

Rapid Thermal Processing Strategies for Highly Uniform and Repeatable Process Results on Patterned Wafers

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Advantages and disadvantages of various types of temperature measurement techniques are reviewed in terms of potential temperature measurement errors and their impact on process consistency. Direct wafer temperature control and indirect wafer temperature control through control of the wafer environment are compared from the viewpoints of process accuracy and repeatability. The origin of both intrinsic and extrinsic pattern effects is identified and its impact on thermal non-uniformities in various wafer heating environments is analyzed. Based on the analysis, effective RTP strategies for highly uniform and repeatable process results on patterned wafers are proposed and discussed.

INTRODUCTION

As device dimensions continue to decrease, the demand for improved process control is growing. In addition to the traditional, basic requirements of accurate and precise temperature measurement and control in rapid thermal processing (RTP) [1 - 4], the reduction of pattern induced, within-wafer thermal non-uniformities and stresses is required to effectively prevent RTP-related yield losses. The challenge (pattern effect) is further complicated by variations of feature size and pattern density across the wafer [3 - 9].

Since the early days of the RTP industry, accurate and precise temperature measurement and control have been the main focus for engineers and scientists [1]. Many types of RTP equipment with different combinations of heat sources and temperature measurement and control techniques have been introduced [1 - 3]. Trial and error approaches of equipment selection for extremely temperature sensitive, advanced device manufacturing is too costly and time consuming.

The effect of pattern size and density can no longer be ignored in advanced device fabrication processing [5 - 9]. The pattern

effect has intrinsic and extrinsic components. The intrinsic component can be minimized by designing device layouts uniformly, but this is not always practical. The extrinsic component of pattern effect can be minimized by selecting the appropriate heat source and a non-fluctuating heating environment. Non-uniform and non-repeatable thermal exposure makes the pattern effect worse, regardless of the heat source.

It is extremely important to understand the source of unintended process variation. Understanding the contribution from both the heat source on the extrinsic component of the pattern effect and from temperature measurement and control errors on process variations are very important in selecting the right RTP strategy.

In this paper, advantages and disadvantages of various types of temperature measurement techniques are reviewed in terms of potential temperature measurement errors and their impact on process variations in both blanket and patterned wafers. Based on the analysis of the potential impact a wafer heating method has on process results, effective RTP strategies for achieving highly uniform and

repeatable process results on patterned wafers are proposed and discussed.

PROBLEMS IN THERMAL PROCESSING

Common flaws in thermal processing can generally be categorized as either uniformity related problems or repeatability related problems. Most real problems have components of both, so that identifying the root cause is rather difficult and time consuming. To minimize process variation as much as possible, it is essential to understand and manage the relevant factors impacting within-wafer process uniformity, wafer-to-wafer repeatability and system-to-system repeatability. Either process uniformity or process repeatability should be achieved to correctly identify most probable causes by analyzing the distribution of process results. Only after the possible causes are identified, can effective corrective action can be taken. In many cases, the possible causes are misidentified due to the lack of process uniformity and/or repeatability. Process uniformity and/or process repeatability should be pursued and achieved by analyzing the distribution of process results and by identifying the most probable causes.

Uniformity Related Problems

Uniformity problems have to do with on-wafer process results. If materials are homogeneous and the thermal process environment is also homogeneous, homogeneous process results are expected, in concept. In order to make a manufacturing process more robust, the source of uniformity related problems must be identified to address or troubleshoot the problems. Potential causes of uniformity related problems are listed below.

Uniformity Related Problems

- **Material Inhomogeneity**
 1. **Materials**
 2. **Pattern size**

3. **Pattern density**
4. **Device structure**

- **Environment Inhomogeneity**
 1. **Temperature**
 2. **Time at temperature**
 3. **Pressure**
 4. **Ambient**

Repeatability Related Problems

Repeatability related problems are usually caused by the system architecture and the accuracy of monitoring and controlling the process variables in a system. When there are more than one system, system-to-system repeatability needs to be considered. Potential causes of repeatability related problems are listed below.

Repeatability Related Problems

- **Within System Repeatability**
 1. **Measurement error**
 2. **Control error**
 3. **Time delay**
 4. **Sequence**
 5. **Noise**
 6. **Degradation**
 7. **Aging**
 8. **Facility**
- **System-to-System Repeatability**
 1. **Configuration**
 2. **Software**
 3. **Offset**
 4. **Degradation**
 5. **Aging**
 6. **Facility**

Compounded Problems

Most process problems have components of both uniformity related and repeatability related problems. Simple analysis of the symptoms can be misleading and lead to wrong conclusions. The real cause of problems should be carefully researched, analyzed and identified from the data. Schematic illustrations of uniformity and repeatability related distributions are shown in Fig. 1.

The author believes that process repeatability (wafer-to-wafer and system-to-system repeatability) even with poor within wafer uniformity, can be more valuable than getting good uniformity randomly. When process results are repeatable, all data becomes very reliable and predictable. The cause of the uniformity problems can be easily identified and addressed. If the process results are not repeatable, all data becomes questionable and unreliable. Even if a target process gives results with excellent uniformity a few times, there is no assurance of repeatability. As repeatability problems are mostly related to system architecture and the monitor and control accuracy of the process variables in a system, the problem may last the lifetime of the system.

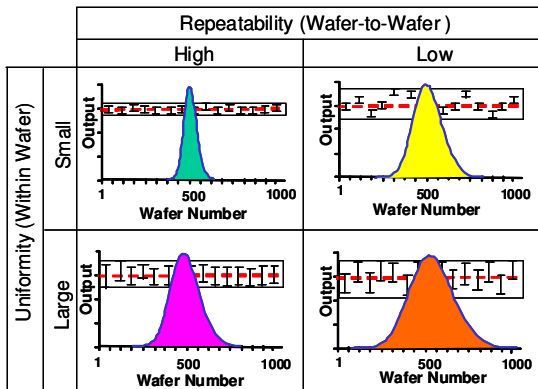


Fig. 1. Schematic illustrations of uniformity and repeatability related distributions.

PHYSICS OF HEAT TRANSFER

Heat Transfer Mechanisms

The heat transfer from a heat source to a receiving object can be classified into three basic mechanisms: conduction, convection and radiation (See Fig. 2) [10, 11]. One or more heat transfer mechanisms will be involved in any type of heat flux movement. Simple descriptions of each heat transfer mechanism are given below.

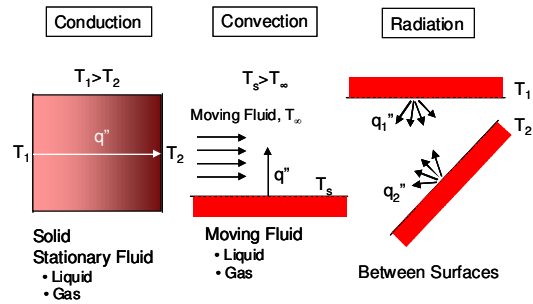


Fig. 2. Three heat transfer modes: conduction, convection and radiation.

Conduction

Conduction heat transfer takes place in all three (solid, liquid and gas) phases of matter. Each material has its own thermal conductivity under different phases and conditions. Except for porous, thermal insulating materials, heat transfer rates (thermal conductivities) of solid and liquid are 3 ~ 4 orders of magnitude higher than that of gases at 1 atm [12 - 14]. As gas pressure decreases, the thermal conductivity decreases [15, 16]. The rate of heat transfer at low pressures (relatively large mean free path between gas molecules) is proportional to both pressure and temperature differences. Some pressure gauges utilize thermal conductivity at low pressure for measuring the pressure of gases in the low pressure regime [16]. Once gas pressure is significantly decreased and the mean free path becomes significantly longer, conduction heat transfer becomes negligible.

Temperature gradients readily occur across materials with lower thermal conductivities. However, it is difficult to generate a large temperature gradient on materials with high thermal conductivities.

One other important concept related to thermal conductivity, is thermal diffusivity. While thermal conductivity deals with one dimensional heat transfer characteristics, thermal diffusivity deals with three dimensional thermal conductivity of specific shapes of material.

Convection

Convection heat transfer only occurs in two phases: liquid and gas. When materials are heated, the volume expands and density is reduced. Due to gravity, higher density materials sink and lower density materials float. A large enough pressure (small mean free path between molecules) or density of gas should be present to allow significant convection heat transfer in gas [15, 16].

To transfer heat flux by convection, the heat source should be located below the heat receiving object. In reality, a combination of convection and conduction heat transfer takes place. When the positions of the heat source and heat receiving objects are reversed, only conduction heat transfer will take place.

Radiation

Radiation is a surface-to-surface heat transfer mechanism which takes place with or without a gas media. Photon emission and absorption characteristics of surfaces and geometric relations (solid angle or view factor) between the heat (emission) source and heat receiving (absorption) object determines the rate of radiation heat transfer [10, 11, 15, 16].

Depending on the global and local optical properties of the surface of the absorbing material, the magnitude or efficiency of radiation heat transfer from identical heat sources can vary greatly (by orders of magnitude). In reality, (mutual) radiation heat transfer between the heat source and object is simultaneous and interactive. The final (global and local) temperature of the object being heated is determined by the balance of mutually interactive radiation heat transfer between the two objects.

To achieve uniform and repeatable process results by radiation-dominant heating, a significantly large radiation heat source without radiation power fluctuations (and/or variations) and uniform optical properties of the object being heated are essential. In the case of blanket wafers, as

the object being heated, reasonably uniform optical properties are easily obtained. However, in the case, of patterned wafers, because of their topology and nature of selective chemical reaction during process, it is not possible to have uniform optical properties. Thus radiation-dominant heat sources may be problematic and inconsistent.

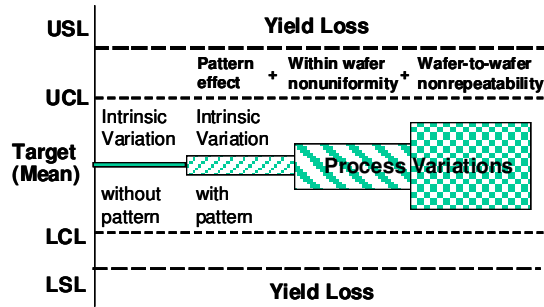
PROCESS VARIATION AND PROCESS WINDOW

There are many sources of variations in process results. For uniform and repeatable process results over a long period of time, sources of variation should be minimized or eliminated. The first step is to understand potential variations and to correctly identify the sources. Effective corrective action can then be taken. Better still, if the potential sources of process variation are identified prior to system design, a nearly optimum system can be designed.

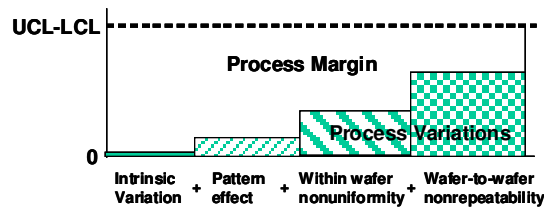
The true process window for a specific process is determined when the materials and structures are known and homogeneous. When variations and uncertainties are introduced, the effective process window narrows compared to the true process window. Since the true process window can only be observed by using ideally homogeneous and repeatable materials and process environments, if the variations or uncertainty of materials and process environment are larger than the true process window, no manufacturing worthy process window will be achieved. Even if a process is feasible, the process yield will be very low and costly.

There are two types of variations in a process: intrinsic variation and extrinsic variation. A brief description of each and potential sources of these variations are summarized below. Proper understanding (and especially, reduction) of extrinsic variation is the key to business success in this very competitive industry. Figures 3

show schematic illustrations of the source of variations and process margin reduction due to the combinations of process variations.



(a)



(b)

Fig. 3. Schematic illustrations of (a) source of process variations and (b) process margin reduction.

Intrinsic Variation

The intrinsic variation of a process is the type of variations which cannot be avoided even if the process environment is uniform and repeatable. The process environment is not responsible for this type of variations.

Topological factors and the nature of selective reactions on patterned wafers are the possible causes of intrinsic variation. Density, size, depth, shape and material combinations of patterns on wafers can be the source. During the process, the desired reaction should occur in a designated area on a patterned wafer. This selective reaction can alter the optical and thermal properties during the process. This type of variation is

a function of the design and is unavoidable unless the density, size, depth, shape and material combinations of the on-wafer patterns are changed.

Only when patterned wafers are processed in systems which provide very uniform and repeatable process environments, can this type of non-system-related variation be identified.

Extrinsic Variation

Extrinsic variations are caused by variations in materials or the process environment (system). Of course, the intrinsic variation will always be present, in any case. To correctly distinguish the component of the extrinsic variation from the compounded variations, a good understanding of variation in materials and process environments is required..

Materials

Material related extrinsic process variations can arise from various sources. Variations in pattern size, density, structure, quality, thickness, dopants, and of as deposited or formed materials, may be responsible for this type of variations. To minimize or eliminate this type of variation, very tight quality control of starting materials is required.

Process Environments

Uncertainty, non-uniformity, fluctuations and variations in process variable measurement and control are often the major source of extrinsic variations. System architecture, with typical compromises for wafer throughput and operational flexibility enhancements, tends to make extrinsic variations more prominent. Whether intended or not, introduction of too many variables and uncertainty of variables often make extrinsic variations problematic.

SYSTEM DESIGN CONSIDERATIONS

Batch Size

When wafers are processed sequentially, using single wafer processing systems, productivity is inversely proportional to the sum of process time and overhead wafer handling time. Since total wafer cycle time is directly proportional to the number of wafers and the sum of process time plus overhead wafer handling time, single wafer processing is a preferred method in an R&D environment. As process time increases, productivity decreases. To overcome this factor, a multi chamber configuration is frequently adopted for production applications.

Large batch processing is a preferred method for longer processes due to its higher productivity. However, it lacks lot size flexibility and requires a significant portion of floor space for wafer and cassette handling. It is also affected by loading. On-wafer uniformity, wafer-to-wafer uniformity within batch uniformity and batch-to-batch uniformity can become issues depending on process applications. Dummy wafers are required in normal operation. In LPCVD applications, the process window is often determined by the pitch between wafers. To reduce cycle time and increase lot size flexibility, a mini-batch system which processes cassette by cassette would be a better choice compared to conventional multi-cassette processing systems.

Heat Source Design

To heat wafers uniformly, the wafer should be processed in an encapsulated, isothermal process environment. A planar heat source or cavity (larger than the wafer size) with high temperature uniformity and large thermal mass is desired.

When an array of point heat sources with limited surface area and small thermal mass is used (such as tungsten halogen lamps), multi-zone power control is necessary to

obtain reasonable on-wafer temperature uniformity. If heat sources with small surface area are used, the heat source temperature must always be higher to get a specific wafer temperature. Thus, lamp-based RTP systems operate at significantly higher filament temperatures. This makes the thermal process more radiation dependent in lamp-based RTP systems compared to furnace-like systems [17].

It is extremely difficult to produce a uniform temperature on wafers using an array of point heat sources. To make a uniform and planar heat source from an array of point heat sources, a heat diffusion media with a large thermal mass and high thermal conductivity has to be inserted between the array of point heat sources and the wafer. Introduction of a large thermal mass would slow down the rate of temperature change (increase time constant), but it would significantly improve temperature stability and provide excellent temperature uniformity. The wafer heating mechanism changes from radiation-dominant direct heating to convection-dominant indirect heating [13, 14, 17]. Priority of RTP process variables should be analyzed and an RTP system designed accordingly. The operational flexibility in terms of process temperature and quality of process (long term uniformity and repeatability) should be balanced in a well-designed RTP system.

Flexibility vs. Stability (Repeatability)

Systems using small thermal masses as heat sources are very flexible to a change of processing temperature and are suitable for single wafer, multi-task operations which are often preferred for R&D applications. The systems usually show reasonable short term process repeatability. However, the system sometimes suffers poor long-term process repeatability and stability due to the difficulty in wafer temperature measurement and control and inhomogeneous degradation of heat sources. Frequent system performance checks, using monitor wafers,

and frequent maintenance are required for production applications.

Systems using large thermal masses as heat sources lack flexibility in frequent operating temperature changes, however, they are superior in both short-term and long-term process repeatability and stability. Frequent system maintenance and process monitoring of system performance are not generally required.

For both R&D and mass production applications, short-term and long-term process repeatability and stability (of the system) should have higher priority than wafer-to-wafer operating temperature flexibility. If the process development is done using systems with long term repeatability and uniformity, developed processes are easily transferred to manufacturing without further characterization or frequent routine process uniformity and repeatability monitoring. In an R&D environment, systems with high flexibility are often preferred, even at the cost of compromised long term uniformity and repeatability. However, it eventually costs more to monitor and optimize the process results to specification. Any kind of process tuning or optimization is done by process environment adjustment and usually results in a less repeatable process. Ideally, a system inherently stable and repeatable should be used from R&D to manufacturing.

TEMPERATURE MEASUREMENT AND CONTROL OPTIONS

To control the temperature of an object, being heated, the temperature of the object has to be monitored. Schematic diagrams of an ideal PID (proportional, integral and derivative) control system and realistic PID control system are shown in Fig. 4.

In the ideal system, it is assumed that there is no measurement error of the monitored values, no control error, no time delay between measurement and control, no offset and no noise in the signals. In a practical system, all the undesired factors

exist. To maximize process repeatability, all the undesired factors must be minimized by designing the process equipment from every aspect (i.e. the system architecture, and methods of process variable monitoring and control, etc.).

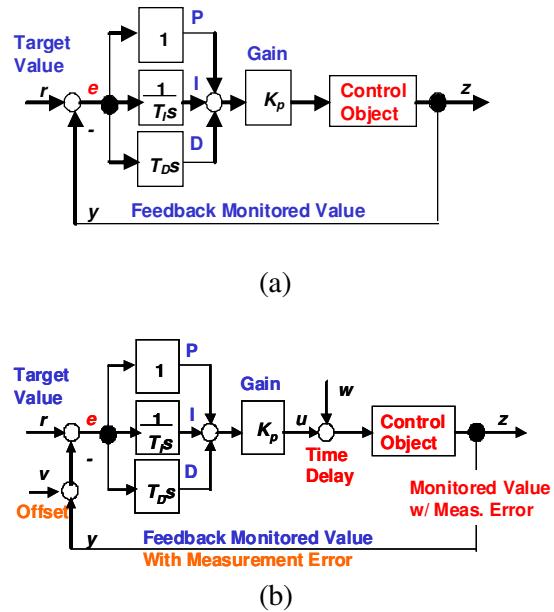


Fig. 4. Schematic diagrams of (a) an ideal PID control system and (b) realistic PID control system.

Temperature Measurement

There are several temperature measurement techniques which are widely used in the semiconductor industry. The effectiveness of a system for a given application can depend on the suitability and the inherent accuracy of the temperature measurement approach.

Thermocouple

Thermocouples are very popular to measure the temperature of objects by making a proper contact between the thermocouple and object. Proper thermocouple selection can be based on the specific temperature and atmosphere. When

direct contact between the thermocouple and wafer is a problem due to metal contamination, a ceramic or quartz sheath or cap can be used. However, by introducing a foreign material between the thermocouple and object, the time constant of temperature measurement will be increased. The thermocouple becomes less sensitive to the temperature change of the object due to the time delay caused by the increase in thermal mass and poor heat conduction. Temperature measurement using thermocouples in vacuum is very difficult due to the uncertainty in contact pressure and change in convection heat transfer characteristics. However, thermocouples have great advantages in terms of their linear response over a wide range of temperature, measurement accuracy and repeatability. Figure 5 shows thermoelectric output of K-type and R-type thermocouples as a function of temperature [18, 19].

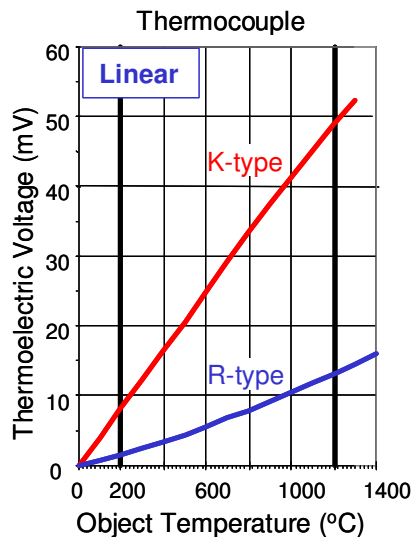


Fig. 5. Thermoelectric output versus temperature.

Optical Pyrometry

Optical pyrometry is frequently used for measuring Si wafer temperature in lamp-based RTP systems as a non-contact temperature measurement technique. It is an effective method of estimating temperature of rotating wafers during annealing, however,

it has significant drawbacks in measurement range and accuracy. Total radiation power (light output intensity) from a heated object is extremely nonlinear and increases as a function of T^4 [20, 21]. As the temperature of the object decreases, intensity of light intensity emission decreases very rapidly. To properly cover a temperature range of 200°C to 1200°C, the pyrometer would have to be able to provide accurate temperature measurement under light intensity changes of 8 to 12 orders of magnitude depending on the monitoring wavelength (Fig. 6), which is not feasible.

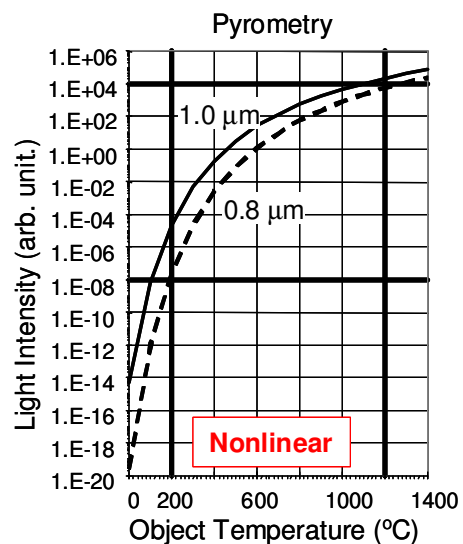


Fig. 6. Light intensity from a heated black body at different wavelength.

The optical properties of Si must be considered when measuring or heating Si wafers by optical means. Lightly doped Si has an absorption edge near 1.2 μm and is semi-transparent in the infrared (IR) region [10, 20]. As temperature increases, Si becomes less transparent and finally becomes opaque in the IR region, at temperatures near 600°C [20]. Wafer temperature measurement below 600°C is not reliable using optical pyrometers. Even above 600°C, the measurement is strongly influenced by the variations in optical properties, both locally and globally, due to

inconsistencies in dopant concentration, device patterns, backside films etc. [4, 22] Thus, both within wafer and wafer-to-wafer measurement accuracy is significantly compromised. Moreover, the emissivity of Si is, itself, a function of temperature. [20] Without knowing the local and global emissivity distribution of a wafer, it is very difficult to measure and control wafer temperature accurately. When measurement sight is blocked or the optical properties of the media, such as the window, is affected (often caused by condensation or coating of materials on the window), the measured temperature value can differ significantly from the true value. This measurement error can cause process shifts without the user even being aware of what is occurring.

Wafer Temperature Control

There are two ways of controlling wafer temperature. The first one is dynamic control using in-situ wafer temperature measurement values. Typical lamp-based RTP systems employ this technique [1 - 9, 23 - 25]. These are often classified as cold wall systems. The second one is to measure and control the process environment (temperature) instead of controlling wafer temperature directly. Typical furnaces fall into this category. These are often classified as hot wall systems [23 - 25].

Direct Control

In a cold wall system (lamp-based RTP system), the wafer is typically heated by tens to hundreds of small, individual lamps. The wafer is the hottest object in the process chamber and it will naturally and constantly lose heat to the cold chamber walls by radiation, conduction and convection. The rate at which the heat transfer occurs is also a function of the physical characteristics of the pattern. Consequently, it is very difficult to maintain temperature stability and uniformity during the process. Temperature repeatability is also dependent on many factors, such as the local and global

emissivity distribution on the wafer, chamber wall temperature and chamber wall reflectivity. There is a large difference in wafer heating characteristics between single side heating and double side heating systems in terms of ramp rates, pattern effect and the depth of hottest spots on a wafer.

In general, real time temperature control, of a small thermal mass with varied optical properties (the wafer), through large lamp power adjustments is extremely difficult to accomplish with accuracy. Temperature overshoot and instability are thus, very common problems. Uniform heating from a non-uniform light source (from tens to hundreds of small lamps) is nearly impossible. By rotating the wafer under the non-uniform light source during process, time averaged uniformity on the wafer, is realized. This means that while the aggregate amount of a reaction may be controlled, the on-wafer reaction rate, at any point of time and at every point on the wafer is inherently non-uniform.

Indirect Control

In a hot wall system (furnace-like system), a wafer is the coldest object in the process chamber at all times. Instead of directly controlling wafer temperature up and down, wafers are moved in and out of a preheated, massive process chamber. The process chamber is controlled at a pre-set process temperature using thermocouple(s). As long as the process environment temperature is uniform and stable, temperature uniformity within the wafer and wafer-to-wafer temperature repeatability should not be a problem. Temperature uniformity is achieved by selecting a material with high thermal conductivity for the process cavity. The temperature stability is achieved by design, by virtue of the large thermal mass of the process cavity (or chamber). Thus we have a very small thermal mass (the wafer) being affected by a very large thermal mass (the process chamber). Local and global wafer temperature repeatability is less dependent

on the emissivity (and optical properties) distribution on the wafer because uniform heat is supplied from its surroundings.

PROPOSED THERMAL PROCESSING SYSTEMS

Three types of hot-wall-based systems have been designed for single wafer [17, 26 - 28], five (5) wafer [13, 14] and twenty-five (25) wafer [30] batch thermal processing to provide excellent process results without sacrificing productivity and long-term process repeatability. All the systems have heat sources with large thermal mass which provides excellent process stability. Systems can be selected based on either lot size flexibility or productivity. All systems are designed to be very compact and very energy efficient.

Repeatability, long term as well as short term, is achieved primarily by the very details of the concept for these system configurations.

- A small thermal mass (wafer) is heated by the environment created by a large thermal mass (heated process chamber).
- In production, the large thermal mass is maintained at the desired POR (Process of Record) temperature, long term.
- Most importantly, the thermal control method, thermocouple sensors, is excellently suited to accurately controlling and maintaining the specific thermal environment.

Thus, if the wafers input to the system are consistent, the results obtained on the first five wafers will be repeated on all wafers for the next week, month or year, as long as the physical integrity of the system is maintained. That is what is meant by long term repeatability.

The simple description for these systems is provided below.

Single Wafer Rapid Thermal Furnace (SRTF)

For single wafer processing the process tube is made of clear quartz and has three quartz standoffs. The process tube is heated to a desired process temperature and the temperature is kept constant. A Si wafer is heated by absorbing energy from the surrounding hot walls during processing. The process tube uses no moving parts for design simplicity and system reliability. (See Fig.7) The wafer is placed on the quartz standoffs in the middle of quartz process tube. The quartz process tube is located in a SiC cavity which acts as a heat distributor to create an isothermal process environment. The SiC cavity is surrounded by a three zone heater assembly. The temperature of the SiC cavity is monitored and controlled at a predetermined process temperature by three embedded R-type thermocouples and the three zone heater assembly. The system is designed to operate from 200°C to 1150°C.

Detailed thermal characteristics and process performance of the system have been reported elsewhere [23 - 29].

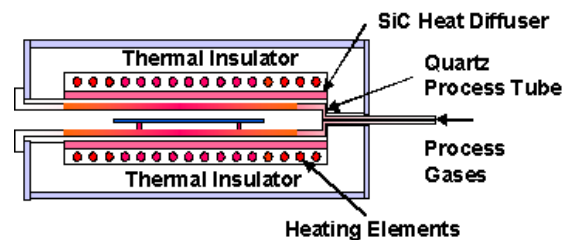


Fig. 7. Schematic illustration of single wafer process chamber.

Stacked Annealing Oven (SAO)

A hot plate-based, stacked annealing oven was designed for low temperature annealing applications in the temperature range of 100°C ~ 450°C and is capable of

processing five wafers simultaneously under controlled process gas environments. It was designed to provide single wafer signature, lot size flexibility and reasonable productivity with minimum facility requirements.

A side view of the stacked hot plates, with five Si wafers, is shown in Fig. 8. The design allows gradual heating of wafers for low temperature annealing and baking applications without sacrificing productivity. The individual hot plates are made of aluminum and have an embedded heater for temperature control. Aluminum was chosen as the hot plate material for temperatures up to 450°C because of its thermal stability, high thermal conductivity and ease of machining. The individual hot plates have three standoffs to accurately maintain the distance between the wafer and the hot plate surfaces. The wafers are heated by natural convection and conduction through ambient gas and to a much lesser extent, by radiation. Hot plate temperature and process gas pressures are controlled and accurately determine the wafer temperature profile. For lower thermal conductivity gases such as N₂, O₂, Ar or air, the wafer temperature rises and approaches the hot plate temperature at a moderate rate [13, 14, 31 - 33]. For gases with higher thermal conductivity such as H₂, He and forming gas containing H₂ gas, the wafer temperature rises more rapidly as it approaches the hot plate temperature. [14]

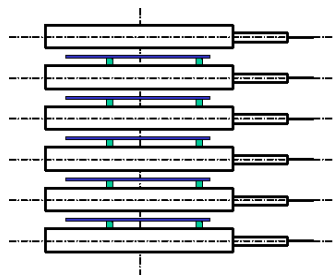


Fig. 8. Schematic illustration of a stacked hot plate system for simultaneous five wafer processing.

Mini-Batch Furnace (MBF)

Thick film growth applications by low pressure chemical vapor deposition (LPCVD) and low temperature baking and curing often takes more than ten (10) minutes at process temperature. In conventional large batch furnaces, temperature ramp-up to process temperature and temperature ramp-down from process temperature takes longer than the actual process time at temperature due to the large thermal mass of the wafers, process tube and heating elements.

To improve cycle time and lot size flexibility, a mini-batch system which processes cassette by cassette has been designed. The mini-batch furnace can process 25 wafers at a time with a minimum (1 or 2) of dummy wafers, or without dummy wafers, depending on process applications. Unlike the large batch furnaces, the system does not require any empty cassette storage areas. As a result, the system design is very compact. By reducing the number of wafers per batch, temperature ramp-up and ramp-down speeds are shortened significantly. This feature makes cassette by cassette mini-batch furnace operation possible without decreasing productivity [30].

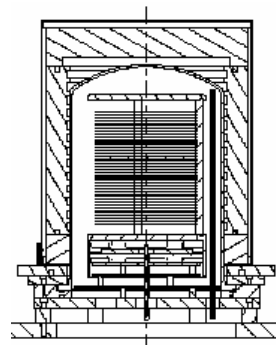


Fig. 9. Schematic illustration of mini-batch furnace for single cassette wafer processing.

PROCESS RESULTS AND DISCUSSIONS

As an example of thermal process applications where the environment temperature is controlled, a hot wall-type RTP system (the SAO-200LP system, described above) was used to investigate NiSi formation characteristics in the temperature range of 280°C ~ 360°C. In this low temperature region, cold wall-type (lamp-based) RTP systems have difficulty and are less accurate in monitoring and controlling within wafer temperature uniformity and wafer-to-wafer average temperature, as they must rely on optical pyrometry.

Sputtered Ni films (~10 nm thick) on Si wafers were annealed in the temperature range of 280°C ~ 360°C to form nickel monosilicide (NiSi) (Fig. 10). The sheet resistance of nickel silicide was measured before and after annealing. The sheet resistance increased from ~20.0 ohm/sq. to 31.0 ohm/sq. after annealing at 280°C for 5 minutes due to Ni₂Si formation. As the annealing temperature increased, the sheet resistance sharply decreased to ~7.8 ohm/sq. at 360°C by forming a lower resistivity NiSi phase. The typical Rs uniformity range after annealing above 330°C was approximately 2.5% in 1σ. The uniformity change, before and after annealing, was below 1% in 1σ.

Long term wafer-to-wafer process repeatability was monitored for ~1 year period in the temperature range of 280°C ~360°C without any adjustments to the SAO-200LP system (Fig. 11). Ten monitor wafers were used for each temperature set points to reproduce the temperature sensitivity curve of nickel silicide sheet resistance shown in Fig. 10. As seen in the figure, the process results were extremely stable and reproducible for ~1 year period, including the phase transition temperature region. When a process is developed using this type of extremely stable and repeatable system, the process transfer from R&D to manufacturing is extremely simple and efficient because of the excellent process repeatability and system reliability. Typically, significant cost and effort are

expended by chip manufacturers detecting process drift and making subsequent system adjustment. This is a never ending process. If one can eliminate the source of process drift, overall productivity will be significantly improved.

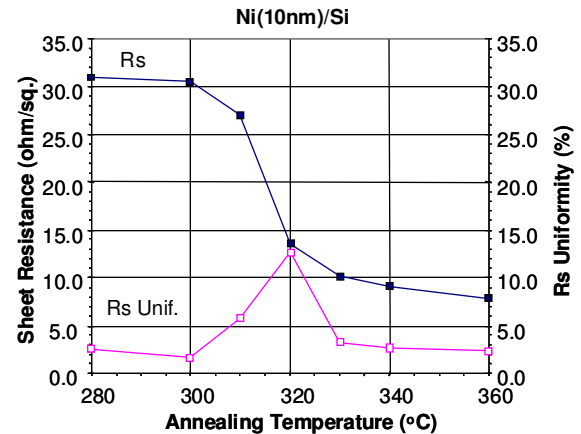


Fig. 10. Sheet resistance and uniformity change of 10 nm thick Ni film on Si substrate under various annealing temperatures.

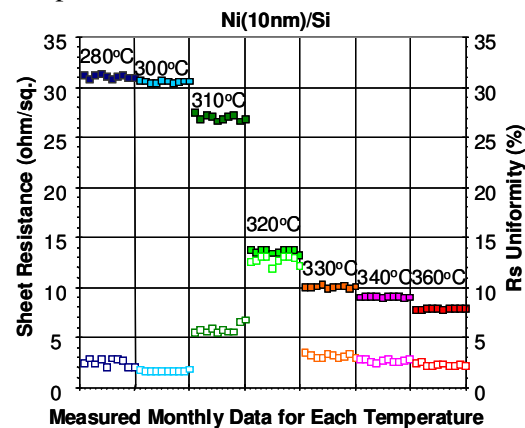


Fig. 11. Sheet resistance and uniformity repeatability of 10 nm thick Ni film on Si substrate using SAO-200LP system under various annealing temperatures for ~1 year period. Monthly data is graphed for the 1 year test at each temperature to show repeatability.

If material properties and true process conditions (not nominal process conditions) are always the same, wafer after wafer, one should expect the exact same (repeatable)

process results. Process conditions always contain some degree of uncertainty in the value of process variables. To make the process results repeatable, the uncertainty in the nominal process conditions should be identified and eliminated. This uncertainty is the source of process variations under actual semiconductor manufacturing conditions. In other words, the real process conditions are never exactly the same as the true (ideal), process conditions. Mischaracterization of the true process condition in a system is the source of wafer-to-wafer process variations in the system. Difference in degree of uncertainty, including offsets of process variables between systems, is one of the sources of system-to-system process variations.

By implementing optimum RTP process strategies, the short-term and long-term process uniformity and repeatability across systems can be achieved. Uniform and repeatable thermal process environments for the wafers being processed are essential for highly uniform and repeatable process results on both blanket wafers and patterned wafers. As discussed in previous sections, patterned wafers have intrinsic variations due to the nature of selective physical and chemical reactions and are subject to the extrinsic source of variations. The variations in pattern size, density, structure, crystal quality, dopant etc. can significantly amplify unwanted within wafer variations in process results depending on the wafer heating mechanism, wafer temperature measurement/control method and thermal uniformity and repeatability of the process environment itself.

By moving away from heating using non-uniform heat sources, like lamp based radiation heating, with inaccurate wafer temperature monitor/control, a significant portion of the extrinsic source of variations can be reduced or eliminated.

Some systems attempt to create uniform temperature on the wafer from a heated bell jar with a large temperature gradient (non-uniform heat source) and attempt to control

wafer temperature profiles by moving the relative position of the wafer in the non-uniformly heated bell jar [34 - 36].

Other commercial systems heat a levitated wafer with heated gasses through upper and lower showerheads by forced convection heating [37 - 39]. This type of system requires complex wafer handling mechanics with numerous moving parts, all of which could cause system reliability and particle generation problems. Unless the heated gas temperature is very stable and uniform throughout the process, unwanted within-wafer and wafer-to-wafer temperature fluctuation may be introduced without notice. These are examples of typical control errors which must be reduced or eliminated to achieve process repeatability.

As seen in Figs. 7 and 8, the hot wall-type RTP system which provides a uniform and stable thermal processing environment by employing large thermal mass process cavities and utilizes even, convection heating, can significantly reduce or eliminate the extrinsic source of process variations in patterned wafers. By placing wafers at exactly the same location within the large thermal mass cavity with near-isothermal temperature profile and excellent stability, highly uniform and repeatable process results on patterned wafers can be easily achieved. Excellent process results in Cu anneal, SOG anneal, nickel silicide formation, cobalt silicide formation, titanium silicide formation, dry/wet oxidation, implant anneal, CVD film densification and BPSG reflow applications have been demonstrated from the temperature range of 100°C to 1150°C using the SAO and SRTF systems [13, 14, 17, 23 - 33, 40 - 42].

SUMMARY

Achieving highly uniform and repeatable RTP process results on patterned wafers is an increasing challenge in today's complex semiconductor architectures. It is further complicated by significant variations of feature geometries, materials and pattern densities. Understanding the design and execution concepts of RTP systems and the factors that cause unintended process variations is the key to selecting the right tool for the job, and selecting the right tool for the job is the key to improved process and device yields.

The problems experienced in thermal processing generally fall into two categories. Uniformity related problems and repeatability related problems. The former are generally homogeneity issues of the materials and of the wafer environment (a specific design issue). Repeatability related issues are more a function of the architecture of the system and the accuracy of the chosen monitor and control systems. Uncertainties or errors in measurement or execution are primary contributors to repeatability problems.

Temperature control is of primary importance and accuracy of temperature measurement is the key. There are two primary methods of temperature measurement. Thermocouples accurately span a wide temperature range, but cannot be used directly on a wafer due to contamination and measurement perturbation. Pyrometry is a non-contact measurement method, however it has significant accuracy and range issues as well as being sensitive to variations in optical properties as in pattern density applications.

There are two philosophies of wafer processing and temperature control, direct and indirect. The first seeks to induce a process to take place by directly managing and controlling the wafer temperature. This is the approach in cold wall, lamp based RTP systems. They employ a large number of small, individual lamps and, as such, heat

primarily by radiation through photon interaction. These systems rely on real-time optical temperature measurements for their accuracy and uniformity. The rate of energy absorption depends on the local optical properties of the target wafer surface and is subject to the same variations.

The second, a hot wall chamber, seeks to manage the wafer's environment by creating a stable, well controlled, large thermal mass (process chamber) into which the wafer is placed. Ideally, the chamber's temperature is maintained (by design) at a constant temperature by thermocouple measurement and control, creating a near-isothermal environment for the wafer. The heat transfer mechanisms are primarily convection and conduction (through gas) with radiation playing a relatively small role.

The cold wall, lamp based RTP system design concept uses many halogen lamps with very small thermal mass and as such, is able to change temperature quickly. However, while this concept provides great flexibility, it sacrifices long term process repeatability and stability due to the inherent limitations in accurate temperature measurement (especially true in high pattern density situations) and continuous change and degradation of the individual, limited life lamps.

By contrast, the hot wall system approach, with large thermal mass, lacks the flexibility described above, but is superior in long term and short term process repeatability and stability. Due to the design concept, the properly designed hot wall chamber is essentially a large thermal mass repetitively and sequentially heating identical, small thermal masses (wafers). The repeatability is therefore a function of the capability of the thermocouple temperature control mechanisms to consistently and accurately monitor the temperature drift of a large thermal mass. This is a function for which thermocouple circuitry is ideally suited. Hence, theoretically, the long and short term repeatability should be excellent.

A thermal process system attempts to make the *effective* process window, the range over which acceptable process results are achieved in practice, be as large as the *true* process window, the range over which acceptable results are achieved using completely homogeneous materials and wafer environments. To accomplish this, all potential variations in a process, must be considered and avoided where possible. Intrinsic variations, those inherent in the design of the semiconductor circuit, including pattern density topology, cannot be avoided by the system choice. But extrinsic variations, which include materials and process environments, can be influenced. Materials can be of the highest quality and the system architecture can be chosen to minimize the number of variables and the uncertainty of those variables. Thus a hot wall system architecture was chosen, for its simplicity and measurement and control accuracies to provide the greatest uniform and repeatable thermal process for patterned wafers.

Several hot wall chamber architectures are suitable for a wide range of process applications. An SAO-200LP system was used to investigate NiSi formation characteristics, and the resulting curves defining the reaction versus temperature were monitored on the same system for over 1 year, without any adjustments to the system, to demonstrate long term stability. The results were excellent and demonstrated that when the factors affecting process variability are examined and addressed by system architecture, a process with long term repeatability can be achieved.

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