/N Ratio Each Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.159</td>
</tr>
<tr>
<td>2</td>
<td>-5.758</td>
</tr>
<tr>
<td>3</td>
<td>-7.463</td>
</tr>
<tr>
<td>4</td>
<td>-8.755</td>
</tr>
<tr>
<td>5</td>
<td>-10.213</td>
</tr>
<tr>
<td>6</td>
<td>-10.213</td>
</tr>
<tr>
<td>7</td>
<td>-8.499</td>
</tr>
<tr>
<td>8</td>
<td>-8.568</td>
</tr>
<tr>
<td>9</td>
<td>-15.181</td>
</tr>
</tbody>
</table>

From the result of S/N value in table 2, the S/N value for each factor can be measured using formula [1] given:

\[
\text{Factors} = \frac{1}{3} (y_a + y_b + y_c) \tag{2}
\]

Which \(y_a\), \(y_b\) and \(y_c\) is the value of S/N in the experiment which that the factor is involved.
Fig. 1: Graphical value of control factors and their levels.

Graph presented in Figure 1 is the S/N value of each factor that is affecting the oxide thickness. The graphical representation is also convenient for drawing qualitative inferences and choosing the optimum level. The optimum level of factor can be achieved by choosing the highest S/N ratio for each factor, this way the oxide thickness below 3nm is achieved. The slope of each factor shows the amount of changes that affect the thickness of the silicon dioxide. The statistical design of experiment was used to evaluate three process variables that are temperature, time and the amount of oxidation flow rate. The analysis of the graphical value indicated that the temperature is the most significant factor in oxide growth. Time and oxygen flow rate also effect the oxide thickness.

Fig. 2: Ultra thin silicon dioxide thickness.

Figure 2 shows the thickness of ultra thin silicon dioxide grown using a high temperature furnace. The thickness varies from 1 nm to 5 nm. From the graph, all of the oxides thicknesses are linearly increasing with the process time. As shown in figure 2, the oxide grown at 750°C with 1 minute time in 0.333 l/min oxygen flow
rate will have a thickness of 1.13 nm, and by increase the time to 2 minutes, the thickness will increased to 1.37 nm. The difference is about 0.25 nm. Then the increase of time to 3 minutes will increase the thickness to 1.67 nm. The difference of the thickness is about the same. The thickness is also dependent with temperature and oxygen flow rate. The slope in figure 1 represents the growth rate of oxides. The higher the process temperature, the higher the slope value will be and thus will increase growth rate of the thin oxide. The increase in oxygen flow rate will also affecting growth rate the same way as the process time. However, the thickness of oxide grown in 1 l/min flow rate will decrease the thickness to less than the oxide grown in 0.667 l/min instead of increasing the oxide thickness.

**Conclusion:**

The statistical design of experiment was used to evaluate three process variables that are temperature, time and the amount of oxidation flow rate. The analysis of the graphical value in figure 2 indicated that the temperature is the most significant factor in oxide growth. Time is factor dependence to temperature. If higher temperature were used, the time will of course need to be shortened to achieve an ultra thin oxide. It is merely a constant rate which affects significantly only to the oxide thickness and the amount of the thickness increase is about the same. Oxidation at higher amount of flow rate (1 l/min) will eventually reduce the oxide thickness compare to the oxide grown in 0.667 l/min flow rate. The study potentially revealed that the statistical design of experiment can be employed to control and optimize the effect of all factors in oxidation process so that it will make the realization of achieving ultra thin silicon dioxide surface come true as it is becoming even more challenging as circuits are made denser and all of the dimensions are reduce correspondingly.

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