ECE 416/516
IC Technologies
Lecture 6:
Rapid Thermal Processing

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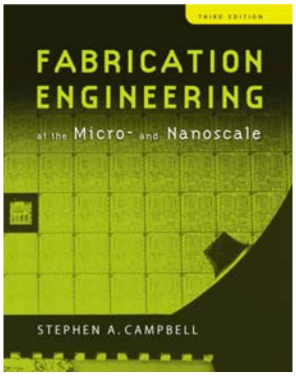
Chapter 6

Rapid Thermal processing



Rapid Thermal Processing (RTP)

Lecture Topics

- RTP Principles, systems, problems
  - Applications
    - Heat Transfer
    - Modeling example: RT anneal

Lecture Objectives

- Can describe RTP, systems, etc.
- Can calculate heat transfer by conduction, convection, radiation
- Can set up annealing model as RTP example

Rapid Thermal Processing (RTP)

RTP Principles

- Short time at high temperature
- High temperature
  - - ion implant damage anneal
  - - oxidation, CVD, epi growth
  - - impurity activation
- Short times
  - - minimize diffusion
  - - minimize wafer warpage

RTP Classifications

- Adiabatic
  - - short laser pulses
  - - t << $\tau_{substrate}$
  - - heats ~ μm from surface
- Thermal Flux
  - - scan laser spot
  - - scan period << $\tau_{substrate}$
  - - avoids thermal gradients
- ISOTHERMAL

Heat Transfer

Conduction (e.g. through wafer from surface)

$$dq(T)/dx = k_{th}(T).A.\Delta T$$

Convection (e.g. from surface)

$$dq/dx = h(T - T_\infty)$$

T_∞ gas temperature far from wafer

h effective heat transfer coefficient

Radiant Heating:

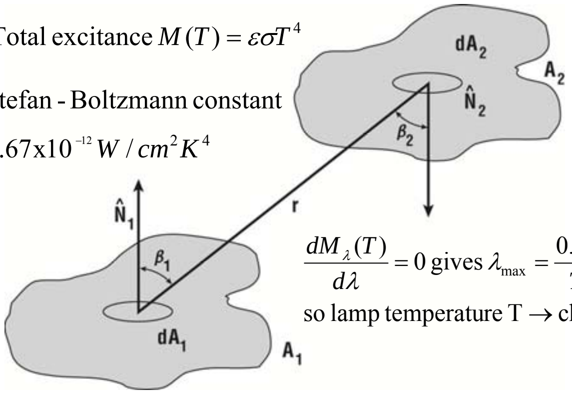
Planck'Radiation Law: Spectral radiant excitance $M_\lambda(T) = \varepsilon(\lambda)\frac{C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)}$

Radiation into black body: C_1=3.71x10^{-12} W/cm^2, C_2=1.44 cm-K,
Absorption ϵ=1 for black body

$$\int_0^\infty M_\lambda(T)d\lambda \rightarrow \text{Total excitance } M(T) = \varepsilon\sigma T^4$$

$$\text{where } \sigma = \text{Stefan-Boltzmann constant}$$

$$= 5.67\text{x}10^{-12}\, W/cm^2K^4$$



$$\frac{dM_\lambda(T)}{d\lambda} = 0 \text{ gives } \lambda_{\max} = \frac{0.29}{T} cm.K$$

so lamp temperature T → characteristic color

Figure 6.1 Geometry for calculating the view factors between two surfaces, A_1 and A_2.

Max Emission Wavelength

$M_\lambda(\lambda) = \varepsilon\, C_1\, \lambda^{-5}\, (\exp c_2/\lambda T - 1)^{-1}$

$dM_\lambda/d\lambda = \varepsilon_1\, C_1\, [(\exp c_2/\lambda T - 1)]^{-1}\, (-5\lambda^{-6})$

$\quad - \lambda^{-5}\, (\exp c_2/\lambda T - 1)^{-2}\, (\exp c_2/\lambda T)\, (-c_2/\lambda^2 T)]$

$\quad = 0$

when $5\lambda^{-1} = (\exp c_2/\lambda T - 1)^{-1} \exp(c_2/\lambda T)(c_2/\lambda^2 T)$

$\quad \approx (c_2/\lambda^2 T)$ for $\lambda \approx 1$ nm, T=500ºC

$\therefore\ \lambda_{max} = (c_2/5)/T = 0.2898$ cm.K/T

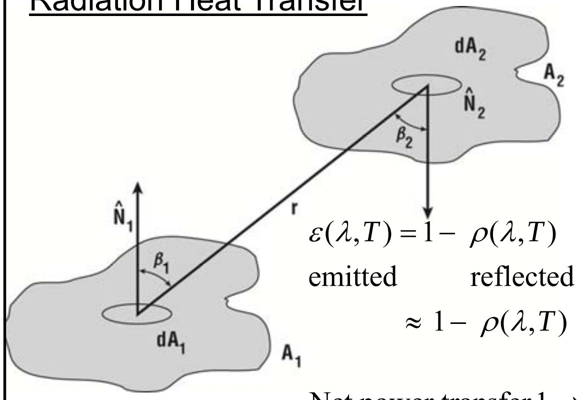
i.e. Temperature T ---> characteristic color

Radiation Heat Transfer

From wafer surface, reflectors, etc:

Incident radiation is transmitted , reflected, or absorbed.

In equilibrium:
absorbed=emitted (fraction ε)



$$\underset{\text{emitted}}{\varepsilon(\lambda,T)} = 1 - \underset{\text{reflected}}{\rho(\lambda,T)} - \underset{\text{transmitted}}{\tau(\lambda,T)} \text{ in equilibrium}$$

$$\approx 1 - \rho(\lambda,T) \quad \approx 0 \text{ for opaque}$$

$$\text{Net power transfer } 1 \rightarrow 2: \ s = \dot{q}_{1\rightarrow 2} - \dot{q}_{2\rightarrow 1}$$

$$= \sigma(\varepsilon_1 T_1^4 - \varepsilon_2 T_2^4) A F_{A_1\rightarrow A_2}$$

(But note:
Si transparent to IR)

$$F_{A_1\rightarrow A_2} = \frac{1}{A_1}\int_{A_2}\int_{A_1} \frac{\cos\beta_1 \cos\beta_2}{\pi r^2} dA_1 dA_2$$

Figure 6.1 Geometry for calculating the view factors between two surfaces, A_1 and A_2.

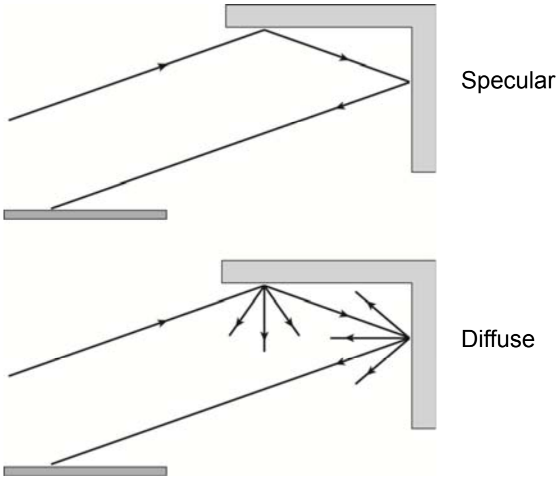


Figure 6.2 Possible optical paths among three surfaces including only single reflections. This diagram assumes diffuse reflections.

Figure 6.3 Tungsten–halogen lamps (left) and noble gas arc lamps (right) for use in rapid thermal systems.

Isothermal Systems

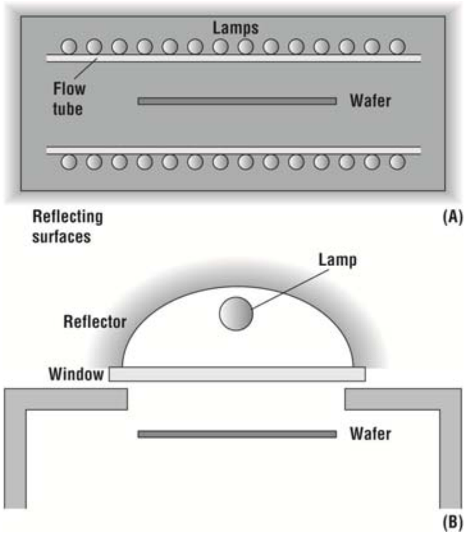


Figure 6.4 Various chamber designs include (A) the reflecting cavity and (B) a windowed system using an intense source and a shaped reflector.

Sources

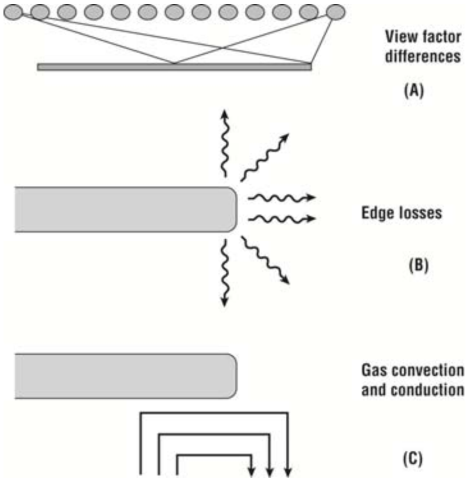
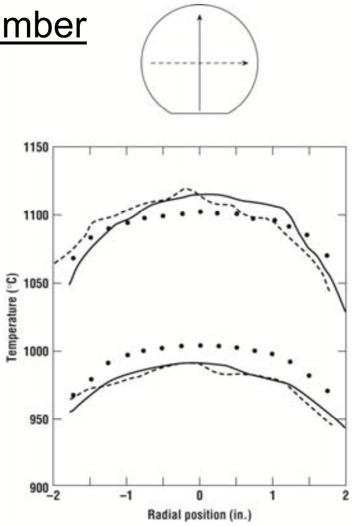


Figure 6.5 Causes of thermal nonuniformity include (A) a reduced view factor to the lamp array for large *r*, (B) very small view factors along the wafer edge, and (C) nonuniform gas phase heat transfer *(after Campbell, 1994)*.

Chamber



Temperature uniformity across wafer:

- compensate for edge losses
- zone heaters

Figure 6.6 Typical wafer temperature distributions across the wafer in an early-generation rapid thermal system (*after Lord, © 1988 IEEE*).

Temperature measurement

Feedback control
Optical pyrometry

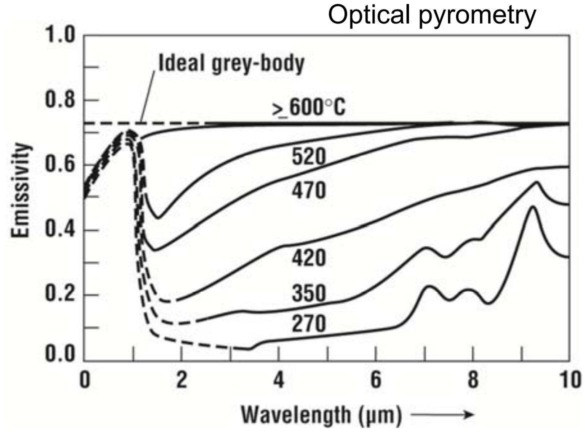


Figure 6.7 The emissivity of silicon as a function of wavelength with temperature as a parameter. Above 600°C the wafer is intrinsic *(after Sato, reprinted by permission, Japan. J. Appl. Phys.).*

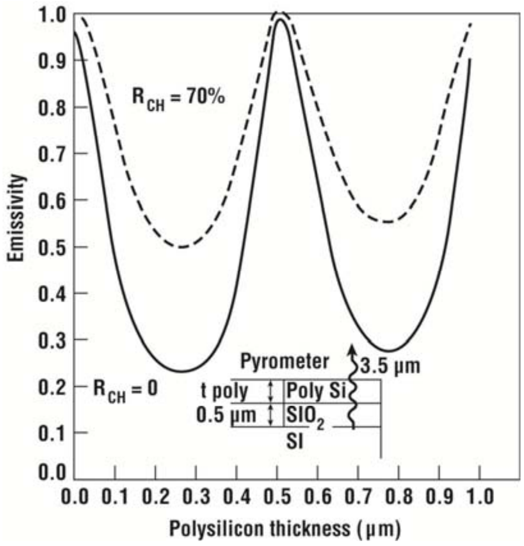
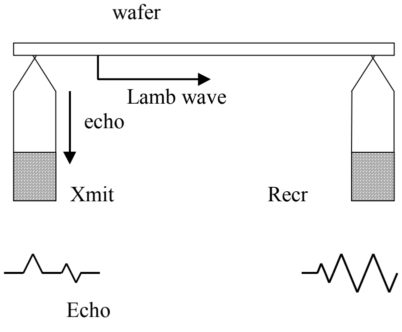


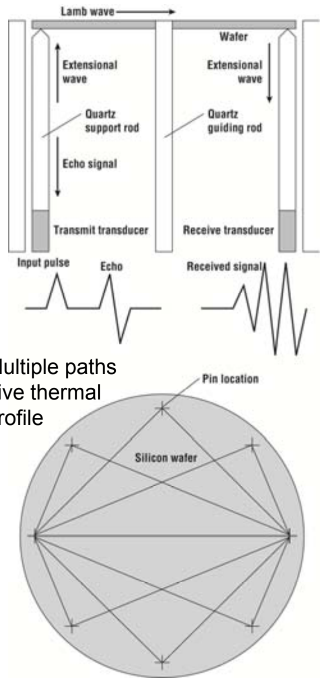
Figure 6.8 The effect of polysilicon thickness on effective emissivity for a polysilicon/SiO_2/silicon structure in nonreflective and 70% reflective cavities *(after Hill and Boys, reprinted by permission, Plenum Publishing).*

Measure T by thermal expansion

Measure T by velocity of sound

Sound velocity α T





Multiple paths give thermal profile

Figure 6.9 Acoustic temperature measurement side and top views *(after Degertekin et al., used by permission, Materials Research Society).*

Thermoplastic Stress

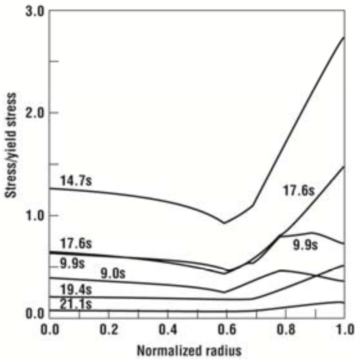


Figure 6.10 Normalized stress versus position on a wafer during a heating transient *(after Lord, © 1988, IEEE).*

$$Radial: \sigma_r(r) = \alpha E\left[\frac{1}{R^2}\int_0^R T(r')r'dr' - \frac{1}{r^2}\int_0^r T(r')r'dr'\right]$$

$$Angular: \sigma_s(r) = \sigma_r(r) - \alpha E T(r)$$

$$\text{where } \alpha = \text{TCE, E = Young's modulus}$$

$$Yield\ strength: \sigma_{yield} = A\left(\frac{\dot{e}}{\dot{e}_0}\right)^{\frac{1}{n}} e^{E_a/kT} = 3.5\ \ to\ \ 60MPa$$

where $\dot{e}$ is strain rate, $\dot{e}_0 = 10^{-3}/s$ as reference

$A = 3630\text{Pa}, E_a = 1.073\text{eV}$, and $n = 2.45$

RTP Applications

Thermal Activation of Impurities
- Non-equilib possible, i.e. active concn. > solid solubility
- insufficient time to cluster

Dielectrics
- Dry oxidation
- process during “initial” stage
    - modeling empirical

Silicidation/contacts (resistivity of doped Si too high)
- deposit Ti (or other refractory metal) on surface
- RTP to form $TiSi_2$ etc.
- lower resistance

RT Activation of Dopants

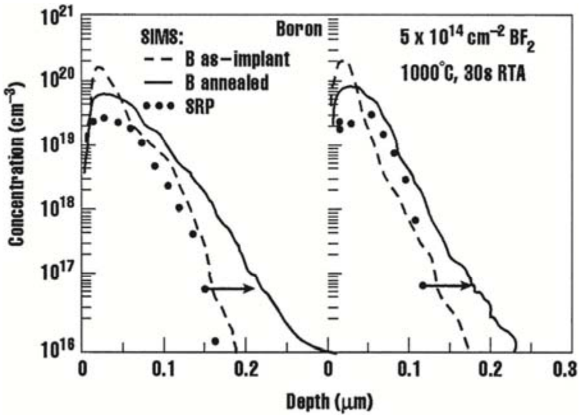


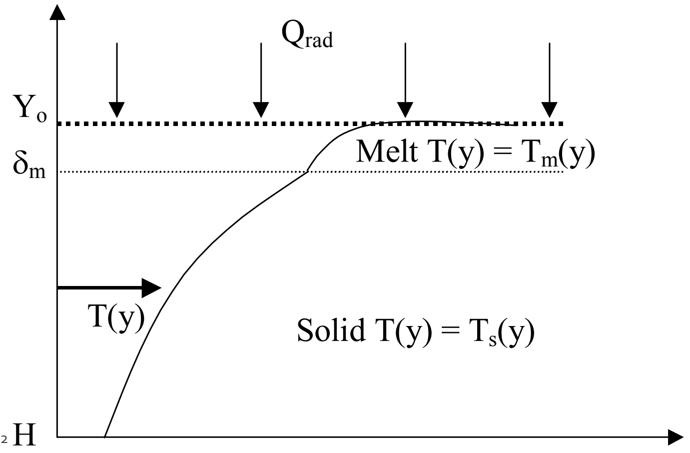
Figure 6.11 Chemical and active boron profiles after incomplete activation in RTP *(after Kinoshita et al., used by permission, Materials Research Society).*

Wafer doesn't reach thermal equilibrium
∴ doping profile may > maximum solid solubility limit

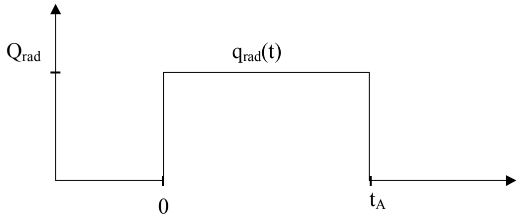
Example: RT Anneal

Rapidly melt surface and recrystallize without significant diffusion

Problem: estimate anneal depth



Boundary Conditions



- $Q_{rad} \approx 100 W/cm^2$ $t_A \approx 10 - 100s$
- Energy equation: heat conduction in y direction only
  - $\rho C_p \, \partial T/\partial t = \partial . k(\partial T/\partial y)/\partial y$
- Thermal conductivity k:
  - $k_{solid} = 0.22$ W/cm.K, $k_{melt} = 0.64$ W/cm.K
- Melting $T_M = 1425^oC$
- Assume time to melt surface << t_A

Energy Equations

$(\rho C_p)_m \, \partial T_m / \partial t = \partial (k_m . \partial T_m / \partial y) / \partial y$, $0 \le y \le \delta_m$

$(\rho C_p)_s \, \partial T_s / \partial t = \partial (k_s . \partial T_s / \partial y) / \partial y$, $\delta_m \le y \le H$

$T_m(y,0) = T_s(y,0) = T_0$, at t=0

At surface y=0: absorbed flux αq = conducted

$k_m \, \partial T_m / \partial y)|_{y=0} - \varepsilon_m \sigma T_m^4 = \alpha q$ radiated

At melt boundary $y=\delta_m$ (t)

$T_m = T_s = T_M$

& differential flux melts interface

$k_m (\partial T_m / \partial y) + k_s (\partial T_s / \partial y) = \lambda_m \rho_m (d\delta_m / dt)$

where λ_m latent heat of melting (1810 J/g) & ρ_m melt density 2.49 g/cm^3

At rear of substrate y=H

$k_s \, \partial T_s / \partial y = \varepsilon_s \sigma T_s^4$

GaAs: Implants need Si_3N_4/SiO_xN_y cap to prevent As out-diffusion.
Instead, capless RTA (annealing)

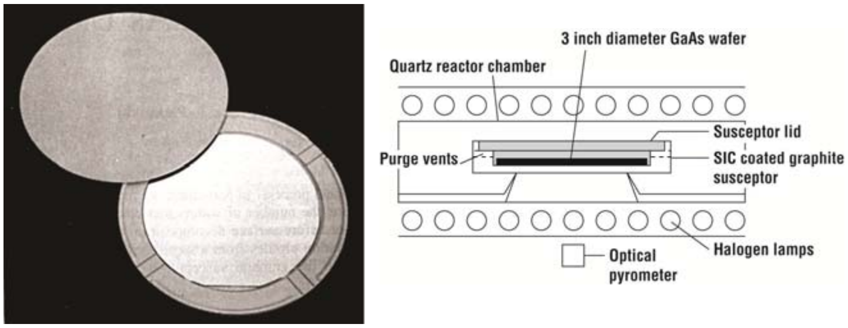


Figure 6.12 Photograph and schematic for capless arrangement for annealing GaAs *(after Kazior et al., © 1991 IEEE).*

RTP of dielectrics: RTO (oxidation)

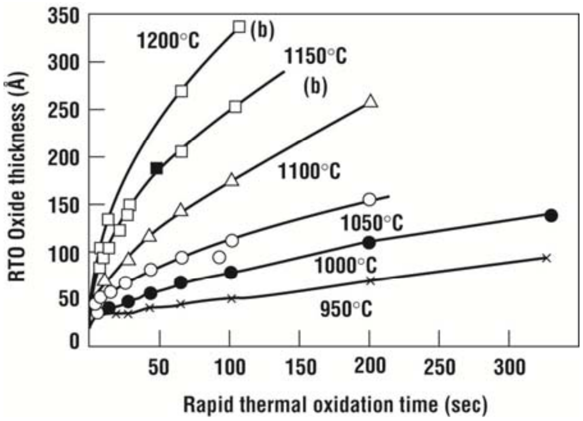
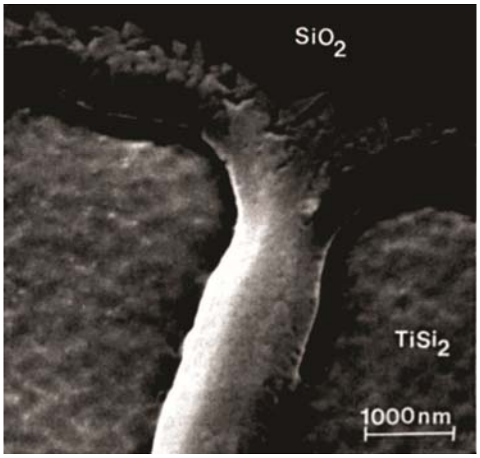


Figure 6.13 Typical data for oxide thickness as a function of time for a rapid thermal oxidation process *(after Moslehi et al., 1985).*

Silicidation Contact Formation



Ti-Si_2 low resistance

Si diffusion in grain boundaries
→ silicide grows over SiO_2

Low T → TiSi
High T →$TiSi_2$

Figure 6.14 Results of a 900°C 30-sec formation of $TiSi_2$ in an oxide window. The ragged edges indicate silicide formed over the edges of the window *(after Brat et al., used by permission, The Electrochemical Society).*

New Systems

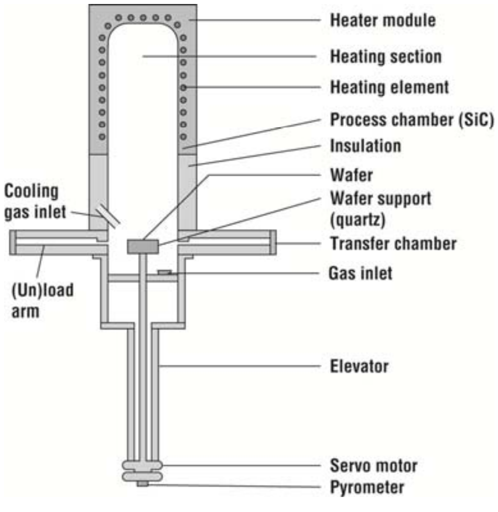


Figure 6.15 New designs for high uniformity RTP include the hot wall system *(after Roozeboom and Parekh).*

Figure 6.16 The Applied Materials Centura RTP Honeycomb source in the lifted position. The wafer is in the lower part of the photograph *(courtesy Applied Materials).*

Summary

- RTP systems
- Thermal measurements for control
- Heat Transfer
- Applications
- RT Annealing