2D REAL TIME TEMPERATURE MEASUREMENTS IN A NEW SHORT WAVELENGTH ARC LAMP RTP CHAMBER FOR IMPROVED UNIFORMITY

D. M. Camm, M. Lefrancois, B. Hickson, D. Parfeniuk and B. Lojek*

Vortek Industries Ltd., 1820 Pandora Street Vancouver BC, Canada V5L 1M5
* Silicon Annealing, Inc. 16 Scenic Terrace, Round Rock, TX 78664

2D REAL TIME TEMPERATURE MEASUREMENTS IN A NEW SHORT WAVELENGTH ARC LAMP RTP CHAMBER FOR IMPROVED UNIFORMITY

D. M. Camm, M. Lefrancois, B. Hickson, D. Parfeniuk and B. Lojek*

Vortek Industries Ltd., 1820 Pandora Street Vancouver BC, Canada V5L 1M5
* Silicon Annealing, Inc. 16 Scenic Terrace, Round Rock, TX 78664

A preliminary report is given on the development of a new short wavelength RTP tool that is being designed to maintain uniform temperature during a wide range of processes. This chamber uses a single 150 kW short wavelength arc lamp and black chamber to maintain uniform temperatures independent from wafer properties. Diagnostics include a 2D, real time temperature measurement technique that makes use of a CCD camera, calorimeter as well as calibration wafers. Initial measurements of transient and steady state temperature distributions are given. Temperature distributions due to variations in irradiance on the wafer and chamber effects are given. The black chamber is shown to effectively control temperature variations during heating and cooling. Results are used to determine design modifications and to estimate improvements in uniformity to below ±3 C^o. Application of these diagnostics to production tools for control and monitoring of process conditions are described.

Introduction

New design concepts involving a "black chamber" were presented at RTP '94 [1]. This high temperature RTP reactor offers improved wafer temperature uniformity independent of wafer properties. These concepts use design opportunities made possible by a new type of 150 kW water wall arc lamp. The goal of this work was to obtain experimental verification of temperature distribution calculations that indicated ±3 C^o (3σ) on 200 mm patterned wafers at 1050 ^{o}C and an ultimate uniformity of ±1 C^o on 300 mm wafers. This paper reports progress toward demonstrating that a black chamber can achieve these goals. The work is broken into three main parts.

The first part includes measurement of the irradiance directly from the source and reflector to the plane of the wafer. This distribution was then used to calculate the expected temperature distribution on the wafer caused by primary irradiance alone. This calculated profile can then be subtracted from measured temperatures in order to determine chamber effects.

The second part is to process test wafers while recording the radiation coming from the wafer with a CCD camera. Comparing camera data to the peak temperatures indicated by sheet resistance of test wafer establishes the accuracy of the camera data. The measured temperatures are used to estimate chamber effects. Camera data was used to estimate temperature during ramp up, soak and cooling to determine transient effects.

Finally the power of the 2D real time temperature measurements for tool development is demonstrated using the black chamber as an example. This initial data indicates that the black chamber can reduce chamber and wafer effects.

Information is obtained on the relative importance of irradiance uniformity and chamber effects and gives quantitative data for parallel modifications to the irradiance pattern and energy transfer in the prototype chamber. A quantitative understanding of these effects allows predictions of the performance of production machines based on this work.

Black Chamber

The black chamber[1] is designed to maintain temperature uniformity across wafers with different optical properties. This is achieved by improved control of radiative and conductive energy transfer. The pattern effect on the device side of wafers, that is caused by variations of emmissivity and reflectivity, is reduced by minimizing radiative transfer through the device side. All energy is transferred to and from the wafer through the back side and the chamber is designed so that any radiation emitted or reflected from the back side does not return to the wafer. Thus the backside is effectively in a black chamber. Since wafer radiation does not return to the wafer the temperature distribution is not effected by wafer radiation. In an ideal black chamber the temperature distribution is then determined by the distribution of incident arc lamp radiation.

Processing

Wafers were processed in nitrogen. At time zero the wafer irradiance is increased to a predetermined value with a rise time of 100 ms followed by constant radiation for 30 seconds and then off.

Irradiance on wafer plane

The wafer and top of the chamber were removed (Figure 1) and a water cooled calorimeter is moved in the plane of the wafer. A two axis robot is used to position the calorimeter within 0.2 mm at each data point while a second calorimeter remains in a fixed position. The fixed calorimeter is used to normalize the irradiance measured by the moving calorimeter. Data was obtained in a grid pattern by using a PC based computer to control the robot motion and calorimeter data acquisition.

Irradiance is used to estimate a temperature distribution by assuming the emissivity on the top and bottom of the wafer are the same. Convective and conductive energy losses as well as radiation exchange through the wafer edge are ignored. With these assumptions energy transfer is purely radiative and the equilibrium temperature will be proportional to irradiance to the 1/4th power. The relative temperature distribution calculated on this basis can then be compared to measured temperatures to determine the importance of the effects that have been ignored.

Radiation coming from the wafer

A CCD camera is mounted directly below the wafer centre. The arc lamp and camera are controlled by a PC based system to take pictures during the processing cycle. Wafer radiation is filtered to a 10 nm band centered on 900 nm. Data can be taken at 30 frames per second with over 180,000 data points per frame. Typical pictures take two readings per mm^2 over the entire wafer surface. A picture taken just after the arc is turned on, but before the wafer has increased in temperature, was used to measure arc radiation reflected from the wafer. Subtracting this initial picture from subsequent pictures gives radiation emitted by the hot wafer. After the lamp is turned off there is no arc radiation and pictures do not have to be modified to give wafer radiation during cooling.

Radiation from the wafer is given by $E_{b\lambda}$ the emissive power of a blackbody per unit wavelength.[2]

$$E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{(C_2/\lambda T)} - 1} \qquad (1)$$

where λ = wavelength, μm
T = temperature, °K
C_1 =3.743 E 8 W•μm^4/m2
C_2 =1.4387E 4 μm•°K

Assuming that the angular variation of the monochromatic emissivity ε_λ in the direction of the camera can be ignored then camera data I is related to $E_{b\lambda}$ by:

$$I \;\alpha\; \varepsilon_\lambda E_{b\lambda} \tag{2}$$

The proportionality constant is measured by using a measured temperature T_0, from measured resistivity, and a camera reading I_0 both from the same point on the wafer. Then the Temperature T at any point is found from:

$$T = \frac{C_2}{l \ln(1 + \frac{I_0}{I}\left(e^{C_2 / l T_0} - 1\right))} \tag{3}$$

Peak temperature distribution

Wafers implanted with As at 1.0E16 and 20 keV were used to measure peak temperature. It is assumed that a surface resistivity of 58 ohms/square indicates 1050 ^{0}C and that they have a sensitivity of 2 C^0/ohm/square from 1030 ^{0}C to 1070 ^{0}C.

Sheet resistivity was measured over the wafer. A region of 58 ohm/square was selected and assumed to be at 1050 ^{0}C to define T_0=1050 ^{0}C. The camera data from this region then defines I_0. These constants are used to convert camera data to temperature using equation 3.

Developmental black chamber

The data was obtained during initial experiments conducted on a developmental chamber as shown in Figure 1. These results were used to test the diagnostics and to determine what chamber modifications were needed.

An arc lamp and reflector were designed specifically for this chamber. A black coating was developed for the walls in the absorbing chamber that reflected 2% per reflection. Water cooling is used for all surfaces in the absorbing chamber, including the window between the single arc lamp and chamber.

A highly reflecting aluminum showerhead was positioned above the wafer. This showerhead is capable of controlled gas flow but for these experiments gas flow was set to zero.

A 25 mm wide ring of silicon is positioned in the plane of the wafer to reduce edge effects.

Results and Discussions

Irradiance on wafer plane

Figure 2 gives the experimental irradiance on the wafer plane. This is the initial raw data taken to determine the radiation that comes directly from the arc lamp and reflector to the wafer. Note that the irradiance drops off by as much as 4% towards the edge of the wafer. Figure 3 includes a temperature distribution due to this irradiance pattern calculated assuming that flux is proportional to temperature to the forth power. Note that the measured drop in irradiance produces a drop of roughly 10 C^0. This drop will be eliminated by modifying the reflector based on the experimentally measured irradiance.

Peak temperature distribution

Temperature based on wafer resistivity as well as temperatures from camera data are given in Figure 3. The camera data was taken less than 50 milliseconds after the arc lamp was turned off. Note that there is good agreement between resistivity and camera based data. This calibrates the camera data so data taken during heating and cooling can be converted to temperatures.

The peak temperature measurements give information on energy transfer and give quantitative results useful for prototype development. The measured peak temperature falls below the temperature predicted by irradiance alone. A difference of 15 C^0 is observed at one edge and 10 C^0 at the other edge. This gives a quantitative measure of edge effects as a function of position that is used to test energy transfer models. Preliminary investigations suggest that this edge effect will be significantly reduced by modifications to the ring of silicon surrounding the wafer and to the showerhead above the wafer.

The instrumental signal to noise of both camera and resistivity data in Figure 3 is roughly ±2

C^0. Work is underway to improve this by a factor of 10, however, the raw data presented in this figure indicates the expected improvements in uniformity due to modifications to arc lamp, reflector and chamber will meet the goal of the black chamber of ±3 C^0 over a 200 mm wafer.

Transient temperature distributions

Figure 4 gives a number of temperature profiles taken during the 30 second heating pulse. Consider the profile at 9 seconds when the wafer has reached 900 ^{o}C. The profile shows a 10 C^o drop toward the edges which is caused almost entirely by irradiance nonuniformity. At this temperature the wafer is radiating roughly 60% as much energy as it is receiving. By 27 seconds the wafer has reached equilibrium at 1050 ^{o}C with a temperature drop of 15 C^o at the edge. This additional drop is due to the increased radiation losses from the edge. Having both steady state and transient temperature profiles is essential for development of accurate models needed to reduce edge effects.

Figure 4 is raw data that uses less than 10% of the camera output. Statistical treatment of the entire data set plus calibration of the relative pixel sensitivity will improve the signal to noise by at least an order of magnitude.

Profiles taken during cooling have a constant profile with the same shape as the equilibrium profile taken at 27 seconds. The largest temperature gradients are obtained at equilibrium and thus can be measured using resistivity or camera based data. The black chamber has effectively eliminated transient temperature nonuniformities.

The black chamber with a single arc lamp sets a minimum scale length for temperature variations that is much longer than corresponding multiple lamp RTP machines. The scale can be seen in figure 4 by noting the most rapid spatial gradient is set by edge losses over a distance of 50 mm. After modifying the system to achieve uniformities in the ±3 C^o instantaneous temperature gradients will be over large areas and very small.

Conclusions

The first conclusion is that the diagnostic system can measure temperatures during the entire heating cycle over the entire wafer. The usefulness of full 2D temperature measurements for tool development has been shown for a new black chamber.

Applying these new diagnostics to the prototype black chamber has given quantitative data that can be used to isolate the effects of incident radiation and chamber effects. Modifications of the arc lamp, reflector and chamber have been initiated based on this data and the black chamber is expected to achieve its targeted uniformity of better than indicated ±3 C^o on 200 mm wafers at 1050 ^{o}C.

Work in Progress

Optics design procedures are being tested with the new data obtained so the arc lamp and reflector can be modified to produce uniform irradiance. Various methods are being investigated to reduce edge losses. Work is progressing to improve the instrumentation and data analysis to measure temperature within ±0.2 C^o. A number of methods of dynamic temperature control will be considered after optimizing the initial design.

Reflected radiation from wafers will be used to measure reflectivity and thus emmissivity. This was not required for the test wafers used for this initial study because they were uniform. The new diagnostics will be used to measure 2D temperature distributions on patterned wafers and to optimize on gas flows in the chamber.

The use of camera data for feedback control of absolute temperature, for dynamic control of temperature uniformity and for recording of process information for each production wafer will be investigated. The main challenge will be to quickly extract the needed information from the large amount of data available.

ACKNOWLEDGMENT

This work was partially supported by the Industrial Research Assistance Program of the National Research Council of Canada

REFERENCES

1D. M. Camm, B. Lojek 2nd International Rapid Thermal Processing Conference. 1994. Page 259.

2see for example J. P. Holdman, "Heat Transfer," 4th edition p278, McGrawHill Book Company, New York 1972

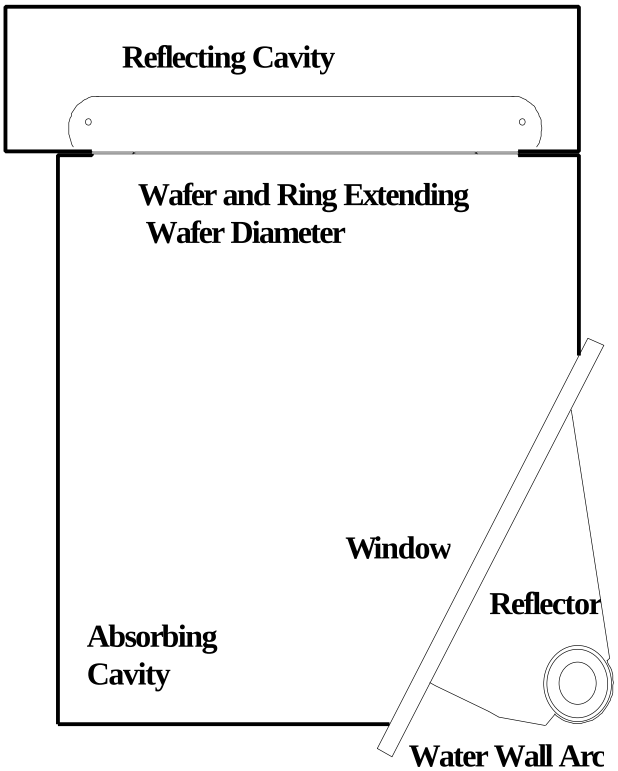

Figure 1. Black chamber RTP prototype

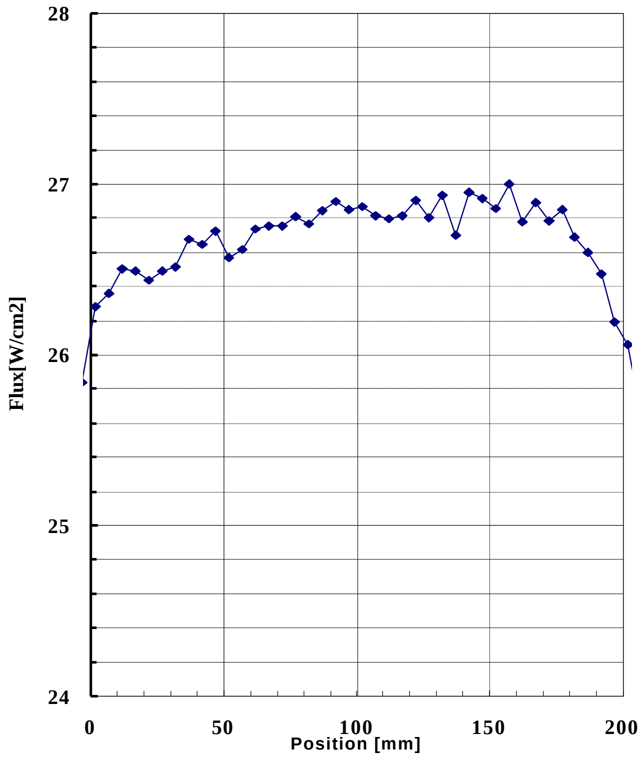

Figure 2. Experimental Irradiance on Wafer Plane

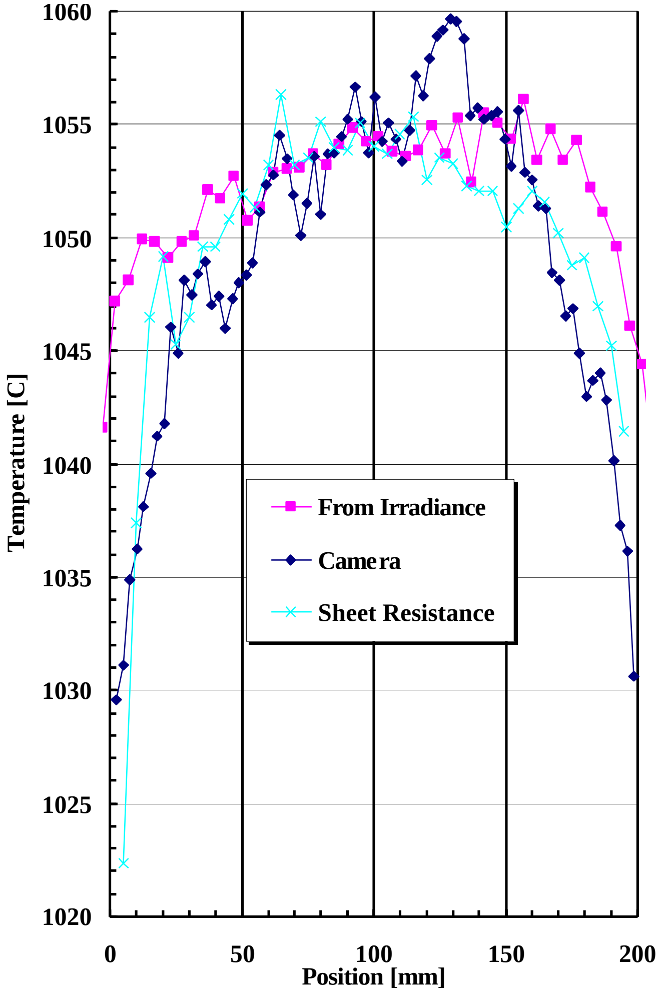

Figure 3. Comparison of Peak Temperature Measurements