Wafer Temperature Characterization during Low Temperature Annealing

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A resistively heated hot plate system was proposed for low temperature (100~450°C) annealing applications. The thermal properties of a single hot plate and stacked hot plates were investigated. The heat transfer effects of the wafer holding method (i.e. direct contact and standoff holding), wafer temperature profile and thermally induced wafer warpage during low temperature annealing were investigated. Wafer temperature profiles during low temperature annealing on hot plates were measured as a function of hot plate configuration, standoff height, hot plate temperature and process atmosphere.

1. Introduction

Silicon wafers are exposed to various thermal environments during the device fabrication cycle. Thermal oxidation, implant anneal, film densification, glass film re-flow and metallization are very common thermal processing applications. As the device size shrinks and device fabrication process becomes complicated, the allowable thermal budget decreases significantly. A good understanding of the thermal effect on wafers is essential to determine process parameters and design suitable processing equipment. Within-wafer and wafer-to-wafer temperature uniformity and repeatability are considered to be the most important process parameters to be monitored and controlled to assure process results. Since wafer warpage during temperature change can cause significant damage in device wafers, thermally induced stress has to be reduced as much as possible.

Due to the lower thermal budget and the flexibility of single wafer processing systems, RTP (rapid thermal processing) is preferred in many thermal processing applications above 600°C. Most of RTP systems available today employ lamp for wafer heating and optical pyrometry for wafer temperature measurement and control. However, accurate and reliable wafer temperature measurement/control below 600°C using optical pyrometry is still a very challenging task [1]. It is because the lamp heated RTP systems use optical interaction between lamps and a Si wafer. Si wafer is transparent to infrared region when its temperature is below 600°C. Wafers with reflective layers and/or patterns are even more difficult to uniformly heat temperature below 600°C using lamp heated RTP systems [2-3]. A new concept annealing systems need to be developed for low temperature annealing applications.

In this paper, a resistively heated hot plate system was proposed for low temperature (100~450°C) annealing applications. Thermal properties of single hot plate and stacked hot plates were measured in the temperature range of 100~450°C. The effects of the wafer holding method (i.e. direct contact and standoff holding at different heights) on heat transfer, wafer temperature profile and thermally induced wafer warpage during low temperature annealing. Wafer temperature profiles during low temperature annealing on hot plates were investigated as a function of hot plate configuration, standoff height, hot plate temperature and process atmosphere.

2. Experiment

Hot Plate Configuration

Resistively heated hot plates were used to heat 200mm Si wafers in this study. Figure 1 shows a side view and top view of a hot plate with a 200mm Si wafer. The hot plate is made of aluminum and has an embedded heater. Diameter and thickness of the hot plate are 250mm and 30mm, respectively. Individual hot plate has three standoffs to keep the distance between a wafer and the hot plate. A thermocouple is embedded in one of the three standoffs to measure approximate wafer temperature of wafer during annealing. The standoffs are equally spaced on the perimeter of a 160mm diameter circle. Single hot plate configuration and stacked hot plate configuration were used for wafer annealing. A schematic diagram of stacked hot plates with a 200mm Si wafer is shown in Fig. 2. A shorter distance between hot plates provides better heat transfer to a wafer, but tolerance in wafer handling height becomes tighter. The distance between the hot plates was kept at 20mm in this study. Wafer temperature profiles on hot plates were investigated as a function of hot plate configuration, standoff height, hot plate temperature and process atmosphere.

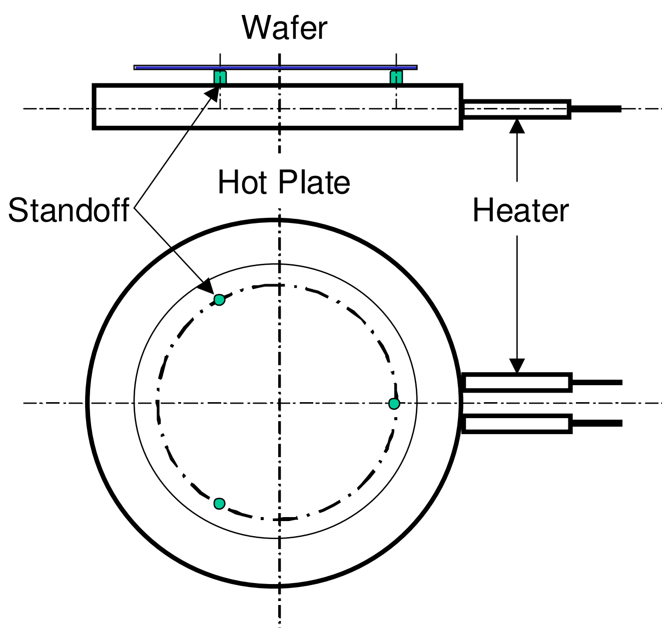

Fig. 1 Schematic diagram of a 200mm Si wafer on a hot plate.

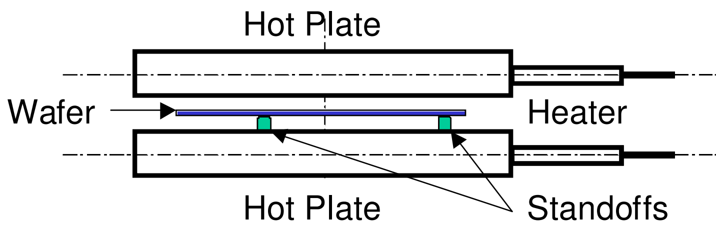

Fig. 2 Schematic diagram of a 200mm Si wafer between hot plates.

Temperature Uniformity of Hot Plates

Temperature uniformity of individual heaters is characterized using infrared thermography in the temperature range of 100~450^{o}C. Temperature uniformity on individual hot plates is excellent. It is due to the high thermal conductivity of aluminum and a relatively large thickness (30mm) of hot plates. Aluminum has almost 2 times higher thermal conductivity compared to Si at room temperature. As temperature increases, the thermal conductivity ratio of Al over Si becomes large and approaches 4 at 600K (327^{o}C). Thermal conductivity of Al, Si and air are summarized in Table 1 [4]. The symmetrical geometry of hot plates also helps getting excellent within hot plate temperature uniformity. Figure 3 shows infrared thermal image of a hot plate heated to 400^{o}C. The temperature variation across the hot plate is within +/- 1.0^{o}C at 400^{o}C.

Table 1. Thermal conductivity of Al, Si and air.

Unit: W/cmK

Temp.	Si	Al	Air
300K	1.48	2.37	26.2×10^{-5}
400K	0.989	2.4	33.3×10^{-5}
500K	0.762	2.36	39.7×10^{-5}
600K	0.619	2.31	45.7×10^{-5}

Wafer Annealing on a Single Hot Plate

Wafer temperature ramp up profiles on a single hot plate heated to 400^{o}C are shown in Fig. 4 as a function of standoff height. Temperature measurement was done in air. The maximum wafer temperatures with different standoff heights are also indicated. The shorter the standoff height, the higher wafer temperature ramp rate and maximum wafer temperature. The wafer directly placed on a hot plate showed thermal stress induced warpage due to non-uniform heat transfer. The warpage relaxes as the wafer temperature gets uniform and lasts about 30s at the hot plate temperature of 400^{o}C. On the other hand, the warpage of the wafer placed on standoffs is negligible. The normalized temperature difference between wafer center and 10mm from wafer edge in wafers with no standoffs and 0.5mm tall standoffs is plotted in Fig. 5. The wafer on standoffs showed better within-wafer temperature uniformity during ramp up compared to the wafer directly on the hot plate.

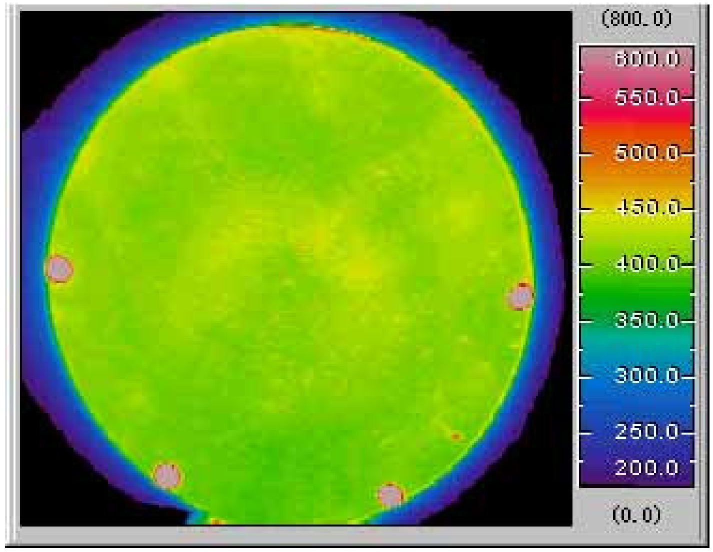

Fig. 3 Infrared thermal image of a hot plate heated to 400^{o}C.

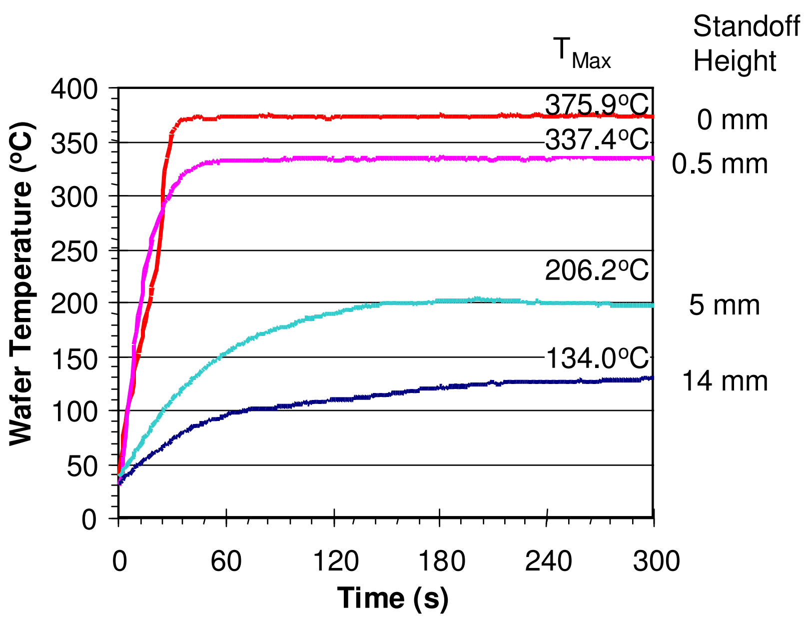

Fig. 4. Wafer temperature ramp up profiles on a hot plate heated to 400^{o}C.

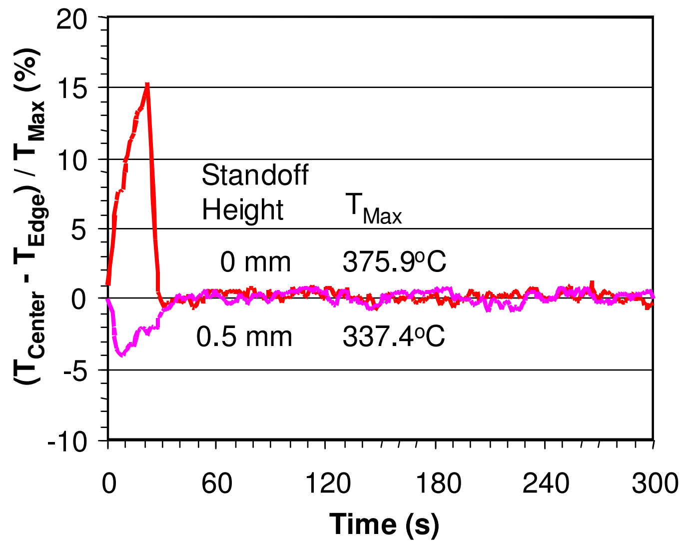

Fig. 5 Normalized temperature difference between wafer center and 10mm from wafer edge in wafers with no standoffs and 0.5mm tall standoffs.

Wafer Annealing in Stacked Hot Plates

200mm bare Si wafers with instrumentation thermocouples were annealed in the stacked hot plates (Fig. 2) at different temperatures under air or He atmosphere. The temperature of the top and bottom hot plates was controlled separately, but the temperature set points of both hot plates were kept same. The distance between the hot plates is 20mm. The wafer was placed on 8mm tall standoffs of the bottom hot plate. Temperature profiles of a wafer in stacked hot plates were measured at hot plate temperature set points of 100, 200, 300 and 400°C under 760Torr. Figure 6 shows the wafer temperature ramp up profiles in the stacked hot plates.

As soon as the wafer is inserted in the stacked hot plates, the wafer temperature initially increases almost linearly and then it saturates at little below the hot plate temperatures. When He gas is used, the wafer temperature ramp rate is higher than that in air. The saturated wafer temperature is also higher in He gas. This is due to the difference in thermal conductivity of gases and the heat transfer mechanism. The heat transfer between the hot plates and the wafer is predominated by thermal conduction through the gas. The thermal conductivity of air and He gas at 300K under 760Torr are 26.2×10^{-5} and 156.7×10^{-5} W/cmK, respectively. The thermal conductivity of gases increases with temperature. The thermal conductivity of air and He gas become 45.7×10^{-5} and 252.4×10^{-5} W/cmK at 600K under 760Torr. Thermal conductivity of selected gases is summarized in Table 2 [4]. Wafer temperature ramp rate varies with the hot plate temperature, standoff height, process pressure and process atmosphere.

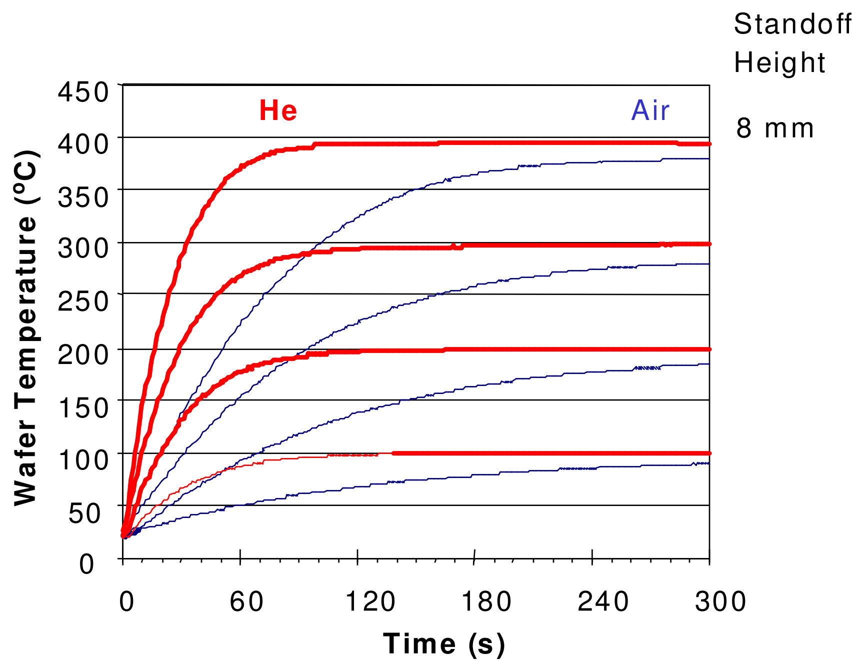

Fig. 6 Wafer temperature ramp up profiles in stacked hot plates. (Hot plate temperature: 100, 200, 300and 400^{o}C)

Table 2. Thermal conductivity of selected gases.

Unit: 10^{-5} W/cmK

Temp.	Air	Ar	H_2	N_2	O_2	He
300K	26.2	17.9	186.9	26.0	26.3	156.7
400K	33.3	22.6	230.4	32.3	33.7	190.6
500K	39.7	26.8	-	38.3	41.0	222.3
600K	45.7	30.6	-	44.0	48.1	252.4

3. Discussion

Traditionally, low temperature annealing was done in batch furnaces. Typical batch size is ranging from 150 to 200 wafers. Due to the inflexibility in lot size and long cycle time, single wafer processing is preferred. In thermal processing applications above 600^{o}C, lamp-heated single wafer RTP systems are widely used. Accurate and reliable wafer temperature measurement/control below 600^{o}C using optical pyrometry is difficult due to transparent optical property of Si wafers in infrared region. Wafers with reflective layers and/or patterns are even more difficult to measure their temperature and uniformly heat them below 600^{o}C. Processes with out gassing during annealing make condensation on chamber interior including window for light incident. In addition to the condensation, degradation of lamps makes temperature measurement/control unstable and causes pattern shift in process results.

Hot plates were made of aluminum with high thermal conductivity for low temperature annealing applications. The temperature uniformity of the hot plates was found to be very uniform. High thermal conductivity of aluminum makes temperature gradient across the hot plates. The thermal conductivity of gases is 3 to 4 orders of magnitude lower than that of aluminum (Table 1 and 2). The poor thermal conductivity of gases makes heat dissipation through the gas phase conduction smaller. The stacked hot plate configuration makes convection between hot plates negligible and provides nearly isothermal environment for the wafer.

Heat transfer from the hot plates to a wafer is predominantly through gas phase conduction in the temperature range of 100~450^{o}C. The wafer temperature profile strongly depends on the hot plate temperature, thermal conductivity of gases and gap between hot plates and the wafer. The direct contact between a wafer and a hot plate provides fast wafer temperature ramp up, but it makes uniform wafer heating during temperature ramp up difficult (Fig. 4 and 5). Wafers directly on a hot plate tend to slide during annealing when they out gas. By keeping an intentional gap between the hot plates and the wafer, good within wafer temperature uniformity can be obtained throughout the process. Wafer sliding can also be prevented.

The wafer temperature profiles suggest that non-contact thermal annealing is gentle and provides repeatable process results. A nearly warpage free thermal annealing is achieved by placing a wafer on standoffs in stacked hot plates. A stacked hot plate system is very promising for wafer warpage sensitive and out gassing low temperature annealing processes such as Cu anneal, Al anneal, SOG (spin on glass) anneal, photoresist baking applications.

4. Summary

A resistively heated hot plate system was proposed for low temperature (100~450^{o}C) annealing applications. Thermal properties of two different hot plate configurations (single hot plate and stacked hot plates) were characterized. Effects of wafer holding method (i.e. direct contact and standoff holding) on heat transfer, wafer temperature profile and thermally induced wafer warpage during low temperature annealing were investigated. Wafer temperature profiles during low temperature annealing on hot plates were measured as a function of hot plate configuration, standoff height, hot plate temperature and process atmosphere.

A nearly warpage free, very uniform low temperature thermal annealing is achieved by placing a wafer on standoffs in stacked hot plates. Stacked hot plate system is very promising for wafer warpage sensitive and out gassing low temperature annealing processes.

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