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Design concepts are presented for a high temperature RTP reactor that offers improved wafer temperature uniformity independent of wafer properties. The concepts use design opportunities made possible by a new type of 150 kW water wall arc lamp. Calculations of temperature uniformity are described that indicate $\pm 3\text{ }^{\circ}\text{C}$ (3σ) on 200 mm patterned wafers at $1050\text{ }^{\circ}\text{C}$ are readily achievable with ultimate uniformity of $\pm 1\text{ }^{\circ}\text{C}$ on 300 mm wafers. The system employs a new high power arc lamp with a spectral distribution between 0.2μ and 1.4μ . High absorption efficiency of these short wavelengths results in precise control of energy deposition. The 1 ms time response of this arc is discussed with application to improved temperature diagnostics. The critical dependence of the design on the unique capabilities of the new water wall arc lamp is established. Reliability and treatment of larger wafers are considered for application of this design to production RTP reactors with application to deep sub-micron VLSI devices

INTRODUCTION

The specifications for RTP reactors are becoming more demanding as device feature size shrinks. Industry roadmaps indicate that high temperature RTP for devices with 0.25μ spacing require temperature uniformity of $\pm 3\text{ }^{\circ}\text{C}$ (3σ) at $1100\text{ }^{\circ}\text{C}$ and 0.18μ will require $\pm 1\text{ }^{\circ}\text{C}$ [1]. This performance must be achieved on patterned wafers, which exhibit variation of their optical properties, under both transient and steady state conditions. Real time temperature measurements of production wafers are needed to maintain consistent processing on a production basis. Measuring absolute and relative temperatures over the entire wafer is required for reproducible process development.

A newly developed type of water wall arc lamp has characteristics that are ideally suited to meet these increasing demands. These lamps operate reliably and reproducibly with standard products up to 300 kW and custom arcs to 1.5 MW. The availability of hundreds of kilowatts of radiation in a single small source means that performance need not be compromised for efficiency. The reproducibility and reliability of these sources make them ideal for production-worthy RTP systems. A second advantage of the water wall arc is its spectral distribution (Fig. 1). The integrated spectra in Fig. 2 shows that over 95% of the arc's radiation is below the 1.2μ band gap absorption of cold silicon compared to 40% for tungsten. As electrical power is reduced the

spectra from tungsten sources shift to the red and absorption drops below 40%. In contrast, arc lamp spectral is constant with power and absorption does not change. Arc lamp radiation is strongly absorbed in silicon due to band-to-band transitions[2] with very low transmission through the wafer. A third major advantage is the arc's 1 millisecond time response that offers improved control of heating profiles and unique opportunities to use pulsed operation for new temperature diagnostics. These new techniques offer the potential for accurate, real time temperature measurements over the entire process cycle.

This paper describes three design concepts for a new type of RTP reactor that capitalizes on the properties of the new high power water wall arc lamp to meet current and future needs of the semiconductor industry.

WHERE TO TRANSFER RADIANT ENERGY

By definition, RTP requires rapid temperature changes. A key consideration in reactor design is how to transfer energy to the wafer and how to manage the wafer emissive power while keeping the entire wafer at the same temperature. Production wafers typically have devices on one side that form a surface pattern with different optical properties such as emissivity, reflectivity and absorption. These patterns will introduce temperature nonuniformity[3,4] which in extreme cases can result in so called "continental drift".

Dependence of net radiative flux on geometrical features can be effectively eliminated if energy transfer on the patterned side is minimized. This can be seen by considering the hypothetical situation of a wafer at uniform temperature that is exposed on all surfaces to black body radiation of the same temperature. Because the system is in equilibrium, temperature uniformity is maintained regardless of any pattern on the wafer. Temperature differences are created if the wafer and black body radiation are at different temperatures because the patterns absorb and emit radiation at different rates which changes the relative rates of heating and cooling of

different parts of the wafer. Minimizing heat transfer through the device side will thus minimize pattern effects.

Radiation exchange through the wafer edge can lead to transient temperature gradients because of increased surface to volume ratios at the edge compared to the wafer centre. Radiation transfer is proportional to surface area and heat capacity is proportional to volume thus heating rates are proportional to their ratio and net heat flux. The solution is to eliminate heat flux through the edge to maintain a constant conditions across the wafer.

Because of the water wall arc's short wavelengths the radiation will be absorbed in a relatively thin layer on the back surface with virtually no transmission through the wafer. The device side will be heated by conduction through the wafer. Selective absorbed by highly doped features on the device side does not occur because no source radiation reaches that side. The elimination of all radiation is particularly important for devices that involve insulating layers such as silicon on oxide (SOI).

The first design concept is to eliminate pattern and edge effects by minimizing energy transfer through the device side and wafer edge. A simple solution is to use a ring to effectively extend the wafer diameter and a highly reflective cavity above the wafer's device side. The addition of auxiliary sources to balance losses in this cavity can improve performance for wafers with particularly strong pattern effects.

WAFER RADIATION

Uniform primary irradiation incident on the product does not necessarily produce uniform wafer temperatures. The wafer reflects primary radiation and at elevated temperatures it becomes a significant source of thermal radiation. Both types of wafer radiation will reach the chamber envelope and a large fraction will eventually return to the wafer. The single source RTP chamber as shown in Fig 3 was used to investigate the effects of reflected radiation. Fig 4 shows the results of Monte Carlo calculations for this reflector assuming a wafer reflectivity of

30% and 95% reflectivity for reflector components. Radiation makes a number of reflections from reflector surfaces and the wafer. Of the $12\text{W}/\text{cm}^2$ (30% of primary $40\text{W}/\text{cm}^2$) initially reflected by the wafer, approximately $8\text{W}/\text{cm}^2$ is returned to the wafer with the remainder absorbed by the reflector or reabsorbed by the source. The 30% reflectivity assumed for Fig 4 is for bare silicon but for patterned wafers reflectivity is typically 40% which will produce more nonuniformities.

The primary radiation is not uniform in order to compensate for the nonuniformity of the secondary wafer radiation. The primary radiation shows a systematic rise toward the edges while the total radiation shows the opposite.

The primary radiation in Fig. 4 is a smooth function of position on the wafer while the secondary light has much larger deviations. Part of the variations of both primary and total radiation is introduced by the Monte Carlo calculations. The amount of error can be seen by observing that the system is symmetric, except for calculation errors, and comparing the symmetry of these traces. Error estimates based on symmetry agree with estimates based on convergence as a function of number of rays traced. Comparing symmetry shows clearly that calculation error dominates the primary radiation and is insignificant for total radiation. Calculations indicate that primary radiation can achieve uniformity much better than 1% while total radiation will be over 4%.

By careful optical design it is possible to modify the primary radiation to be uniform or, as in Fig 3, to make it nonuniform to partially compensate for nonuniform secondary radiation. However, compensation is only effective for a single given wafer reflectivity. Even at this reflectivity, and including the reduced thermal conductivity[5] of the wafer, calculations predict ultimate temperature uniformity of $\pm 10\text{C}^\circ$ at 1100C° . Thus, if the reflector and chamber of an RTP system are designed so that secondary radiation reaches the wafer then the ultimate temperature

uniformity will depend on wafer reflectivity and uniformity will be poor.

By comparison, if secondary radiation is absorbed, and the optics are designed to give uniform primary radiation, then the limit to temperature uniformity is calculated to be $\pm 1\text{C}^\circ$ at 1100C° .

The second design concept is to eliminate effects of multiple reflections by designing a chamber, water wall arc lamp and reflector that absorbs virtually all the wafer radiation before it can return to wafer. Fig. 5 schematically shows an implementation of this type of design. The source of primary radiation subtends a small solid angle as viewed from the wafer to minimize the amount of wafer thermal radiation reaching the reflector. The reflector, chamber and window are designed for maximum absorption of wafer radiation. The source of primary radiation is positioned such that radiation reflected from the wafer along with most of the emitted radiation from the wafer reaches the totally absorbing walls of the RTP chamber.

This type of design typically requires a source of primary radiation of much higher power (150 kW) than can be provided by standard sources. This power is required for three main reasons. First, the small optics and large standoff distance reduces optical coupling efficiency. Second, the absorption of all wafer radiation means there will be no secondary radiation and the total power shown in Fig. 3 will equal the primary lamp radiation. Third, the ring extending the wafer diameter, used to reduce edge effects, is irradiated with the same power as the wafer, thus significantly increasing the target area. The virtually unlimited power available from water wall arcs and their small size make this design possible.

WINDOW EFFECTS

The window needed to isolate the wafer in a clean environment can introduce significant nonuniformities. The quartz window reflects about 8% of the wafer radiation producing the wafer image shown in Fig. 3. This image

subtends a solid angle close to 2π steradians from a point at the wafer centre while a point near the edge subtends about half that. Assuming the wafer is a uniform body, its image will add irradiance equal to about 8% of its emitted radiation at the wafer centre and about 4% at the edge. The presence of the window introduces an irradiance nonuniformity of a few percent of the wafer radiation. During steady state conditions as little as 1% variation of irradiance results in a 3 C° variation.

The quartz window also adds to thermal memory due to the low thermal conductivity of quartz. During processing the window will absorb part of the radiation from the source as well as thermal radiation from the wafer. The window is transparent to most of the lamp radiation because of its short wavelength but absorbs most infrared radiation from the wafer. Since the points on the window opposite the wafer centre receive more radiation than points near the edge a radial temperature gradient will be created in the window centered on the wafer.

The requirement to reduce window effects results in the third design concept in which the window is repositioned as shown in Fig. 5. Thermal memory is reduced because the window receives less radiation and thus stays cooler. The large distance between the window and wafer reduces radiation transfer and makes the contribution more uniform. The wafer image in the window does not cause a problem because secondary radiation from the wafer that is reflected by the window is directed to the highly absorbing chamber walls and does not return to wafer. The extremely high power and small volume, of the new water wall arcs, are essential properties of the small distant source shown in this figure.

TEMPERATURE MEASUREMENT

It is essential that the absolute temperature be reliably measured on a real time basis to be able to close the control loop for consistent process results. It is desirable to be able to monitor the relative temperature distribution over the entire wafer area for process development and to maintain quality control during production.

Temperature measurements must be made on production wafers and must be independent of wafer properties.

The use of a water wall arc and absorbing chamber opens new measurement opportunities. The arc can be turned off and on in less than 1 millisecond due to its low thermal mass. This is much shorter than the wafer's thermal time constant. With this fast time response it is possible to turn the lamp off, measure the wafer thermal radiation and then turn the lamp back on before the wafer temperature changes. A measurement of radiation reflected from the wafer is obtained by comparing measurements with the lamp on and off. Using the known spatial and angular distribution of primary radiation on the wafer combined with the measured reflected radiation from the wafer surface provides an estimate of reflectivity as a function of angle and thus hemispherical reflectivity. Using these real time measurements of reflectivity to estimate emissivity and using the thermal radiation measurements permits calculation of wafer temperature. The absorbing chamber eliminates the cavity effect so true wafer emissivity is measured. The "deep" reactor chamber provides easy access to the sensors with an unobstructed view of the wafer as well as protection from source and wafer radiation.

REACTOR RELIABILITY

The use of the new type of water wall arc will contribute to reliability because of constant output over its long life. The 150 kW water wall arc needed for processing 200 mm wafers is half the power of the standard 300 kW lamps used for over five years by the aerospace industry and is based on a new design developed for lamps up to 1.5 MW. Operating at 10% of maximum power means the reliability is greatly increased. The new 150 kW water wall arc has ten times the life of the 100 kW lamp used eight years ago in Eaton's ROA 400 and is expected to process 100,000 high temperature anneals per set of electrodes. Performance does not change with lamp life or arc maintenance.

LARGE WAFERS

The new water wall arcs make scaling to the thicker 300 mm wafers straightforward. Larger area, thicker wafers have increased thermal mass which will require higher radiation flux over larger areas to maintain heating rates in the range of 100 C°/sec. Calculations for thick 300 mm wafers indicate a 300 kW source will be required which is well within arc capabilities.

ULTIMATE UNIFORMITY

The overall design philosophy is to produce a basically uniform temperature by eliminating wafer effects on the device side by chamber design and uniformly heating and cooling through the back side. As the demands for uniformity become more demanding, effects due the spatial variations of back side optical properties and nonuniform chamber effects may require some form of spatially varying irradiance or "zone" control. This can be accomplished with small sources added to the backside chamber. These "shim" sources will be relatively few in number and will supply a few percent of total radiation. Using thermal imaging as described above the control of these shims will be straightforward. The final approach will involve an engineering tradeoff between shim design and control versus control of wafer processing to improve backside optical properties and chamber characteristics. The ultimate uniformity will depend on the quality and reproducibility of chamber and optical components but calculations predict that ± 1 C° at 1100 °C will be possible with production silicon wafers.

CONCLUSIONS

A new approach to RTP reactor design has been shown to offer improved temperature uniformity independent of wafer properties. This simpler approach balances all energy losses through the wafer's device side and edge while heating and cooling entirely through the wafer's backside. The backside chamber is designed to totally absorb radiation reflected and emitted from the wafer thus removing any dependence on wafer

properties. The source radiation and reflector constitute a small portion of the backside chamber thus giving easy to diagnostics.

The design depends on a new small volume, high power water wall arc. The arc's short wavelength spectrum gives efficient absorption by silicon at all temperatures and precise control of where energy is absorbed without significant radiation passing through the wafer. The arc's ability to be rapidly pulsed opens new opportunities for real time temperature measurements.

The reactor is relatively simple with improved diagnostic capabilities. Design calculations predict that temperature uniformity of ± 1 C° at 1100 C° is possible on a production basis.

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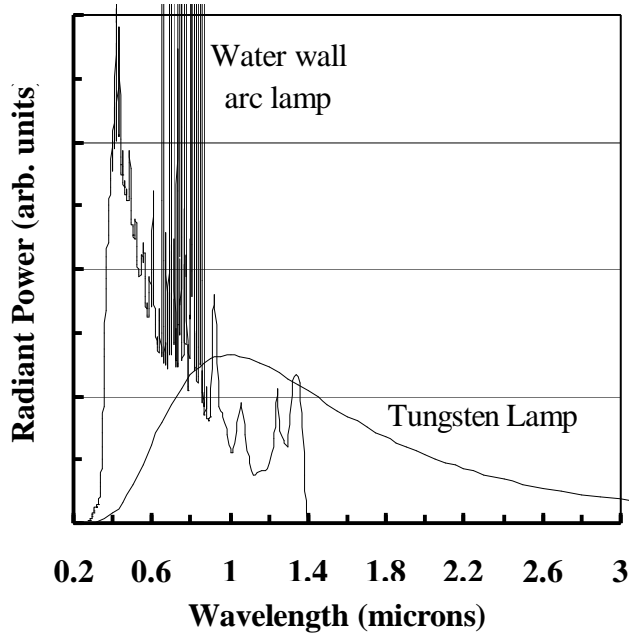


Fig. 1 Spectral distribution of water wall arc and tungsten at 2900 °K

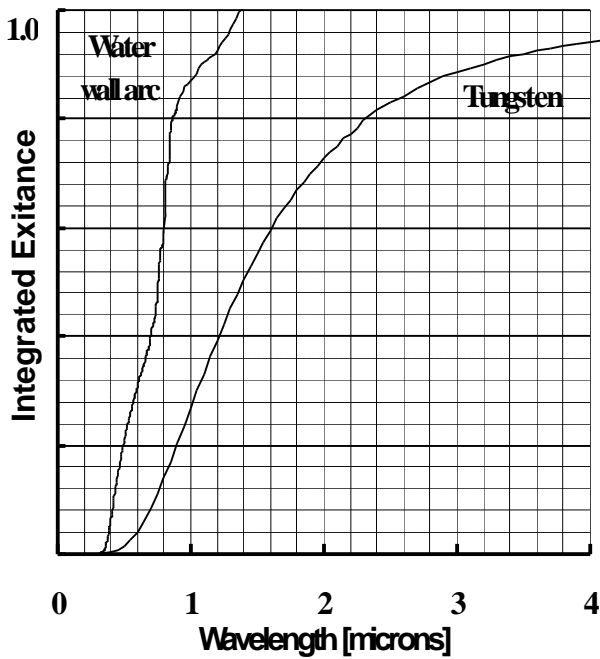


Fig 2 Integrated spectra for water wall arcs and tungsten at 2900 °K.

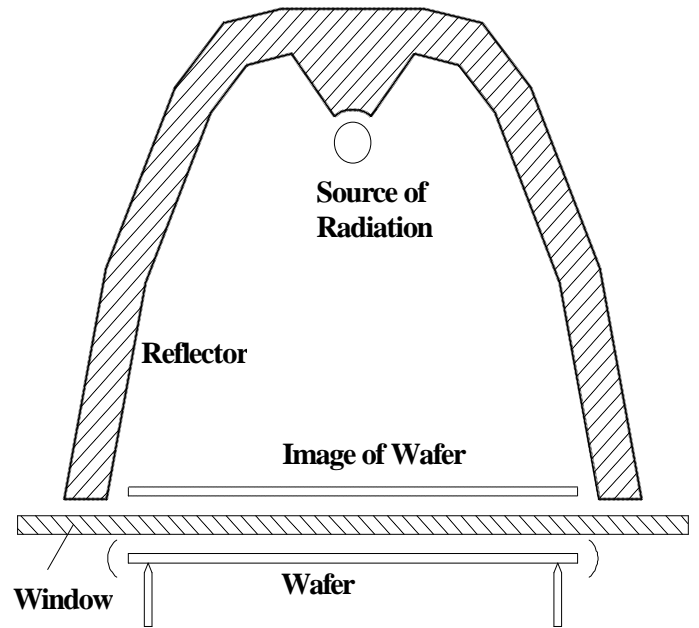


Fig. 3 A single source RTP reactor with the wafer image produced by reflection in window.

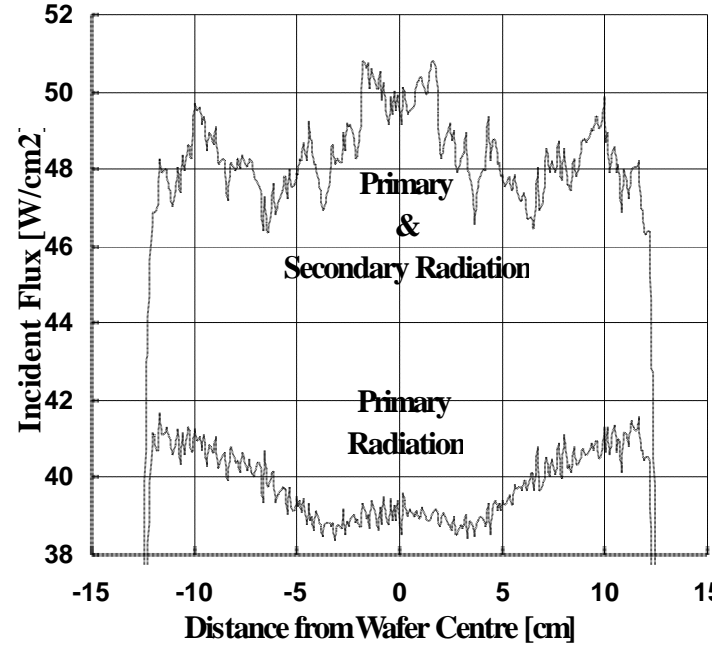


Fig. 4 Monte Carlo calculations of primary and primary plus secondary radiation on target wafer shown in Fig. 3. Wafer reflectivity = 30%. Along a line perpendicular to arc axis.

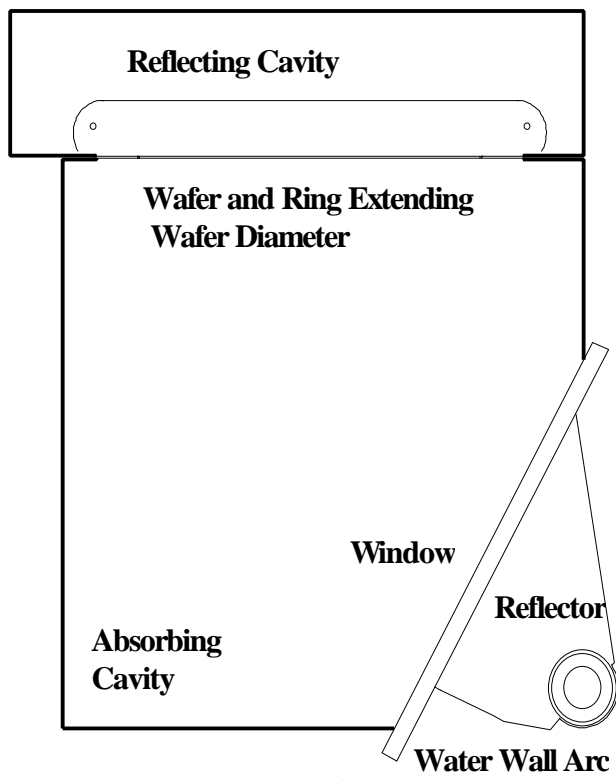


Fig. 5 Absorbing reactor for high temperature RTP.