Lecture 4

Photolithography

Department of Mechanical Engineering

In Brief

- **Lithography is the process of imprinting a geometric pattern from a mask onto a thin layer of materials called resist which is a radiation sensitive polymer**

- **Process to fabricate a certain structure:**

  - *A resist layer is spin-coated or sprayed onto the wafer*
  - *A mask is then placed above the resist*
  - *A radiation is transmitted through the 'clear' parts of the mask*
  - *The structure pattern of opaque mask materials (usually Cr) blocks some of the radiation*
  - *The radiation is used to to change the solubility of the resist in a known solvent*
  - *The pattern transfer process is accomplished by using a lithographic exposure tool which emits radiation*

Lithography

- The performance of the radiation tool is determined by three parameters:

  - ***Resolution***: the minimum feature size that can be transferred with high fidelity to a resist film on the surface of the wafer

  - ***Registration***: a measure of how accurately patterns on successive masks can be aligned with respect to previously defined patterns on a wafer

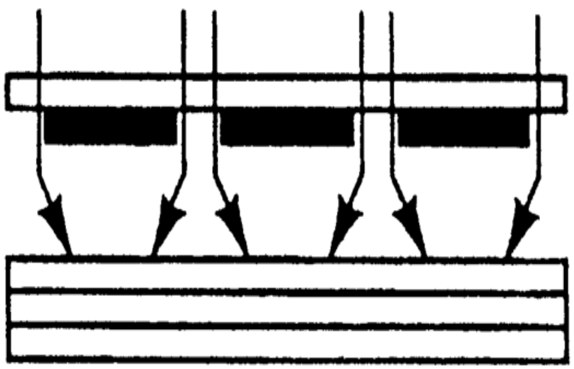
  - ***Throughput***: the number of wafers that can be exposed per hour for a given mask level

- Depending on the resolution different types of radition may be employed in lithography:

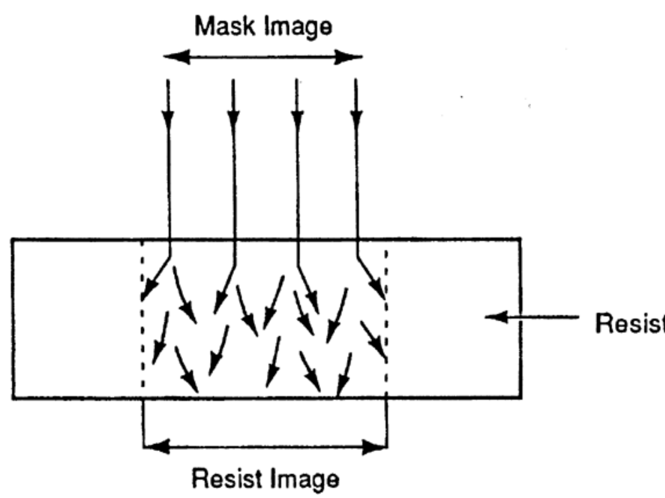
  (UV) light (optical lithography), electrons, X-ray, and ions

Lithography

- Resolution capabilities of the aligner and resist are primarily function of the wavelength of the exposing light
- The shorter the wavelength, the higher the resolution capability
- Shorter wavelengths carry more energy, enable shorter exposure thus less scattering

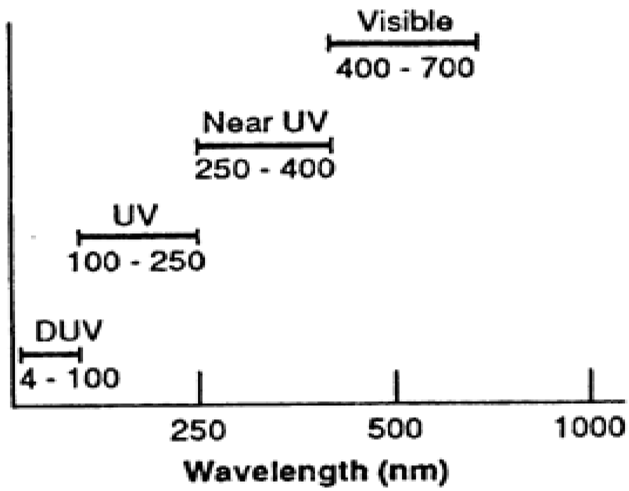


Diffracting reduction of image in resist



Light scattering in resist

Photoresist exposure source



Ultraviolet and visible spectrum

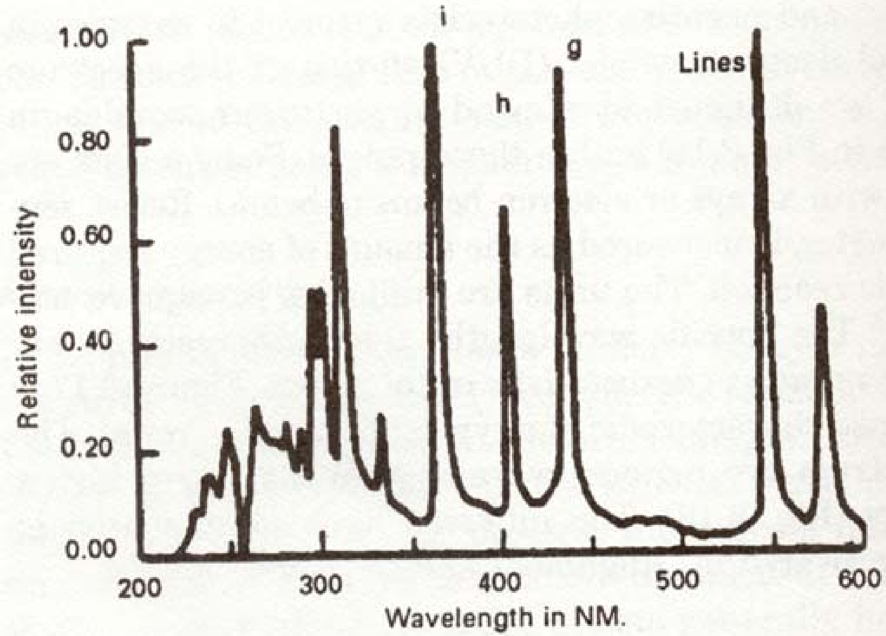
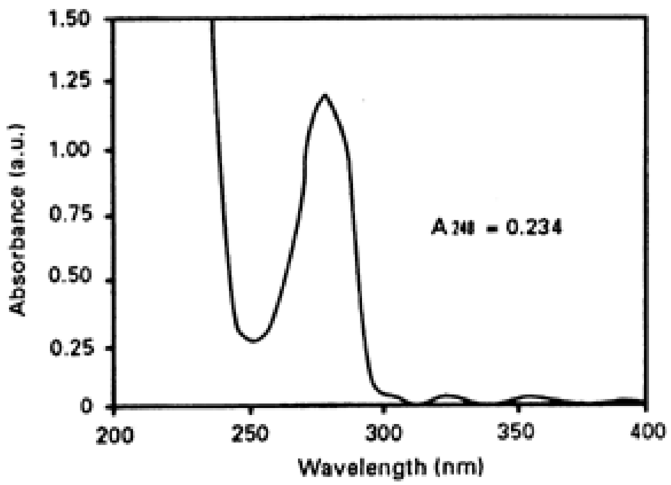


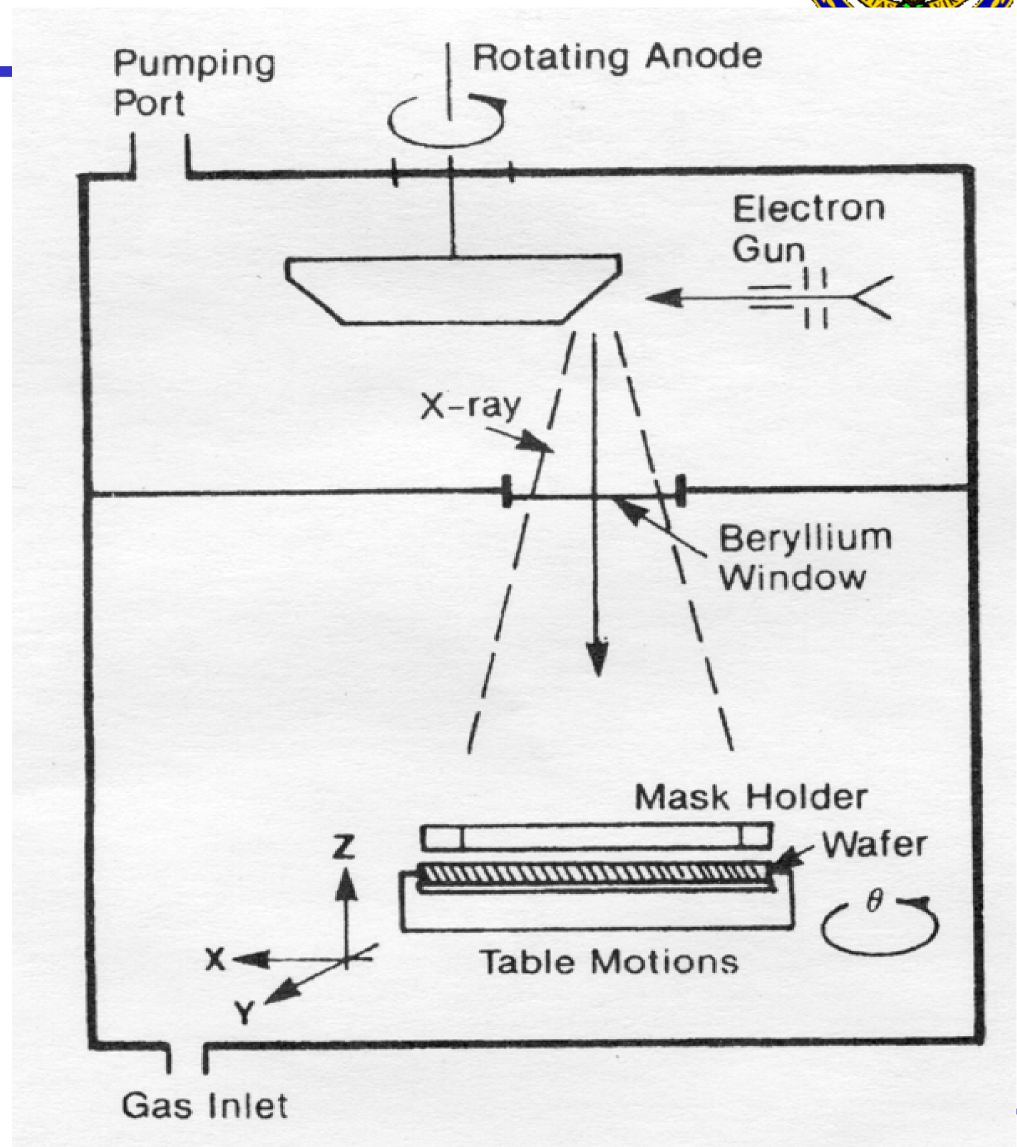
Figure 8.18 Mercury (Hg) spectrum. (*From Silicon Processing for the VLSI Era by Wolfe and Tauber.*)



Exposure response curve
(source: Shipley Megaposit XP-89131 photoresist)

X-Ray exposure system

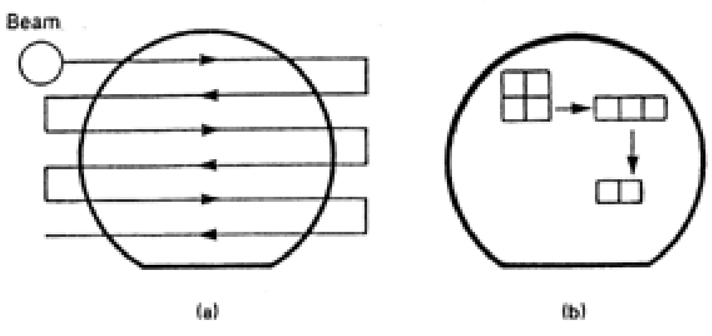
- Similar to UV and DUV systems
- Mask made from gold
- The development of high performance x-ray capable resist is slow



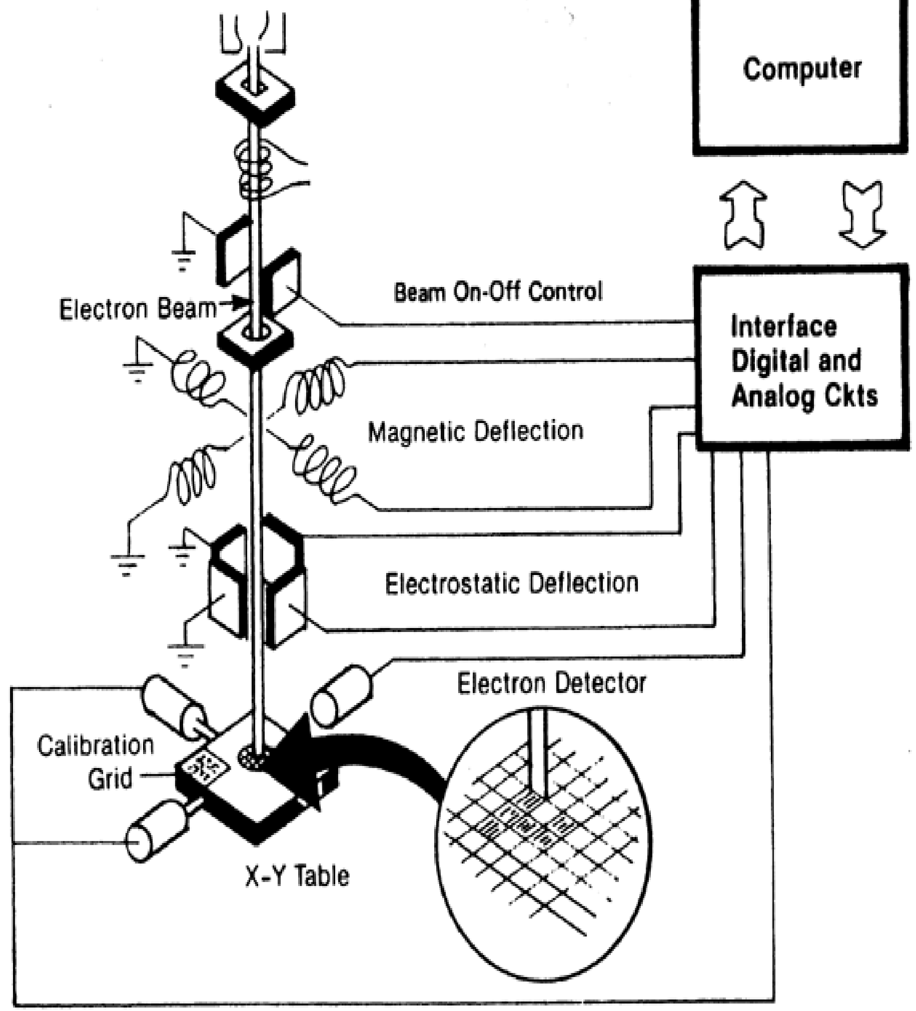
Electron beam exposure system

- Pattern generated from computer

- No mask direct writing



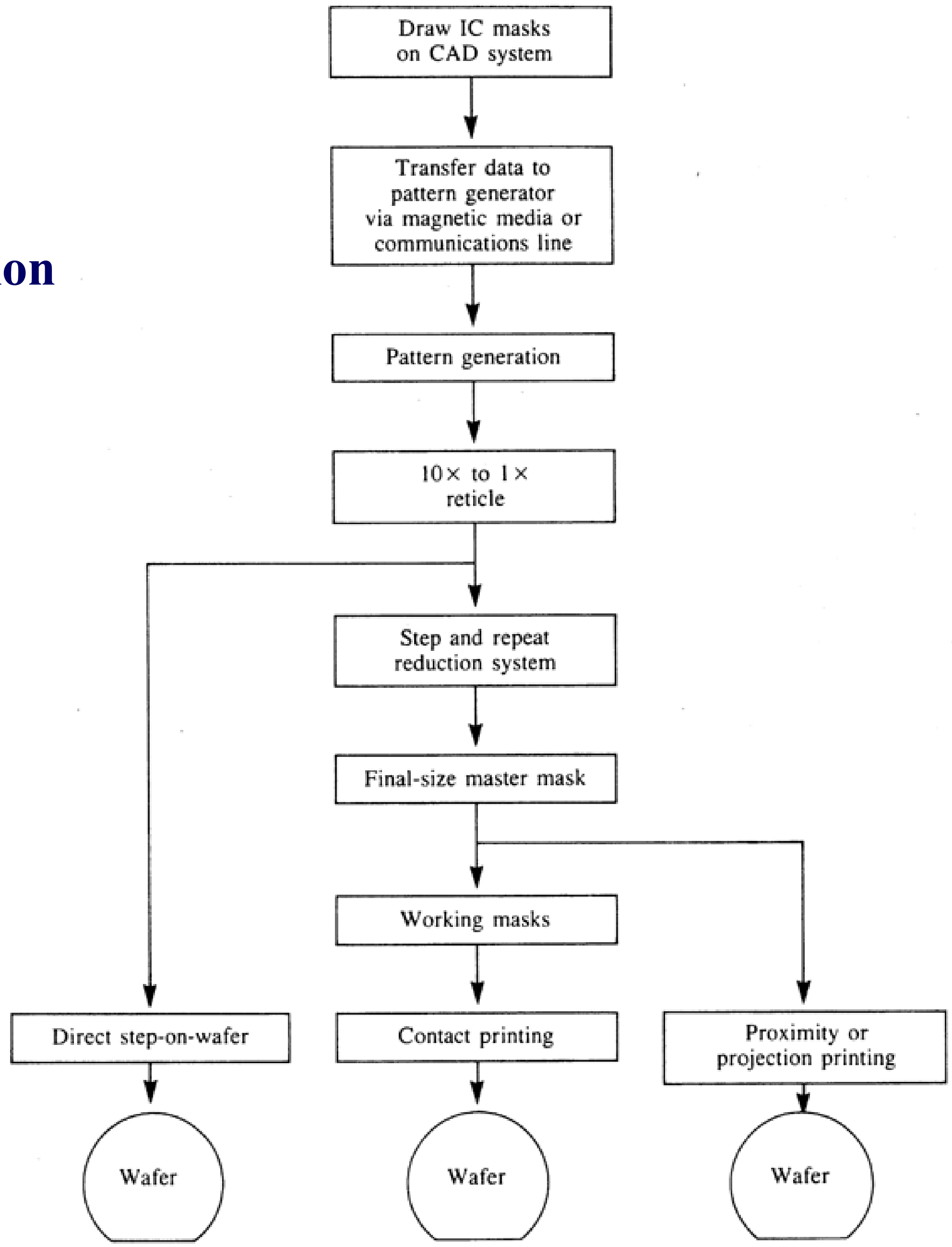
Electron beam scanning
(a) Rasters scan
(b) Vector scanning



Aligner System	Mask	Reticle	Exposure Sources	Resolution (microns)	Throughput 150 mm waf./hr.
Contact/Proximity	X		Hg	0.25-0.50	30-120
Scanning Projection	X	X	Hg	0.9-1.25	30-100
Step and Repeat		X	Hg/ExL/KrF/DUV	0.35-0.80	65-90
Step and Scan		X	Hg/ExL/KrF/DUV	0.25-0.40	50*
X-Ray	X	X	X-ray	0.10-	20+
E-Beam	Direct	write	Electron beam	0.25-	2-10

Figure Aligner tool comparison table. (*Source: Solid State Technology, April 1993, p. 26.*)

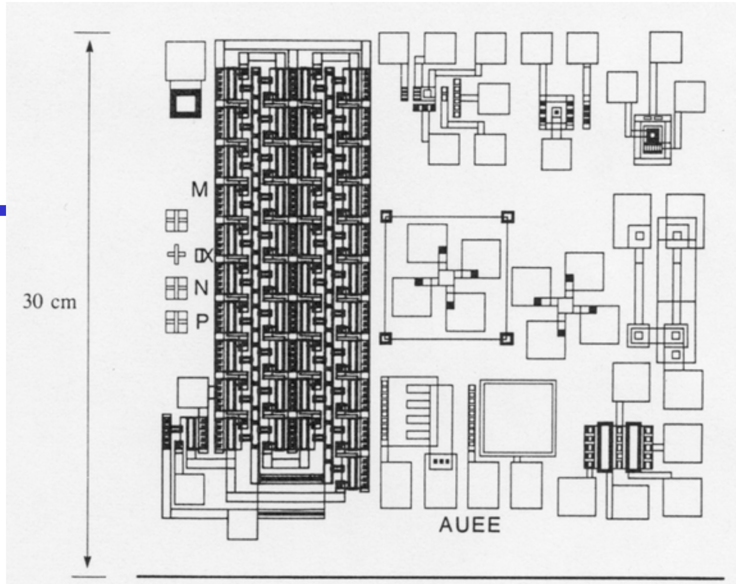
Mask Fabrication Process



Mask Fabrication

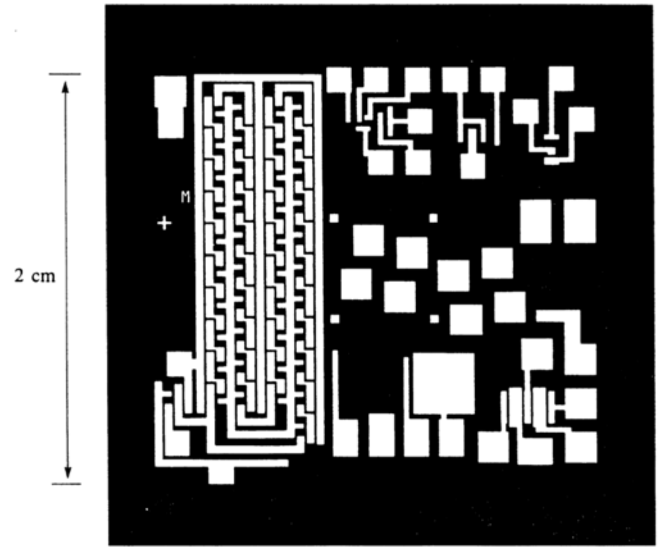
- For a certain MEMS or IC device, a large composite computer graphics plot of all masks is drawn first
- This plot is typically a hundred to a few thousands times the final size
- The composite graphics plot is then broken into mask levels that corresponding to a particular process sequence such as isolation region on one level, the metallization on another, etc.
- An image for each masking level is drawn, and transferred to a pattern generator which uses a flash lamp to expose the series of rectangles composing the mask image directly onto a photographic plate called ***reticle.*** Reticle images range from 1 to 10 times final size
- The final mask is made from the reticle using a special projection printing system.
- The choice of mask materials depends on the desiraed resolution. For feature sizes of 5 μm or larger, masks are make from glass plates covered with a soft surface materials such as emulsion. For smaller feature size, masks are made from glass covered with hard surface materials such as Cr or ion oxide

Mask fabrication



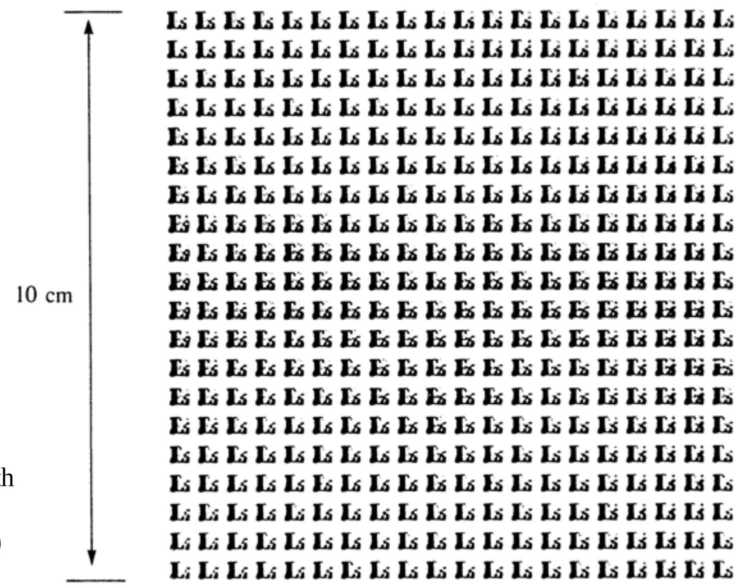
(a)

Composite computer graphics plot of all mask for a simple integrated circuit



(b)

10x reticle of metal-level mask

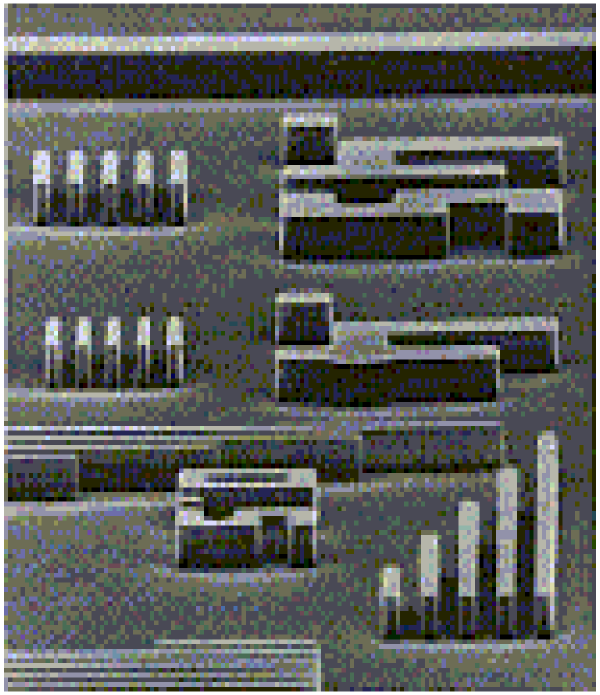


(c)

Final-size emulsion mask with 400 copies of the metal level of the integrtaed circuit in (a)

Resist Requirements

- Sensitivity - high sensisity reduces exposure time
- Adhesion - resist must adhere to the surface and not lift-off
- Fabrication properties - etch resistance, temperature stability.
- Resolution - what linewidth can we achieve?



Resolution profiles of photoresist

Photoresists

- **UV Negative Resist Formulation**
  - **Polyvinyl cinnamate (early 1960's)**
  - **Cyclized polyisoprene polymers**
  - **sensitizers**
    - quinones (polyvinyl)
    - azido compounds (polyvinyl & polyisoprene)
    - nitro compounds (polyvinyl)
  - **Solvents/Developers**
    - acetic acid (polyvinyl)
    - notrobenzene (polyvinyl)
    - Furfural (polyvinyl)
    - Xylene (polyisoprene)
    - Benzene (polyisoprene)
  - **Disadvantages**
    - linewidth
    - swelling and shrinks
- **UV Positive Resist Formulation**
  - **Common phenol formaldehyde novolac**
  - **Sensitizer**
    - napthoquinone diazide
  - **Solvents/Developers**
    - ethylene glycol monomethyl with dilvents butyl acetate
    - xylene
  - **Advantages**
    - broader optical range
    - easier to remove

Photoresist

Semiconductor Photoresists & Auxiliaries

(http://www.tok.co.jp/index-e.htm)

- **g-line photoresists**
  - OFPR series (Standard photoresists)
  - TSMR series (Submicron patterning photoresists)
- **i-line photoresists**
  - TSCR series (Dyed photoresist for halfmicron patterning on high/mideum reflective substrates)
  - THMR-iP/iN series (Halfmicron patterning photoresists)
  - TDMR-AR series (Sub-halfmicron patterning photoresist)
  - TSQR-iQ series (Sub-halfmicron patterning photoresist)
- **Deep-UV (KrF) photoresists**
  - TDUR-P/N series(Quartermicron patterning photoresists)
- **Electronic Beam photoresists (EB)**
  - OEBR series
- **Auxiliary chemical products**
  - Developing solution/Rinsing solution/Stripping solution/Diluting solution / Thinner

Other Lithographic Technologies

- **Deep U.V. Exposure Technology**
  - Deep U.V. - 180-330 nm
  - Disadvantages
    - » lack of availability of lamps
    - » mismatch between lamp and resist
    - » contact printing
  - Advantages
    - » low cost
    - » easier technology
    - » wide range of resist

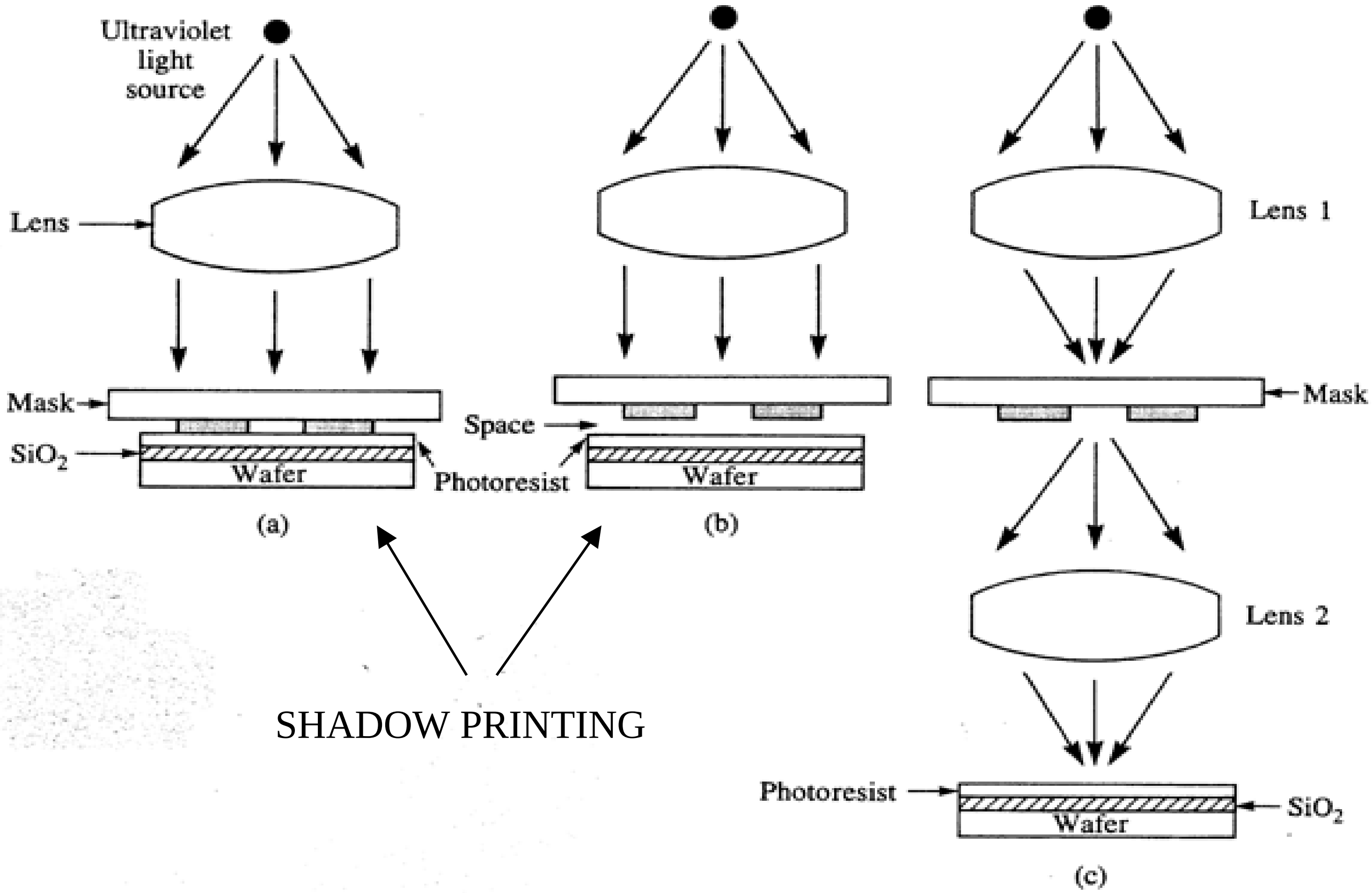
- **E-Beam Lithography**
  - **Electron- beam wavelength << optical wavelength**
  - **Disadvantages**
    - » high cost
    - » resolution limits beam spread (50 A - 300 A)
    - » scattering
      - (a) in resist during transit
      - (b) backsaattering from the substrate
  - **Advantages**
    - » higher resolution

Other Lithographic Technologies

- **X-Ray Lithography**
  - X-Ray lithography (XRL) consists of proximity printing of a mask onto a wafer.
  - Advantages
    - » resolution and process simplicity (linewidth<1 mm)
    - » no need for multilevel resist systems used in e-b lithography
    - » XRL parallel writing process, e-beam is a serial; XRL higher throughput

Techniques	**Cost**
E-beam	1-2 million
X-ray	4 million
Direct stepping	0.5 million
UV-DUV	15,000 - 0.5 million

Contact printing Proximity printing Projection printing



SHADOW PRINTING

- The theoretical resolution of an *optical projection aligner* is given by

$$\omega = \frac{\kappa\lambda}{NA}$$

ω is the minimum feature size
k is a process dependent constant between 0.5 and 1,0
λ is the wavelength of t he exposure light
NA is the numerical aperture of the aligner's optics

- The theoretical depth of focus:

$$\delta = \frac{\lambda}{2(NA)^2}$$

- The resolution limit of shadow printing is due to diffraction effects, the minimum printable linewidth is:

$$b_{min} = 3/2\sqrt{\lambda(s+d/2)}$$

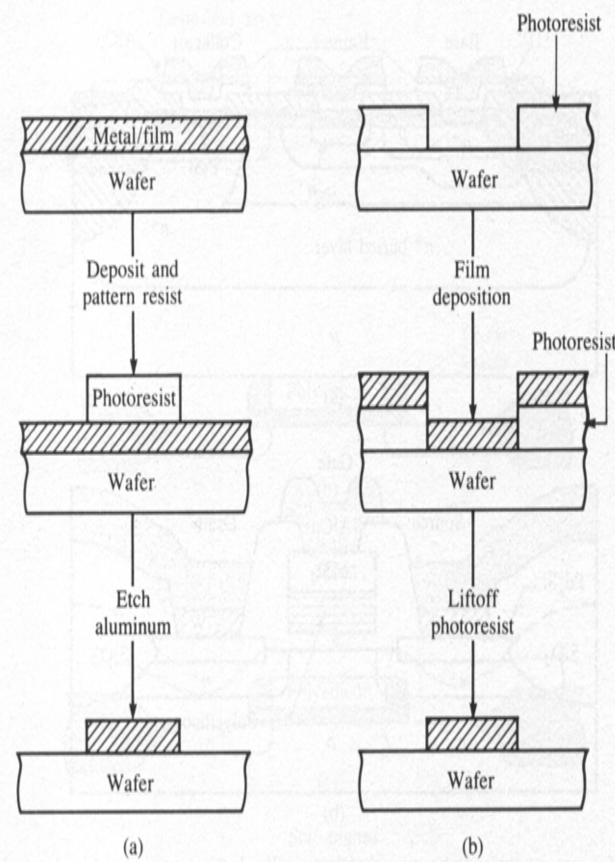
b is the grating linewidth
s is the gap between the mask and the photoresist
d is the photoresist thickness

- In the case of hard contact printing, $s = 0$, the minimum printable linewidth is:

$$b_{min} = 3/2\sqrt{\lambda s}$$

Lift-off

- Lift-off is a additive process for metal film patterning:
  - The wafer is completely covered by a photoresist layer pattened with openings where the final material is to appear
  - The thin film layer is deposited over the surface of the wafer
  - Any material deposited on top of the resist will be removed with the resist, leaving the patterned materials on the wafer
- Lift-off requires the metal film to be thinner than the photoresist. This requirement limits the metal linewidth. Thinner linewidths normally require thinner photoresist layers.



Fig—— A comparison of interconnection formation by (a) subtractive etching and (b) additive metal liftoff.

Topographical height variation

- Resist spinning and imaging become difficult for wafer with deep cavity or trench (depth >10 μm)
- Contact and proximity tools are not suitable
- Projection tool may be used by adjustment of focus at each height level

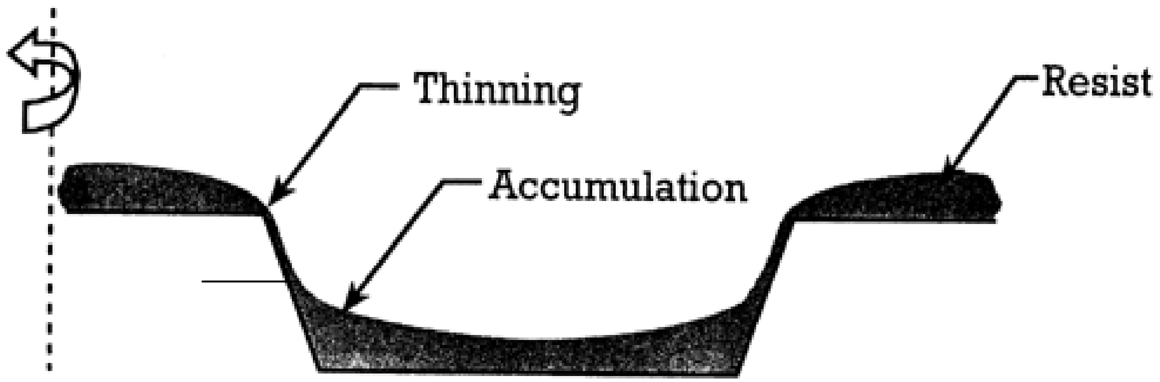


Figure Undesirable effects of spin coating resist on a surface with severe topographical height variations. The resist is thin on corners and accumulates in the cavity.

Double-Sided Lithography

- For MEMS device, there is a need for double-sided lithography tool
- Two companies:
  - *Karl Süss GmbH, Munich, Germany*

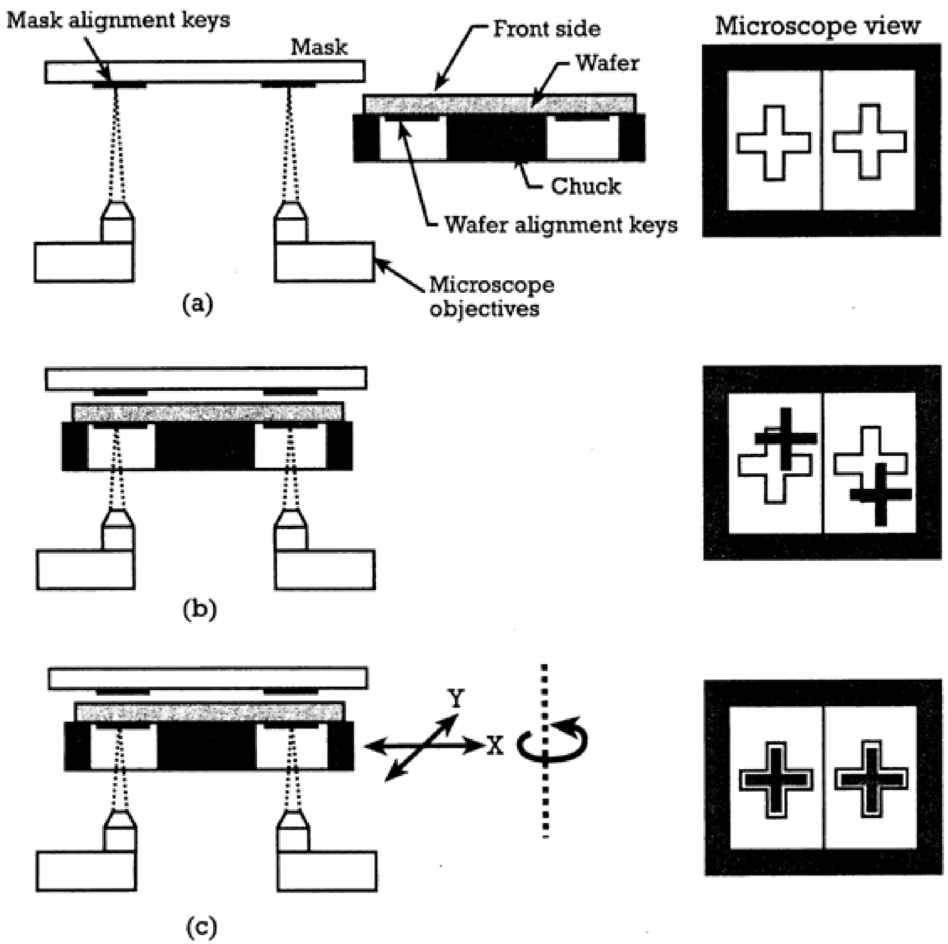
    Karl Süss MA-150 production mode system

  - *Electronic Versions Campany, Schärding, Austria*
- Operation
  - *The mask is mechanically clamped*
  - *The alignment marks on the mask are viewed by a set of dual objectives, and image is electronically stored*
  - *Wafer is then loaded with backside alignment marks facing the microscope objectives*
  - *The alignment marks is aligned to the stored image.*
  - *After alignment, exposure of the mask onto the front-side of the wafer*

Misalignment $\leq 2\mu m$

Double-Sided Lithography

The use of "back-side" alignment using the SUSS patented "frame-grabbing" technique is available on the SUSS MA6 BSA and SUSS MA150 BSA aligners.



Figure——Double-sided alignment scheme for the Karl Süss MA-150 production mode system: (a) The image of mask alignment marks is electronically stored; (b) The alignment marks on the back-side of the wafer are brought in focus; (c) The position of the wafer is adjusted by translation and rotation to align the marks to the stored image. The right-hand-side illustrates the view on the computer screen as the targets are brought into alignment. Adapted from product technical sheet (Karl Süss GmbH, Munich, Germany).

Mask Aligners

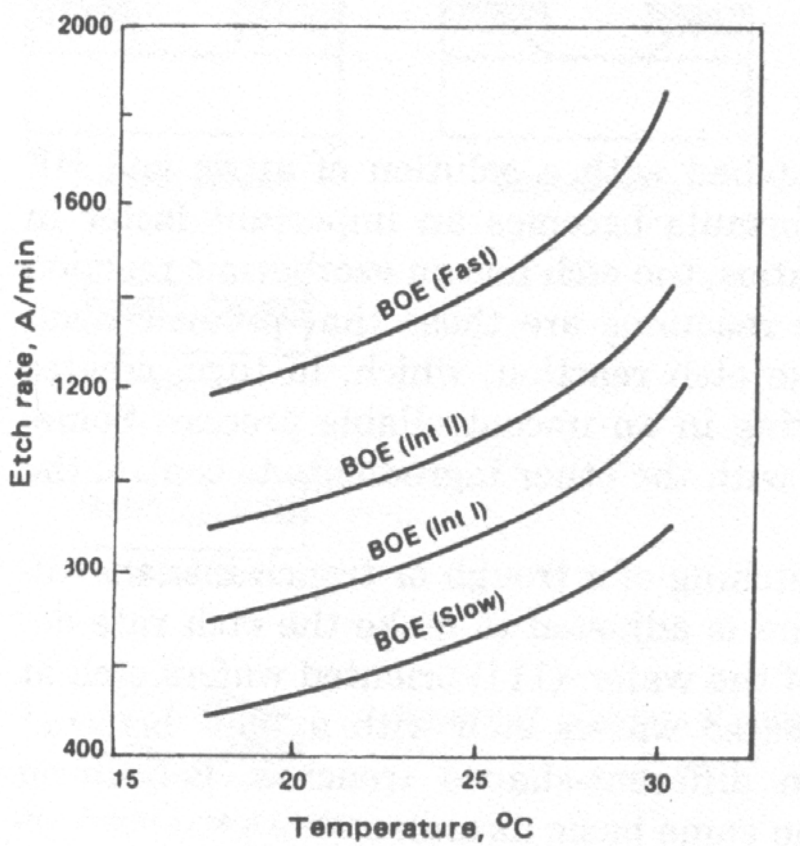
SUSS Manual Mask Aligners, the M6

SUSS Manual Mask Aligners, the MA8

Thin Film Etching

- SiO_2 wet etching
  - Buffered oxide etch (BOE)

    HF + NH_4F+H_2O are mixed at different strength
- For SiO_2 passivation layer
  - Using NH_4F + CH_3COOH
- Al wet etching
  - Using phosphoric based acid solution as etchant
  - By product: H_2 bubbles. The bubbles may cling to the wafer surface and block the etch action. Agitation such as ultrasonic or megasonic waves are used.



Etch rate vs. T

Thin Film Etching

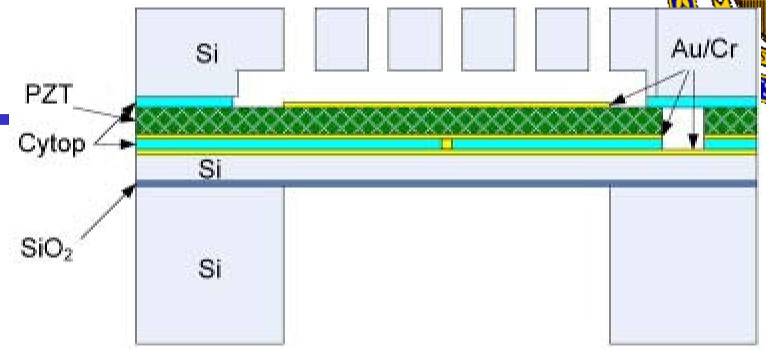
Table
Wet and Dry Etchants of Thin Metal Films and Dielectric Insulators.
Adapted from Williams and Muller [3].

	Wet Etchants (aqueous solutions)	**Etch Rate (nm/min)**	**Dry Etching Gases (plasma phase)**	**Etch Rate (nm/min)**
Silicon dioxide	HF	20–2,000	$CHF_3 + O_2$	50–150
	$HF:NH_4F$ (buffered HF)	100–500	$CHF_3 + CF_4$	250–500
Silicon nitride	H_3PO_4	5	SF_6	150–250
			$CHF_3 + CF_4$	100–150
Aluminum	$H_3PO_4:HNO_3:CH_3COOH$	660	$Cl_2 + SiCl_4$	100–150
	HF	5	$CHCl_3 + BCl_3$	200–600
Gold	KI	40		
Titanium	$HF:H_2O_2$	880	SF_6	100–150
Tungsten	H_2O_2	20–100	SF_6	100–150
	$K_3Fe(CN)_6:KOH:KH_2PO_4$	34		
Chromium	$Ce(NH_4)(NO_3)_6:HCl_4$	2	Cl_2	5
	HCl			
Organic layers	$H_2SO_4:H_2O_2$	> 1,000	O_2	35–3,500
	CH_3COCH_3 (acetone)	> 4,000		

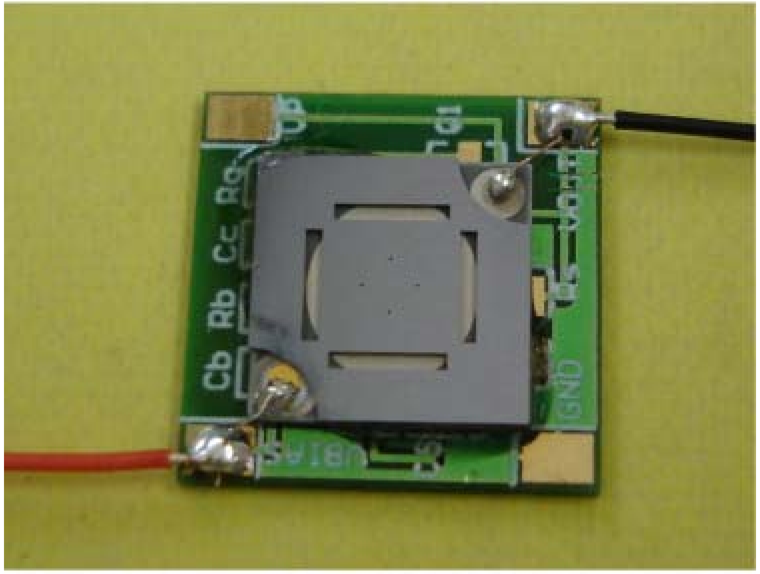
Device Example

(a) Schematic cross-section view of the transducer with perforated damping backplate.

(b) A final device with backplate mounted and wired to a printed circuit board. Four acoustic slots and acoustic holes in the backplate are clearly seen.



(a)



(b)

Z.Wang, et al., Acoustic transducers with a perforated damping backplate based on PZT/silicon wafer bonding technique, Sens. Actuators A: Phys. (2008),

Device Example

Fabrication process of the transducer.

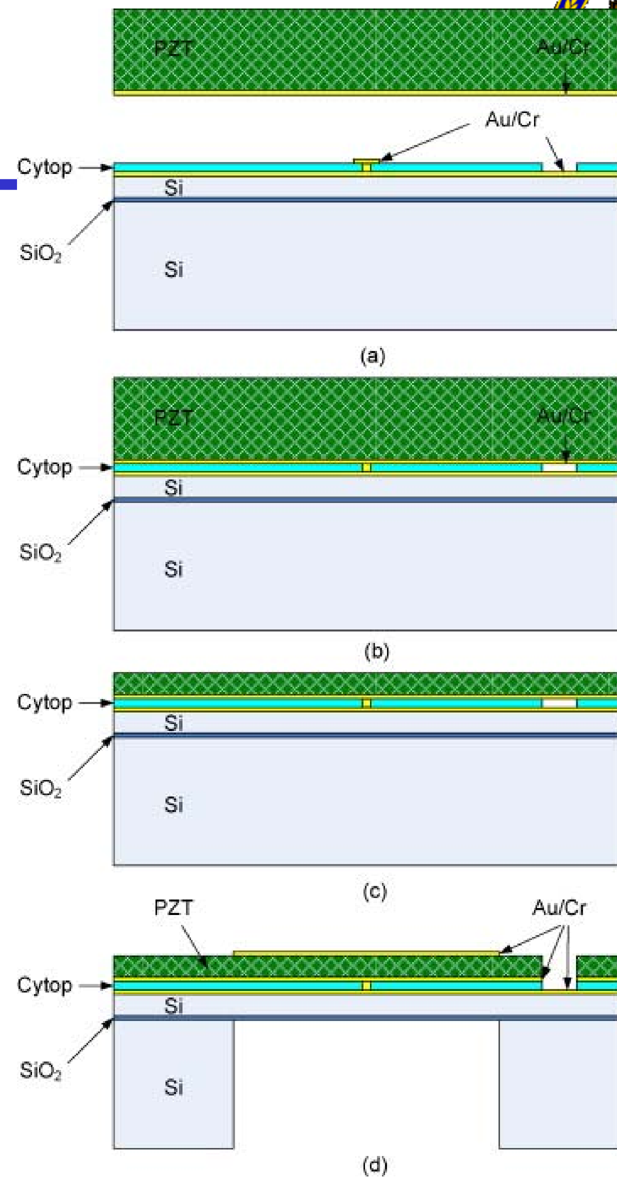
(a) Sputtering Cr/Au on both PZT and SOI wafer; spin-coating and patterning of Cytop on the SOI wafer.

(b) Bonding the PZT and SOI wafers together with the Cr/Au layers facing with each other.

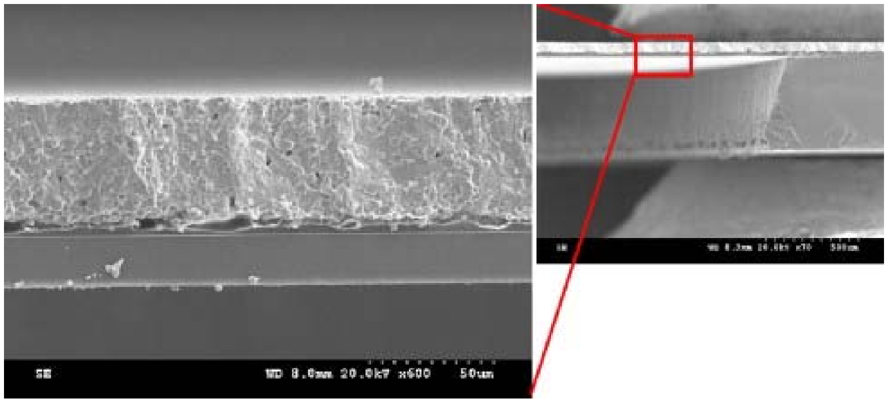
(c) Thinning down the PZT layer by using CMP.

(d) Sputtering and patterning of Cr/Au as top electrode; wet etching of PZT to expose bottom electrode; and etching the backside Si by using DRIE to release the diaphragm.

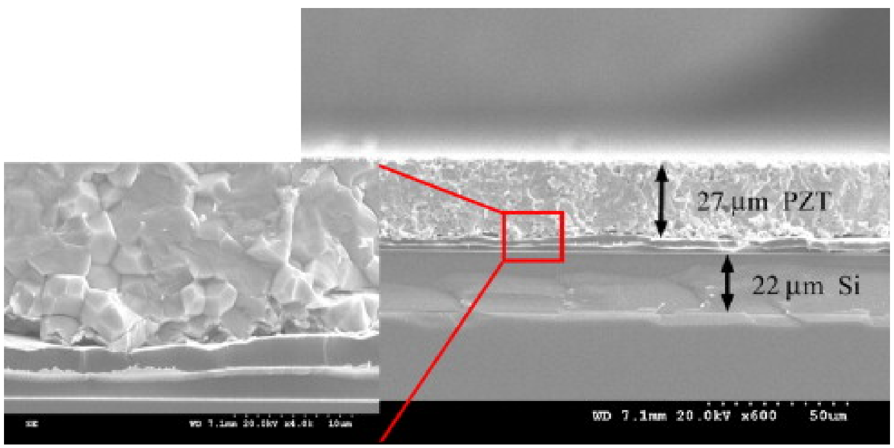
Z.Wang, et al., (2008),



Device Example



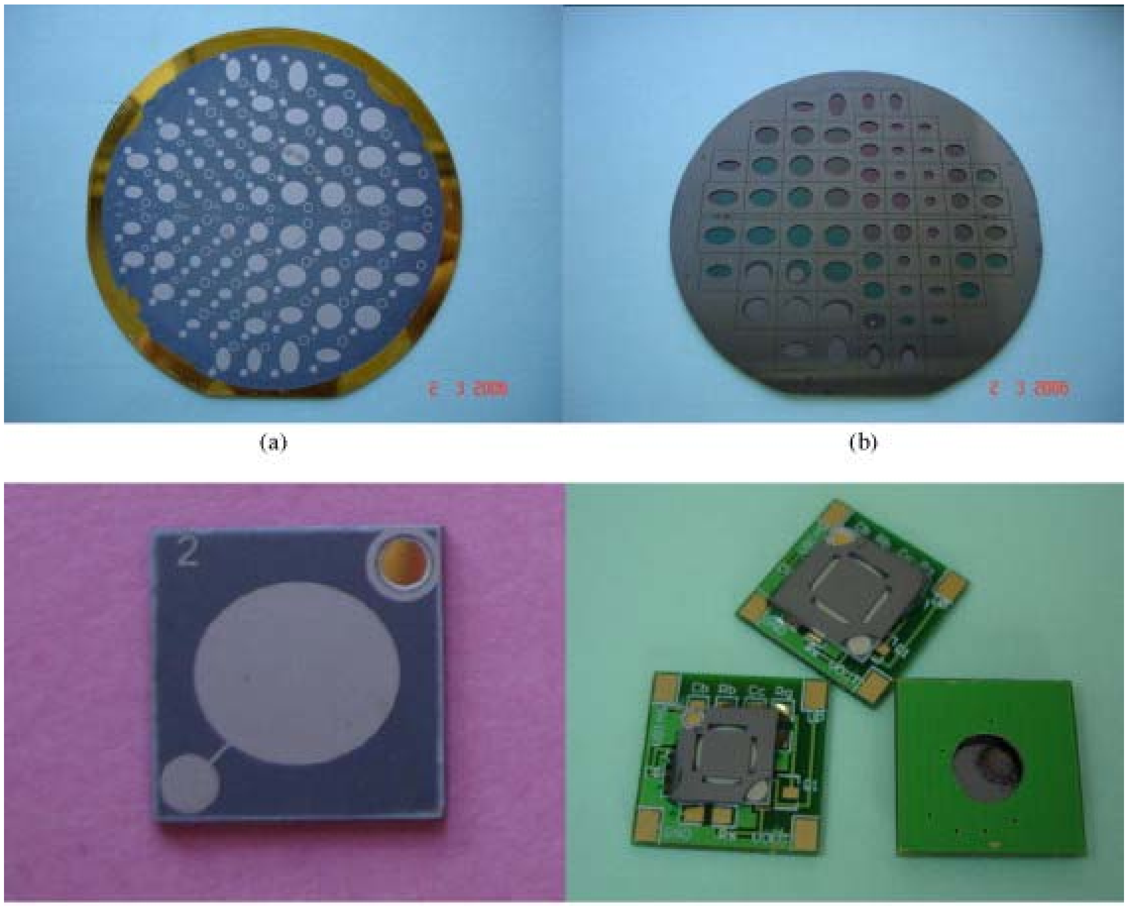
- SEM images of the released diaphragm structure show the uniform thickness and well crystallized bonded PZT layer.



- SEM images of the PZT/Cytop/Si bonding interface after the PZT was thinned down by CMP.

Z.Wang, et al., (2008),

Device Example



(a) (b) (c) (d)

Fabricated acoustic transducers at various stages of the fabrication process.

(a) Front side of a 4 in. SOI wafer after Si/PZT bonding and CMP shows the top electrode patterns of the transducer.

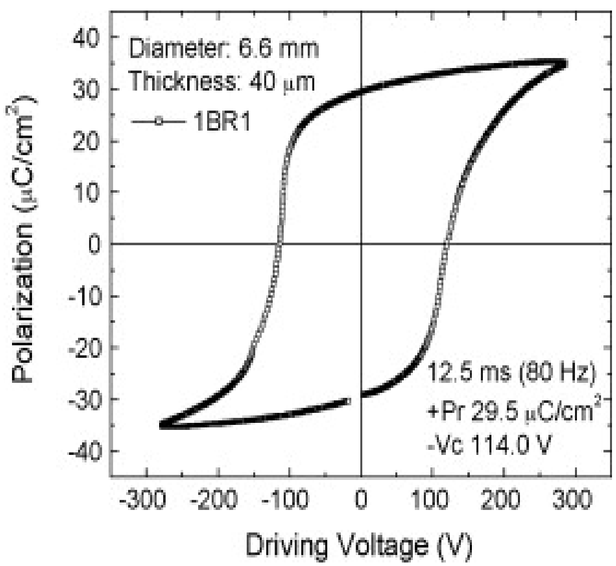
(b) Back side after DRIE shows the boundary of the individual transducers and the released diaphragm.

(c) Single transducer after dicing.

(d) Transducers with backplate, mounted on PCB board.

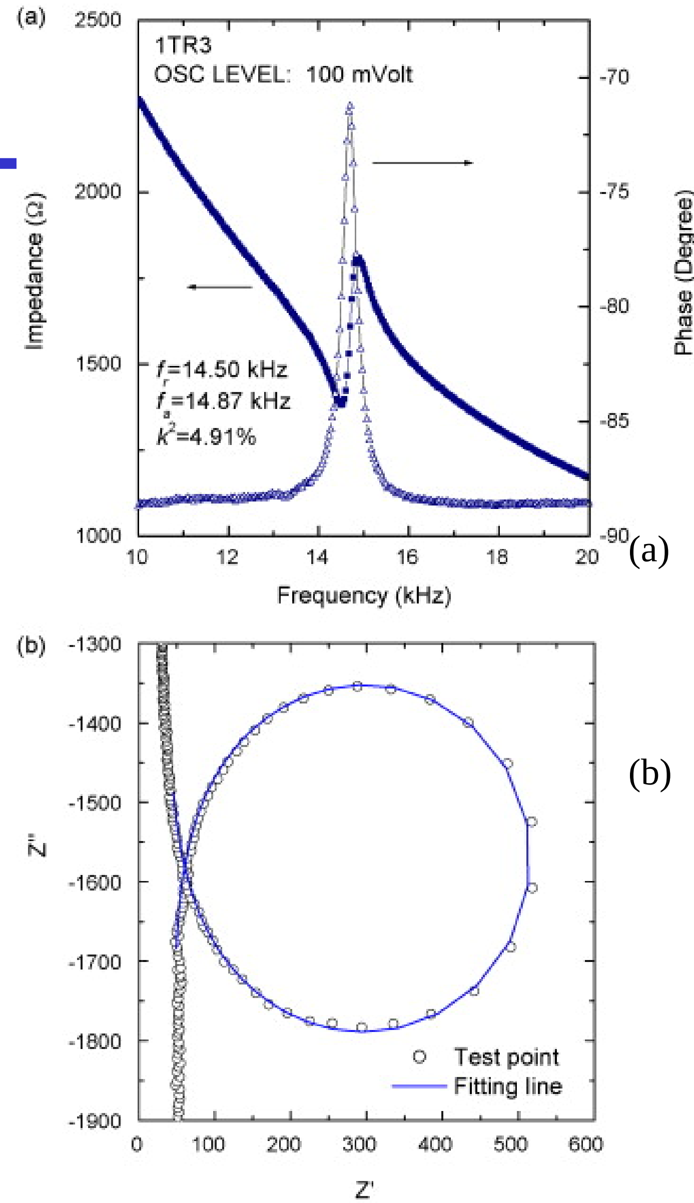
Z.Wang, et al., (2008),

Device Example



P–E hysteresis curve of the bonded PZT plate after CMP to around 40-μm thick.

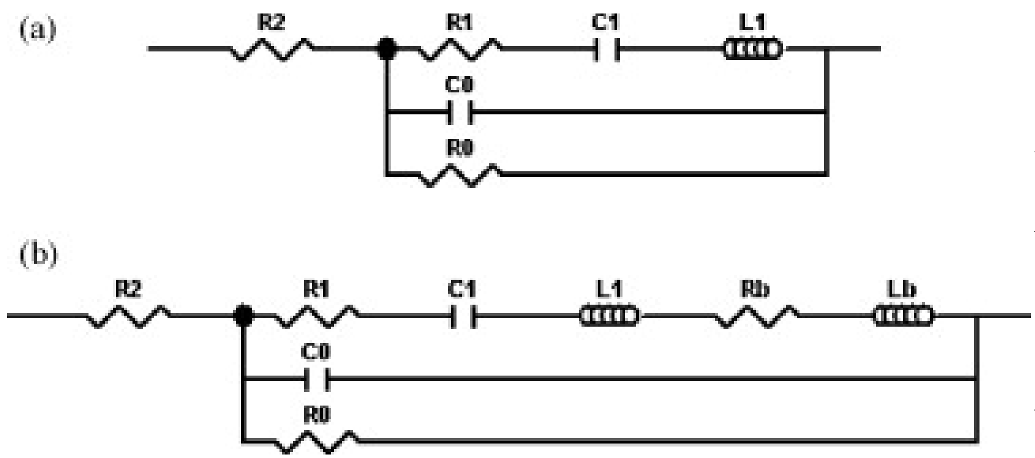
Z.Wang, et al., (2008),



(a) Impedance spectrum shows a transducer (1TR3) has electromechanical coupling coefficient of 4.91%.

(b) Complex impedance circle shows the difference between the test results and fitting results. Q value of the same transducer obtained from the fitted equivalent circuit is 37.7.

Device Example



Equivalent circuit of the transducer.
(a) The transducer without backplate taking into account the dielectric loss R0 and contact resistance R2.
(b) The transducer with backplate taking into account the damping Rb and mass Lb caused by the backplate.

Z.Wang, et al., (2008),

Things to know:

1) DRIE: Deep reactive ion etch
2) Cytop: a dielectric polymer coating for bonding
3) SOI: silicon on insulator
4) PZT thin/thick films
5) CMP: chemical-mechanical polishing