



BASICS OF TRANSISTORS AND CIRCUITS

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TEXTBOOK

- For these slides I am using many figures from the second edition of the Principles of CMOS VLSI Design by Weste and Esharaghain, and the fourth edition of CMOS VLSI Design: A Circuit and Systems Perspective

INTRODUCTION

- There are two ways to view radiation effects in electronics:
 - Start from the material science and work upward to transistors to circuits
 - Start from computer circuits and work downward to transistors and then to material science
- There are advantages and disadvantages to both

TOP/BOTTOM VS. BOTTOM/TOP

Top/Bottom

■ Pros:

- Understanding of how the entire circuit works (sort of)
- Understanding of the effect of electrical, temporal, and logical masking, which can be used to limit the effects to the ones that cause noticeable effect

■ Cons:

- Hard to scale down to the material science
- Might not understand the mechanism

Bottom/Top

■ Pros:

- Deep understanding of the mechanism
- Deep understanding the potential of the effect, able to determine whether new effects are possible

■ Cons:

- Lack of understanding about electrical, temporal, and logical masking
- Hard to scale up

WHICH WAY TO GO?

- Likely depends on your background
 - I'm a computer architect that learned radiation effects OJT, so I feel more comfortable personally going top down
 - Some of my team is better versed in radiation effects are learning the circuit part OJT
 - Either way, it is almost impossible to do both well, unless you would like to earn two PhDs, so working in teams is always best
- At the end of the day, the middle ground of understanding the basics of the transistors and the basics of circuit design are necessary to understand why things are the way they are
- The most important part to remember:
 - Electronics are not monolithically a single material
 - The transistors are in an unnatural, rigid structure
 - The transistors and/or circuits can fail when either the transistor is affected by radiation or the circuit is affected by radiation

CATEGORIZING RADIATION EFFECTS

- Each component has inherent radiation effects
 - It helps to be able to weed out what could be a problem and what won't be
- High-level categories:
 - What is the type of transistor?
 - What is the feature size of the transistor?
 - How was the transistor manufactured?
 - What is the logic of the component?
- For example, a 350nm power MOSFET on bulk planar:
 - Likely to have problems with some types of TID, and destructive SEEs.
 - Not likely to have issues with all types of transient SEEs



WHAT IS A TRANSISTOR?

AND WHY IS IT IMPORTANT TO RADIATION EFFECTS?



WHAT IS A TRANSISTOR?

- It is essentially an electric switch
- Transistors can be combined to make logical gates:
 - NOT
 - AND
 - OR
 - NAND
 - NOR
 - Or memory cells
- These logical gates are combined to make all sorts of circuits:
 - Combinational
 - Sequential

TRANSISTORS, TRANSISTORS EVERYWHERE

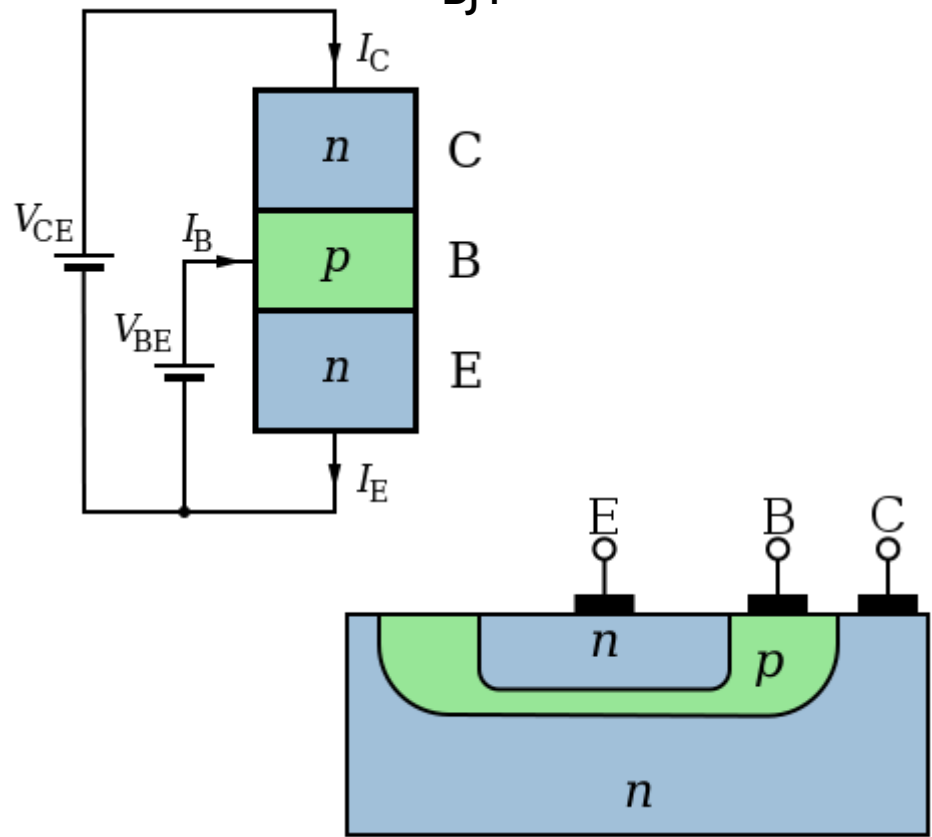
- The word transistor is overloaded
- There are two basic types of transistors:
 - Bipolar junction transistors (BJT): use both the majority and minority charge carriers
 - Field Effect Transistors (FETs): use majority charge carriers (unipolar)
 - In the coming slides we will talk about a particular types of FETs (NMOS, PMOS, CMOS)
- BJTs are predominately used for analog circuits and FETs are predominantly used for digital circuits
- Currently, BJTs and CMOS FETs are designed completely differently
 - BJTs are computer optimized, but hand designed/hand laid out, so variability is a huge issue
 - CMOS FETs are no longer hand designed/hand laid out, because the variability had to be controlled

BJT VS. FET

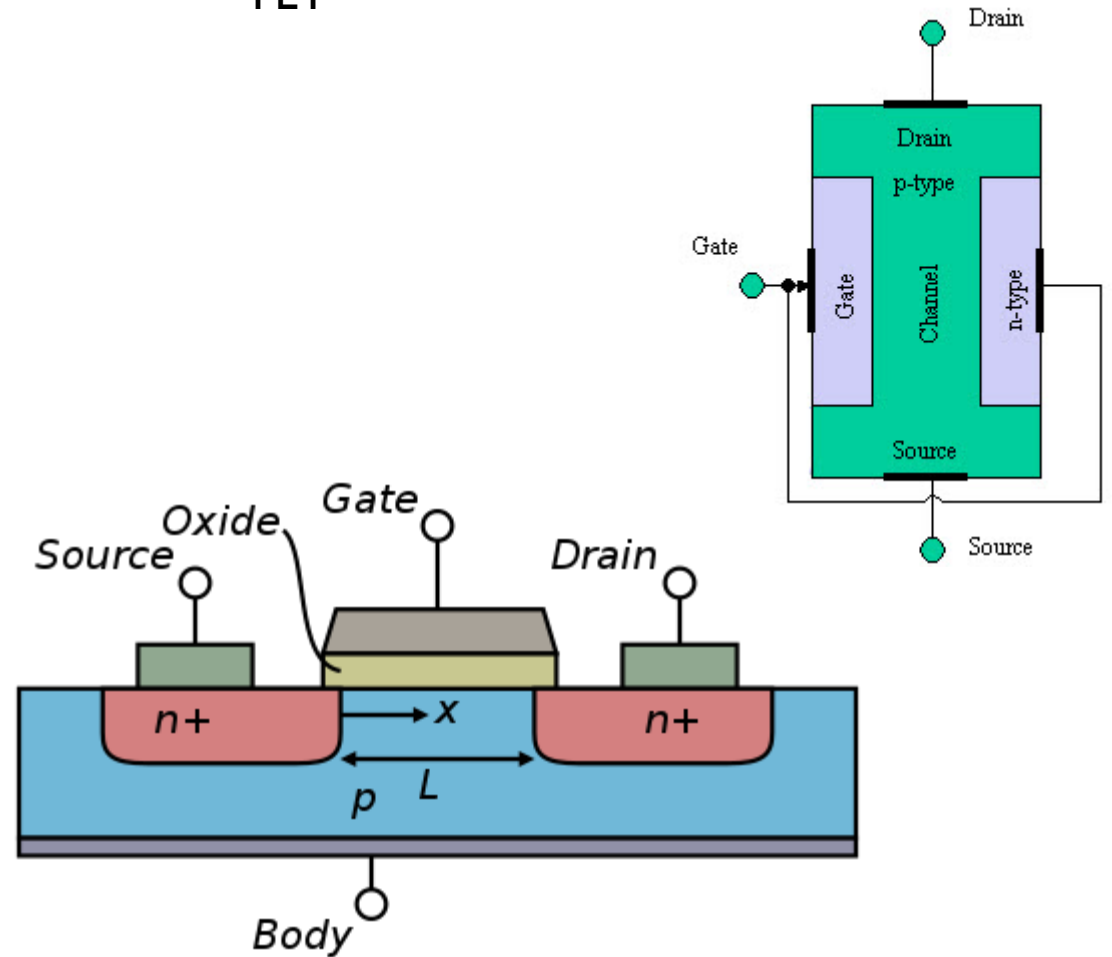
- | BJT | FET |
|--|--|
| <ul style="list-style-type: none">■ Current controlled, and can operate at low currents■ Three terminals: base, emitter, collector■ Low input impedance■ Faster switching■ Sensitive to particular issues with TID, DD, transients, and destructive SEEs | <ul style="list-style-type: none">■ Voltage controlled, and can operate at low voltages■ Three terminals: source, drain, gate■ High input impedance■ Slower switching■ TID does not trend, DD likely not an issue, a full range of non-destructive SEEs, and only affected by a single type of destructive SEE |

BJT VS. FET

BJT



FET



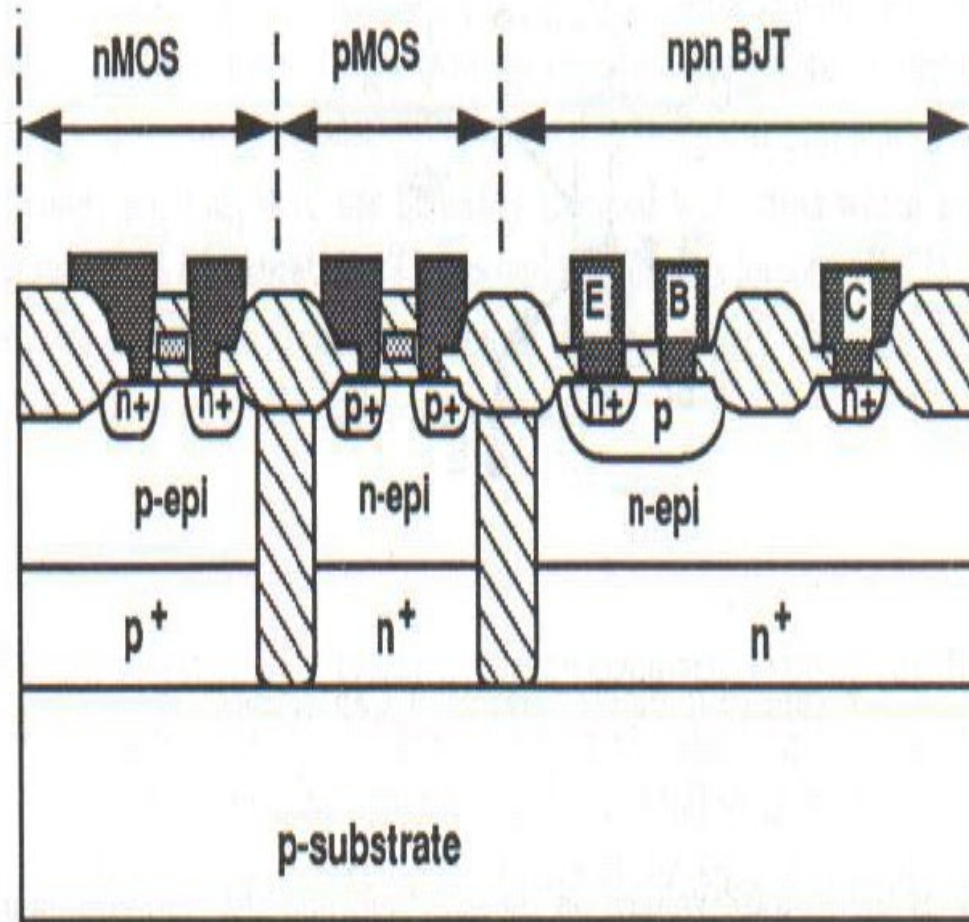
BJTS AND FETS

- It can be confusing which is which
- They both have NPN and PNP inherent in the transistor structure
 - The biggest distinguishing feature is the use of current or voltage
 - Even in the previous slide, the labeling can help determine whether it is a BJT or a FET

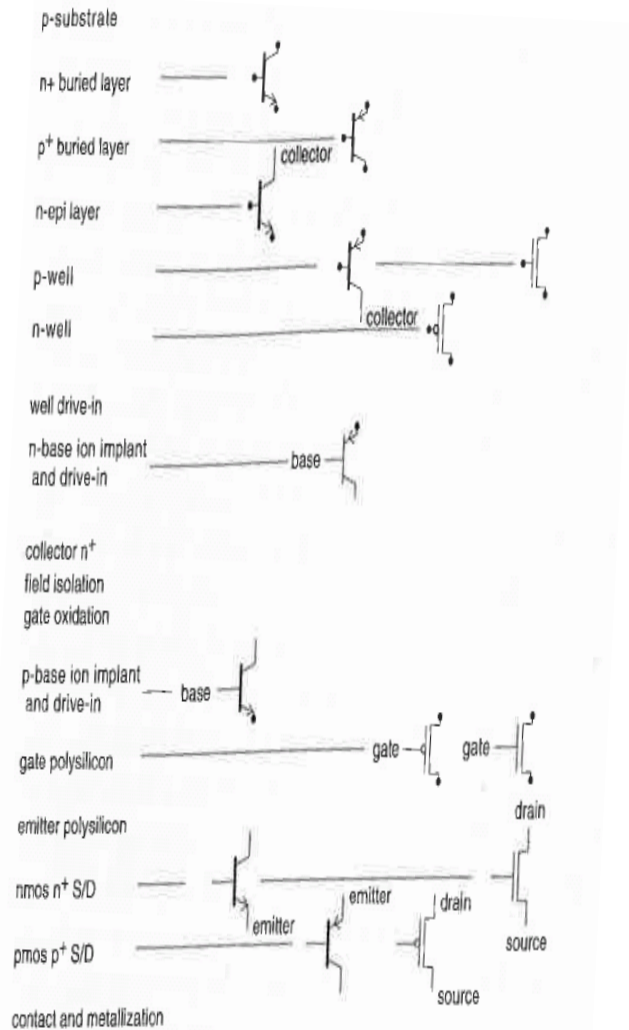
THE BEST OF NO WORLDS: BICMOS

- There is something called BiCMOS transistors
 - Macro granularity: analog/digital circuits might have both separately
 - Micro granularity: in the 2000s there were microprocessors that were designed with both bipolar and CMOS transistor characteristics
- The idea was that you could use the best of both BJTs and FETs, but it turns out that most of the time it was the worst of both
- BiCMOS parts can have both of the worst of radiation effects, too

BICMOS PROCESS (I)



BICMOS PROCESS (2)



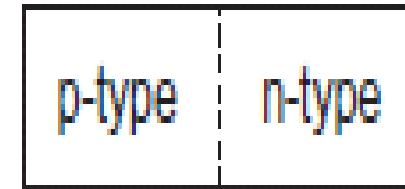


DIODE AND BIPOLAR TRANSISTORS

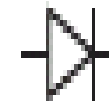


DIODES

- Diodes are the most basic form of a semiconductor device:
 - Two types of opposite polarity diffusions make a junction, which is called a junction diode
 - Metal + semiconductor make a Schottky diode via Ohmic contact
 - Reminder for future: in the upcoming discussion on CMOS, the Schottky diode is only made around the metal contacts to the diffusion in the source and drain
- Part of the problem of making any transistors is that diodes can show up parasitically by just sandwiching materials next to each other

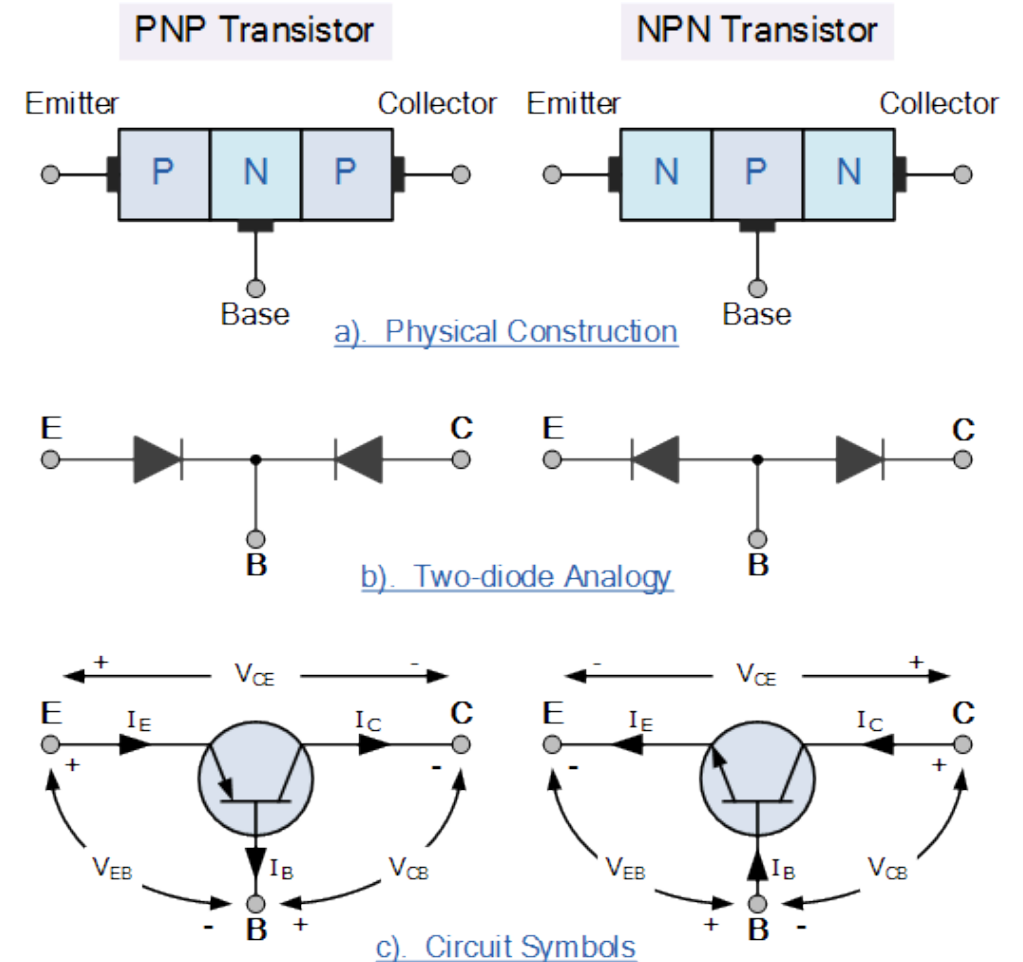


Anode Cathode



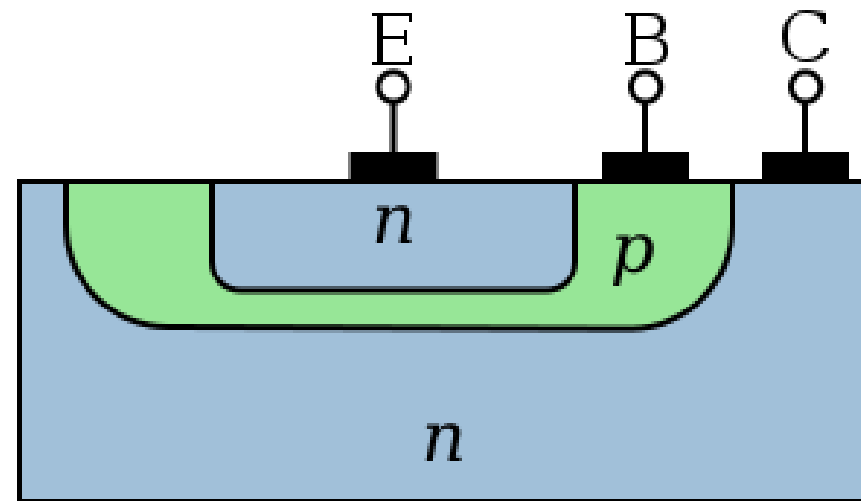
BIPOLAR TRANSISTORS

- Are made by making diffusion sandwiches
 - NPN
 - PNP
- Notice that there are basically two diodes with the bipolar structure
- These also show up parasitically in CMOS transistors



RADIATION ISSUES WITH THE MATERIALS

- One of the issues with ionizing radiation is that it causes electron-hole pairs (ehps)
- This transistor only works when the electrons stay in the n locations and the holes stay in the p locations
 - The holes moving out of their locations are problematic because of their relatively lower mobility
 - The holes are also necessary for electron movement
 - If the holes are not abundant in the p material, it then takes more current to get the electrons to move





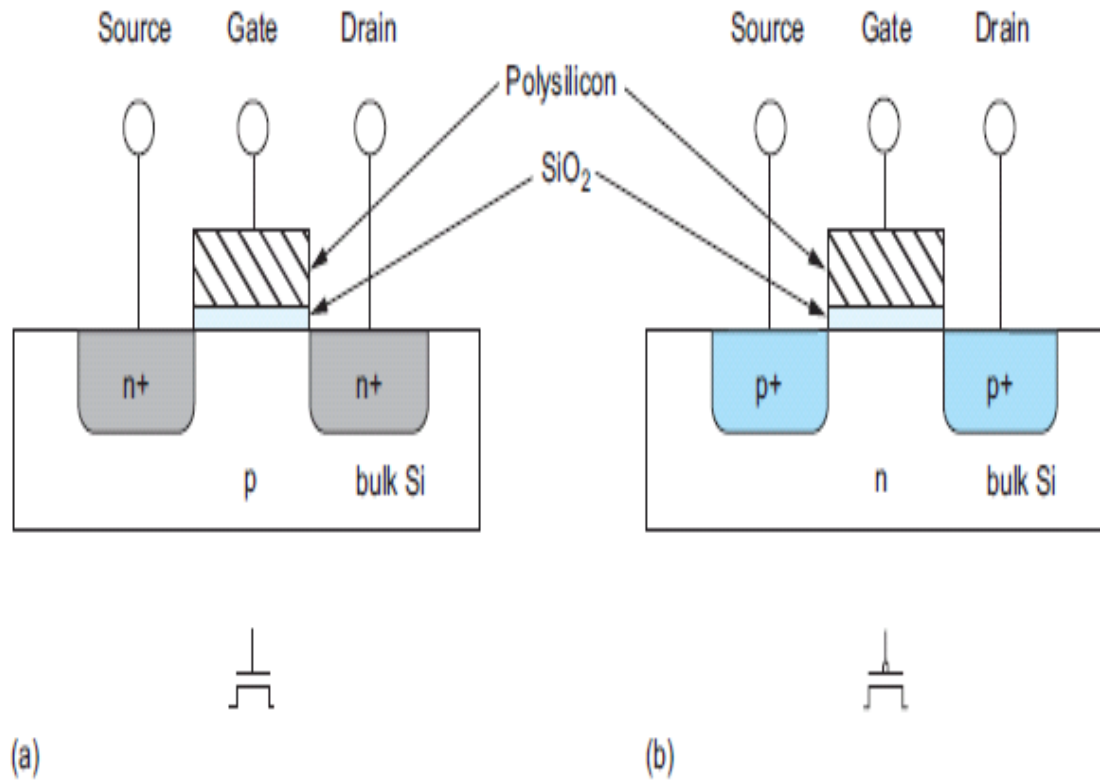
MOS, NMOS, PMOS, CMOS TRANSISTORS



METAL OXIDE SILICON (MOS)

- The basis of the transistor is a MOS structure that is “created by superimposing several layers of conducting, insulating, and transistor-forming materials to create a sandwich-like structure.” [Weste and Eshraghian, 1993]
 - A sandwich is not a bad metaphor here – while it is true that some of the layers are more swiss cheese than Velveeta, the models that most radiation effects people use are essentially an open-faced Dagwood sandwich with layers and layers of different materials stack one on top of another
- There are two basic types of MOS transistors:
 - nMOS (or NMOS): negatively doped transistors that have donor electrons
 - pMOS (or PMOS): positively doped transistors that are missing a valence electron, which in electronics are called holes

NMOS AND PMOS DESIGNS

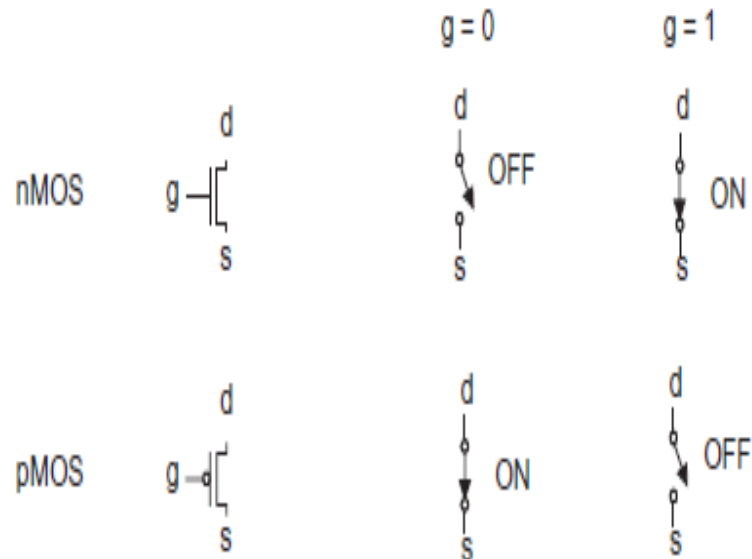


- The gate is control input – it affects the flow of electricity
- The tiny circle on the gate of the PMOS is a logical NOT
 - One way to think about PMOS is that is the NOT of NMOS

SWITCHING

- The transistor are semiconductor switches:
 - The gate controls the whether current flows from source to drain
 - If you apply voltage to the gate, then the transistor switches ON and current flows
- The problem with NMOS and PMOS is that both are not great switches
 - NMOS: strong zero
 - PMOS: strong one

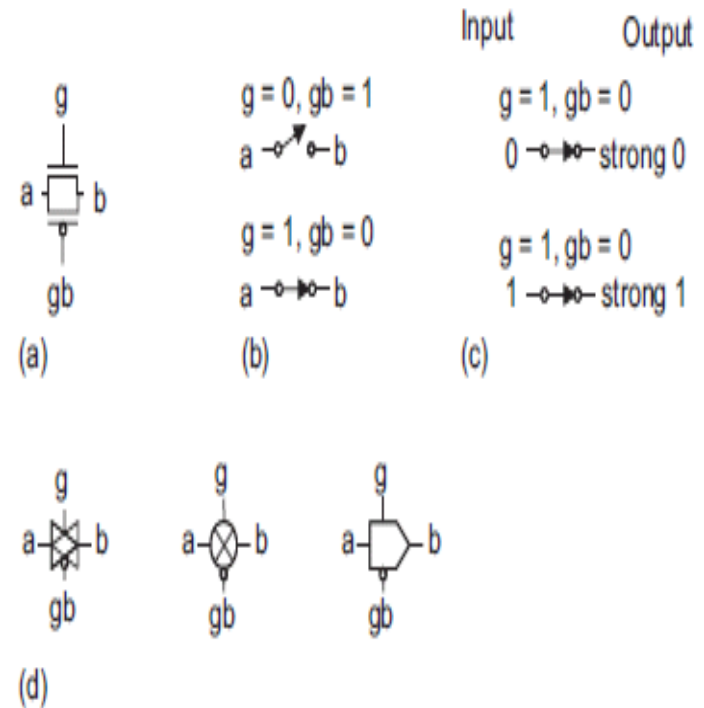
NMOS AND PMOS SWITCHING



- Pure NMOS and pure PMOS are not great
 - Each has one strong signal and one weak signal
- NMOS: Strong 0
- PMOS: Strong 1
- Maintaining signal integrity is one of the hardest parts of circuit design. It seems like a bad idea to use switches that are only good in one direction only

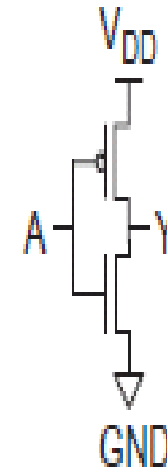
COMPLIMENTARY METAL OXIDE SILICON (CMOS) TRANSISTORS: THE BEST OF BOTH NMOS AND PMOS

- CMOS is an improvement on just using NMOS or PMOS – use both
 - Use PMOS for its strong 1 and NMOS for its strong 0
- The gate to the right is a transmission gate
 - Used for gating signals which can be controversial

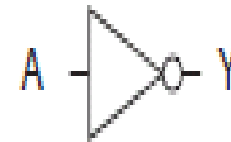


THE INVERTER

- The inverter is the most common example of any circuit:
 - Smallest, realistic gate (you would think it is the transmission gate, but most designs have tons of inverters and few transmission gates)
 - Can be used to make all sorts of other circuits, like static memory, latches, NANDs, NORs, etc.

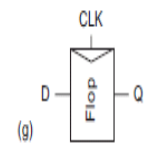
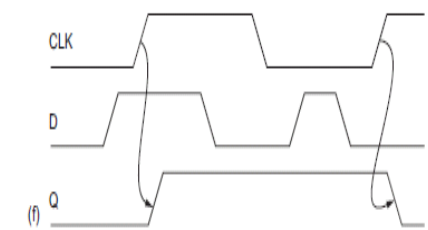
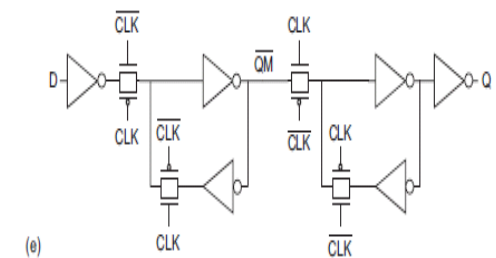
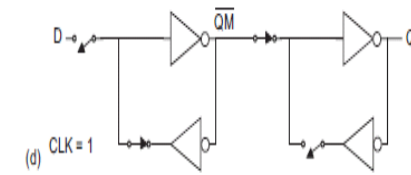
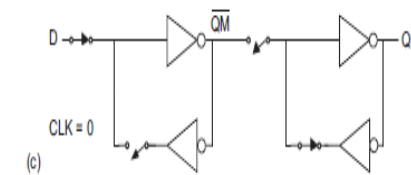
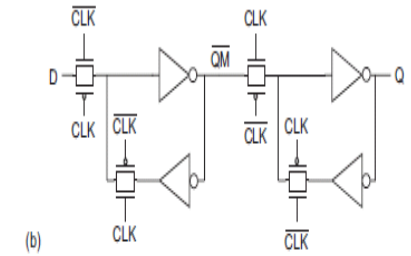
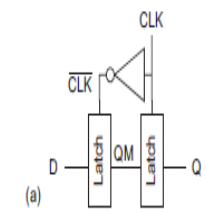
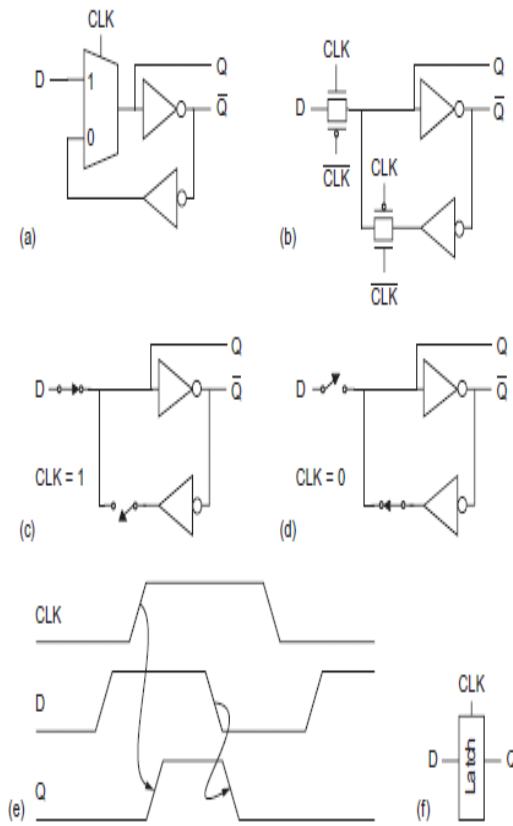


(a)



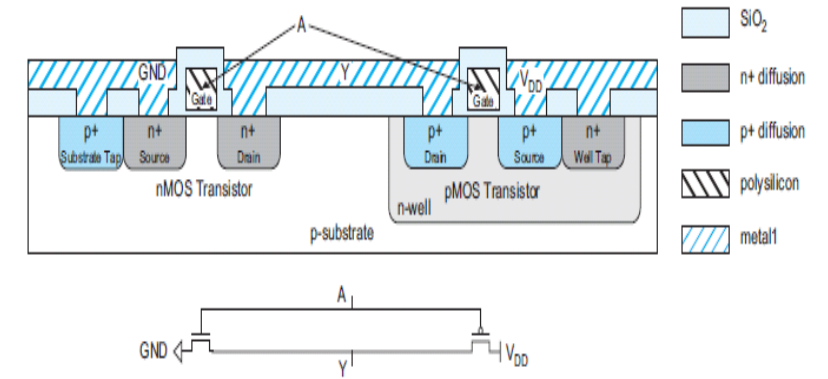
(b)

MEMORY: LATCHES AND REGISTERS

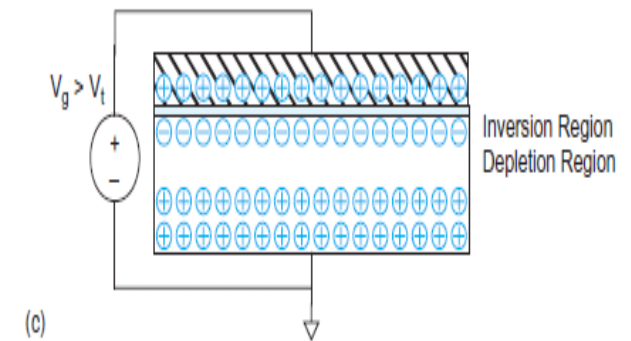
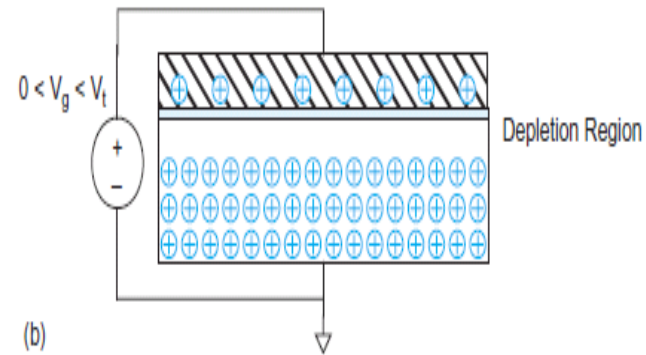
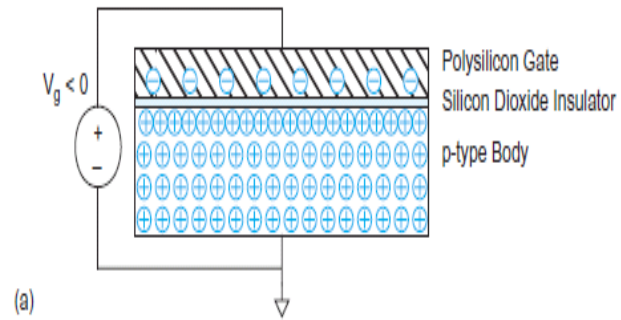


TRANSISTORS: THREE DIFFERENT DRAWING

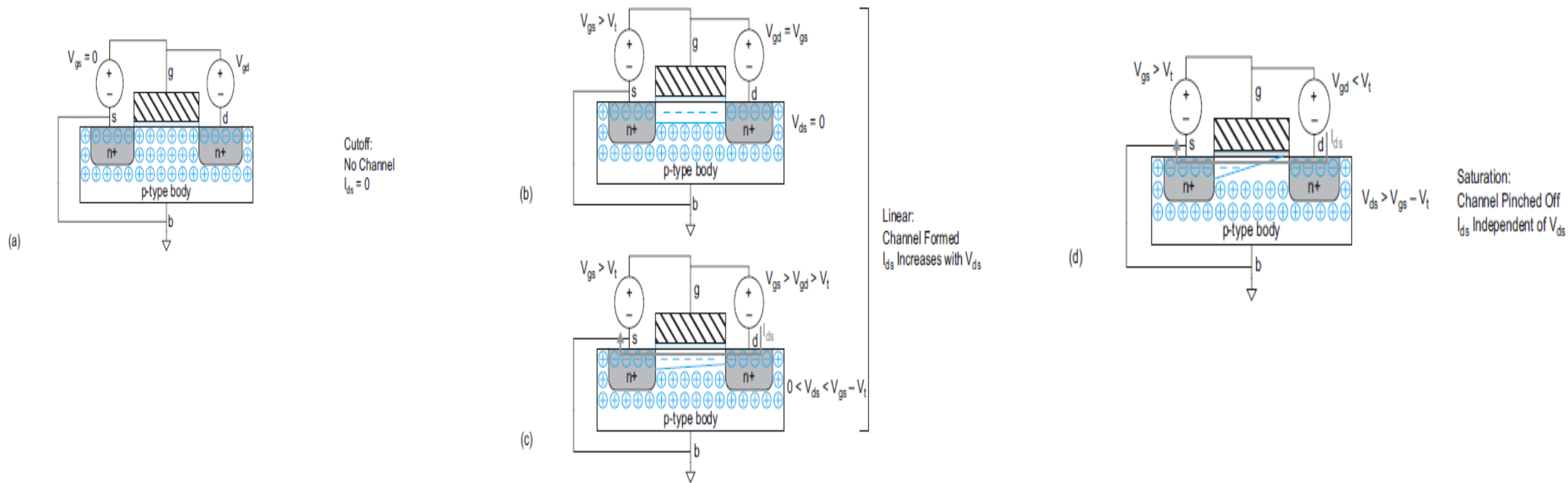
- Electrical switch
- Materials
- Reality



WHAT IS REALLY GOING ON: DEPLETION AND INVERSION IN MOS



NMOS BEHAVIOR

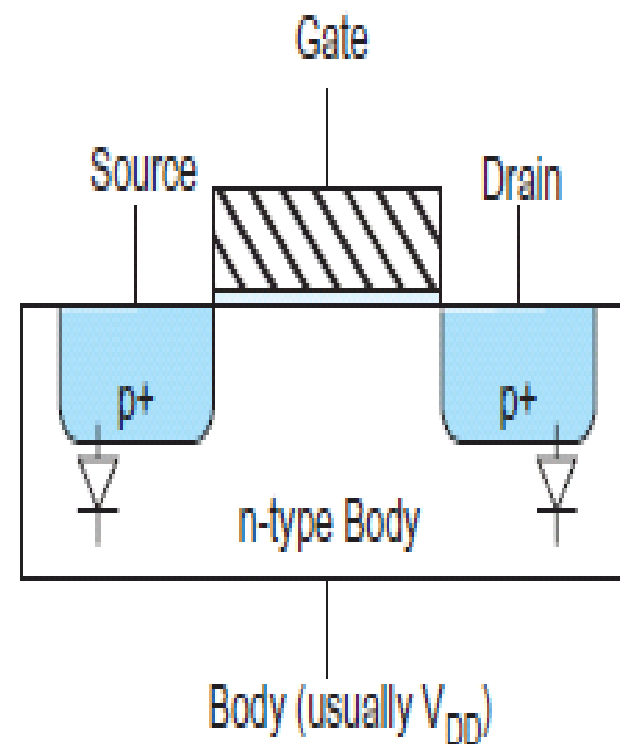


THRESHOLD VOLTAGE

- At the end of the day, the voltage between the gate and the source must exceed the threshold voltage to turn on the transistor
- Radiation mucks with the situation:
 - Total ionizing dose and displacement damage cause the threshold voltage to shift, causing more current to be needed to switch the transistor
 - In single-event effects electron-hole pairs around the charged particle create the depletion region to form, causing a voltage transient on the transistor output

RADIATION ISSUES WITH CMOS

- As discussed with Bipolars, it is necessary for the electrons and holes to remain in their expected locations for proper switching behavior
- Another issue is that ehps in the channel and substrate cause charge generation, which can turn an OFF transistor ON
- One issue is that CMOS transistors have parasitic diodes, transistors, and thyristors to form in the manufacturing process
 - If those transistors turn ON, which can cause a destructive effect called latchup





SUBSTRATES, INSULATORS AND BODIES



SUBSTRATES AND BODIES

- Frequently the entire component is manufactured on a common substrate or body
- As discussed earlier, these substrates and bodies can create parasitic transistors that can have radiation problems
- Another issue for single-event effects is that the charge generation can travel through a common substrate
 - If the channel of a CMOS transistor is connected to the common substrate, that means the charge generation traveling through the substrate can affect multiple transistors
- These body effects can lead to issues with latchup and increase the effective size of SEU problems

SILICON ON INSULATORS (I)

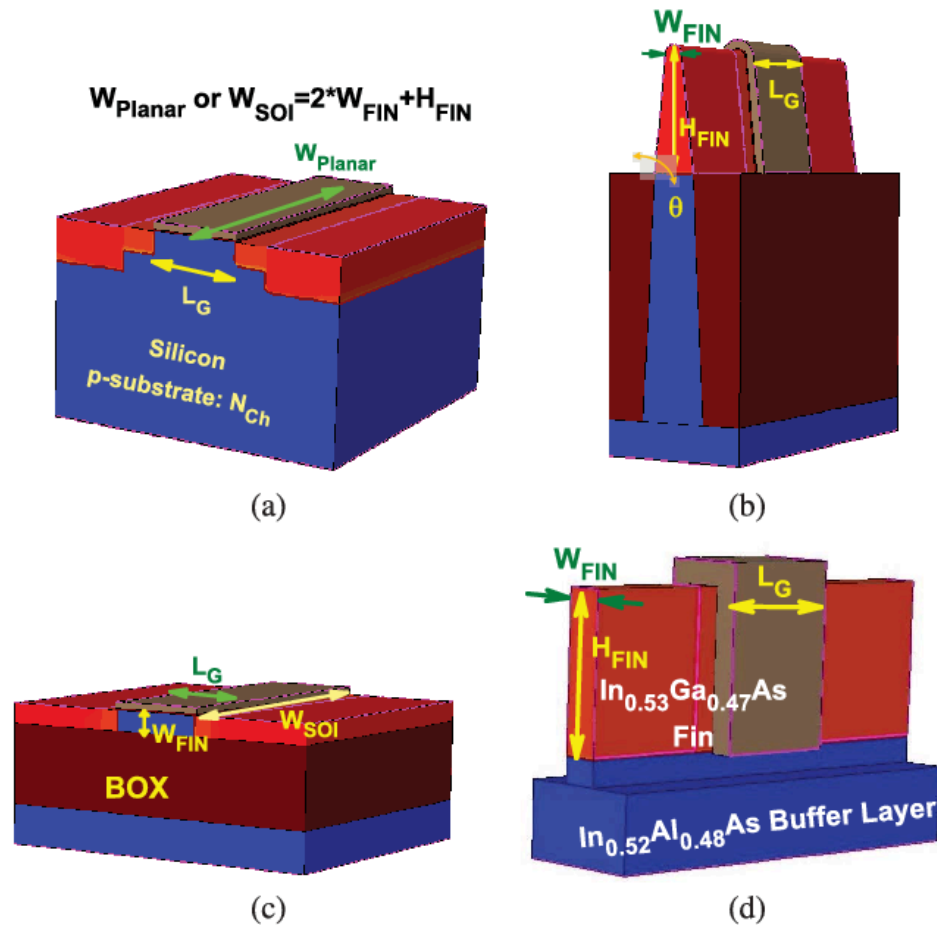
- Building on top of insulators can reduce issues with the body effect
 - Charge generation is minimized
 - The material junctions are not formed
 - Increased radiation tolerance
- While radiation tolerance is currently the only reason to use SOI technology, at one point it was pretty common to use for all technologies



DESIGN AND MANUFACTURING PROCESSES



MANUFACTURING PROCESS



- The most common form of transistor design and manufacturing has been bulk planar
 - The transistors are etched into the silicon
 - Lithographic issues arise as transistors shrink
- Trigate or FinFETs are one way to solve the manufacturing issues
 - Easier to keep shrinking the transistors
 - Easier to manufacture
 - A one time decrease in SEE sensitivity by 100x

RADIATION-HARDENED BY PROCESS (RHBP)

- Commonly for high radiation environments, designers would want to use RHBP parts
- The transistor design and manufacturing process is changed to make the base transistor more radiation tolerant
 - TID tolerance is very high
 - No Latchup
 - Relatively insensitive to other SEEs
- The problem is the non-recurring engineering costs, the need for specialized fabrication plants, and the relatively small market makes the parts really expensive
- It is also really difficult to continue to shrink the feature size and maintain insensitivity to SEEs: 130nm is the last good feature size for RHBP

RADIATION-HARDENED BY DESIGN (RHBD)

- RHBD was the way to get around the issues with RHBP in 90nm and smaller
 - Designed to be built in a traditional fabrication plant
 - The transistors are changed to mask and/or suppress SEEs
 - TID tolerance is not guaranteed
- The current issue is that there is that designers are uncertain about the ability to shrink below 28nm
 - Reminder: commercial industry is at 14nm



COMBINATIONAL VS. SEQUENTIAL



COMBINATIONAL CIRCUITS

- These are logic only circuits
 - There is no clock in a logic circuit
 - Every time the input changes, the logic circuit output changes
- By definition, the circuits have to be small
 - The circuit can be represented as both resistance and capacitance
 - The capacitance means the current/voltage decrease as the signal must drive more and more logic
 - In a voltage-based circuit, as the signal decreases it becomes impossible to tell the difference between a 1 and 0
 - In a current-based circuit, the signal becomes too noisy
 - Need to de-noise your circuits

LATCHES

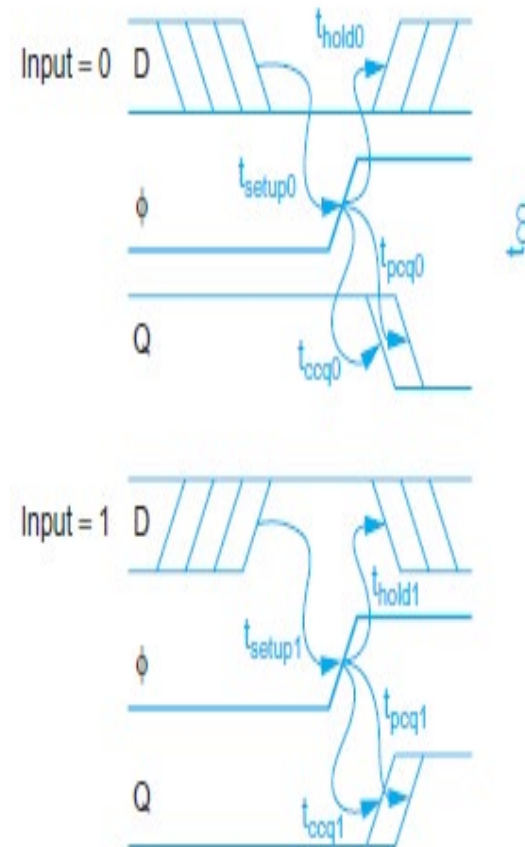
- Latches are specialized memory cells that are designed to store data
 - Data are stored in the latch
 - Data storage is triggered by the clock signal
- Designers use latches to store data from logic circuits, so that the signal can be restored

SEQUENTIAL CIRCUITS

- When combinational circuits are combined with latches, the circuit is called sequential
- Sequential circuits are dependent on clocks for timing
 - Outputs only change on the clock edges
- The total logic in a sequential circuit is more complex than a combinational circuit, because the signal is constantly restored
 - With the uses of latches, there is now an understanding of 0s and 1s being encoded values
 - The latches maintain the 0s and 1s
- The values stored in the latches is called the circuit state
 - One thing radiation testers do to understand circuits under test is to read the circuit state

SETUP AND HOLD TIME

- Latches require a setup and hold time
- Setup time is defined as the minimum amount of time before the clock's active edge that the data must be stable for it to be latched correctly. Any violation may cause incorrect data to be captured, which is known as setup violation.
[<https://www.edn.com/design/analog/4371393/Understanding-the-basics-of-setup-and-hold-time>]
- Hold time is defined as the minimum amount of time after the clock's active edge during which data must be stable. Violation in this case may cause incorrect data to be latched, which is known as a hold violation. Note that setup and hold time is measured with respect to the active clock edge only.
[<https://www.edn.com/design/analog/4371393/Understanding-the-basics-of-setup-and-hold-time>]



SETUP AND HOLD TIME IN RADIATION EFFECTS

- If radiation causes a transient fault, one of two things will occur
 - The transient will decrease in amplitude due to the circuit's capacitance until it dampens
 - The transient makes it to a latch during the setup and hold, and enters into circuit state
- To change the circuit state, the transient has to make it to the latch during setup and hold, and last long enough to meet the setup and hold criteria
- Clock speed is important
 - The faster the clock is the higher % setup and hold time is of the total clock period
 - Unfortunately a request I have never gotten: could you slow down this circuit?



SUMMARY



TRANSISTOR BASICS SUMMARY

- There are a number of different types of transistors: bipolar, CMOS, BiCMOS
- Each type of transistor has specific radiation sensitivities
- Each type of transistor is particularly rigid in structure, making it sensitive to radiation that causes the materials to change or damage to the structure
- Transistor design and process change the effect of radiation on the circuit

CIRCUIT BASICS SUMMARY

- Combinational circuits are pure logic – output only changes when the input changes
- Sequential circuits are logic with memory elements – outputs only changes when the clock changes
- The memory elements have timing characteristics
 - Signals have to be stable during setup and hold times to enter into circuit state
 - Radiation can cause transient signals that might enter into circuit state