EE-527: MicroFabrication

Thermal Processing Systems
Outline

• Principles of heat transfer
• Temperature controllers
• Hot plates
• Box ovens
• Vacuum ovens
• Tube furnaces
• Induction furnaces
• Rapid thermal processors (RTPs)
Heat Transfer

• Heat (thermal energy) can be transferred in three ways:
  – Conduction: heat flux is proportional to $\Delta T$,
  – Convection: heat flux is proportional to $\Delta T$ and $v$, and
  – Radiation: heat flux is proportional to $T^4$.

• All three mechanisms occur to varying extents in any thermal process.

• All three mechanisms can be developed into useful methods for thermal processing in microfabrication.
Heat Conduction

• Fourier’s Law: \( q = -\kappa \nabla T \)
  
  \( q = \) heat flux [W/cm\(^2\)]
  
  \( \kappa = \sigma_T = \) thermal conductivity [W/cm-\(^\circ\)C]
  
  \( T = \) temperature [K or \(^\circ\)C]

• Thermal energy density: \( E_T = \rho C_p T \) (assumes that \( C_p \) is constant)
  
  \( \rho = \) mass density [g/cm\(^3\)]
  
  \( C_p = \) heat capacity at constant pressure [J/kg-\(^\circ\)C]

• 1\(^{st}\) Law of thermodynamics: conservation of energy; continuity:

\[
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot q = G(x, y, z, t)
\]

• Conduction of heat:

\[
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-\kappa \nabla T) = G(x, y, z, t)
\]
Heat Convection

• With a moving medium:
  – \( \mathbf{u} = \) velocity vector of medium

  \[
  \mathbf{q} = -\kappa \nabla T + \rho C_p T \mathbf{u}
  \]

• Conduction and convection of heat:
  – \( \rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-\kappa \nabla T) + \rho C_p \mathbf{u} \cdot \nabla T = G(x, y, z, t) \)
    – Both are driven by temperature gradients, \( \nabla T \).

• Accurate analysis of convection involves the fluid mechanics of either liquids or gases.

• Most models of convection attempt to reduce the heat transfer to an equivalent thermal resistance for conduction.

• Example: Free air convection cooling of a finned aluminum heat sink:
  – Empirical thermal resistance of the heat sink to the ambient air:
  – \( \theta_{ha} = 0.5 \) to \( 5.0 \) °C/Watt for a 3-inch square aluminum heat sink.
Heat Radiation

• Planck’s black-body radiation formula: energy spectral density

\[ u(\nu, T) = \frac{8\pi h \nu^3}{c^3} \frac{1}{e^{h\nu/k_B T} - 1} \quad \left[ \frac{J}{m^3 \cdot Hz} \right] \]

\[ u(\lambda, T) = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{hc/\lambda k_B T} - 1} \quad \left[ \frac{J}{m^3 \cdot m} \right] \]

\[ I(\lambda, T) = \frac{c}{4\pi} u(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda k_B T} - 1} \cos \theta \quad \left[ \frac{W}{m^2 \cdot sr \cdot m} \right] \]

• Differentiating with respect to \( \lambda \): Wien displacement law:

\[ \lambda_{\text{max}} T = \frac{hc}{4.965 k_B} = 2.90 \times 10^{-3} \text{ m} \cdot \text{K} \]

• Integrating over all wavelengths: Stefan-Boltzmann law:
  – \( \varepsilon \) = surface emissivity [dimensionless], \( 0 < \varepsilon < 1 \).
  – \( \sigma \) = Stefan-Boltzmann constant
  – \( A \) = surface area [m²]

\[ P = \varepsilon \sigma A T^4 \cos \theta \quad \sigma = \frac{2\pi^5 k_B^4}{15c^2 h^3} = 5.6704 \times 10^{-8} \frac{W}{m^2 \cdot K^4} \]
Incandescent objects have blackbody spectra which peak around $\lambda = 1.0 – 2.0 \ \mu \text{m}$ in the near infrared.

This spectra overlaps the visible range, so incandescent objects appear red or orange in color.

The quartz, tungsten, and nichrome heaters used in rapid thermal processors and annealing ovens usually fall into this range.
Room temperature objects have blackbody spectra which peak around \( \lambda = 10.0 \, \mu m \).
Thermal Circuit Analogs

- Many thermal systems can be conveniently and rigorously modeled by circuit analogs.
- Circuit theory can then be used to analyze the system and predict the dynamics.

<table>
<thead>
<tr>
<th>Electrical Domain</th>
<th>Thermal Domain</th>
</tr>
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<tbody>
<tr>
<td><strong>Quantity</strong></td>
<td><strong>Symbol</strong></td>
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<tr>
<td>Charge</td>
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<tr>
<td>Potential</td>
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<tr>
<td>Current</td>
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<td>Resistance</td>
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<tr>
<td>Capacitance</td>
<td>C</td>
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<td>Inductance</td>
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<td><strong>Quantity</strong></td>
<td><strong>Symbol</strong></td>
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<tr>
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<td>Heat Flow</td>
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<td>Resistance</td>
<td>θ</td>
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<tr>
<td>Capacitance</td>
<td>C</td>
</tr>
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</table>

\[
I = \frac{dQ}{dt}
\]
\[
V = IR
\]
\[
Q = CV
\]
\[
P = \frac{dQ}{dt}
\]
\[
T = P \theta
\]
\[
Q = CT
\]
Modeling of a Thermally Conductive Layer Stack

- Many situations can be modeled by thermal circuit analogs.
- Example: one-dimensional heat flow through a three layer stack of materials:

\[ \begin{align*}
\theta &= \frac{d}{\sigma_T} \quad [\text{cm}^2\text{C/W}] \quad \text{thermal resistance per area} \\
C &= \rho C_p d \quad [\text{J/cm}^2\text{C}] \quad \text{thermal capacitance per area} \\
\tau &= \theta C \quad [\text{sec}] \quad \text{thermal time constant}
\end{align*} \]
Distributed Versus Lumped Elements

- Diffusive processes, such as conductive heat transfer, normally required distributed circuit models.
- Lumped element approximations become increasingly more accurate when either the resistance or capacitance element predominates over the other.
- Various techniques exist for dividing the distributed elements between the two nodes:
Modeling of a Thermal Chuck

Maximum ramp rate:
\[ \frac{P_e}{(C_h + C_b)} \] [^\circ C/\text{sec}]

Final temperature:
\[ T_w = T_a + P_e \theta_{wa} \] [^\circ C]

Cooling time constant:
\[ (C_h + C_b)(\theta_{bw} + \theta_{wa}) \] [sec]

Silicon:
- CTE = 2.6 ppm/^\circ C
- \( \sigma_T = 150 \text{ W/m} \cdot ^\circ \text{C} \)
- \( C_p = 700 \text{ J/kg} \cdot ^\circ \text{C} \)
- \( \rho = 2.33 \text{ g/cm}^3 \)
Open Loop Hot Plate Temperature Scaling

\[ T_2 = T_a + (T_1 - T_a) \frac{\theta_{2a}}{\theta_{12} + \theta_{2a}} \]

scale factor \( \frac{\Delta T_2}{\Delta T_1} = \frac{\theta_{2a}}{\theta_{12} + \theta_{2a}} = \frac{5}{7} \)

ambient: \( T_a = 25 \text{ C} \)

<table>
<thead>
<tr>
<th>Set ( T_1 )</th>
<th>Get ( T_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 C</td>
<td>25 C</td>
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<tr>
<td>60 C</td>
<td>50 C</td>
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<tr>
<td>95 C</td>
<td>75 C</td>
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<tr>
<td>130 C</td>
<td>100 C</td>
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<td>165 C</td>
<td>125 C</td>
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<td>200 C</td>
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<td>235 C</td>
<td>175 C</td>
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<td>270 C</td>
<td>200 C</td>
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<td>305 C</td>
<td>225 C</td>
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<tr>
<td>340 C</td>
<td>250 C</td>
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<tr>
<td>375 C</td>
<td>275 C</td>
</tr>
<tr>
<td>410 C</td>
<td>300 C</td>
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</table>

\( \Delta T_1 = 35 \text{ C} \quad \Delta T_2 = 25 \text{ C} \)

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Simple Unloaded Heater Block Transfer Function

- A single pole system.
- The thermal time constant is $\tau = \theta_{ba} C_b$, [sec].
- The transfer function is:

$$\frac{T_b - T_a}{P_e} = \frac{\theta_{ba}}{1 + s \theta_{ba} C_b} = \frac{\theta_{ba}}{1 + s \tau}$$
Heater Block with Thermal Payload Transfer Function

- If $\theta_{bs}$ is significant, a two-pole system results.
- The transfer function becomes:

$$\frac{T_b - T_a}{P_e} = \frac{\theta_{ba} \left( \theta_{bs} + \theta_{sa} + s \theta_{bs} \theta_{sa} C_s \right)}{\theta_{ba} \left( 1 + s \theta_{sa} C_s \right) + \left( 1 + s \theta_{ba} C_b \right) \left( \theta_{bs} + \theta_{sa} + s \theta_{bs} \theta_{sa} C_s \right)}$$

$$\frac{T_s - T_a}{P_e} = \frac{\theta_{ba} \theta_{sa}}{\theta_{ba} \left( 1 + s \theta_{sa} C_s \right) + \left( 1 + s \theta_{ba} C_b \right) \left( \theta_{bs} + \theta_{sa} + s \theta_{bs} \theta_{sa} C_s \right)}$$

A common laboratory situation:
A glass beaker on a hot plate.
Temperature Control

• Open loop:
  – Constant electric power or voltage is applied to a heating element.
  – No feedback of actual temperature.
  – Usually delivers constant power to the sample; does not maintain a constant temperature unless the heat loss rate is constant.

• Closed loop:
  – A temperature sensor is used to provide feedback and adjust the electrical power input to keep the temperature of the sample at a given set point.
  – “bang-bang” control: heater power is simply turned off when the set point temperature is reached, usually with some hysteresis to avoid chatter.
  – P control: simple proportional feedback
  – PI control: proportional + integral feedback
  – PID control: proportional + integral + derivative feedback
Feedback Temperature Controller

ELECTRICAL DOMAIN

V_{SP} --> controller --> V_C --> driver --> P_E --> heater --> T_O

V_{FB} --> sensor --> V_S

THERMAL DOMAIN

signal conditioner
PID Temperature Controllers - 1

\[ V_{SP} \rightarrow \text{controller} \rightarrow V_C \]

\[ V_{FB} \rightarrow \text{controller} \rightarrow V_C \]

\[ V_{SP} \rightarrow + \rightarrow V_E \]

\[ V_{FB} \rightarrow - \rightarrow V_E \]

\[ K_p \]

\[ K_i \int \frac{dt}{dt} \]

\[ K_d \frac{d}{dt} \]

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PID Temperature Controllers - 2

• Thermal time constants are normally long compared to electrical response times, so the driver, sensor, and signal conditioner respond instantaneously in the context of the heating element.

• Transfer functions of each block:
  – PID controller: $V_C = (K_P + K_I s^{-1} + K_D s)(V_{SP} - V_{FB})$
  – driver: $P_E = I_S V_C$
  – heater: $T_O = P_E \theta / (1 + s\theta C)$
  – sensor: $V_S = k_S T_O$
  – signal conditioner: $V_{FB} = AV_S$

• Closed-loop response function:

$$\frac{T_O}{V_{SP}} = \frac{\left(K_P + K_I s^{-1} + K_D s\right)I_S \frac{\theta}{1 + s \theta C}}{1 + A k_S \left(K_P + K_I s^{-1} + K_D s\right)I_S \frac{\theta}{1 + s \theta C}}$$
PID Temperature Controllers - 3

• Proportional-only control: $K_I = K_D = 0$:
  – Retains a single-pole response, so the system is unconditionally stable.
  – Exhibits a loop error: $V_E = V_{SP} - V_{FB}$
  – Since the overall loop gain is limited for a heating system, the loop error can be significant, and it grows with increasing temperature set point.

• Closed-loop response function and error:

\[
\frac{T_O}{V_{SP}} = \frac{K_P I_S \theta}{1 + A k_s K_P I_S \theta + s \theta C}
\]

\[
\frac{V_E}{V_{SP}} = \frac{1}{1 + A k_s K_P I_S \theta + s \theta C}
\]
• PI control: $K_D = 0$:
  – The integral term reduces the residual error to zero.
  – This produces a 2-pole system, whose damping must be adjusted.
  – The response can overshoot, ring, or undershoot, depending on the damping.
• Closed-loop response function:

$$\frac{T_O}{V_{sp}} = \frac{K_I I_s \theta + K_P I_s \theta s}{Ak_s K_I I_s \theta + \left(1 + Ak_s K_P I_s \theta \right)s + \theta C s^2}$$

• Critical damping ($\zeta = 1$) is achieved by setting:

$$\left(1 + Ak_s K_P I_s \theta \right)^2 = 4Ak_s K_I I_s \theta^2 C$$

• This produces two equal, real-valued, negative poles.
• The parameters of the left-hand side can be empirically determined by setting $K_I = 0$ and measuring the response of the system.
• PID control: the general case:
  – This creates a 3-pole system when the heater is a 1-pole response function.
  – This provides greater flexibility of the control loop, but at the expense of more complicated tuning.
  – The derivative term is used to create greater control output when the input set point changes quickly, allowing the control loop to respond faster than waiting for the measured output to lag behind the set point.
  – Too much $K_D$ (over anticipating the input change) usually will produce underdamped ringing, or worse, sustained oscillations.
  – Careful controller loop tuning is therefore required.
• Unless fast response is a premium requirement, most thermal chucks can be adequately controlled by simple PI controllers which are stable, but may require only damping adjustment.
PID Controller Time Constants

- Standard industrial form for a PID controller:

\[ V_C = K_P \left( e(t) + \frac{1}{T_I} \int_0^t e(\tau) d\tau + T_D \frac{d}{dt} e(t) \right) \]

- Relations between PID coefficients and time constants:
  - Loop error = \( e(t) = V_{SP} - V_{FB} \)
  - Integration time constant = \( T_I = \frac{K_P}{K_I} \) [sec]
  - Derivative time constant = \( T_D = \frac{K_D}{K_P} \) [sec]
  - Controller gain = \( K_P \)
PID Temperature Controller Tuning

• Ziegler-Nichols method: (a classical control technique)
  - Set $K_i = K_d = 0$ and increase $K_p$ to the value $K_u$ where system oscillations begin. $P_u$ is the oscillation period at this point.
  - Then set the PID coefficients, depending upon the type of the controller:

<table>
<thead>
<tr>
<th></th>
<th>$K_p$</th>
<th>$K_i$</th>
<th>$K_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P controller</td>
<td>$0.50 K_u$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PI controller</td>
<td>$0.45 K_u$</td>
<td>$1.2 \frac{K_p}{P_u}$</td>
<td>0</td>
</tr>
<tr>
<td>PID controller</td>
<td>$0.60 K_u$</td>
<td>$2.0 \frac{K_p}{P_u}$</td>
<td>$\frac{K_p P_u}{8}$</td>
</tr>
</tbody>
</table>

• These values generally produce a good balance of bounded output, stability, regulation, and command tracking.
Peculiarities of Temperature Controllers

• Resistive heating elements are fundamentally nonlinear!
  – Reversing the voltage polarity on a heating element does not produce cooling. This nonlinearity at the origin causes a great deal of grief in properly tuning PID temperature controllers.
  – One exception to this are thermoelectric elements which both heat and cool. But their efficiency is so low (~2-3%) that they are not commonly used for thermal processing.
  – There will exist different time constants for heating and cooling.
  – Dual mode temperature controllers employ independent PID loops for heating and cooling to address this.
  – Switching between the two PID loops is simply based upon the set point temperature going up or down.
  – But, the two PID loops must be adjusted to provide a smooth transition between heating and cooling.
Advanced Temperature Controllers

• Cascaded controllers:
  – These involve two PID loops, an outer one controlling the inner one.
  – The setpoint for the inner PID loop is the controlled output of the outer PID loop.

• Feed-forward controllers:
  – If the system is known sufficiently well, the proper controller output change to produce a desired controlled variable change can be directly sent to the actuator.
  – These have the inherent advantage of absolute stability, since there is no feedback, and potentially faster response.
  – These have the inherent disadvantage that if the system response changes, e.g. a change in thermal loading, the controller never knows about it, and cannot compensate.
Commercial OEM PID Temperature Controllers

• Usually include input signal conditioners for TC or RTD inputs.
• Standard outputs:
  – Relay closure
  – Digital pulse, typically 12-15 VDC
  – 4-20 mA current loop level
• External solid-state relays (SSRs) or thyristors are used for the heating element drivers.
Hot Plates

- The simplest and most common laboratory method for heating.
- Maximum temperatures of ~500°C.
- Aluminum or ceramic (porcelain) tops.
- Often integrated with an immersion probe for improved temp control of liquids.
- Often integrated with a magnetic stirring motor.
  - Typically, 50 to 1200 rpm.
  - Magnetic stirring bars must be separated from parts to avoid breakage.
  - Use a drop-in basket or tray to suspend the parts above the path of the stirring bar.
- Hazards:
  - High temperature ignition source for fires.
    - Flammable solvents and hot plates do not mix!
  - Burns to hands.
    - Be careful and be aware of what the hot plate is doing!
Hot Plate Styles

immersion probe setup

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Conductive Heat Transfer on Hot Plates

- For heating wafers on hot plates, uniform and rapid heating requires good thermal conductivity at all points on the back side of the wafer.
- While thermal greases and oils are often used to promote conductive heat transfer, all wafer hot plating is performed DRY.
- Dry conductive heat transfer requires extremely flat and clean surfaces.
- Aluminum foil, which is commonly placed over hot plates as a protective covering, is too wrinkled to provide good heat transfer.
- A polished glass, aluminum, or stainless steel block is used over the foil to provide the flat conductive surface for hot plating.
- Note that excess photoresist on the back side of a wafer should be removed to keep the wafer from becoming glued down to the hot plate.
- Note that the surface of the hot plate is not the temperature that is being controlled by the thermostat – use a calibrated surface thermometer to check the hot plate surface and find the correct setting to produce the desired surface temperature.
Heating Mantles

- Used for heating laboratory glassware, most commonly closed-top vessels with standard taper (ST) ground glass fittings.
- Preferable when a volatile liquid must be heated, or in other situations where the vapor must be retained.
- Commonly used in distillation apparatus and steam boilers.
- Must be sized to the flask being used.
- Must be used with a power controller or variac.
  - Never directly connect to 120VAC line power!
Heating Mantle Steam Bubbler for Oxidation Furnace

- This system uses standard taper glassware with teflon valves and tubing connections.
- Note temperature sensor in the thermometer well for closed-loop control of water temperature.
- The bypass line around the bubbler allows both wet and dry oxidation to be performed using the same furnace tube system.
Box Furnaces

- An electrically heated ceramic enclosure, usually with a drop-open front door, similar to a small kitchen oven.
- Maximum temperatures up to ~1200°C; some up to ~1700°C.
- Also known as “muffle” furnaces.
- Units with built-in gas flow systems are known as “ashing” furnaces.
- Internal capacities vary from ~4 inch to ~14 inch cubes.
- Most have simple PID closed-loop temperature controllers.
- Once the door is closed, the internal cavity soon becomes isothermal because of convective mixing flows of the air inside.
Box Furnace Styles
Vacuum Ovens

- Similar to a box oven, but with a door seal and vacuum and leak ports.
- Usually connected to a rotary-vane mechanical pump, so the best vacuum is only ~10 millitorr.
- Useful for heating samples within a reduced oxygen environment.
- Excessive vacuum and heating profiles can produce solvent burst effects in thin films like photoresist.
  - Trapped solvent rapidly vaporizes and blows out craters in the film.
Tube Furnaces

- The industry standard for achieving processing temperatures in the range of ~800 to 1200°C with tight control of temperature and gas flows.

- Horizontal style
  - Traditional, most common for laboratory R&D work.
  - Multi-tube stacks (4 ea.) were very common for production work.

- Vertical style
  - Newer technology, most common for IC production.
  - Better suited for larger wafers sizes (> 200 mm).

- Both use electrically heated furnace blocks that surround a quartz (fused silica) tube.
Small Laboratory Clam-Shell Tube Furnace

- 3-zone: 6 in / 12 in / 6 in, up to 1200°C in each zone.
- 2 in diameter fused silica tubes with ground & tapered end caps.
- N₂ gas flow system, 0 to 20 SCFH (Standard Cubic Feet per Hour).
3-Zone Horizontal Furnace Tube - Atmospheric

Atmospheric pressure system:

3-zone tube furnaces are most common, but 5-zone tube furnaces also exist.
3-Zone Horizontal Furnace Tube – Low Pressure

Low pressure or vacuum system:

- Inlet nipple from gas supply panel
- Gas flow to vacuum pump and/or scrubber
- Electric heating elements
- 'Quartz' tube
- Water-cooled flange
- Flange door on loader
- Outlet mouth
- Wafers on carrier
- Zones 1, 2, and 3 labeled as "SOURCE", "CENTER", and "LOAD"
4-Tube Semi-Production Furnace Stack

- Laminar bench loading area with automatic boat loaders:
Tube Furnace Quartzware

- “Quartzware” is actually fused silica ($\text{SiO}_2$), a glass, not a crystal.
- Fused silica can normally withstand temperatures up to $\sim 1800^\circ\text{C}$.
- The high purity of the silica allows it to introduce minimal contamination to wafers being processed in the furnace.
- However, at the high temperatures of a furnace, alkali cations can very rapidly diffuse through fused silica.
  - A single fingerprint on the outside of a fused silica tube can contribute enough Na$^+$ ion to completely contaminate a furnace tube.
  - A tube that has been contaminated in this way has to be discarded! ($\$$
  - The diffusion coefficient for Na$^+$, K$^+$, and Li$^+$ through SiO$_2$ at $\sim 1000^\circ\text{C}$ is high enough that it only takes $\sim 30$-60 seconds for these ions to diffuse through a 3 mm thick tube wall.
- All furnace quartzware MUST be handled ONLY with clean gloves.
- Small accessories are also often fragile and brittle, like any glass.
Quartzware Wafer Boats

- Boats usually hold up to one cassette of 25 wafers.
- Boats must be matched to the wafer size: 3, 4, or 6-inch.
- Boats are hand loaded, so care must be taken to insure each wafer is properly slotted.
Tube Furnace Temperature Sensing Points

• Heater block temperatures
  – Obtained from thermocouples embedded inside the heating elements

• Spike temperatures
  – Obtained from thermocouples fed down the inside of the tube through a sealed rod known as the “spike”

• Gas flow through the tube produces convective cooling, and lowers the spike temperatures from the heater block temperatures.
  – Controlling the furnace temperature using the thermocouples on the spike thus eliminates the need for gas flow corrections to the temperature set points.

• Temperature sensors
  – Most commonly K-type thermocouples (chromel / alumel)
  – Can be used up to 1200°C (type-2 K TC)

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Tube Furnace Operation Styles

• Laboratory style:
  – Manually loaded wafers using quartzware pushrods,
  – Manually controlled gas flows (needle valves + rotameters),

• Production / development style:
  – Automatically loaded wafers,
  – Automatically controlled gas flows (MFCs),
  – Automatic control system for executing temperature/gas flow/time/loader recipes,
  – Computer control system for storing, recalling, and editing recipes.
  – Computer supervisory system for tracking wafer lots.
Furnace Control System

- Typical of most fabrication process control systems:

  serial interfaces: e.g. RS-485
  set points ↔ read backs

  local process control computer
  zone temperature controllers
  gas flow controllers (MFCs)
  boat position controllers
  (local, embedded controllers)
  furnace hardware

Program Functions:
- Process Controller: executes a recipe – send out set points, display read backs, check for alarms
- Process Run Data Logger (Event Logger): creates a detailed history of each run
- Recipe Manager / Librarian
- Recipe Editor
- Calibration Assistant: runs calibration routines for zone temps, gas flows, and boat positions
- Job Supervisor: tracks wafer lots, schedules maintenance, interfaces with centralized production databases, provides networked coordination with other processes
Automatic Tube Furnace Gas Panel
Time – Temperature Profiles

- All thermal processing steps need to be engineered around a time – temperature schedule which forms the core recipe.
- Elements of a time – temperature schedule:
  - Ramps – periods of controlled heater power increase or decrease to move the temperature up or down at a prescribed rate
  - Stabilization periods to allow equilibration of temperatures and thermally induced stresses; maximum rates are needed to avoid thermal shock
  - Processing periods, e.g. oxidation, nitridation, reducing; often switched on and off by gas flow changes
  - Thermal free falls – periods where the heater power is turned off and the chuck/tube and sample simply cool at their natural rate.
  - Load / unload periods and timing within the schedule
Typical Tube Furnace Wet Oxidation Recipe

Temperature, C

Time, hrs

Gas Flow Rate, SLPM

- ramp rate: 8.3 C/min
- ramp rate: 20 C/min

This recipe would produce about 0.5 μm of SiO₂.
Induction Furnaces - 1

- Induction heating uses a high RF current through a coil to produce a rapidly varying magnetic field in its interior.
- The magnetic field produces eddy currents, also known as Foucault currents, in any conductor inside. Ferromagnetic materials usually work best because they concentrate the magnetic field flux.
- The eddy currents produce heating through ohmic losses.
- Normally a graphite susceptor is required to provide uniform wafer heating.
Induction Furnaces - 2

- Induction furnaces are usually more efficient than resistance heated furnaces because the heat is created only in the sample and/or susceptor. Less thermal mass allows them to cycle faster.
- Induction furnaces are capable of higher temperatures than resistance heated furnaces, often over 1500 C.
- Induction furnaces are commonly used for:
  - Melting, refining, and pulling semiconductor crystals, e.g. silicon.
  - Chemical vapor deposition (CVD) tube systems.
  - Many other metallurgical uses: annealing, surface hardening, etc.
- Excitation: High current RF, typically 5 – 500 kHz, 10-100 Amps.
- Eddy currents in the sample depend upon its geometry and its conductivity, so a susceptor is usually needed to homogenize the heating. Graphite susceptors are commonly used for this because of their good conductivity and high melting point.
- Copper tubing is often used for the coils, since it can be water cooled.
Rapid Thermal Processors (RTPs)

- Capable of high throughput and precise energy transfer.
- Control and measurement of transient temperatures is exceedingly difficult, if not impossible.
- Control is therefore based upon the energy dose which is applied.
- Applications:
  - Annealing (RTA)
  - Oxidation (RTO)
  - Nitridation (RTN)
  - Diffusion drive-in (RTD)
  - Chemical vapor deposition (RTCVD)
  - Others being developed (RT...)
- Suitable for single-wafer and small batch processing.
- Economical!
RTP Modes

 Isothermal

 Adiabatic

 Focused, Direct-Write
RTP Sources

• Broad beam sources:
  – Quartz IR lamps
  – Tungsten halogen bulbs
  – Noble gas discharge lamps (Hg arc)
  – Flash lamps (Xe)

• Focused sources:
  – Excimer lasers
  – CO$_2$ lasers
  – Nd:YAG lasers
  – Electron beams
  – Ion beams
Radiation Heat Transfer Between Two Objects

- Integrate the Stefan-Boltzmann relation over both the sourcing and receiving areas to obtain the power transfer between the objects:

\[
P_{1\to2} - P_{2\to1} = \sigma \left( \varepsilon_1 T_1^4 - \varepsilon_2 T_2^4 \right) \iint_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{\pi r_{12}^2} dA_1 dA_2 \quad [\text{Watts}]
\]
RTP Trade-Offs

• The Good:
  – Extremely fast temperature ramp rates can be obtained.
  – Well suited for single wafer processing.
  – Can perform many annealing operations without causing dopant redistribution.
  – Highly flexible design which can be used for multiple operations.
  – Cold wall systems offer less cross-contamination than hot wall systems.

• The Bad:
  – Absolute temperature maximums are very difficult to determine.
  – Must work in terms of dose rather than time-temperature profile.
  – Careful design is required to create a highly uniform source.

• The Ugly:
  – No simple formulas are very helpful; detailed numerical simulations are usually required to predict performance.
  – Process tuning is mostly empirical.