3D Modeling of Rapid Thermal Processors for Design Optimization of a New Flexible RTP System

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Abstract

A *"virtual reactor"* methodology for optimal design of a rapid thermal processor (RTP) to obtain the best possible wafer temperature uniformity is described in this paper. Given the equipment configuration, e.g., the lamp array, a three-dimensional simulator is used to predict the wafer temperature profiles for various lamp array designs for different processing conditions. The only experimental input needed is the spatial light flux distribution of the individual tungsten-halogen bulb which forms the lamp array. The simulations show that the flux distribution of the heating source significantly affects the temperature pattern of the wafer. Based on these results, a new RTP system with an adjustable reflector and multi-variable control has been designed.

Introduction

The acceptance of Rapid Thermal Processing in the IC industry has been restricted by temperature nonuniformity, mainly caused by the nonuniform nature of wafer radiation heat loss, convective cooling, as well as inappropriate lamp design. Various methods, such as guard rings, specially shaped reflectors, and multi-zone lamps with multi-variable control have been tried to compensate for the nonuniform heat loss. However, most of the existing RTP systems were designed without rigorous treatment of the light flux distributions of the heating sources and their impact on wafer temperature patterns. In that approach the design optimization can not be achieved until the RTP system has been constructed and tested through temperature measurement.

While a number of papers [1-3] have described the simulation of RTP systems to explain the problem of temperature nonuniformity, little work has been done to provide a methodology for optimal design of a new RTP system for better temperature uniformity. In this paper, we describe a methodology that leads to an optimal design of a new RTP system (Fig. 1) using a 3D simulator.

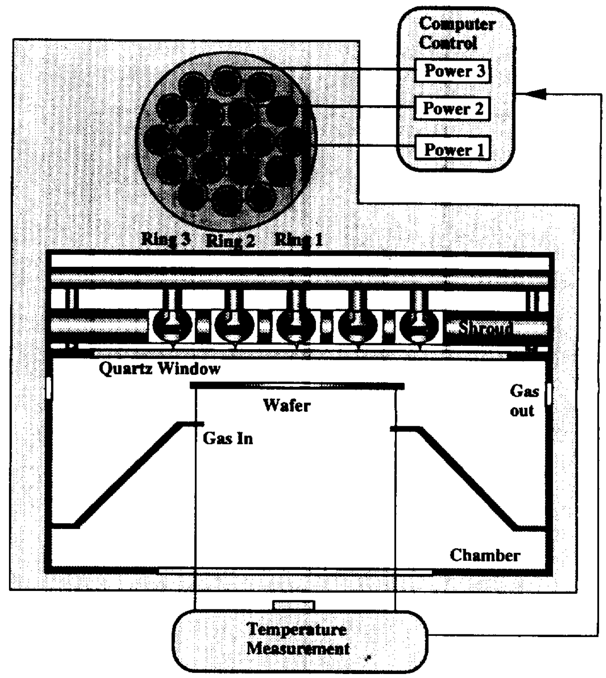

Fig. 1 A new RTP system with multi-variable and flexible lamp control. The power of each lamp ring is controlled independently and the position of shroud reflector can be adjusted to obtain the optimal lamp light flux distributions for various process conditions.

Design Methodology & Characterization

The design methodology is illustrated in Fig. 2. First, the light flux distribution of a bulb is experimentally characterized by photo diode scanning in order to provide more accurate and practical design. The lamp array is then designed by specifying the positions of the light bulbs, reflector geometry, etc. The 3D simulator is then used to predict the temperature profile of the wafer by taking into account of direct lamp heating, reflections (by reflector, chamber walls and wafer), radiation, conduction and convective cooling (by processing gas). If the temperature uniformity is not good, the bulb flux distribution and the positions are adjusted iteratively to obtain the optimal design. The design optimization is achieved virtually before the prototype is constructed.

Two kinds of tungsten-halogen bulbs, one with a vertical filament (Fig. 3) and the other with a horizontal filament (Fig. 4), have been characterized. The latter has never been used before in any RTP system. To provide flexible control

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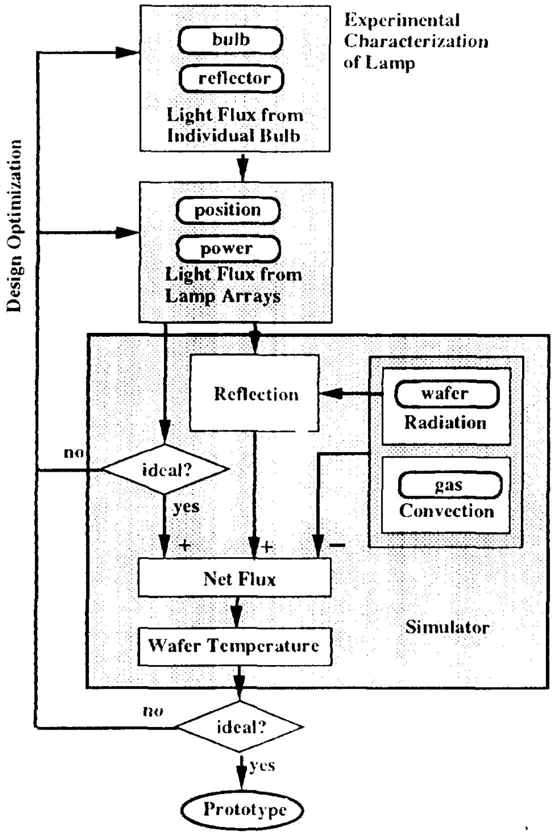

Fig. 2 RTP design methodology using 3D simulator

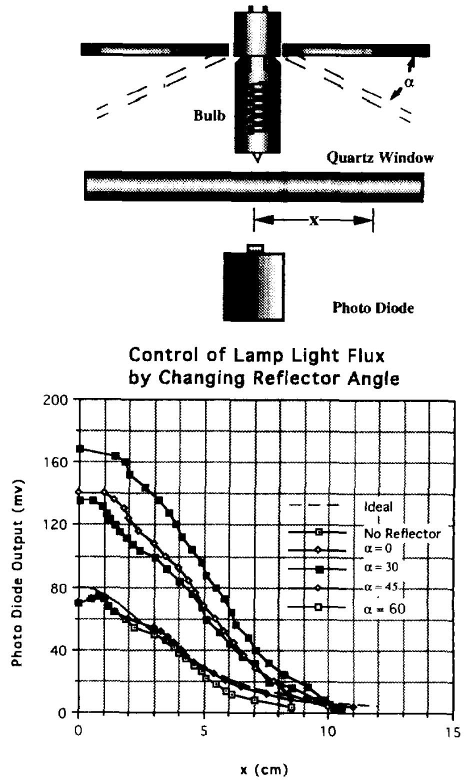

Fig. 3 Characterization and control of the light flux distribution for bulb with vertical filament.

over the bulb flux profile, an adjustable gold-plated reflector (flat plates for vertical filament bulb and cylindrical shroud for horizontal filament bulb) is placed around the bulb at different positions and the corresponding light flux profiles are obtained. One typical 3D flux profile of horizontal filament bulb is also shown in Fig. 5. The real bulb flux distribution is different from that of ideal light source commonly assumed in the literature, and can be effectively modified by the adjustable reflector. For a given lamp array design, there may exist an optimal reflector position which provides the best temperature uniformity. The bulb with horizontal filament offers better heating efficiency and its cylindrical shroud requires smaller spacing in lamp array design. Hence, it is selected as the candidate for the new RTP system.

Modeling

The thermal energy balance equation used in the model is given by,

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q_{absorb} - q_{rad} - q_{conv}$$

where ρ, c, k are the mass density specific heat, and thermal conductivity of silicon wafer, respectively. q_{absorb} is the heat absorbed by wafer from the lamp illumination and reflections. q_{rad} is the wafer heat loss due to radiation, and q_{conv}, the heat loss due to convective cooling by the surrounding gas. q_{rad} and q_{conv} have been described in previous work [4], and a new approach is used to obtain q_{absorb}.

Most of the reflection models in the past [3-4] have assumed diffuse surfaces. This assumption is not valid for highly specular surfaces such as gold-plated reflector, highly polished silicon wafer or stainless steel chamber wall. Although ray-tracing method is generally used to simulate specular reflection, it is computationally very expensive. In this

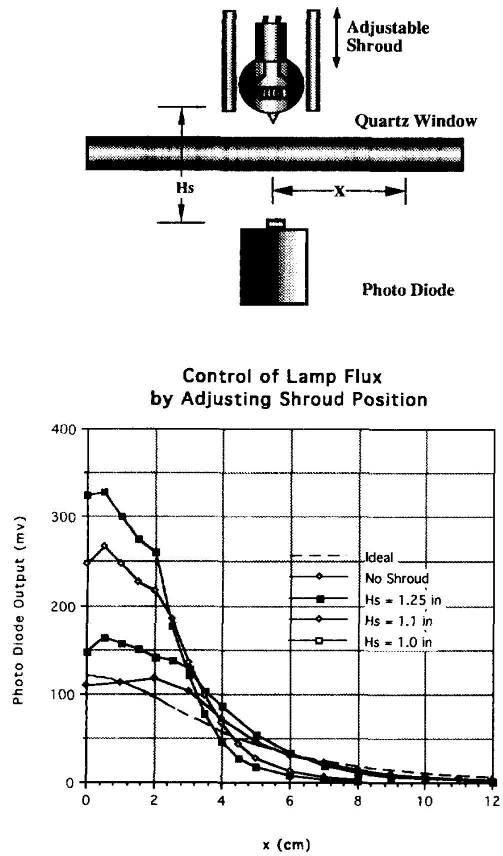

Fig. 4 Characterization and control of the light flux distribution for bulb with horizontal filament.

work, a micro-facet model [5] is used to simulate the reflections for surfaces with different reflection properties (Fig.6). For specular surfaces, the reflected light is highly directional around the specular direction. For rough surfaces, the incident light is scattered to all directions. The surface roughness is specified by the root mean square slope of the micro facets, which is taken as the parameter for material reflection property in the simulator.

A recursive method has been developed to simulate multiple reflections inside the RTP chamber. All surfaces are divided into small surface elements. First, every element that is exposed to the heating sources is illuminated and the reflected light flux distribution can be obtained by using micro facet model. These elements are then treated as new heating sources and illuminate other elements. This procedure is recursively performed until the reflected light energy becomes considerably smaller than the initial incident energy from lamp.

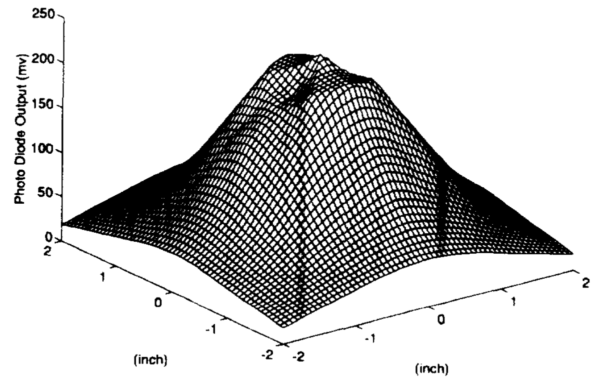

Fig. 5 A typical 3D light flux distribution from bulb with horizontal filament.

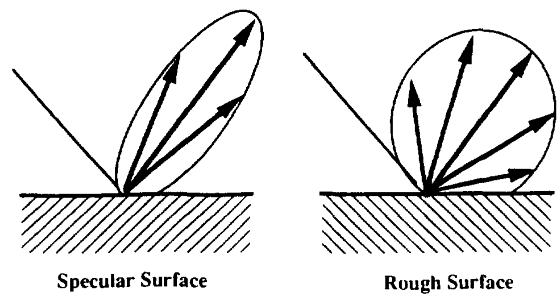

Fig. 6 Surfaces with different reflection properties can be simulated in the 3D simulator

Results

A new RTP system (Fig.1) with multi-zone lamp in which tungsten-halogen point sources are configured in concentric rings to provide a circularly symmetric flux profile, adjustable reflector, and multi-variable real-time control whereby each of the rings are independently and dynamically controlled to provide for control over the spatial flux profile and has been designed and optimized by using the methodology and simulator described above.

Various lamp array designs have been compared using the simulator to identify the optimal design of lamp array positions. Two typical three-zone circularly symmetric concentric lamp rings and their resulting temperature patterns for four inch wafers are shown in Fig. 7. The simpler lamp array design, with 1, 6, and 12 bulbs at the inner, intermediate and outer ring, has been selected for the first prototype.

Fig. 8 shows that for a given lamp array design, changing the shroud position can significantly affect the temperature patterns in both low temperature (500 °C) and high temperature (1100 °C) ranges. For multiprocessing, the position of the shroud may be adjusted to different positions

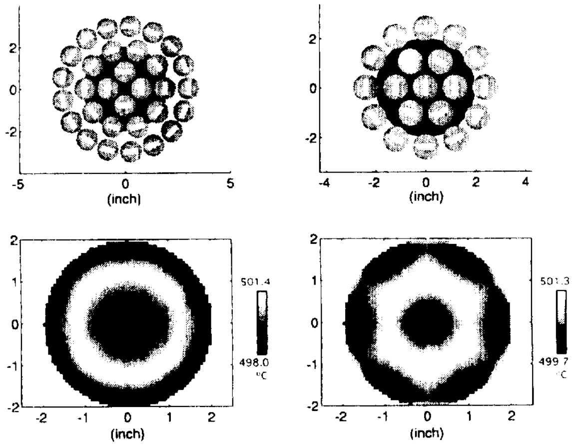

Fig. 7 Two different lamp array designs and their wafer temperature profiles.

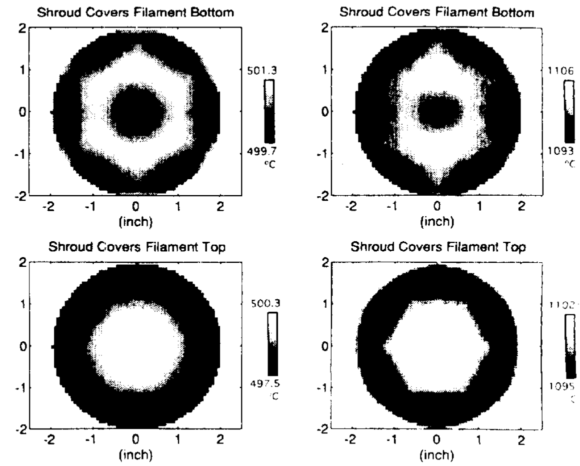

Fig. 8 Changing of shroud positions for different process temperatures (500 and 1100 °C).

to provide the optimal heating flux profile for different processing conditions. This result suggests another way to control temperature uniformity in addition to the multi-variable control [4] over the power ratio of lamp rings.

The computer-aided design of RTP system can not be practically accomplished without a 3D simulator and experimental characterization of the heating source flux distribution. As the design optimization is performed using simulator instead of real prototypes, financial cost and development time for a new RTP system can be dramatically reduced.

A low power prototype (Fig. 9) of such system has recently been constructed for 4 inch wafer, to test the idea of shroud reflector, to validate the model, and to improve the simulator for computer-aided design of new RTP systems for 8 and 12 inch wafers.

Although the prototype was originally designed for use at low temperatures around 500 °C with 650 watt bulbs, the most recent experiments shows that it is capable of achieving a uniformity of ± 3°C at 940°C. One of the major problems in rapid thermal processing is that wafer temperature can not be measured reliably. At present, the temperature uniformity is obtained by growing SiO_2 and relateting the oxide thickness to growth temperature. A more advanced technique using acoustic sensors [6] is currently being developed and tested in the same RTP system, which will provide more reliable experimental results to verify the model.

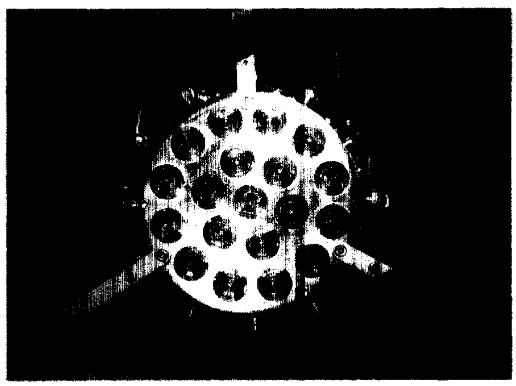

Fig. 9 A new RTP lamp with adjustable gold-plated reflector.

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