Laser Processing of Materials

Heat Flow

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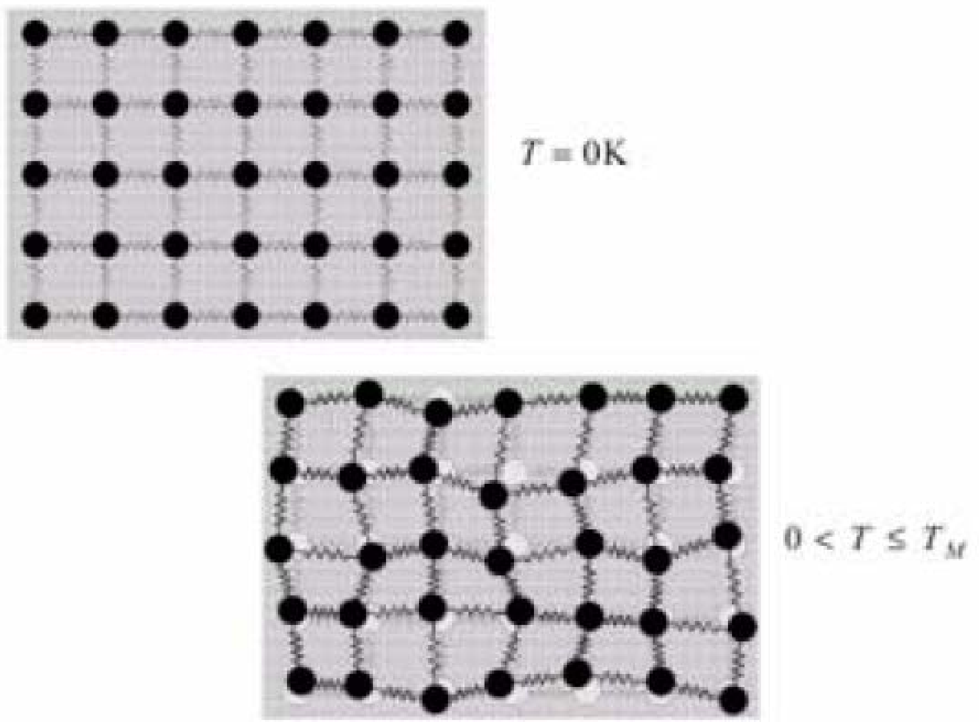
Contents

- Absorbed light $\rightarrow$ Heat
- Heat flow (heat equation)

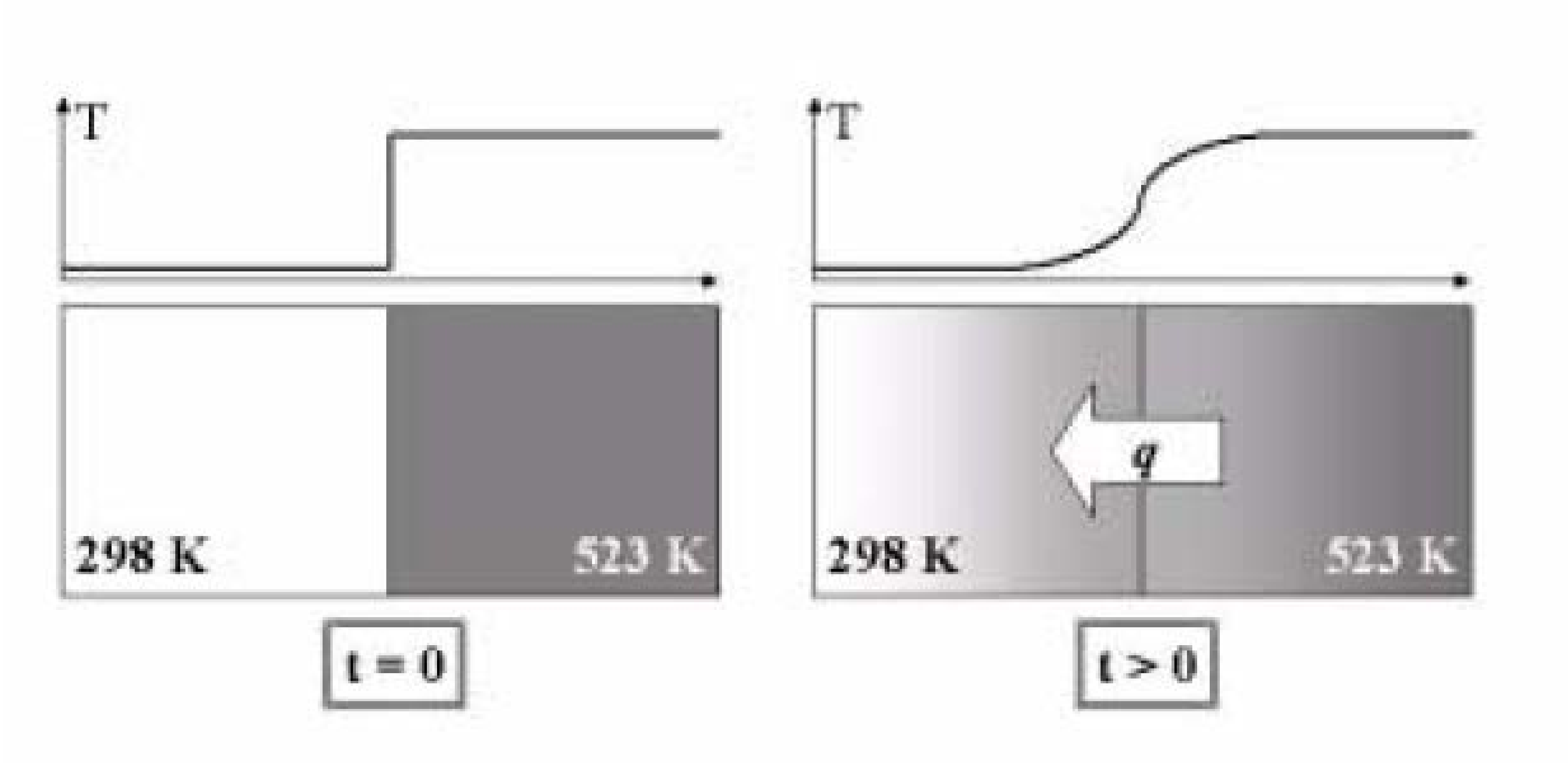
Heat



Heat flows from warm to cold, Fourier law

Heat = energy contained in excited phonons (lattice vibrations)
for liquids: additionally in rotation of molecules

Heat flux



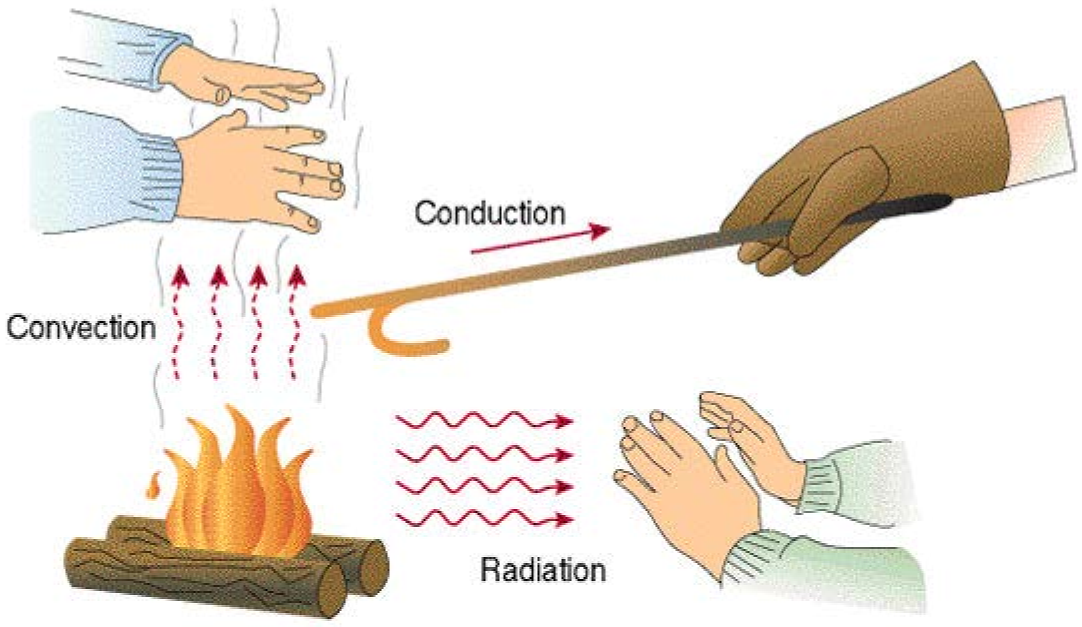
Which parameters determine the final state (temperature distribution) ?

thermal capacity, density/mass

Which parameters influence the dynamics of the flow?

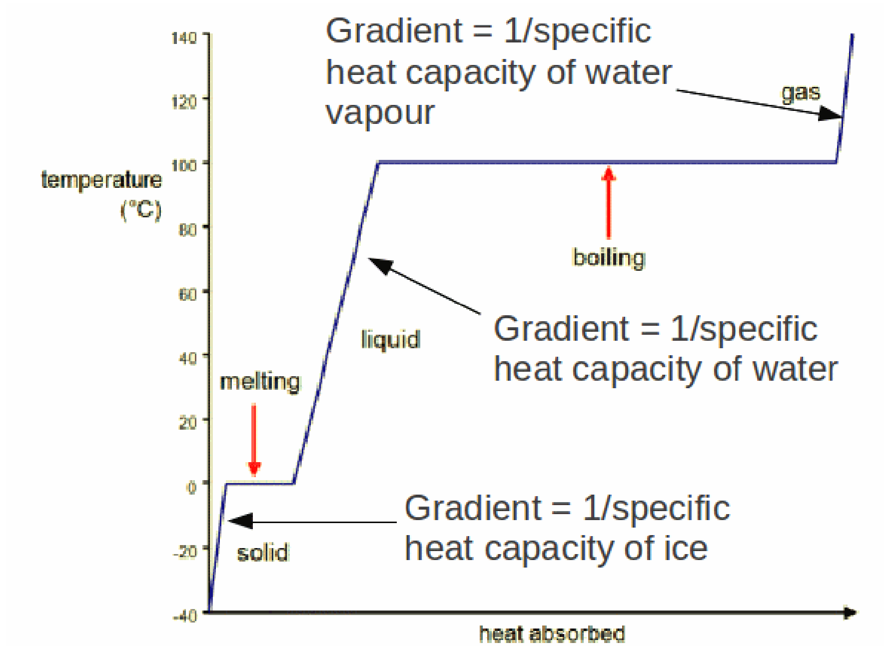
thermal capacity, thermal conductivity, density

How heat can be transported?

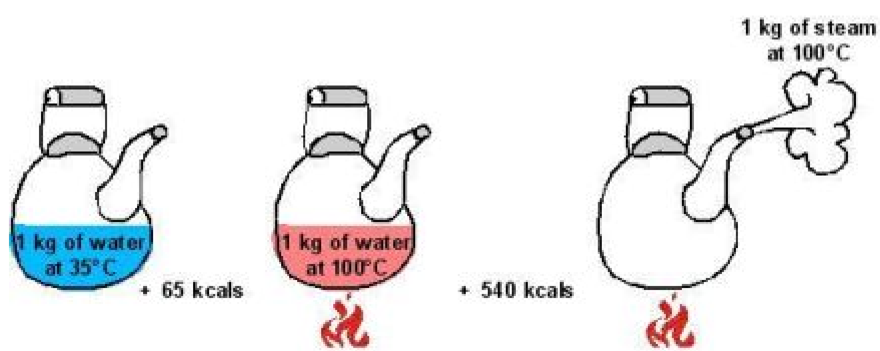


Other (indirect) means?

Phase Transition

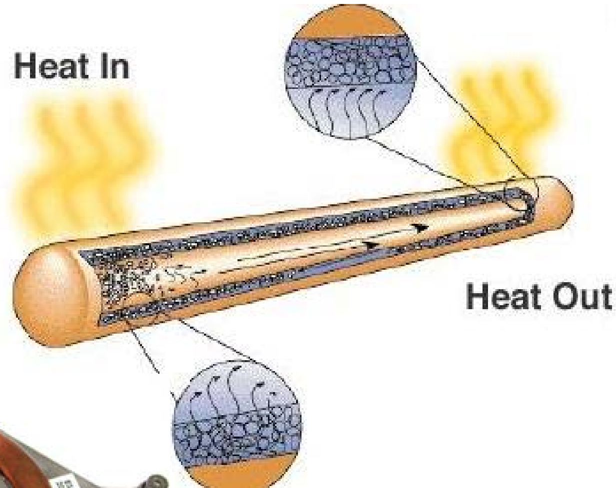


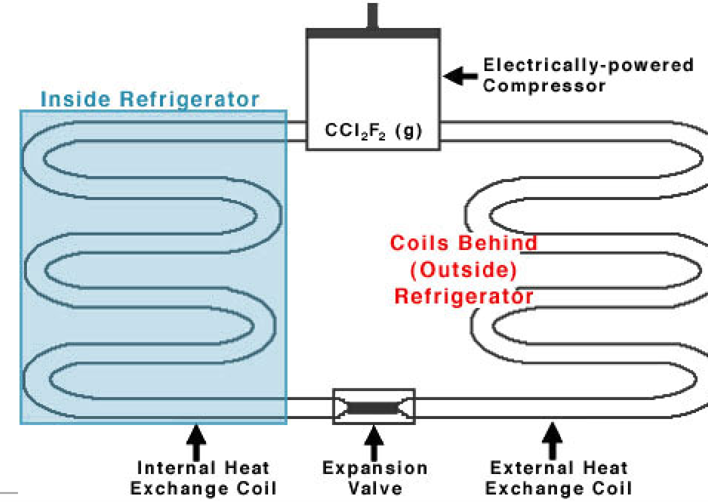
evaporation needs much more (5x-10x) energy than melting and heating the material !!!

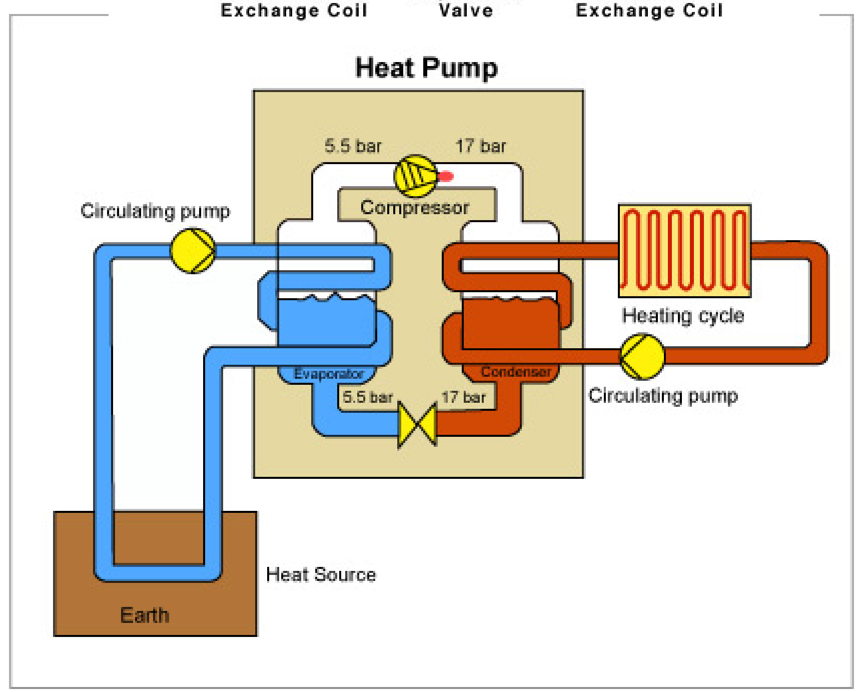


Heat Transfer Using Phase Transition

Heat Pipe







Evaporation require a lot of heat – efficient heat transfer

In laser processing can generate high losses - important to consider for efficient laser processing!!!

Transport Phenomena

- Heat flow
- Materials flow (diffusion)
- Viscosity

Driving force for transport are spatial inhomogeneities, i.e. gradients

$$j = -C grad \varphi$$

$$\frac{\partial \varphi}{\partial t} = C \nabla^2 \varphi$$

	Transported quantity	System state	Material property
Nom de l'eq. V.1-1	**j**	**φ**	**C**
Fourier	Heat flow	T	$k/\rho c_p$
Fick	Mass flow	[n]	D
Newton	Momentum flow	v	μ

- Solution of Fick's law

Solutions to these equations
exist for simple cases such as a grain of salt in water

same solution for the point source of heat
in homogeneous medium

$$[n](r,t) = \frac{n_{tot}}{8(\pi D_{diff})^{3/2}} e^{-r^2/4Dt}$$

Table of material properties

Matériaux	ρ [g/cm^3]	T_m [K]	T_v [K]	c_p [J/gK]	κ [W/cm K]	D [cm^2/s]
Al	2,7	933	2720	0,90	2,4	1,03
Al_2O_3	4,0	2324		0,75	0,30	
Al_2O_3(cerami-que)	3,89	2340	3800	0,9	0,3	0.086
Au	19,3	1338	2980	0,13	3,15	1,22
$C_{graphite}$	2,24	3923	4623	0,71	20; (22,3 ‖; 0,11 ⊥)	
$C_{diamond}$	3,52	> 3822		0,50	20	
Cr	7,2	2130	2945	0,46	0,95	0,29
Cu	8,95	1357	2840	0,39	3,95	1,14
Fe (coulé)	7,4			0,57	0,56	0,12
Acier (0.1% C)	7,85			0,49	0,46	0,12
Acier inox (304)	8,03	1723	3273	0,5	0,15	
H_2O	1	273	373	4,18	0,06	0,014

good metal

ceramics

good metal

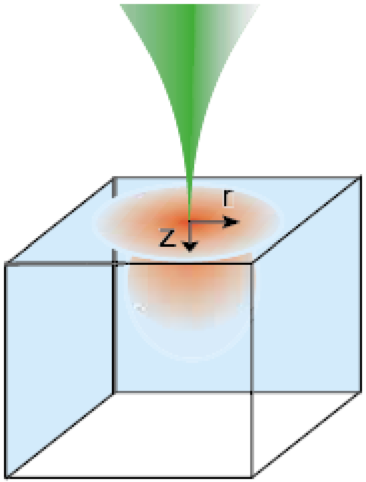
"bad" metal

"bad" metal

water & polymer

Heat flow

form of the equation in case the external heat source is present



how temperature field changes in time

$$\frac{\partial T}{\partial t} = D\nabla^2 T + \frac{Q}{\rho c_p}\delta(\vec{x}, t)$$

based on existing temperature distribution

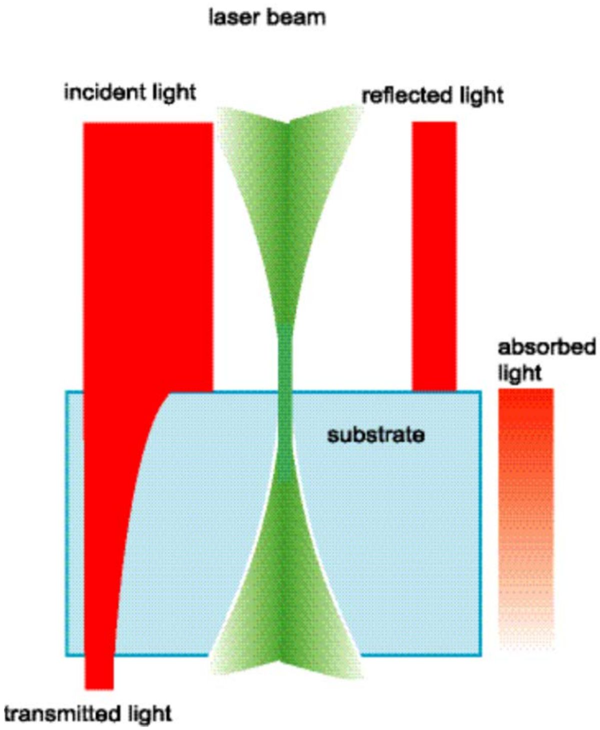
and external heat sources and heat losses

Heat Source – Laser Irradiation

- Heat flux
  - Laser heating depends on a large number of parameters
    - Optical properties of material (R, α, ..)
    - Heat transport in and out of irradiation zone
    - Heat storage in and out of zone
    - Phase transition Enthalpies
    - Chemical reaction Enthalpies
    - …

Laser (light) Source Term

$$Q_{(x_\alpha,t)} = I_{(x,y,t)}(1-R)\,f_{(z)} = I_{(a)}\,g_{(x,y)}\,f_{(z)}\,q_{(t)}$$



$$I_{(a)} = I_{(0)}(1-R)$$

the (maximum) laser light intensity not reflected from surface (z=0).

$g_{(x,y)}$ the intensity distribution of the laser light in the xy-plane.

heat distribution in depth

$$f_{(z)} = \alpha(T(z))\exp\left[-\int_0^t \alpha(T(z'))dz'\right]$$

in simplified case α(T)=const

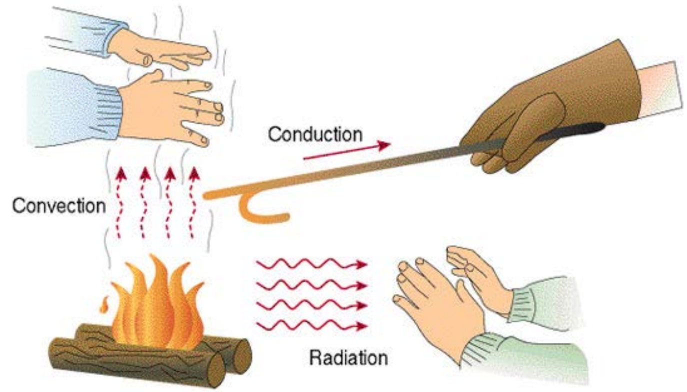
$$f_{(z)} = \alpha\exp(-\alpha z)$$

Heat Losses and Other Terms

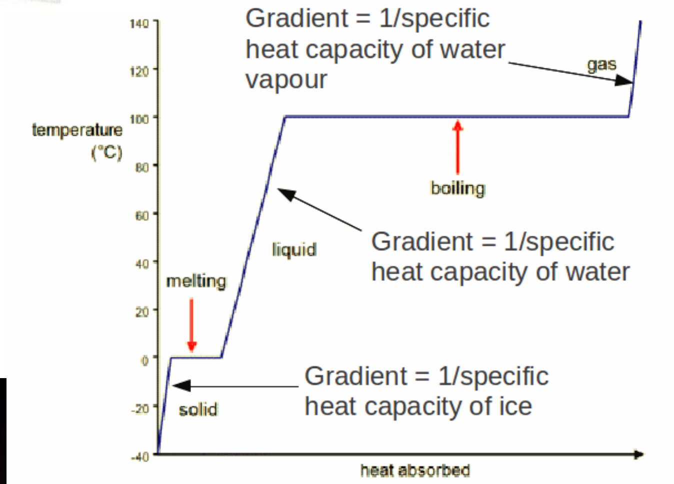
Conduction

Convection

Radiation



Phase transitions



Chemical reactions

Free Convection

$$\eta = \eta(T)$$

$$\eta(T_s) = \eta_0 ' \left(\frac{T_s - T_m(\infty)}{T_m(\infty)} \right)^{\frac{1}{4}}$$

For surface A > 1cm²

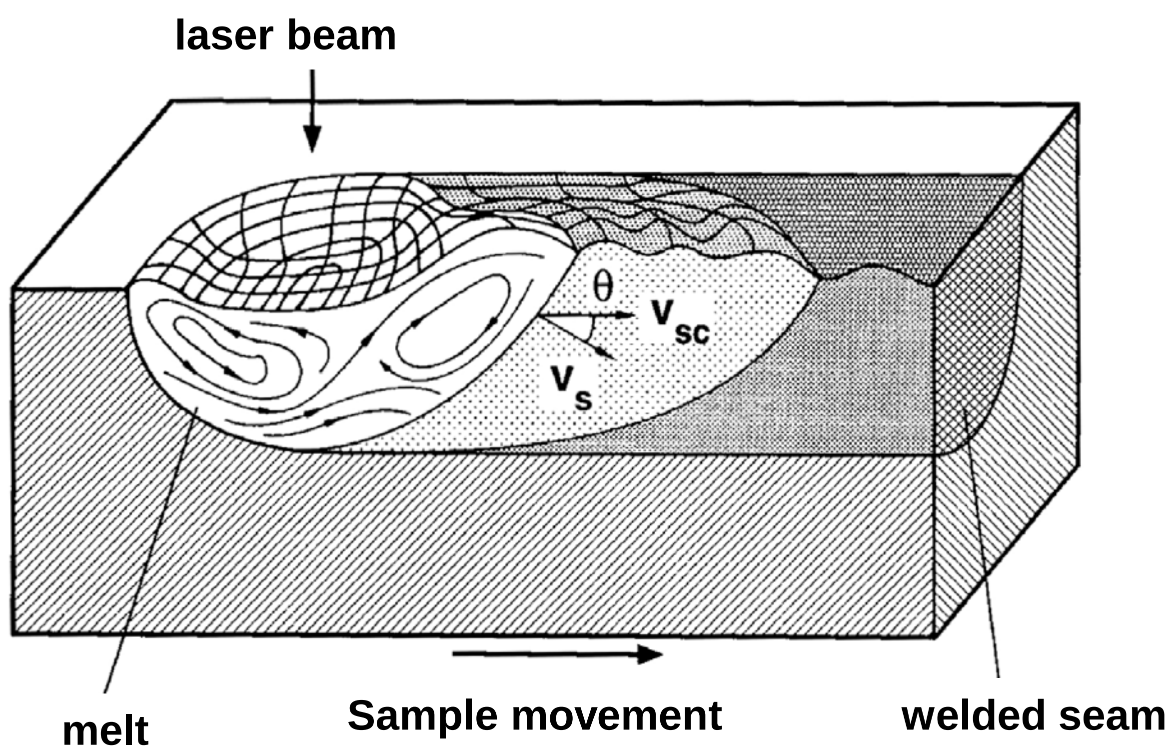
air $\eta_0 ' \approx 10^{-4} \left[W / cm^2 K \right]$

liquid $\eta_0 ' \approx 0.1 - 0.3 \left[W / cm^2 K \right]$

cooling by gas convention is not very efficient

Laser Welding

Liquid convection still plays an important role in “slow” processes.
e.g. welding (drilling, cutting)



Radiation Cooling

Stefan–Boltzmann law

$$J_{radiat.} = \sigma \cdot \varepsilon \cdot T^4$$

Stefan-Boltzmann constant: $\sigma = 5.7 \cdot 10^{-12} \left[\frac{W}{cm^2 K^4} \right]$

Total emissivity: $\varepsilon \equiv \varepsilon(T)$

polished metal: $\varepsilon \approx 0.02 - 0.05$

oxidized metal: $\varepsilon \approx 0.6 - 0.7$

glass, silica: $\varepsilon \approx 0.93$

soot: $\varepsilon \approx 0.98$

increases very strongly with temperature!!!

maybe important in some cases.

Phase changes & Chemical reactions

$$Q_{phase.trans.} = v_{solid-liquid} \cdot \Delta H_{melting} + v_{liquid-gas} \Delta H_{vaporasation}$$

ΔH_m= 2-10 kcal/mol ΔH_v= 50-100 kcal/mol

Comparison: Convection - Radiation

$$J_{loss} = J_c + J_r$$

$$J_{loss} = \eta\left[T_s(x,y,0,t) - T_m(\infty)\right] + \sigma_r \varepsilon_t \left[T_s^{\,4}(x,y,0,t) - T_m^{\,4}(\infty)\right]$$

Example: emissivity 0.4

$$\text{At}: \quad T_s = 1000K \qquad J_c \approx J_r \cong 3\left[W / cm^2\right]$$

Cooling/heating terms

- Convection may place a role for cooling of the whole machined piece of material – not relevant for machining

- Radiation maybe have contribution at very high temperatures

- In most cases cooling of the laser machined region takes place by heat conduction in the piece

Thermal Penetration Depth

- Pulsed laser irradiation results in a temperature rise in the material to a limited depth.

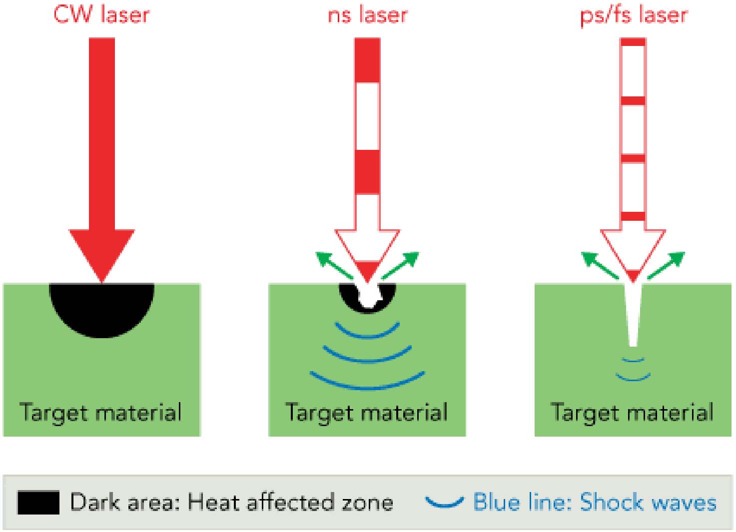
Thermal penetration depth

$$l_{thermal} = 2\sqrt{D\tau_{pulse}}$$

Heat diffusivity

$$D = \frac{\kappa}{\rho\, Cp}$$

κ – heat conductivity
ρ – material density
C_p – heat capacity



Heat equation moving substrate

heating of the material | heat brought by moving | heat conducted away

$$Q(\vec{x},t) = \rho(T)c_p(T)\frac{\partial T(\vec{x},t)}{\partial t} - \nabla[\kappa(T)\nabla T(\vec{x},T)] - \rho(T)c_p(T)v_s\nabla T(\vec{x},t)$$

$Q(x,t)$ $[\mathrm{W/cm^3}]$ = Heat source

= Energy deposited, consumed or absorbed by unit of volume

$\rho(T)$ $[\mathrm{g/cm^3}]$ = Mass density

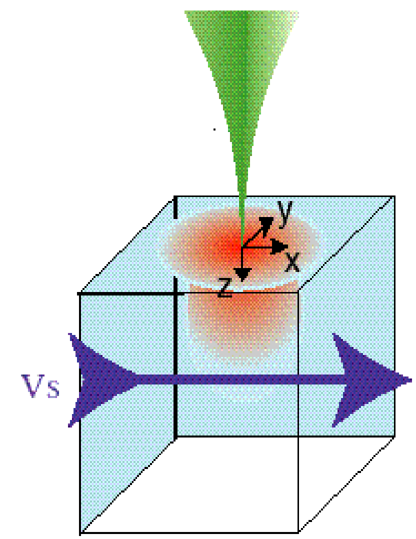
$c_p(T)$ $[\mathrm{J/gK}]$ = Specific heat at constant pressure

v_s $[\mathrm{cm/s}]$ = Relative speed of sample to beam

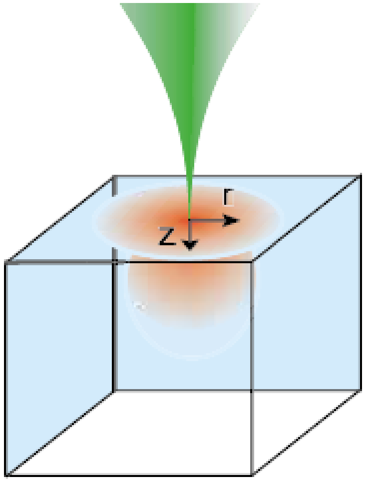
κ $[\mathrm{W/cm\ K}]$ = Thermal conductivity

D $[\mathrm{cm^2/s}]$ = Heat diffusivity

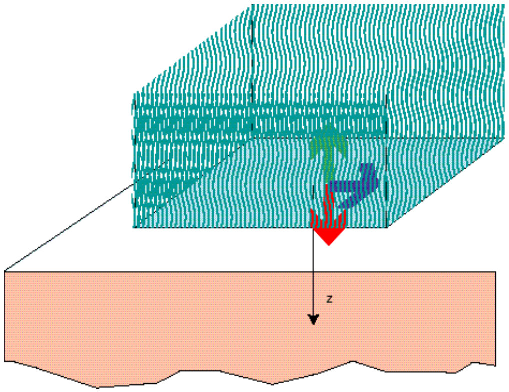
$$D = \frac{\kappa}{\rho c_p}$$



Heat flow in 3 dimension



$$\frac{\partial T}{\partial t} = D\nabla^2 T + \frac{Q}{\rho c_p}\delta(\vec{x}, t)$$



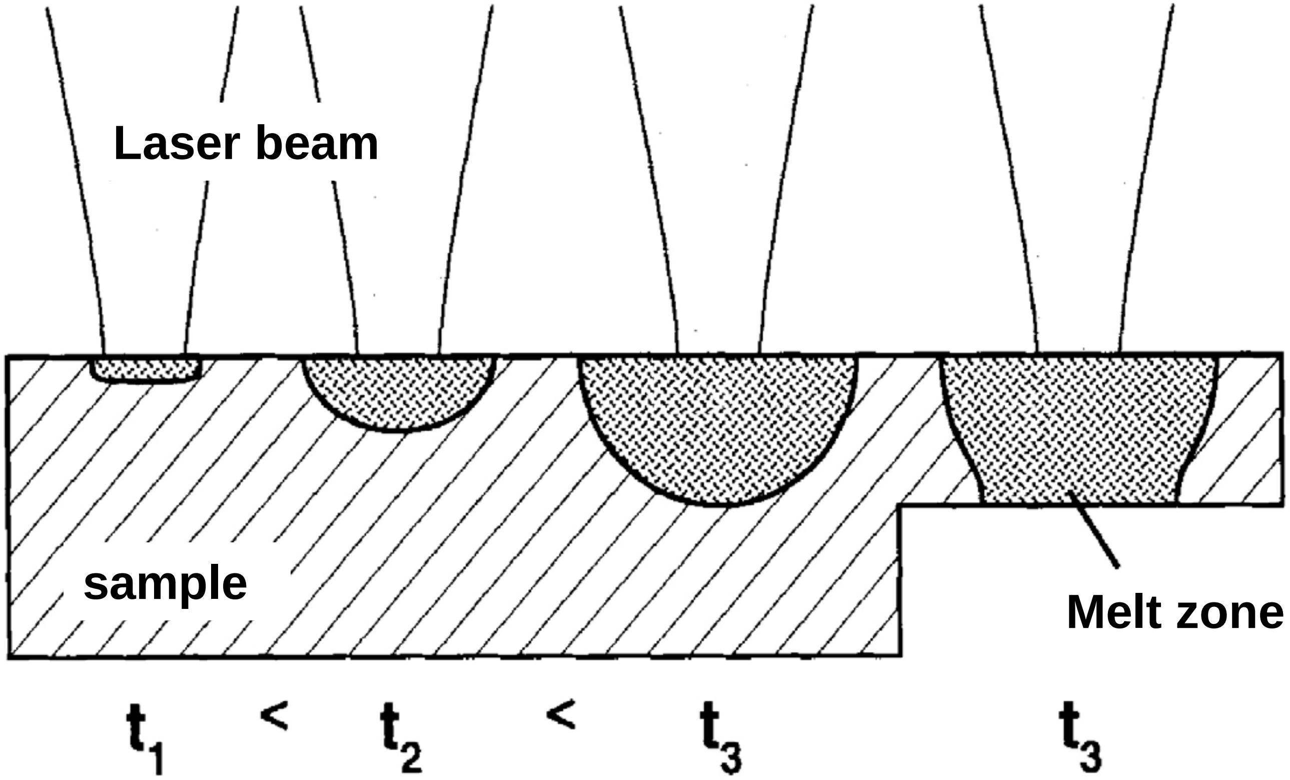
Solution:

$$T(x,t) \approx \frac{Q}{\rho c_p (4\pi D t)^{m/2}} \exp\left(-\frac{|x|^2}{4Dt}\right)$$

m = dimension of problem (m = 1, 2, 3)
Q = total energy deposited
ρ = mass density per distance, surface or volume (g/cm^m)

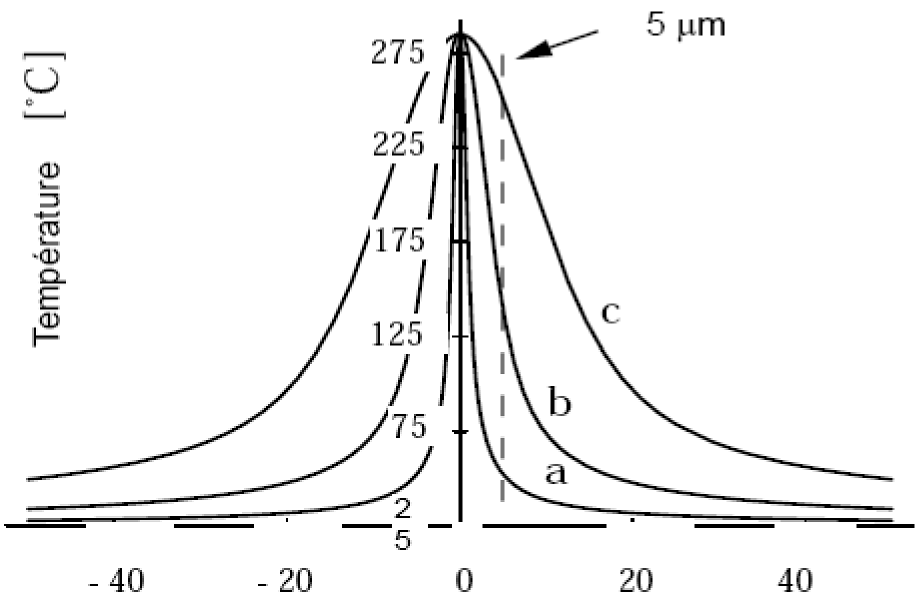
Laser Welding

What is the dimensionality of the heat flow problem at each of the stages?



Result of linearized heat equation

- Semi-infinite substrate
- Si, λ = 514 nm
  - All optimized to get T_{max} in center of 287°C

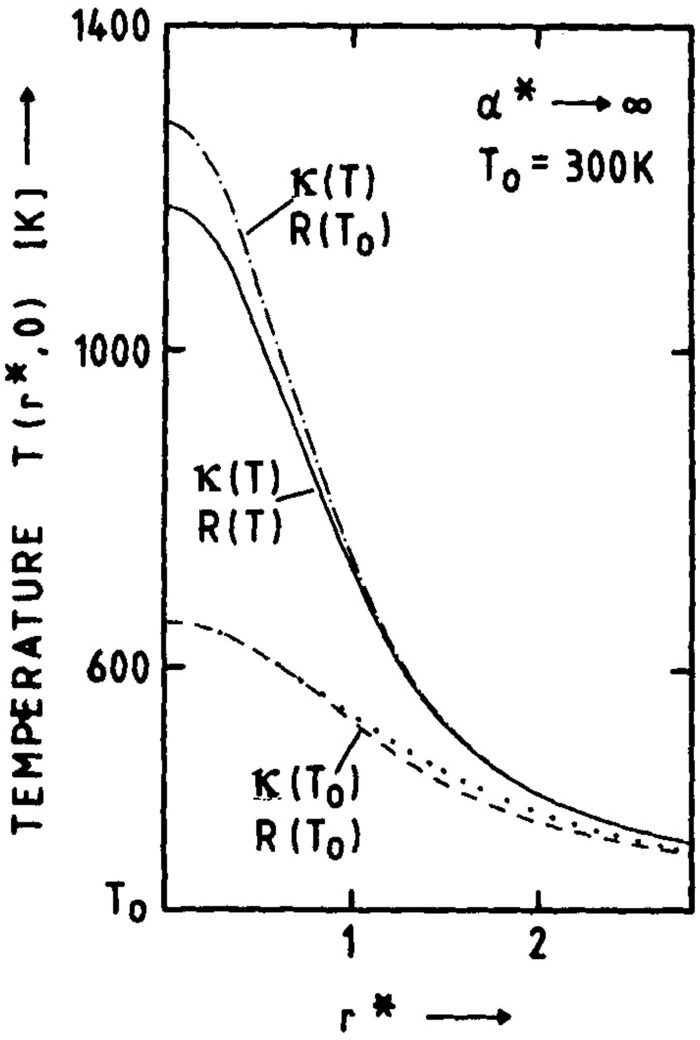


Distance from spot center r (μm)

case	Waist w_0 (μm)	Power (mW)
a	1	173.5
b	5	574
C	15	1535

Result of numerical heat flow simulations

- Semi-infinite substrate
- Si, λ = 514 nm



temperature dependence of heat conductivity and reflectivity is important to consider!!!!

Heat Accumulation - Effect of the Repetition Rate

Photoresist Vacrel 8230
α~5000cm^{-1}@308nm – deep light penetration
effect visible at low rep.rate

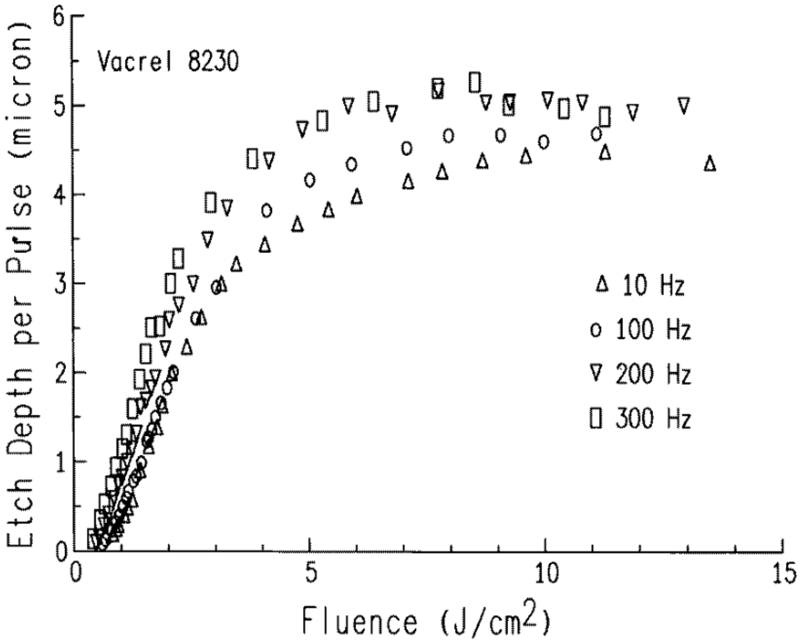


Figure 3. Ablation etching rate curves for Vacrel™ 8230 photoresist measured at 308 nm and 10, 100, 200 and 300 Hz. There is a clear shift in the ablation etching rate curves to lower fluence as the repetition rate increases.

Polyimide
α~10^{5}cm^{-1}@308nm - absorption on the surface
Effect will be visible only at high rep.rate

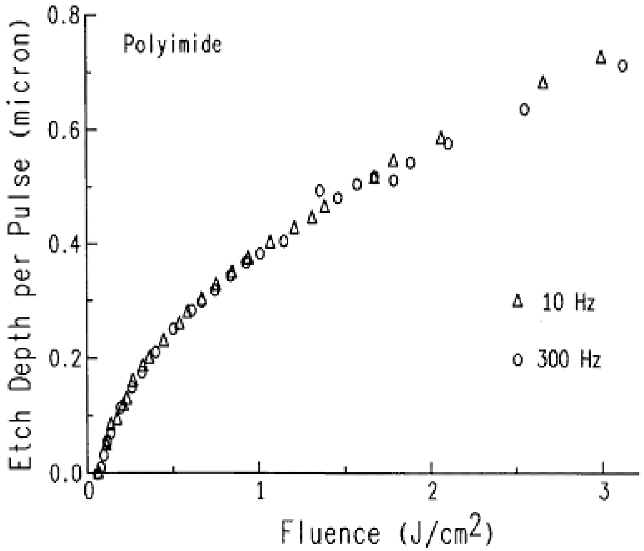


Figure 2. Ablation etching rates for polyimide measured at 308 nm and 10 and 300 Hz. There is no repetition rate effect for polyimide in this range of repetition rates.

Heat Accumulation

Polyimide
$\alpha \sim 10^5 cm^{-1}$@308nm - absorption on the surface
Effect will be visible only at high rep.rate

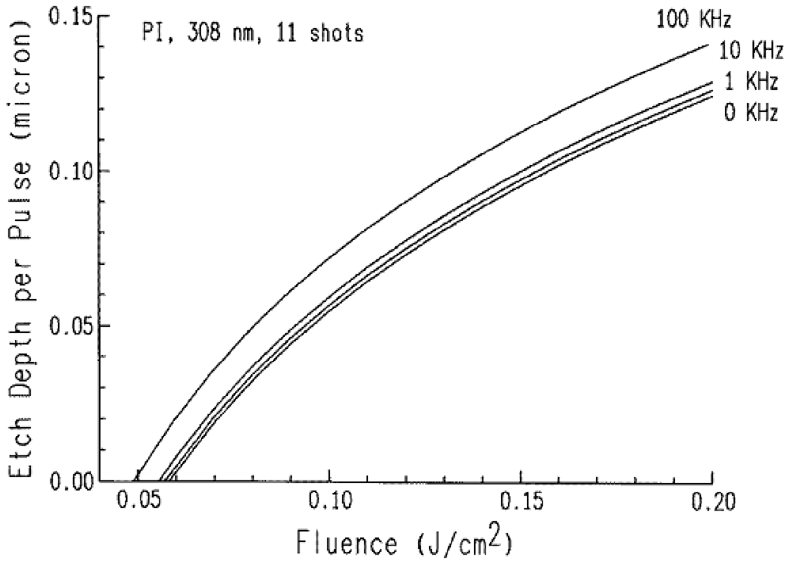


Figure 6. The simulated etching rate versus fluence for PI at 308 nm. Curves for repetition rates of 0, 1 and 10 kHz are closely grouped.

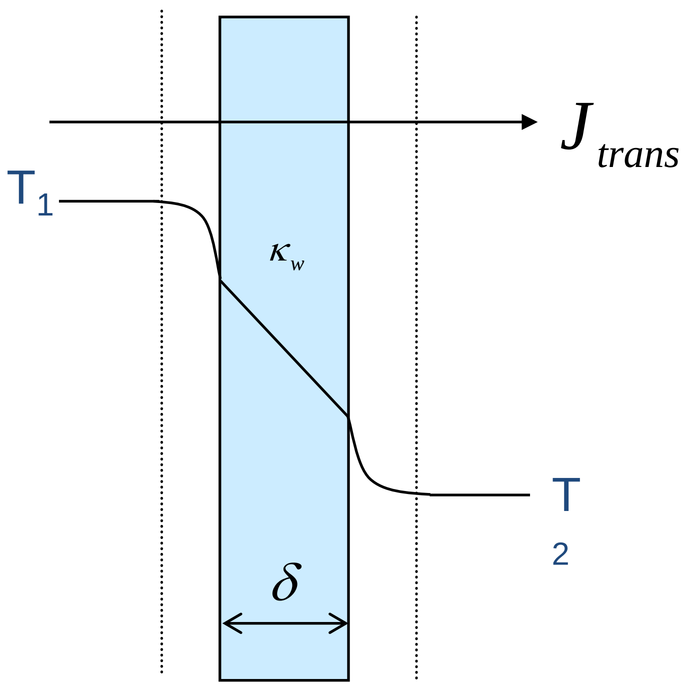
high repetition rate ν results in heat accumulation effect and increase in ablation rate

$$\nu \approx 0.1 D \alpha_{eff}^2 / N$$

Burns F.C. and Cain S.R.;
J. Phys. D. Appl. Phys., 29 (1996) 1349

Complete heat transfert through wall/window

$$J_{trans} = A(T_1 - T_2)\eta_{trans} \qquad J_{trans} : [J/s = W]$$

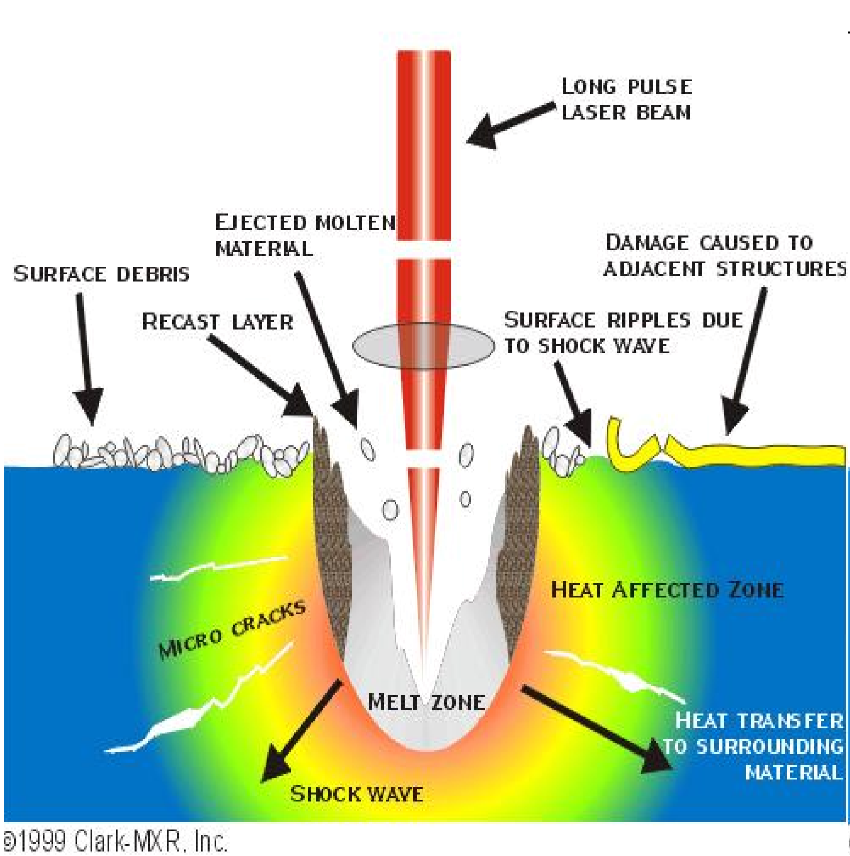


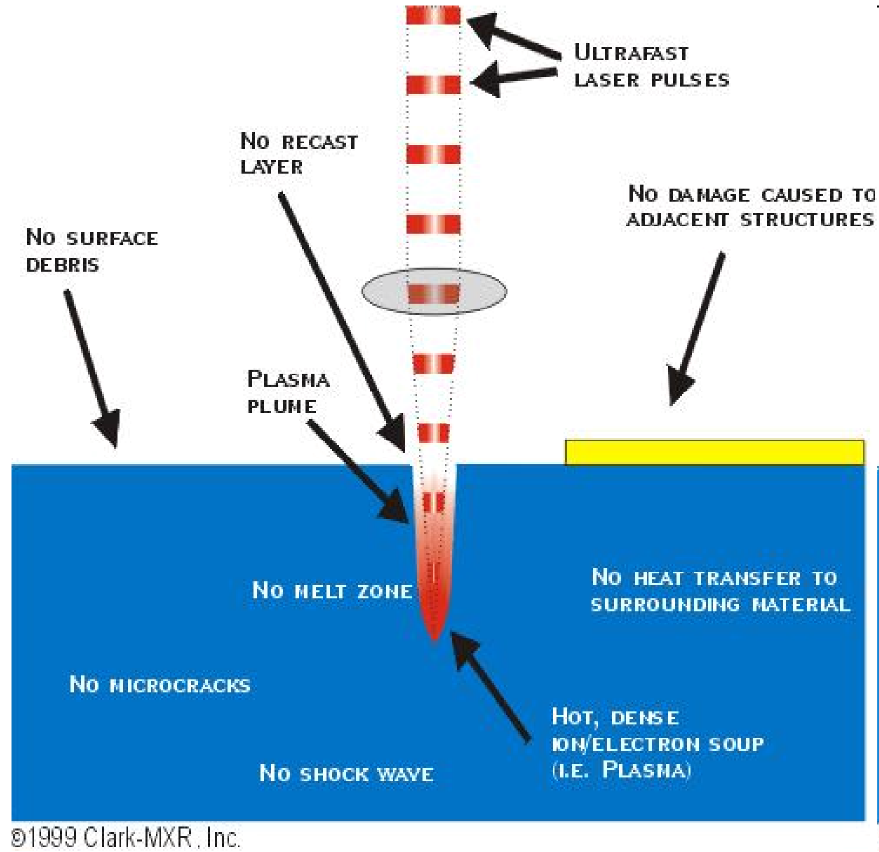
$$\eta_{trans} = \frac{1}{\frac{1}{\eta_1} + \frac{\delta}{\kappa_w} + \frac{1}{\eta_2}} \left[\frac{J}{cm^2 sK}\right]$$

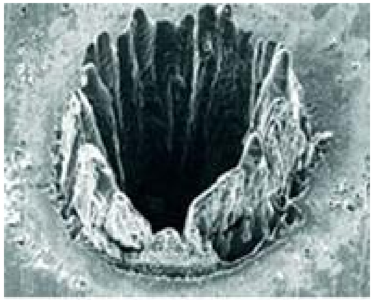
window $\eta_{trans} = 2 \cdot 10^{-4} \left[W/cm^2 K\right]$

wall $\eta_{trans} = 0.5 \cdot 10^{-4} \left[W/cm^2 K\right]$

ns-machining vs. fs-machining





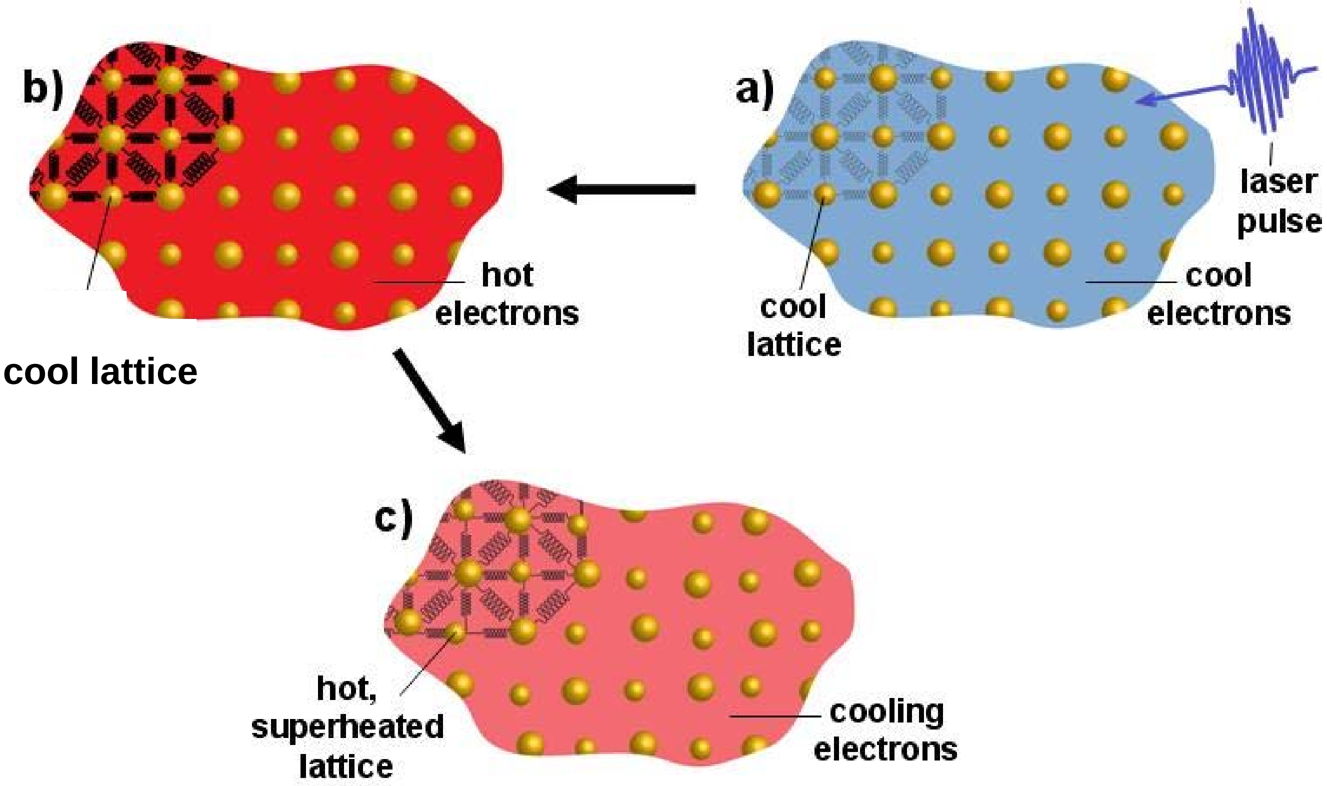


ns

fs

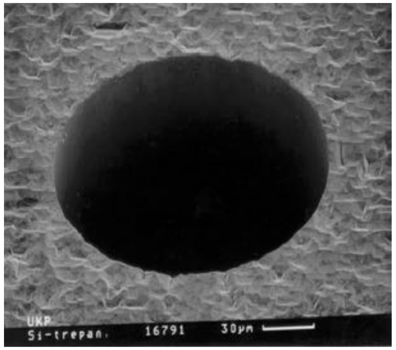
Ultrafast Laser Pulses

for **τ<1-10 ps** pulses - light absorption is faster than heat transfer from electron to atoms

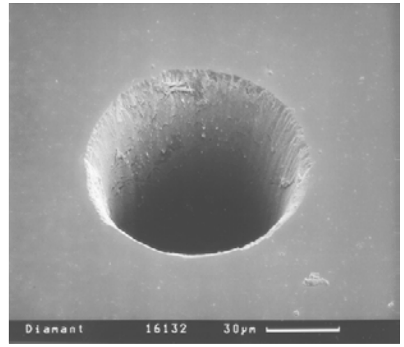


heating rate is very high – heat penetration is low $l_{th} \approx 2(D\tau_l)^{1/2}$

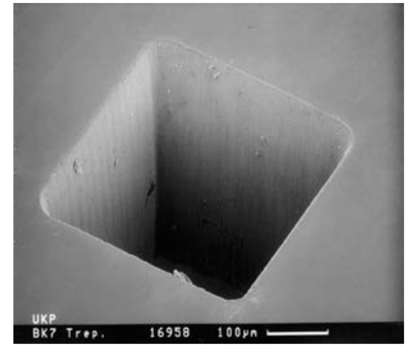
fs-laser machining



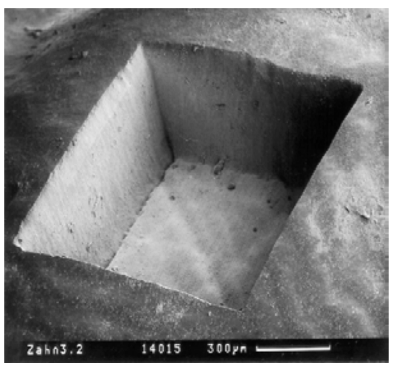
Silizium



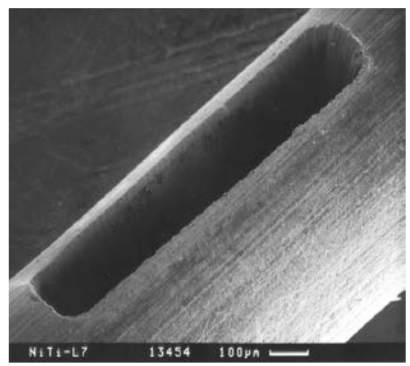
Diamant



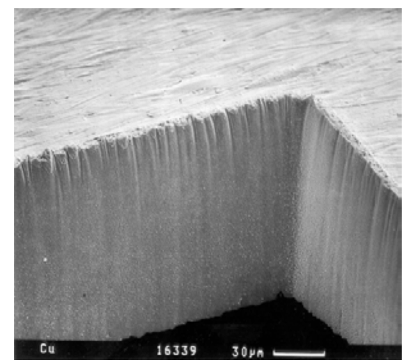
Glas



Zahnschmelz



Speziallegierungen



Kupfer

LASER ZENTRUM HANNOVER E.V.