Reflector Influence on Rapid Heating of Minimal Manufacturing Chemical Vapor Deposition Reactor

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A small-sized reactor for producing a silicon epitaxial film on a half-inch silicon wafer was studied, taking into account the heat transport near the wafer. The wafer temperature slowly changed over a long time period when the reflector was made of thick plates. In contrast, when thin plates were employed as the reflector material, the wafer temperature quickly increased and easily reached a steady state. Thus, the reactor parts set near the wafer should be small, slim and thin. With the help of wafer rotation and a highly heat-conductive susceptor, a symmetrical and uniform silicon epitaxial film thickness profile could be obtained.

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Silicon electronic device manufacturing has two trends, that is, the increasing silicon wafer diameter and the shrinking design rule.1 These trends have continued for the several past decades in order to decrease the mass production cost of the device chips. However, for a future manufacturing system using silicon wafers larger than 300-mm diameter, the investment will be significant. Thus, an additional or an alternative choice is expected.

The candidate for the future manufacturing system is the Minimal Manufacturing (MM),2–5 which consumes less materials and less energy. It employs a quick process using small wafers with a 12.5-mm diameter. This system can flexibly produce the required number of electronic device chips, from one to a million, on-demand and on-time. For achieving the MM, chemical vapor deposition (CVD) is one of the key technologies.

The MM CVD reactor was designed and developed in our previous study6 taking into account the entire thermal and chemical processes. Using halogen lamps and reflectors, the infrared light was concentrated to heat the wafer surface while only consuming a reasonable amount of electric power. The silicon wafer temperature was affected by various parameters, such as the lamp voltage, total gas flow rate and precursor gas concentration.6–8 Furthermore, a reasonable and quick reactor cleaning process was achieved using the chlorine trifluoride gas.9

For obtaining a uniform epitaxial film thickness profile by the quick process, the thermal conditions should be further improved. In addition to the most important issue, such as the infrared ray reflection design,8–11 the heat transport through the reactor parts set around the wafer may be important, particularly about the lamp heating apparatus. The CVD reactor for the large wafer has a large infrared light heater consisting of thick and wide reflector plates.8,10 While the reflector effectively reflects and concentrates the infrared rays from the halogen lamps to the wafer surface, the reflector surface simultaneously absorbs the heat from the lamps and is heated to a high temperature. The heat absorbed by the reflector is slowly transported to the wafer via various reactor parts and the gas phase. When the reflector surface temperature gradually changes during reaching the thermal steady state, the wafer temperature is considered to simultaneously show the same behavior. Particularly, when the massive metallic parts are placed near the wafer, the wafer temperature needs a long time to reach a thermal steady state. In such a case, the heating process will become difficult, because it consumes a significantly high amount of electric power and requires the precise control of the heat distribution. In order to design a quick heat transport through the reflector while consuming a very small amount of electric power, a thin and slim reflector is expected. Although the heat transport through the reflector has not been evaluated, it might be a significant issue for the small system. Thus, the reflector geometry should be optimized for the MM CVD reactor.

In addition, the heat distribution over the wafer should be optimized. Because infrared rays tend to converge to generate a hot spot,9–11 any heat transport along a wafer surface should be utilized for broadening the locally high and low heat profile. For this purpose, a silicon carbide susceptor having high heat conductivity is a convenient tool. Additionally, wafer rotation is a popular and effective method in many CVD reactors for averaging the temperature distribution and the film growth rate over the concentric circle of the wafer.12

In this study for achieving a quick thermal process, the heating behavior was evaluated using two types of reflectors, i.e., the Type-I reflector made of thick mirror plates used in our previous studies8–10 and the Type-II reflector made of thin plates developed in this study. Additionally, the wafer rotation and the silicon carbide susceptor were shown to be effective for preparing a uniformly thick silicon epitaxial film.

Experimental

Figure 1 shows the CVD reactor which was designed for the MM. This reactor consists of a half-inch silicon wafer (12.5-mm diameter and 0.25-mm thick), a transparent quartz

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Figure 1. Half-inch silicon CVD reactor developed for the MM in this study.
tube, a wafer holder made of quartz, a gas inlet, three halogen lamps, and three reflectors. The inner diameter of the quartz tube is 24 mm. The wafer holder diameter is 19 mm. The gas inlet is divided into two zones, such as the inner inlet and the outer inlet. The inner inlet diameter is 7 mm. The distance between the wafer and the low end of the inner inlet is 51–56 mm, which significantly influence the wafer thermal condition. The typical temperature in the reactor was measured using an R-type thermocouple attached to the bottom side of the wafer holder, the thickness of which was 3 mm. The silicon carbide plates were inserted beneath the wafer as a susceptor for improving the heat conduction in a horizontal direction along the wafer.

In such the small reactor, the small displacement of the wafer and wafer holder can cause an asymmetrically localized gas flow. However, the displacement is expected to have small influence on the film formation at low temperatures in the reaction-limited regime,13 when the wafer temperature is well managed.

Reflectors.—Figure 2 shows the Type-I and Type-II reflectors evaluated in this study. Three reflectors were tightly and horizontally arranged around the quartz tube, as shown in Fig. 1. Figure 2a is the Type-I reflector, which was used in our previous study.6–8 The main body of the Type-I reflector is a 50-mm-thick mirror plate whose surface is covered with an electroplated gold film. Its thick body maintains a stable temperature during the very long process, because the temperature of the massive body is not sensitive to fluctuations in the outside temperature. However, it may result in slow heat conduction through it.

Figure 3 shows the heat transport from the halogen lamps to the silicon wafer. (a) and (b) are the Type-I and Type-II reflectors, respectively. As shown in Fig. 3, the heat conduction from the lamp to the inside of reflector plate, as indicated using the solid lines, helps heating the wafer, in addition to the radiation heat indicated using the dotted lines. Because the heat flux by conduction decreases with the increasing distance, the large and thick Type-I reflector body may require a long time for reaching the steady state. Overall, the thermal process is considered to become slow and long.

Figure 2b shows the Type-II reflector. This reflector consists of a 5-mm-thick plate which has only a thickness 10% of that of the Type-I reflector. This plate is expected to make the heat transport through itself, shown in Fig. 3b, quicker than that of the Type-I reflector, and reduce the temperature difference between the inside and outside of the reflector plate. Overall, the thermal process by the Type-II reflector is expected to be quicker than that of the Type-I reflector.

Process.—The silicon CVD process using the Type-I and -II reflectors are shown in Fig. 4. The entire process was in ambient hydrogen at atmospheric pressure. The gas mixture of hydrogen (H2) and trichlorosilane (SiHCl3, TCS) was vertically introduced from the top of the reactor normal to the half-inch silicon wafer, as shown in Fig. 1. TCS is the most widely used precursor for the silicon epitaxy.14,15 The gas flow rates of the H2 and TCS were 215 sccm and 9 sccm, respectively. The electric power supplied to the halogen lamps was from 55 to 65 W. The total electric power was less than 1500 W. Typically, the epitaxial film formation process consisted of two major steps, Step-A and Step-B. During Step-A, the native oxide film on the silicon wafer surface was removed at high temperatures, such as 1100 °C, for 1 min. Next, the wafer temperature was adjusted to that for the silicon epitaxial film formation, i.e., 700–1000 °C. During Step-B, the silicon epitaxial film was formed for several minutes by the chemical reaction13 described by Equation 1.

\[
\text{SiHCl}_3 + \text{H}_2 \rightarrow \text{Si} + 3\text{HCl}.
\]  

[1]

After finishing the film formation by terminating the TCS gas supply, the wafer temperature decreased by reducing the halogen lamp power.
As shown in Fig. 4a, Step-C was inserted between Step-A and Step-B. Step-C is the stand-by step waiting for Step-B while maintaining the clean silicon surface after Step-A. This step was for evaluating the effect of the parallel process. When the two reactors are serially arranged, virtually the A and B-Reactors for Steps-A and B, respectively, the wafer is transported through Step-C from the A-Reactor to the B-Reactor while maintaining a moderate heating. Although the operation for increasing and decreasing the temperature is necessary, Steps-A and -B can be simultaneously performed. The surface of one wafer is cleaned in the A-Reactor during forming the epitaxial film on the other wafer in the B-Reactor. Overall, the parallel process of Steps-A and B may reduce the total process time. Thus, in the first part of this study, Step-C was intentionally performed using the Type-I and -II reflector, in order to compare their thermal behaviors using exactly the same process, particularly for evaluating the heating-up rate and the period for reaching the steady state. In the second part, the effect of Step-C was evaluated.

**Wafer rotation and susceptor.**—In order to obtain the epitaxial film having a uniform thickness profile, the wafer rotation and the silicon carbide susceptor were utilized, as shown in Fig. 5, as the classical ways. Because the slow wafer rotation at 4 rpm has the effect of averaging the film growth rate along the concentric circle, the epitaxial film thickness was expected to become flat over the wafer. Silicon carbide has a high thermal conductivity which can help decrease the temperature difference over the wafer. The diameter and the thickness of the silicon carbide plate were 16 mm and 0.58 mm, respectively. In this study, three silicon carbide plates were stacked beneath the silicon wafer.

**Wafer temperature evaluation.**—Because the thermocouple could not be directly attached to the wafer surface during the epitaxial growth, the wafer holder temperature, \( T_{WH} \), was studied. The half-inch silicon wafer temperature, \( T_w \), can be obtained by the silicon epitaxial growth rate. When the epitaxial film is formed at the wafer surface temperature lower than 1000 °C and at the TCS gas concentration higher than 1%, the silicon epitaxial growth rate is governed by the chemical reaction and thus expressed as a function of the wafer temperature, \( T_w \), as follows:

\[
\text{Growth rate (μm/min)} = 1.95 \times 10^9 e^{(-26100/T_w)} \quad (T_w < 1000°C),
\]

When the wafer holder temperature, \( T_{WH} \), was 650 °C, the silicon epitaxial film growth rate was about 1.2 μm/min, which corresponded to the \( T_w \) value near 960 °C.

**Results and Discussion**

**Wafer holder temperature.**—Using the two types of reflectors, the silicon epitaxial film was formed by introducing the TCS gas and the \( \text{H}_2 \) gas at the flow rates of 9 sccm and 215 sccm, respectively, as shown in Fig. 6. In this figure, Step-C for cooling the reflector was intentionally introduced in order to compare these reflectors under exactly the same process. The dotted line and the solid line in Fig. 6 show the wafer holder temperatures using the Type-I and II reflectors, respectively, during Step-B immediately after Step-C.

For the Type-I reflector, the TCS gas was added from 0 to 5 min. The wafer holder temperature finally became 573 °C at 5 min when the halogen lamp voltage was 63 V. The solid line shows the temperature change when the Type-II reflector was used. The wafer holder temperature reached 621 °C at 4 min when the halogen lamp voltage was 62 V. Thus, the Type-II reflector could increase the wafer temperature higher and faster than the Type-I reflector.

Because the wafer holder temperature using the Type-I reflector did not reach a steady state yet in Fig. 6, the film formation period was extended in Fig. 7. As shown by the dotted line, the wafer holder temperature using the Type-I reflector at 62 V and at 10 min could reach 553 °C which was 70 °C lower than that using the Type-II reflector. This difference was recognized to be significant. Additionally, the temperature using the Type-I reflector was entirely lower than that of Type-II through Steps-A, B and C. Thus, the Type-II reflector is considered to achieve a quicker heating process.

At the early stage of Step-B in Figs. 6 and 7, the wafer holder temperature slightly increased immediately after introducing the TCS gas. TCS has the infrared light absorption at 3000 cm\(^{-1}\) (3.3 μm) and 4500 cm\(^{-1}\) (2.2 μm), which is overlapped with the wide and strong light emission peak near 1 μm from the halogen lamp. Thus, the TCS existing above the wafer can effectively absorb the infrared light from the halogen lamps to increase the gas phase temperature and consequently increase the wafer temperature, when the lamp heating power is fixed.

**Process optimization.**—In order to optimize the thermal process, the influence of the cooling step, Step-C, on the wafer temperature was evaluated using the Type-II reflector. The wafer holder temperature with and without Step-C was measured and shown in Fig. 8. The \( \text{H}_2 \) gas at the flow rates of 9 sccm and 215 sccm, respectively, as shown in Fig. 6. In this figure, Step-C for cooling the reflector was intentionally introduced in order to compare these reflectors under exactly the same process. The dotted line and the solid line in Fig. 6 show the wafer holder temperatures using the Type-I and II reflectors, respectively, during Step-B immediately after Step-C.

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The dotted line shows that the wafer holder temperature changed during Steps-A, C and B. From 0 to 2 min in Step-A, the wafer holder temperature increased to 650 °C. During Step-C after showing the peak temperature, the wafer holder temperature decreased to nearly 250 °C, because the halogen lamp voltage decreased to 30 V from 80 V set in Step-A. The wafer holder temperature was increased again at 8 min in Step-B. Using the halogen lamp voltage of 62 V, the highest temperature was 621 °C at 14 min, which was 6 min after beginning Step-B. However, even at 14 min, the wafer holder temperature was recognized to still increase and had not reached the steady state.

The solid line in Fig. 8 shows the wafer holder temperature changed during Step-A and B without Step-C. The temperature during Step-A overlapped with the dotted line. After Step-A, at 2 min, the halogen lamp voltage was adjusted to 62 V. At 3 min, a shallow dip in the wafer holder temperature appeared. However, the wafer holder temperature soon recovered and reached a steady state at 618 °C at 6 min. Thus, the process skipping Step-C was concluded to be quicker and more stable than that containing Step-C, because the significant down and up behavior of the wafer temperature could be skipped.

**Influence of wafer rotation and susceptor.**—Using the Type-II reflector with the process consisting of Steps-A and B, the silicon epitaxial film was formed on the half-inch silicon wafer surface. In this study, the flow rates of the TCS and H₂ were 9 sccm and 215 sccm, respectively, for 4 min. The halogen lamp voltage was 60 V for Step-B. The epitaxial film thickness was obtained by means of measuring the wafer thickness before and after the epitaxial film formation. The film thickness distribution was evaluated at five points along the longitudinal and transverse lines, using the dotted line and the solid line, respectively, as shown in Fig. 9. Figure 9a shows the thickness profile of the epitaxial film formed without using the wafer rotation and without using the silicon carbide susceptor. The epitaxial film thickness along the x-axis was distributed over a wide range from 1.5 to 3.5 μm, while that along the y-axis was very flat near 2 μm. In this figure, the film thickness showed a simple trend, that is, a decrease from right to left. Additionally, because the epitaxial growth rate was near 0.5 μm/min, corresponding to 950 °C by Equation 2, the epitaxial growth rate in Fig. 9 could be governed only by the surface chemical reaction. Based on the relationship between the wafer temperature and the gas flow rate obtained in our previous study, the gases injected from the gas inlet were considered to reach the wafer surface and decrease its temperature. This condition is schematically shown in Fig. 10. As shown in Fig. 10a, following the asymmetric gas flow from right to left, the surface temperature in the left region becomes lower than that in the right region. Corresponding to this thermal situation, the formed epitaxial film thickness of the left region becomes lower than that in the right region. Additionally, in an adiabatic-like environment, such as that the wafer is directly placed on the wafer holder made of quartz glass, a locally high temperature region can be produced by the infrared rays which tend to be concentrated to a small local spot. The non-uniform heat easily produces the non-uniform thick film.

The asymmetric condition was expected to be adjustable by the wafer rotation. Figure 9b shows the epitaxial film thickness profile formed on the rotating silicon wafer. The thickness profile along the y-axis and the x-axis showed a hill and a valley. Although the thickness profile was expected to be averaged along the concentric circle of the rotating wafer as shown in Fig. 10b, the thickness profile became rather complicated and far from symmetric. Because the gases from the inlet locally and slightly decrease the temperature in the wafer center region, the epitaxial film seemed to be thinner than in the other region. However, this result indicated that the local spot, denoted by the letter L, having high and low temperatures might remain due to reasons other than the gas flow. Thus, an additional method should be
Figure 10. Film formation influenced by gas flow from the inlet, wafer rotation and silicon carbide susceptor. (a) without rotation and without silicon carbide susceptor, (b) with rotation rate of 4rpm and without silicon carbide susceptor, and (c) with rotation rate of 4rpm and with three silicon carbide susceptors.

developed in order to decrease the temperature difference in order to improve the thickness uniformity. The locally high and low temperatures over the wafer surface might be produced due to the quartz material, because its thermal conductivity is very low.16 The heat transport in the horizontal direction should be improved using the silicon carbide material having a very high heat conductivity. As shown in Fig. 10c, by means of the heat transport through the silicon carbide susceptor, the local non-uniformity of the wafer temperature remained even using the wafer rotation is expected to be reduced in order to obtain a uniform temperature profile and uniform epitaxial film thickness profile. As shown in Fig. 9c, the epitaxial film thickness along the x- and y-axes was recognized to be very flat by employing the silicon carbide susceptor.

In Fig. 9c, the growth rate was about 0.38 μm/min, which was lower than that in Figs. 9a and 9b. The growth rate decreases from 0.5 to 0.38 μm/min corresponds to the temperature decrease of about 15K. This was considered to be due to the heat release improved by the three SiC plates. Because the film deposition rate in this temperature region is similarly governed by the surface reaction, the entire and slight temperature shift does not influence the discussion about the film thickness distribution.

By using the method which enables the thin and simple geometry of the reflector along with maintaining the small dimensions of the reactor, the quick epitaxial growth process producing a uniformly thick silicon epitaxial film could be developed. The wafer temperature management should account for the influence of the heat transport through the reflector body for various reactors, not only for the MM CVD reactor. For the further optimization, the heat transport over entire reflector should be quantitatively analyzed accounting for the reflection, the light absorption and heat conduction.

Conclusions

A small-sized reactor for producing a silicon epitaxial film on a half-inch silicon wafer was studied, taking into account the heat transport near and around the wafer. A gradual wafer temperature change occurred and continued for a long time, when the reflector was massive. In contrast, the reflector made of thin plates could make the wafer temperature process quick. Additionally, a thermal steady state could be easily obtained. Thus, the reactor parts placed near the wafer should be small, slim and thin, consistent with the MM concept. The wafer rotation and the highly heat-conductive susceptor helped to produce the symmetrical and uniform silicon epitaxial film thickness profile.

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