Summary of ELEC 402

Tom Wang

Fall, 2024

1 Fabrication of ICs

1.1 Digital Circuits

1.1.1 Packaging

- Packaged or covered with epoxy resin (plastic) or ceramic
- Wire bonding: connect the chip to the package
- PADS: connect the package to the PCB

IO buffer: connect the chip to the package

- change the voltage level
- remove noise
- improve rise/fall time
- protect the chip from ESD
- provide a constant current source

Driving PADs:

- connect the package to the PCB
- provide a constant current source
- remove noise
- protect the chip from ESD

1.2 Wafer Fabrication

Built in a clean room.

Wafer: a thin slice of semiconductor material.

- Silicon
- Gallium Arsenide
- Silicon Carbide

Growing a Silicon Crystal:

- Czochralski process
- Float zone process
- Epitaxial growth

1.3 MOSFET

MOSFET (Metal Oxide Semiconductor Field Effect Transistor):

- NMOS: n-channel MOSFET
- PMOS: p-channel MOSFET
- CMOS: complementary MOSFET

1.4 Lithography

- Photolithography: use light to transfer a geometric pattern from a photomask to a light-sensitive chemical (photoresist) on the substrate.
- Etching: remove the unwanted material
- Ion implantation: change the electrical properties of the material

1.4.1 N/P-Well CMOS Process

2 RLC Circuits

2.1 Circuits Review

2.1.1 Resistor

- $V = IR$
- $P = IV = I^2R = \frac{V^2}{R}$

2.1.2 Capacitor

- $I = C\frac{dV}{dt}$
- $V = \frac{1}{C}\int Idt$
- $P = IV = CV\frac{dV}{dt} = \frac{V^2}{R}$

2.1.3 Inductor

- $V = L\frac{dI}{dt}$
- $I = \frac{1}{L}\int Vdt$
- $P = IV = LI\frac{dI}{dt} = \frac{I^2}{R}$

2.2 RLC Circuits

2.2.1 Series RLC Circuit

Wires have resistance, inductance and capacitance. Thus the circuit is not ideal.

For a change of voltage to propagate through the wire, it takes time.

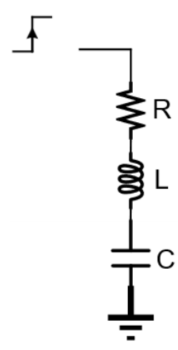

Figure 1: RLC Circuit

2.2.2 Rise/Fall Time

Rise time is the time it takes for the voltage to rise from 10% to 90% of the final value.

Fall time is the time it takes for the voltage to fall from 90% to 10% of the final value.

If there is no inductance, then the time of fall $t_f = RC \times \ln(9) = 2.2RC$.

Let $\tau = RC$, then $t_f = 2.2\tau$. If τ is too large, the signal will converge given a fluctating input since it never reaches the final value before the next fluctuation.

3 MOSFET

3.1 Structure

The given image shows a MOSFET with P-type boday and N-type source and drain. This is a NMOS transistor. Voltage applied to gate will allow current to flow from source to drain.

- **Polysilicon**: Silicon formed from many small silicon crystals.
- **Gate Oxide**: Insulating layer between the gate and the channel.
- Source and Drain are doped with N-type impurities. PMOS has P-type impurities with body as N-type.
- **Bulk**: Body of the transistor.

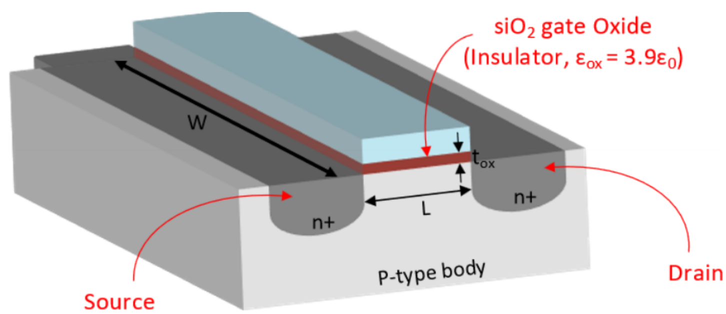

Figure 2: MOSFET

3.1.1 Gate-body Structure

1. Accumulation mode: Gate voltage is negative or zero. Holes are attracted to the gate thus forming a channel. Low resistance.
2. Depletion mode: Gate voltage is positive but less than threshold voltage. Holes are repelled from the gate. High resistance.
3. Inversion mode: Gate voltage is greater than threshold voltage. Electrons are attracted to the gate thus forming holes at the body. Low resistance.

3.2 NMOS and PMOS

Drain-Source current is controlled by the gate-source voltage.

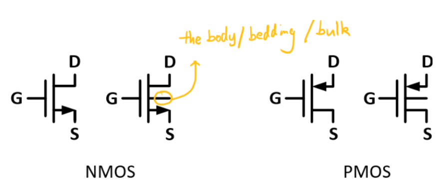

Figure 3: MOSFET

NMOS: When $V_{GS} > V_{th}$, the transistor is on. When $V_{GS} < V_{th}$, the transistor is off.
PMOS: When $V_{GS} < V_{th}$, the transistor is on. When $V_{GS} > V_{th}$, the transistor is off.

3.2.1 nMOS modes

Source and drain are symmetric diffusion termninals. For nMOS, source is the termnial at lower voltage ($V_ds > 0$)

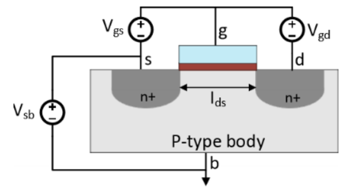

Figure 4: nMOS modes

- Cutoff: $V_{GS} < V_{th}$, $I_{DS} = 0$. It is the depletion mode.
- Triode/Linear: $V_{GS} > V_{th}$, $V_{DS} < V_{GS} - V_{th}$. It is the linear mode.
  - Conductivity is proportional to $V_{GS} - V_{th}$. The larger the $V_{GS} - V_{th}$, the larger the conductivity, the smaller the resistance.
  - Current flow from D to S. Electrons flow from S to D.
- Saturation: $V_{GS} > V_{th}$, $V_{DS} > V_{GS} - V_{th}$. It is the saturation mode.
  - Channel is pinched off at the drain end. The current is independent of V_{DS}.

3.3 MOSFET Characteristics

Carrier velocity is proportional to the electric field. $v_d = \mu_n E$. μ_n is the carrier mobility of the electrons.

Electric field is proportional to the voltage gradient. $E = \frac{dV}{dx}$. Can approximate as $E = \frac{V}{L}$ where L is the length of the channel.

Thus time it takes for the electron to travel from source to drain is $t = \frac{L}{v_d} = \frac{L}{\mu_n E} = \frac{L^2}{\mu_n V}$.

C_{ox} is the capacitance of the oxide layer. $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$. With W as the width of the channel, L as the length of the channel, $C_{ox} = \frac{\epsilon_{ox} WL}{t_{ox}}$.

Let $\beta = \mu_n C_{ox} \frac{W}{L}$ be the gain factor.

- Cut-off: $I_{DS} = 0$.
- Triode: $I_{DS} = \beta(V_{GS} - V_{th} - \frac{V_{DS}}{2})V_{DS}$.
- Saturation: $I_{DS} = \frac{\beta}{2}(V_{GS} - V_{th})^2$. independent of V_{DS}.

For a fixed V_ds and $V_{GS} > V_{th}$, the current is proportional to:

- L: The length of the channel. The longer the channel, the longer the time it takes for the electron to travel from source to drain.
- W: The width of the channel. The wider the channel, the more electrons can flow through.
- V_{th}: The threshold voltage. The larger the threshold voltage, the larger the current.
- ϵ_{ox}: The permittivity of the oxide layer. The larger the permittivity, the larger the current.
- t_{ox}: The thickness of the oxide layer. The thinner the oxide layer, the larger the current.
- μ_n: The carrier mobility of the electrons. The larger the carrier mobility, the larger the current.
  - $\mu_n = 500cm^2/V \cdot sec \approx 2.5\mu_p$. $\mu_p = 180cm^2/V \cdot sec$.
  - Thus need to increase the size of pmos to match the current of nmos.

For small V_{DS}, the transistor is viewed as a linear resitor.
$R_{on} = \frac{1}{\beta(V_{GS}-V_{th})}$.

3.3.1 Region of Operation

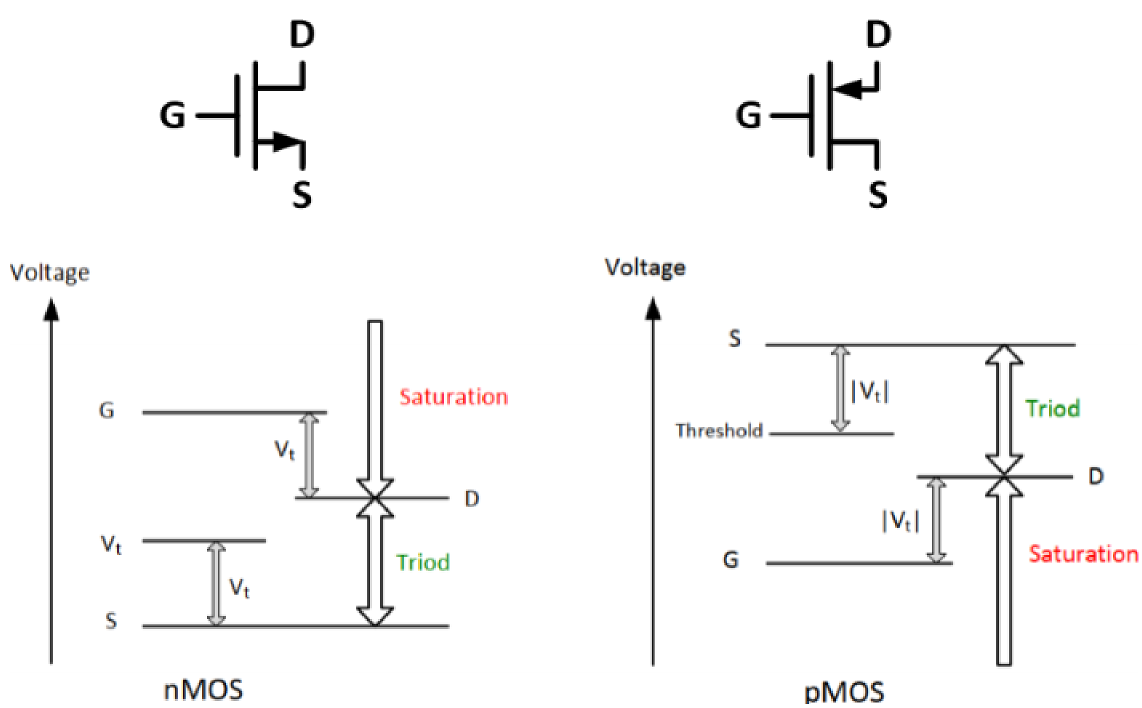

Figure 5: Region of Operation