

Method and Apparatus for Improved Temperature Control in Rapid Thermal Processing (RTP) Systems

FIELD OF THE INVENTION

The present invention relates to an apparatus and a method for measuring and controlling the temperature of an object heated in a Rapid Thermal Processing (RTP) system. More specifically, the present invention discloses a method and apparatus for measuring and controlling the temperature of an object if interference effects disturb the conventional pyrometric methods of temperature measurements. The present invention is particularly useful in the case of semiconductor wafers which have layers of material deposited on the back side of the wafer, and in the case of Rapid Thermal Chemical Vapor Deposition (RT-CVD). The starting point of the present invention is that an in situ or ex situ in line broadband reflectometer measurement of the wafer is integrated in the equipment and in the process flow. On the basis of the reflectometer measurement results the RTP system selects corresponding calibration file for the prior art wafer temperature measurement system, usually comprising a pyrometer, or an corresponding open loop heating file for determining the lamp power vs time needed for the wafer in process. The present invention improves the repeatability of the prior art "emissivity independent" heating control methods. In case of large differences in wafer emissivity these methods have about ± 10 °C error in temperature control. The present invention improves the situation to the requirement of the industry for a maximum ± 2 °C error.

BACKGROUND OF THE INVENTION

The field of rapid thermal processing has been chiefly concerned with uniformly heating semiconductor wafers to a known temperature, and measuring and controlling the temperature time profile of the wafer for the various annealing, chemical reaction, and film growth techniques required by the various processes. To achieve uniformity of

1 heating, the individual lamps of the heating systems have been separately controlled by
the control system, and the reflector systems have been carefully designed to irradiate
the wafer in a known pattern.

5 Optical pyrometric temperature measurements in RTP systems require the selection of a
wavelength and an optical bandwidth of the measurement. This choice is made on the
basis of the material parameters of the wafer, the reactor chamber, the reflectors, and the
radiation sources (See for example U. S. Patent 5,188,458 and DE 4012615C2).

10 The so called "Ripple Technique" (U. S. Patent 5, 154, 512) is a special case of optical
pyrometric measuring. The heating lamp power supply is modulated with a frequency of
5-120 Hz, and the infra-red light emission from the wafer is measured in a narrow band
through a first optical fiber while light emission from the lamps is measured in the same
narrow band infra-red region through a second optical fiber. The wafer temperature
15 usually cannot change fast enough for the emitted radiation to follow the modulation
frequency, while the lamp filaments and hence the lamp radiation can be modulated at
the modulation frequency. The radiation measured with the first fiber can be used to
determine the radiation reflected from the wafer since the variation in the radiation must
20 be due to the reflected light from the lamps. The variation in light reflected is measured,
and the reflection coefficient for the wafer is deduced. Once the reflection coefficient for
the wafer is known for a particular wavelength, the emissivity of the wafer at that
wavelength is known, and the unvarying part of the radiation collected by the first
25 optical fiber due to the emission from the wafer can be used to calculate the
temperature. This technique is, however, very sensitive to temperature and the
arrangements for the necessary mechanical adjustments of the light fibers are very
expensive.

30 Use of optical fibers and light pipes to collect the light does not change the principles of
the measurements cited above.

The best prior art signal to background ratios that can be reached using monochromatic
or narrow bandwidth pyrometric techniques is about 1000:1 (ED 4012615C2), which
35 allows good reproducibility of the temperature measurement. However, such
monochromatic or narrow bandwidth pyrometric measurement can be very strongly

1 influenced by layers of material of different indices of refraction on the surface of the
object being measured, and the method is practically unusable if the measured wafer
surface has optically thin layers of variable layer thickness deposited thereon. The
5 reflection coefficient at any wavelength, and hence the emissivity (which is 1 minus the
reflectivity) of the surface, varies enormously at the various layer thickness vary. For
example, as one layer of silicon dioxide grows from 0,25 micron thickness on a silicon
wafer the reflectivity for 1.5 micron light varies from a minimum of 6% to a maximum
10 of 42 %. In such cases a pyrometer can only be used if the bandwidth of the measured
radiation is broad enough that the constructive and destructive interferences within the
measuring bandwidth compensate each other. In the case cited above, wavelength of 3
micron light has a reflectivity maximum when the wavelength at 1.5 microns has a
reflectivity minimum. A measurement band of from 1.5 to 3 microns(or a measurement
15 wavelength of 2.25 ± 0.75 microns) would be preferable to compensate the variations in
emissivity. In such a case, it can be shown (on conservation of energy grounds) that the
broadband wavelength filter cannot filter out the radiation from the background, and the
signal to background ration becomes very small.

20 Specifications for emissivity variations for RTP often mention only a range of the
emissivity factor (e.g. 0,3 - 0,9) without wavelength or wavelength range definition.
These specifications implicitly contain the wavelength of the control pyrometer which is
sensitive to only a narrow band of infra-red wavelengths. Emissivity measured only in a
25 narrow band where the temperature measuring pyrometer measures, however, does not
give a good account of the energy coupling of the radiation to the wafer. Coupling
depends on the integral of the emissivity of absorptivity in the total wavelength range of
the radiative energy transfer from the RTP system lamps. The lamp light incident on the
30 wafer has a very much broader spectral width than the pyrometer sensitivity.

The coupling of a coated wafer is very different from that of an uncoated wafer. The
uncoated wafer is to first order a "gray" body. In optics, a grey body has an emission or
absorption spectrum where the emission or absorption constant does not change. A
35 "black" body has emission constant is equal to 1, whereas the emission constant of a
"grey" body is less than one. Since the emission or absorption coefficient is constant

1 over a large wavelength range, a single emissivity or absorption coefficient defines the
light absorption and emission properties of a grey or black body. Different layer
constructions result in a non "grey" body and the emission and absorption coefficients
5 may vary wildly throughout the spectral region of the lamp radiation. A broad band
measurement of the emissivity or reflectivity can, however, be used to predict the
coupling to the radiation to the wafer and thus to set the system parameters of RTP
system so that uniform heating to the desired temperature results.

10 Front and backside couplings of production wafers are very different. The front side
may have many layers of patterned "spots", each spot having different spectrally
integrated reflectivity and emissivity. The backside of the wafer is generally spatially
uniform, and the spectrally integrated backside emissivity is generally quite different
15 from the spatially and spectrally averaged emissivity of the front side of the wafer. In
the case of a spectrally varying "Non-gray-body" emissivity, a monochromatic (or
narrow spectral band width) pyrometer signal has little to do with temperature. On the
one hand at a given temperature different wafers give different pyrometer signals. On
20 the other hand in the case of a fixed heating power level the different coupling results in
a different wafer temperature.

25 RELATED APPLICATIONS

Reactors based on the RTP principle often have the entire cross section of one end of the
reactor chamber open during the wafer handling process. This construction has been
established because the various wafer holders, guard ring, and gas distribution plates,
30 which have significantly greater dimensions and may be thicker than the wafers, must
also be introduced into the chamber and must be easily and quickly changed when the
process is changed or when different wafer sizes, for example, are used. The reaction
chamber dimensions are designed with these ancillary pieces in mind. US Patent
35 5,580,830, assigned to the assignee of the present invention, teaches the importance of

1 the gas flow and the use of an aperture in the door to regulate gas flow and control
impurities in the process chamber.

5 The importance of measuring the temperature of the wafer using a pyrometer of very
broad spectral response is taught in U. S. Patent 5,628,564, which is assigned to the
assignee of the present invention. The wafer to be heated in a conventional RTP system
typically rests on a plurality of quartz pins which hold the wafer accurately parallel to
10 the reflector walls of the system. Prior art systems have rested the wafer on an
instrumented susceptor, typically a uniform silicon wafer. Copending patent application
08/537,409, assigned to the assignee of the present invention, teaches the importance
susceptor plates separated from the wafer. Rapid thermal processing of III-IV
15 semiconductors has not been as successful as RTP of silicon. One reason for this is that
the surface has a relatively high vapor pressure of, for example, arsenic (As) in the case
of gallium arsenide (GaAs). The surface region becomes depleted of As, and the
material quality suffers. Copending patent application 08/631,265, assigned to the
20 assignee of the present invention, hereby incorporated by reference, supplies a method
and apparatus for overcoming this problem. A method of raising the emissivity of a
lightly doped, relatively low temperature wafer by locally heating the wafer with a pulse
of light is disclosed in copending application 08/632,364, which is assigned to the
assignee of the present invention. The above identified U.S. patents and applications
25 are hereby incorporated by reference.

SUMMARY OF THE INVENTION

30 According to this invention an off line, or an in line in situ or ex situ, broad band
reflectivity measurement is combined with another energy transfer or heating control
method in an RTP system. The RTP system has means for creating and storing different
calibration files and/or means for creating and storing different "open loop" files which
35 determine the power to be delivered to the lamps as a function of time. These files are in
the form of "look-up" tables, but may be in the form of functions of one or more

1 variables. In accordance with preselected ranges of the measured reflectivities the
equipment selects automatically a corresponding calibration file or open loop heating
file for the given wafer in process, and carries out the process using the stored time
5 history or the stored values for calibration of the temperature measurement devices.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a flow chart of the most preferred method of the invention.

10 Fig. 2 is a flow chart for a closed loop process flow.

Fig. 3 is a flow chart for an open loop process flow.

Fig. 4 is a diagram of an RTP system for in situ implementation of the invention.

Fig. 5 is a plan view of equipment location for implementation of the invention.

15 Fig. 6 is an expanded view of an in situ measurement method.

Fig. 7 shows the measured broadband reflectivity for wafers of various batches.

Fig. 8 shows the oxide thickness for the wafers of fig. 7 treated according to various
prior art processes and by the process of the invention.

20 DETAILED DESCRIPTION OF THE INVENTION

Fig. 1 shows a flow chart of the most preferred embodiment of the invention which is an
25 in line ex-situ measurement of the broad band reflectivity. The cassette of wafers to be
processed are loaded into a device from which a robot arm can withdraw a wafer at a
time and transfer the wafer to a wafer aligning tool where the wafer is aligned in step
12. After the wafer has been aligned so that the flat on the wafer is in the correct
orientation and the center of the wafer is correctly aligned, the robot arm picks up the
30 wafer again and transfers the wafer to a broadband reflectivity measurement tool where
the broadband reflectivity is measured in step 14. The spectrally integrated reflectivity
may be measured in step 14, or the spectrally resolved reflectivity may optionally be
measured using a spectrometer or other device as is known in the art. The robot arm
35 removes the wafer from the reflectivity measurement tool, and inserts the wafer into the
chamber of the RTP system in step 16. Independently of step 16, the system computer

1 receives the results of the measurement in step 14, and adjusts a system parameter in
step 17 so that the system may process the wafer in step 18. In step 19, the processed
wafer is removed from RTP chamber and moved to a cassette for receiving the
5 processed wafers.

Fig. 2 shows a flow chart of a "closed loop" process flow. The closed loop process is
used when a pyrometer can be relied upon to give reproducible and reliable
measurements related to the temperature of the object being measured, and is the normal
process. When the temperature of the object is very low, however, or the object is
10 partially transparent at the wavelength which the pyrometer measures, an open loop
process such as shown in fig. 3 must be used.

The broadband reflectivity of the wafer is measured in step 22, and the results of the
measurement or measurements is used by the computer controlling the system to adjust
15 the parameters of the system. In the case shown in fig. 2, the computer chooses in step
24 one of eight files which give the wafer temperature as a function of the pyrometer
reading. The wafer is then processed in the normal way in step 26, where the pyrometer
reading is used to give the wafer temperature from the "look up" file chosen in step 24.
20 The system then compares the wafer temperature with the temperature required by the
process, and adjusts the lamp power up or down to bring the wafer temperature to the
required temperature in the normal feedback loop process.

The broadband reflectivity may be measured only once, as in the ex situ set up detailed
25 in fig. 1, or an iterative set up may be used in an in situ measurement where the wafer
reflectivity may be measured multiple times, and the system parameters changed as a
result of the measurements. The decision step 28 decides whether the wafer processing
has been finished, and if so the process is terminated in step 29. If the wafer processing
30 has not been finished, the system returns to step 22 to remeasure the broadband
reflectivity.

The in situ reflectivity measurement is very difficult to carry out if stray light from the
heating lamps is intercepted by the optical system used to measure the reflectivity. In
35 this case, the lamp power may be reduced for the few milliseconds necessary to measure
the broad band reflectivity.

1 The prior art power controlled open loop processes eliminates the effect of any
variations in monochromatic emissivity at the pyrometer wavelength, since the
pyrometer is essentially not used to control the heating lamps. However, running the
5 system in the open loop mode will give greatly varying wafer temperature due to
coupling variations between wafers. The measurement of the broadband reflection
coefficient of the wafer as shown in process step 32 of fig. 3 can greatly reduce this
variation. Once again, the system adjusts a parameter, in this case the system chooses a
10 file of lamp power vs time in step 34 to run the RTP process outlined in step 36. Once
again, an in situ measurement may be used to decide whether the wafer processing has
been finished in step 38, and if not, return to step 32 to remeasure reflectivity. One
option in this case is that the system may decide on the basis of the reflectivity to switch
form an open loop to a closed loop control system.

15 HotLiner (TM) technology detailed in copending patent application 08/537,409, uses a
light absorbing, thermally and optically stable plate beneath the production wafer. The
temperature of the plate can be measured accurately and the system can tolerate small to
medium coupling variations on the wafer. In the case of larger coupling differences, an
20 appropriate calibration file must be chosen, since the measured temperature of the plate
will imply a different temperature for the wafer depending on the coupling or the
broadband reflectivity measurement. In HotLiner (TM) technology the temperature of
this plate is measured by conventional (monochromatic) pyrometry. The measured
25 temperature is then fed back to the system set the lamp power to produce the required
temperature vs time profile of the HotLiner plate. The appropriate calibration file
determines the temperature and/or the dual side heating in independent top and bottom
heater bank control mode to control the mutual energy coupling between the wafer and
30 the plate, so that the measured HotLiner (TM) temperature accurately controls the
temperature of the production wafer.

The method "total reflectivity at pyrometer wavelength" shifts wafer emissivity at the
pyrometer wavelength artificially upwards to the blackbody radiation curve. Using a
35 highly reflective sealed gold coating on the bottom part of a heating chamber beneath
the wafer the effective emissivity of the wafer can be enhanced near to "1.0" in the

1 infrared range. As a further improvement the coating may be designed for total
reflection at pyrometer wavelength. The method is accurate in the case of small to
medium monochromatic emissivity variations. In the case of lower monochromatic
5 emissivity values (down to 0,3 at 0,9 μm), it is shown by Terrence F. Riley, Arun K.
Nanda, G. Miner et al.: "Evaluation of Applied Materials Rapid Thermal Processor
Using SEMATECH Methodologies for 0,25 μm Technology Thermal Applications"
Part I., a presentation at the Rapid Thermal and Integrated Processing Conference. MRS
10 Spring Meeting '96, San Francisco CA., that the effective emissivity can not
approximate well the value of "one" and the error grows.

The method can tolerate greater coupling variations only in the case when the cause of
the smaller emissivity is not a partial transparency. This is the case for bulk silicon
materials and a pyrometer wavelength below the band gap energy (e. g. at 0,9 μm for
15 Si). It is also shown in the paper by Arun K. Nanda, Terrence J. Riley, G. Miner et al
entitled "Evaluation of Applied Materials Rapid Thermal Processor Using SEMATECH
Metrologies for 0,25 μm Technology Thermal Applications" Part II at the same
conference that the major drawback of this method is that a small error in the
20 assumption of 2 fully reflective surface will cause the effective emissivity to reduce
significantly, resulting in larger temperature error. In the case that the reflector is cold
and near the wafer backside, deposition from wafer out gassing may arise easily.

In accordance with the present invention we complete the existing "emissivity
25 independent" methods with an in line broad band reflectivity measurement and select by
software the proper calibration file or open loop heating file for the wafer in process. A
preferred combination is a broad band reflectometry with power controlled open loop
processing. Another preferred combination is a broad band reflectometry with HotLiner
30 application or with wavevector selective pyrometry. In case of HotLiner application the
temperature control of the HotLiner can be performed by any of the existing
monochromatic or narrow band pyrometry.

Fig. 4 shows a sketch of a prior art RTP system with the addition of an in line in situ
35 broadband reflection measurement system. A hole 49 is introduced into the reflecting
wall 41 of the RTP system so that the wafer 42 can be seen by the measurement system.

1 A broad band light source such as a tungsten lamp in a quartz envelope 43 is used to provide the light for the measurement. Lenses 44 are used to collimate and focus the light incident on and reflected from the wafer 42. A mirror 410 which reflects part of the light from the lamp 43 is used to deflect the light reflected from the wafer 42 to the
5 broad band detector 45. The broad band light source 43 may be controlled by a computer 46, and the measurements of the reflected light by the broadband detector 45 can be used by the computer to adjust parameters for the RTP process. A number of optical pyrometers 47 are shown for use in a closed loop process. The computer 46
10 controls the lamp 411 power for the open loop process.

Fig. 5 shows a floor plan of an RTP system. Cassettes with wafers to be processed are loaded into a cassette holder 51. A vacuum pan (not shown) on the end of a scissor like robot arm 52 lifts a wafer 42 from the cassette and withdraws the wafer 42 from the
15 cassette holder 51. The robot arm 52 swivels around an axis 53 and inserts wafer 42 into an alignment tool 54. The alignment tool 54 rotates the wafer until the wafer flat is correctly aligned, and centers the wafer. The robot arm picks up the wafer 42 from the alignment tool 54 and moves it to the broad band reflectivity measuring tool 55. The
20 wafer is now accurately aligned with respect to the robot arm. After the broadband reflectivity is measured, the robot arm removes the wafer from the broadband reflectivity measuring tool 55, and inserts the wafer 42 into the processing chamber 56 of the RTP system. After processing, the robot arm picks up the wafer 42 from the
25 processing chamber 56 and moves it into a cassette contained in the receiver 58. The inventors anticipate that the station for aligning 54 and the broadband reflection measurement system 55 may be combined in one tool to save floor space.

Fig. 6 shows a detail of an in situ broad band reflection measuring set up where a wafer 42 is held inside the chamber (not shown) of an RTP system above an auxiliary plate 61. A guard ring 62 is also shown. The radiation from a source of broad band radiation 43 is collimated by lens 63 into a parallel beam of radiation which impinges on a broad band reflecting mirror 64. The mirror may reflect 50 % of the radiation from the light source
30 43 to a broad band detector 65. The signal from the broad band detector 65 gives the intensity of the light from source 43. About half of the collimated beam from the light

1 source 43 and lens 63 continues in a straight line and reflects from the wafer 42. The
reflected light reaches the mirror 64 and is reflected in part to a detector 66. In a
preferred embodiment, the detector 66 is a bolometer. In another preferred embodiment,
5 the detector 66 is a detector having spectral resolution capability such as a spectrometer
and bolometer combination.

Common RTP equipment heats semiconductor wafers dominantly in the range of 0,4 –
4 micrometer wavelength. The broadband reflectometer should match this range as
broadly as possible. In a preferred embodiment, the wafer reflectivity integrated over the
10 spectral range and over the surface area of the wafer is used as an input parameter to
select proper calibration or open loop files.

In our application the sensitivity range is about 0,4 – 3 micrometer. In a preferred
embodiment the reflectometer has a thermoelectric sensor (bolometer). The bolometer
15 has a completely flat spectral response to radiation throughout the relevant spectral
region. The source of light in the reflectometer is a tungsten halogen lamp.

The sensor receives the direct and indirect reflected light through a quartz filter. A
preferred reflectometer collects the reflected direct and indirect light by a spherical
20 mirror in the line ex situ embodiment of the invention. This arrangement is suitable
to measure reflectivity on one side of the wafer. The above mentioned optical
components result in a sensitivity range of the measurement between 0,4 – 3 μm .

Lightly doped silicon wafers are above 1,1 – 1,3 μm are semi transparent. This is a
25 source of error in measurement. To reduce or eliminate this error, a mirror can be used
on the side of the wafer opposite to the light source. This mirror can also be a spherical
one. In this case the absolute reflectivity can be measured. Another improvement
possibility is the local free carrier generation at the measurement spot. This can be
30 achieved by a strong focused signal of the measurement light itself or by local laser
introduction in addition. A radiative preheating of the total wafer is also feasible.

EXPERIMENTAL RESULTS

We prepared 150 mm [100] "N" type 5 – 10 ohm-cm production quality Si wafers in four groups. One group was a reference without any coating. The other 3 groups were coated on the backside with the following layer combinations:

- a) 19nm SiO₂ + 100nm Si₃N₄
- b) 200 nm SiO₂ + 110nm poly-Si (undoped)
- c) 580 nm SiO₂ + 160 nm poly-Si (undoped)

The frontside of the wafers were etched and prepared for oxidation. The backside layer combinations are known to have extremely different integral emissivity in our RTP equipment. The RTP equipment has tungsten halogen lamps and the heating chamber is gold coated. We have dual side heating.

Representative measured broad band reflectivity values from wafers of each batch are plotted in Fig. 7.

We performed rapid thermal oxidation at 1130 °C for 45 s in different processing modes. A HotLiner was used for all experiments. Using only one calibration or only one open loop heating file, the repeatability of the oxidation was in the range of about 10 – 11,2 nm. This range corresponds to a total temperature variation of 15 °C.

When we used the results of the reflectivity measurement and selected the corresponding calibration file automatically, the repeatability of the oxidation was within 0,2 nm. This corresponds to a temperature variation of 3 °C. The comparison of the oxidation results in case of the different heating methods is illustrated in Fig. 8.

Extensions of the invention controlling system parameters other than those enumerated in this disclosure on the basis of the measurement of broad band reflectivity are anticipated be the inventors.

1 We claim:

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- 5 1. A method of rapid thermal processing (RTP) of an object using an RTP system,
the object having a surface with a reflectivity comprising;

measuring the reflectivity of the surface of the object in a broad band of
10 wavelength and

adjusting a system parameter of the RTP system in response to the measured
reflectivity.

- 15 2. The method of claim 1, where the system parameter is an emissivity correction
to a temperature measurement of the object by an optical pyrometer.

- 20 3. The method of claim 1, where the system parameter is a calibration file to
calibrate a temperature measurement of the object by an optical pyrometer.

- 25 4. The method of claim 1, where the system parameter is file of lamp power vs
time settings for an "open loop" heating cycle.

- 30 5. The method of claim 1, where the RTP system further comprises an auxiliary
plate between the object and at least one heating lamp of the system, and the
system parameter comprises a file of temperature of the object as a function of
temperature of the auxiliary plate.

- 35 6. The method of claim 1, where the RTP system further comprises an auxiliary
plate between the object and at least one heating lamp of the system, and the
system parameter is a file of lamp power vs time settings for an "open loop"

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1 heating cycle.

7. The method of claim 1, where the measured reflectivity is the spectrally
5 integrated reflectivity over the broad band of wavelengths.

8. The method of claim 1, where the measured reflectivity is the spectrally
resolved reflectivity over the broad band of wavelengths.

10 9. The method of claim 1, where the reflectivity is measured in the process line as
an ex-situ process.

15 10. The method of claim 1, where the reflectivity is measured in the process line as
an in-situ process.

20 11. A method of rapid thermal processing (RTP) of an object using an RTP system,
the object having a surface with a reflectivity, comprising the following steps
in order;

- 25 a) introducing the object into a reaction chamber of an RTP system;
b) irradiating the object with radiation from radiation sources of the RTP
system;
c) measuring the reflectivity of the surface of the object in a broad band of
wavelengths; and
30 d) adjusting a system parameter of the RTP system in response to the
measured reflectivity.

12. The method of claim 11, further comprising:

- 35 e) further irradiation the object with radiation from radiation sources of the
RTP system.

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13. The method of claim 12, where the irradiation from the radiation sources is reduced during step c).

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