Metal-Oxide-Silicon (MOS) devices

- Principle of MOS Field Effect Transistor transistor operation

  Metal (poly) gate on oxide between source and drain

  Source and drain implants of opposite type to substrate.

  Gate is biased to **invert** channel below oxide

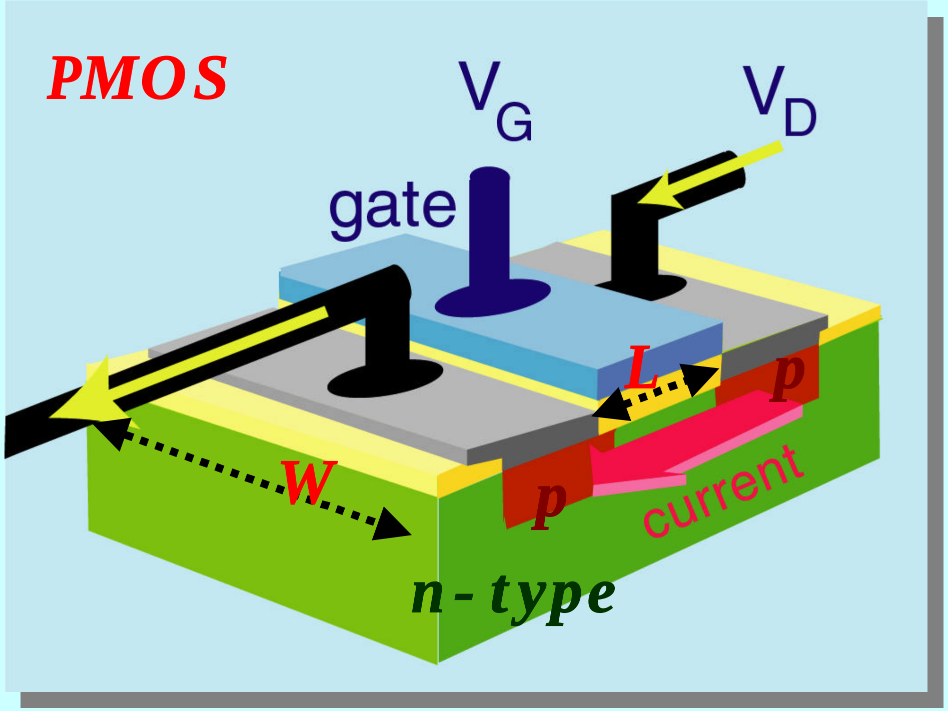
  apply voltage bias to gate, which...

  gives field across oxide

  modulates current in conducting channel

  transistor can be used as

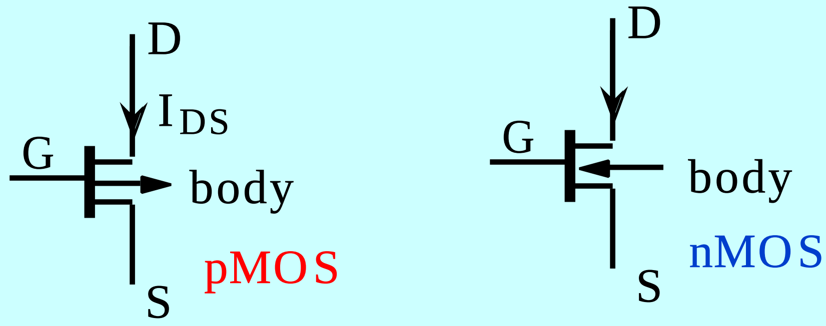
  switch (digital) or amplifier (analogue)



MOS Field Effect Transistor

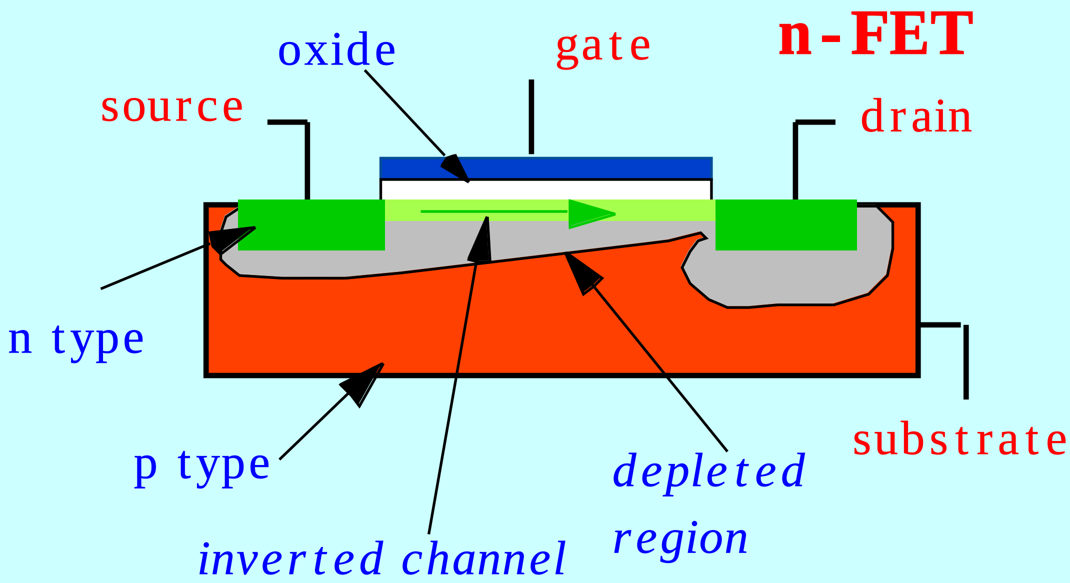
•Operation - input signal is voltage on gate

very high input impedance > $10^{12}\Omega$



•I-V behaviour nMOS

$V_G > V_T$ to switch on, vary V_{DS}



linear region

$I_{DS} \sim (V_G - V_T)V_{DS}$

saturation region

channel "pinch off" near drain

$I_{DS} \sim (V_G - V_T)^2$

$\partial I_{DS}/\partial V_{GS} = i_{ds}/v_{gs} = g_m = (2\mu C_{ox} I_{DS} W/L)^{1/2}$ transconductance

defined by geometry & current only - important for IC design

Designing with MOSFETs

•Mostly operate in saturation - choice of gate-source voltage determines current

but often bias with current source, so gate voltage "selected by" current

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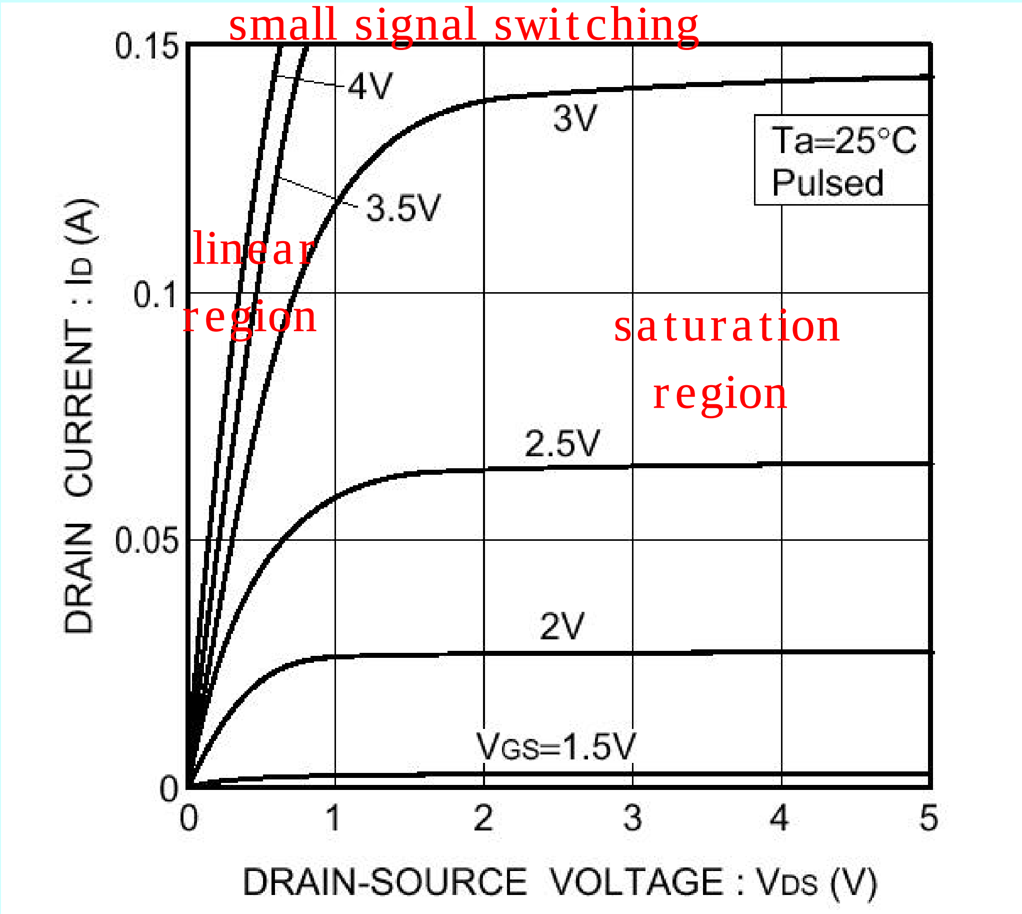
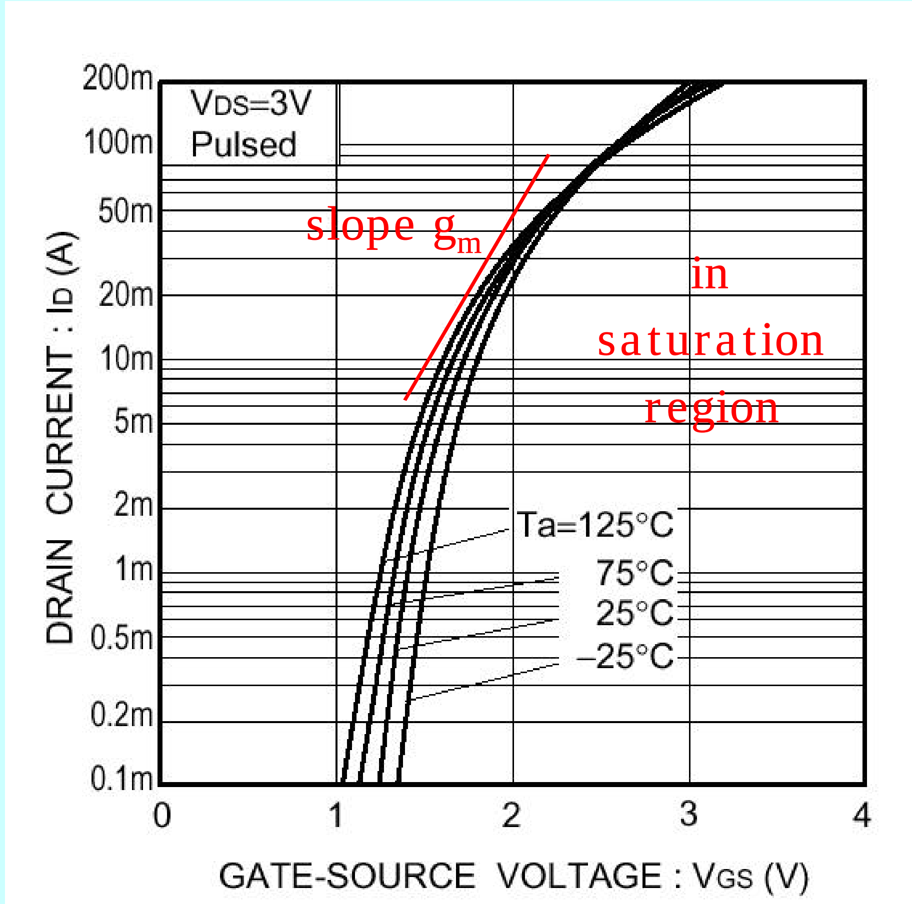




Simple MOSFET applications

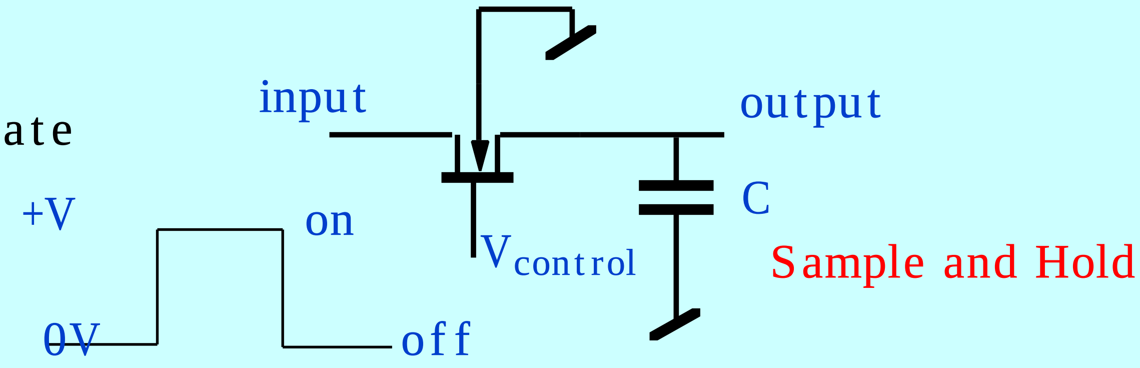
- Voltage controlled switch

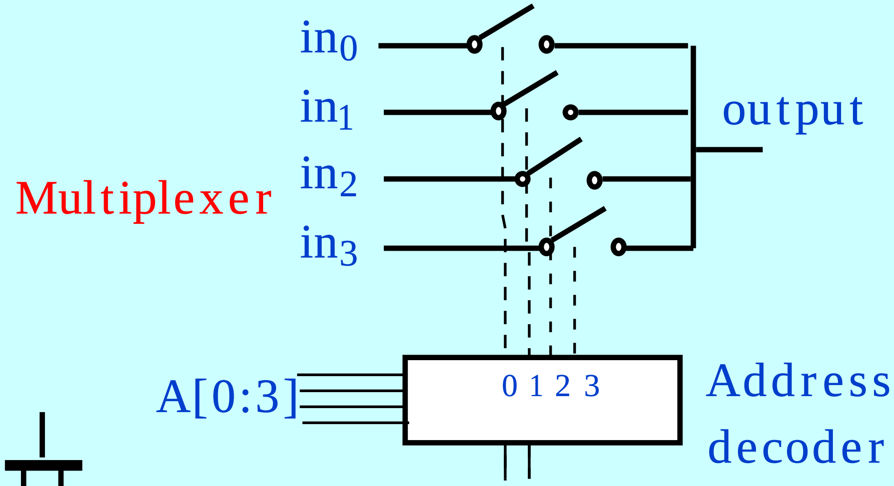
  very high resistance in OFF state

  R_{ON} ~ 5 - 100Ω

  fast response ~nsec

  bi-directional



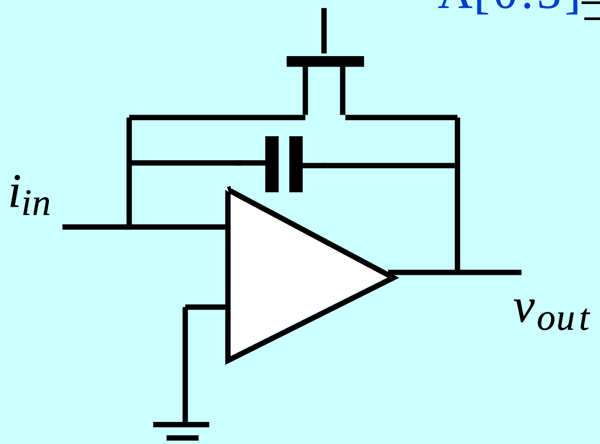


- Voltage controlled resistor

  operate in linear region

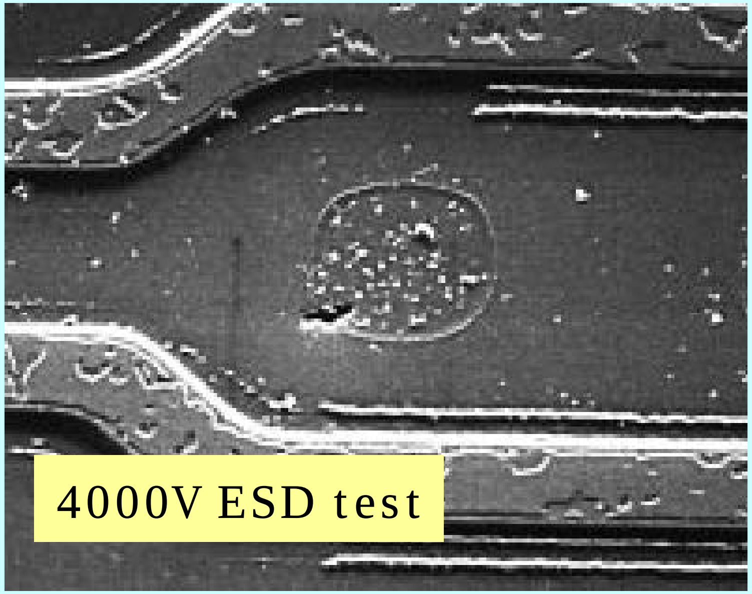
  $R_{DS} \sim 1/(V_G - V_T)$

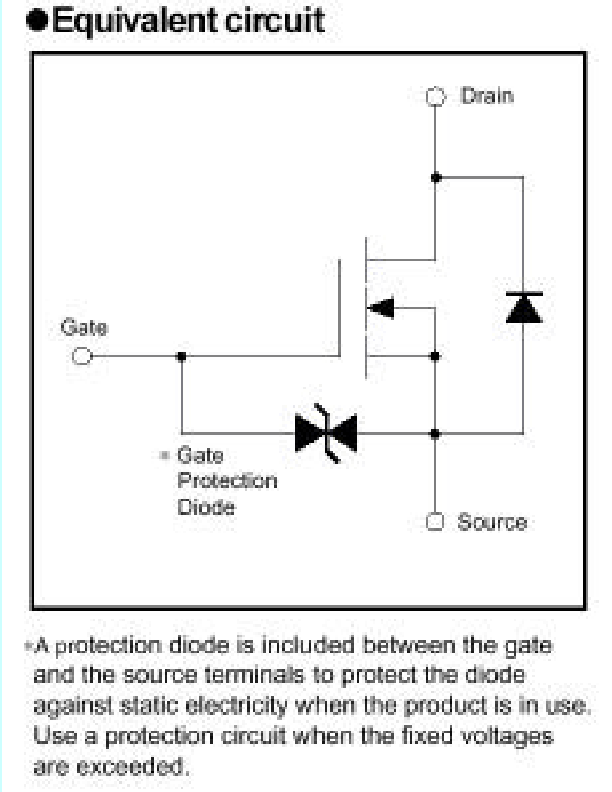
  convenient for IC design



ElectroStatic Discharge

- MOS circuits are prone to damage from ESD
  - gate oxides are thin layers - few nm in advanced technologies
  - oxide breakdown field < 1000MV/m = 1V/nm
- Human body can easily charge to 30-40kV walking across carpet on a dry day
  - precautions:
  - circuits designed with protection diodes
  - stand on conductive pad and earth body with wrist strap





CMOS = Complementary MOS

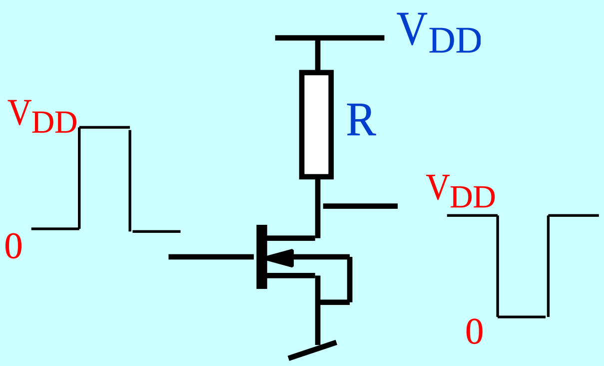
- Both pMOS and nMOS transistors on same wafer

  by putting p-type "wells" into n-type wafer (or vice-versa)

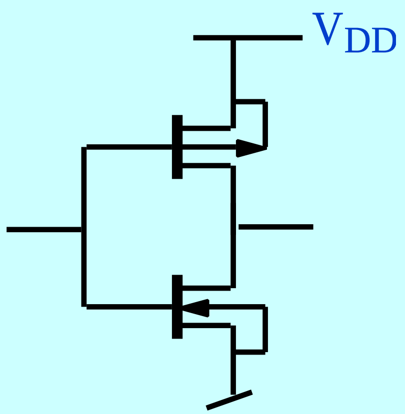
  build nMOS transistors in locally p-type region

- Why?

NMOS inverter



CMOS inverter



NMOS consumes power in low state

CMOS version consumes power only when switching

basis of almost all modern logic

In IC technologies, accurate resistors are harder to make than C and transistors

Junction FET

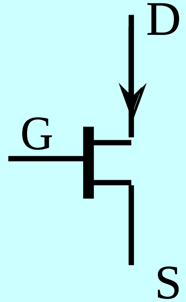
- Almost identical to MOSFET - difference is

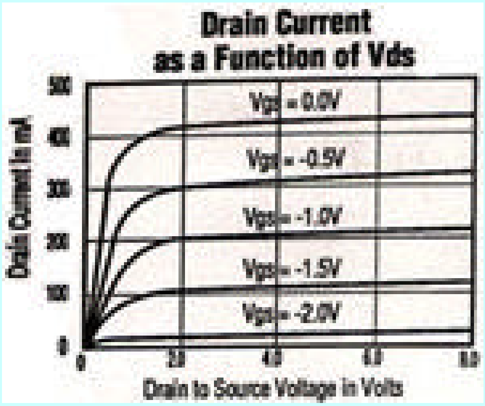
  Gate is implanted p-n junction

  voltage on gate depletes bulk silicon

  current conducting channel reduced or enlarged

  $\Delta V_{GS} \rightarrow \Delta I_{DS}$





- Characteristics - similar to MOSFET

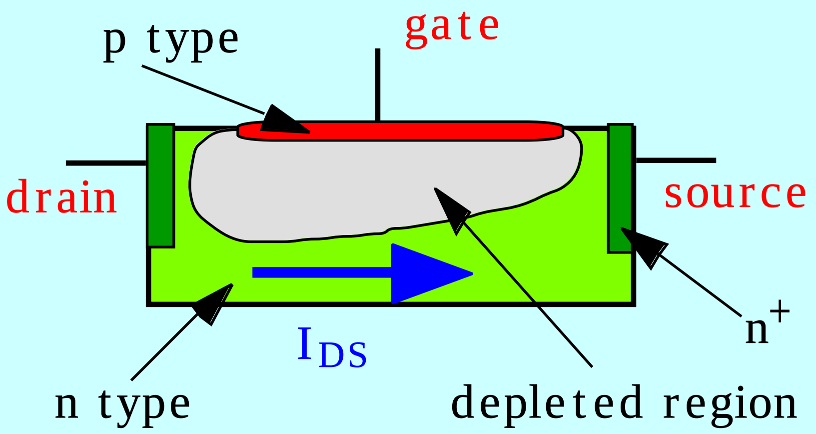
  gate is reverse biased diode

  high input impedance ($\geq 10^9\ \Omega$)

  small current from diode leakage

  usually operated in saturation

  channel 'pinched off' by depletion.



"typical" values

$g_m \sim 10\text{mA/V} = 1/100\Omega = 10\text{mS}$

FET circuits

- Building blocks resemble bipolar circuits
- Source follower (cf emitter follower)

$i_{ds} = g_m(v_g - v_s) = g_m(v_{in} - v_s)$

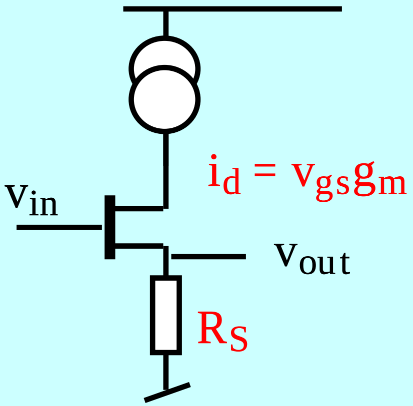
$v_{out} = v_s = i_{ds}R_S = g_m(v_{in} - v_s)\,R_S$

$v_{out}/v_{in} = g_mR_S/(1 + g_mR_S) \leq 1$

$R_{in} \sim 10^9 - 10^{12}\Omega$

$R_{out} = R_S||R_{DS} = R_S/(1 + g_mR_S)$

not low

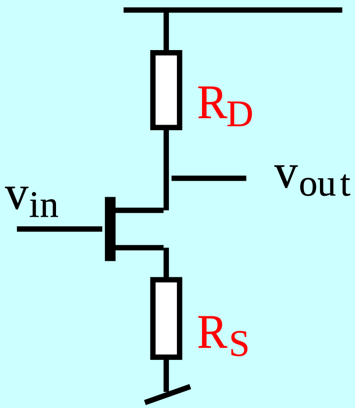


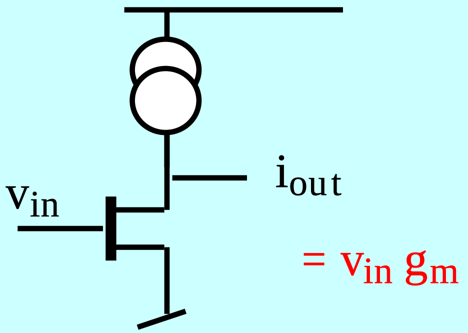
- Common Source amplifier -

$v_{out}/v_{in} = -g_mR_D\ /(1 + g_mR_S)$

R_{in} high

$R_{out} \approx R_D||R_{DS} = R_D/(1 + g_mR_D)$





but more common configuration uses current source with suitable load $i_{out} = g_mv_{in}$

FET limitations

- On Resistance
  - although small, it contributes to RC time in fast switches
- Capacitance
  - inevitable capacitances between nodes, important for high speed circuits
  - $C_{gate} \sim C_{ox}WL$ for MOSFETs
- Relevance to op-amps
  - FET amplifiers have much <u>higher input impedance</u>
    - and draw much lower currents
- Cautions
- Latch-up
  - under certain conditions, parasitic bipolar transistors formed
  - MOS circuits can go into high current states - destructive
- ESD
  - care needed in handling
    - protection networks can degrade performance

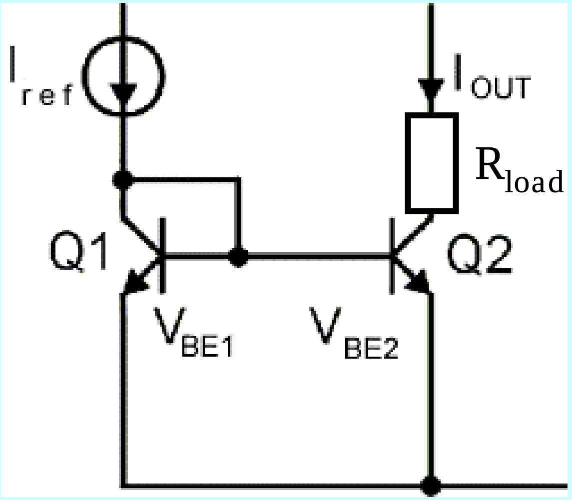
Another building block - the current mirror (if time)

- Q_1 & Q_2 are identical transistors

  $V_{BE1} = V_{BE2}$ and $V_{BE} \approx (kT/q)\log_e I_E$

  so $I_{out} = I_{ref}$

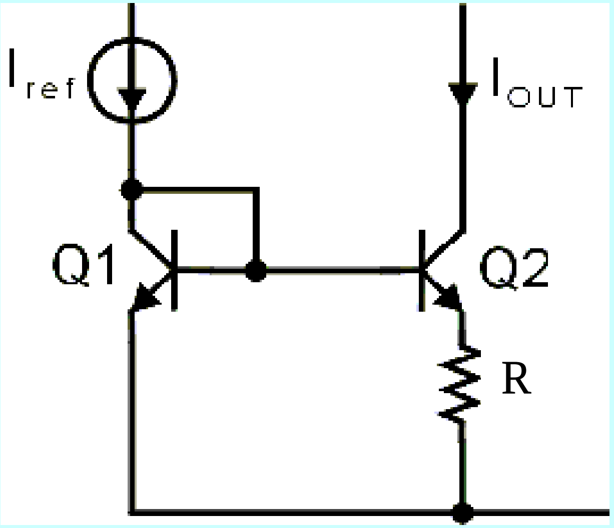
  widely used in ICs where closely matched transistors are easy to construct - useful to program currents



- add a resistor

  $I_{out} = (kT/qR)\log_e(I_{ref}/I_{out})$

  eg R = 1kΩ, I_{ref} = 1mA => I_{out} = 67μA

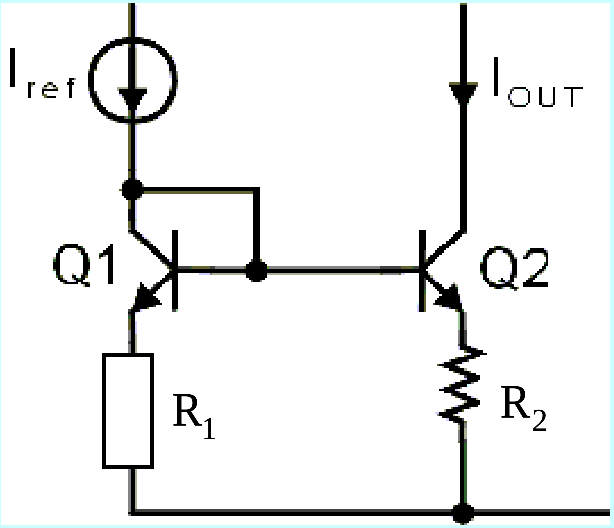


add another resistor

$V_{BE1} \approx V_{BE2}$

$I_1/I_2 = R_2/R_1$

also works for discrete circuits



Band-gap circuit

- To be more precise,

  V_{BE} ~ log(current density) so in non-matched transistors

  with same current, and ratio of emitter areas r

  $V_{BE1}-V_{BE2} = (kT/q)\ln(r)$

  easy to achieve in IC technology

- Principle of AD590 T sensor

  Proportional To Absolute Temperature (PTAT)

  $I_1 = I_2$

  $\Delta V_{BE} = (kT/q)\ln(r) = I_1R$

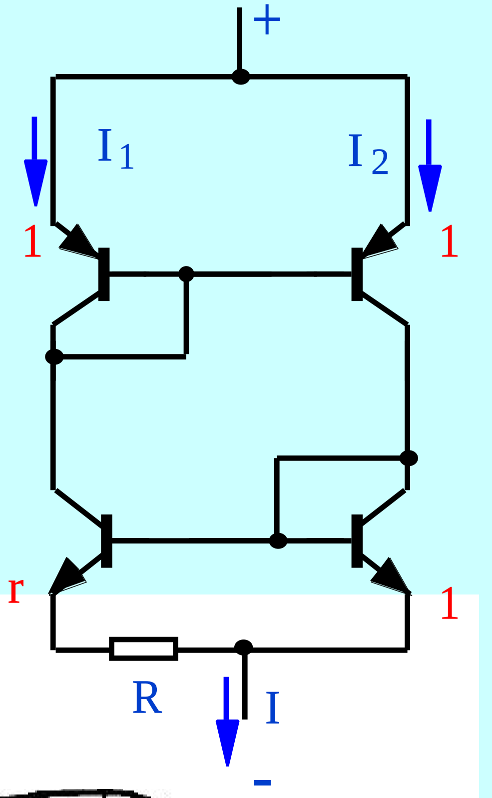
  $I = I_1 + I_2 = (2kT/qR)\ln(r)$

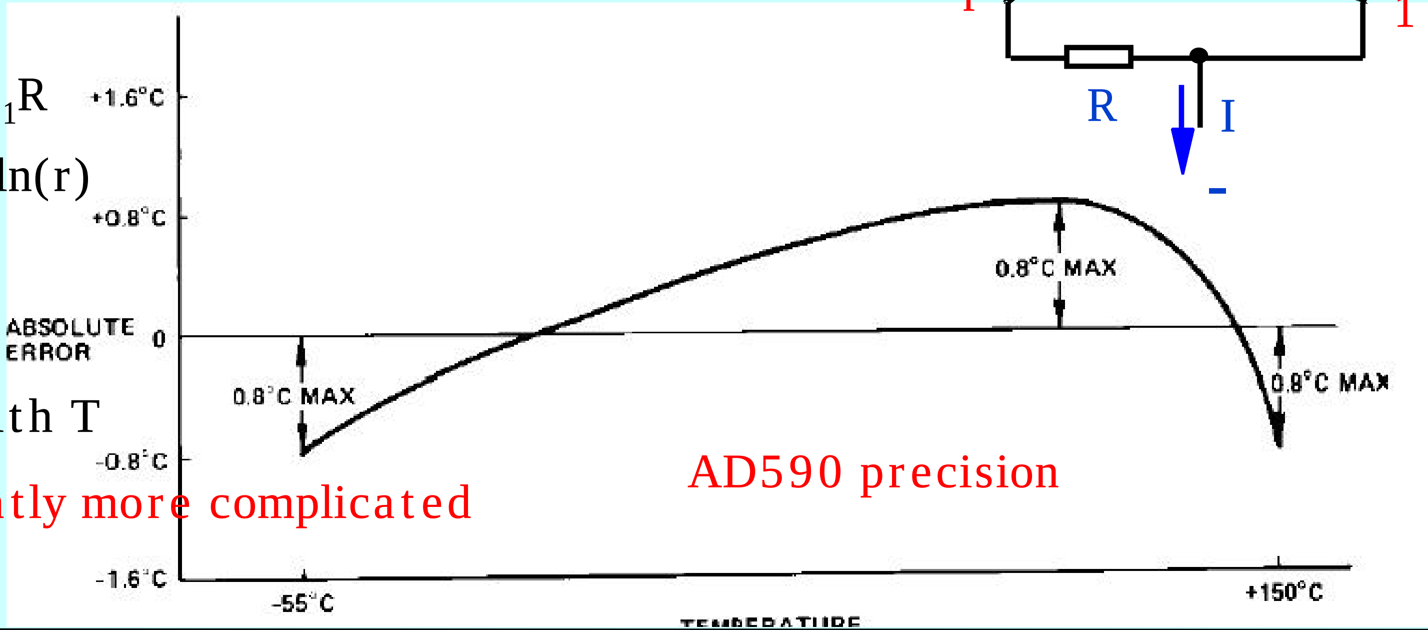
  $r = 8 \quad R \approx 1k\Omega$

  $I \approx 1\mu A/K$ @ 300K

  R should vary little with T

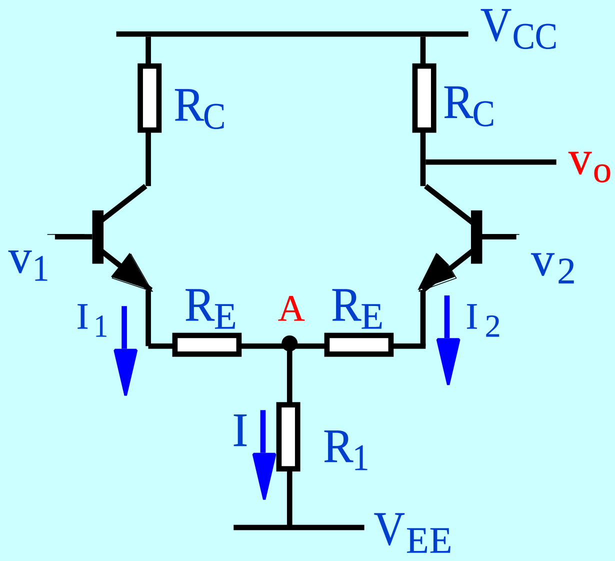
- actual AD590 only slightly more complicated





AD590 precision

Transistor differential amplifier (for the ambitious)



• DC R_1 is large, to act as current source

$V_A = V_{EE} + IR_1$

$V_{E1} = V_A + I_1R_E$ $V_{E2} = V_A + I_2R_E$ (ignoring r_e)

• AC

$v_1 = v_A + i_1R_E = iR_1 + i_1R_E$

$v_2 = v_A + i_1R_E = iR_1 + i_2R_E$

$i = i_1 + i_2$

$v_1 - v_2 = (i_1 - i_2)R_E$

$v_0 = - i_2R_C$

• For differential inputs $v_1 = - v_2$ so $i = 0$

$G_{diff} = v_0/(v_2 - v_1) = R_C/2R_E$

• Common mode $v_1 = v_2 = v_{cm}/2$

$v_1 + v_2 = 2iR_1 + (i_1 + i_2)R_E = i(2R_1 + R_E)$

$G_{cm} = v_0/v_{cm} = -R_C/(2R_1 + R_E)$

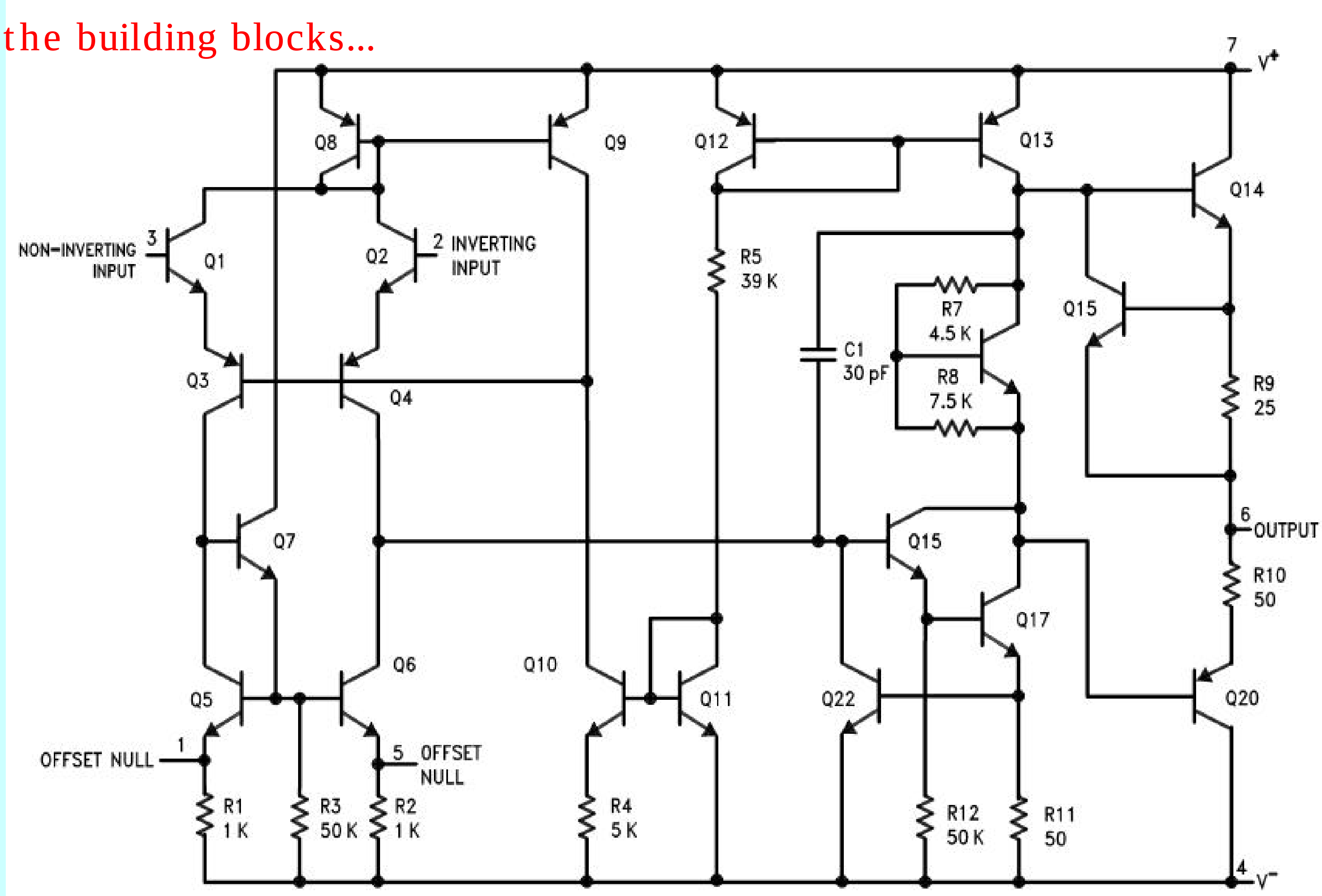
CMRR $\approx 2R_1/R_E$ $R_1 \gg R_E$

Variants

- R_C in Q1 loop omitted
- replace R by current source
- omit R_Es
- differential outputs

What's inside an op-amp...

• Look for the building blocks...



MOS IC amplifiers look similar but currents determined by transistor aspect ratios