

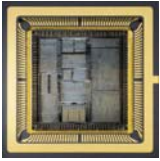
Lecture 3: Manufacturing

CSCE 6651

Advanced VLSI Systems

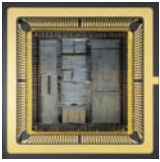
Instructor: Saraju P. Mohanty, Ph. D.

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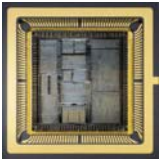
Lecture Outline

- Silicon as Semiconductor
- CMOS Fabrication
- Packaging
- Testing



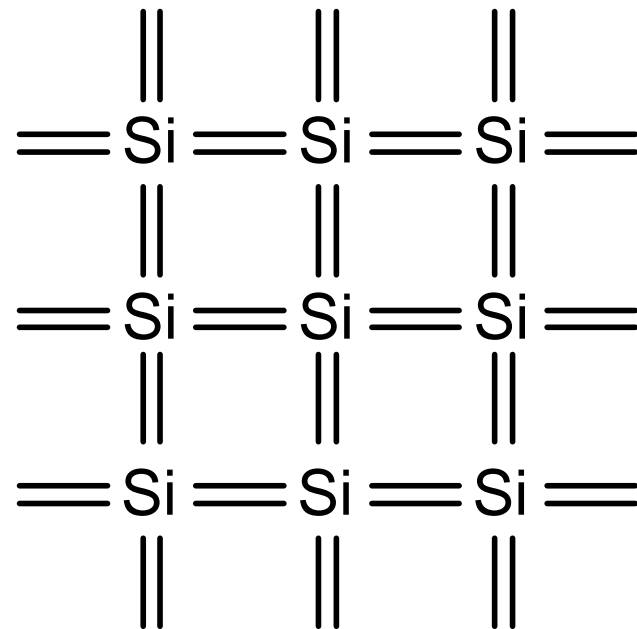
Introduction

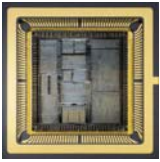
- Integrated circuits: many transistors on one chip.
- *Very Large Scale Integration (VLSI)*: very many
- *Complementary Metal Oxide Semiconductor*
 - Fast, cheap, low power transistors
- How to build your own simple CMOS chip
 - CMOS transistors
 - Building logic gates from transistors
 - Transistor layout and fabrication



Silicon Lattice

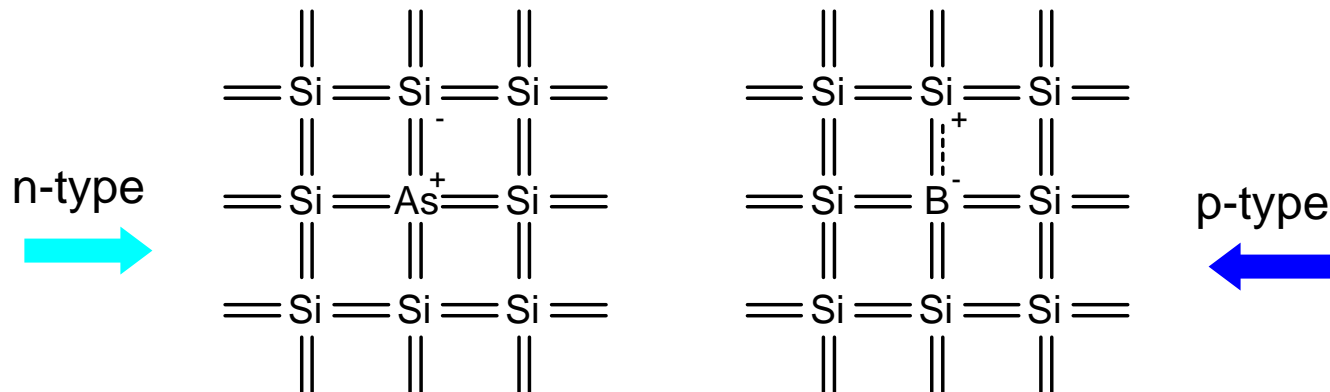
- Transistors are built on a silicon substrate
- Silicon is a Group IV material
- Forms crystal lattice with bonds to four neighbors

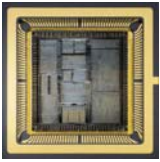




Dopants

- Silicon is a semiconductor
- Pure silicon has no free carriers and conducts poorly
- Adding dopants increases the conductivity
- Group V: extra electron (n-type)
- Group III: missing electron, called hole (p-type)



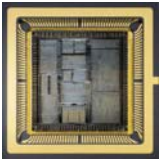


Why Silicon?

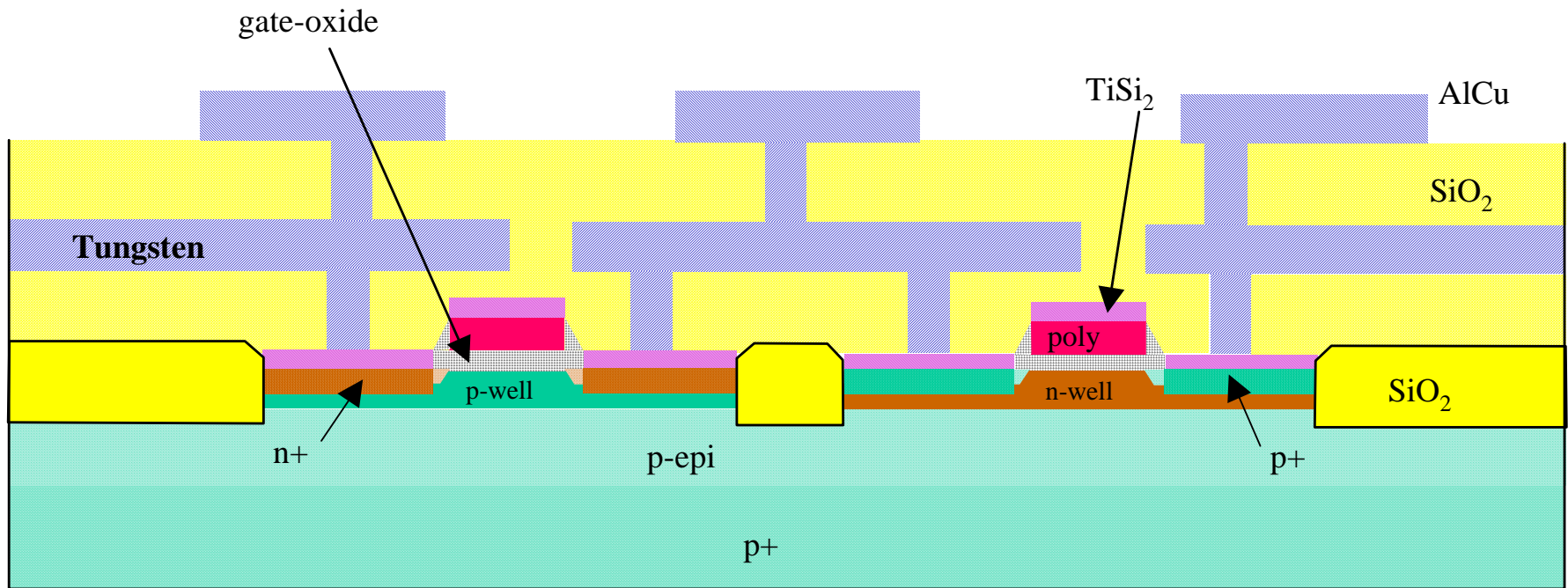
Could any other group IV metal serve purpose ?

Key Advantages:

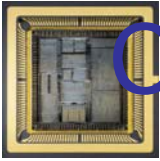
- Available abundantly in nature.
- Has excellent physical and electrical properties.
- Matured chemistry for fabrication



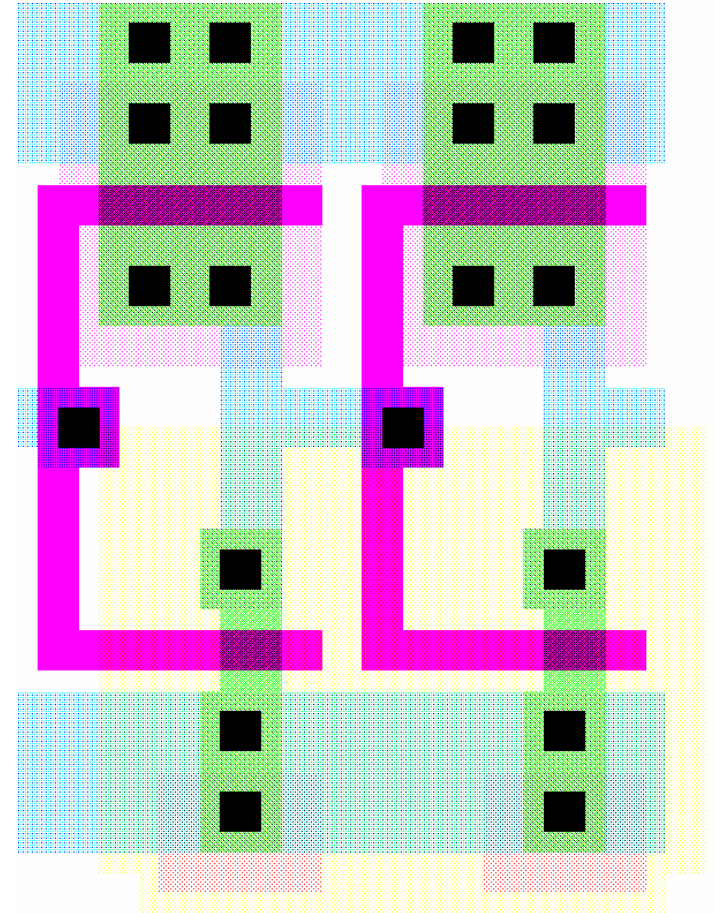
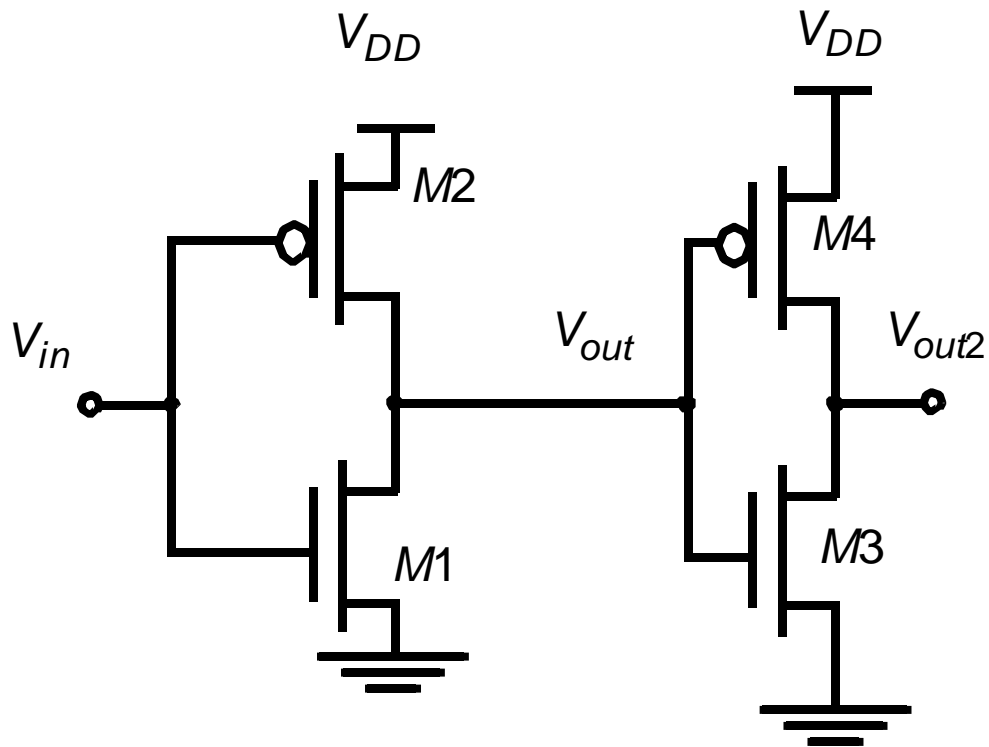
A Modern CMOS Process

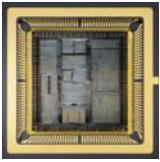


Dual-Well Trench-Isolated CMOS Process



Circuit Under Design and Its Layout





CMOS Fabrication

- CMOS transistors are fabricated on silicon wafer.
- Lithography process similar to printing press is used for the fabrication.
- On each step, different materials are deposited or etched.
- Easiest to understand by viewing both top and cross-section of wafer in a simplified manufacturing process.

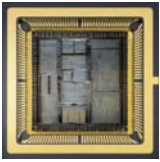
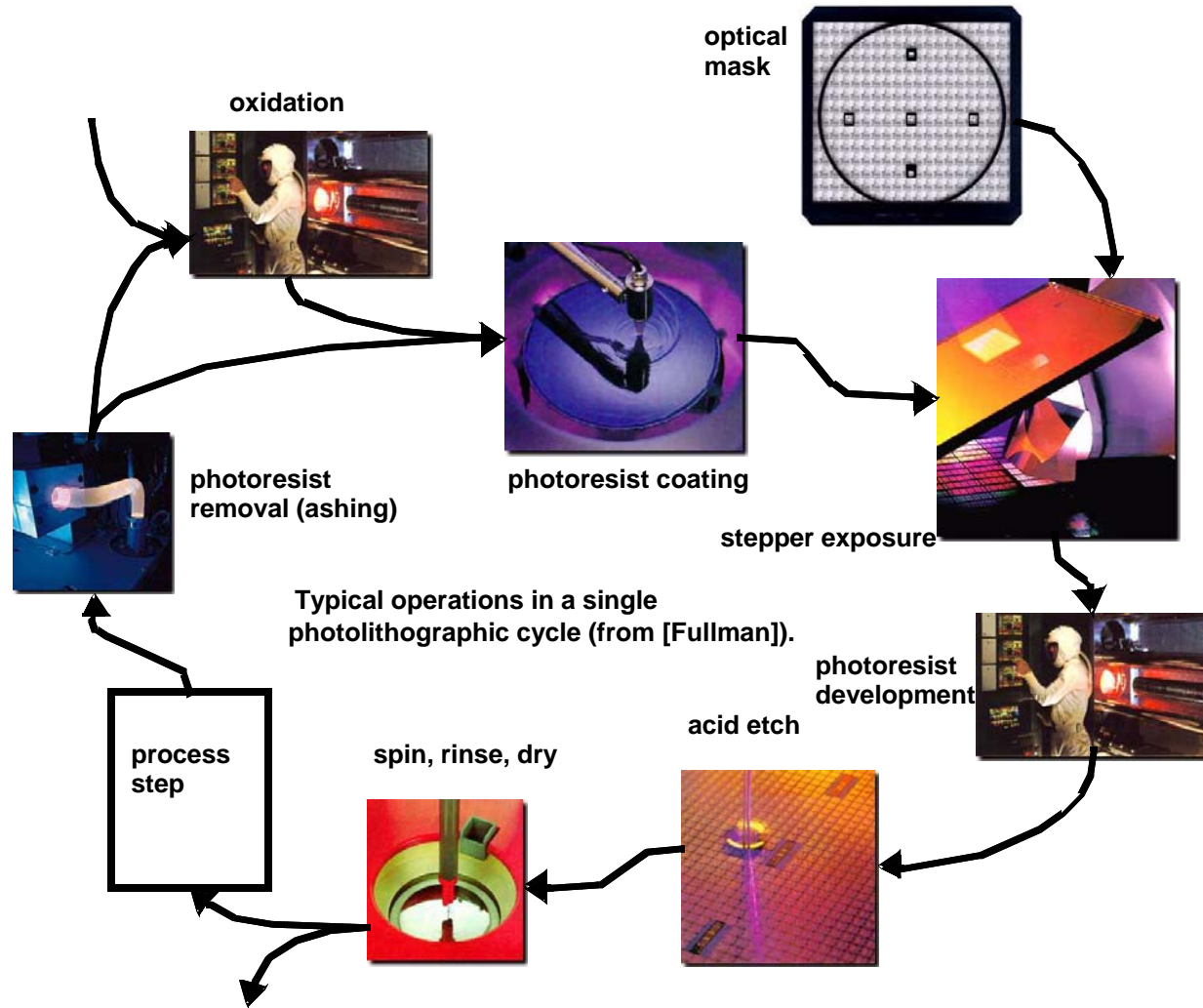
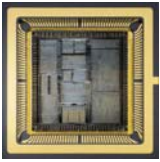
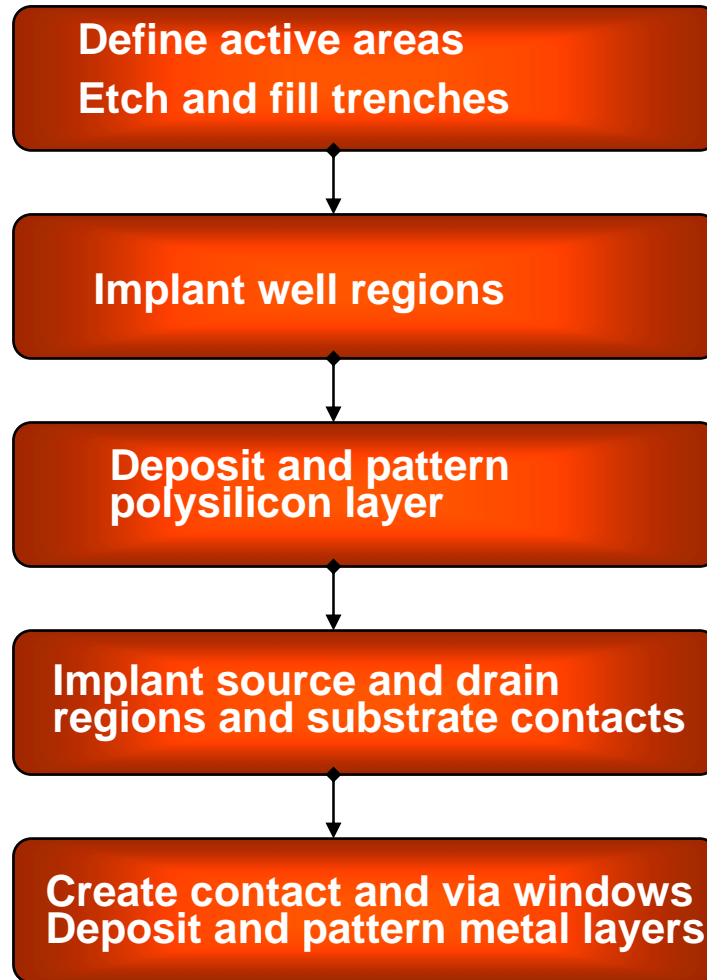


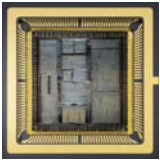
Photo-Lithographic Process





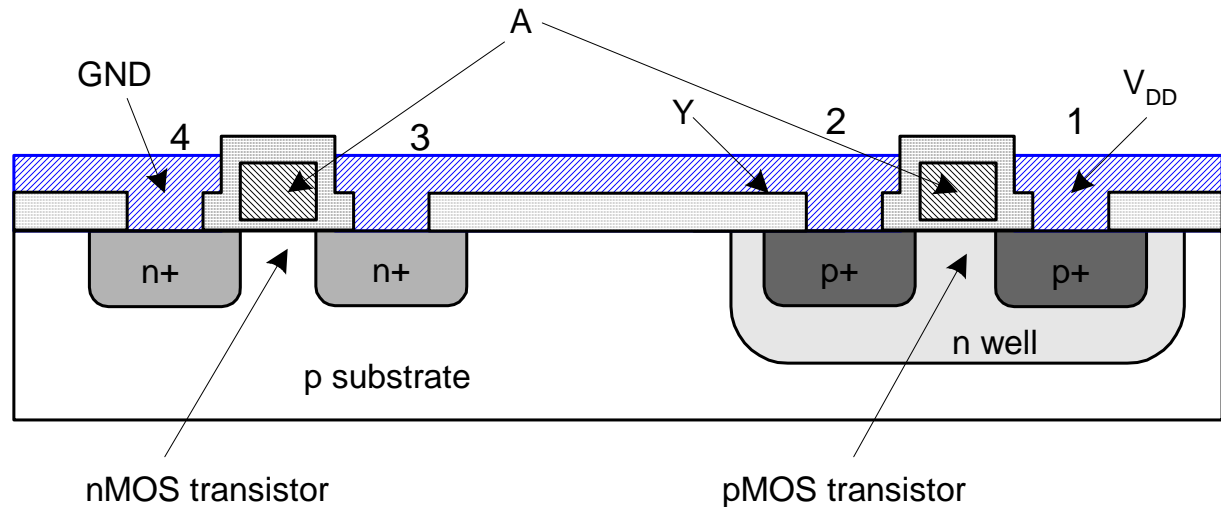
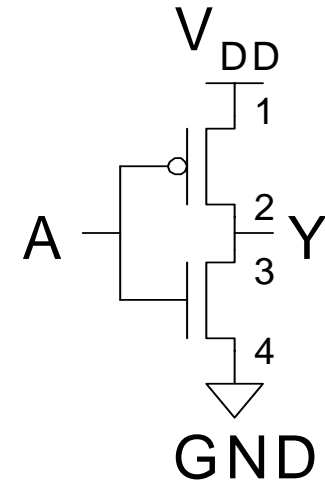
CMOS Process at a Glance



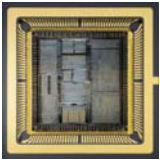


Inverter Cross-section

- Typically use p-type substrate for nMOS transistors.
- Requires n-well for body of pMOS transistors.

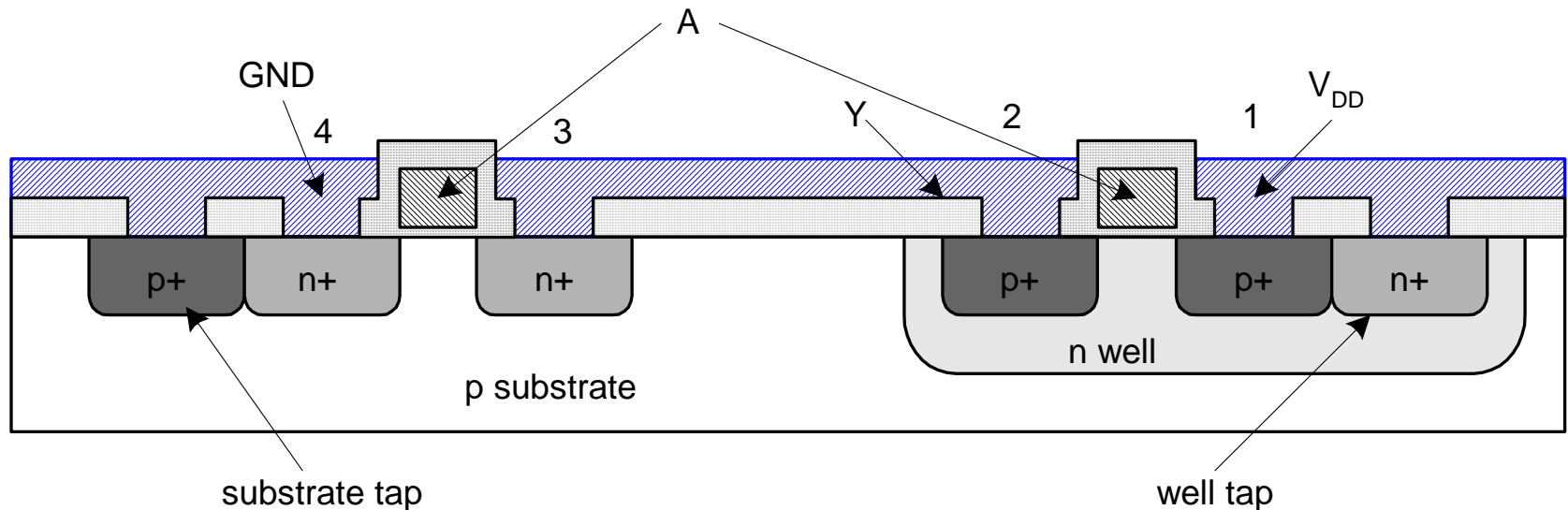


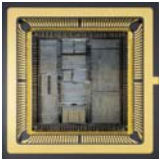
	SiO ₂
	n+ diffusion
	p+ diffusion
	polysilicon
	metal1



Well and Substrate Taps

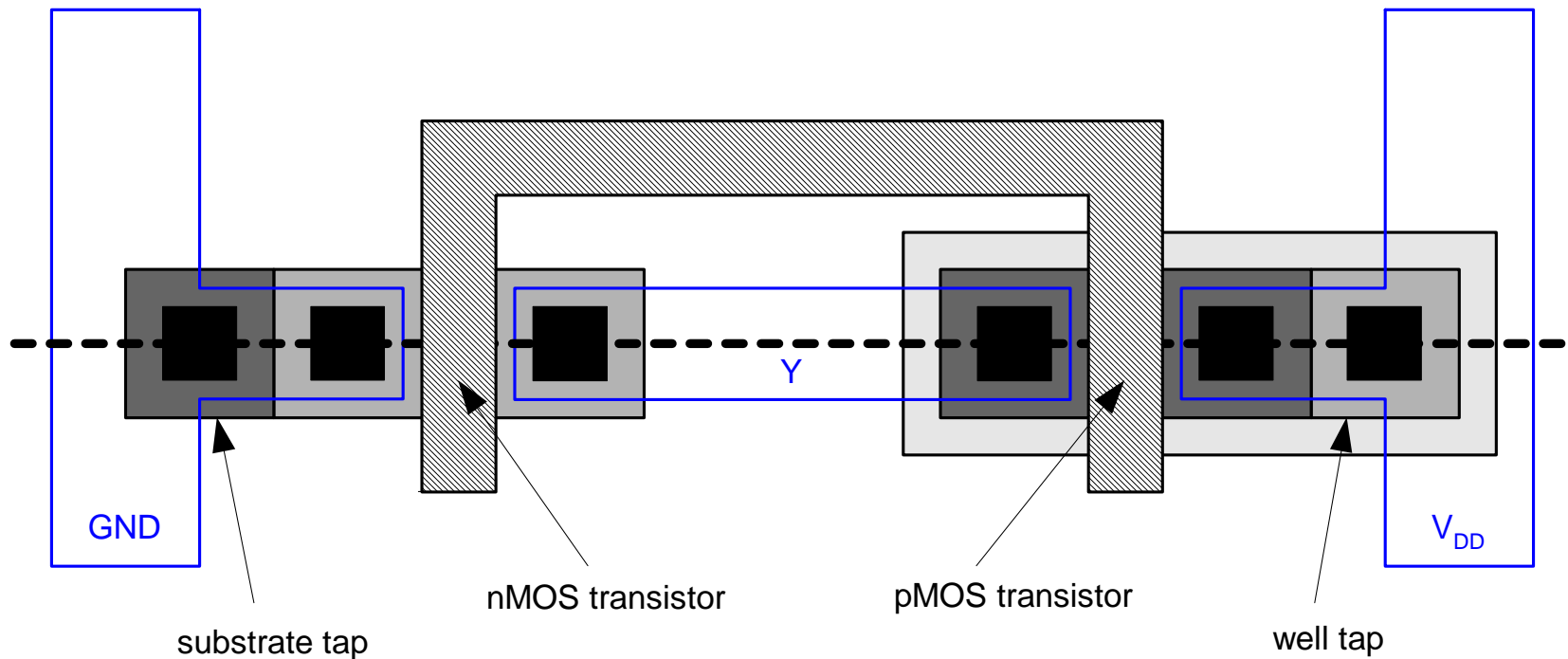
- Substrate must be tied to GND and n-well to V_{DD}
- Metal to lightly-doped semiconductor forms poor connection called Schottky Diode
- Heavily doped well and substrate contacts or taps form good ohmic contacts.

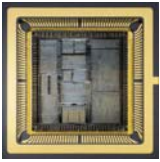




Inverter Mask Set

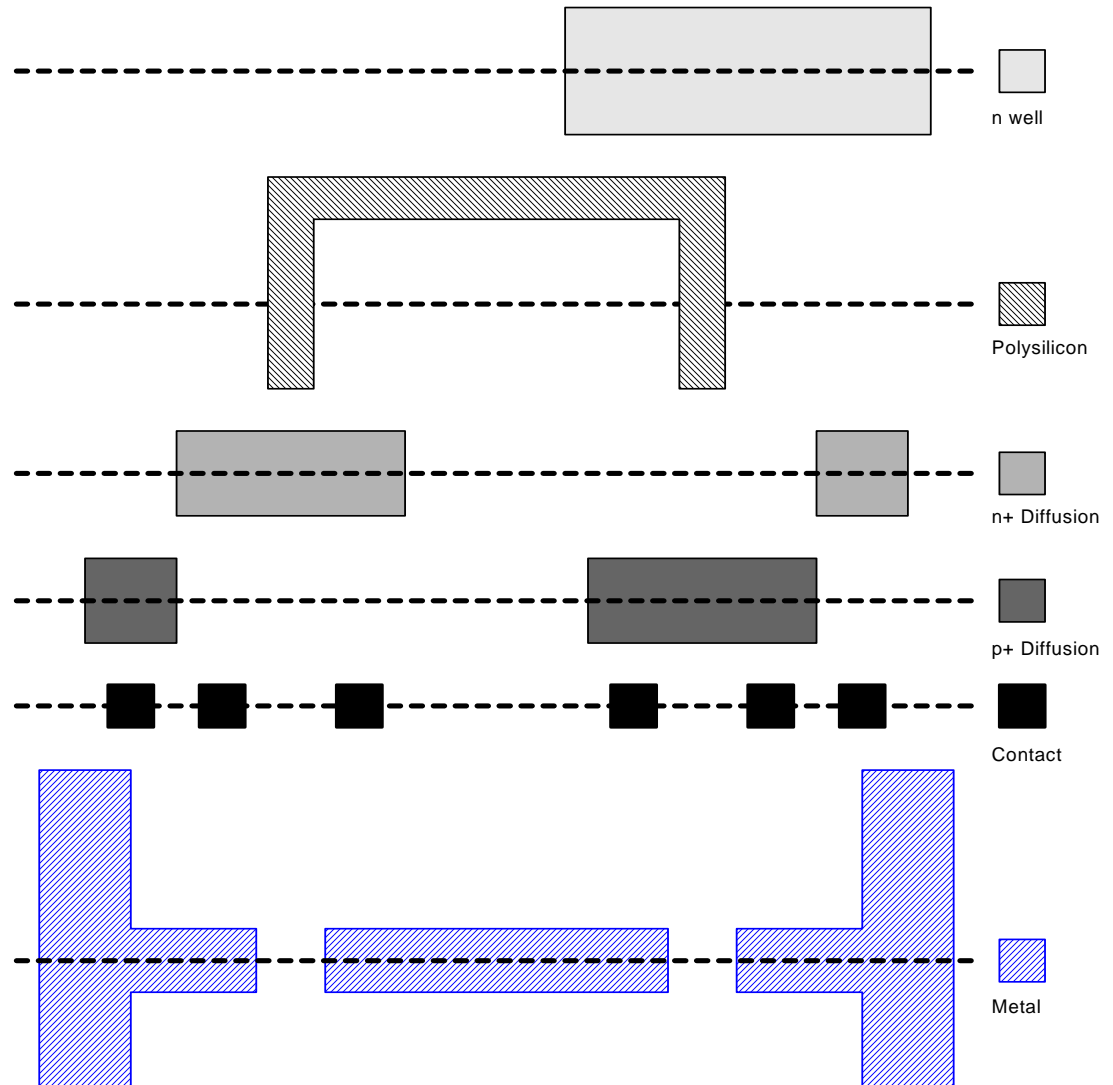
- Transistors and wires are defined by *masks*
- Cross-section taken along dashed line

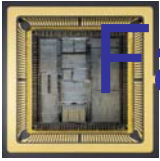




Detailed Mask Views

- Six masks
 - n-well
 - Polysilicon
 - n+ diffusion
 - p+ diffusion
 - Contact
 - Metal

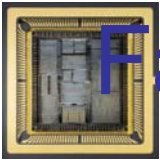




Fabrication Steps: Creation of n-well

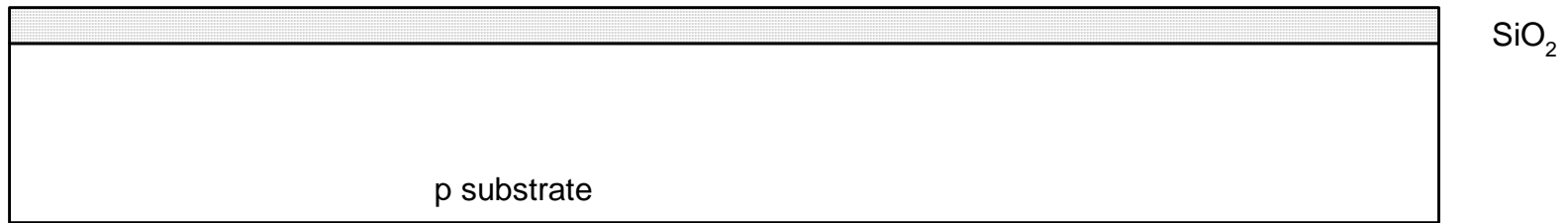
- Objective is to build inverter from the bottom up
- First step will be to form the n-well
 - Cover wafer with protective layer of SiO_2 (oxide)
 - Remove layer where n-well should be built
 - Implant or diffuse n dopants into exposed wafer
 - Strip off SiO_2
- n-well : Start with blank p-type silicon wafer



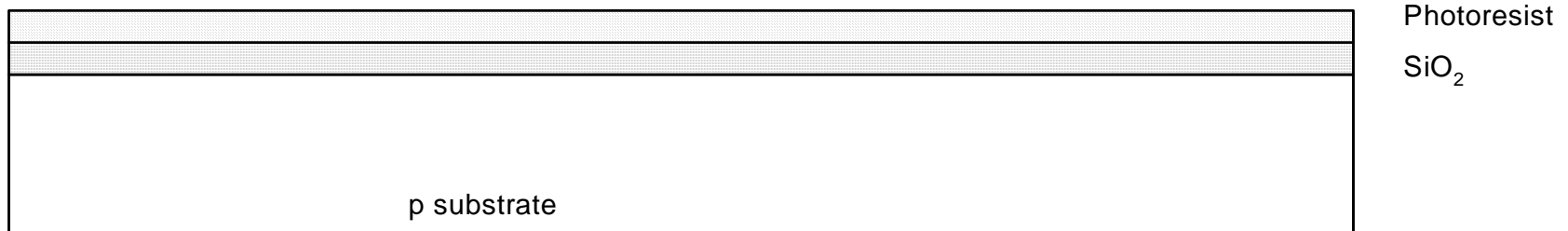


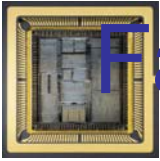
Fabrication Steps: Creation of n-well

- n-well: Grow SiO_2 on top of Si wafer
 - 900 – 1200 C with H_2O or O_2 in oxidation furnace
 - The oxide is patterned to define n-well.



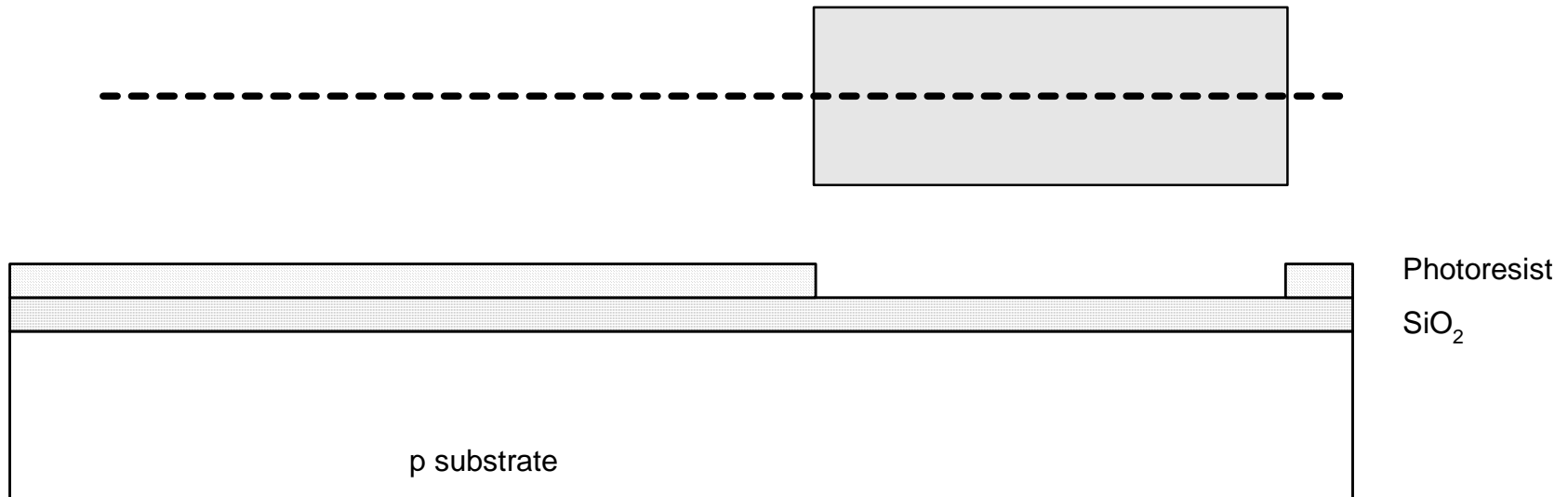
- n-well: Spin on photoresist
 - Photoresist is a light-sensitive organic polymer
 - Softens where exposed to light

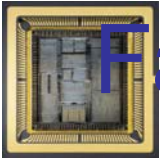




Fabrication Steps: Creation of n-well

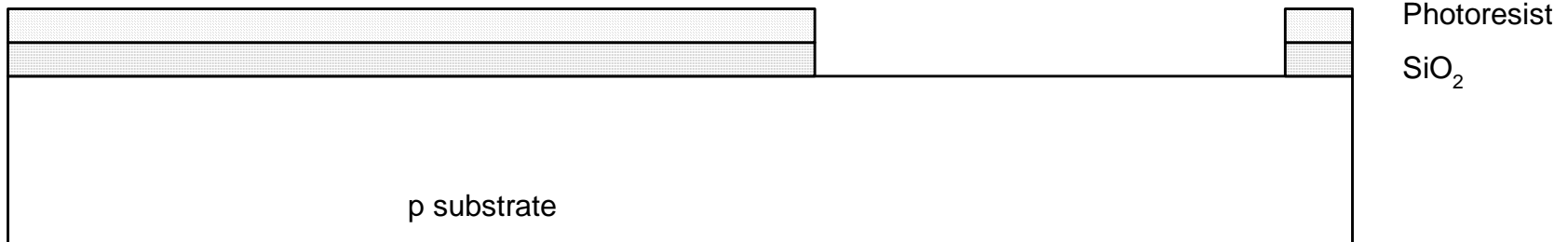
- n-well: Expose photoresist through n-well mask
 - Allows light to pass through only where the n-well need to be created.
 - Strip off exposed photoresist





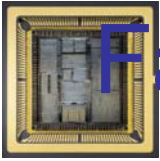
Fabrication Steps: Creation of n-well

- n-well: Etch oxide with hydrofluoric acid (HF)
 - Only attacks oxide where resist has been exposed



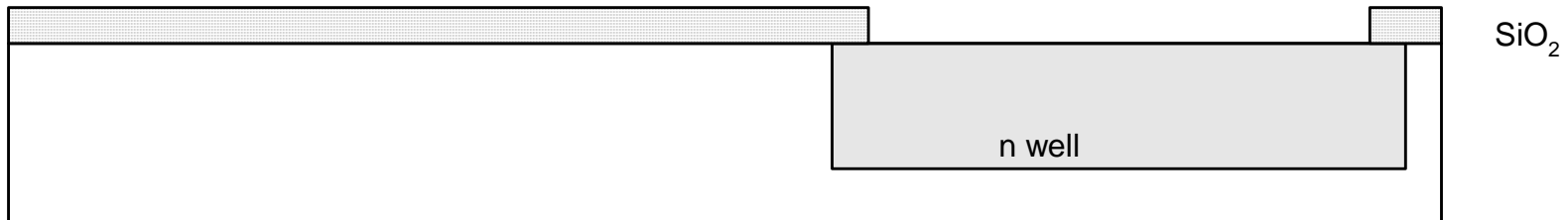
- n-well: Strip off remaining photoresist
 - Use mixture of acids called piranha etch
 - Necessary so resist doesn't melt in next step





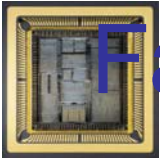
Fabrication Steps: Creation of n-well

- n-well: created with diffusion or ion implantation
 - Diffusion: Place wafer in furnace with arsenic gas and heat until As atoms diffuse into exposed Si
 - Ion Implantation: Blast wafer with beam of As ions



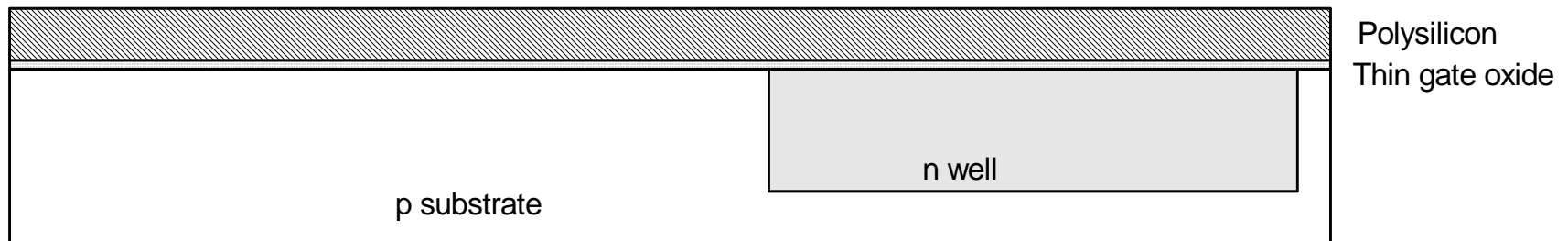
- n-well: Strip off the remaining oxide using HF
 - Back to bare wafer with n-well
 - Subsequent steps involve similar series of steps

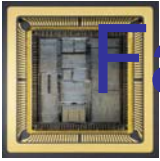




Fabrication Steps: Creation of Gates

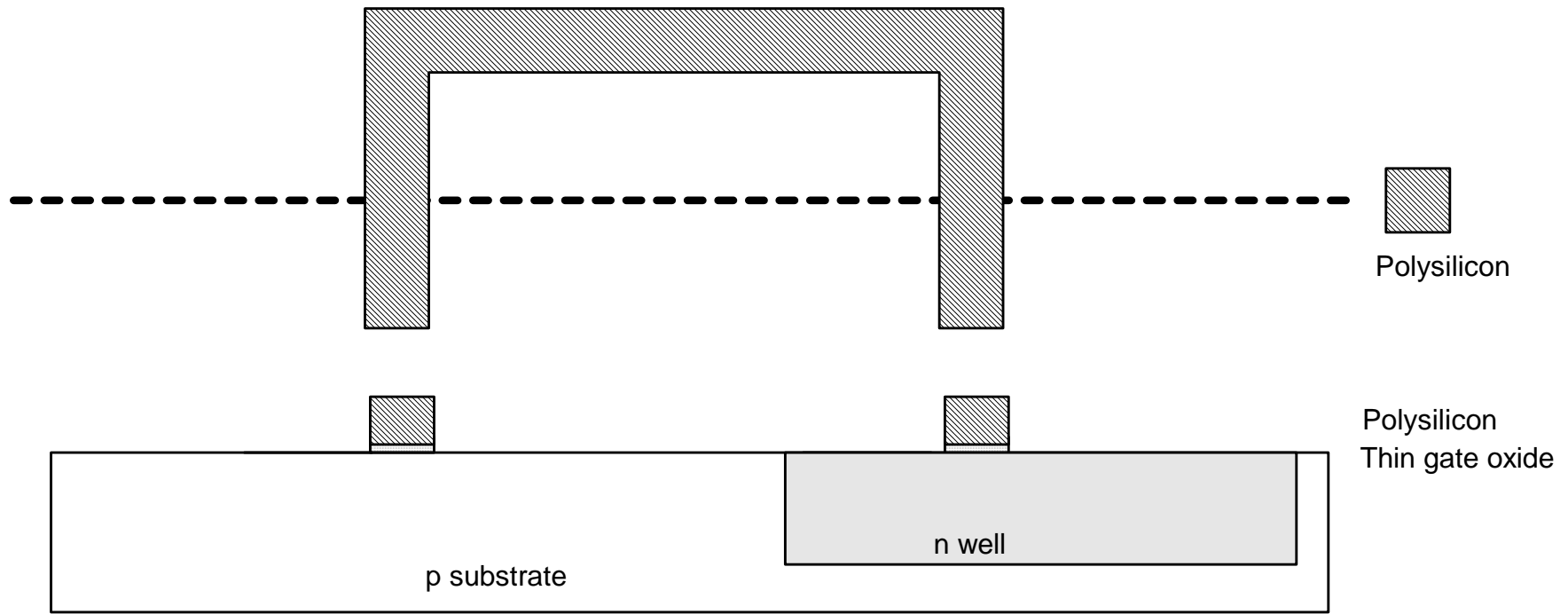
- Gate consists of polysilicon over thin layer of silicon oxide.
- Very thin layer of gate oxide is grown in furnace
 - $< 20 \text{ \AA}$ (6-7 atomic layers)
- Chemical Vapor Deposition (CVD) of silicon layer for polysilicon deposition
 - Place wafer in furnace with Silane gas (SiH_4)
 - Forms many small crystals called polysilicon
 - Polysilicon is heavily doped to be a good conductor

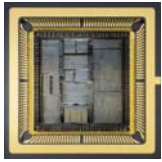




Fabrication Steps: Creation of Gates

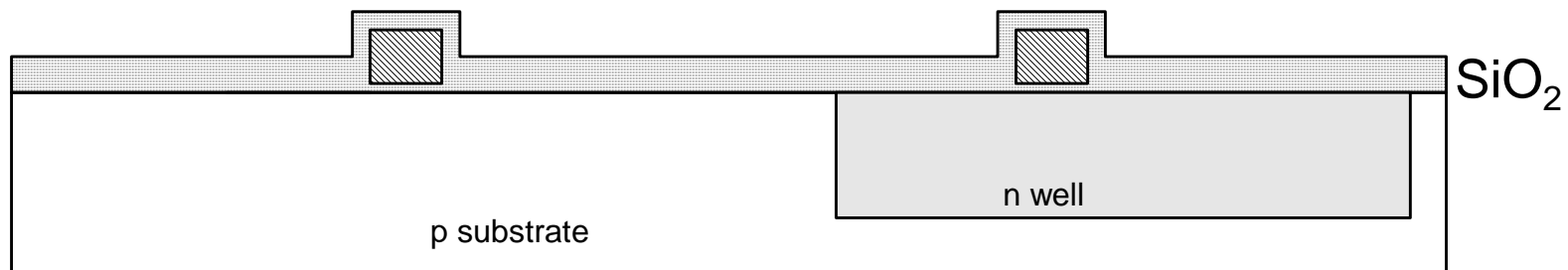
- Use same lithography process that used to create n-well to pattern polysilicon using photoresist and the polysilicon mask.

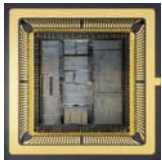




Fabrication Steps: Creation of n+

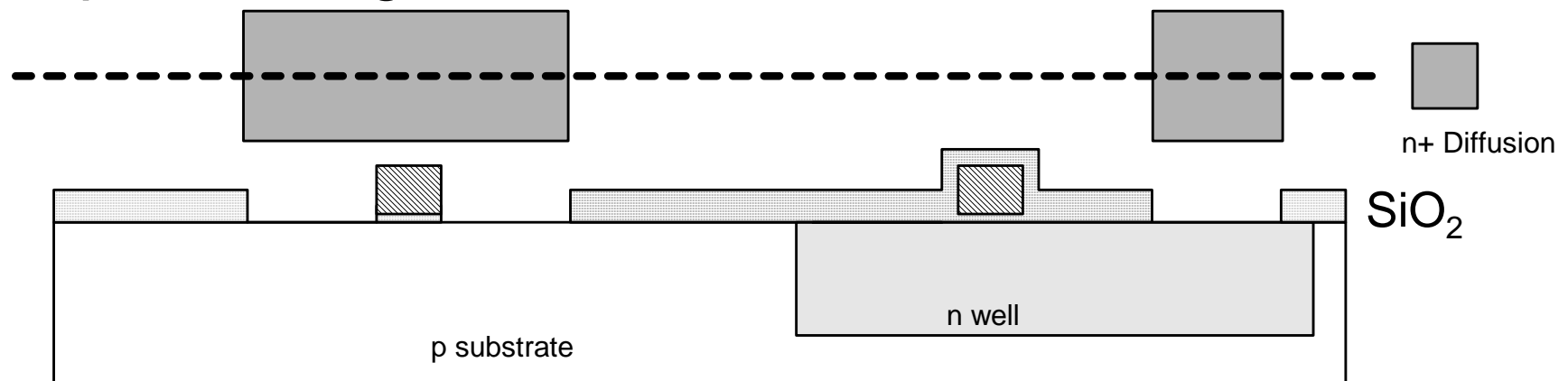
- Transistor active area and well contact are n+.
- N-diffusion forms nMOS source, drain, and n-well contact
- Use oxide and masking to expose where n+ dopants should be diffused or implanted

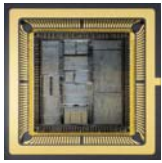




Fabrication Steps: Creation of n+

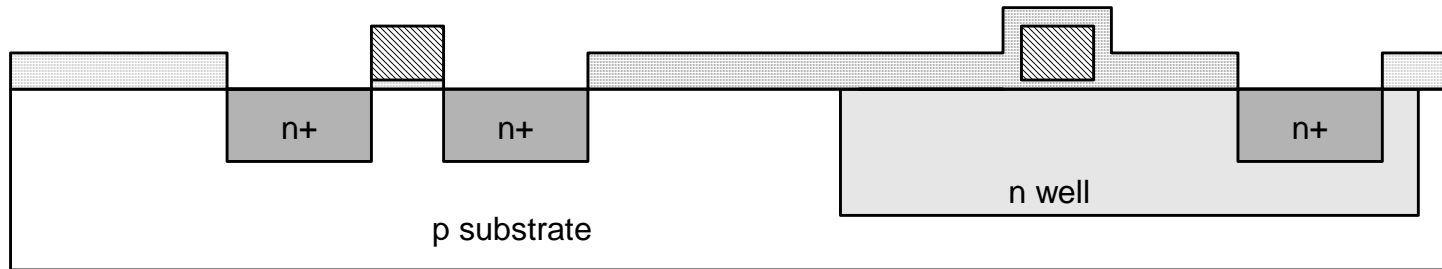
- Pattern oxide with the n-diffusion mask and form n+ regions
- *Self-aligned process* where gate blocks diffusion
- Polysilicon is better than metal for self-aligned gates because it doesn't melt during later processing



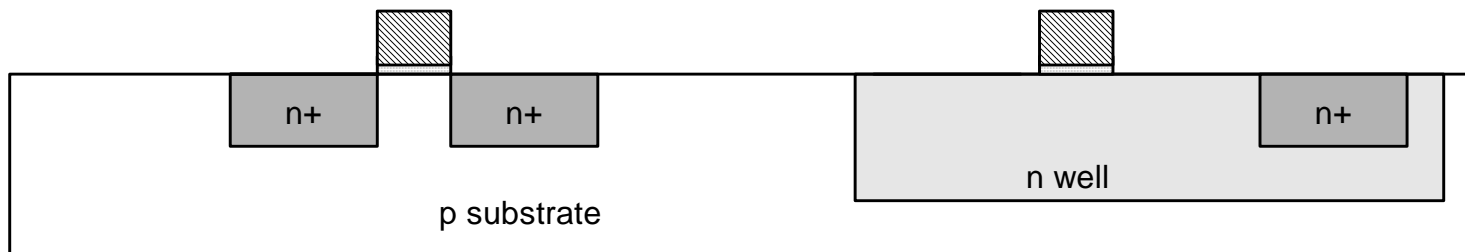


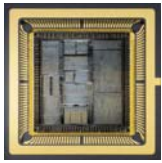
Fabrication Steps: Creation of n+

- Historically dopants were diffused
- Usually ion implantation today
- But regions are still called diffusion



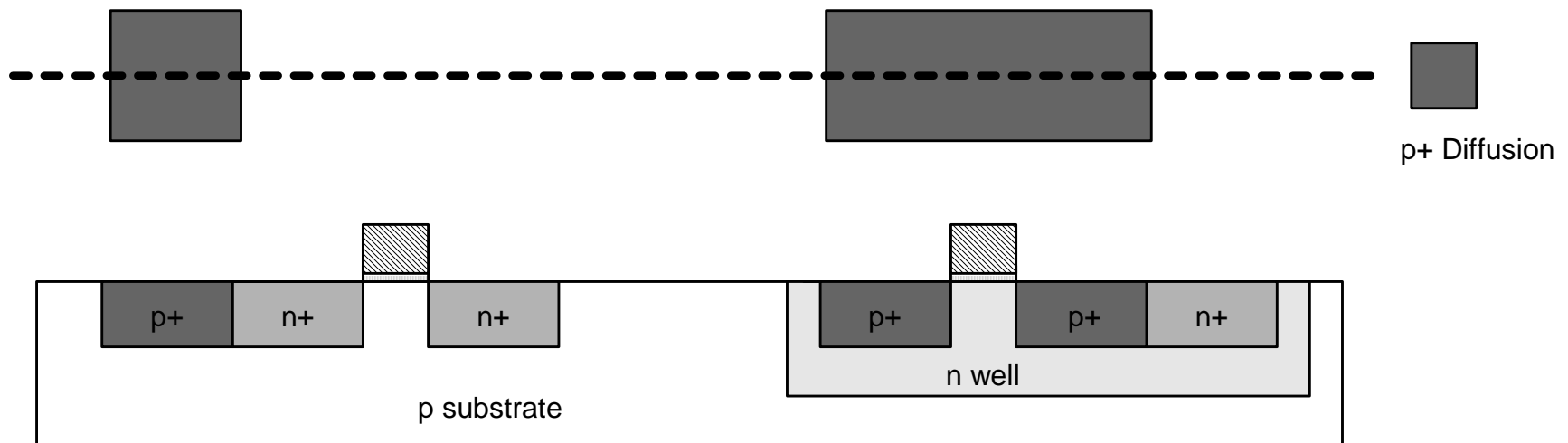
- Strip off oxide to complete patterning step

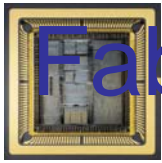




Fabrication Steps: Creation of p+

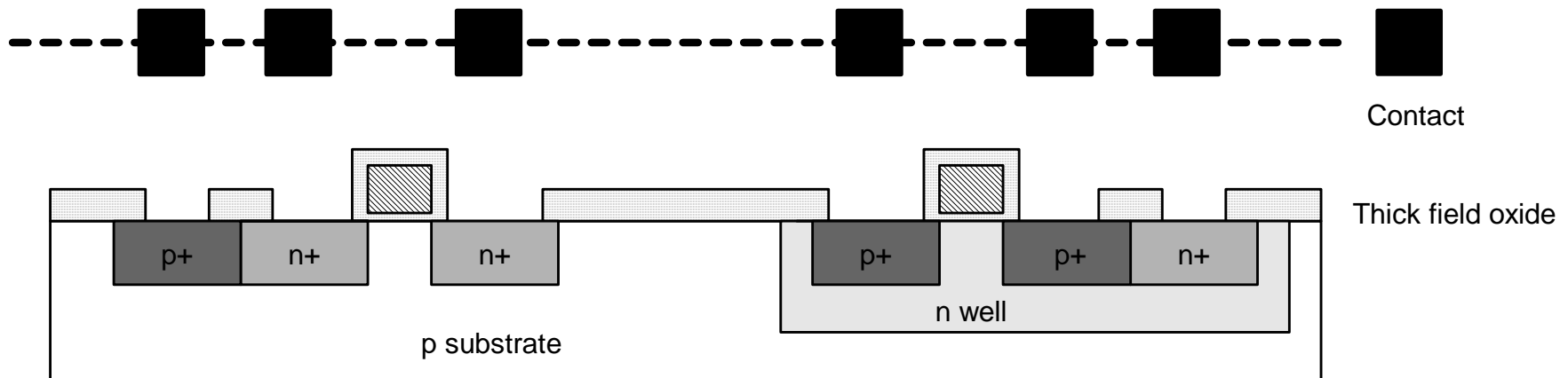
- Similar set of steps form p+ diffusion regions for pMOS source and drain and substrate contact
- Pattern oxide with the p-diffusion mask and form p+ regions

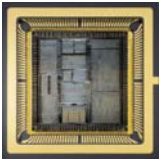




Fabrication Steps: Creation of Contacts

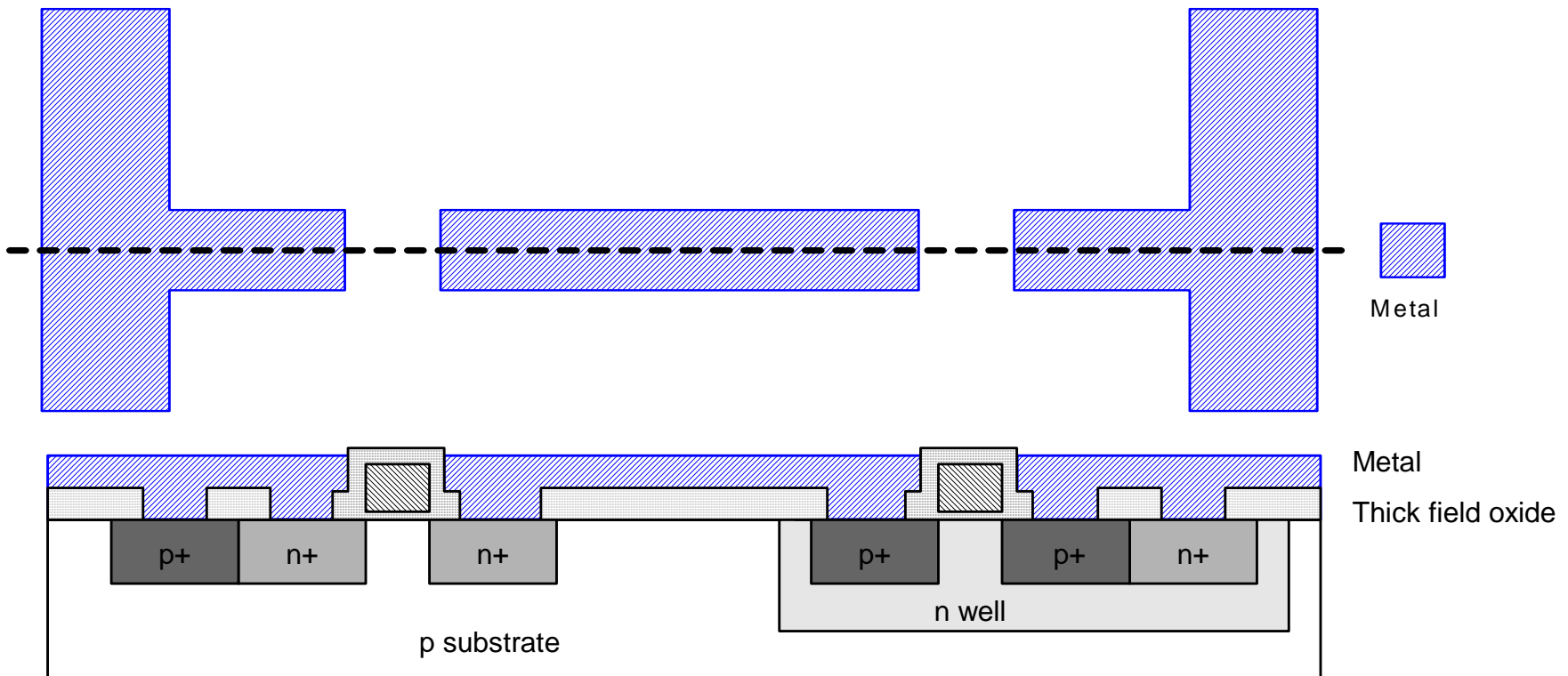
- Now we need to wire together the devices
- Cover chip with thick field oxide
- Etch oxide where contact cuts are needed using contact mask.

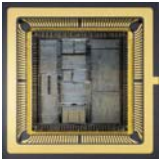




Fabrication Steps: Metalization

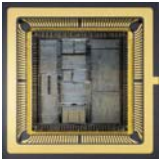
- Sputter on aluminum over whole wafer
- Pattern to remove excess metal, leaving wires
- Metal mask is used during this step.





Advanced Metallization

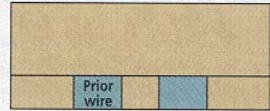




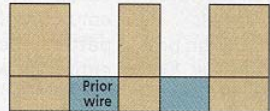
Advanced Metallization

Dual damascene IC process

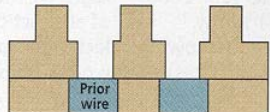
- Oxide deposition



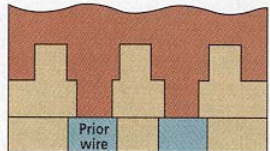
- Stud lithography and reactive ion etch



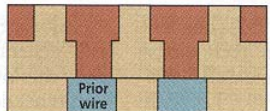
- Wire lithography and reactive ion etch



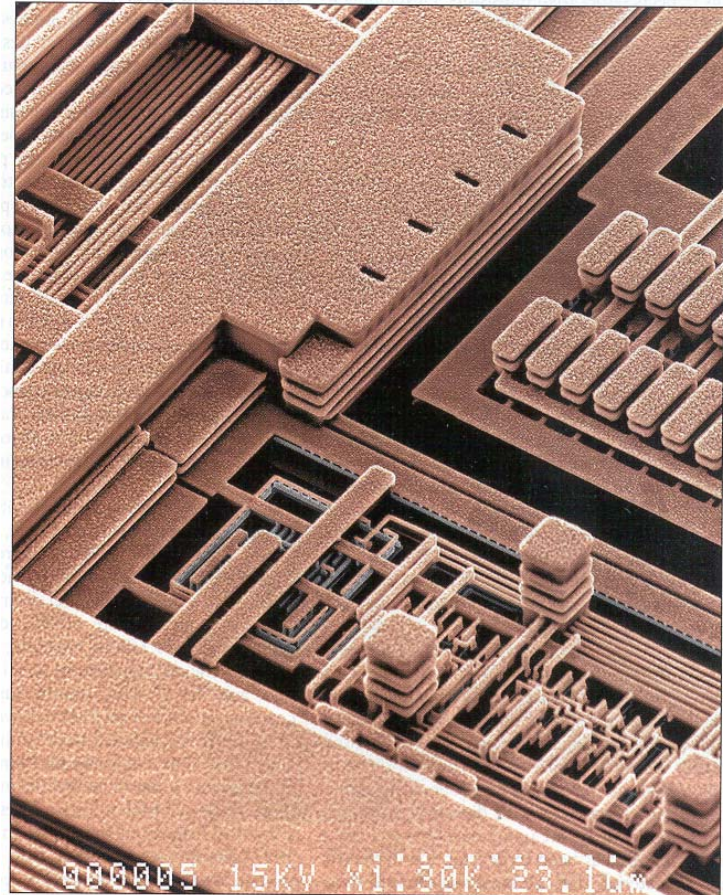
- Stud and wire metal deposition

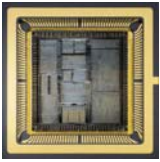


- Metal chemical-mechanical polish

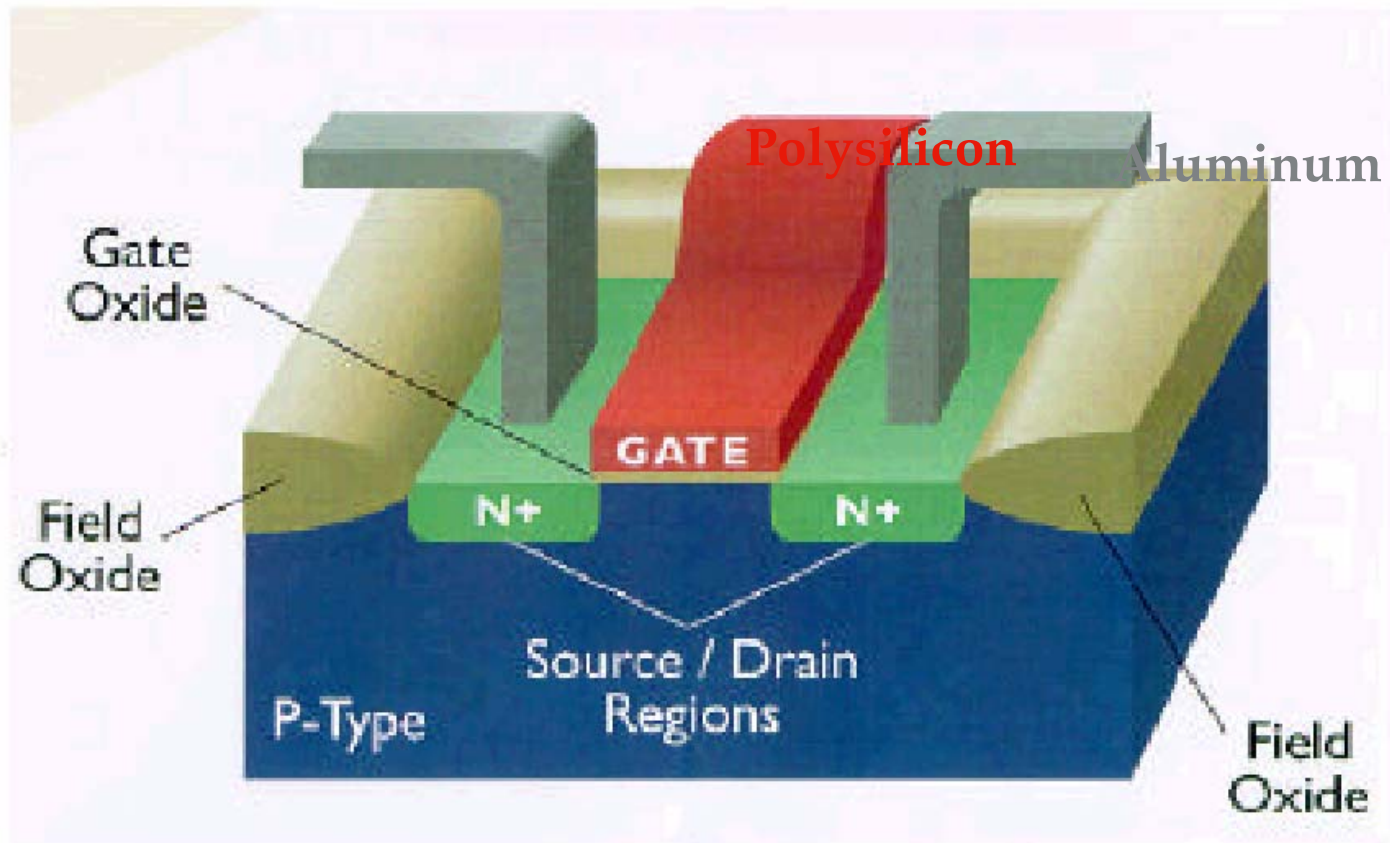


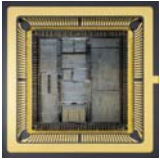
Source: IBM Corp.





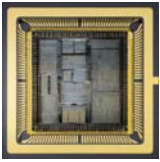
3D Perspective





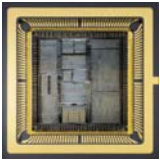
Layout Design Rules

- Interface between designer and process engineer
- Guidelines for constructing process masks
- Unit dimension: Minimum line width
 - scalable design rules: lambda parameter
 - absolute dimensions (micron rules)












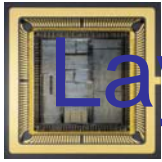
Layout Design Rules

- Chips are specified with set of masks
- Minimum dimensions of masks determine transistor size (and hence speed, cost, and power)
- Feature size f = distance between source and drain
 - Set by minimum width of polysilicon
- Normalize for feature size when describing design rules
- Express rules in terms of $\lambda = f/2$
 - e.g. $\lambda = 60$ nm in 120 nm process




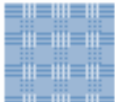
















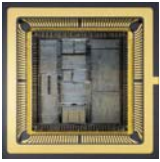
CMOS Process Layers

Layer	Color	Representation
Well (p,n)	Yellow	
Active Area (n+,p+)	Green	
Select (p+,n+)	Green	
Polysilicon	Red	
Metal1	Blue	
Metal2	Magenta	
Contact To Poly	Black	
Contact To Diffusion	Black	
Via	Black	

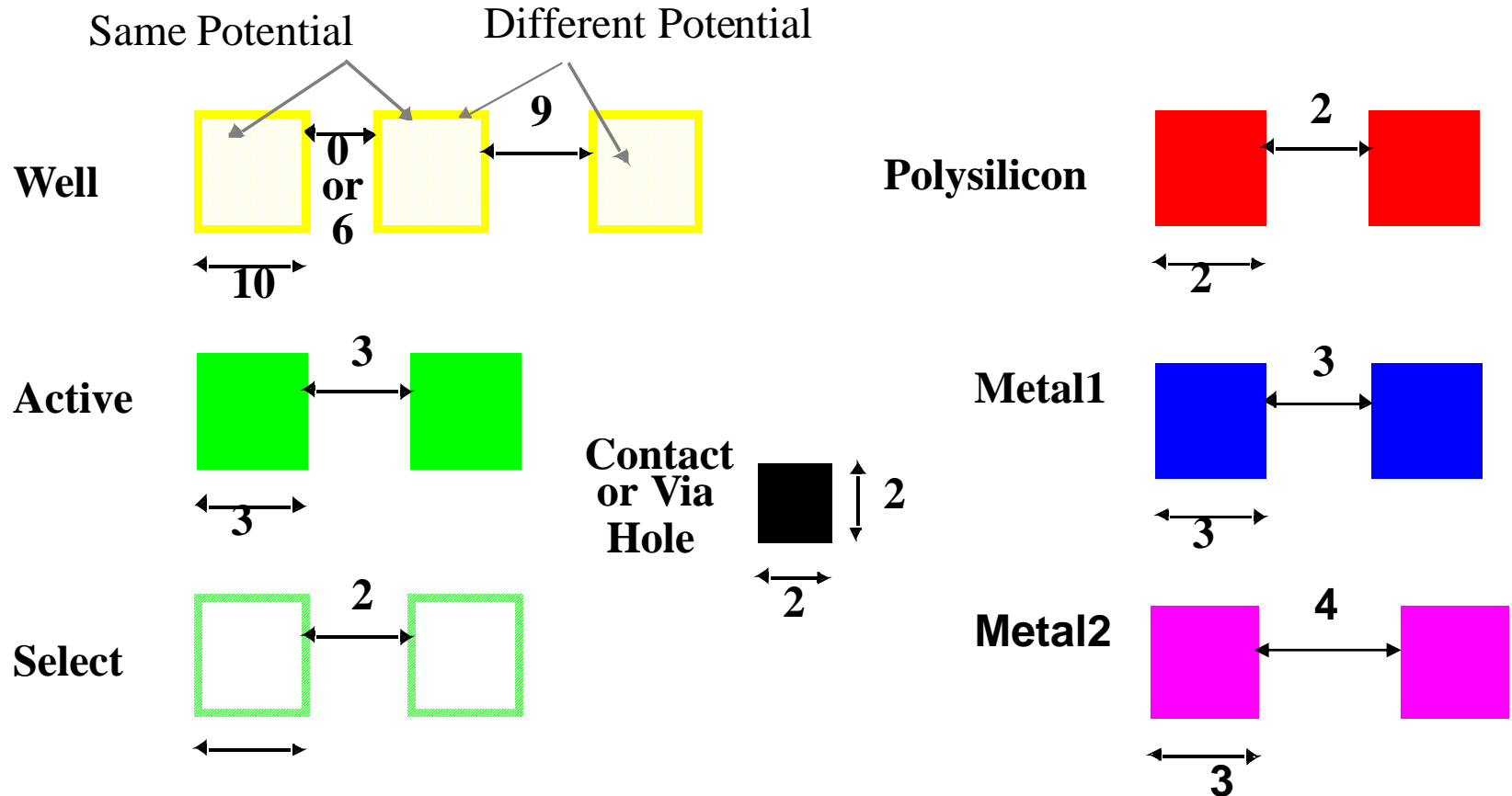


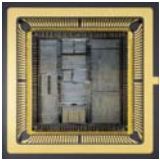
Layers in 0.25 μm CMOS process

Layer Description	Representation				
metal					
	m1	m2	m3	m4	m5
					
	nw				
					
	poly				
contacts & vias					
	ct	v12,v23,v34,v45	nwc	pwc	
					
	ndif	pdif	nfet	pfet	
select					
	nplus	pplus	prb		

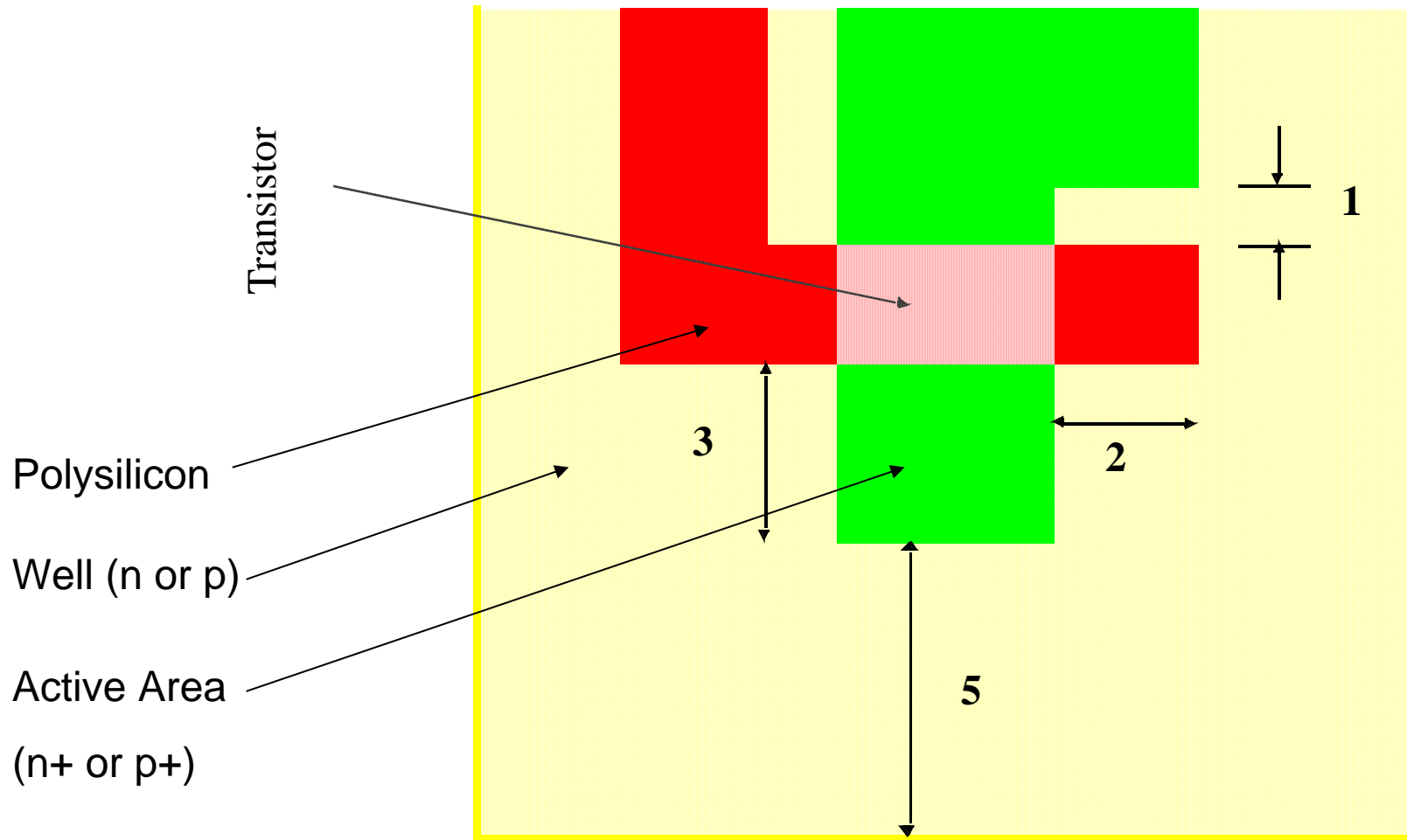


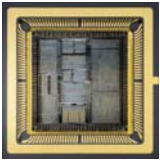
Intra-Layer Design Rules



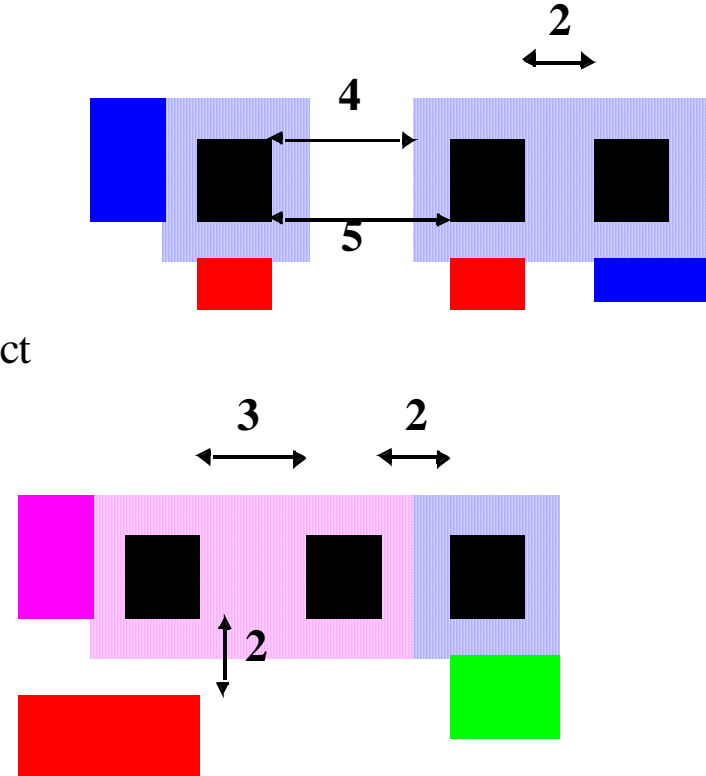
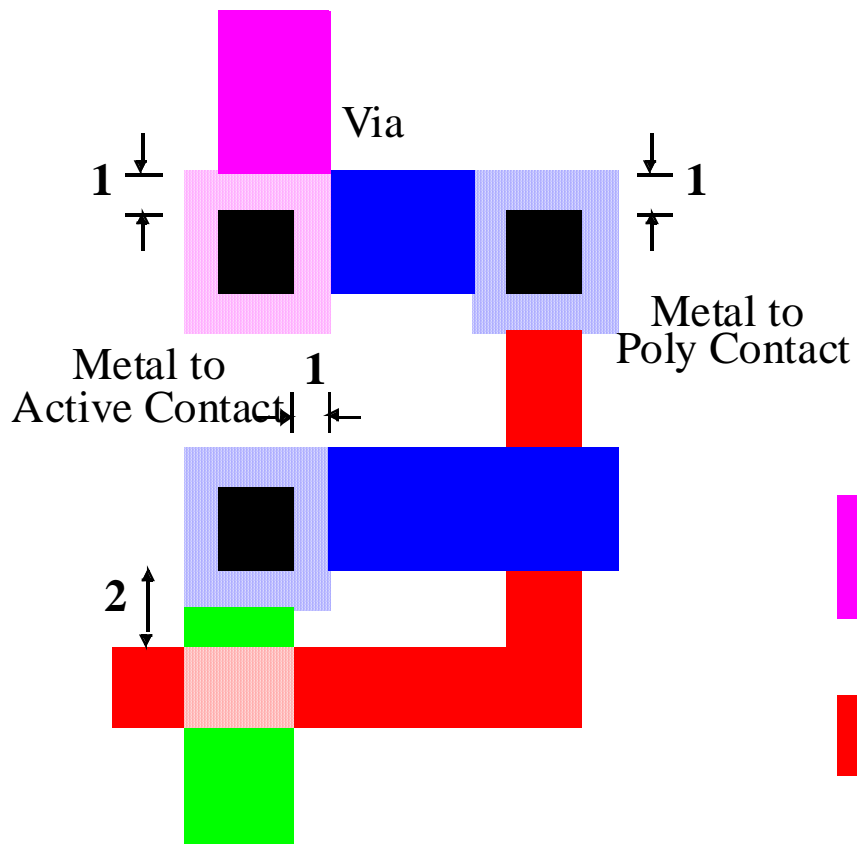


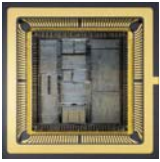
Transistor Layout



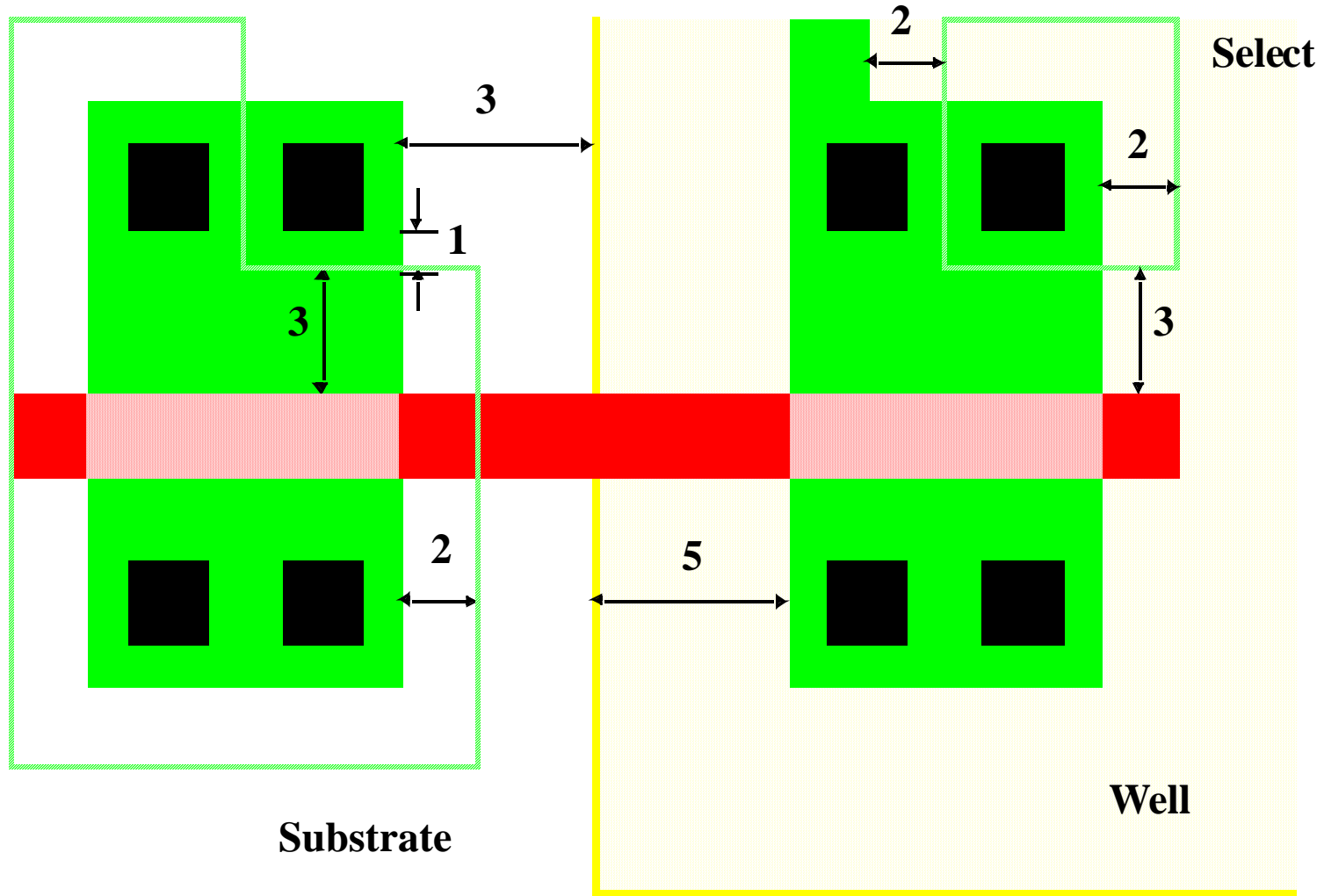


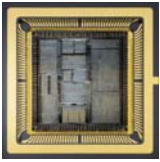
Vias and Contacts



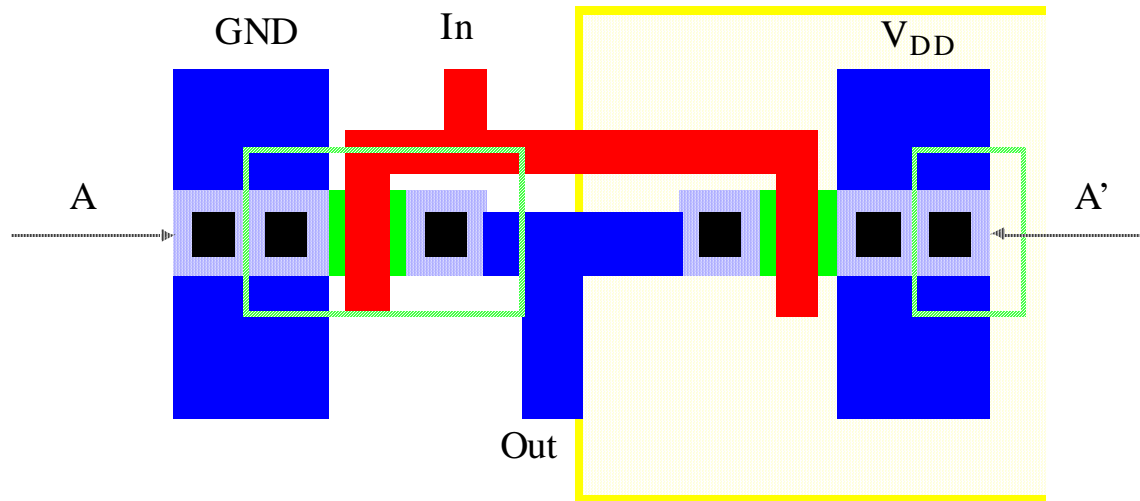


Select Layer

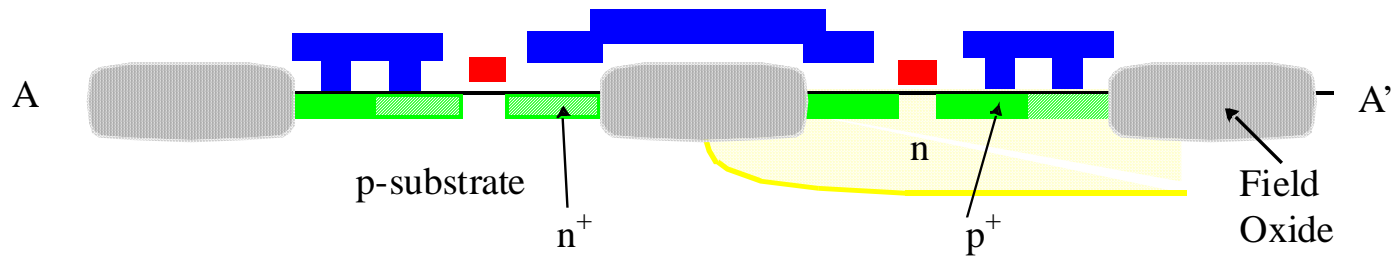




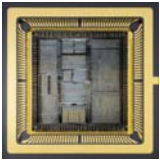
CMOS Inverter Layout



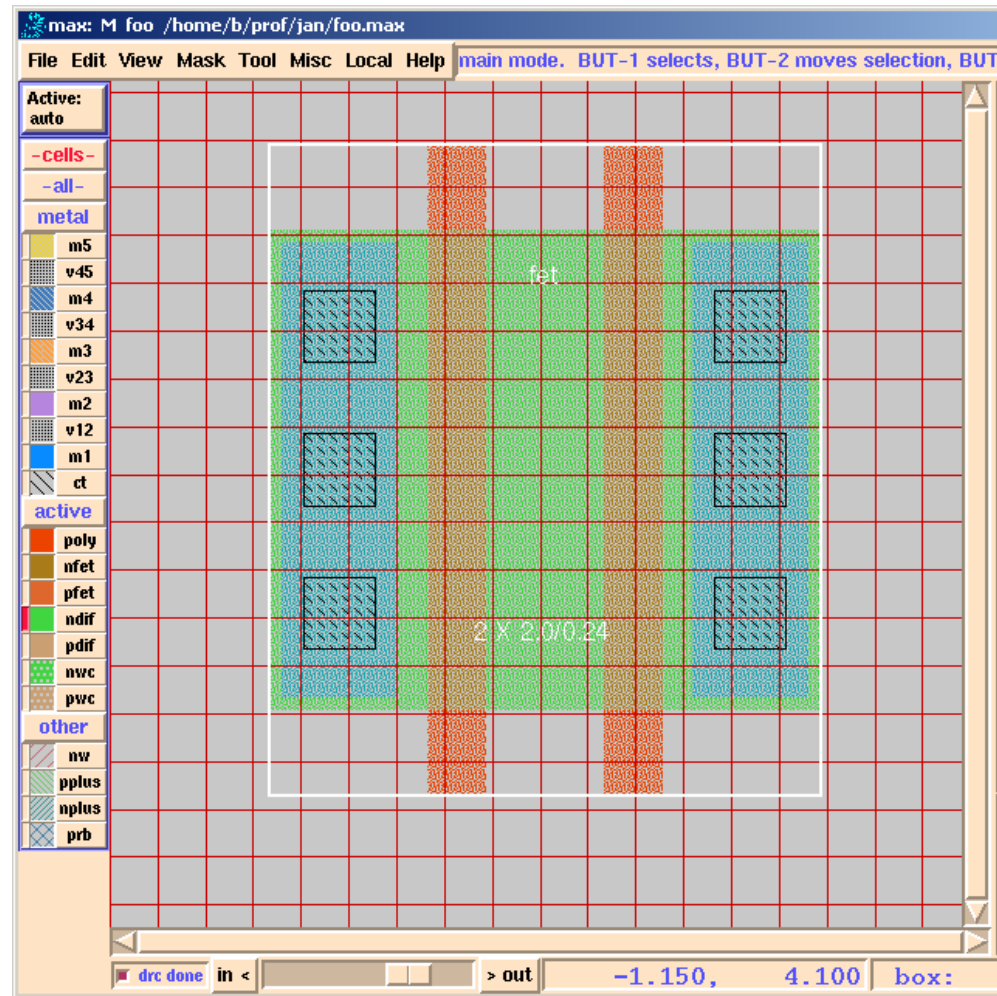
(a) Layout

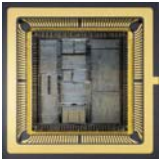


(b) Cross-Section along A-A'

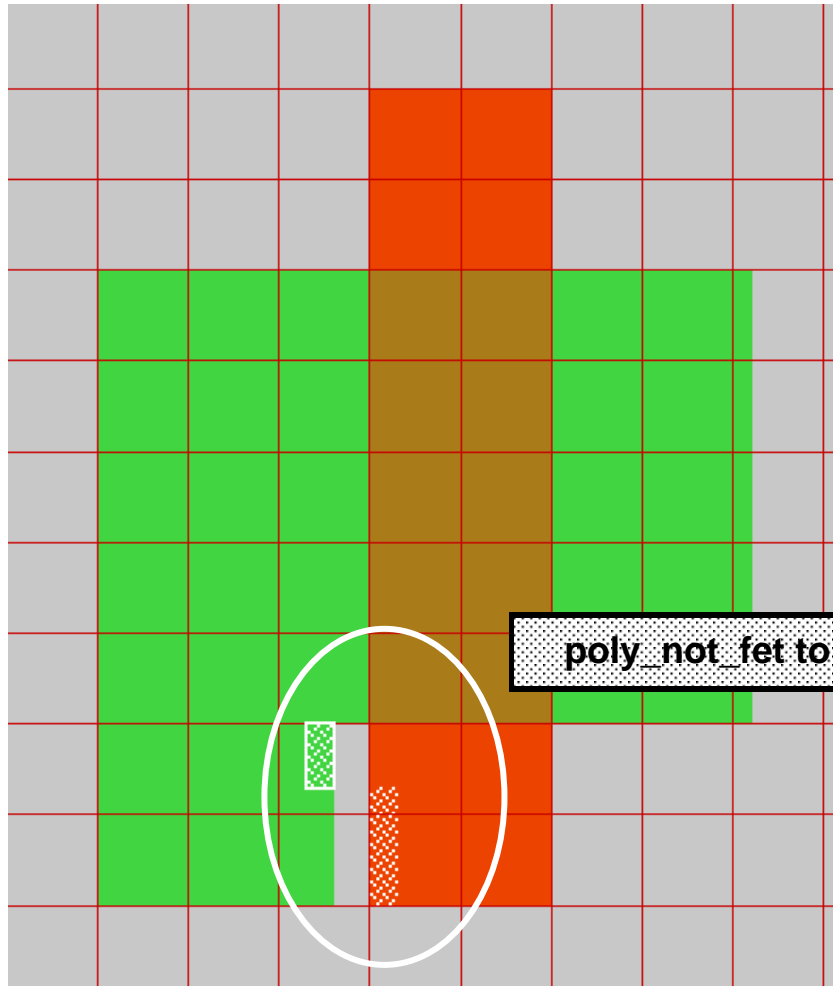


Layout Editor

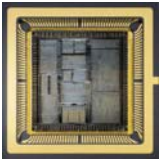




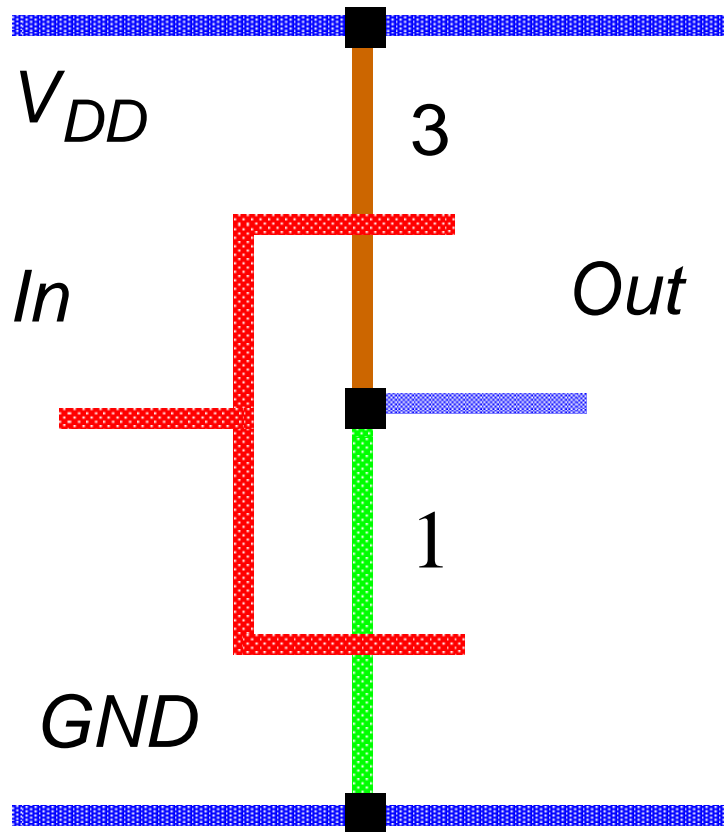
Design Rule Checker



poly_not_fet to all_diff minimum spacing = 0.14 um.

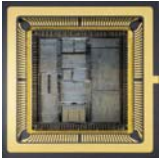


Sticks Diagram



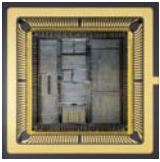
- Dimensionless layout entities
- Only topology is important
- Final layout generated by “compaction” program

Stick diagram of inverter



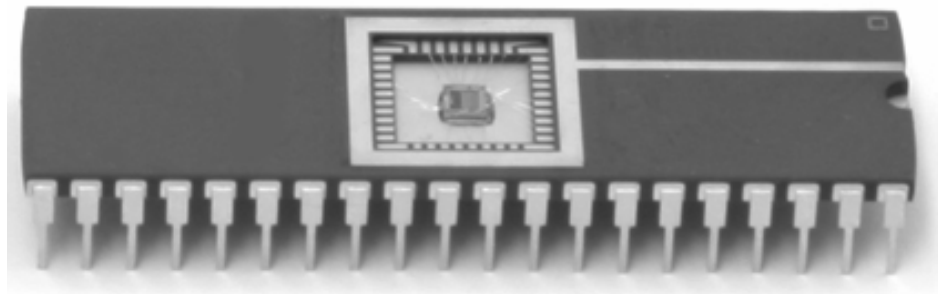
Logic Gate Layout

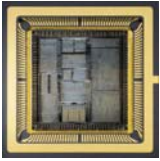
- Layout can be very time consuming
 - Design gates to fit together nicely
 - Build a library of standard cells
- Standard cell design methodology
 - V_{DD} and GND should abut (standard height)
 - Adjacent gates should satisfy design rules
 - nMOS at bottom and pMOS at top
 - All gates include well and substrate contacts



Packaging

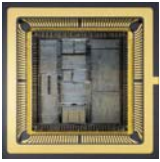
- Tapeout final layout
- Fabrication
 - 6, 8, 12" wafers
 - Optimized for throughput, not latency (10 weeks!)
 - Cut into individual dice
- Packaging
 - Bond gold wires from die I/O pads to package





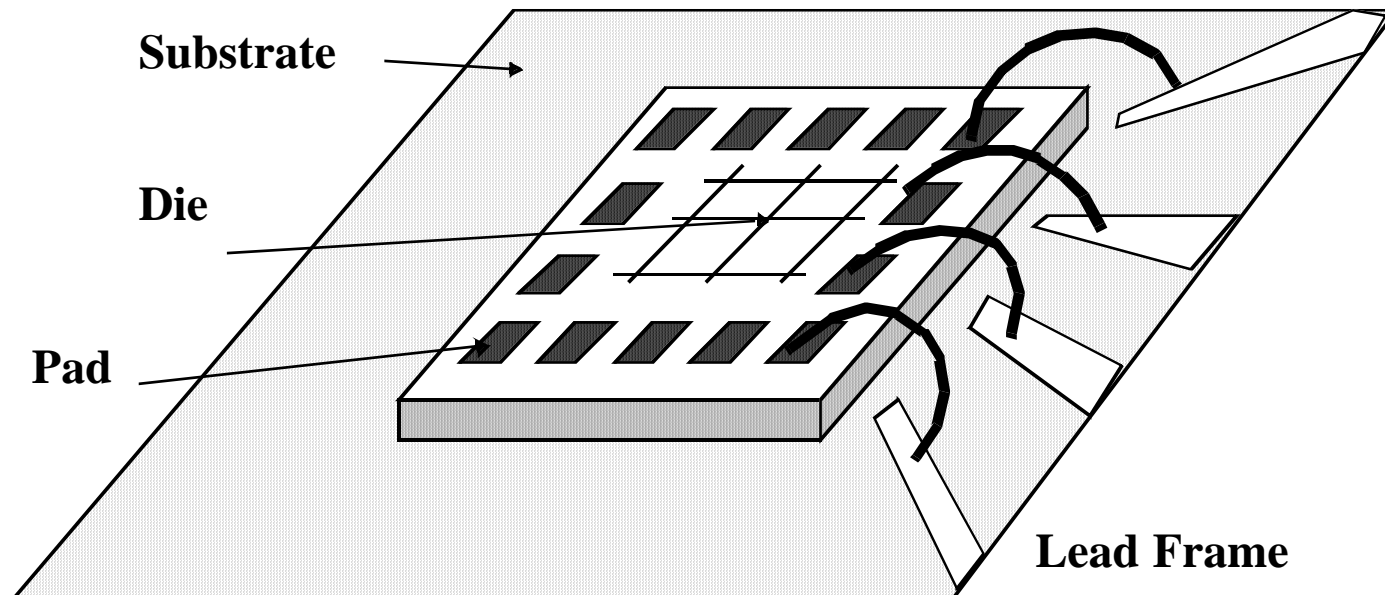
Packaging Requirements

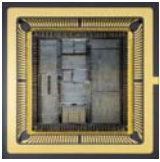
- **Electrical: Low parasitics**
- **Mechanical: Reliable and robust**
- **Thermal: Efficient heat removal**
- **Economical: Cheap**



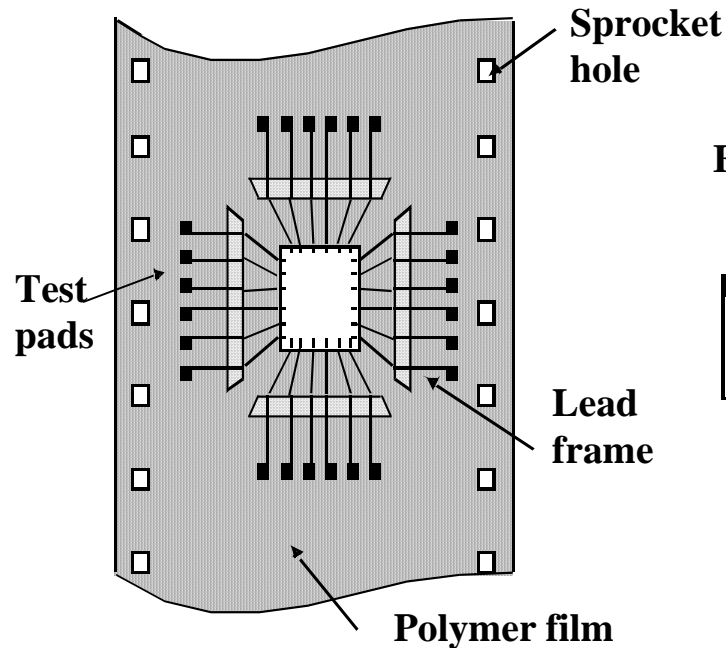
Bonding Techniques

Wire Bonding

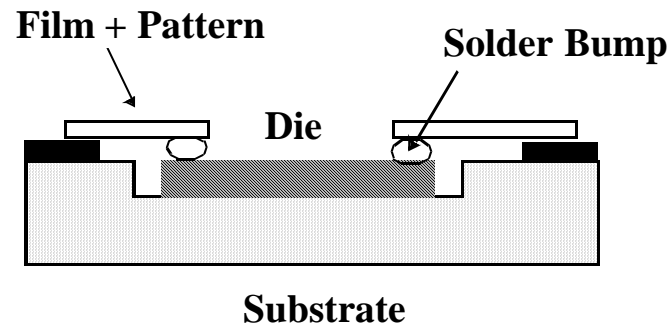




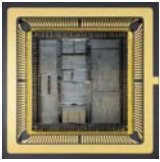
Tape-Automated Bonding (TAB)



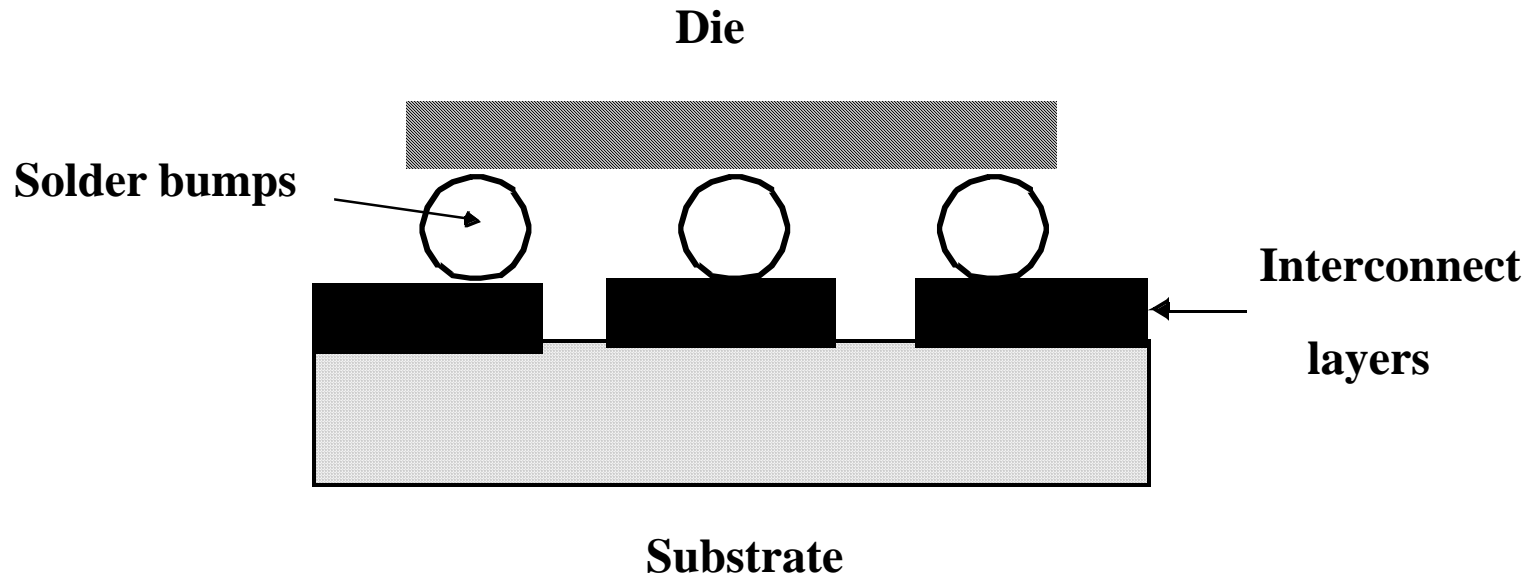
(a) Polymer Tape with imprinted wiring pattern.

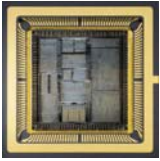


(b) Die attachment using solder bumps.

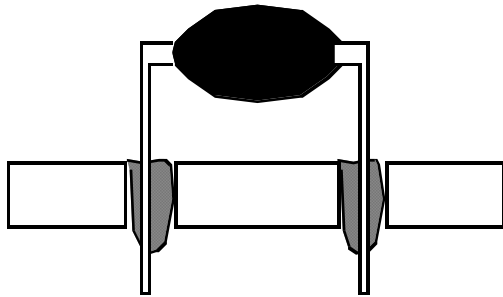


Flip-Chip Bonding

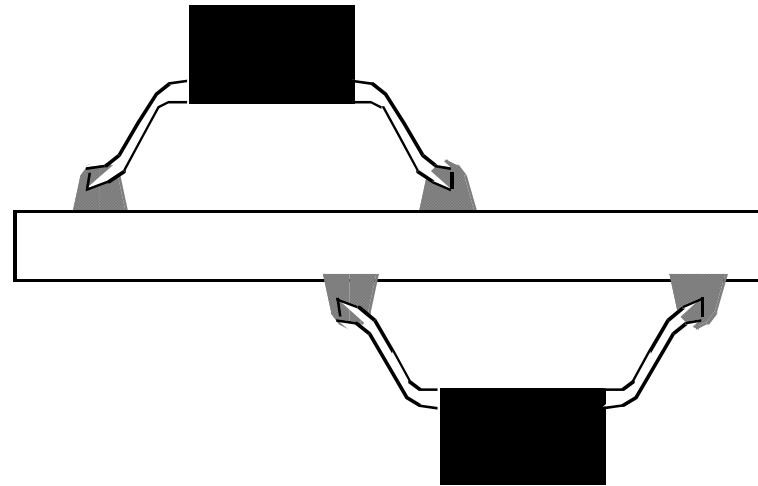




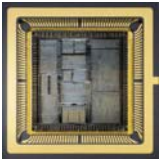
Package-to-Board Interconnect



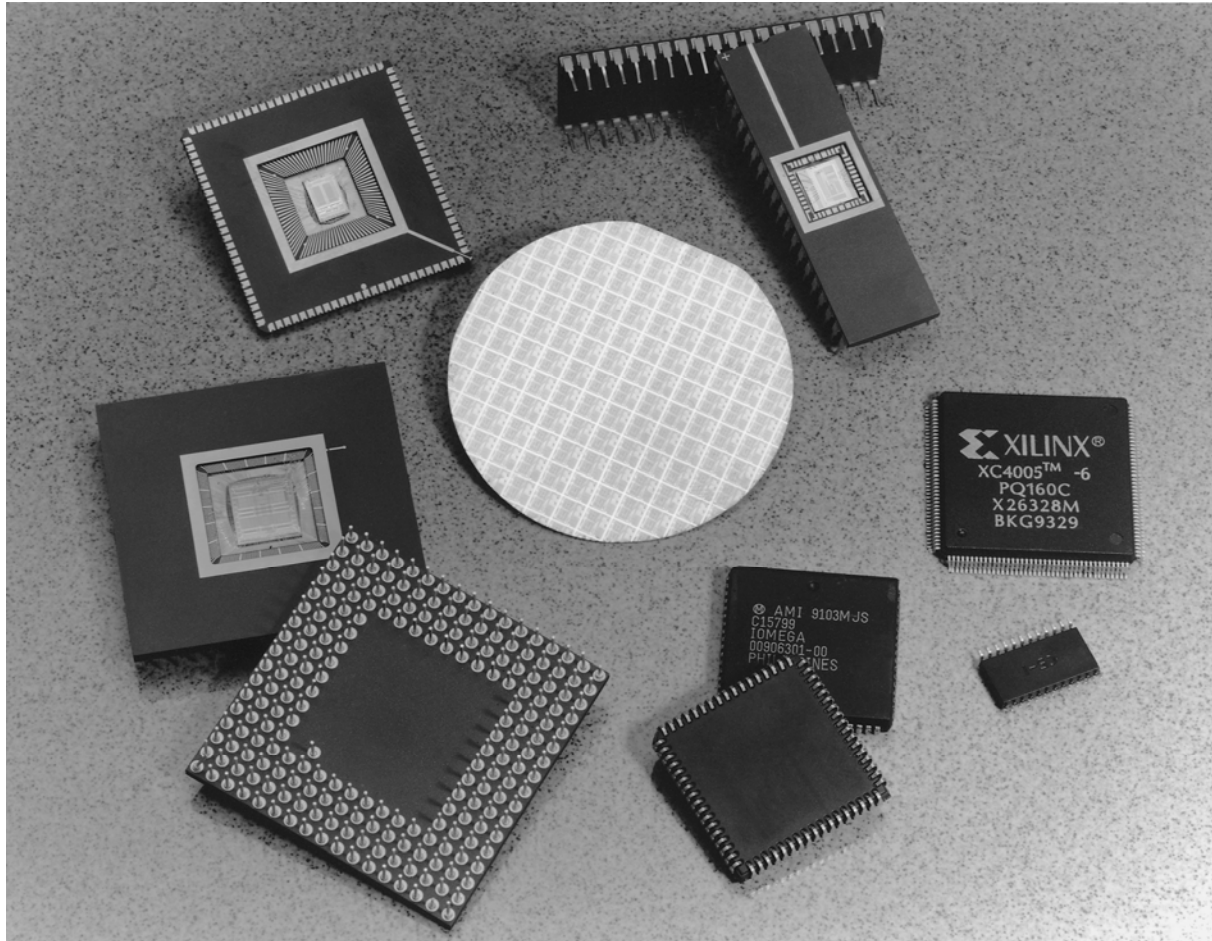
(a) Through-Hole Mounting

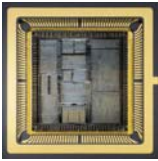


(b) Surface Mount



Package Types

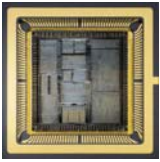




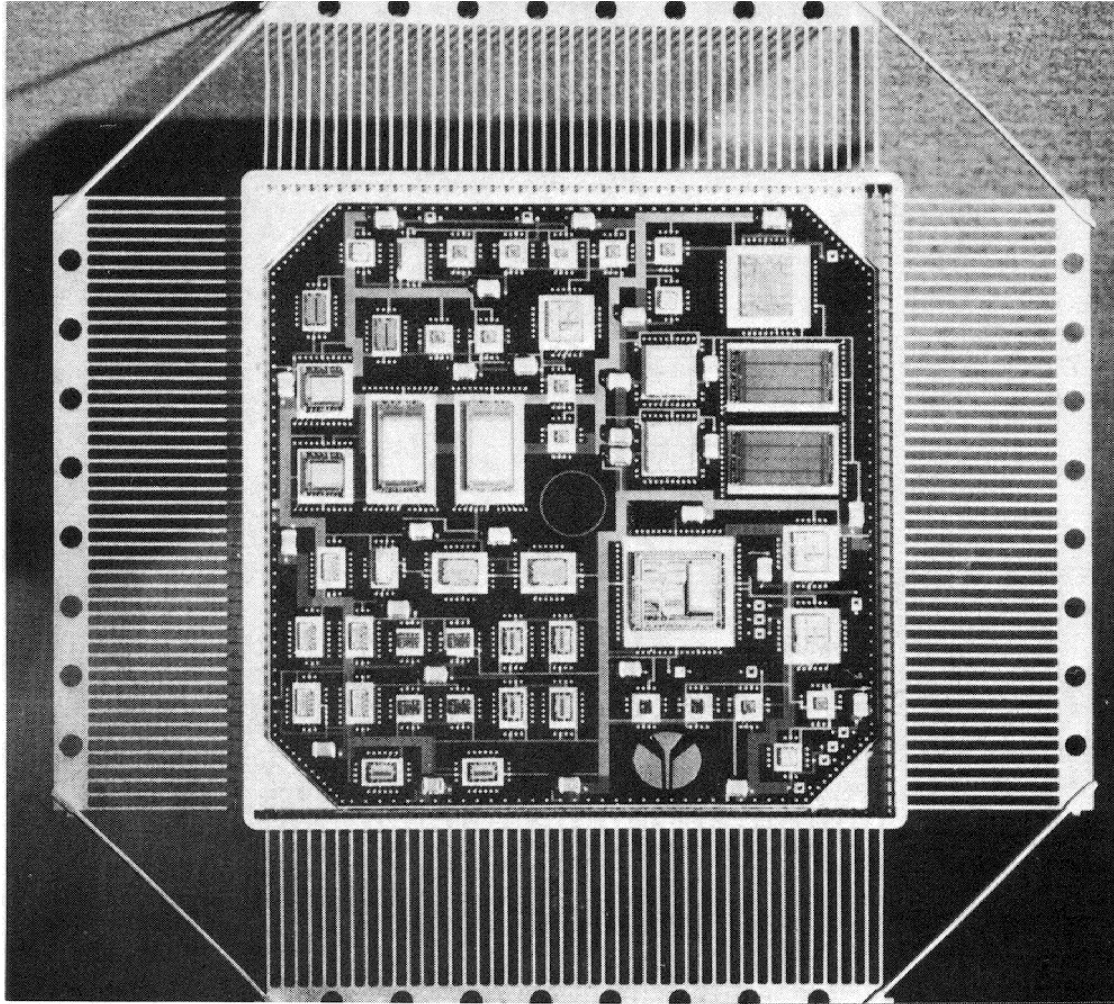
Package Parameters

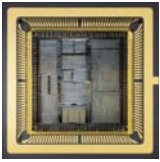
Package Type	Capacitance (pF)	Inductance (nH)
68 Pin Plastic DIP	4	35
68 Pin Ceramic DIP	7	20
256 Pin Pin Grid Array	5	15
Wire Bond	1	1
Solder Bump	0.5	0.1

Typical Capacitances and Inductances of Various Package and Bonding Styles (from [Sze83])



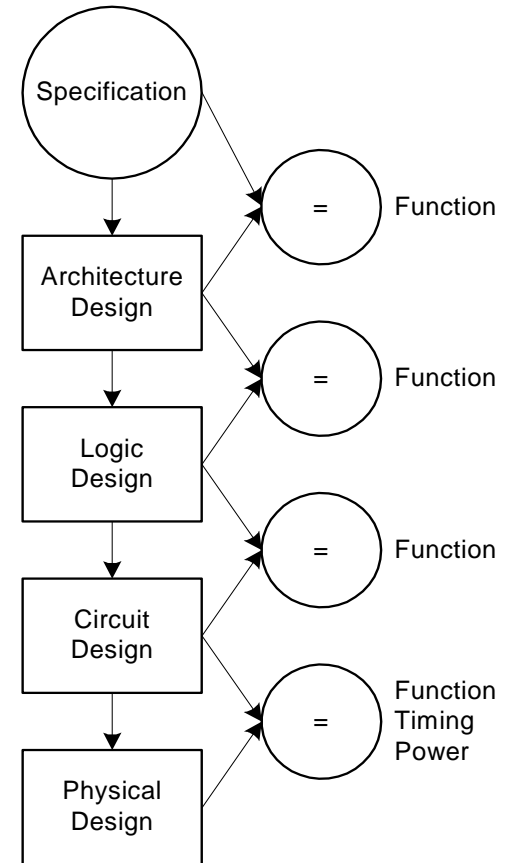
Multi-Chip Modules

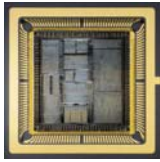




Design Verification

- Fabrication is slow & expensive
 - MOSIS 0.6 μ m: \$1000, 3 months
 - State of art: \$1M, 1 month
- Debugging chips is very hard
 - Limited visibility into operation
- Prove the design before building!
 - Logic simulation
 - Ckt. simulation / formal verification
 - Layout vs. schematic comparison
 - Design & electrical rule checks
- Verification is > 50% of effort on most chips!





Testing

- Test that chip operates
 - Design errors
 - Manufacturing errors
- A single dust particle or wafer defect kills a die
 - Yields from 90% to $< 10\%$
 - Depends on die size, maturity of process
 - Test each part before shipping to customer