Designing Heated Chucks for Semiconductor Processing Equipment

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Abstract

The purpose of this analysis is to achieve thermal uniformity of a heated chuck used for semiconductor processing. Heated chucks are used to initiate or accelerate a physical or chemical reaction. The design of the heated chuck often finds the physical, thermal, chemical, and time-response goals in conflict. In this analysis, you will find how finite element analysis (FEA) combined the selection of heating elements, materials and accessories as well as heat requirements, desired response time, and heat capacity will help you achieve thermal uniformity while satisfying all other functional requirements of the heated chuck.

Initial considerations

Temperature control is a critical factor in most chemical and physical reactions. A well-designed heating source for a wafer chuck will improve the temperature uniformity and stability of the system, and detailed thermal analysis is a key part of the design process.

A typical heat chuck consists of two main parts: a resistive heating element to generate heat, and a metallic plate to distribute the heat uniformly and supply mechanical support for the wafer. The primary goal of a heated chuck is to provide an acceptable level of thermal uniformity so that the processing will yield consistent properties across the entire product. Thermal gradients are caused by non-uniformity of heat input from the heating element to the plate, and by effects of the heat transfer between the plate and its surroundings.

Many parameters enter into the design of the chuck, including:

- plate dimensions and mounting
- plate material
- maximum temperature requirements
- response time
- outgassing and chemical resistance
- type of heating element

This white paper will focus on how these parameters affect thermal uniformity, including how they may affect or limit each other.

Plate dimensions

The size and shape of the plate is second only to the heating element in its practical effect on thermal uniformity. To heat a 300mm silicon wafer, for example, one could simply laminate a uniform watt density etched foil heater to the bottom of a 300mm diameter plate. However, due to the surface area of the peripheral walls, there would be greater heat loss at the edge of the plate. Therefore, the temperature of the plate surface would decrease from the center of the plate to the edge, as shown in Figure 1.

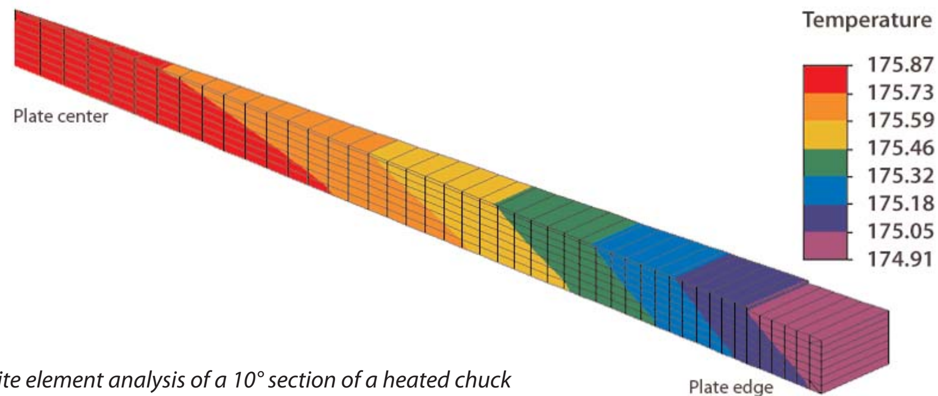


Figure 1: Finite element analysis of a 10° section of a heated chuck with a uniform watt density heater laminated to the bottom surface.

The effect of heat loss from the walls of the plate can be reduced by increasing the diameter of the plate in conjunction with appropriate changes in the heating element.

This in effect moves the cause of the greater heat loss away from the wafer. Figure 2a illustrates, using finite element analysis (FEA), the benefit of using a heater designed to provide optimal thermal uniformity to a 300mm wafer by biasing the heating elements toward the edge. Figure 2b includes the additional improvement of increasing the diameter of the plate, with the wafer in the more uniform center area of the chuck. The results are summarized in Table 1.

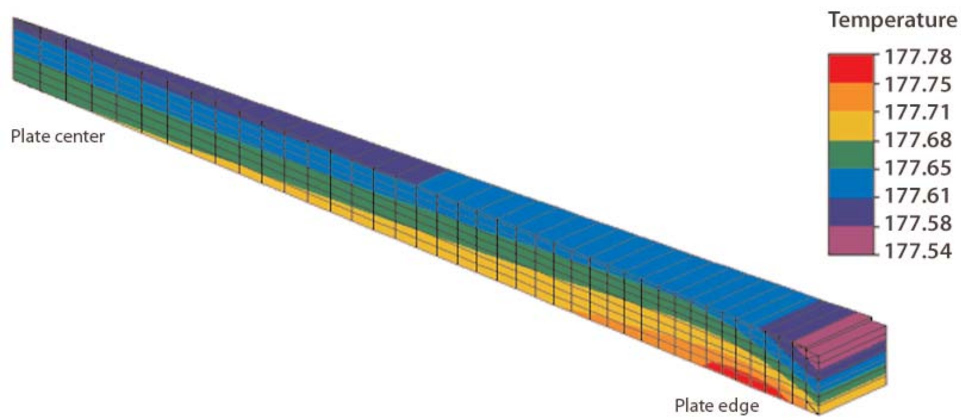


Figure 2a

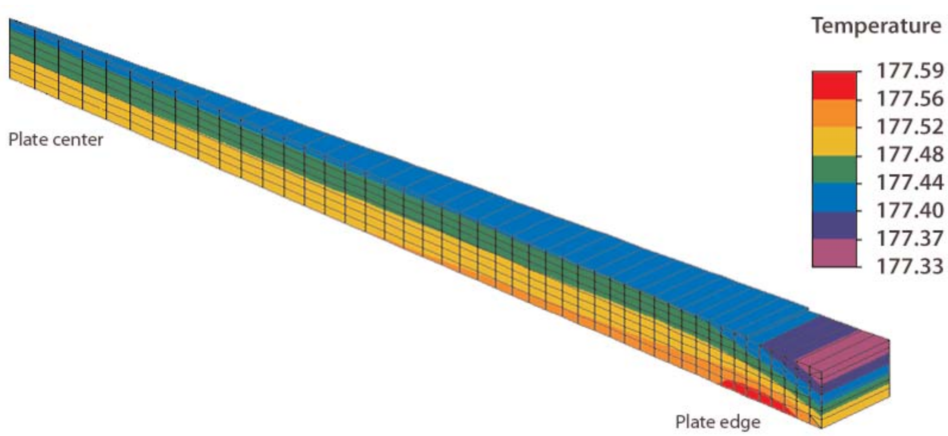


Figure 2b

Figure 2: Finite element analysis of a heated chuck with a profiled watt density heater laminated to the bottom surface of the chuck, with a) a diameter the same as the wafer, and b) a diameter greater than the wafer

Chuck diameter	**Heating element**	**Temperature range on chuck surface under the wafer**
330	Uniform	0.82°C
305	Optimized	0.11°C
330	Optimized	0.04°C

Table 1: Heating element design and chuck diameter

Increasing the thickness of the plate will affect thermal uniformity differently depending on the heating element being used. Increasing the plate thickness increases the cross-sectional area for heat to conduct laterally before it reaches the surface of the plate. This can be beneficial to a point, if the heat input is not uniform or well profiled. However, increasing internal cross-sectional area increases the surface of the plate walls, which contributes to the original problem of elevated heat loss near the edge. Eventually a point is reached where the benefit is outweighed by this drawback. For example, an aluminum plate with a cast-in tubular heater near the surface will have hot spots above the heating element and relatively cold spots between the elements. As the elements get farther from the surface and the plate gets thicker, the cold spots and the hot spots become less evident. However, the heat loss from the walls of the plate increases and the temperature difference from the center of the plate to the edge become more evident. Once the difference from center to edge becomes greater than that between hot and cold spots, increasing plate thickness will be detrimental. In the case of a profiled heater, a thicker plate increases the distance from the heater to the top surface, reducing the benefit because it reduces the ability of the heater to influence the wafer temperature.

System accessories

In addition to the diameter and thickness of the plate, one must consider the requirements for mounting it in the chamber, monitoring its temperature, mating with wafer handling mechanisms, and holding the wafer in position. Each of these accessories will have an effect on either the heat input to the plate or the heat transfer out of the plate. When mounting a heat chuck to a chamber, any paths of thermal conduction to the chamber should be minimized or be of a high thermal resistance. A relative cold spot will form wherever a stand-off is in contact with the plate. If a thermally insulating plate matching the chuck's diameter is used, it will eliminate these cold spots, but it will have the effect of adding heat capacity.

A temperature sensor must also be incorporated into the heated chuck for the monitoring and control of the heating. Generally, a resistive temperature detector (RTD) is embedded into the plate. For the best accuracy, the sensor should be away from the edge of the plate in an area with good thermal uniformity. Again, the sensors will have some effect on the heat transfer throughout the system and consideration should be given to minimizing the thermal conduction out the sensor lead-wires.

Often special fixturing of the chuck is required to make it compatible with loading and unloading mechanisms. These might be stand-offs for wafer support, recesses in the plate surface to allow grippers to get underneath, or holes through which pins may come through to lift the wafer off the surface of the plate. In some cases, an application may require access for vacuum ports on the surface to hold down a wafer, or channels inside the plate for a cooling fluid. All of these accessories will add to the difficulty of obtaining thermal uniformity, and they should be accounted for in modeling or other analysis done to optimize the design.

Plate material and coatings

The choice of plate material will affect thermal uniformity, dimensional stability, and chemical compatibility of the heated chuck. Thermal conductivity of candidate materials vary widely and therefore should be a factor in choosing the plate material. Dimensional stability of the material is also critical, especially when the heated chuck is going to be used at temperatures approaching the softening point of the material. Depending on the ratio of plate diameter to plate thickness, sagging of the plate can occur because of the reduced mechanical stiffness at high temperatures. Stand-offs can be added at strategic locations under the interior of the plate for support, again at the cost of additional heat loss at those points. Also, with relatively low thermally conductive materials, such as stainless steel, warping can occur because of non-uniform expansion due to non-uniform heat distribution.

Finally, consideration has to be given to the compatibility of the plate material to the process and any chemical or physical environment it is likely to be exposed to in its intended use. Bronze, for instance, is not accepted for use in many semiconductor processes because it has the potential of contaminating the wafer. Instead, aluminum is the most commonly used plate material in semiconductor processes. Special chemical and/or abrasive resistant coatings may be added to aluminum plates to improve compatibility. For example, loose aluminum oxide powder can form on the surface of a bare aluminum plate. It can also be easily scratched or marred. Standard anodization will stop the formation of loose powder. To protect the surface from both powdering and scratching, the aluminum can be hard-coat anodized. The anodized aluminum may also be impregnated with Teflon for added wear resistance.

Maximum temperature requirements

The plate material (and the type of heating element, to be discussed later) will depend on the required maximum temperature. Aluminum is a commonly used material because of its good thermal conductivity, processibility, and cost. However, it is limited to applications below 500°C. Stainless steel can handle temperatures up to 650°C, but it has a low thermal conductivity. Bronzes have been used in operations over 800°C and have thermal conductivities two to ten times greater than standard stainless steels.

Response time and heat capacity

The time required for the chuck to come to temperature when it is initially powered up, and the time required for the chuck to recover to its steady state of temperature after a load is introduced, are functions of the heat capacity of the plate, the watt density of the heater, and the coverage of the heater. The heat capacity of the plate is a function of its size and the density of the material. If minimizing response time is critical, then special attention should be paid to these factors. Watt density of the heater specifies the amount of power put into a heater per the surface area of that heater. This is limited by the maximum temperature that the heater materials can withstand and by how well the heater can transfer its heat to the plate. Clearly, the greater the amount of element area per surface area of the plate, the more rapid the heat transfer will be to the plate.

Outgassing

The outgassing of materials is a common problem in vacuum processes. With a heated chuck, the heater element and its mounting could be sources of outgassing, but when properly constructed, polyimide insulated and tubular heating elements should have minimal outgassing. They may require an initial burn-in period to allow surface volatiles acquired during handling to dissipate. Care should be taken in choosing the proper adhesive for mounting a heater to a plate to minimize its effect. Mica insulated and other heaters designed for high-temperature operation generally contain binders that will outgas in a high temperature vacuum environment. In this case, the heater can be hermetically sealed between two plates, with an electrical feed-through used to supply power.

Heating element selection

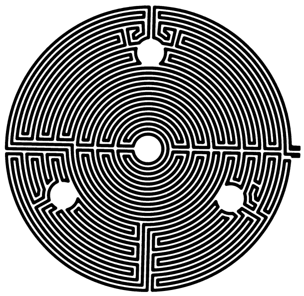
The two most common types of heaters used in heated chuck applications are tubular and etched foil.

A tubular heater consists of a small coiled resistive wire running inside a tube that is filled with a ceramic dielectric material. When current is applied to the wire, it generates heat that is transferred to the ceramic filler and then to the outer tube. Generally, the tubes are formed into multiple loops, similar to the heating element on an electric stove, and cast, swaged, or brazed into aluminum or bronze plates. For reasonable thermal uniformity, the plate containing a tubular heater will have to be significantly thicker than what is required for etched foil heaters. Tubular heating elements can operate up to 1600°F (870°C). The coverage (i.e., the ratio of element surface area to the total heater surface, expressed as a percentage) can vary considerably, with 12% being typical.

An etched foil heater consists of a resistive foil with a pattern etched through it to form a complex, maze-like, current path. This foil is sandwiched between two sheets of adhesive and a dielectric material, such as polyimide or mica. In the case of polyimide, heaters are then laminated to the bottom of the chuck plate. In this situation, the heat has to transfer through 25 µm of adhesive and 50 µm of polyimide (although the construction can vary slightly). Polyimide insulated heaters can operate up to 260°C and can have element coverage up to 75% of the heater surface.

Mica heaters are attached mechanically by bolting them between the chuck plate and a thin metal plate, or they can be hermetically welded inside the plate. With this construction, the heat has to transfer through 250-500 µm of mica before it reaches the plate. Mica insulated heaters can operate up to 600°C and have element coverage of about 45% of the heater surface.

The foil patterns for both polyimide and mica can be generated in conjunction with FEA. The need for FEA is dependent upon the complexity and thermal uniformity requirements of the final product. The CAD-generated heater patterns take into account the areas of the plate that have greater heat loss and strategically narrow the current path in those areas, which increases the power input there. Because of this, the plate thickness is generally as thin as possible while still maintaining the necessary mechanical properties of the plate. Figures 3a and 4a show layouts of uniform and profiled heaters, respectively, while Figures 3b and 4b show the resulting temperature distributions during operation. The degree to which thermal gradients will be countered depends on the complexity of the heater profiling. Profiled heaters are commonly designed with 2 to 10 different watt density zones with more possible.



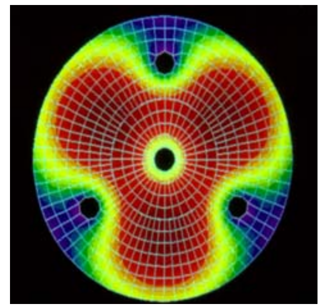
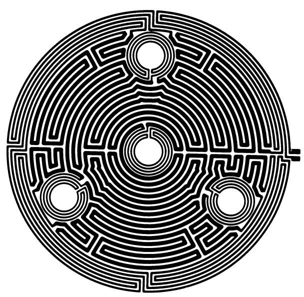


Figure 3a

Figure 3b

Figure 3: The layout of the heating element for a heater that supplies uniform heat and the resulting temperature distribution, derived by FEA.



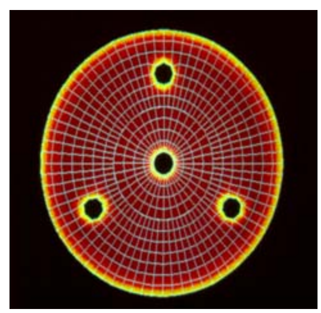


Figure 4a

Figure 4b

Figure 4: The layout of the heating element for a heater that supplies profiled heat and the resulting temperature distribution, derived by FEA.

Summary

When designing a heated chuck for a specific vacuum process, many factors must be considered and balanced against each other to obtain the optimal properties. Generally, the goal is to obtain the best possible thermal uniformity while satisfying all other functional requirements for the plate. Detailed thermal analysis integrated with the design process can make a polyimide-insulated, etched foil heater a good choice for providing thermal uniformity and a fast time response for applications below 260°C. For higher temperature applications, a mica insulated, etched foil heater designed with the same approach is appropriate.

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