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

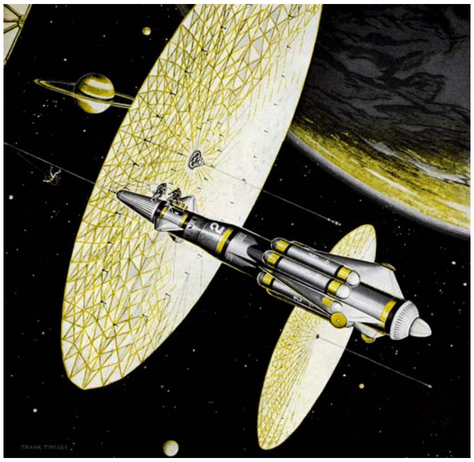
- Also photons also transfer momentum p

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

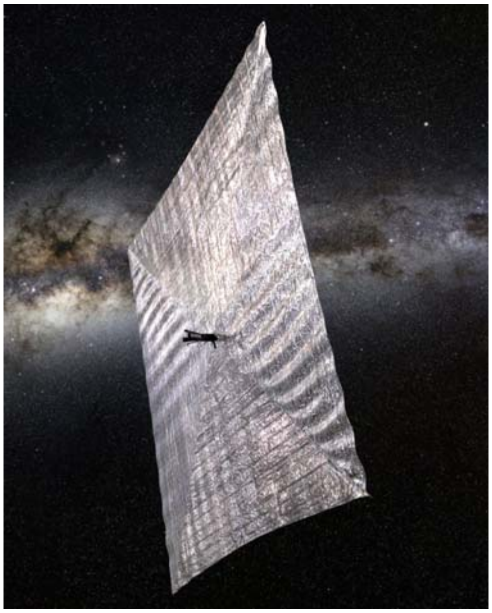
- Note: when light reflects from a mirror momentum transfer is doubled
- eg momentum transferred from Nd:YAG laser photon hitting a mirror (λ= 1.06 microns)

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

- Not very much but Sunlight 1 KW/m^2 for 1 sec =5x10^{21} photons
- Generates force of 6.25x10^{-6} N/m^2
- Solar Light Sails in space small acceleration
- Very large velocity – 67 Km/s in 3 years

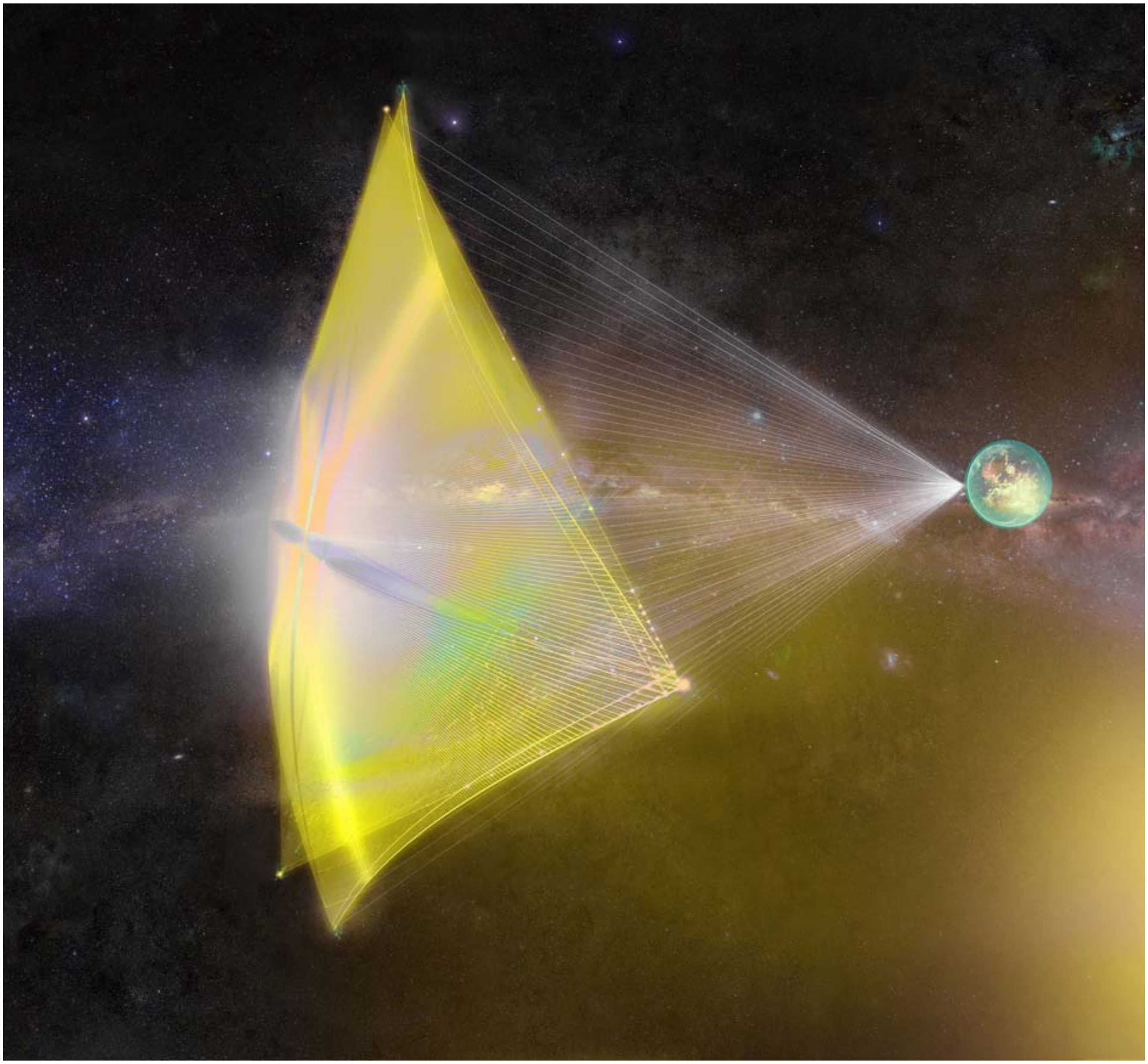


Planetary Society Lighsail 1 deployed
June 9-2015



Breakthrough Starshot

- Laser driven light Sail to Proxima Centura (4.2 light years)
- Target is planet Proxima Centura b
- Cargo is Starchip – 1 cm chip sized satellite
- Sail is only 5 m dia
- 1 sq Km Phased array of lasers totalling 100GW
- Accelerate at 100Km/s^2 until 20% light speed (6x10^7 m/s)
- Fleet of 1000 spacecraft



Absorbing Solids

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

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

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

- Absorption coefficient dependent on wavelength, material & intensity
- High powers can get multiphoton effects
- Rayleigh scattering, Brillouin scattering, Raman scattering
- Tissues, liquids, have low absorption but high scattering
- Add a scattering coefficient α_s & to absorption α_a & modify law

$$I(z) = I_0 \exp(-[\alpha_a + \alpha_s]z)$$

- I then is amount of light transmitted unscattered
- However scattered light still emerges but contains no information
- Turbid (scattering) media where $\alpha_s >> \alpha_a$ (100x greater)
- Most laser processing done on non-scattering materials $\alpha_s \sim 0$

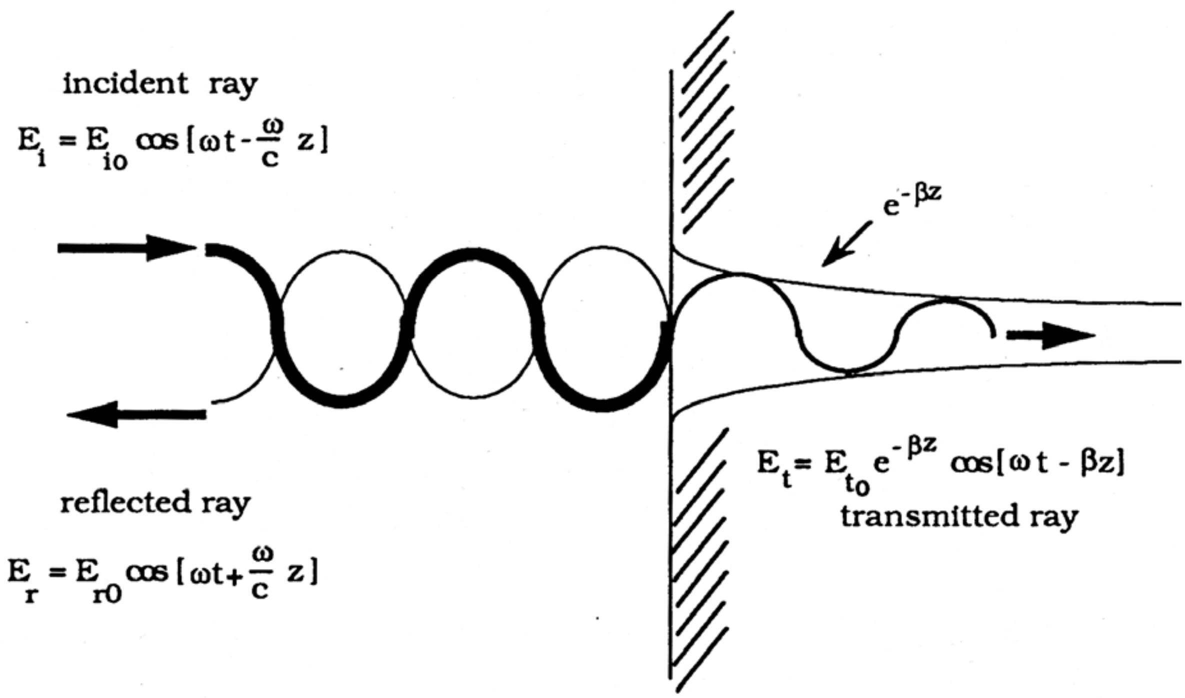


Fig. 2.1. The phase and amplitude of an electromagnetic ray striking an air/solid interface and undergoing reflection and transmission.

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

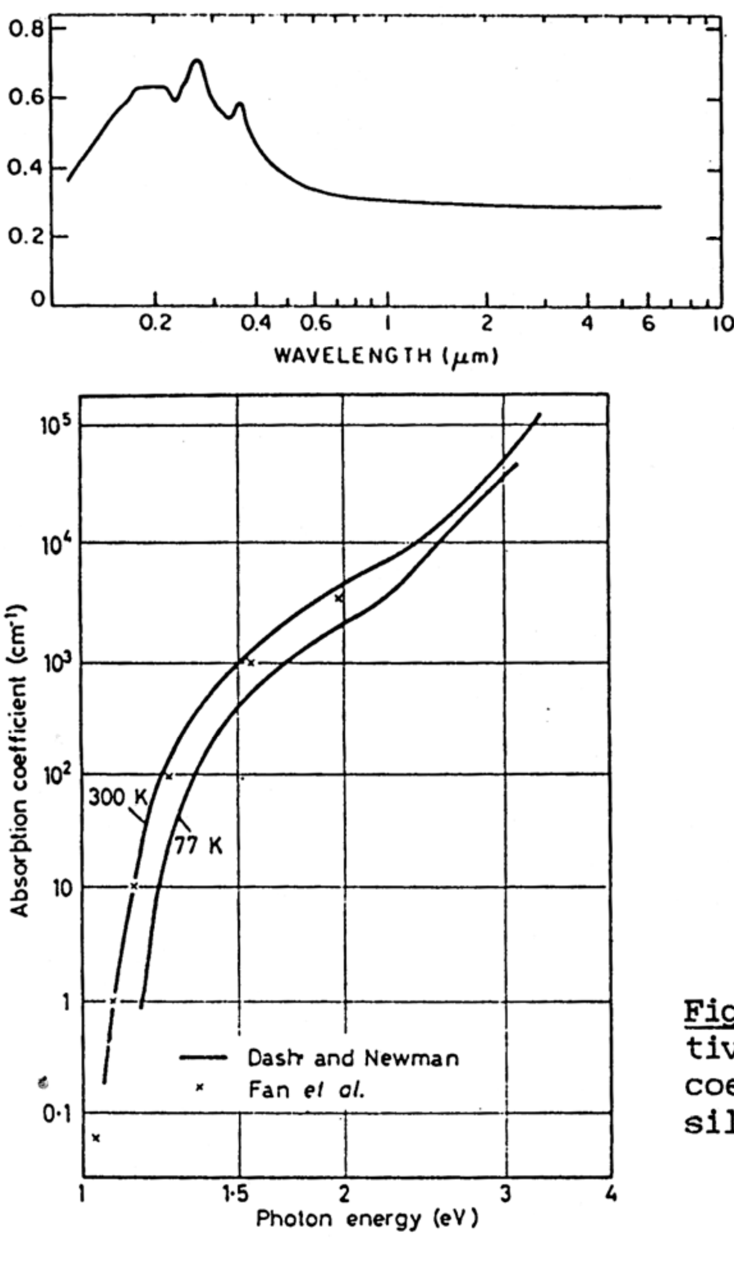


Fig.2.8. (a) Optical reflectivity, and (b) absorption coefficient of single crystal silicon [2.89,90],

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

$$\vec{E}(t,z) = \hat{i}E_0 \exp\left[j\left(-\omega t + \frac{\omega n_c z}{c} \right)\right]$$

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

- The k can be related to the Bear's law 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.

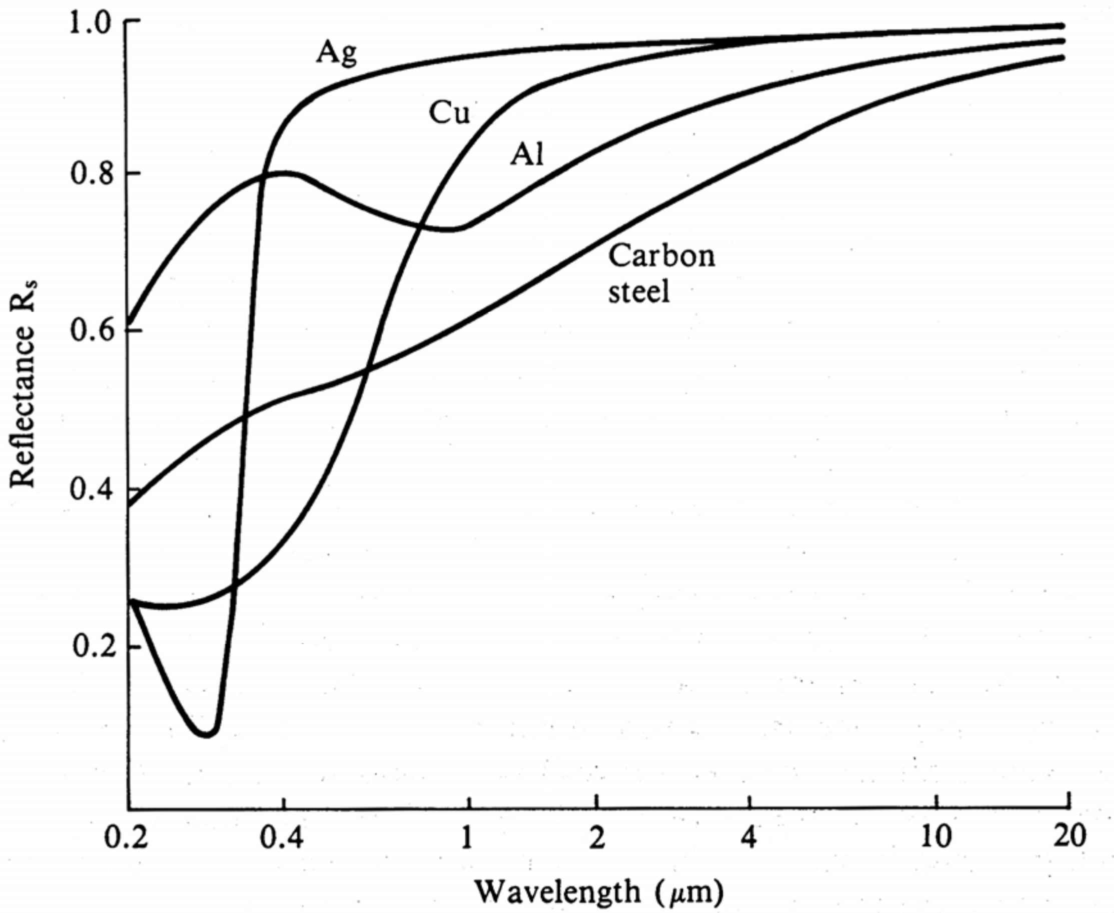


Fig. 5.1 Reflectance versus wavelength for various polished metal surfaces.

Temperature Dependence

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

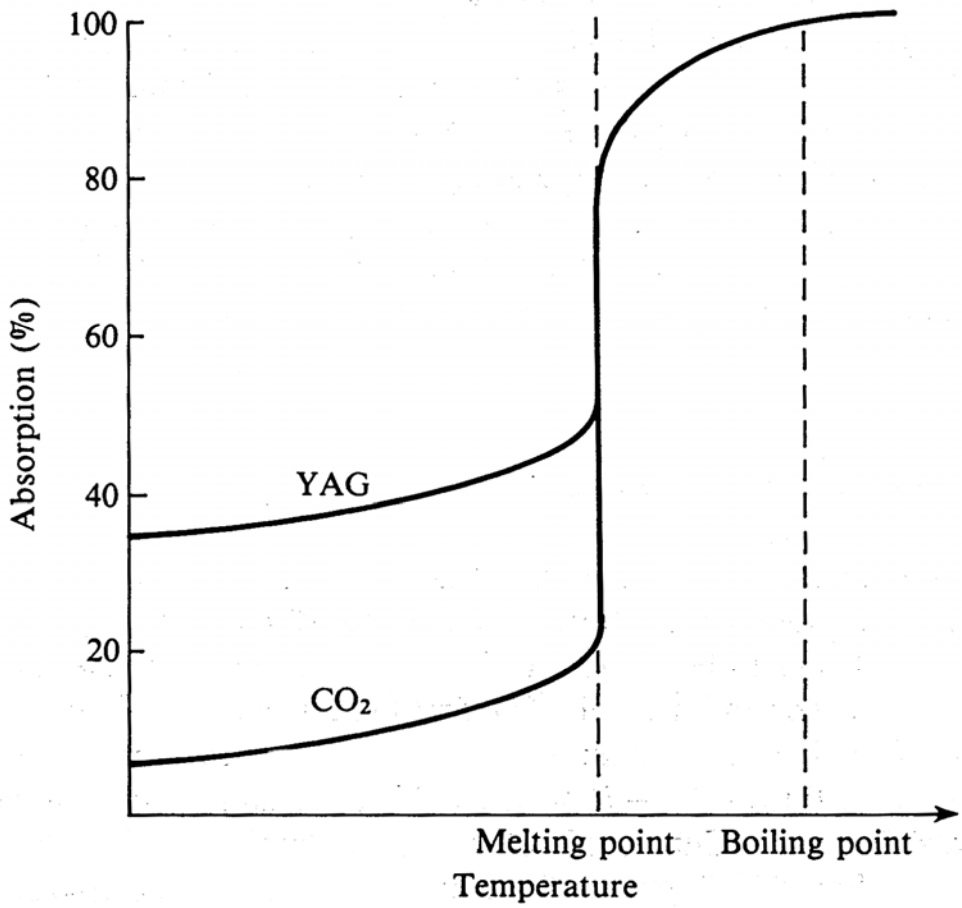


Fig. 5.2 Schematic variation of absorption with temperature for a typical metal surface for both the YAG and CO_2 laser wavelengths.

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)

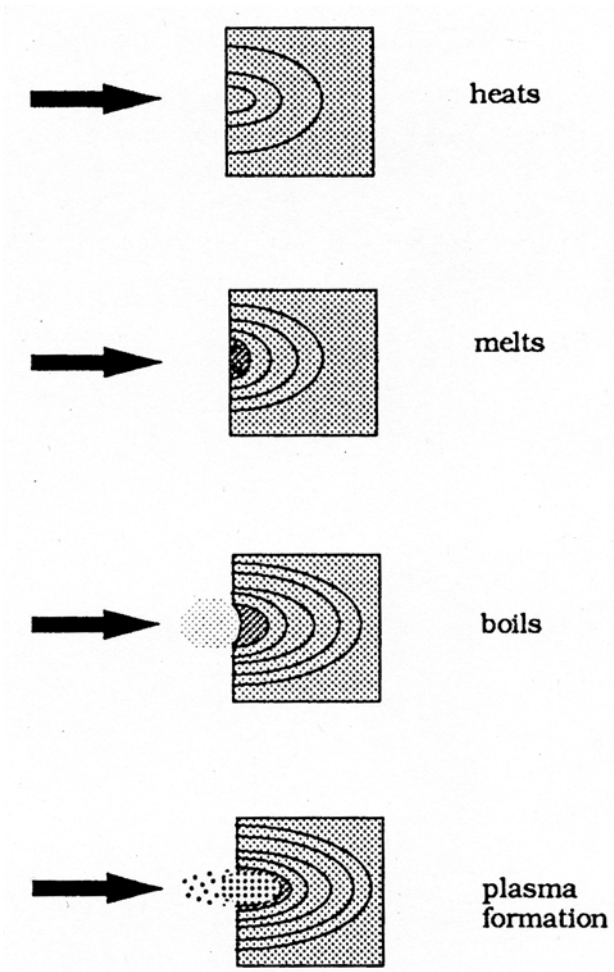


Fig. 2.4. Sequence of absorption events varying with absorbed power.

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

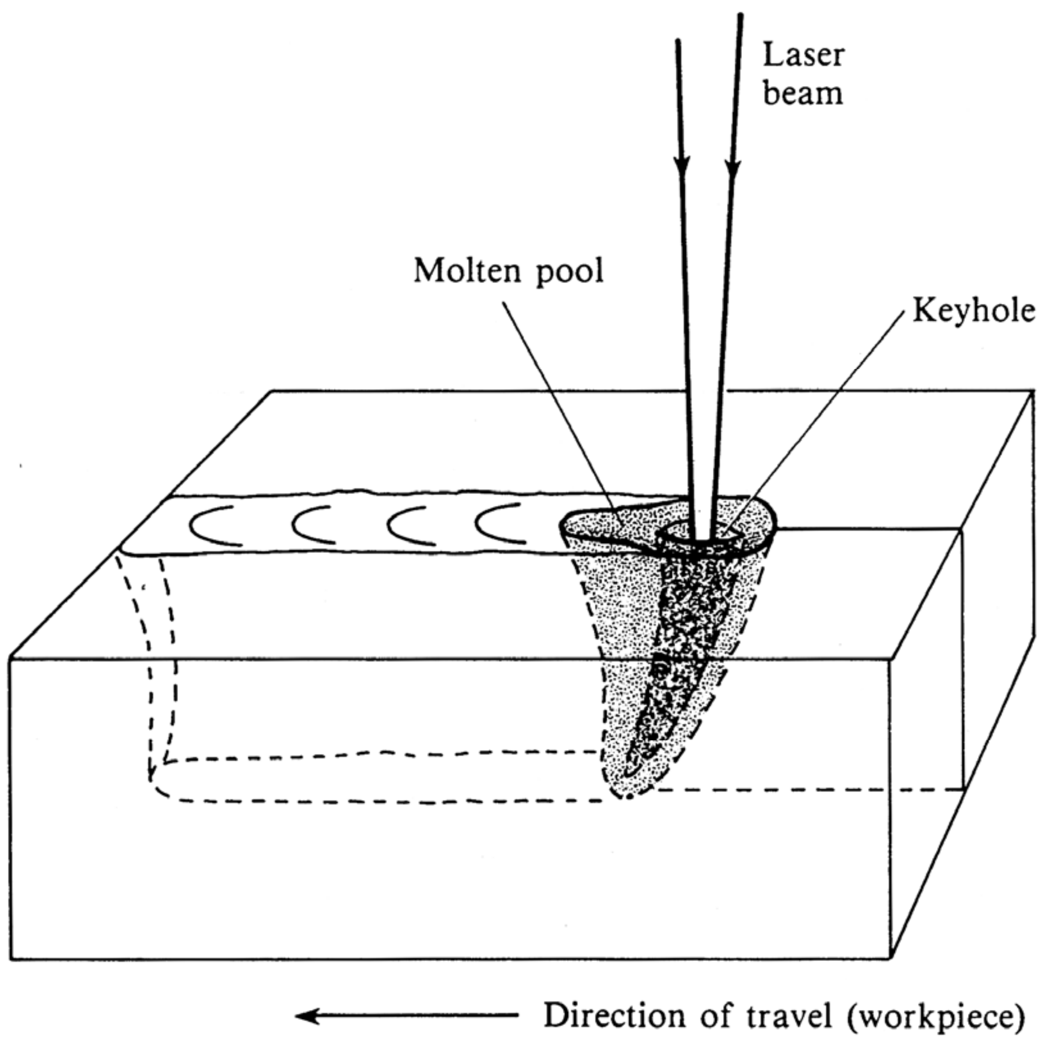


Fig. 5.15 Formation of a 'keyhole' during high-power laser welding.

Laser Cutting: Simple Thermal

- Six basic ways

Vaporization

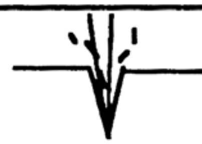
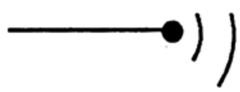
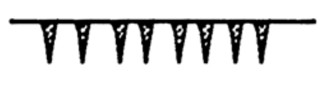
- beam heats local area above melting point
- material boils and ejects

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

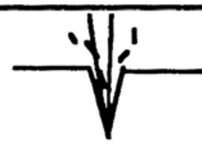
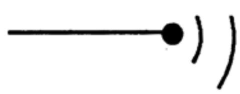
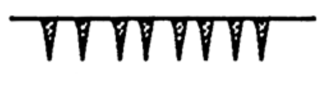
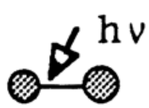
- Heat/cool cycle creates thermal stress, material breaks
- Requires least energy

Scribing

- Cut creates small stress point, breaks with force

Cold Cutting

- Laser photons in UV 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

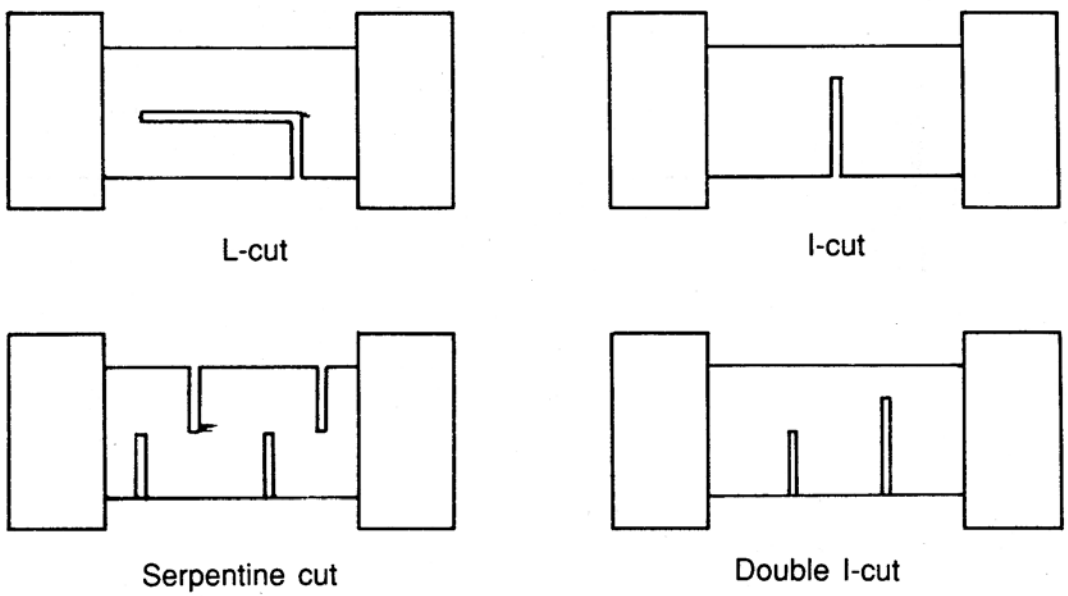
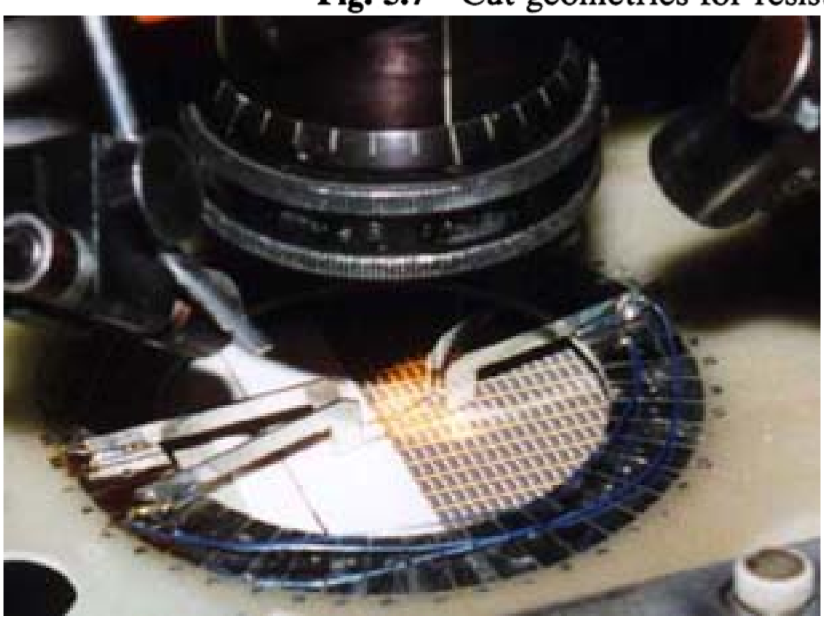
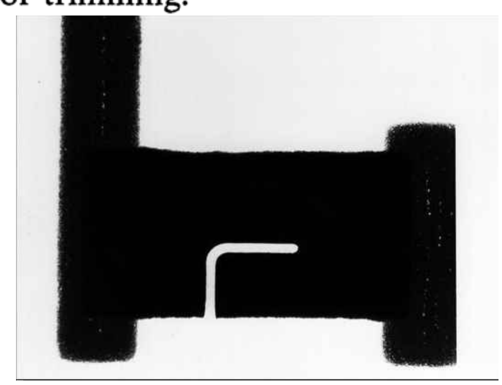


Fig. 5.7 Cut geometries for resistor trimming.





Laser Defect Correction

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

Laser Microsurgery

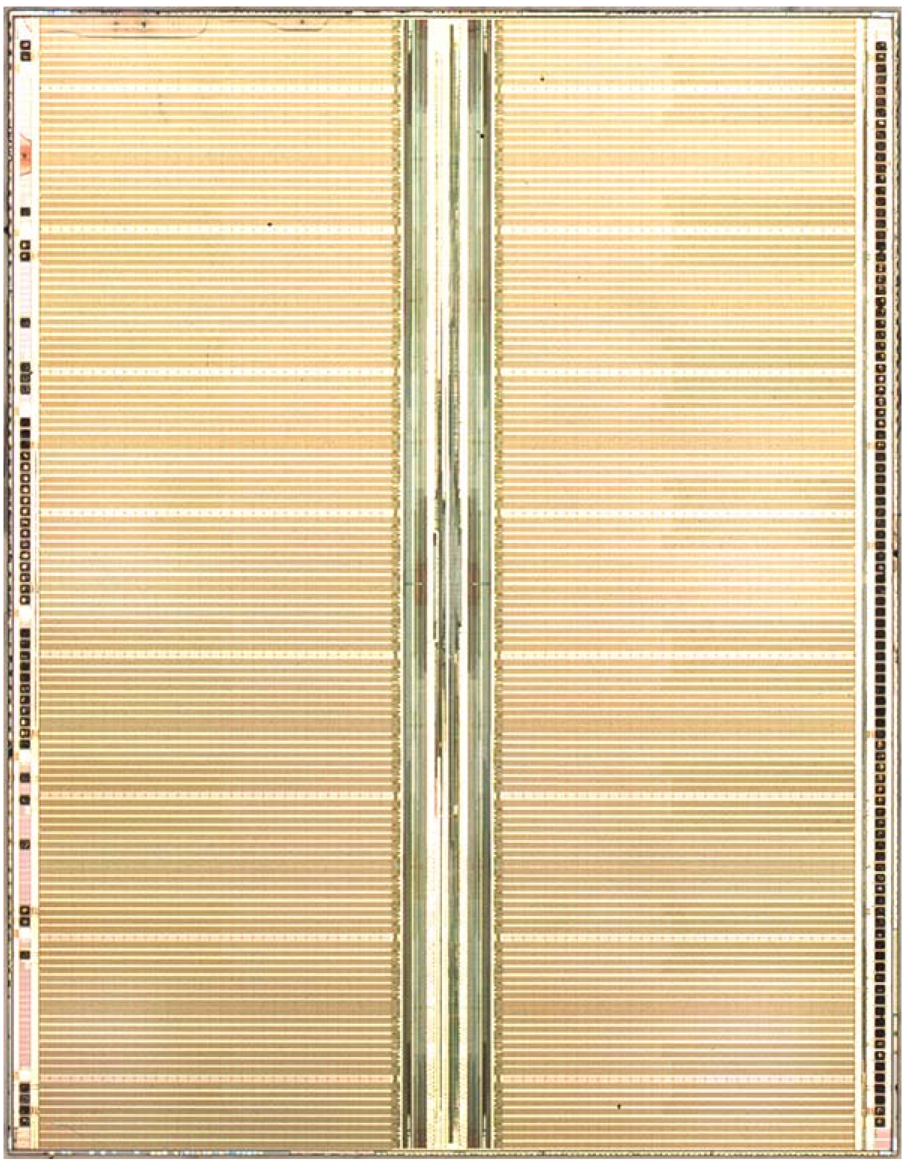
- Repair defects on chip sized structures

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



Laser Line Cutting

- Used in Laser microsurgery:Laser acts as a local heat source
- Laser power used to segment signal/power lines
- Cutting of 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

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

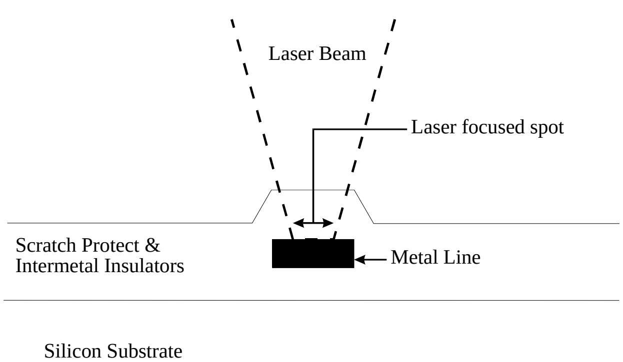
Materials

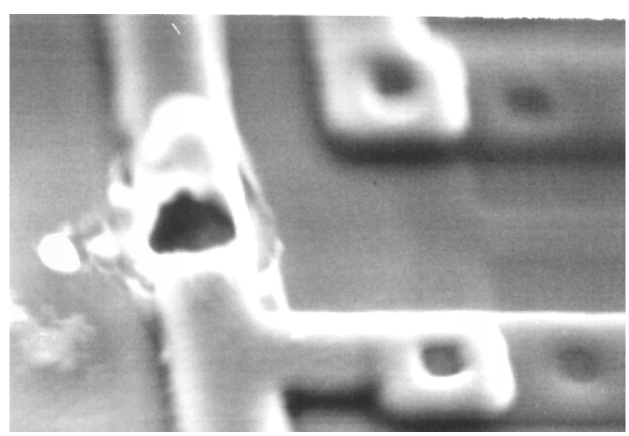
- Metals highly reflective & high thermal conductivity
- Mixed alloys can significantly

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
- (PolySi) thin layers mean less energy absorbed

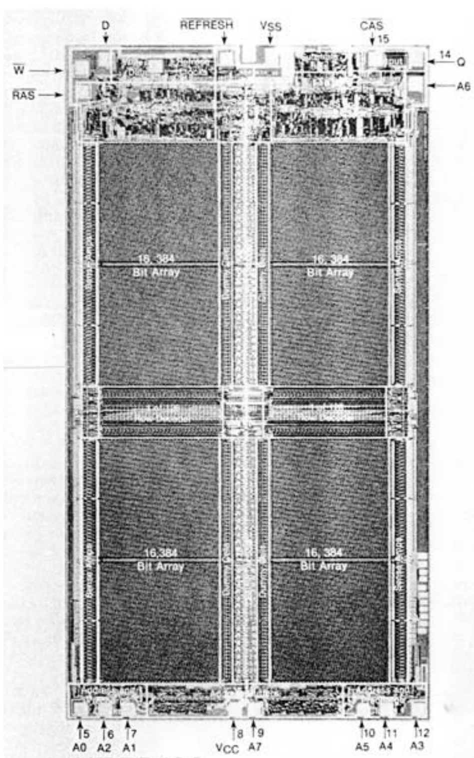
Laser Line Cutting



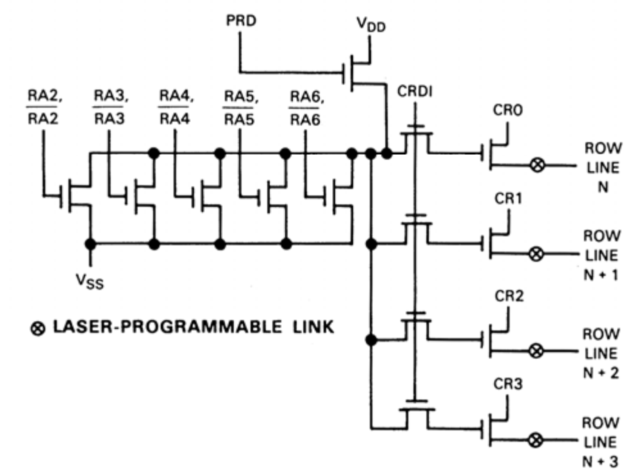


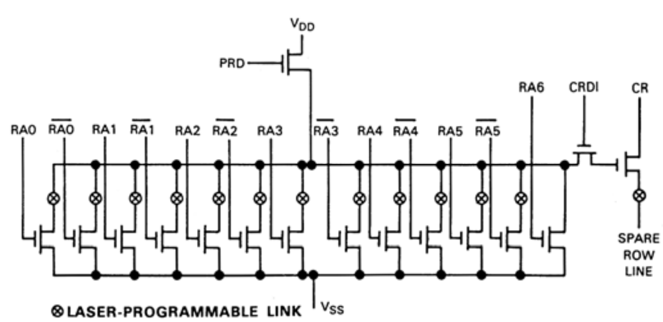
Lasers Defect Correction in DRAM's

- Problem: very hard to make memory chips with no defects
- Memory chips have maximum density of devices
- Repeated structures all substitutable
- Create spare rows and columns of memory
- After testing locates defective bit cut off that column
- Substitute in working column/row for defects
- Use laser cutting program in that column address in spare
- Typically have 4 spares in each half a DRAM
- Started with 64K DRAM's in 1979
- Difficult to build DRAM's without this
- Now also important for embedded SRAM/DRAM
- Embedded rams typically > 256K
- Very Important for Systems on a Chip (SoC)



64K DRAM





Poly Silicon Cuts (Fuses)

- Use laser to cut polysilicon lines
- Melts back the poly
- Some damage to coverglass
- Each die test, defects determined, and laser cut
- Commercial machines >$750- 2,000K do this (e.g. ESI)

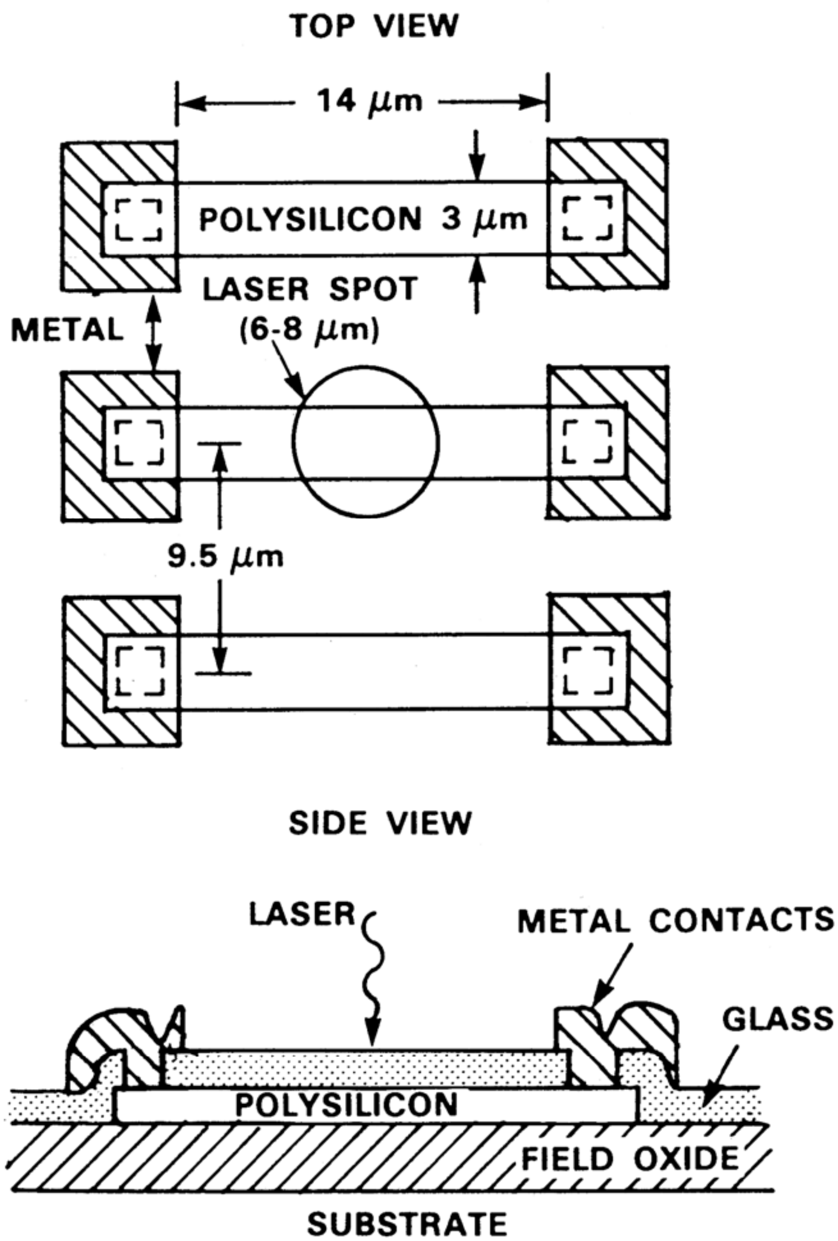
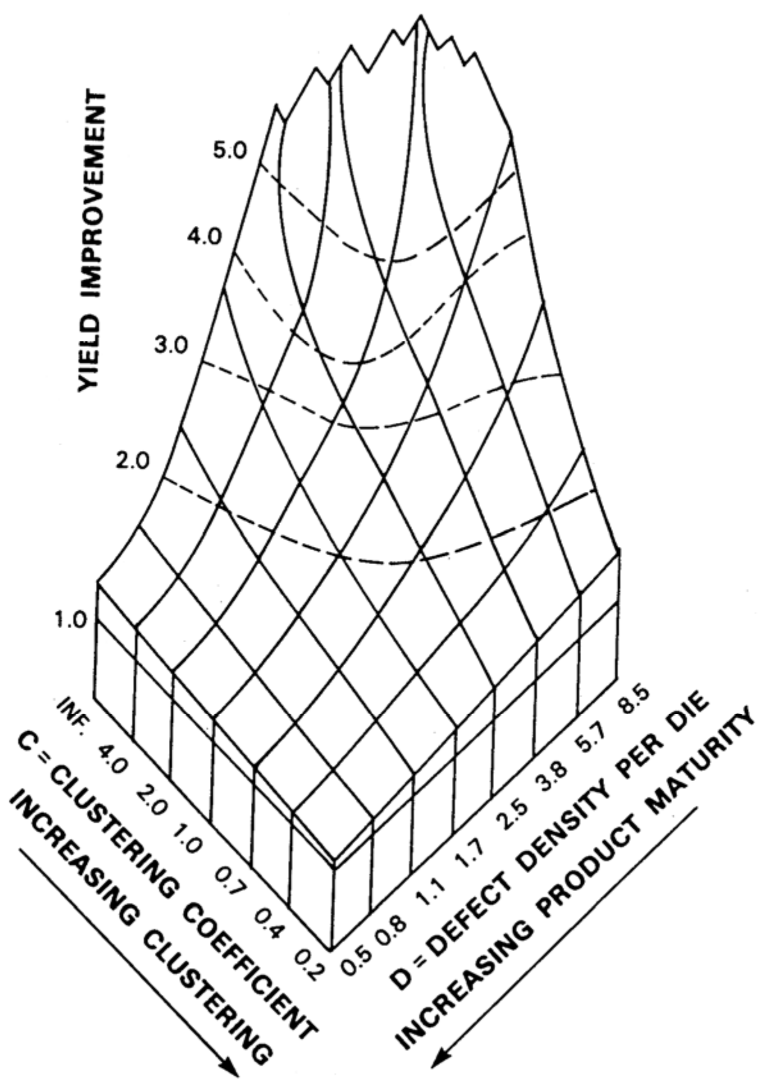


Fig. 27. Polysilicon laser cut point (fuse). (After Wells and Stewart [70].)

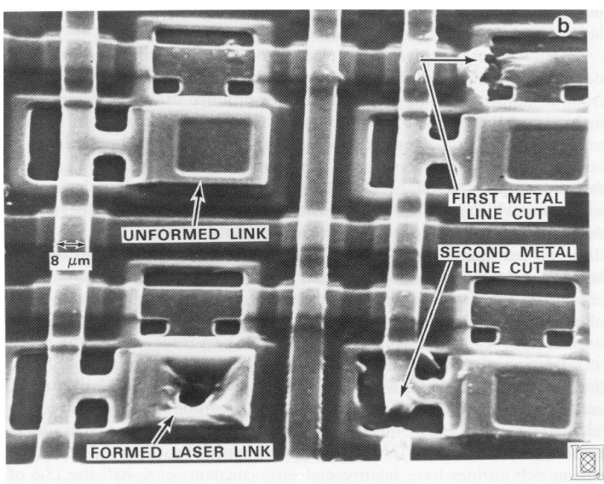
Yield Improvement on DRAM's With Laser Repair

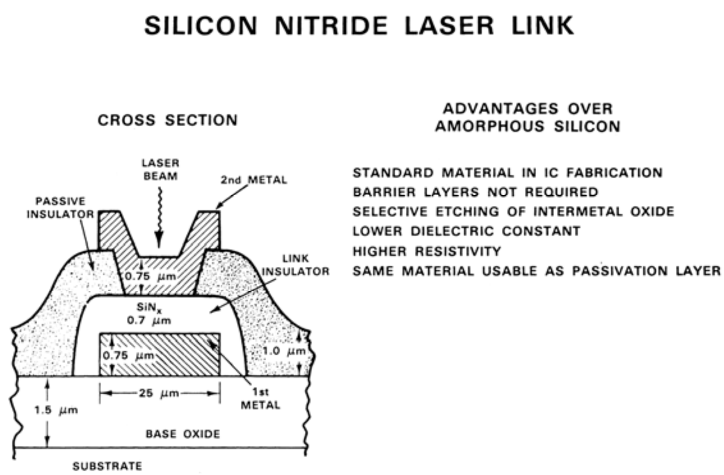
- New DRAM's uses highest density Microfab process available
- Currently generation using 0.045 micron 5/6 level metal
- Typical new DRAM design has low yield ~ 1-3%
- Cost of production independent of yield
- Hence if can increase yield by 100% drastically cut costs
- Yield follows Negative Binomial Statistics (defects cluster) has a "Culster Coefficient" that measures this
- Average defects may be 2-5 per chip but a few have only 0-1
- Can get 2-4 times improved yield

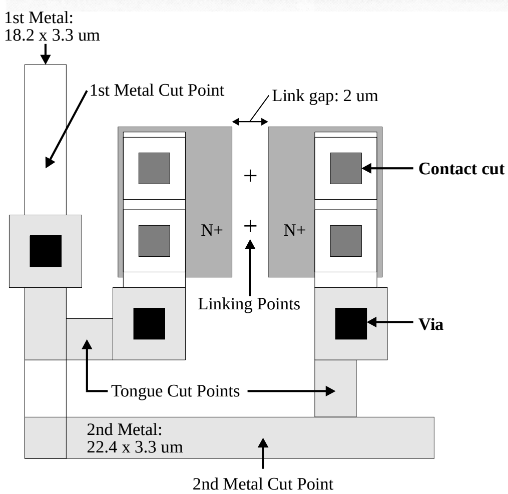


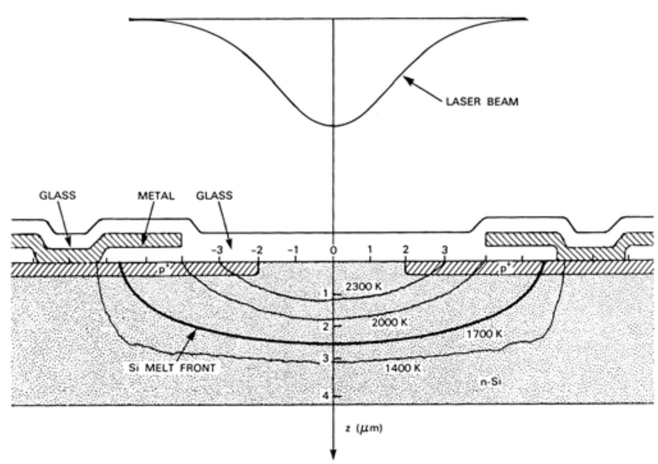
Laser Links

- Vertical laser links used to make permanent connections
- Metal 1 over metal 2 with silicon rich Silicon Nitride SN_x between
- Laser melts top metal creates Al Si short 1st to 2nd metal
- Unconnected R > 1GΩ, Laser Linked ~1-2Ω
- Argon laser focused on pad top ~ 1 μm spot, 1 msec at 1 W
- Developed MIT Lincoln Lab 1981: Chapman, Raphel, Herdon
- Used to create worlds first wafer scale device
  DSP integrator on 5x5 cm substrate 1983
- Horizontal link: Two doped areas separate by min allowed gap
- Laser pulse melts silicon, causes dopant to cross gap
- Creates permanent connections ~50-100 ohm
- Developed at MIT Lincoln Lab 1986: Chapman, Raphel, Canter



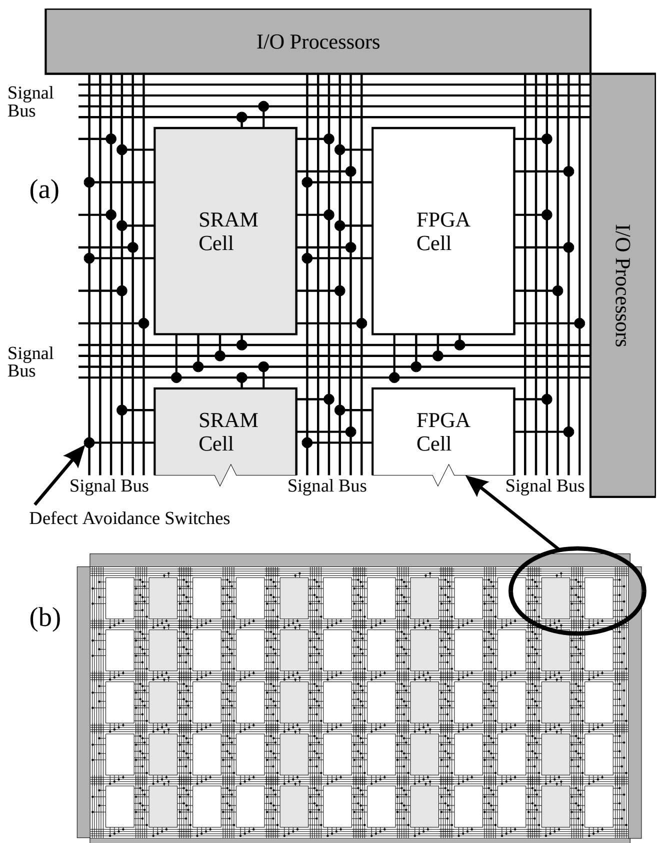


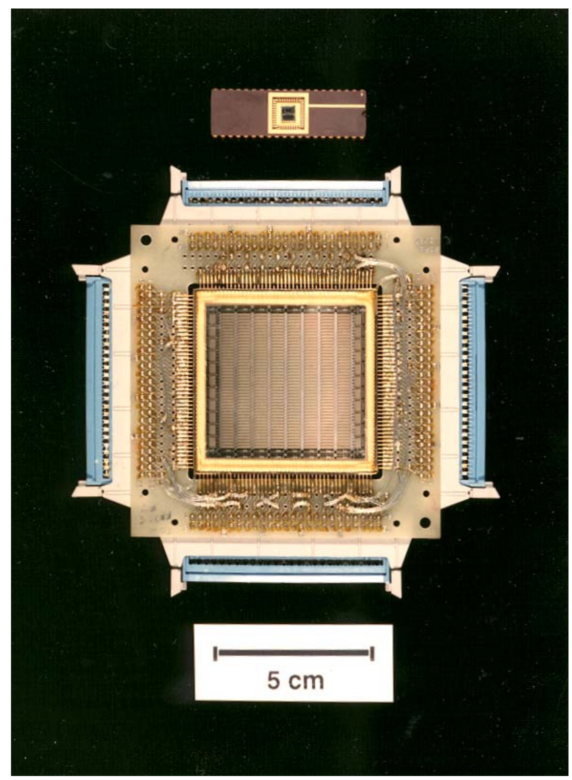


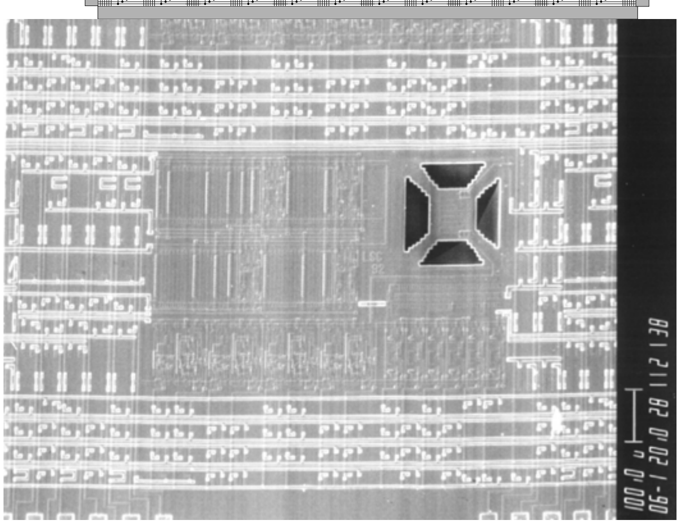


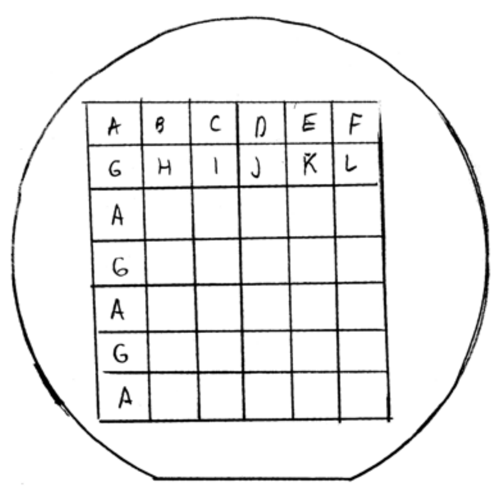
Large Area/Wafer Scale Silicon Systems

- Large area structures: problem is yield declines with square of area
- Break system into repeated circuit blocks cells with buss
- Many cells some defective use laser links to make connections
- Laser links make permanent connections – very fast
- Important for combinations of Transducers & links
- Several Designs of Wafer Scale Devices at MIT Lincoln Labs
- At SFU made Laser area Transducer Arrays
- Combine micromachining and WSI techniques



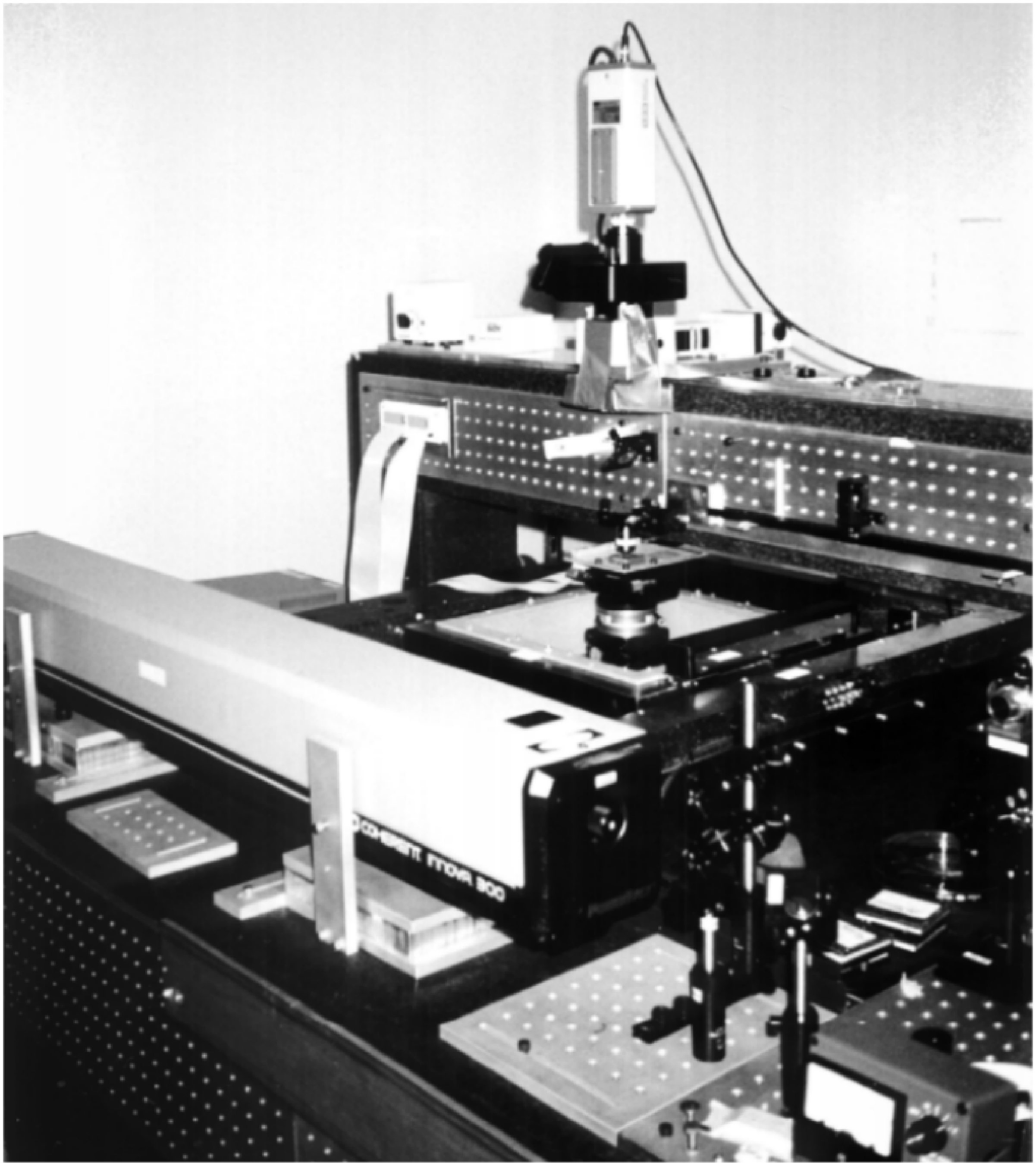






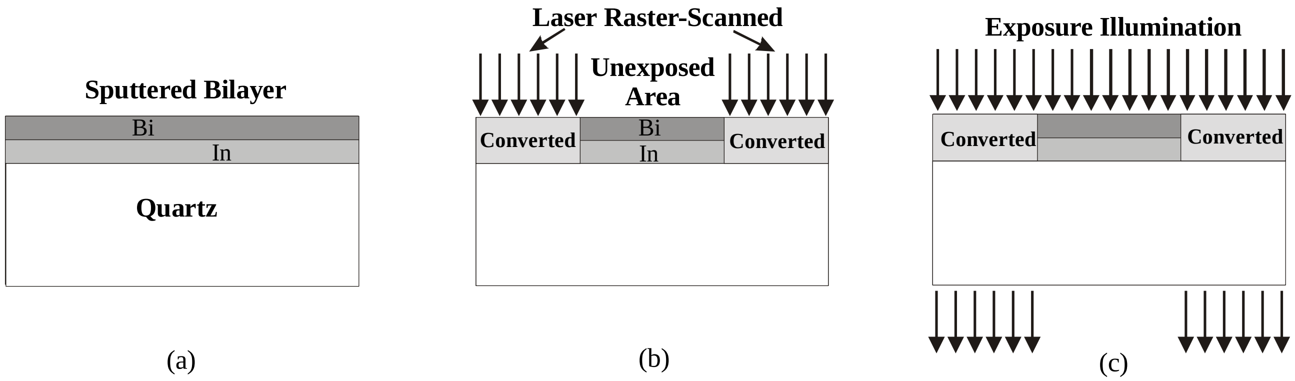
Laser Linking/Microsurgery Table

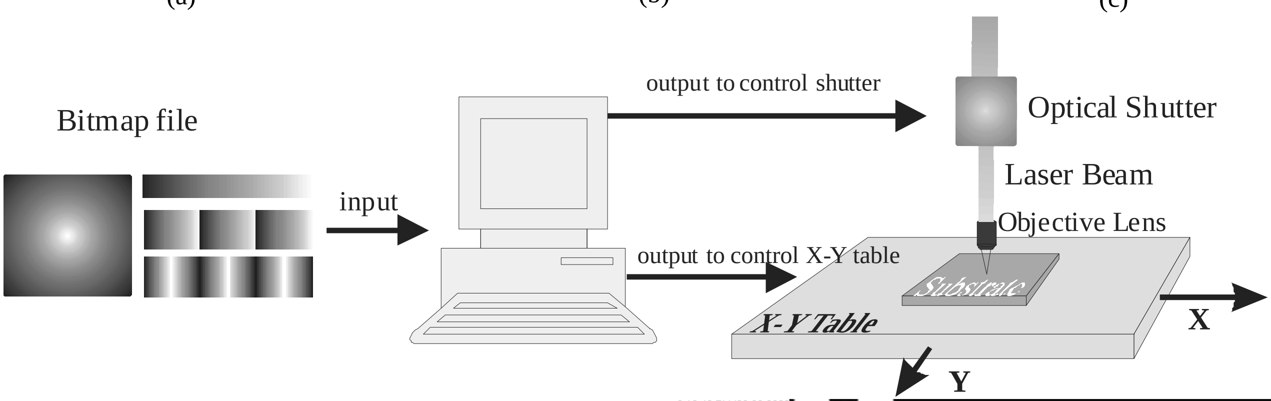
- Table moves circuit under focused laser spot
- Position done by laser interferometry: 0.02 micron positing
- Microscope/TV system shows circuit
- Electro-optical shutter gives control of laser pulse duration

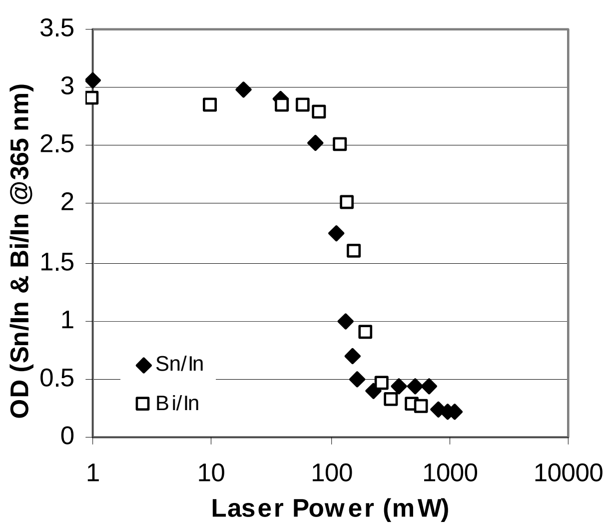


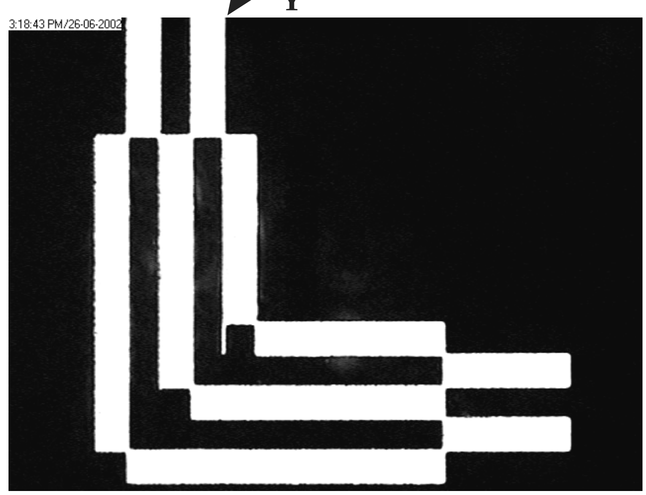
Laser Direct Write Photomasks

- Photomasks create the patterns used in microfabrication (IC's)
- Patterns projected on wafer to make circuits
- Creation of regular masks expensive
- Requires several exposure, development and etching steps
- Created a direct laser write photomask
- Put down ~15-100 nm film of Bismuth & Indium
- When hit with laser turns transparent: change from 3OD to 0.2 OD
- When laser hits Bi/In or Sn/In film creates transparent oxide



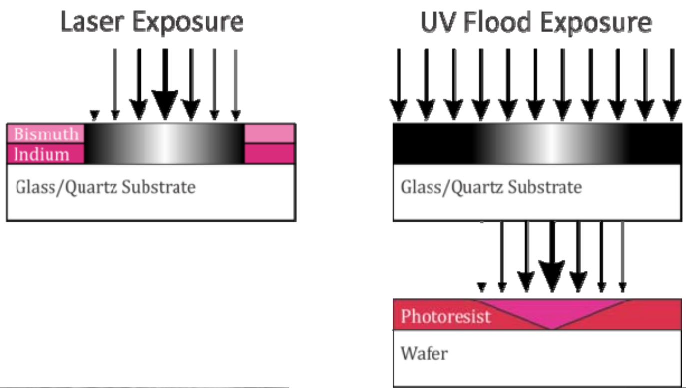


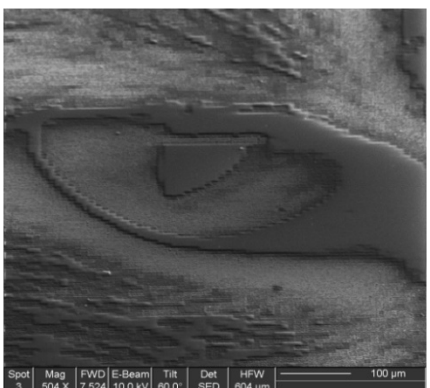


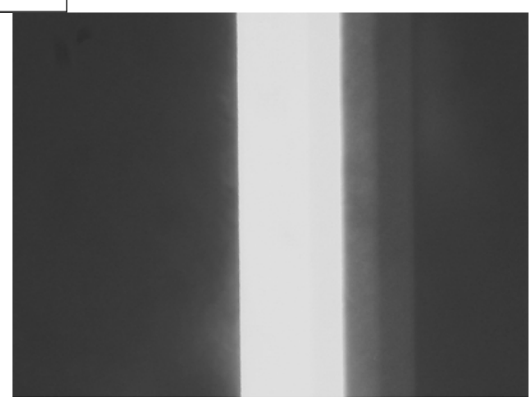


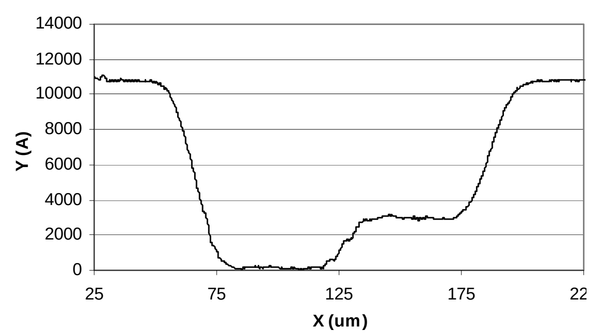
Bimetallic Grayscale Photomasks

Grayscale masks contain many gray levels
When hits photoresist developed thickness function of exposure
Can create 3D microfabricated devices (eg. Microoptics, MEMS)
Better OD range and cheaper than existing grayscales









Original picture
Grayscale mask