Laser Beam Interactions with Solids

- In absorbing materials photons deposit energy

$$E = h\nu = \frac{hc}{\lambda}$$

where h = Plank's constant = 6.63 x 10^{-34} J s
c = speed of light

- Also photons also transfer momentum p

$$p = \frac{h}{\lambda}$$

- Note: when light reflects from a mirror momentum transfer is doubled
- eg momentum transferred from Nd:YAG laser photon hitting a mirror (λ= 1.06 microns)

$$p = \frac{h}{\lambda} = \frac{2\left(6.6x10^{-34}\right)}{1.06x10^{-6}} = 1.25x10^{-27}\,kg\ m/s$$

- Not very much but 1 KW for 1 sec has $5x10^{21}$ photons
  force of $6.25x10^{-6}$ N
- Proposed for Solar Light Sails in space (get that force/sq m of sail) small acceleration but very large velocity over time.

Absorbing Solids

- Beam absorbed as it enters the material
- For uniform material follows Beer Lambert law

$$I(z) = I_0\, exp(-\alpha\, t)$$

where $\alpha = \beta$ = absorption coefficient (cm^{-1})

- absorption coefficient dependent on
  wavelength, material & intensity
- High powers can get multiphoton effects
- Rayleigh scattering, Brillouin scattering, Raman scattering

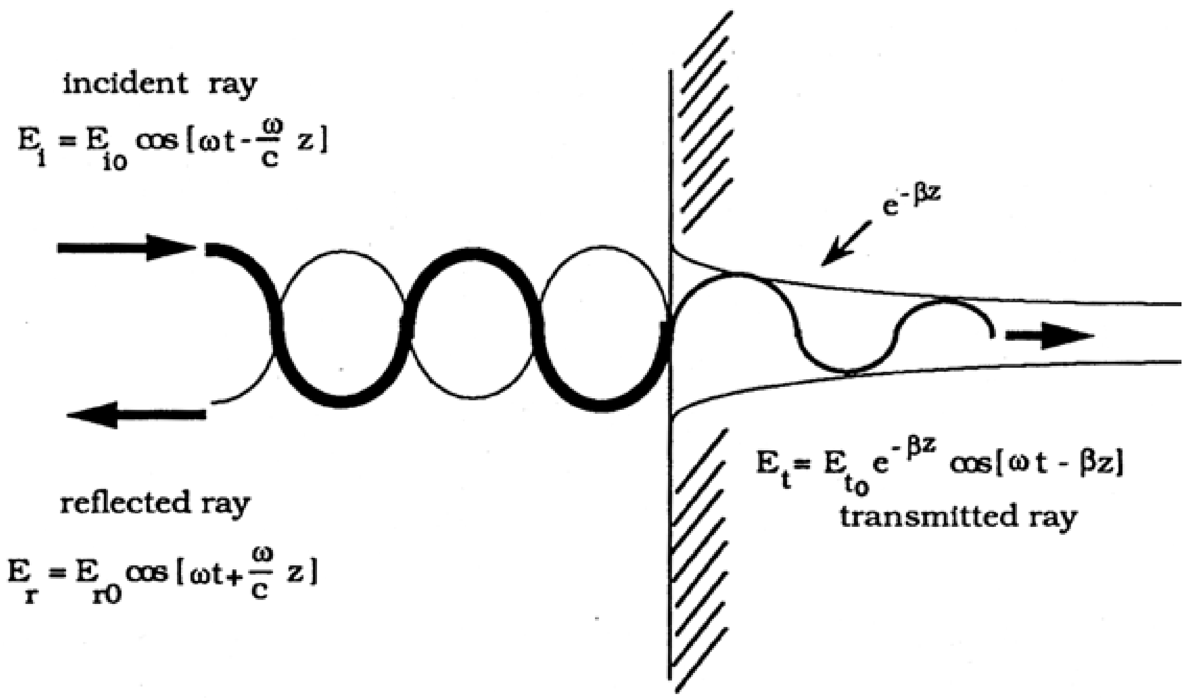
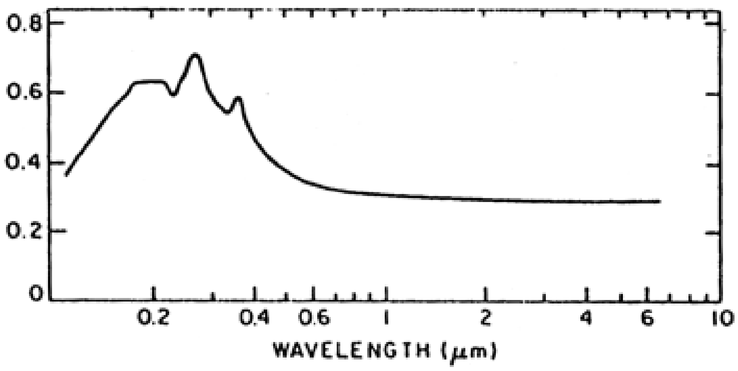


Fig. 2.1. The phase and amplitude of an electromagnetic ray striking an air/solid interface and undergoing reflection and transmission.

Single Crystal Silicon

- Absorption Coefficient very wavelength dependent
- Argon light 514 nm α = 11200/cm
- Nd:Yag light 1060 nm α = 280/cm
- Hence Green light absorbed within a micron
  1.06 micron penetrates many microns
- Very temperature dependent
- Note: polycrystalline silicon much higher absorption
  : at 1.06 microns α = 20,000/cm



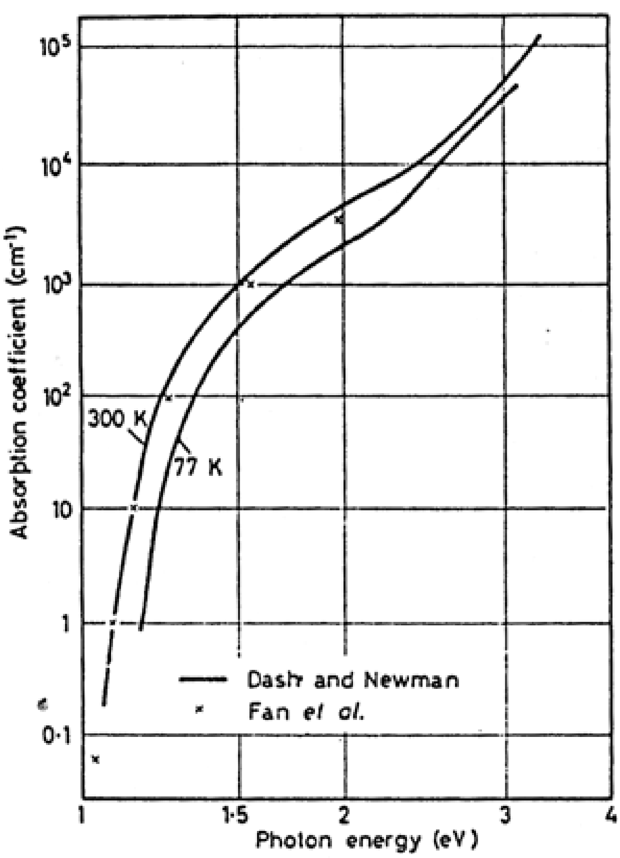


Fig.2.8. (a) Optical reflectivity, and (b) absorption coefficient of single crystal silicon [2.89,90],

Absorption Index

- Absorbing materials have a complex index of refraction

$$n_c = n - ik \qquad v = \frac{c}{n_c}$$

where n = real index of refraction

k = absorption index or extinction coefficient

- The Electric field then becomes

$$E(t,z) = E_0\, exp\left(i\left[\omega\, t - \frac{\omega\, nz}{c} \right] \right) exp\left(-\frac{\omega\, kz}{\lambda} \right)$$

- The k can be related to the absorption coefficient by

$$\alpha = \frac{4\pi\, k}{\lambda}$$

where wavelength is the vacuum value

Table 2.2. The optical functions of c-Si (n and R, ϵ_1 and ϵ_2) together with the optical absorption coefficient α, and the calculated normal-incidence reflectivity R at several wavelengths. Also shown are the parameters relevant to the empirical fit to $\alpha(T)$ [2.10,11]

Laser	n	k	ϵ_1	ϵ_2	α [1/cm]	R
Ruby	3.763	0.013	14.16	0.10	2.4×10^3	0.336
HeNe (633nm)	3.866	0.018	14.95	0.14	3.6×10^3	0.347
double Nd:YAG (530nm)	4.153	0.038	17.24	0.32	9.0×10^3	0.374
Argon (514nm)	4.241	0.046	17.98	0.39	1.12×10^4	0.382
Argon (488nm)	4.356	0.064	18.97	0.56	1.56×10^4	0.392
N2-pumped dye (485nm)	4.375	0.066	19.14	0.58	1.71×10^4	0.394
Argon (458nm)	4.633	0.096	21.45	0.89	2.64×10^4	0.416
N_2-pumped dye (405nm)	5.493	0.290	30.08	3.19	9.01×10^4	0.479
triple Nd:YAG (355nm)	5.683	3.027	23.13	34.41	1.07×10^6	0.575
N_2	5.185	3.039	17.65	31.51	1.12×10^6	0.560
XeCl	4.945	3.616	11.37	35.76	1.48×10^6	0.587

Absorption Index & Electrical Parameters

- k and n are related to the dielectric constant ε and the conductivity σ of the material

$$n^2 - k^2 = \varepsilon$$

$$nk = \frac{\sigma}{\nu}$$

where ν= the frequency

- High conductivity Metals have high k relative to n: hence high R
- Note n can be less than 1 for absorbing materials but n_c>1
- Insulators: k=0 when transparent

Table 2.2.

Complex refractive index and reflection coefficient for some materials to 1.06μm radiation (8).

Material	k	n	R
Al	8.50	1.75	0.91
Cu	6.93	0.15	0.99
Fe	4.44	3.81	0.64
Mo	3.55	3.83	0.57
Ni	5.26	2.62	0.74
Pb	5.40	1.41	0.84
Sn	1.60	4.70	0.46
Ti	4.0	3.8	0.63
W	3.52	3.04	0.58
Zn	3.48	2.88	0.58
Glass	0	1.5	0.04

Opaque Materials

- Materials like metals have large numbers of free electrons
- High conductivity, reflectivity and absorption
- Reflectivity given by (for normal incidence of light)

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

- For opaque materials light absorbed A is

$$A = 1 - R$$

- R and k are very wavelength dependent
- Also these are very dependent on
  the absence of other materials from the surface.

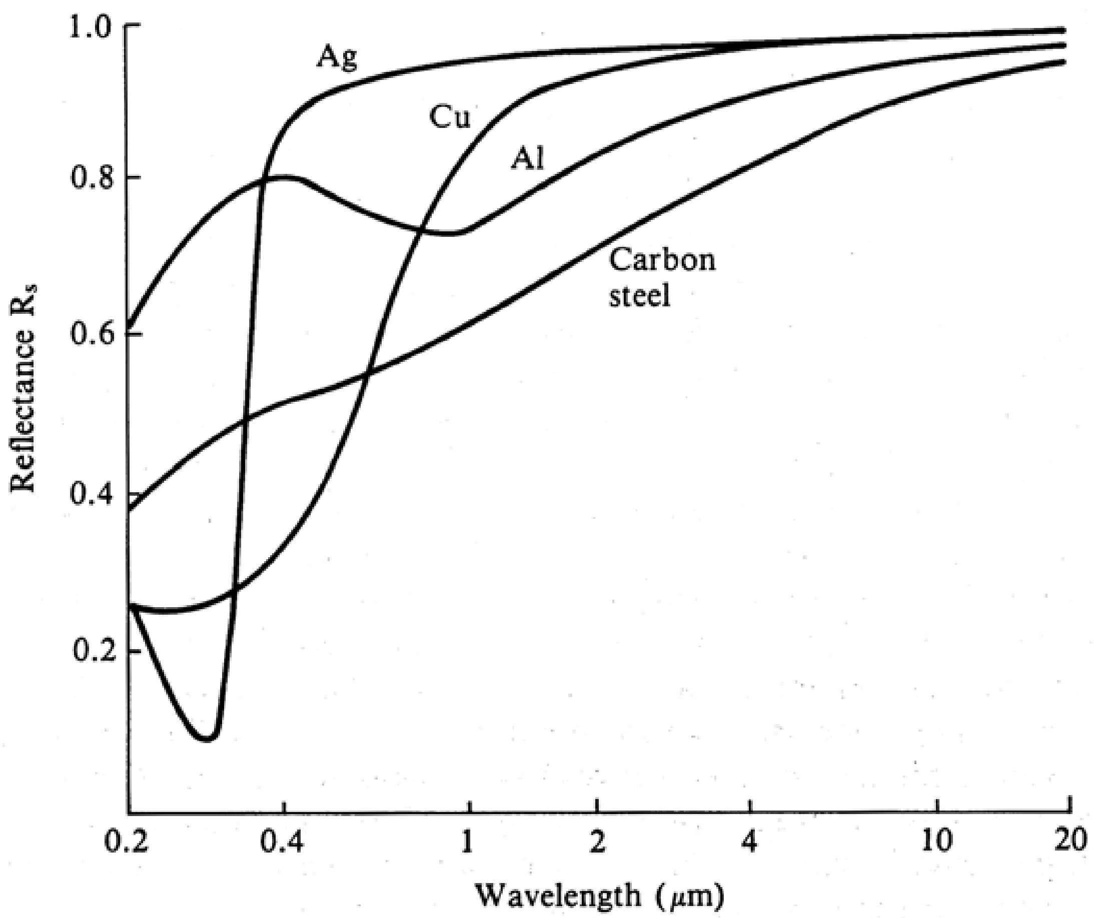


Fig. 5.1 Reflectance versus wavelength for various polished metal surfaces.

Temperature Dependence

- Absorption and reflectivity are very temperature dependent
- Often undergo significant changes when material melts
- eg Silicon, steel becomes highly reflective on melting

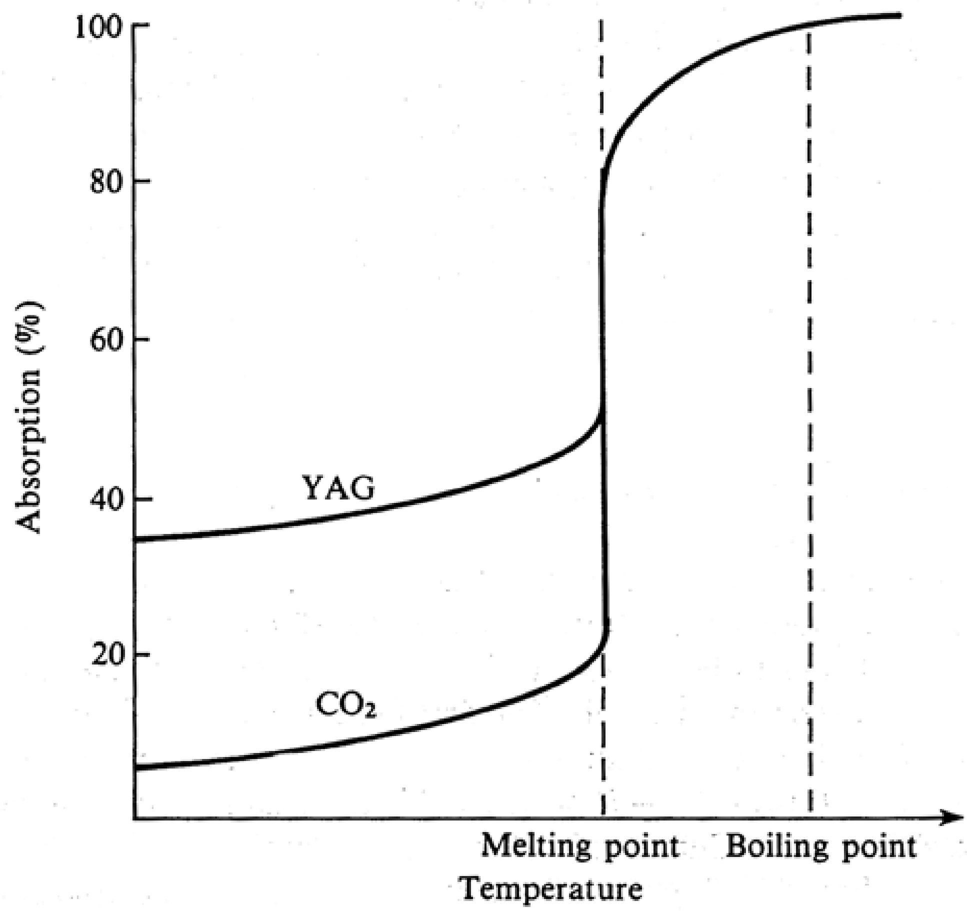


Fig. 5.2 Schematic variation of absorption with temperature for a typical metal surface for both the YAG and CO_2 laser wavelengths.

Laser Processing of Materials

- Use the laser as a local heat source for most applications

Basic Processes

- Laser cutting (removing material)
- Laser Welding (joining materials)
- Laser heat treatment (modify materials)
- Laser disassociation (cause material to break down)

With increasing beam power the material

- Heats
- Melts
- Boils
- Forms a plasma (ionized material)

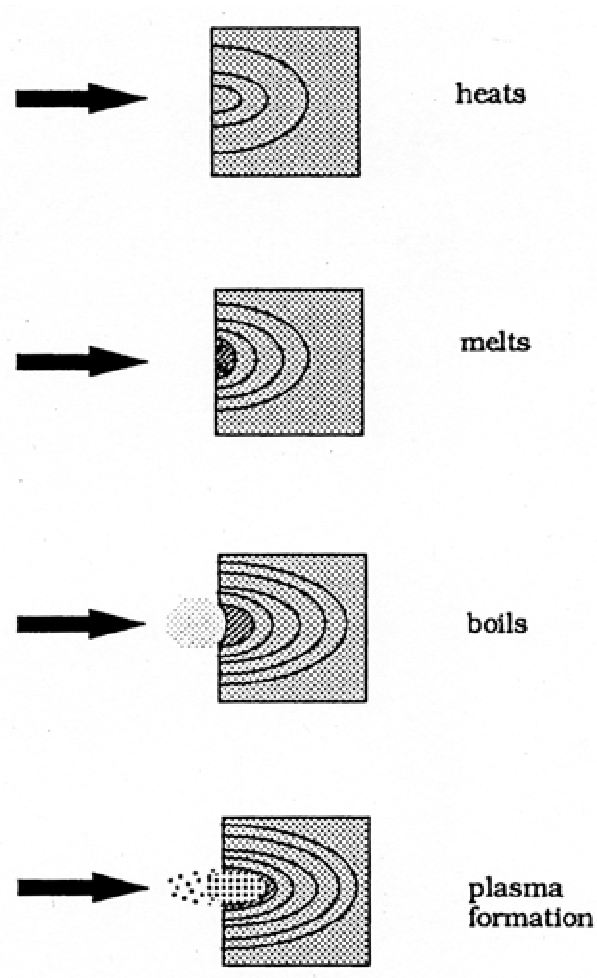


Fig. 2.4. Sequence of absorption events varying with absorbed power.

Laser Beam Impact on Surface

- Laser absorbed into the surface
- Creates local hot spot
- If hot enough melts to some depth
  (function of thermal and optical properties
- Material removed - forms keyhole in material
- Keyhole allows beam to penetrate further

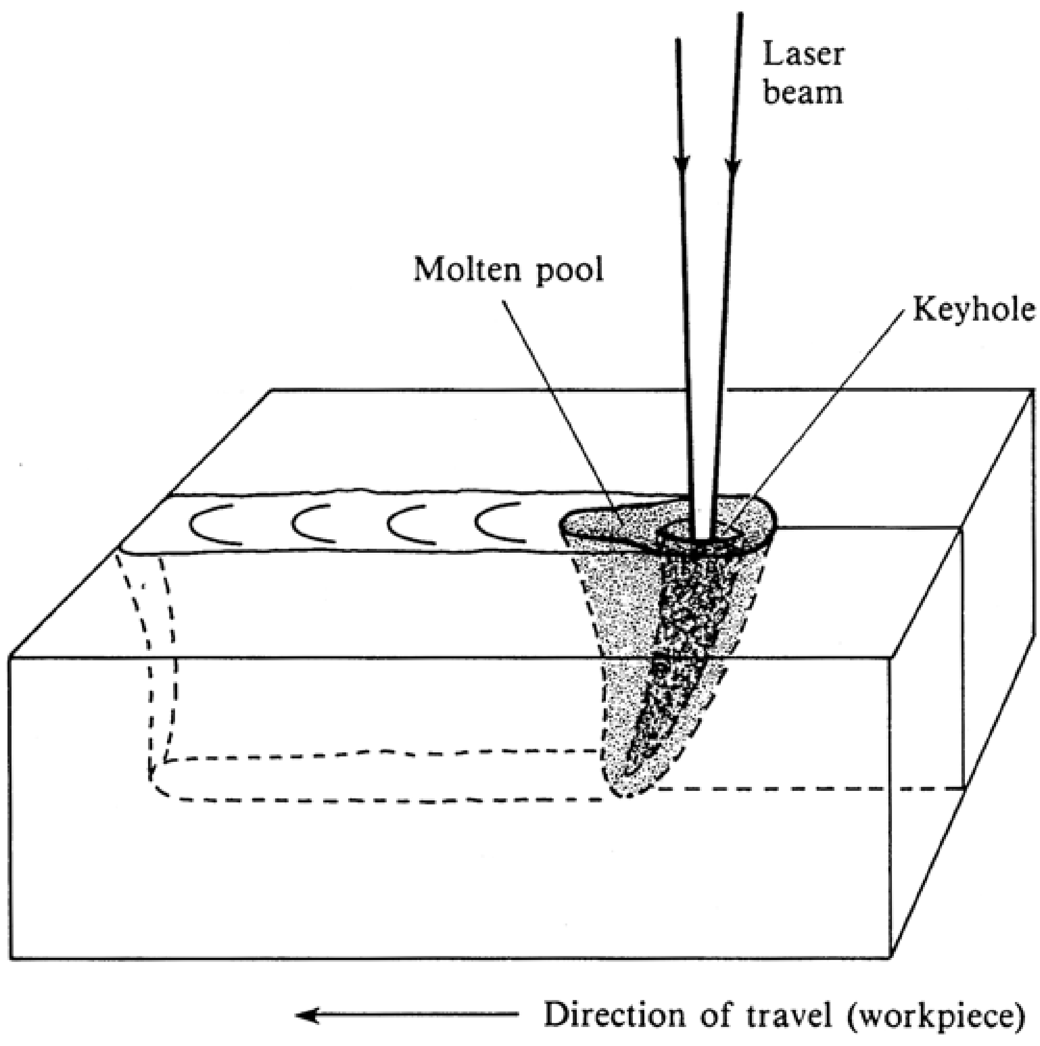


Fig. 5.15 Formation of a 'keyhole' during high-power laser welding.

Laser Cutting: Simple Thermal

- Six basic ways

Vaporization

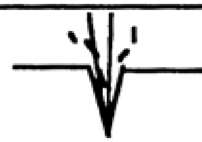
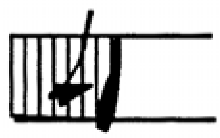
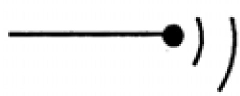
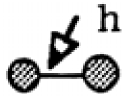
- beam heats local area above melting point
- material boils and ejects

Melting and Blowing

- Beam melts surface, jet of inert gas removes material

Burning in Reactive Gas

- Beam melts surface, jet of reactive gas removes material
- gas (usually oxygen) reacts with material, adds energy

Table 3.2.	Different ways in which the laser can be used to cut.	
Method	Concept	Relative Energy
1. Vaporisation		40–100
2. Melt and blow		20
3. Melt, burn and blow		10
4. Thermal stress cracking	Tension 	1
5. Scribing		1
6. "Cold cutting"	 hν High energy photons	100

Laser Cutting: Other Effects

Thermal stress Cracking

- Heat/cool cycle creates thermal stress, material breaks
- Requires least energy

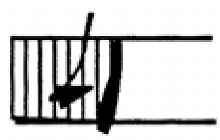
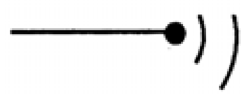
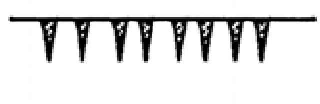
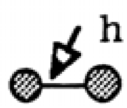
Scribing

- Cut creates small stress point, breaks with force

Cold Cutting

- Laser photons cause material to disassociate

Table 3.2. Different ways in which the laser can be used to cut.

Method	Concept	Relative Energy
1. Vaporisation		40 – 100
2. Melt and blow		20
3. Melt, burn and blow		10
4. Thermal stress cracking	Tension 	1
5. Scribing		1
6. "Cold cutting"	 High energy photons	100

Lasers in Microelectronics

- Laser cutting, heat processing
  widely used in microelectronics now
- Oldest application, resistor trimming
- Polysilicon resistors are deposited thin film resistors
- However polySi resistance varies considerably with process
- Use laser cutting to Trim resistance to desired values
- This is how A/D & D/A are made accurate
- Growing applications in laser microsurgery, defect avoidance

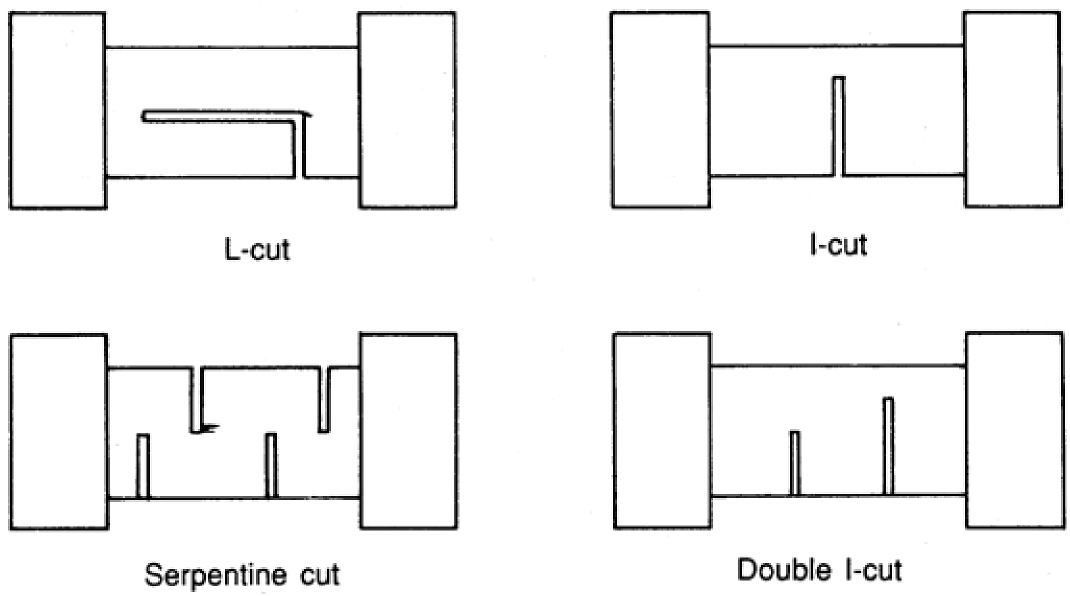


Fig. 5.7 Cut geometries for resistor trimming.

Laser Defect Correction

- Using laser circuit modification to make postfabrication changes in Integrated Circuits
- Generally cutting lines and making connections

Laser Microsurgery

- Repair defects on chip sized structures

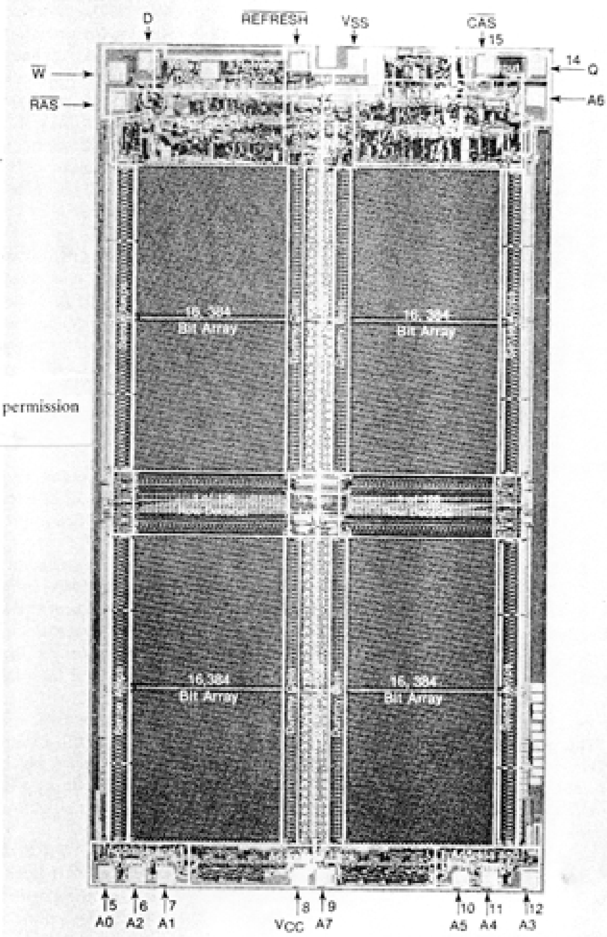
Laser process not part of original design

- Chip repair

Laser process as part of original design

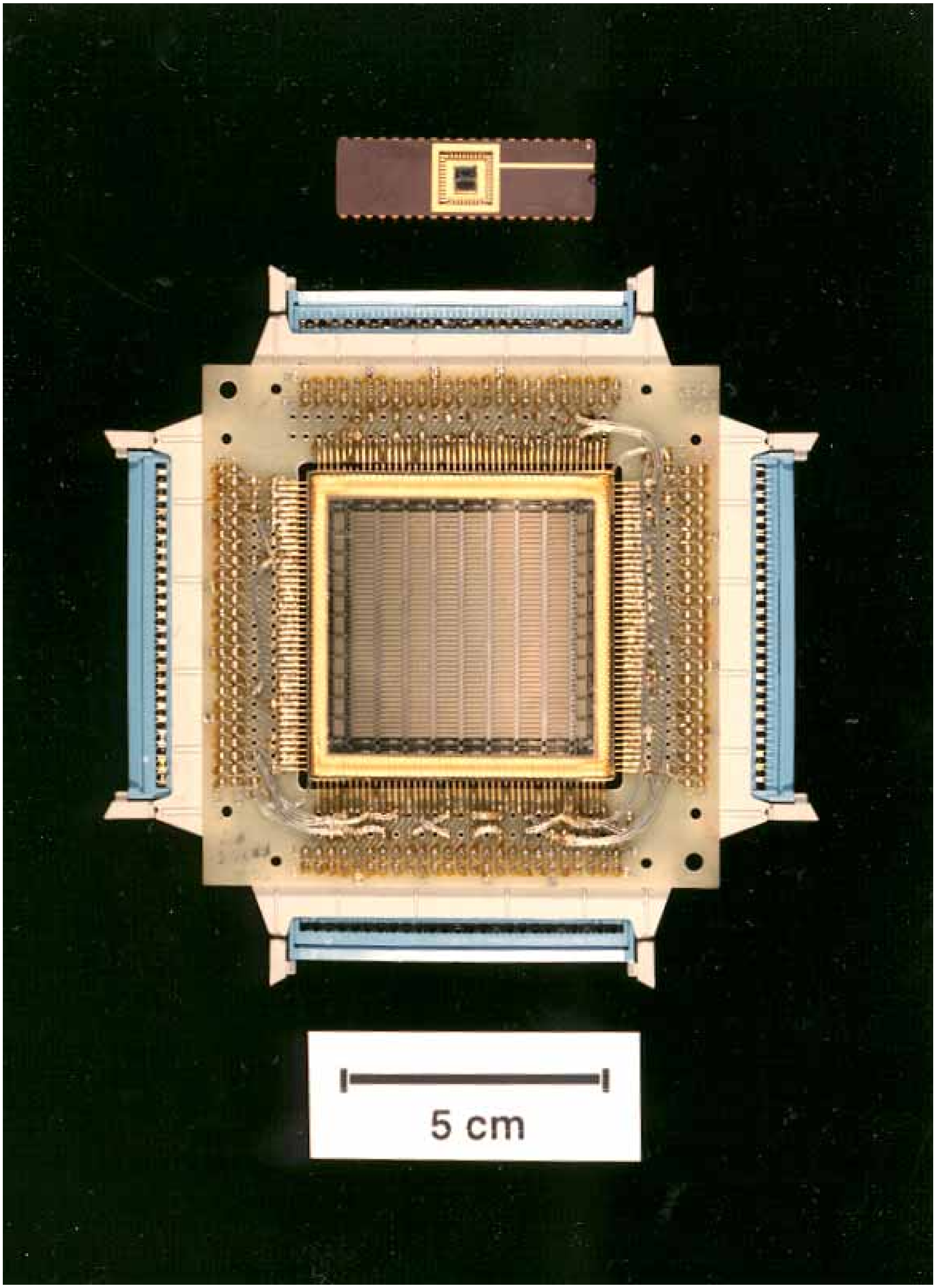
- Used at production repair process (eg DRAM's)
- Laser chip customization

64K Dynamic RAM die photograph. (Reproduced by permission of Motorola Inc.)



Wafer Scale Restructurable Silicon system

- Using laser corrections to build more complex systems
- System design integrated closely with the laser repair technique
- Done at Lincoln Lab in 1985



Laser Microsurgery

Reasons for Laser Microsurgery

- Shortening the Design to Working Device time line
- To remove defects that prevent circuit from working

Sources of Chips Defects that can be repaired

Power bus shorts

- Often not seen in DRC
- cut the power/ground connections

Design/circuit errors

- Circuit isolation to remove defects

Removal of processing errors

- Design errors (unexpected process errors)
- Random errors (expected random errors) eg DRAMS

Mask errors, Design correct

- Problems in mask fabrication
- Problems in design to mask generator software

Analysis of Field Chip Failures

- Requires removal of package
- Cut out circuit segments to identify failure points

Design Correct but chip Misbehaves

- Circuit appears to be correct but does not fully work
- Cut out segments to identify problems

Laser Line Cutting

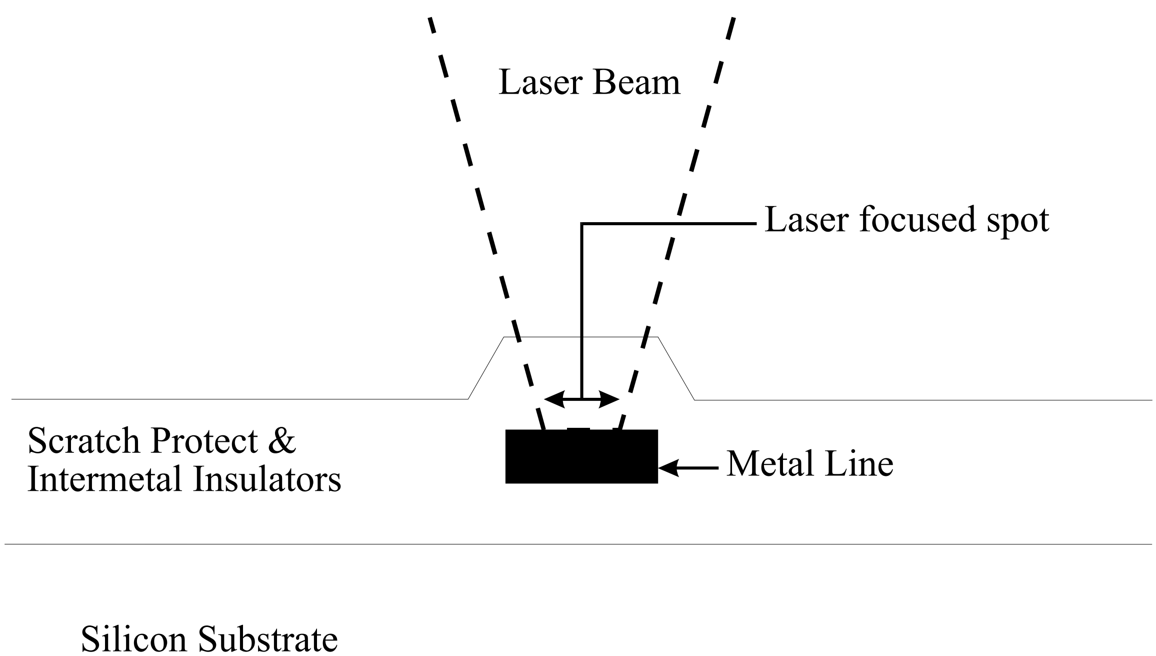
- Most used process in laser microsurgery
- Laser power used to segment signal/power lines
- Laser acts as a local heat source
- Cutting of
  - First and Second Metal
  - Polysilicon
- Call each laser pulse on a point a "Zap"
- Effects of intermetal insulators and scratch protect important
- Usually cause openings in Scratch Protect

Laser Line Cutting Parameters

Items affecting Laser cutting parameters

- Laser light power
- Focused Laser spot size for best operation
- Pulse duration of laser light
- Wavelength

Laser Line Cutting



Factors Affecting Laser Line Cutting Parameters

Power delivered to cut point

- Reflectivity/Absorption of light
- Thermal flow in line

Laser Light Wavelength

- Poly Silicon must be visible (usually Green)
- Metals have low wavelength sensitivity

Materials

- Metals highly reflective & high thermal conductivity
- Mixed alloys can significantly

Layer thicknesses

- Thicker metal layers, more heat flow
- Thicker intermetal layer below, less heat to substrate
- Thicker intermetal/insulator above: more power to move layer
- For partially absorbing (PolySi)
  thin layers mean less energy absorbed