

CORRELATION BETWEEN HOT PLATE EMISSIVITY AND WAFER TEMPERATURE AT LOW TEMPERATURES

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The effect of aging (oxidation) of aluminum hot plates in ambient air at 550 °C and the surface roughness of hot plates was studied to investigate the correlation between hot plate emissivity and wafer temperature at low temperatures (200 – 500 °C). Four different types of wafers (i.e. p⁻ Si, p⁺⁺ Si, GaAs and quartz) and hot plates with three different surface conditions were tested. As aging time elapsed, the emissivity gradually increased and approached specific saturated values depending on its surface roughness. The hot plate with rougher surface resulted in a larger emissivity value than a plate with smoother surface. There was good correlation between the emissivity of the aluminum hot plate and wafer temperature. Wafer temperature increased with higher emissivity due to the higher radiative heat transfer between the hot plates and the wafer. No significant correlation between wafer temperature and wafer type was observed. To make the wafer temperature repeatable and close to the hot plate temperature, the emissivity of hot plates must be tightly controlled.

INTRODUCTION

Device fabrication processes include many low temperature annealing steps below 500 °C because of the low melting point (660 °C [1]) of aluminum (Al), which is used as interconnects. A five-wafer batch annealing system using resistively heated, stacked hot plates has been designed for low temperature (100 – 500 °C) annealing applications such as spin-on-glass (SOG), low-k film baking, Cu annealing, contact alloying, and for Al sintering of 150 – 300 mm wafers. The silicon wafer temperature in the stacked hot plate annealing system was characterized as a function of hot plate temperature, stand-off height and ambient process temperature [2-4].

Non-contact wafer heating using stacked hot plates with stand-offs provides very gentle wafer temperature ramp-up characteristics which is suitable for outgassing applications such as drying, baking and curing processes [2-4]. Unlike the contact wafer heating method, heat is transferred from hot plates to a wafer via conduction from gas (air), convection and radiation. Given the fact that the hot plate temperature is the same, the resulting wafer temperature may be influenced by the emissivity of hot plates and optical properties of the wafer itself. Compound semiconductors (i.e. GaAs, InP, GaP etc.) and quartz wafers often require low temperature thermal processing. Each material has its own energy bandgap and has different optical characteristics. The optical characteristics of each material depend on the dopant, dopant concentration and

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temperature [5]. In the case of Si wafers, heavily doped Si wafers are less transparent than intrinsic Si wafers in the infrared (IR) region (below the absorption edge of Si). For low temperatures, it is important to understand the effect of radiation (on wafer temperature) from both the system design and process quality control point of view.

In this study, we have investigated the effect of radiation on wafer temperature at low hot plate temperatures (200 – 500 °C) using different types of wafers (i.e. p⁻ Si, p⁺⁺ Si, GaAs and quartz) and hot plates with different surface roughness and conditions.

EXPERIMENTAL

Six hot plates are stacked with 20 mm gaps between hot plates to be able to process five wafers simultaneously and to enhance the productivity without deteriorating process results. Figure 1 shows a schematic diagram of an experimental apparatus (stacked annealing oven: SAO). Except for the top hot plate, the rest of the hot plates have three 9 mm-long stand-offs from the surface for wafer placement. A circular-shaped resistive heating element and a K-type sheathed thermocouple are embedded in the individual hot plates. The temperature of each hot plate is individually monitored and controlled by the embedded thermocouple. After a wafer is placed between two stacked hot plates, the wafer is gradually heated by thermal conduction, convection and radiation in ambient gas (air).

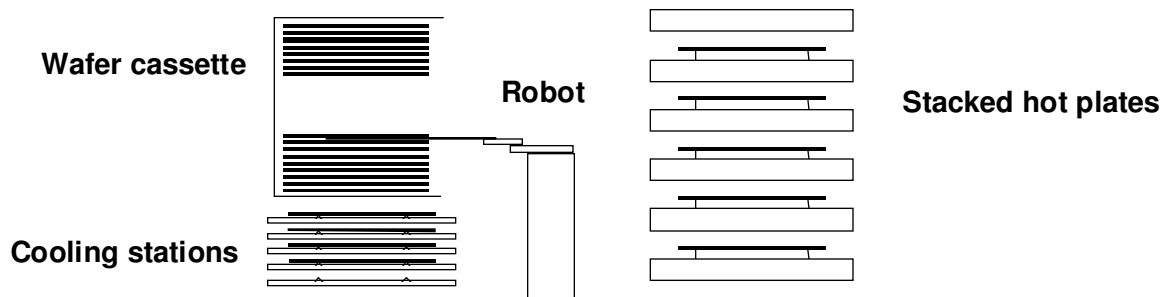


Fig. 1. Schematic diagram of a five-wafer stacked annealing oven (SAO) system.

Three kinds of aluminum hot plates, with different surface roughness, were tested. One pair of hot plates was as machined. Two pairs of hot plates were prepared by blasting ceramic powders with an average grain size of 120 μm and 600 μm into machined hot plates to roughen the hot plate surface. The emissivity of the hot plates was measured as a function of aging (oxidation) time. The aging was performed at 1 atm (air ambient) at 550 °C. The hot plate emissivity was estimated by infrared imaging ($\lambda = 3.0 - 5.3 \mu\text{m}$, wave number = $3333 - 1887 \text{ cm}^{-1}$) and the temperature of the hot plates was measured with an embedded thermocouple.

Four different types of 150 mm wafers (i.e. p⁻ Si, p⁺⁺ Si, GaAs and quartz) and three hot plates with different surface conditions were tested. The resistivity of p⁻ doped Si wafers were between 1 and 10 Ω·cm and the resistivity of p⁺⁺ doped Si wafers were 0.005 Ω·cm. After the wafer is placed on the stand-offs in between the stacked hot plates, the wafer temperature was measured using thin, K-type thermocouples bonded to the surface of the wafers.

RESULTS AND DISCUSSION

The surface roughness (R_a) of as-machined hot plates was measured to be $0.08 \mu\text{m}$. For machined hot plates, blasted with $120 \mu\text{m}$ and $600 \mu\text{m}$ ceramic powders, the surface roughness was $2.1 \mu\text{m}$ and $8.3 \mu\text{m}$, respectively. The measured emissivity of these hot plates is plotted in Fig. 2 as a function of aging time at $550 \text{ }^\circ\text{C}$ in air. Initial emissivity of as-machined or roughened hot plates ranged from 0.12 to 0.59. The blasted hot plates showed higher emissivity values than as-machined hot plates. The emissivity of the hot plates roughened with $600 \mu\text{m}$ ceramic powders was lower than that of those roughened with $120 \mu\text{m}$ ceramic powders. This may be due to the effective surface area per unit area. As grain size increases, the effective surface area per unit area decreases and eventually approaches that of the as-machined flat surface. In addition, the emissivity of the hot plates gradually increases with aging time. It saturates after approximately 25 hours of oxidation at $550 \text{ }^\circ\text{C}$. The emissivity of machined hot plates saturates at around 0.18. The emissivity of hot plates blasted with $600 \mu\text{m}$ and $120 \mu\text{m}$ ceramic powders saturate at approximately 0.70 and 0.80, respectively. Thus, the emissivity of hot plates can be controlled by their surface roughness and oxidation.

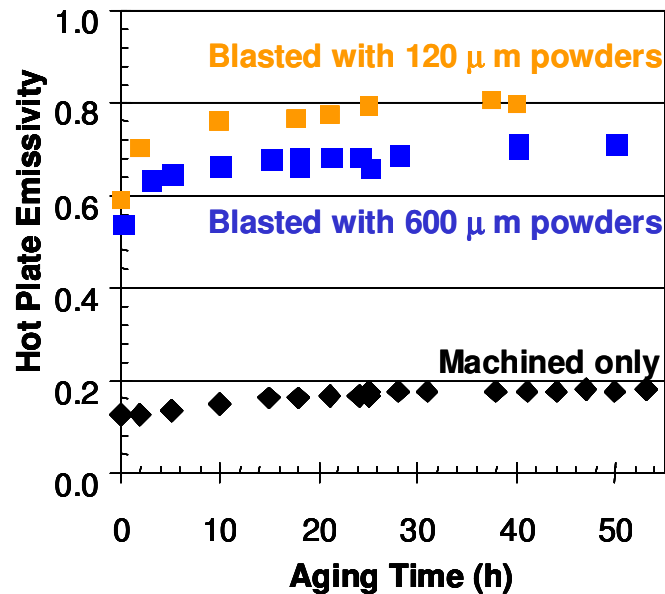


Fig. 2. Emissivity of hot plates as a function of aging time at $550 \text{ }^\circ\text{C}$ in 1 atm air.

Figure 3 shows the change of wafer temperature during aging of the machined hot plate at $550 \text{ }^\circ\text{C}$ in 1 atm air. A p⁻ Si wafer (150 mm diameter) was placed between stacked hot plates during aging and the wafer temperature was measured using a thin thermocouple bonded to the wafer surface. As the aging of the machined hot plates progressed, the emissivity of the hot plates increased. The increase of the hot plate emissivity from 0.12 to 0.18 resulted in an increase of the wafer temperature from $464 \text{ }^\circ\text{C}$ to $482 \text{ }^\circ\text{C}$ at a constant hot plate temperature of $550 \text{ }^\circ\text{C}$. A very strong correlation between wafer temperature and hot plate emissivity was observed even at a constant hot plate temperature of $550 \text{ }^\circ\text{C}$. This result indicates that the surface condition must be controlled to achieve very repeatable wafer temperatures when the aluminum hot plates are used at high temperatures (where the oxidation of aluminum cannot be ignored). Once an Al hot plate is fully oxidized, one would expect very repeatable results in wafer temperature.

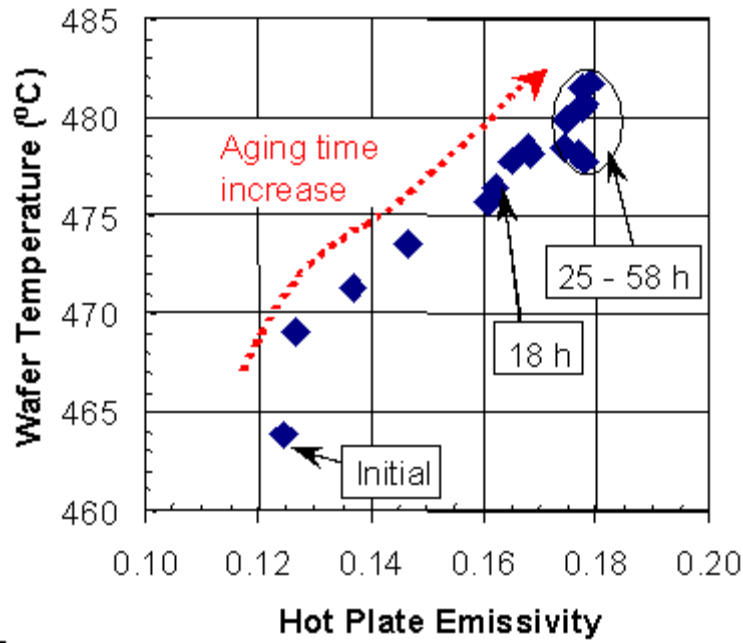


Fig.3. Change in wafer temperature and hot plate emissivity for different aging times of machined hot plate at 550°C in 1 atm air.

The correlation between wafer temperature and hot plate emissivity of prepared (as-machined or blasted) surfaces and 25 hour-aged hot plates at 550 °C were measured at hot plate temperatures of 200, 300, 400, and 500 °C. The wafer temperature was plotted as a function of emissivity and hot plate temperature in Fig. 4. Regardless of the hot plate surface condition, the wafer temperature shows a very strong correlation with hot plate emissivity. Hot plates with a higher emissivity value resulted in higher wafer temperatures at a given hot plate temperature.

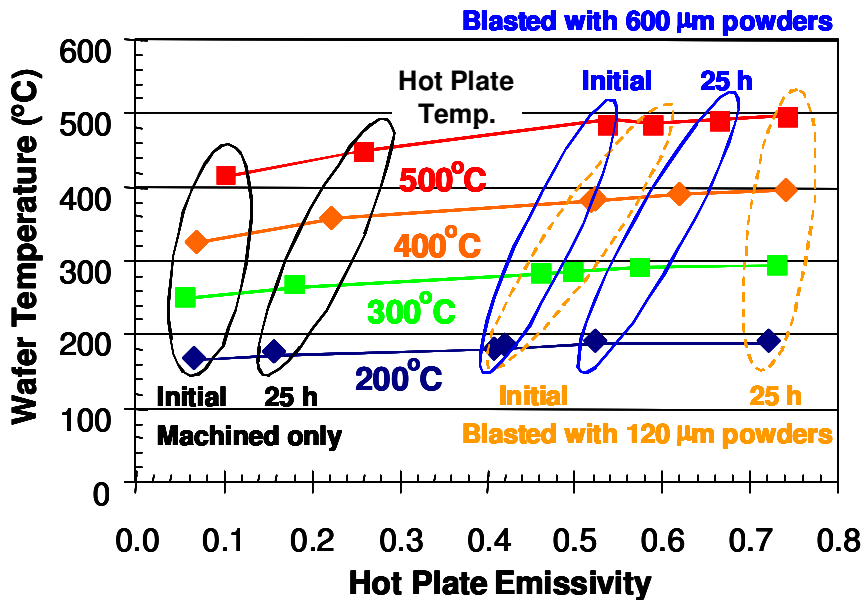


Fig. 4. Correlation between wafer temperature and hot plate emissivity of as-prepared and 25 hour-aged hot plates at 550 °C in the hot plate temperature range of 200- 500 °C.

The effect of hot plate emissivity on the *difference* between the temperature of the hot plate and that of the wafer at steady state was plotted in Fig. 5 as a function of hot plate emissivity. Even at steady state, the wafer temperature is always lower than the hot plate temperature. As the hot plate emissivity increases, the difference between the hot plate temperature and wafer temperature is reduced due to the enhancement in radiative heat transfer from the hot plate surface to the wafer surface. At a hot plate temperature of 500 °C, the difference decreases from 83 to 4 °C as the hot plate emissivity increases from 0.10 to 0.75. The radiation effect on wafer temperature cannot be ignored at hot plate temperatures as low as 200 °C. This result suggested that the emissivity of the hot plate must be tightly controlled to make wafer temperatures repeatable. Also, hot plates with a higher emissivity value can make the wafer temperature relatively close to the hot plate temperature in the non-contact, stacked hot plate configuration employed in the SAO system.

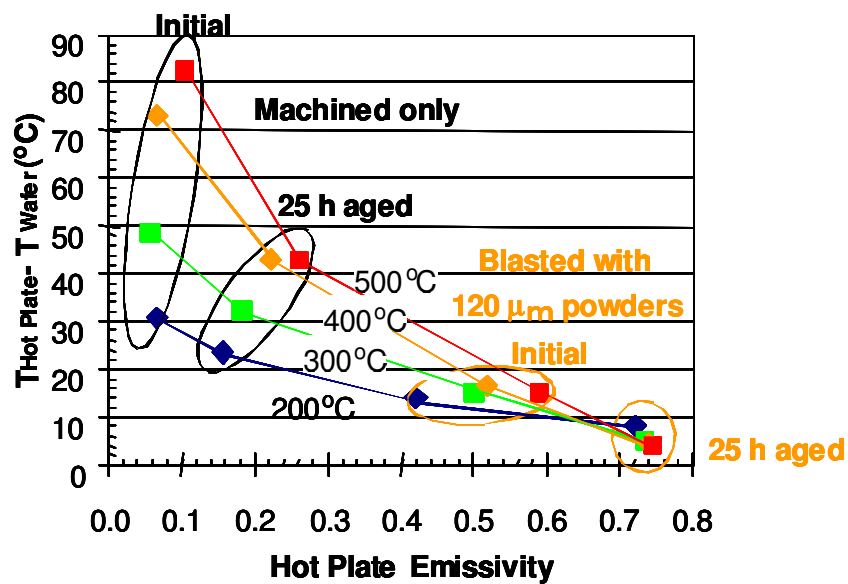


Fig. 5. The effect of hot plate emissivity on the *difference* between hot plate temperature and wafer temperature at steady state hot plate temperatures (200 – 500 °C).

Low temperature thermal processing is commonly used in a wide range of semiconductor fabrication processes including crystalline Si, amorphous Si and compound semiconductors such as GaAs, InP and GaP. Sapphire and quartz wafers are also used as insulating substrates and optical window materials for photoelectric devices. Understanding the effect of radiation on wafer temperature at low temperatures is important not only for system design, but also from the process quality control point of view.

The effect of the optical properties of wafers on the wafer temperature, for a given hot plate temperature and emissivity was investigated using four types of wafers (i.e. p⁻ Si, p⁺⁺ Si, GaAs and quartz). Figure 6 shows the optical transmittance spectra of four types of wafers in the wavenumber range of 400 – 4000 cm⁻¹ (25 – 2.5 μm). The p⁺⁺ Si wafer is less transparent than the p⁻ Si wafer in the measured IR region. The GaAs wafer shows very similar IR transmittance to the p⁻ Si wafer. The quartz wafer is only transparent in the wavenumber region of 2000 – 4000 cm⁻¹ (5.0 – 2.5 μm). Corresponding wavenumber for the emissivity measurement using an IR camera is indicated in Fig. 6.

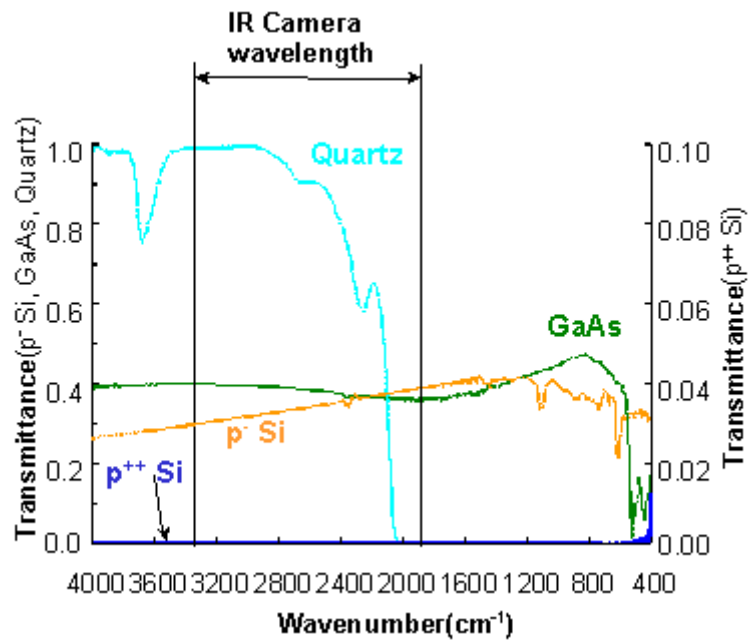


Fig. 6. Transmittance spectra of various wafers in IR region.

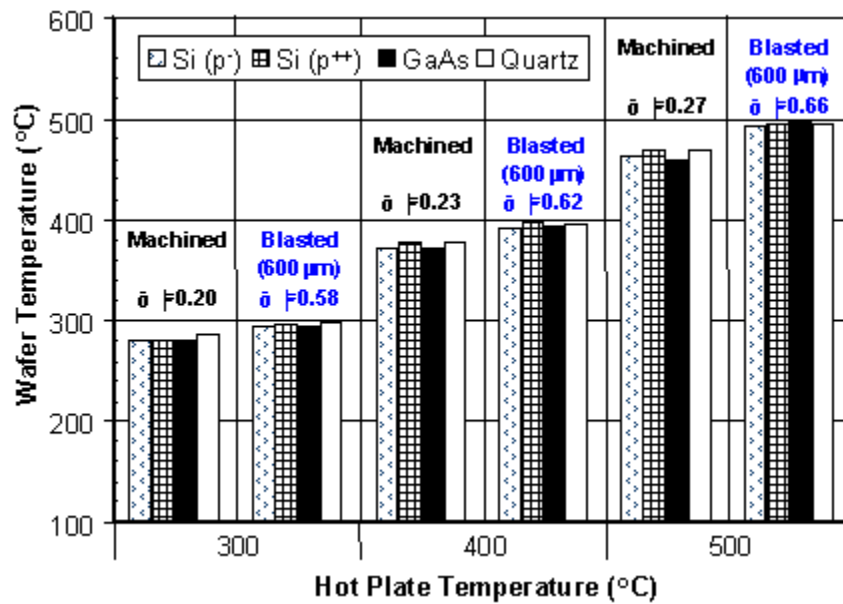


Fig. 7. Steady state temperature of various types of wafers placed between stacked hot plates with different emissivity values.

Figure 7 shows the steady state temperature of various types of wafers placed in between stacked hot plates with different emissivity values and temperatures (300, 400 and 500 °C). At steady state, no significant temperature difference between different types of wafers was observed. Higher wafer temperature was measured in wafers placed in between stacked hot plates with higher emissivity values. The wafer temperature is less dependent on the optical properties of the wafer itself, but it strongly depends on hot plate

emissivity. The stacked hot plate-based system can be used for low temperature processing applications, irrespective of the wafer type without wafer temperature calibration.

CONCLUSIONS

The effect of aging (oxidation) of aluminum hot plates in ambient air at 550 °C and surface roughness of the hot plates was studied to investigate the correlation between hot plate emissivity and wafer temperature at low temperatures (200 – 500 °C). Four different types of wafers (i.e. p⁻ Si, p⁺⁺ Si, GaAs and quartz) and hot plates with three different surface conditions were tested to investigate the effect of the emissivity of the hot plate surface and the optical properties of the wafers on wafer temperature. The emissivity of hot plates gradually increased and approached specific saturated values depending on their surface roughness and their degree of oxidation. Hot plates with rougher surfaces resulted in larger emissivity values than that with smoother surfaces. Higher emissivity resulted in higher wafer temperature due to the higher radiative heat transfer between hot plates and wafer. No significant correlation between the wafer temperature and wafer type was observed. A higher wafer temperature was measured on wafers placed between stacked hot plates with higher emissivity values. The wafer temperature is less dependent on the optical properties of the wafer itself, but it strongly depends on the hot plate emissivity. To make wafer temperature repeatable and as close to the hot plate temperature as possible, the emissivity of hot plates must be tightly controlled. The stacked hot plate-based system can be used for low temperature processing applications for a wide range of materials regardless of their optical properties without wafer temperature calibration.

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