Heat Transport and Temperature Gradient in a Silicon-On-Insulator Wafer during Flash Lamp Annealing Process

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Abstract

Temperature gradient formed in a silicon-on-insulator (SOI) wafer during a flash lamp annealing (FLA) process is calculated on the basis of the heat transport theory. The temperature of SOI wafer, having a 40 nm-thick active layer and a 100 nm-thick buried oxide (BOX) layer, is calculated. Within 1 ms, the active layer surface reaches the maximum temperature higher than 1473 K. Because the most amount of heat is transported by heat conduction, very large temperature gradient, such as $3 \times 10^7$ K/m, is formed in the BOX layer because of its very small heat conductivity.

1. Introduction

Functions and capability of the ultra large scale integrated (ULSI) circuits continue to increase by means of shrinking its design rule, following expanding demand of world-wide communication. Thus, the junctions formed in ULSI tend to become very shallow, such as nearly 20 nm depth from the surface [1]. In order to fabricate such the ultrashallow junction (USJ), diffusion of implanted dopant atoms must be suppressed during the high temperature process for activating the dopant and for recovering the crystallinity of the implanted layer. Therefore, many researchers [2-10] have studied very short annealing process within several milliseconds, such as the flash lamp annealing (FLA) process using Xe lamp.

For manufacturing the advanced silicon devices for high performance and low energy consumption, the silicon-on-insulator wafer, [11] having a very thin silicon dioxide film as a buried oxide (BOX) layer, is used. However, many researchers have reported several problems for the SOI wafer, such as the fine pattern damage and the wafer breakage, [12] during the FLA process. For solving these problems, the time-dependent temperature change over the SOI wafer should be studied. Additionally, the influence of the thickness of the active layer and the BOX layer on the temperature profile over the SOI wafer should be evaluated. Here, calculation of heat flux and temperature on the basis of the heat transport theory [13] is a practical way [9, 14] because the FLA process gives a quite fast temperature change, to which an ordinary temperature measurement method cannot respond.

In this study, the temperature of the SOI wafer during the FLA process is therefore calculated taking into account the conduction heat transport in the entire SOI wafer and the radiation heat transport through the BOX layer. Particularly, the temperature gradient formed in the active layer and BOX layer is studied.

2. Theoretical Calculation

Geometry of the SOI wafer used in this study is shown in Fig. 1. Top of the SOI wafer is the active layer, which is a very thin silicon film having the thickness of 40 nm. The buried oxide (BOX) layer, made of silicon dioxide film having the thickness of 100 nm, exist between the active layer and substrate. The total thickness of the SOI wafer is 725 $\mu$m.

Fig. 1 schematically shows the dominant heat transport processes for the SOI wafer during the FLA process, consisting of the followings:

(A) heat radiation from the lamp to the silicon surface,
(B) reflection at the silicon surface,
(C) heat radiation from the hot silicon surface, obeying the Stefan-Boltzmann's law,
(D) light absorption in silicon, obeying the Lambert-Beer's law,
(E) thermal conduction in silicon and silicon dioxide, obeying the Fourier's law, and
(F) radiation heat transport through the BOX layer between the bottom surface of active layer and the top surface of substrate, obeying the Stefan-Boltzmann's law.
3. Results and Discussion

3.1 Time-dependent temperature change

Fig. 2 shows the depth profile of temperature in an entire SOI wafer changing with time after the initiation of the FLA process. At 0.1 ms, the temperature of the front surface is still low, less than 800 K, the heat from the front surface can reach within the depth of 100 μm. At 0.3 ms, the front surface is heated to higher than 1000K. The temperature of the front surface reaches the maximum value of 1480 K at 0.7 ms. When the front surface temperature reaches the maximum value, the heat transported from the front surface reaches the position of ca. 400 μm from the front surface in the wafer, as shown in Fig. 2. After showing this peak, the temperature of the front surface monotonically decreases along the time. At 1.5 ms, although the front surface has about 1100 K, the temperature at 600 μm is still near the initial temperature of 673 K.

Fig. 3 shows the time-dependent temperature change at various positions in the active layer and the BOX layer, such as 0-140 nm from the active layer surface, from 0 to 2 ms after the initiation of heat. Because these positions are very near the front surface, within 140 nm, of the SOI wafer, the temperatures are very close to that of the front surface. Fig. 4 magnifies the temperature profile near the surface of SOI wafer showing the maximum surface temperature at 0.7 ms after the initiation of the FLA process. The temperature gradient in the active layer is shown to be very small. The temperature difference between the top and bottom surface of the BOX layer is shown to be less than 2 K. Although the temperature difference is very small in Fig. 4, it often gives very large temperature gradient in such a very thin layer. Thus, in next section, the entire heat transport and the temperature gradient are evaluated.
3.2 Heat transport and temperature gradient.

The difference of temperature gradient between the active layer and BOX layer is quantitatively expressed. There are two major processes of heat transport, such as thermal conduction and heat radiation, between silicon and silicon dioxide.

Thermal conductivity of silicon and silicon dioxide is shown in Fig. 5. Although thermal conductivity of silicon dioxide gradually increases with the increasing temperature, it is nearly ten times smaller than that of silicon over entire temperature range used for manufacturing silicon devices.
The other heat transport is radiation. Silicon effectively absorbs infrared, visible and ultra violet light.\textsuperscript{14} In contrast to this, silicon dioxide has a transparent nature from ultra violet light and infrared light.\textsuperscript{15} Thus, the infrared light emitted from the hot bottom surface of the active layer can be recognized to go through the BOX layer to directly reach the top surface of the substrate. Following our previous study,\textsuperscript{14} the most amount of light entering from the active layer surface is absorbed within the active layer, thickness of which is 40 nm. Thus, in this study, only heat conduction is taken into account in the BOX layer.

Fig. 6 shows the heat flux emitted from the Xe lamp, the entire heat flux through the active layer and the radiation heat flux through the BOX layer. The heat flux in the BOX layer is evaluated at various positions, such as 40-140 nm from the active layer surface. The lamp emission and the heat flux through the active layer and the BOX layer show their peak at nearly 0.4 ms. As shown in Fig. 6, the heat fluxes at various positions of the active layer and the BOX layer are shown to be overlapped with each other. The heat flux transported in the SOI wafer is reduced to \textit{ca.} 20\% of that emitted from Xe lamp, due to reflection at the active layer surface and absorption in silicon.

Fig. 6 Heat flux changing with time at various positions in an active layer and a BOX layer. Position is indicated using the depth from the active layer surface. Plots at 20-40 nm in active layer, and those at 40-140 nm in the BOX layer are overlapped.

It is noted here that the radiation heat flux between the bottom surface of active layer and the top surface of substrate through the BOX layer is significantly smaller than the entire heat flux at various positions, as shown in Fig. 6, because very small temperature difference, such as 1 or 2 K, between the two surfaces produces very small radiation flux, following the Stefan-Boltzmann's Law. Therefore, the major heat transport process is concluded to be heat conduction.

Because the heat flux for the active layer is the same as that for the BOX layer, the temperature gradient in the two layers must be quite different from each other, following the Fourier's law. Fig. 7 shows the temperature gradient at various positions in the active layer and the BOX layer, such as 40-140 nm from the active layer surface. Although the temperature gradient in the active layer is small, \textit{ca.} 0.3 \times 10^7 K/m, which is similar to that in silicon wafer,\textsuperscript{14} those in the BOX layer is ten times larger than that in the active layer. This difference is consistent with the difference of thermal conductivity, shown in Fig. 5.
4. Conclusions

Temperature and heat transport in a silicon-on-insulator (SOI) wafer during the flash lamp annealing process are studied on the basis of the heat transport theory. The SOI wafer having a 40 nm-thick active layer and a 100 nm-thick buried oxide (BOX) layer, heated by the Xe lamp within 2 ms, shows very large temperature gradient of $3 \times 10^7$ K/m in the BOX layer, when the active layer surface has the maximum temperature of 1480 K. This temperature gradient is nearly ten times greater than that in the active layer. The large temperature gradient is simply formed due to smaller heat conductivity of silicon dioxide than that of silicon. The dominant heat transport process is the heat conduction; the radiant heat flux through the BOX layer is significantly smaller than the conduction heat flux.

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References