PART I

Temperature Measurement in RTP Systems

IN SITU WAFER EMISSIVITY VARIATION MEASUREMENT IN A RAPID THERMAL PROCESSOR

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ABSTRACT

Wafer backside reflectivity measurements at room temperature have been performed in a rapid thermal processor equipped with two rows of heating lamps by measuring, with the process optical pyrometer, the light emitted by the lower row of the heating lamps and reflected by the wafer. The differences in reflectivity have been correlated with the process temperature variations induced by emissivity changes. Optical pyrometer recalibration procedures have then been established. It has been demonstrated that the reflectivity measurement, performed automatically for each wafer prior to the thermal cycle, may drastically improve the accuracy of temperature control.

INTRODUCTION

For Rapid Thermal Processing to be accepted in a production environment, it is essential to develop repeatable temperature measurement means. Nearly all Rapid Thermal Processors currently used for production purposes include optical pyrometers [1] aiming at wafer backside, and therefore use radiothermometry for temperature measurement. In radiothermometry, a sensor, i.e. the optical pyrometer, measures the power radiated by a surface. The surface temperature can then be calculated using Planck's law and taking into account the surface emissivity.

However, problems have still to be overcome before radiothermometry could be used for rapid thermal processing in an industrial environment. Most important among these are the effects of reflections from the wafer surroundings, and the unplanned variations of wafer backside emissivity with the nature of the surface being measured, i.e roughness or presence of a dielectric coating. In other words, having calibrated the optical pyrometer with a thermocouple instrumented wafer does not assure that, when used with other wafers, the pyrometer will measure the true temperatures. Procedures are therefore needed to adjust the optical pyrometer output vs. surface nature, to obtain the proper temperature measurement.

Consequently, optical pyrometers are calibrated at two distinct levels [1]. As already explained, manual calibration must first be performed at the system level, by comparing the pyrometer output with that of a thermocouple in contact with a wafer. This sacrificial wafer must be representative of the lot to be processed, and is used for calibration purposes only. If the emissivity is likely to change from one wafer to another, a wafer level calibration must be done for all wafers before processing.

Recently, new techniques [2, 3, 4, 5] have been introduced for emissivity correction at wafer level. However, extra sensors have to be used, irrespective of the method involved. In this paper, a means for automatic emissivity corrections is proposed, without the need for additional hardware.

THEORETICAL BACKGROUND

The intrinsic spectral emissivity $\varepsilon(\lambda,T)$ of a wafer surface is defined in a low temperature non-reflective environment, so that reflected background radiation is insignificant, as the ratio of the radiation power density at wavelength λ emitted from this surface at temperature T, to the radiation power density at the same wavelength emitted from a blackbody at the same temperature. This intrinsic emissivity is likely to be affected by thin film layers [6], roughness of the wafer surface [7], or wafer transmittivity and therefore wafer temperature [8].

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By invoking the Helmoltz reciprocity relationship and conservation of energy, it can be established (Kirchhoff's law) how at thermal equilibrium wafer backsurface emissivity is related to wafer optical properties :

$$\varepsilon(\lambda, T) = 1 - \rho(\lambda, T) - \tau(\lambda, T) \qquad (1)$$

where the symbols are respectively the spectral emissivity, reflectivity and transmittivity at wavelength λ and temperature T (ε, ρ, and τ are all unitless). Equation (1) is the more familiar form of Kirchhoff's law, where directional quantities are not considered : the total emissivity for radiation emitted in an hemisphere is related to the total reflectivity (in all directions) for uniform incident radiation, and to the total transmittivity [9]. For opaque materials (Si above 700 °C), $\tau = 0$. On the other hand, it has been experimentally shown that over 700 °C Si emissivity is nearly constant vs. temperature [8,10] (emissivity actually slightly decreases [11]).Thus, equation (1) reduces to :

$$\varepsilon(\lambda) = 1 - \rho(\lambda) \qquad (\text{for } T > 700°C) \qquad (2)$$

Quantities in equation (2) are involved in heat transfer, where energy received or emitted in all directions has to be accounted for [9]. However, for radiothermometry purposes, directional emissivity is the quantity of importance, as far as hemispherical surface pyrometers are not used. If the optical pyrometer receives radiation from the wafer in direction (θ, ϕ), then the following relationship holds :

$$\varepsilon(\theta, \phi, \lambda) = 1 - \rho(\theta, \phi, \lambda) \qquad (3)$$

where $\varepsilon(\theta, \phi, \lambda)$ is the spectral emissivity in direction (θ, ϕ), $\rho(\theta, \phi, \lambda)$ is the reflectivity of the surface, i.e. the reflectivity of the wafer for radiation incident from the direction (θ, ϕ) reflected into the total emisphere, or equivalently, the reflectivity into the direction (θ, ϕ) of radiation incident uniformly over the total emisphere. This reflectivity is difficult to measure without losing the advantage of remote sensing. Nevertheless, reflectivity measurement from wafer backside has recently been used for emissivity measurement and optical pyrometer adjustment [4, 5, 7] : a blackbody source together with an optical pyrometer have been utilized in a preload station to measure at room temperature wafer backside reflectivity within the optical pyrometer wavelength band.

On the other hand, inside a rapid thermal processor reflective chamber, wafer emissivity is also affected by multiple reflections and is then referred to as the effective emissivity of the wafer. It has been shown that effective emissivity (inside the chamber) is also changed by thin films and roughness. However, the effective emissivity dependence upon roughness in a reflective chamber is different from that in a non-reflective environment [8]. If an emissivity measurement has to be done, it is therefore of great interest to perform the measurement in situ.

The approach described in this paper consists of an in situ measurement, with the process optical pyrometer, of the incoherent radiation emitted by some of the lamps used as heating source during the thermal process, and reflected by the wafer backsurface [12].This method obviates the need for additional sensor and light source, and as an in situ technique allows measurement of the effective emissivity variations, geometric effects being accounted for.

A rapid thermal processor equipped with two rows of lamps placed above and below the wafer is needed. During the measurement, only the lower row of lamps is turned on. The electrical power applied to the lamps must be low enough to avoid excessive heating of the illuminated wafer, while the optical pyrometer gain is increased to give a measurable output. The incident radiation being assumed to be uniform, and the reflected intensity being measured into the process optical pyrometer direction, the operating conditions are close to those needed for the measurement of directional reflectivity. However, the reflectivity, as measured by the method described above, is only a reflectivity factor and not the actual directional reflectivity [13] appearing in equation (3). The basic assumption is made, first that the variation of this factor with experimental conditions is the same as the variation of the actual reflectivity $\rho(\theta, \phi, \lambda)$,

variation at low temperature. Only variations vs. a reference value will be used. The reflectivity reference value being obtained with the thermocouple instrumented wafer.

EXPERIMENTAL DETAILS

The rapid thermal processor used in our experiments consists of two rows of tungsten-halogen quartz lamps placed above and below a quartz processing chamber. The lamps are located inside a high-reflecting, double-walled, water-cooled, stainless-steel chamber. The annealer is equipped with a closed-loop temperature control system and a programmer allows thermal cycles to be constructed. The temperature can be measured by K-type thermocouples or an optical pyrometer. In the followings, an IRCON pyrometer, having a 3.7 μm-to-4 μm wavelength band, has been utilized. It aims at wafers within a direction normal to wafer backsurfaces. An emissivity setting is utilized for calibration.

Two wafer batches were used for the experiments. In a first group of (100), 4" wafers from the same vendor, i.e. having the same backside roughness, SiO_2 films were grown to modulate the emissivity through optical interference phenomena. The SiO_2 thicknesses range from 1000 Å to 10 000 Å. In a second group, (100) and (111) wafers from different vendors were employed, whose backsurface roughnesses range from mirror-like to very rough surfaces.

In a first set of experiments, the optical pyrometer was calibrated vs. a thermocouple using a reference wafer from each batch. All wafers were then sequentially submitted to a thermal cycle with a temperature plateau at 800 °C. The process ambient atmosphere was nitrogen. During this plateau, the true temperature was kept constant by the control system, the thermocouple providing the feedback signal and the optical pyrometer output being simultaneously recorded. The difference between the true wafer temperature and that indicated by the pyrometer was plotted vs. oxide thickness or roughness.

The reflectivity of each individual wafer was then measured by illuminating wafer backsurfaces at a constant level with the lower row of lamps only. A low power value was used to avoid wafer excessive heating, i.e., less than 100°C. The reflected light intensity was measured by the process optical pyrometer whose sensitivity was increased for this purpose. For each batch, the reference value, that is, the reflected intensity obtained from the corresponding reference wafer, was subtracted to give the reflectivity variation values.

RESULTS AND DISCUSSION

It can be seen from equation (3) that a reflectivity decrease results in an emissivity increase. This is experimentally demonstrated in figure 1, where the reflectivity variations measured at low temperature (less than 100°C), together with the corresponding variations of the optical pyrometer output at 800°C (controlled with a thermocouple), are plotted vs. oxide thickness.

As already demonstrated theoretically [6] and experimentally [10, 14], oxide thickness affects temperature measurement : when the oxide thickness increases from 1000 up to 8000 Å, reflectivity decreases and the temperature measured with the optical pyrometer rises, thus corresponding to an emissivity increase. Above 8000 Å, the measured temperature decreases, emissivity being a periodical function of oxide thickness [6, 14] as silicon dioxide alternatively creates destructive and constructive interferences, causing an alternately rising and falling emissivity.

It thus appears from figure 1 that temperature measurement errors as large as 45 °C are generated by variations of SiO_2 film thickness, when an optical pyrometer is used without recalibration. However, figure 2 shows a close relationship between reflectivity and temperature variations. Such a curve can therefore be used for optical pyrometer recalibration, provided a reflectivity measurement is performed on each wafer to be processed, and a recalibration curve similar to that of figure 2 has been previously established. Similar calibration curves have to be created for all processing temperatures to take into account, first emissivity dependence on temperature, and then the non-linear effect of emissivity on temperature measurement [15].

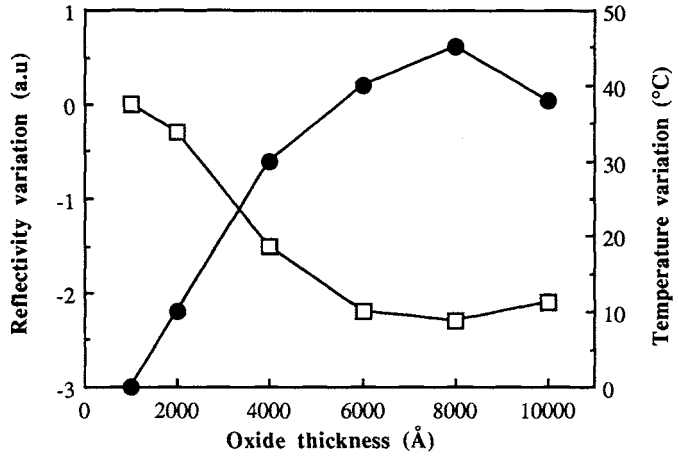

Figure 1 : reflectivity (squares) and pyrometer output (black circles) variations vs. backside oxide thickness. The 1000 Å oxidized sample was chosen as the reference wafer. Process temperature is 800°C.

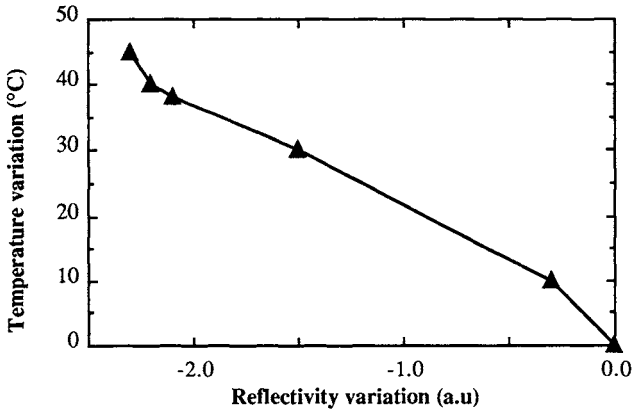

Figure 2 : correlation between optical pyrometer output (without recalibration) and reflectivity variations.

Figure 3 shows experimental results similar to those of figure 2, except for roughness is now causing the changes in the optical properties of the wafer backsides. There again (see figure 4), a close relationship exists between reflectivity and temperature variations (as measured by the optical pyrometer without recalibration).

However, if one compares figures 2 and 4, the slopes of the temperature vs. reflectivity curves appear to be different. In other words, when roughness causes a change in emissivity, a reflectivity factor increase corresponds to an effective emissivity decrease. This contradicts equation (3) correlating wafer intrinsic emissivity and reflectivity. This phenomenon is most likely due to the detection by the optical pyrometer, during the thermal process, of lamp radiation reflected from the wafer backsurface, this parasitic light being proportional to the reflectivity factor measured in our experiments. We can therefore conclude that roughness predominantly

affects the amount of parasitic light detected by the optical pyrometer, and that effects related to the intrinsic emissivity variations are in this case negligible.

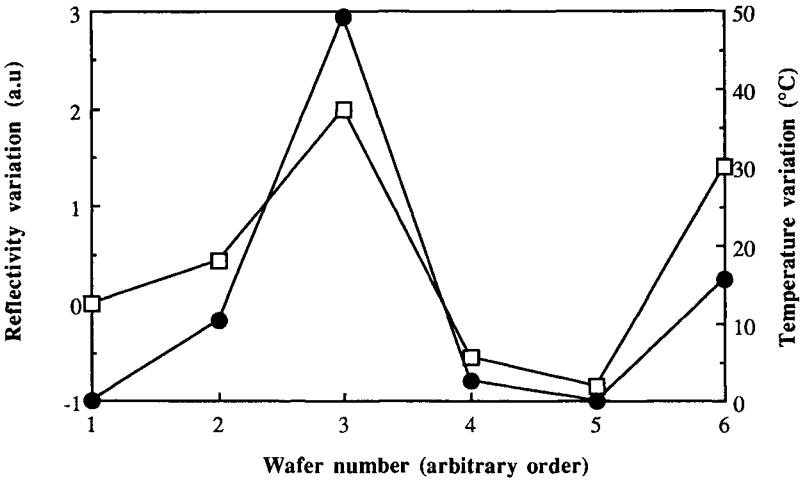

Figure 3 : reflectivity (squares) and pyrometer output (black circles) variations vs. wafer number. Wafer n° 1 was chosen as the reference wafer. Process temperature is 800°C.

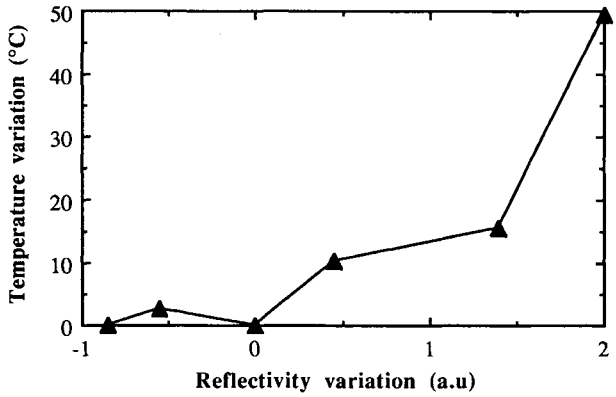

Figure 4 : correlation between optical pyrometer output (without recalibration) and reflectivity variation.

With respect to pyrometer recalibration, figures 2 and 4 show that for a given reflectivity variation, optical pyrometer output has to be differently adjusted depending on the nature of the wafer backside structure modification. The reason for the emissivity change has therefore to be known in advance in order to select the proper pyrometer output adjustment.

One possibility of dealing with simultaneous variation of roughness and thin film thickness, would be to measure the reflectivity of each bare wafer prior to the first process step, in order to detect a possible roughness variation. Only wafers presenting nominal roughness would be processed. Reflectivity would be measured again before the Rapid Thermal Processing step. Discrepancies in the results obtained for different wafers would prove that films exhibiting

non-constant thicknesses are present within the wafer lot, and that an optical pyrometer recalibration is necessary. However, further studies are needed to assess the effect of roughness on correlation between reflectivity and effective emissivity, when the change in emissivity is due to thin films. This would allow creation of relevant optical data, needed to correct for emissivity variations between wafers of arbitrary backside condition.

CONCLUSION

It has been demonstrated that by measuring, in a rapid thermal processor, the amount of light emitted by the lower row of lamps and reflected by a Si wafer backsurface, by comparing this reflected light value to those obtained with a reference wafer, and by correlating the reflection variation to the experimentally predetermined modification of the optical pyrometer output, changes in emissivity between individual wafers can be accounted for at temperatures higher than 700 °C. In its most sophisticated implementation, the above method makes it possible to automatically recalibrate an optical pyrometer before the thermal process, therefore compensating for varying backside conditions. More simply, the method can also serve as a diagnostic tool to detect unforecast emissivity variations within a wafer lot.

As the reflectivity measurement is done in situ, using the process optical pyrometer, it is performed at the same location as the temperature measurement. Therefore, wafer backsurface non-uniformity will have no effect on the recalibration step. Moreover, once the temperature vs. reflectivity curves have been established, no additional piece of hardware is needed, the computer handling all data manipulations and setting the processing chamber for reflectivity measurement.

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TEMPERATURE CONTROL AND SYSTEM DESIGN ASPECTS IN RAPID THERMAL PROCESSING

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ABSTRACT

The main factors influencing the thermal performance (and thus product yield) of a rapid thermal processor are the heat source, the reaction chamber, the temperature measurement system, and as complicating factors, their total configuration and the optical wafer properties.

The characteristics of 19 currently available commercial RTP systems are highlighted with focus on temperature control including the spectral characteristics and measures to suppress perturbations due to stray radiation.

In addition recent developments and trends in the system configuration and in the optimization of temperature or layer thickness control are discussed. The improvements in temperature control focus especially on in situ temperature control, irrespective of wafer condition, and at system constructions that optimize dynamic temperature uniformity. Some novel optical process control and novel system design aspects to compensate for emissivity changes and temperature non-uniformity are included.

INTRODUCTION

As the semiconductor industry is moving to deep submicrometer details Rapid Thermal Processing, with its inherently smaller thermal mass, is steadily replacing batch furnace steps. RTP started with pulsed laser beams.[1] In recent articles [2–4] the advantages of isothermal heating with incoherent lamp or resistive heating are reviewed.

Today, a broad spectrum of rapid thermal processes is applied or in development, such as deposition of polysilicon [5] as well as epitaxial Si and Ge_xSi_{1-x}[6,7], gate dielectric formation,[5] glass curing,[9] selective silicide deposition,[10] shallow dopant diffusion, etc. Other areas are opening, such as processing of III-V semiconductors,[11] ceramic films [12] and magnetic films for devices or storage media.[13]

The worldwide number of RTP systems is estimated to be around 1500, with incoherent lamps as the predominant heat source. Although this number shows a large annual growth, the main obstacles for wide acceptance of RTP are reproducible temperature and dynamic process uniformity control.[14] Furthermore, the selection of an RTP system is highly dependent on the application and complicated by the multitude of system designs. Recently a selection guide appeared, describing seven commercial systems,[15] but many more manufacturers are active.

This paper tries to give a review of temperature control and system design, and can be read in conjunction with an earlier review.[14] First a short summary of current system characteristics is given (heating sources and chamber designs), next the techniques for temperature measurement. A compilation of present features for 19 commercial systems follows. The paper concludes with emissivity correction options and related trends in process control and system design.

GENERAL SYSTEM CHARACTERISTICS

Absolute temperature and temperature uniformity are primarily affected by *heat source* parameters (size, shape, location, color temperature, reflector set) and *process chamber* parameters (dimensions, shape, optical wall/window material properties, gas flow dynamics, etc.). The third primary component of an RTP system is its *temperature sensor* and control system. A short discussion of each component follows next.

Heat sources and processing chambers

Three *heat source* types are used in commercial RTP, all with isothermal temperature profile across the wafer thickness [3]: 1) the tungsten lamp, 2) the noble gas long-arc lamp and 3) the continuous resistively heated SiC bell-jar. Their maximum color temperatures are around 3300, 6200, and 1700 K, respectively. A more detailed description is found elsewhere.[14]

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The three heat source types have some characteristic differences. First is their *color temperature*, mentioned above, which has a direct impact on the initial heating rate of semiconductor wafers. For example the arc lamp, with its highest color temperature, emits most of its spectrum ($\lambda_{peak} = 0.5\ \mu m$) at wavelengths within the silicon band gap ($\lambda = 1.2\ \mu m$), see Fig. 1.

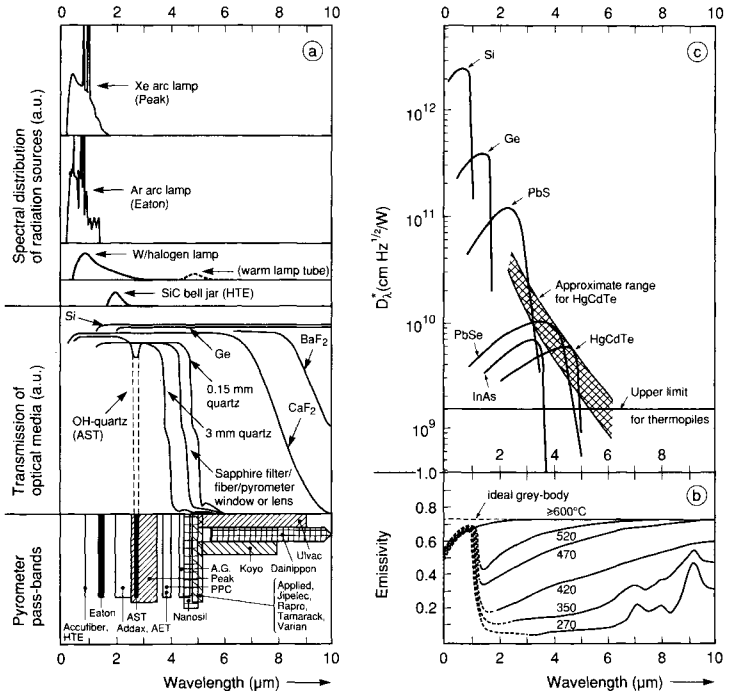

Fig. 1: Spectral features in RTP systems
a) heat sources, optical media and pyrometers ; b) emissivity of silicon after Sato [16] ;
c) detectivity/sensitivity for temperature sensors at room temperature, after Dimmock.[18]

Thus most of the initial heating is accomplished by electronic valence to conduction band absorption and only a small portion by intrinsic free carrier absorption.[16] This latter fraction increases for the tungsten-halogen lamp ($\lambda_{peak} = 1.0\ \mu m$) and even more for the SiC bell jar ($\lambda_{peak} = 2.0\ \mu m$). So here the initial heating rate depends more on temperature and hence on the dopant level of the wafer.[16] Note that this dependence disappears above 600 °C, where heating occurs through band to band absorption only (cf. Fig. 1b). Consequently, if one assumes identical lamp/reflector geometry and the same installed power, only below this temperature the lamp choice affects the heating rate. Typical overall heating rates range from 300 K/s for arc lamps to 100 K/s for the resistively heated bell jar.[15]

Second difference is the *symmetry* of the heat sources. Unlike lamp sources with their line symmetry the continuous heat source has circular symmetry and is heated continuously. This symmetry is conformal to the wafer, which implies easier temperature uniformity control.[14,17]

Currently available RTP systems use three different *chamber designs:* 1) cold wall (water cooled metal with top or bottom quartz plate), 2) warm wall (quartz envelope within reflective metal housing) and 3) hot wall (resistively heated silicon carbide bell jar [17]). A more detailed description of the three designs, including their process limitations, was published before.[14]

The three design have different characteristics, a striking one being the *upgradability*: without the use of thin susceptors cold and warm wall systems face an increasingly complicated dynamic uniformity control (cross-lamp geometry, differentiated lamp powering and complex reflector design), while the hot bell jar wall is easily upgradable up to 300 mm wafer diameter.[15]