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1501 to 1530 Process Probe Instrumented Wafer Conversion for RTP Pyrometer Calibration

OVERVIEW

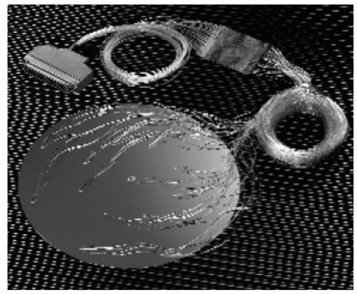
In 1987, SensArray introduced the Process Probe® 1501 thermocouple instrumented wafers for RTP pyrometer calibration. While its basic design has remained the same, many improvements have been made to achieve increased accuracy and ease of use. The recent adoption of many new RTP processes for production of devices with features below 0.5 µm requires a much tighter process temperature control. There was also a need to improve the wafer to wafer matching exhibited by the 1501, since it was being used by many customers as a reference for temperature calibration in RTP systems. In 1994, SensArray started the development of instrumented wafers with improved accuracy. Various methods of sensor embedding and attachment were evaluated. The most promising methods were modeled with finite element analysis to enable further design optimization. The result is the Process Probe 1530 thermocouple instrumented wafers with an improved design for embedding the thermocouple sensors into the substrate. With more than a factor of 4 improvement in wafer to wafer matching and repeatability, the 1530 is replacing the 1501 for use in RTP systems.

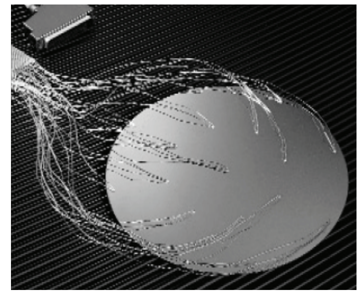
The improvements of the 1530 are primarily due to improved heat transfer between the wafer and the thermocouple measurement junction. In the older 1501 design, the thermocouple measurement junction was influenced by the temperature of the thermocouple wire above the wafer. The limited depth of immersion of the thermocouple junction allowed conductive cooling or heating of the junction if the wire temperature above the wafer was lower or higher than the wafer temperature. Since the wire temperature above the wafer is easily influenced by many factors that are not practical to control, run-to-run, wafer-to-wafer, absolute wafer temperature errors resulted. In the 1530 a longer length of TC wire is embedded into the wafer, so the junction is much less sensitive to the wire temperature above the wafer. Also, the indicated temperature of the 1530 thermocouples is much closer to the silison temperature.

Over the past three years, many semiconductor facilities have evaluated the new 1530 wafers and have converted from 1501 wafers. Their improved control of RTP processes using the new 1530 has convinced SensArray that all customers will benefit from a transition to 1530 wafers. The 1501 wafer is phased out for cold wall applications. For new process development, only the 1530 wafers should be used. For processes where the RTP system calibration is established by means of 1501 wafers, better accuracy and repeatability of the system calibration can be achieved by a conversion to 1530 calibration wafers. This requires a careful and complete transfer of pyrometer calibration standards from 1501 to 1530.

Since the 1530 wafers have an improved absolute temperature measurement accuracy, there will be a shift in thermocouple indicated temperature of up to 20°C, with the 1530 wafers typically indicating a higher temperature than the 1501 wafers in similar conditions. If the system or process recipes are not corrected at the time of conversion from 1501 to 1530 calibration standards, product wafers will be processed at lower temperatures in most RTP systems even though the system indicates the same process temperature. The benefits of conversion are significant. Tighter process temperature limits can be readily maintained over longer periods of time, calibration to calibration and TC wafer to TC wafer. Some customers have reported that conversion to the Process Probe 1530 has enabled them to optimize and improve device parameters.

By carefully reviewing the data and methods to correct system calibration suggested in this application note, conversion to the new temperature standards can be readily accomplished.





1501 & 1530 MATERIALS AND PROPERTIES

The Process Probe 1501 instrumented wafers typically are fabricated from the following materials:

1. Substrate Material: p-Boron, 8 - 80 Ω.cm doping, (1-0-0) orientation, silicon wafers, or customer supplied bare coated or patterned silicon wafers with a min. thickness of 525 µm
2. Number of Thermocouple Sensors: From 1 to 34
3. Thermocouple Wire Type: Type-K (Chromel-Alumel) or Type-R (Platinum - Platinum, 13% Rhodium)
4. TC Wire Diameter: 0.005” (0.127 mm)
5. TC Wire Insulation: Braided Silica Sleeving or Micro

The Process Probe 1530 instrumented wafers typically are fabricated from the following materials:

1. Substrate Material: p-Boron, 8 - 80 Ω.cm doping, or p+ Boron .015 to .030 Ω.cm doping, (1-0-0) orientation, silicon wafers, or customer supplied bare coated or patterned silicon wafers with a minimum thickness of 525 µm
2. Number of Thermocouple Sensors: From 1 to 34
3. Thermocouple Wire Type: Type-K (Chromel-Alumel)
4. TC Wire Diameter: 0.003” (0.076 mm)
5. TC Wire Insulation: Micro Quartz Tubing

COMPARISON OF 1501 VS. 1530 STRUCTURES

Figure 1 shows the physical differences between these two configurations. The 1501 configuration used relatively large 0.005” (0.127 mm) diameter wire, and the TC junction bead was positioned near the center of the bond area with a limited embedding of the TC wires in the cement. This made the 1501 structure sensitive to temperature gradients in the wire above the wafer and gradients in the cement bond area.

The 1530 configuration is designed to minimize wafer-towafer and installation variations by reducing the thermal resistance between the TC junction and the silicon, and by isolating the junction from the thermal gradients in the external wire and in the cement. The improved 1530 configuration uses smaller diameter 0.003” (0.076 mm) TC wire. This wire conducts less heat from the junction to the ambient, because of the smaller cross sectional area. The smaller wire is

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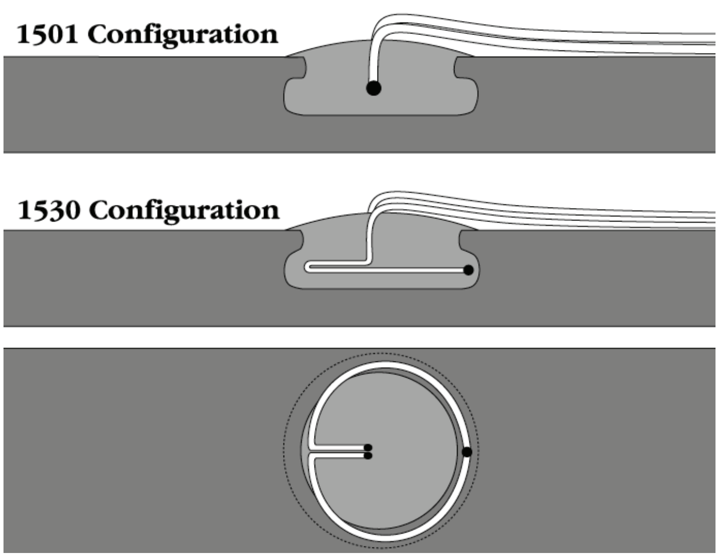

FIGURE 1:
TC mounting method in 1501 and 1530

mounted near the perimeter of the cavity, thus providing a much longer path length in close proximity to the silicon side wall, in an area of the cement with shallow thermal gradients at a temperature which is very close to the silicon temperature. The thermocouple junction is also placed in the undercut area in close proximity to the silicon. This design (US patent #5,746,513) significantly reduces the variability of manufacture, improves absolute temperature accuracy, and minimizes the influence of the wire temperature and thermal gradients above the bond, significantly reducing the influence of installation variability on the calibration temperature.

POTENTIAL SOURCES OF MEASUREMENT ERROR IN 1501 STRUCTURES

The principal error sources limiting measurement accuracy in 1501 type structures in cold-wall systems are:

1. Heat transfer errors resulting from:
   - The thermal resistance between the TC junction and the silicon
   - Temperature gradients in the TC wire causing heat flow in or out of the junction
2. Proximity of wire insulation of this TC and other TCs to the ceramic bond area, influencing wire temperature gradients near the bond.

Additional errors that are common to 1501 and 1530 structures are:

3. Changes in TC wire calibration due to chemical processes (oxidation, …) or mechanical stress.
4. Deviation of TC wire calibration from ideal NIST temperature vs. millivolt curves.

Of these sources of error, the first, heat transfer errors, is by far the most significant in 1501 structures. The improvements shown in Figure 1 are designed to reduce such errors. Also, the second listed error source is large in the 1501, but significantly reduced in the 1530 structure, because the junction temperature is much less sensitive to the temperature of the thermocouple wires outside of the bond area. The 1501 and 1530 configurations are nearly identical with respect to the last two error sources, because they are related to the thermocouple wire material.

The errors resulting from the imperfect heat transfer in the 1501 impact the instrumented wafers in the following ways:

- small variations in sensor geometry or ceramic properties, introduced during manufacturing, can result in measurement variability from TC-to-TC and from wafer-to-wafer;
- additional variations are related to changes in the position of the wire leads with respect to both the wafer and the RTP chamber. On a micro scale, the cause appears to be a change in the length of exposed bare TC wire between the TC bond and nearby insulation.

The result is a possible run-to-run variability in calibration temperature. This is referred to as “installation effects”. Some of the sources of variability and their influence on pyrometer calibration are shown in Table 1.

Type of variability	Source of variability	When does it effect the pyro calibration
Installation-to-installation variability	Movement of TC lead insulation near bond area	At each installation
TC-to-TC wafer variability	Manufacturing variability	At TC wafer change
TC wafer calibration drift	Wire oxidation, stress, TC wire oxidation	At TC wafer change, & over life of TC wafer
Thermocouple calibration is offset from NIST standards	TC wire alloy deviation from ideal composition	With a different wire lot at manufacturing. After many TC wafer changes.
TC wafer emissivity to product wafer emissivity differences & variability	Product wafer backside films and roughness. Calibrating with polished side of wafer towards pyro	At TC wafer change and with changing product characteristics

Table 1: Overview of the various sources of variability for Process Probe 1501 wafers

The first four types of variability affect the first level of pyrometer calibration: calibration to the absolute temperature of the TC wafer. The fifth type of variability affects only the second level of pyrometer calibration, that is temperature offset due to the sensitivity of the pyrometer to emissivity differences between the calibration wafer and the product wafer. Some users of 1501 instrumented wafers reduce these variables by selecting only those wafers that lie within a tight group. Since the variability includes the manufacturing variability as well as installation effects, it is not possible to select a group that is any tighter than the variability of installation. From the experimental data it will be clear that the installation variability can be a major portion of the total variance. So a screening process may not always result in a tighter distribution. Also, if a tighter distribution is achieved, the mean of this screened group can differ significantly from the mean of the original group.

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DATA ON 1501 VS. 1530

Experiment series 1

A group of 10 different 1501 wafers and a group of 10 different 1530 wafers were tested in a stable RTP system equipped with a pyrometer at 3.4 µm. The feedback loop was controlled from the thermocouple wafer under test and the pyrometer indicated temperature was recorded for every wafer in the steady state. The pyrometer was viewing the frontside of the wafers. The thermocouple temperature was controlled to be equal to 700°C in one set of experiments and 1100°C in another set of experiments. The results are shown in Figs. 2a & 2b.

Fig. 2a: Around 700°C, the worst case variation among the 10 different wafers is ±5°C for the 1501 and only ±0.25°C for the 1530 wafers. Fig. 2b: Around 1100°C, the worst case variation among the 10 different wafers is ±6°C for the 1501 and only ±1°C for the 1530 wafers. This is more than a factor 5 improvement in wafer precision.

Also, there is a systematic offset between the pyrometer indicated temperature under control of 1501 or 1530 wafers. When a 1501 wafer is used for control, the pyrometer indicates a higher temperature. This means that in a condition with equal silicon temperature, the 1501 wafer indicates a lower thermocouple temperature. Around 700°C, a 1501 wafer will indicate a temperature between 12°C and 22°C lower than a 1530 wafer, in case of equal silicon temperature. Around 1100°C, a 1501 will indicate a temperature between 17°C and 29°C lower than a 1530 wafer.

Experiment series 2

Two special TC wafers were prepared, each with 6 TC junctions equally spaced around an 8 mm radius circle at the center of the wafer. On each wafer 3 of the junctions were 1501 type and 3 were 1530 type. The 1501 and 1530 TCs alternated around the circle as shown in Figure 3. The two wafers were used in a round robin test in a system with lamp power control (typical stability at the time of the experiment 1°C). Each wafer was removed from its plastic storage tray and installed onto a quartz tray and placed in the RTP chamber. A 30-second cycle at 1050°C was run and data from all 6 thermocouples was recorded. The wafer was then removed from the oven and packaged back in the plastic storage tray. Both wafers were run sequentially on a daily basis for 8 days.

The data in Figures 4, 5, and 6 compares the temperature measured by each of the 1501 TCs at the same location on both wafers. For the same TC on the same wafer, run to run deviations up to 8°C are seen. For the same location on the different wafers, deviations up to 12°C are seen. Figures 7, 8, 9 show the same data for the 1530 TCs mounted on the same 2 wafers. For the same TC on the same wafer, run to run deviations up to 2°C are seen. For the same TC location on the different wafers, also deviations up to 2°C are seen. It is clear that temperatures for 1530 junctions are much more stable. Due to oven nonuniformity, there is a systematic offset up to 2°C between the various positions on the wafer on which the TCs are mounted (this was also confirmed with experiments involving wafer rotation). Also, due to the limited system stability of 1°C at the time of the experiment, part of the variability can be attributed to oven nonuniformity.

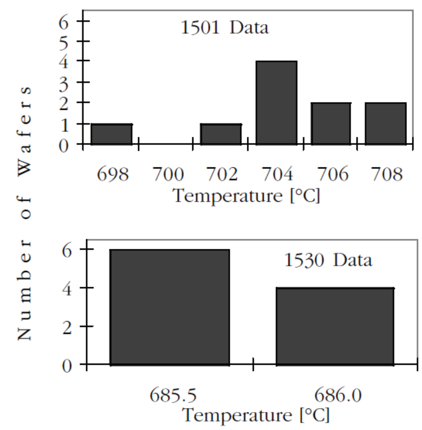

FIGURE 2a:
Histogram of indicated pyrometer temperatures of an RTP system under control of 10 different 1501 (top) and 1530 (bottom) Process Probe® wafers with the TC temperature controlled at 700°C.

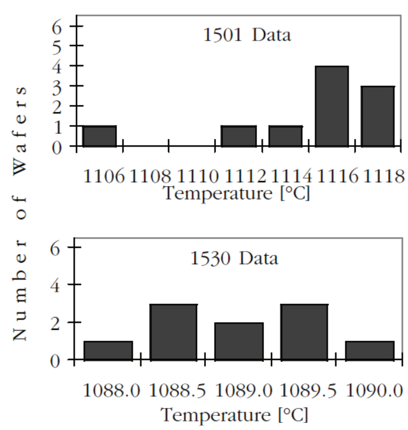

FIGURE 2b:
Histogram of indicated pyrometer temperatures of an RTP system under control of 10 different 1501 (top) and 1530 (bottom) Process Probe® wafers with the TC temperature controlled at 1100°C.

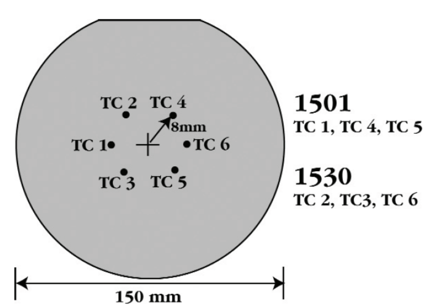

FIGURE 3:
Location of the thermocouples on the wafer controlled at 1100°C.

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Experiment series 3

One wafer, similar to the type in Experiment series 2, was used in a consequence of 50 heating cycles in the same RTP system under lamp power control. After every 10 heating cycles, the wafer was removed from the system and then mounted back into the system. Fig. 10 shows the resulting temperature stability of the 6 TCs over the 50 heating cycles.

The 1530 show a stability and a TC to TC matching within ±1°C over the 5*10 heating cycles. The 1501 thermocouples show three types of deviations:

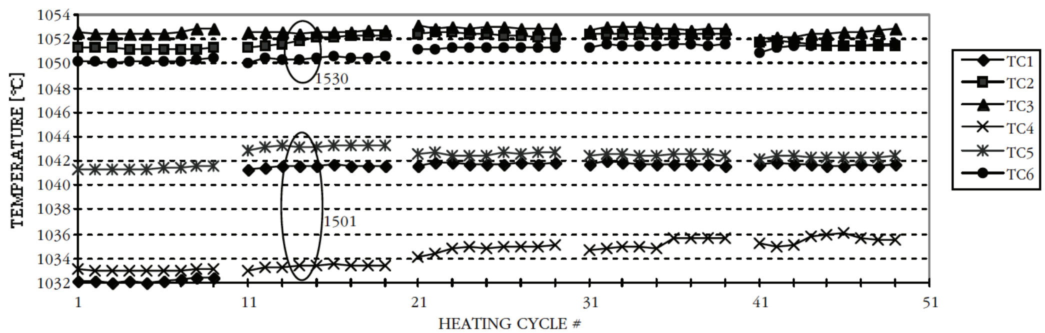

FIGURE 10: Repeatability of 1501 and 1530 TCs during 5*10 heating cycles; wafer unload after every 10 heating cycles.

- the temperature indicated by the 1501 TCs is between 10 and 20°C lower than the indicated temperature of the 1530 TCs.
- the temperature indicated by the 1501 TCs deviates up to 10°C from one another.
- the indicated temperature of TC1 changes by 10°C upon the first case of unloading/reloading the wafer.

The graphs shown right compare two different wafers, each with three (3) 1501 bonded TCs (#s 1, 4, 5) andthree (3) 1530 bonded TCs (#s 2, 3, 6). It is comparing the same locations on each wafer within each graph.

1501

Below are comparisons of two wafers each with the same location of 1501 TCs:, #1, #4, #5 (from Figure 3).

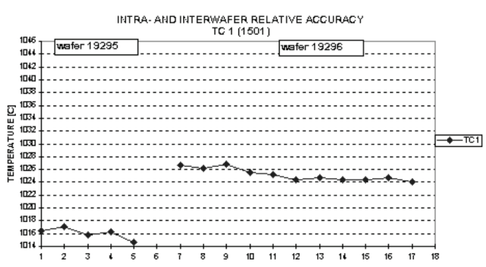

FIGURE 4: Wafer-to-wafer and run to run stability of a 1501 thermocouple (#1) on two wafers.

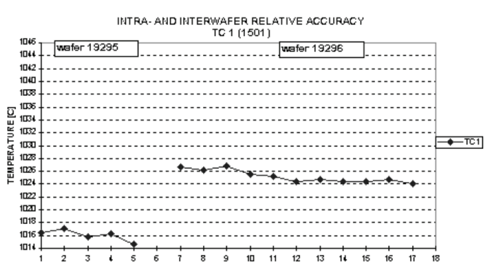

FIGURE 5: Wafer-to-wafer and run to run stability of a 1501 thermocouple (#4) on two wafers.

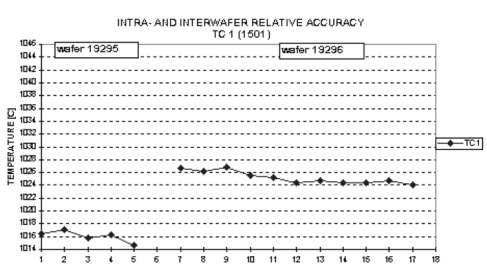

FIGURE 6: Wafer-to-wafer and run to run stability of a 1501 thermocouple (#5) on two wafers.

1530

Below are comparisons of two wafers each with the same location of 1530 TCs:, #2, #3, #6 (from Figure 3).

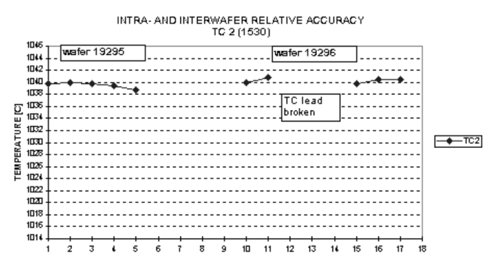

FIGURE 7: Wafer-to-wafer and run to run stability of a 1530 thermocouple (#2) on two wafers.

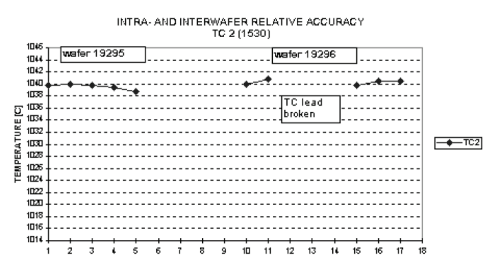

FIGURE 8: Wafer-to-wafer and run to run stability of a 1530 thermocouple (#3) on two wafers.

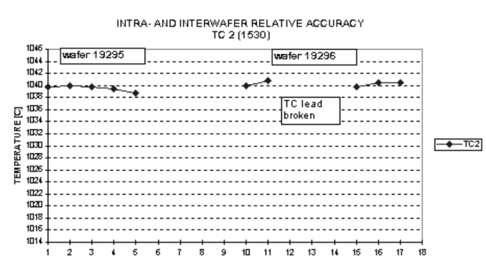

FIGURE 9: Wafer-to-wafer and run to run stability of a 1530 thermocouple (#6) on two wafers.

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SUMMARY OF MEASURED DATA

A summary of the experimental data is shown in Table 2. From this it can be concluded that the total uncertainty of the 1530 wafers (including thermocouple to thermocouple variability, installation effects and the drift over life) is a factor of four better than the uncertainty of 1501 wafers. The values shown, reflect the maximum deviations found over the measured wafers and under normal operation conditions (a high purity non oxidizing ambient).

Table 2: Summary of the measured data

Process Probe Model	Single wafer uncertainty = installation uncertainty + drift over life	Total uncertainty = wafer-to-wafer + installation uncertainty + drift over life
1501	±5°C	±6°C
1530	±1°C	±1.5°C

BEST USE PRACTICES FOR 1530 TC WAFERS

Configuration of the thermocouple instrumented wafers

Customers typically use instrumented wafers for two purposes. The first is to provide a temperature standard for the pyrometer calibration in the RTP system. Other sensors such as direct contact thermocouples (DTCs) or thermocouple instrumented susceptors are also calibrated by means of the thermocouple instrumented wafer. The second application is for mapping and adjusting the RTP system uniformity by observing the wafer temperature nonuniformity on 9, 13, 17, or 34-point TC wafers.

Pyrometer calibration is usually performed using a singlepoint TC wafer. Sometimes a redundant second TC is located near the primary TC. The primary TC is positioned on the wafer close to the point where the pyrometer measurement is made, without interfering with the measurement. Pyrometer calibration can be performed to one of two levels.

1. The first level calibration is that of calibrating the physical pyrometer system using a wafer of known emissivity. The way to obtain the most reproducible emissivity in this case is to put the wafer in the system with the polished side facing the pyrometer. The wafer TC is bonded into the backside of the wafer at a location around 10 mm away from the field of view of the pyrometer. This calibration method assures the most consistent system level calibration. For pyrometer calibration below 700°C it is important to use wafers with doping levels which are high enough to prevent wafer transparency. The use of p+ wafers is strongly recommended for low temperature calibration. SensArray supplies highly doped wafers for low temperature pyrometer calibration.
2. The second level of calibration includes the actual emissivity of the product wafer in the procedure. When only a level 1 calibration is executed, the process temperature of a product wafer will be offset from the indicated pyrometer reading because of emissivity differences between the calibration wafer and the product wafer. This is due to the sensitivity of the pyrometer to emissivity variations. The emissivity variations of product wafers are caused by the backside roughness and the presence of layers on the backside of the product wafers. The second level calibration, involves mounting a TC in the frontside of a product wafer of the appropriate process step and loading it in the system with the backside facing the pyrometer.

To achieve the needed calibration accuracy, the conversion of the thermocouple signal to temperature requires an RTP system with sophisticated input electronics.

The thermocouple voltage signals need to be acquired and processed by data acquisition hardware with a minimum of 16 bits of resolution. Also required are signal filtering to eliminate SCR switching noise, a stable and accurate reference junction compensation circuit, and an accurate thermocouple linearization method. Many RTP systems have limited performance in this area.

Installation

Although the Process Probe 1530 exhibits low sensitivity to TC lead positioning, measurement errors can be induced by shadowing a measurement junction with thermocouple leads from another thermocouple. In particular, there are four positioning details that need to be carefully controlled. These are:

1. The wafer should be carefully centered on the tray.
2. The TC wires should be draped away from the TCs so that the wire does not shadow any TC.
3. If multiple TCs are used, do not allow the wires to exit the wafer edge in one massive bunch: spread them out avoiding shadowing the TC junctions as they exit the wafer edge.
4. The TC wires insulated with quartz/silica micro tubes should not be bent sharply at the tube ends. Sharp bends can increase probability of wire breakage at that location. The best way to insure that these details are reproducibly controlled is to install the instrumented wafer on a dedicated wafer tray. Ideally, that tray should have means for centering the TC wafer along with anchor points for the TC wires. One possible solution for centering the wafer on the tray is the use of a slip-free ring, mounted at the height of the wafer.

The polyimide flat cable feedthrough needs to be positioned across the O-ring seal of the load door. The best procedure is to first install the wafer and the wafer tray and make sure the wires are properly positioned. It is important that the proper length of wire is specified. Too much wire length will cause bunching up of the wire in the vicinity of the door. Too little wire length will cause the wafer to be pulled off center when positioning the flat cable. With the proper wire length, the flat cable needs to be placed across the O-ring with 4 to 6mm of polyimide extending beyond the metal flange into the process chamber. The micro quartz tube insulation segments are bonded into the first 3 mm of the polyimide flat cable. If the flat cable is installed with too short a length extending into the chamber, the micro quartz tubes will be crushed between the metal flange and the door when it closes, which may cut the TC wire. Once positioned, the flat cable should be taped to the flange outside the O-ring, Kapton tape can be used.

In systems with misaligned, bent or warped doors, it is possible to cut through the polyimide film and into the flat cable's TC wires when closing the door. This may short the thermocouple leads. The thermocouple will then indicate the door temperature, regardless of the wafer temperature. This can lead to system overheating if the system is operated under TC control. It is strongly advised to test the RTP system in pyrometer or lamp power control mode after each TC wafer installation to detect this potential problem.

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Purging

After the door is sealed, it is critical that oxygen and water vapor are purged from the wafer, the chamber, and the thermocouple materials prior to bringing the wafer to high temperature. The Type-K thermocouple wire used in the Process Probe 1530 will undergo rapid decalibration if exposed to an oxidizing ambient at temperatures in excess of 500°C. A long purge time is needed to achieve the desired level of gas purity. This allows oxygen trapped under the tray and inside the micro quartz tube to diffuse out. We recommend a purge of 2 minutes at a N2 flow rate of 20 slpm or greater. Longer TC wafer life can also be achieved by incorporating a thermal dehydration step into the calibration recipe. Such a step would consist of 30 seconds at 300°C with a N2 flow of 20 slpm. The temperature could be slightly above 300°C; the exact temperature is not critical and can be achieved through open loop power control.

RE-CALIBRATION FROM 1501 TO 1530

The improved accuracy of the 1530 technology is an important benefit but also presents a complication in the conversion from the older technology to the improved 1530 technology. No instrumented wafer measures the exact wafer temperature without calibration correction. The older 1501 design indicated a lower apparent wafer temperature than actual silicon temperature. Many users have set up their processes using this lower indicated temperature. Converting to the 1530 will require a change in the recipe temperature (and the associated spec changes). However, for processes with a wide temperature latitude, no adjustments may be required. Below we include a suggested conversion procedure.

CONVERSION PROCEDURE

Most RTP systems lack a feature found in most diffusion furnace temperature control systems; that is a table to input TC calibration offset values to correct the temperature control point. Because this feature is not available, the correction of calibration of the TC wafer must be accomplished by changing the process recipe temperature setpoint.

We assume that a SensArray 1501 TC wafer in good condition is available and it has been used previously for establishing the pyrometer calibration of the process. This wafer will be defined as a 1501 golden wafer; it is assumed to be stable and typical of TC wafers used to establish your existing process temperatures. It should be configured with the TC on the backside so the polished side will face down toward the pyrometer during calibration.

A SensArray 1530 TC wafer in good condition is required to measure the difference in calibration between a typical 1501 and 1530. The proposed procedure is detailed in the following Table 3.

Table 3: Suggested procedure for the conversion from 1501 to 1530 pyrometer calibration.

1. Verify that the 1501 and the 1530 wafers have a similar emissivity and a similar doping level.
2. Dial in the normal emissivity used during pyrometer calibration with the 1501 wafer (e.g. 0.70).
3. Put in the 1501 and run a step recipe(s) under TC1501 control (a calibration cycle typically consists of consecutive step cycles).
4. Acquire the Pyro output and generate a standard calibration table. (Up to this point is the standard calibration cycle with the old 1501 wafer.)
5. Replace the 1501 with the 1530 wafer.
6. Rerun the step recipe(s) under Pyro control.
7. Acquire the TC1530 temperature indications.
8. The resulting data will look something like:
   Conversion Table for 1501 to 1530 conversion

T_{target}	T1501	T1530	ΔT
700	700.2	705.2	5.0
800	800.1	806.1	6.0
900	899.5	908.9	9.4
1000	1000.2	1011.0	10.8

9. These ΔTs can be used to rationalize the calibration. (Assuming the process is stated in terms of the Pyro indicated temperature.)
10. Generate a new pyrometer calibration file by means of the 1530 wafer.
11. Change the process spec to call for Ttarget + ΔT. Now the higher process spec temperature will match the higher indicated temperature of the 1530 wafer (the increased process spec temperature will be close to the true absolute temperature).

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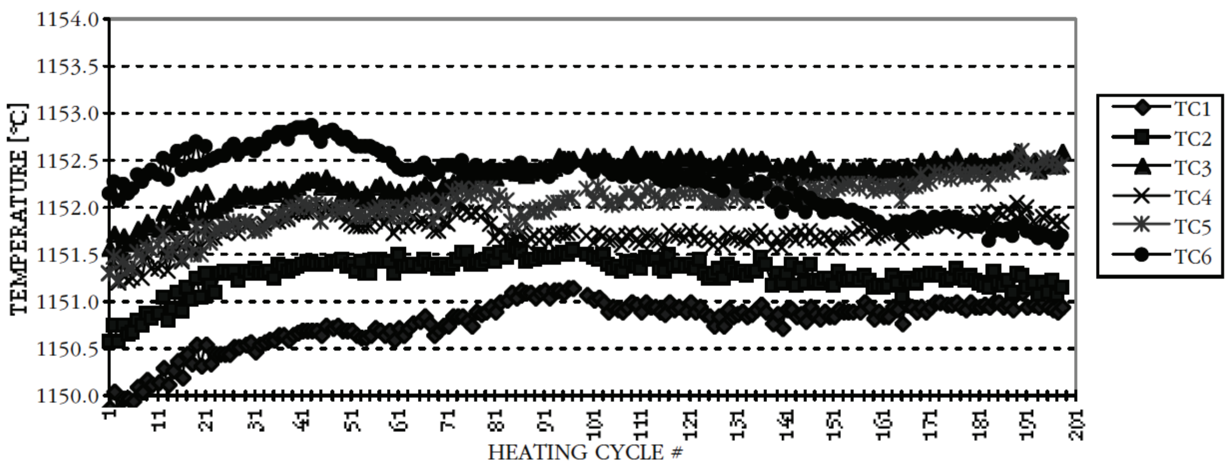

FIGURE 11: Life time and drift over life time during 200 heating cycles at 1150°C for 30 seconds.

CAUTION

There is significant risk of RTP system calibration instability if extreme care is not exercised in a facility using both Process Probe 1501 and 1530 standards. If at all possible, a conversion to 1530 technology for a fab should be accomplished at a single point in time after appropriate evaluation of Process Probe 1530 wafers.

1530 THERMAL LIFE

The drift of a wafer with six 1530 TCs mounted near the center of the wafer was measured during processes at 1150°C. The result is shown in Fig. 11. The drift over 200 heating cycles is in the range from -0.5°C to +1.0°C. No breakage of the wire was found over this 200 heating cycle experiment.

An important condition for drift free operation is the establishment of an oxidation free ambient in the chamber before the heating process is started. This requires the use of pure N2 (<10 ppm O2) and long enough purging before the initial heating of the TC instrumented wafer (see the section on purging).

It is believed that the main cause of the measured drift over the life time is rather a degradation of the silicon wafer surface properties (due to pitting, oxidation, …) than a degradation of the thermocouple structure.

CONCLUSIONS

If one proceeds with care, the conversion from 1501 technology to the improved 1530 technology can be easily accomplished. The physics that explain the performance improvements displayed by the 1530 are simple and straightforward.

RTP tool suppliers have continuously improved the accuracy and repeatability of their in-process temperature measurement and control technology. In many cases, calibration uncertainty is now the major source of error in the control of RTP processes. In order for the user to benefit from tool improvements and to exploit the potential for tighter process control, the transition from 1501 technology to 1530 technology is essential.

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