Principles of Electrostatic Chucks

4 — Chuck Thermal Transport

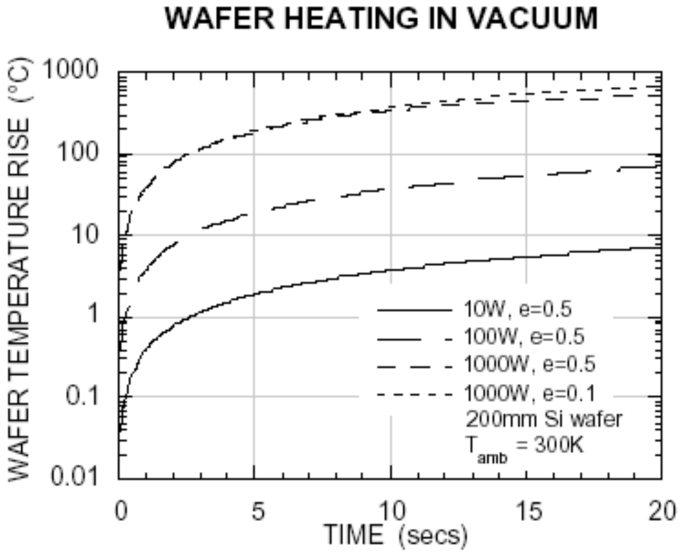
Overview

Electrostatic chucks with accurate thermal control can increase processing rates in microfabrication processes and improve yields. Electrostatic clamping, with or without gas backside feed, can hold substrate temperature low or even control substrate temperature significantly above that at the chuck surface with appropriate design.

Radiative and gas-assisted thermal transport are described here. Thermal edge effects due to wafer overhang are described in our "rf chuck edge design" document.

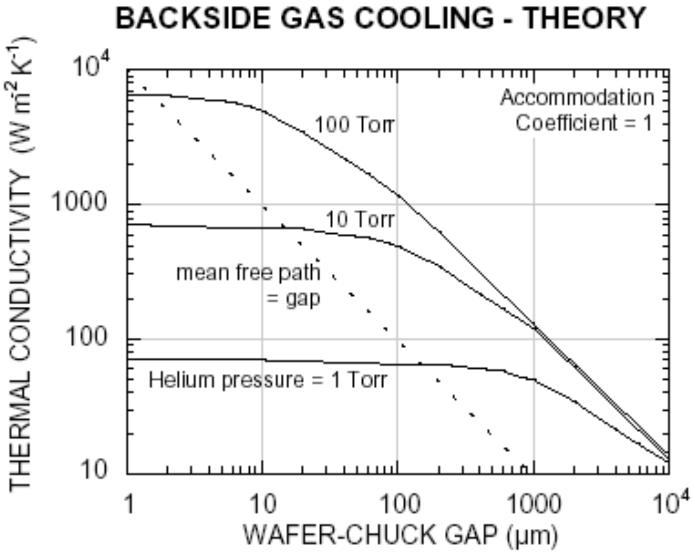
Vacuum Thermal Transport

Heat transfer may be by convection, conduction or radiation. At the low pressures of typical plasma processes, even on pressurised wafer backsides, convective transfer of heat via gas flow is negligible compared to the other two processes. This section describes radiation, and the following section gas conduction. Direct solid-solid contact is also relevant and will be mentioned in the gas conduction section and the conclusion.



The power radiated from a body of area A and emittance e (allowable range: 0 to 1) at temperature T (K) is $P = A\, e\, \sigma\, T^4$ where $\sigma = 5.67\ 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$, the Stefan-Boltzmann constant. The radiation absorptance of a body at a given wavelength is equal to its emittance, resulting in the following net power flow from a body at T to an enclosure of emittance = 1 at a lower temperature T_0; $P_{net} = A\, e\, \sigma\, [\, T^4 - T_0^4\,]$. In general emittances are a function of temperature and processing conditions.

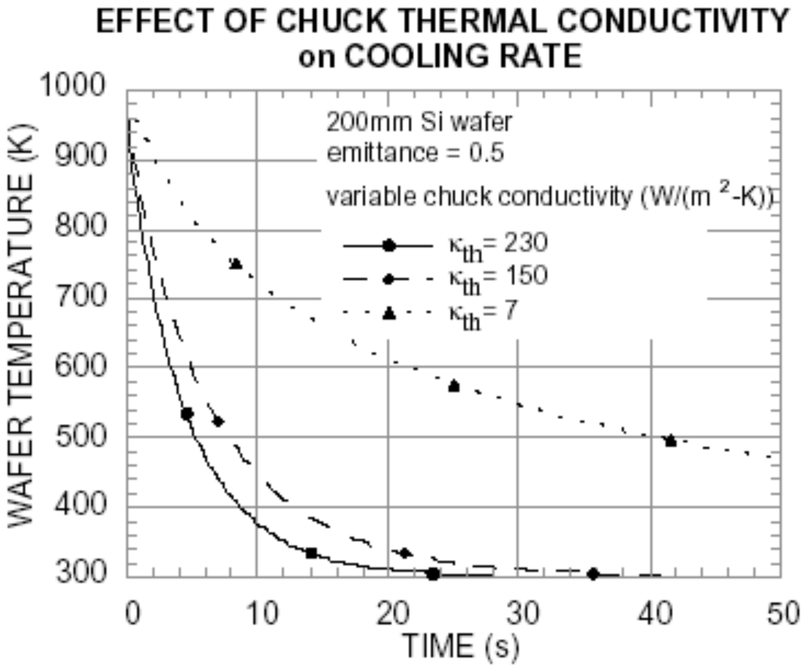
If a Si wafer resting on a 25°C rf target is exposed to plasma power, the initial rate of temperature rise will be controlled by wafer heat capacity, and the maximum attainable temperature will be set by the above radiation formula. This ignores radiation from the plasma and neutral heating, which are generally much smaller than the ion bombardment power incident on the target wafer surface. The figure above shows typical results, with radiation only having an effect at the highest temperatures, as evidenced by the curves for differing emittances at 1000W power input. Radiation in plasma processes can only be expected to play a minor role in temperature control.

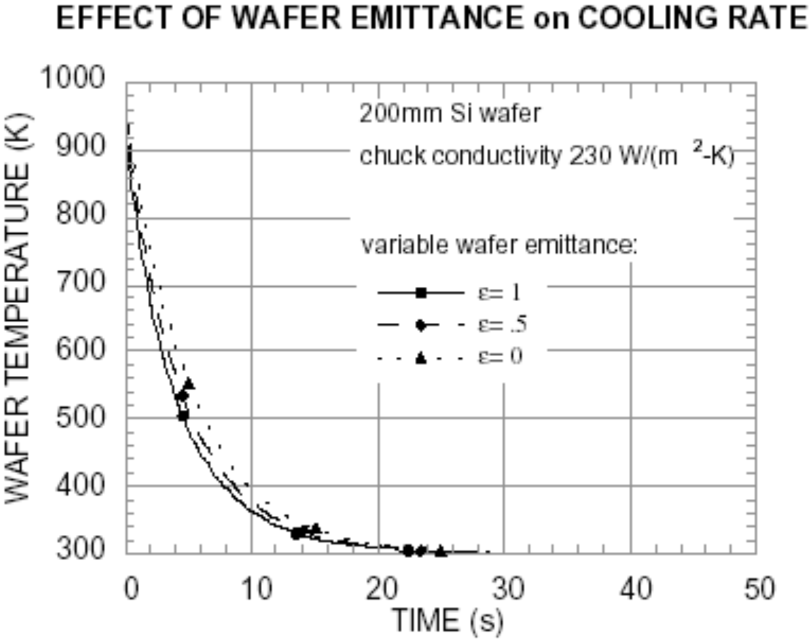


Gas Thermal Conduction; Theory

Gas molecules bounce between substrate (wafer) and chuck surface, transferring energy between the surfaces. This energy transfer is most efficient when three criteria are satisfied:

- *Accommodation*: Gas molecules should spend time migrating on the surfaces to randomise their velocity. The surface accommodation coefficient is 1 when this randomising is complete, and 0 when molecules bounce off elastically without energy transfer between surface and molecule. A typical value of this coefficient is 0.3 for Si wafers on rf chucks.
- *Gas collisions*: Gas molecules should travel without collision between the surfaces, so that energy is not returned to the surface that it came from. Thus the mean free path between collisions should be greater than the gap between surfaces. Hence high gas pressure requires a small gap for most efficient heat transfer.
- *Pressure and type*: Gas molecules should be plentiful and fast-moving. Hence a high pressure of a light gas such as He or H2 will provide the best cooling. The graph above on the prior page illustrates gap-pressure interactions predicted for He gas. The effect of He gas additions on the cooling of a wafer from 1000K (700°C) to room temperature can be gauged from the graphs here.


EFFECT OF CHUCK THERMAL CONDUCTIVITY on COOLING RATE


EFFECT OF WAFER EMITTANCE on COOLING RATE

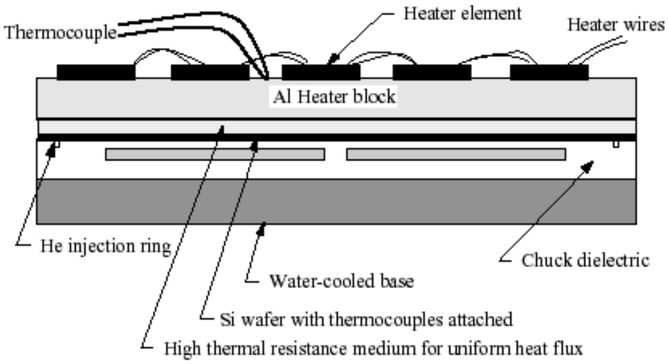
The κ_{th} parameter in these curves is the chuck thermal conductivity to be discussed in the following section, and is high when gas backpressure is present. The wafer is assumed to be held on a room-temperature chuck. In the presence of gas cooling clearly there is a relatively small radiative contribution.

Gas Thermal Conduction; Experiment

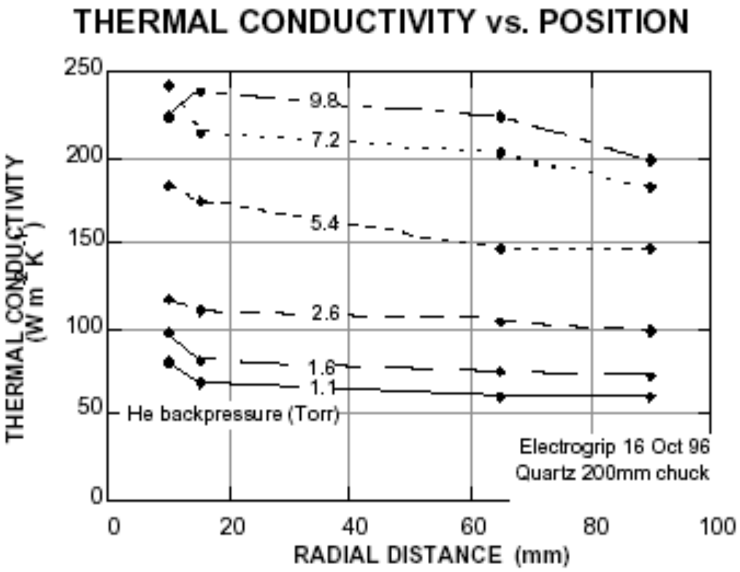
Two methods of thermal transport measurement are:

Transient; a heated substrate with attached thermocouples is clamped to a chuck. Gas is injected suddenly between substrate and chuck. The substrate rate of temperature decay can yield, after deconvolving the separate exponential decay terms, the thermal transfer rates of gas gap, chuck surface layer, and its backing plate. This method could yield the most complete information with high accuracy transient temperature measurement.

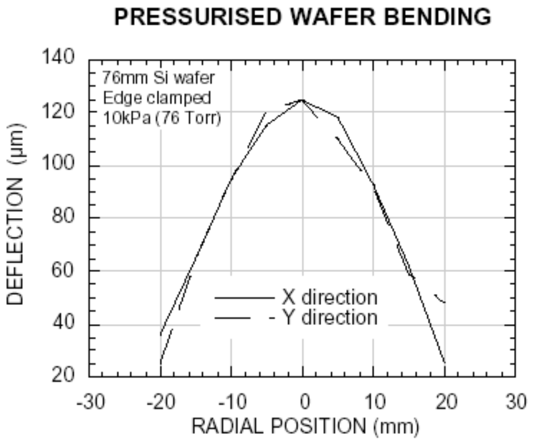
Static; the steady-state temperature difference between a heated substrate clamped on a chuck and cooling water is measured. This method yields the total thermal transfer rate of the complete assembly, and is used by Electrogrip as shown across. The top thermocouple shown is used as a heater check; other thermocouples across the substrate wafer surface are used for the temperature difference measurements. Thermal conductivity κ_{th} is quantified in units of W m^{-2} K^{-1}, as an area-based thermal conductivity. For a given chuck κ_{th} value, the temperature difference (°C) between a substrate and chuck coolant line is $[T_s - T_c] = P_{rf} / [\kappa_{th} A]$ where P_{rf} is the true plasma or ion beam power on the substrate, and A the substrate area.



An early measured result is shown to the right for an older-model quartz Electrogrip chuck operating in the low grip pressure 'Coulombic' regime, and shows an asymptotic heat transfer level at zero He pressure. This is probably is caused by solid-solid contact and would increase with increasing grip pressure. The measurement error size is roughly 20 W m^{-2} K^{-1} at high He pressures, so the crossed curves in the top left of the figure may not be significant. Thermal transport appears to be uniform within about 40 W m^{-2} K^{-1} at high He pressures. The lower values are at the outer edge, where there is an uncooled Si wafer overhang. In addition lower cooling is expected in the chuck sealing ring, due to its He pressure gradient from the backside fill pressure to vacuum.



Mechanical Clamping



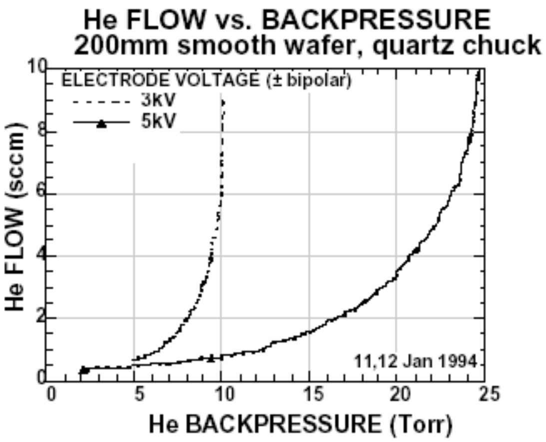
When a substrate is supported only around its edge, gas backpressure results in substrate bow. Thermal and rf contact are maintained across the wafer surface if the chuck surface has at least this degree of convex bow.

For a circular substrate of thickness t (mm), radius R (mm), with simply supported edge and exposed to a pressure P (Pa), the maximum tensile stress in the plate S (Pa) is given by; $S = [0.39\ \pi\ ]\ [\ P\ R^2\ ]\ /\ t^2$. Note the rapid increase with radius. The maximum deflection of this plate is given by d (mm) where E is the modulus of elasticity (Pa); $d = [\ 0.221\ \pi\ ]\ [\ P\ R^4\ ]\ /\ [\ E\ t^3\ ]$. The figure to the right shows bow of a 38mm radius Si wafer. *Ideal contact* to Si wafers yields the highest rf and thermal uniformity, requiring dome asymmetry due to differing Si crystal plane moduli. Simple domes result in wafer stress concentrated in a line across wafers.

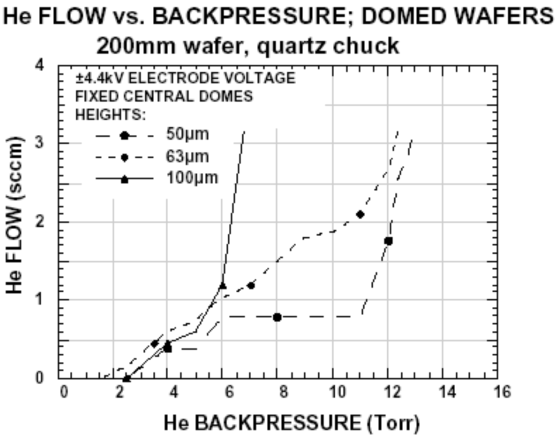
Size limit before breakages for Si wafers is approximately 150mm; and smaller for GaAs.

Gas Retention in Electrostatic Chucks

Some chucks have electrostatic gripping electrodes extending over the entire substrate (wafer) backside for the highest grip force. Tripolar designs such as those available from Electrogrip encapsulate the gripping electrodes, which in some designs leaves the outer substrate rim ungripped. Backpressure then causes substrate lifting and higher gas leakage. Lifting of only 2µm around a 200mm dia. wafer will typically raise leak rates by 10sccm of He. Hence gas leakage rates are very sensitive to the quality of contact between substrate and chuck. Newer Electrogrip chucks have typ. 0.1sccm leakage at 20 Torr pressure. Data for an early-model 200mm Electrogrip chuck operated in the ‘Coulombic’ low grip pressure regime is shown here. For the 5kV curve the rapid leakage rise above 15Torr He backpressure indicates wafer edge peel. The wafer has not blown ("popped") off, but its edge has lost intimate contact.



The effect of particles under a wafer may be studied similarly. The figure to the right shows how the performance shown in the previous figure alters with rising thicknesses of a 30mm dia. "particle" of packing tape. Note that in order to attain edge sealing, the wafer is electrostatically deformed around the central ‘particle’. Such deformation is possible with chucks that have thick dielectrics, operating in the kV grip voltage range, rather than at the 100V level. While the data above indicates a high tolerance of particles in Electrogrip chucks, a particle at the edge of any chuck will cause unacceptably high He leakage.



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