Demonstrating Real-Time Precision Temperature Control in Electrostatic Chucks (ESCs)

Summary:

Semiconductor fabrication demands a high level of control of process parameters related to equipment temperature. This is especially true when it comes to temperature uniformity of the electrostatic chuck. Controlling temperature variation in real time is a challenge, and current systems require a number of wires and filters to sense temperatures and change individual zone power within heaters. We tested an ESC with 106 independent heater zones where separate sensor wires were not required and demonstrated that precise control of temperature is possible with only 61 individual wires, with a 53% reduction in temperature range and 59% reduction in temperature variation.
Introduction: The Need for Precise Equipment Temperature Control

Semiconductor fabrication demands a high level of control of process parameters related to equipment temperature. This is especially true when it comes to temperature uniformity of the electrostatic chuck (ESC, or simply “chuck”), which plays an important role in adsorbing and cooling/heating of wafers. Indeed, one of the primary functions of a chuck is to provide an acceptable level of temperature uniformity so that the system yields consistent results.

That said, thermal gradients do occur as a result of non-uniform heat input from heating elements and heat transfer between the system and the surrounding environment.¹ For example, heat loss at the edge of the plate is not uncommon, creating unfavorable temperature uniformity.²

We set out to demonstrate that, with the appropriate control systems, it is possible to measure and control temperature differences at a small scale, in real time. This allows temperature corrections to be made “on-the-fly,” removing the need for pre-run setup and eliminating waste in the process.

Current Approaches to Temperature Control

In many fabrication processes, ESCs are divided into a number of zones, each with its own heater elements. Thus, adjustments can be made by changing the power set points of each zone. But fine-tuning the temperature of each zone in order to get a uniform temperature across the ESC surface occurs by something of trial-and-error: A process qualification wafer is sent through the process, and based on the measurements of this wafer, adjustments are made to the system by altering the power set points for each zone. The process repeats until an acceptable wafer is being produced consistently.

Not only is this procedure wasteful during process setup, but it can also run into problems if there are any changes to boundary conditions during the process itself. For example, a change in temperature in one part of the chuck will likely go unnoticed until a number of wafers come back that do not meet standards or that are suboptimal. Then the calibration procedure will need to be repeated, wasting more time and resources.

One way to improve this process is to embed sensors into the chuck to record temperature in several regions, preferably in as close to real time as possible. While this is a step in the right direction, there are currently some limitations. For one, additional sensors require additional wires, which adds to the complexity of the system: These wires take up space and require design considerations for countering any thermal shunting effects.

Furthermore, these sensors must attach to a controller that can adjust the heating elements on-the-fly as well, to create the kind of closed-loop in-situ temperature feedback needed to achieve uniform temperature over time.³

This is exactly the kind of system we set out to test, but using the same wires for heating, sensing and control.

³ We note here that there are other approaches currently being tried to achieve uniform temperatures, such as planar heating elements. See Dong-Hyeok Im, Woo-Sig Min and Sang-Jeen Hong. “Planar heating chuck to improve temperature uniformity of plasma processing equipment.” Japanese Journal of Applied Physics, Volume 59, April 2020, The Japan Society of Applied Physics. Note that these approaches do not improve control, but rather suggest optimal chuck design based on thermal-electrical simulation analysis.
Set-Up and Testing of the System

We devised an ESC with 106 independent zones, with 61 externally run wires (see Figure 1). These were then connected to a controller for monitoring and controlling the temperature of the chuck in real time. An IR camera was positioned above the chuck to take measurements of surface temperature.
Each of the 106 zones in this system can be controlled independently. No secondary sensors are present: The system uses information directly from the heater circuitry itself to control temperature variations.

We began testing the system by taking a baseline temperature reading from our IR camera. An example is shown in Figure 2.

The presence of warmer and colder spots, like those shown in the figure, can lead to suboptimal wafer production.

The next series of images shows the same baseline image next to an image of the same chuck taken after the controller has been brought online. The third of the images shows the change in temperature that the controller enabled; this image is generated by subtracting the first image from the second image.

![Figure 2: Baseline temperature for an ESC.](image1)

![Optimized image](image2)

Overall, the system is showing a 55% reduction in temperature range and an overall 59% reduction in temperature variation across the ceramic surface.

To indicate the level of control possible for each zone, we took similar subtraction images under a number of circumstances. Figure 4 shows the degree of independent pixel control possible, varying each neighboring zone in an opposite direction. This shows that temperature changes can be discrete and, in fact, quite different from zone to zone.

![Figure 3: Baseline and optimized ESC temperatures and change in temperature by the controller.](image3)

![Figure 4: Subtraction image showing independent pixel control. Here, the range of power control is 15% and the range of temperature control is +/- 1.7°C. Pixel groupings will yield larger values for range of temperature control.](image4)
We experimented with a number of patterns. Figure 5 shows a radially symmetric picture of temperature change:

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2 MINUS 1 = Symmetric Pattern (20%) Range of Control
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Figure 5: Subtraction images showing independent pixel control, radial pattern.

Changes in temperature need not follow a radial pattern, however. Figure 6 shows axial symmetry—a rough “W” for Watlow.

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2 MINUS 1 = 58 Thermal Zones (20%) Range of Control
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In-situ Testing and Adaptive Response

Demonstrating precise control of an array of heaters is one thing; showing that this mechanism can allow heaters to adapt to changing environmental conditions is quite a step further. We thus ran tests to see if a 106 zone ESC plus a PID controller could adjust temperature across its surface when impinged upon by some disturbance—in this case, a puff of cold air.

The setup can be seen in Figure 7. A series of flexible impingement hoses were attached to a manifold that was positioned just above the ESC. For this test two hoses, positioned opposite from each other, were used to introduce a puff of air at a precise time, effectively cooling the area of the chuck in the path of the air.
With this setup, we tested two conditions: One where a multi-parallel (MP) PID controller was used to monitor the temperatures of the zones and make adjustments to their temperature on-the-fly (before, during and after the delivery of the air), and a control condition where no such adjustments were made. We expected the control condition to register a sustained cooling effect of the air on the ESC, whereas the experimental condition with the PID would adjust the zones as necessary, introducing closed-loop feedback into the system. The results can be seen in Figure 8.

For both control settings, the thermal disturbance is introduced at Time = 5 seconds and remains throughout the balance of the test.
Both rows in the image show IR camera frame grabs indicating the temperature of the chuck surface at three time slices: T=0 seconds, T=15 seconds and T=30 seconds. The puff of air is introduced at 15 seconds. The top row shows the ESC with constant power, i.e. no adjustment from the PID controller. The bottom row shows the ESC with the controller in use.

As can be seen, the temperature drop is much more noticeable in the constant power case, with a 37.5% drop in temperature for the affected zones when the puff of air is introduced. This drop can be seen in the upper right and lower left quadrants of each image—exactly where the air hoses are located. Over time, the temperature drop continues, with an overall 62.5% drop between test start and 30 seconds.

In the PID controlled case, the temperature drop is much less dramatic than for the control. The puff or air only manages to change the zone temperatures by 14.3% when introduced, showing that the controller is responding to the impinging air appropriately. At 30 seconds, the overall change from start is only 28.6%, reflecting a 0.2°C drop.

Figure 9 here shows the time-course for three different variables in the control condition: The average surface temperature of 11 zones chosen at random, the internal filament temperature of the heaters at those zones and the power being supplied to each. As expected, the air disturbance creates a significant and sustained drop in temperature almost immediately, as registered by the IR camera and the internal filament temperature.

Table 1: IR image statistics for the constant power (control) and PID control conditions.
Implications and Further Research

What we have demonstrated here is quite modest but has some important implications for semiconductor fabrication.

There are heated ESCs that have far more temperature zones than the one we have worked with here, which has 106. But we have demonstrated that we can precisely control these zones with minimal wiring (61 external wires). We have also demonstrated that our controller can adjust temperatures on-the-fly, in close to real time, and we have demonstrated that this can be done in response to external disturbances using a closed feedback loop.

This kind of control eliminates the need for expensive calibration runs even while ensuring a higher count of optimal wafers. It also eliminates the need to stop processing in order to make adjustments during a run. The result is much less waste and greater control of the process.

We are continuing to test this system and make improvements. For example, we are looking into systems with multiple layers to enable both coarse and fine temperature control in one system. We also continue to develop the algorithms for the controller, enabling a greater degree of automation in the system. Finally, we are working to bring much of the networking internal to the tool.

Further information is available at: www.watlow.com