Lecture 6

Rapid Thermal Processing

Reading:

Chapter 6

Rapid Thermal Processing (RTP) (Chapter 6)

Categories:

Rapid Thermal Anneal (RTA)
Rapid Thermal Oxidation (RTO)
Rapid Thermal Nitridation (RTN) (and oxynitrides)
Rapid Thermal Diffusion (RTD)
Rapid Thermal Chemical Vapor Deposition (RTCVD)
Silicides and Contact formation

Advantages:

1.) Single wafer processing produces the best uniformity, especially for large wafer sizes.
2.) Minimize redistribution of dopants, minimal sqrt(Dt) with maximal D (high Temperature) allows repair of damage from ion implantation.
3.) Cold walls allow multiple processes to occur without cross contamination.
4.) Photochemistry can be exploited.

Disadvantages:

1.) Absolute temperatures are almost never known.
2.) Nonthermal-equilibrium conditions make modeling and predicting difficult.
3.) Uniform heating is more critical than traditional furnace processing due to high ramp rates and the resulting stress.

Definitions:
stress: force per area => units are the same as pressure

Rapid Thermal Processing (RTP)

RTP Physics

Heat Flow Mechanisms can be related to temperature rise by:

$$\frac{dT}{dt} = \frac{\dot{q}(T)}{(C_p)(\rho)(thickness)}$$

Where C_p is the specific heat ([J/kg-K] a measure of how much energy a material can absorb before it manifests in a temperature rise), ρ is the gram/cm^3 density, and q-dot is the heat flow density (W/cm^2) Note your book is inconsistent on how it uses q-dot.

$$\dot{q}(T) = \frac{Watts}{cm^2} = \frac{Joules}{Second\ cm^2}$$

Temperature ramp rate can be enormous!!!!!

Rapid Thermal Processing (RTP)

Types of RTP

1.) Adiabatic (without heat transfer): Excimer laser pulses (<uS) anneal the thin skin of material.=>huge vertical temperature gradients

2.) Thermal flux: rastering a focused beam (electron or laser) across a wafer. =>huge vertical and lateral temperature gradients

3.) Isothermal: Broad area optical illumination. => minimal temperature gradients.

RTP Physics

3 types of Heat Flow Mechanisms:

1.) Conduction: Flow of heat between two bodies in intimate contact.

Heat flow per unit area in a solid is expressed in terms of a solids thermal conductivity, k(T), as,

$$\dot{q}(T) = k(T)\frac{\Delta T}{x}$$

Where k(T) has units of Watts/(cm-K) and x is the thickness measured between the two temperatures. Note this is different from your book.

2.) Convection: Flow of heat between two bodies through an intermediate medium (a gas in our case)

For a gas with effective heat transfer coefficient, h with units (Watts/cm^2-K) is,

$$\dot{q}(T) = h(T_{wafer} - T_{\infty})$$

Notice that both of these expressions are linear in temperature

Rapid Thermal Processing (RTP)

Example: Assuming constant power delivery, what is the initial temperature rise rate for a 700 um thick Si wafer in a furnace heated from T=30 C to T=1000 C in a gas with a effective heat transfer coefficient of 2e-4 W/(cm^2-C)?

Power density needed to get to 1000 degrees C

$$\dot{q}(T) = h(T_{wafer} - T_{\infty})$$

$$\dot{q}(T) = 2e-4(30-1000) = 0.19W/cm^2$$

$$\frac{dT}{dt} = \frac{\dot{q}(T=30)}{(C_p) \quad (\rho) \quad (thickness)}$$

$$\frac{dT}{dt} = \frac{0.19W/cm^2}{0.75(J/gm-C) \quad 2.33(gm/cm^3) \quad 0.07(cm)} = 1.7 \circ C/\sec$$

For an 8 inch wafer this only requires about 60 W ***IF*** all other losses such as radiative losses are ignored. However, radiative losses become dominant at high temperatures (~>400 degrees C)

Rapid Thermal Processing (RTP)

3.) Radiation: Flow of heat between two bodies through radiation and absorption of light. We can use the spectral radiant exitance= the radiated power per area per unit wavelength,

$$M_\lambda(T) = \varepsilon(\lambda)\frac{c_1}{\lambda^5\left(e^{\left(\frac{c_2}{\lambda T}\right)}-1\right)}$$

where $c_1 = 3.7142\text{x}10^{-16}\ \text{W}-\text{m}^2, c_2 = 1.4388\text{x}10^{-2}\ \text{m}-\text{K}$ and $\varepsilon(\lambda)$ is the wavelength dependant emissivity.

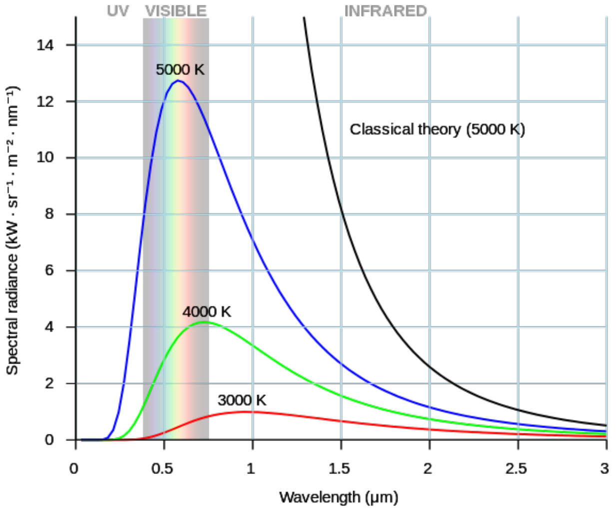
If $\varepsilon(\lambda)$ is independent of λ, then the total power radiated per unit area, the total exitance,

$$M(T) = \dot{q}(T) = \varepsilon\sigma T^4$$

where $\sigma = 5.6697\text{x}10^{-8}\ \text{W/m}^2 K^4$ is the Stefan - Boltzmann constant.

NOTE:1). The unit change to meters and 2) The radiated power depends on temperature to the forth while conduction and convection depend on temperature linearly. Thus, radiation is the dominate mechanism at high temperature while conduction and convection dominate heat flow at lower temperatures.

The emissivity is related to the absorbance by Kirchoff's law of conversation of power which states that in steady state at (constant temperature and absorbed and emitted power), the power absorbed by a wafer must be equal to the power emitted.



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The net heat flow between 2 hot bodies is,

$$\dot{q}_{1to2}-\dot{q}_{2to1}=\sigma\left(\varepsilon_1 T_1^4-\varepsilon_2 T_2^4\right)A_1 F_{A_1\ to\ A_2}$$

$$where\ F_{A_1\ to\ A_2}\ \ is\ the\ view\ factor$$

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

For most real life surfaces (even flat wafers have finite thicknesses) this equation is not very useful unless computer calculations or simplifying assumptions are used.

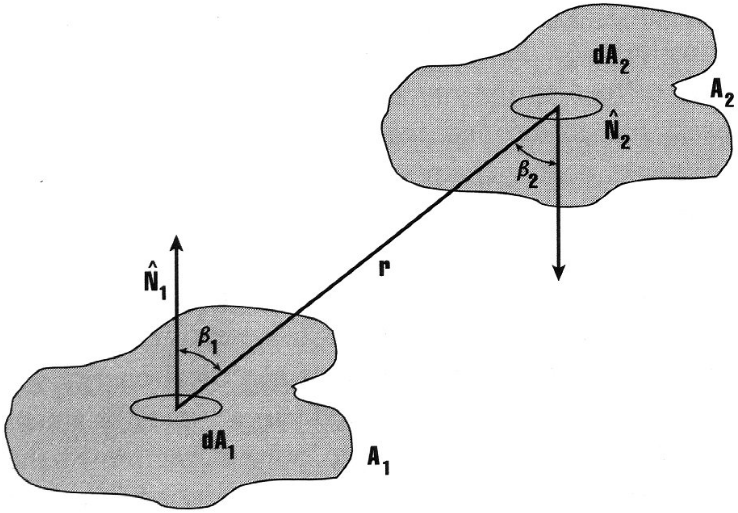


Figure 6-1 Geometry for calculating the view factors between two surfaces, A_1 and A_2.

Rapid Thermal Processing (RTP)

Hardware for RTP

Bulbs can be classified by their ‘color temperature”,

$$\lambda_{\text{max spectral radiant exitance}} = \frac{0.2898\ cm-K}{T}$$

The more power per unit area emitted by a bulb, the higher the color temperature (peak of exitance moves to lower wavelengths).

Tungsten Halogen Bulbs: Moderate color temperatures~moderate output power density. As tungsten filament gets hot, the W evaporates and begins to coat the glass. The halogen species forms volatile (gases with high vapor pressures) W-halogen compounds that diffuse back to the hot filament, break apart and redeposit the W. Thus, longer bulb life is obtained.

Arc Noble Gas Discharge Lamps: A fused silica tube containing a noble gas (or mixtures) is ignited with a high voltage pulse to ionize the gas. Once ionized the bulb can carry a huge DC current. The effect is a very intense light source with very high color temperature and additional discrete gas line spectra superimposed on the radiant exitance. Low melting point metals such as Hg are also used to increase output power in certain desired wavelengths.

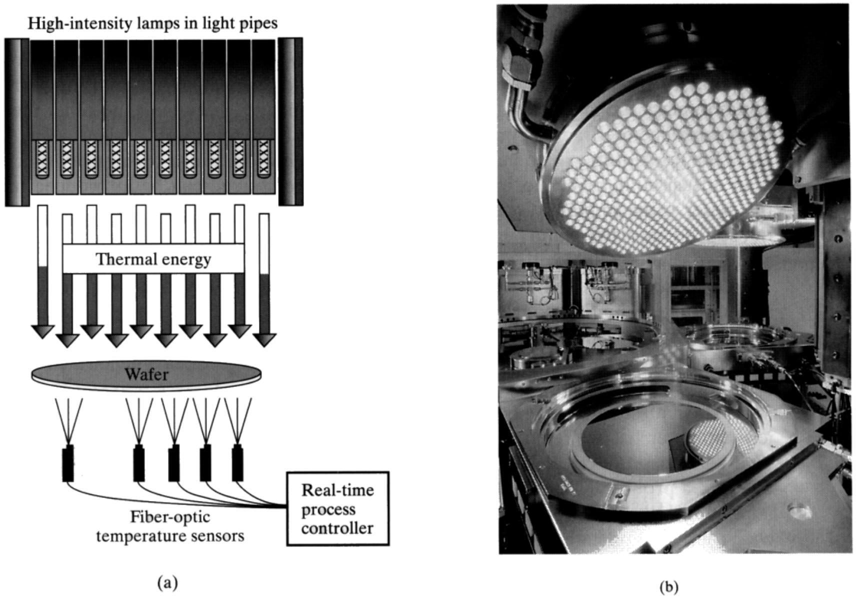
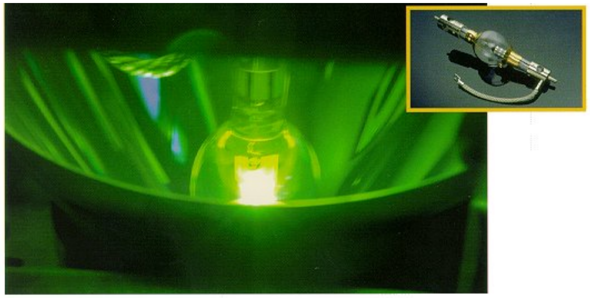


FIGURE 5.12

(a) Concept of a rapid thermal processing (RTP) system. (b) Applied Materials 300 mm RTP System. (Courtesy Applied Materials, Inc.)



Rapid Thermal Processing (RTP)

Uniformity Issues:

Multizone bulb arrangements are used to supply more power to wafer edges to compensate for increased radiated power loss and lower optical “view factors”. Loss of uniformity results in inconsistent dopant activation, inconsistent dielectric properties, inconsistent stress resulting in defect generation and many other problems.

Temperature Measurement:

Most often in today’s RTP systems a combination of pyrometry, acoustic and in some rare cases thermocouples in a susceptor are used.

1.) Pyrometry measures the intensity of light within a certain operating bandwidth emitted from a wafer and relates it to the the spectral exitance. Disadvantages are that transmission through process gases and glassware, errors in the assumed emissivity, pickup of background radiation from the lamps themselves, and even destructive interference from deposited layers can result in errors in the measurement. Several points on the wafer must be sampled to adjust the wafer uniformity.

2.) Acoustic Measurements: The velocity of sound is measured between pairs of quartz pins supporting the wafer. The sound velocity is a linear function of temperature. Thus, with proper calibrations, the temperature at many positions can be measured.

3.) Thermocouples in a susceptor: High thermal conductivity materials such as a silicon, SiC or Graphite susceptor may be used to absorb the lamp power and re-radiate a more uniform distribution of light to the wafer to be processed. In this configuration, a thermocouple (metal junction of dissimilar metals whose difference in work functions produces a measurable voltage that depends on the temperature of the metal junction) can monitor the susceptor temperature. The wafer temperature can be found from the total exitance.

Rapid Thermal Processing (RTP)

Rapid Thermal Annealing of Implanted Dopants

- Due to lower activation energies in implanted regions (point defects already exist in high concentrations, so the defect formation energy is not needed) the implants tend to diffuse faster than standard diffusion theory would predict. If longer time (minutes) low temperature anneals are performed before the high temperature anneal used to activate the implant, the enhanced diffusion goes away.

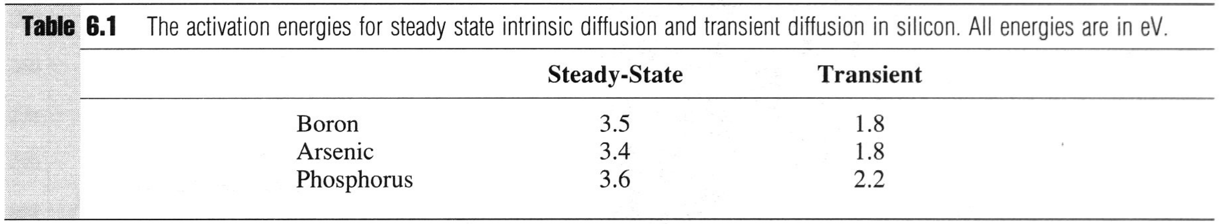


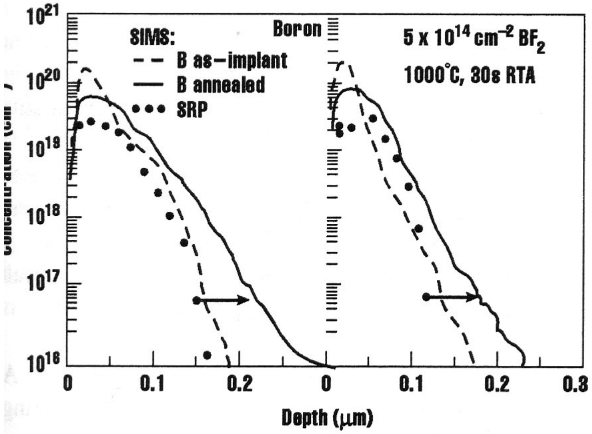
Table 6.1 The activation energies for steady state intrinsic diffusion and transient diffusion in silicon. All energies are in eV.

	Steady-State	Transient
Boron	3.5	1.8
Arsenic	3.4	1.8
Phosphorus	3.6	2.2

Data taken from Fair [33].

- Since thermal equilibrium may not be reached, doping profiles can actually exceed the solid solubility limit.

- Chemical and electrical profiles may not be the same (peaks and tails may not be activated). The electrical junction follows the implanted junction very well, even though the impurities may diffuse.



igure 6-11 Chemical and active boron profiles after ncomplete activation in RTP *(after Kinoshita et al., used y permission, Materials Research Society).*

Rapid Thermal Processing (RTP)

Dielectric Processing

Very high quality “ultra-thin” oxides can be produced by introducing oxygen, fluorine (NF_3) and/or nitrogen gases during a RTA high temperature step. These rival diluted gas thermal oxides, but can have better uniformity (if strain near the edges is controlled).