Improvements in wafer temperature measurements

A. Cardoso and A. K. Srivastava

Axcelis Technologies, Inc., 7600 Standish Place, Rockville, Maryland 20855

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Accurate and repeatable wafer temperature measurement and control is critical in many semiconductor processing applications. Many of these applications are done at moderate pressures (0.5–2 Torr) where thermal contact resistance between the wafer and a contact temperature probe is high, and could vary wafer to wafer. The result is an unpredictable difference between the actual wafer temperature and contact measurement probe due to heat transfer across this interface from exothermic reactions, hot plasma gases, or radiant heating. In some applications, this temperature difference is so great that backside helium cooled electrostatic chucks are used to minimize this effect. In many applications, the use of this type of solution is not practical but accurate and repeatable wafer temperature measurement is still required. A new temperature sensor has been developed that utilizes gas injection through a pinhole in a thermocouple pad that creates a “microenvironment” between the pad and the wafer. This results in reduced thermal contact resistance, and more accurate and repeatable temperature measurement. Temperature data on the operation of this probe will be presented, verifying the robustness of this probe. Additionally, diffuse reflectance spectroscopy will be used as a noncontact temperature measurement technique to corroborate data from the new gas-cushion thermocouple. © 2001 American Vacuum Society. [DOI: 10.1116/1.1358857]

I. INTRODUCTION

Accurate and repeatable wafer temperature measurement and control is critical in many semiconductor processing applications. For this purpose, the state of the art in thermometry techniques essentially employs two classes of temperature sensors: thermoelectric and photon detectors. Examples of techniques using photon detectors are diffuse and specular reflectance spectroscopy (DRS), infrared (IR) thermometry, and pyrometers or thermopiles, which have the advantage of being noncontact, noninvasive techniques. Pyrometers operate on both photon and thermoelectric principles, by measuring in a noncontact manner infrared photons emitted by a hot object. Conversely, the most common use of thermoelectric detectors, usually thermocouples, requires the sensor to be in physical contact to the object being measured. Although it is not always the ideal solution, direct contact of thermocouples has the advantage of being a very simple and inexpensive technique. Indirect temperature sensing techniques have also been developed, like those measuring the expansion of materials. However, they require expensive vision and data processing systems, and some techniques require imprinting a known grating on the wafer, a situation mostly undesirable on production wafers.

Each of these techniques can be very effective under the right conditions, but can also produce inaccurate results if those conditions change. For example, pyrometers can be very accurate if the emissivity of the wafer is well known. However, a small deviation in the wafer surface’s emissivity due to different patterns, doping, and surface materials, can cause large temperature measurement errors. More importantly, pyrometers are not suited to measure temperatures below ∼300 °C. Another aspect to be taken into account is the relative cost of these thermometers, where thermocouples have the great advantage of being extremely inexpensive, while spectroscopy based systems are beyond the cost structures of most semiconductor equipment.

The use of a thermal chuck to maintain the wafer at the desired temperature is a widely utilized technique; however, it is the chuck’s temperature that is typically being measured and controlled using a set of thermocouples attached to the chuck. The problem now is to guarantee the wafer is at the same temperature as the chuck. At low pressures typical of plasma processing, the thermal discontinuity between wafer and chuck is greatly magnified; that is, the wafer–chuck thermal conductivity dramatically decreases with low pressure. On one hand, the wafer can take a long time to reach setpoint (chuck temperature) due to the slow wafer–chuck heat transfer (at low pressure) and may not even reach the setpoint because the thermal conductivity between wafer and chamber walls, which are usually cooler, may not be negligible. On the other hand, any exothermal reaction occurring at the wafer’s surface, as well as excessive plasma/gas temperature, causes the wafer’s temperature to drift away from the setpoint (chuck) because the low thermal conductivity is not enough to quickly sink the energy from these parasitic heat sources. The result is that the real wafer temperature is unknown and not controlled. To minimize this problem, helium cooled chucks and electrostatic chucks (and the combination of both) were developed, the former using the good thermal conductivity of helium to improve the wafer–chuck thermal interface, while the latter accomplishes a better mechanical contact. However, it is difficult to show how effective these solutions are to actually control wafer
temperature, so the problem of measuring and controlling wafer temperature still remains. In any case, the use of electrostatic/helium cooled chucks is not a cost-effective solution for resist stripping applications.

In order to improve the thermal contact between a thermocouple probe and the wafer at low operating pressures, a new probe was developed in which the wafer–probe gap is filled with helium. This creates a microenvironment at a pressure set by the wafer’s weight (instead of that set by the process), causing thermal conductivity to be higher and more stable (Fig. 1). The following sections present proof of concept and results for this new probe, referred to from now on as the gas cushion probe. It demonstrates that the introduction of a “helium cushion” between the wafer and the probe’s disk creates a localized pressure of \(>20\) Torr, thereby greatly reducing and stabilizing the temperature error. DRS, a noncontact wafer temperature monitoring technique, is used to corroborate the gas cushion probe improvements.

II. EXPERIMENTAL SETUP

Two experiments were designed to evaluate the gas cushion probe. Tests were conducted in a plasma chamber for a commercial dry ash tool operating at \(1.0–3.0\) Torr pressure, the details of which may be found in U.S. patents.\(^2\)\(^3\) In the main experiment, the temperature read by the probe during a predefined test cycle and under three difference test conditions was compared to that measured by a reference thermocouple “glued” onto a test wafer (Fig. 2). In a second experiment, the temperature read by the gas cushion probe during a different test cycle was compared to that measured by DRS. It should be stressed that both these experiments were designed to exaggerate the wafer–probe temperature error, so that relative comparisons would be well above noise levels.

A. Gas cushion probe description and setup

The gas cushion probe consists of an aluminum disk with an embedded thermocouple (TC), and a stainless steel capillary tube inserted through a small hole on the disk (Fig. 1). The capillary tube and TC wires are protected and brought outside the chamber using a narrow quartz tube.

Helium flow was adjusted through the capillary to values ranging from \(18\) to \(36\) sccm, for a chamber at room temperature (leakage back into the chamber measured at \(3–6\) Torr/min, respectively). The flow was set by adjusting the output pressure of the helium bottle and by changing the length of the capillary tube feeding the probe. No mass flow controller was used, since the chamber-to-bottle pressure differential and the wafer’s weight naturally set the gas flow.

In the main experiment (described in Sec. IID and in Fig. 2), the probe was tested for three different flow conditions: (a) no flow, (b) \(36\) sccm, and (c) \(18\) sccm. Conditions (b) and (c) will be explained in detail in Sec. III. For the second experiment (described in Sec. IID), the probe was tested under conditions (a) and (b) only.

B. Test wafer

A high infrared absorption wafer (metallized) was used for reference instead of an instrumented wafer, e.g., a SensArray™ test wafer. The SensArray™ wafer is made of bare silicon with a maximum ramp rate of \(\sim12\) \(^\circ\)C/s under \(100\%\) radiant heating power while the metallized wafer ramps at \(\sim26\) \(^\circ\)C/s. The use of a high absorption wafer has several advantages over a SensArray™. (1) It provides a worst-case scenario for the wafer–probe temperature difference because the difference of temperature \(\Delta T\) across the wafer–probe interface is magnified when a wafer with high IR absorption characteristic is used. Considering the wafer–probe heat transfer as a first order system characterized by a time constant \(\tau\), \(\Delta T\) is proportional to the time derivative of wafer temperature \(dT_w/dt\):

\[
\Delta T = \tau \cdot \frac{dT_w}{dt} \left(1 - \exp\left(-\frac{t}{\tau}\right)\right).
\]

(2) In a SensArray™, the thermocouples glued to the top surface are directly exposed to radiation above \(\sim1.1\) \(\mu\)m because silicon is transparent above that wavelength. Since the metallized wafer is opaque to IR, the instrumentation error in the reference TC due to radiant heating is eliminated.

(3) The fast, metallized wafer represents real production conditions, since bare prime wafers are very seldom processed.

C. Data acquisition

For the main experimental setup, an acquisition system recorded probe and wafer (reference) temperatures simultaneously. The temperature difference, or error, was calculated.

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**Fig. 1.** Gas cushion probe. Wafer–probe gap is filled with helium, at pressure \(>20\) Torr.

**Fig. 2.** Diagram of main experimental setup: gas cushion probes vs reference TC glued onto a high IR absorption wafer for the three gas flow conditions.
ex situ and its maximum value was registered on a graph for run-to-run comparison. The sample rate was set at 4 Hz. One consequence of the time sampling was that temperature values measured during the ramp were affected by a sampling uncertainty equal to temperature increasing rate times 0.25 s. By definition, the sampling error equals the average temperature derivative during that sample period, divided by the sample rate.

For both probe and reference TC, this error is approximately 6 °C if the average rate of temperature increase is 24–26 °C/s. Since both probe and wafer readings were taken simultaneously, the temperature difference was not significantly affected by the sampling error.

D. Main experimental setup

In the test cycle (shown in Fig. 3) for the main experimental setup, the radiant heating system was turned on at full power for 8.0 s, heating the wafer from 25–35 °C to 220–230 °C, after which the wafer was allowed to cool down. No close loop temperature control was used. The chamber was filled with N₂ at 1.5 Torr by maintaining 200 sccm of flow. Figure 3 shows the temperature error reaching its maximum value at the end of the ramp. This has been generally observed for all runs: since the wafer–probe heat transfer can be approximated to a first order system, the error is a (1 − e⁻²τ) function, characterized by a time constant τ. For τ<1.6 s, the 8 s ramp (equivalent to τ>5 τ) allows the error to stabilize (at >99%), therefore the error will already be at its maximum at the end of the ramping step.

As previously mentioned, the test cycle was designed to exaggerate the wafer–probe temperature difference, or error. In that sense, the test is not representative of a realistic scenario, in which close loop temperature control typically reduces the error approaching the setpoint by 1 order of magnitude. This explains the need for the “exaggeration” procedure: an error of 10 °C in this test would suggest an error of just ~1 °C, therefore comparable to instrumentation noise.

E. Second experimental setup: comparison to diffuse reflectance spectroscopy

For the second experiment, DRS was used as a noncontact temperature measurement technique to corroborate data from the gas cushion probe (Fig. 4). The DRS method (described in detail elsewhere⁴–⁶) relies on the variation of band edge in a semiconductor wafer as the wafer’s temperature is changed. Broad spectrum chopped light is impinged on the wafer and spectra of the diffuse reflection studied. As the wafer transitions from opaque (reflecting/absorbent) to transmitting at about 1.1 μm wavelength for the bare, prime silicon wafer, the “knee” of the transmission curve can be correlated to the wafer temperature. As the temperature increases, this knee shifts to a higher wavelength.

In this experiment, a high IR absorption wafer was used to compare the temperature measured by the DRS to that measured by the gas cushion probe, with and without helium. A closed loop proportional integral differential (PID) temperature control was established, with temperature setpoint at 120 °C. The PID setup was such that the temperature would overshoot, i.e., PID control with a high closed loop gain and
lagged feedback. The purpose of this setup was to amplify the effect of the delay introduced by the probe, which translated to a larger or smaller overshoot. (A low gain, overdamping PID setup would cause the temperature to increase slowly, reducing or even eliminating the effect of a probe with poor thermal contact.)

III. RESULTS

Figure 5 shows the maximum error observed for the gas cushion probe in three different setting conditions. On this graph, the left ordinate scales the temperature error (triangles), while the right ordinate scales the temperature increase of both probe (diamond) and reference TC (square), during the 8 s power step. The starting temperature ranged from 25 to 35°C and had the sole effect of offsetting the final temperature of both probe and wafer.

Figure 5 shows the temperature error of the gas cushion probe for three testing conditions. The first four runs show the probe’s error with no gas flow. For runs 5–22, a helium flow is set (at 36 and 18 sccm) and the error is shown to be much more stable and with lower average than that for standard probes. These two sets of runs, runs 1–4 and runs 5–22, demonstrate that injecting helium in the wafer–probe gap causes a probe that was inconsistent to become stable.

In runs 5–15, a gap between the probe and the wafer was forced by tilting the probe, and the helium flow was set at 36 sccm (6 Torr/min) of helium, previously set with the chamber at room temperature, would not cause the wafer to skate. The average gap distance was estimated to be 0.1–0.15 mm, with a tilting angle <3°.

Although the heat transfer between the wafer and the gas cushion probe is now relatively good, a temperature gradient across this gaseous interface still exists. Under the standard operating conditions for a standard probe, where the existing gap was filled at 0.5–2 Torr with the gases used in the plasma process, the temperature gradient across the gap is a function of heat transfer rate and gas pressure. As suggested by some studies on heat transfer in gases,7 the wafer–probe gap would not significantly affect the heat transfer characteristics if the mean free path of the gas at those pressures was much longer than the average gap distance. Conversely, under the estimated pressure of 40 Torr attained with the gas cushion probe, the temperature gradient across the gap is now a function of the average gap distance (and heat transfer rate). It is, however, practically independent of the pressure because the behavior of helium at such pressure is closer to that at atmospheric conditions than that at 0.5–2 Torr. For the estimated average gap of 0.1–0.15 mm, the experiments indicated the temperature gradient to be about 18°C. The logical step to follow was to reduce both the gap and helium flow, in order to reduce the average gap distance and not to cause the wafer to skate. In runs 16–22, instead of forcing an angle, a wafer–probe gap was created by roughening the disk surface and the helium flow was reduced to ~18 sccm (3 Torr/min leakage back in the chamber, at room temperature). As expected, under these new conditions, the average pressure for the helium to lift the wafer is 40–45 Torr. So, the gas cushion probe does have the ability to create a microenvironm at much higher pressure than typical process pressures (0.5–2 Torr). At that pressure, helium already presents good thermal conductivity.

(b) Since good wafer–probe coplanarity is not required, there is no need to design a probe that pivots and accommodates to the backside of the wafer. A gas cushion probe can be rigid, without moving parts, hence being mechanically robust.

Note that there is a fundamental difference between the helium injection on the temperature probe and the helium cooled chuck system mentioned in Sec. I. Although both situations make use of the good thermal conductivity properties of helium to reduce the interface’s thermal contact resistance, the helium pressure attained in the gas cushion probe is much higher because 1/3 of the wafer’s weight is “focused” on a small aluminum disk. Conversely, for an 8 in. wafer (~27 g) over a chuck, a top–bottom differential pressure of 63 mTorr would be enough to lift it up. If a differential pressure of 1 Torr is set by side clamping the wafer, a total force of ~0.43 kgf is already applied to the wafer, which can be close to or even above the mechanical stress threshold of the wafer, leading to breakage.

Due to the minute dimensions, it was difficult to determine exactly how wide the wafer–probe gap was. As a rule, the probe was tilted until the 36 sccm (6 Torr/min) of helium, previously set with the chamber at room temperature, would not cause the wafer to skate. The average gap distance was estimated to be 0.1–0.15 mm, with a tilting angle <3°.

Assuming that a 8 in. wafer weighs 27 g and that its weight is equally distributed by the three supporting points (one of which is the 4.5 mm probe’s pad), then...
error became even smaller (avg. = 11.0 °C, std. = 2.4 °C).

As mentioned earlier, the relatively large dimensions of the probe cause a shadowed area on the wafer, locally reducing the temperature increase rate. This effect is now added to the good thermal contact that the probe exhibits, which effectively couples the probe’s mass to the area where temperature is being measured. However, the improvements demonstrated by the gas cushion probe are not a consequence of the local reduction of wafer’s temperature time derivative. Since the error is a direct function of the wafer’s temperature time derivative, extrapolating the average error for a rate of 26.4 °C/s would yield 11.8 °C/s. In addition, the reduction of the wafer’s temperature time derivative cannot explain a stable error.

The “temperature well” around the probe is also a source of variability for the reference TC. If this reference TC is offset from the probe’s location (it was difficult to guarantee the same exact position), then it will read a higher temperature and will indicate an apparently higher probe error. Note that in run 20 of Fig. 5, the reference temperature is clearly above the average of runs 16–22, while the probe temperature is within the normal variation range (±3° due to acquisition error). If run 20 is neglected (error = 15.9 °C), the average error is reduced to 10.2 °C, with std. = 1.3 °C.

Figure 6 plots both DRS and gas cushion temperature readouts for two runs, both close loop controlling the temperature to 120 °C. In the first run (two curves starting at \( t = 0 \) s), no helium flow was set, so the gas cushion probe behaved similarly to the standard probe. In the second run (two curves shifted to \( t = 5 \) s), a helium flow was set and no other factors were introduced. Figure 7 shows the difference of temperature between the wafer (DRS), and the probe for both runs of Fig. 6, synchronized at \( t = 0 \) s.

It is clear from these figures that the introduction of helium in the wafer–probe gap reduces the temperature error, that is, it improves the heat transfer across the wafer–probe gap. Figure 7 suggests a threefold error reduction, which is significant if one takes into account the short duration of the test cycle. (A short cycle prevents the temperature error on probe with a poor thermal contact from reaching its maximum value—the error increases as in Fig. 3.)

In terms of dynamic control, the wafer–probe heat transfer characteristic (i.e., the probe’s time constant) translates to a delay introduced in the temperature control. In Fig. 6, the DRS–probe temperature error at any instant can also be interpreted as a probe–wafer temperature delay. Comparing both runs, the introduction of helium reduces this delay by ~1 s. In turn, this shorter delay reduces the temperature control overshoot (probe’s overshoot) from 21 to 7 °C.

Another indicator for the temperature measurement improvement introduced by the gas cushion probe is to measure and compare the time derivative of the probe’s temperature in both runs of Fig. 6 (with and without helium). Since the wafer temperature ramps at the same rate under the same heating power, a higher probe temperature time derivative indicates a better wafer–probe heat transfer. The second run in Fig. 6 (with helium), although having a smaller overshoot, has a maximum temperature gradient of 26 °C/s, while the first run (without helium) only reaches 21 °C/s.

IV. CONCLUSIONS

In a broad low pressure applications spectrum, this study demonstrated the efficacy of the gas cushion concept. While measuring the wafer temperature inside the plasma chamber, the gas cushion probe proved to be accurate and very stable, despite the experimental nature of the gas cushion probe.

Unlike noncontact temperature measurement methods, such as IR thermometry and DRS, the gas cushion concept is independent of the composition of the target, silicon wafers in our case, and its optical properties (color, emissivity, reflectivity, film coating).

The comparison between the gas cushion probe and DRS system also confirmed the gas cushion concept, showing that the introduction of helium in the wafer–probe gap increases the wafer–probe heat transfer, causing the temperature sens-

![Fig. 6. DRS temperature readings vs gas cushion probe, with and without helium flow. The introduction of helium reduces the temperature error, temperature readout delay, and overshoot.](Image)

![Fig. 7. DRS–gas cushion probe temperature error is reduced to ~1/3 with the introduction of helium.](Image)
ing to become faster and more accurate. The DRS system was used as a noncontact temperature reference since it provides good temperature accuracy. However, the DRS technique was required to be calibrated to the wafer being used, because it is sensitive to the material being measured and surface conditions, as opposed to the gas cushion probe.

The use of helium is well suited due to its high thermal conductivity and inert properties. However, this concept is applicable for a wide variety of gases, as their thermal conductivity, in general, increases with pressure. Nitrogen or argon, for example, could also be used in this probe due to their inert properties, although the error they would produce would be higher since their heat transfer properties do not compare well with helium. Hydrogen, being the gas with the highest conductivity, would produce better results than helium but, for safety reasons, was not tested. The amount of gas required by the probe is small enough not to affect the chamber’s low pressure (18–36 sccm) and since it is injected downstream of the wafer, it does not disturb the process on the upper surface of the wafer. Also, as the chamber temperature increases, the amount of gas flow reduces.

Regarding future developments for the gas cushion probe, the reduction of the overall probe’s dimensions, specifically the aluminum disk diameter, would provide significant advantages by eliminating the ‘‘temperature well’’ effect. Also, a smaller disk area would allow: (a) increasing the gas pressure in the gap without causing the wafer to skate, thus further improving the thermal contact; (b) reducing the gas flow required to attain the same pressure within the gap as with a larger disk; or (c) widening the gap angle, relaxing the mechanical tolerance requirement for the wafer–probe coplanarity.

Another advantage foreseen by the gas cushion probe is the ability to protect the disk and TC wires from the corrosive environment of plasma. The presence of helium in the gap instead of plasma prevents the surface degradation of the aluminum disk, increasing the lifetime of the probe. Finally, the same method of creating a gas cushion above contact thermometry may be used for other temperature measurement techniques that suffer from the contact resistance issues that the gas cushion probe remedies. Specifically, one could envision fiber optic probes and IR light emitting diodes with a similar gas cushion as described in this article so as to alleviate the thermal contact problems.


2M. Kamarehi et al., US patent number 5,498,308.
3M. Kamarehi et al., US patent number 5,961,851.