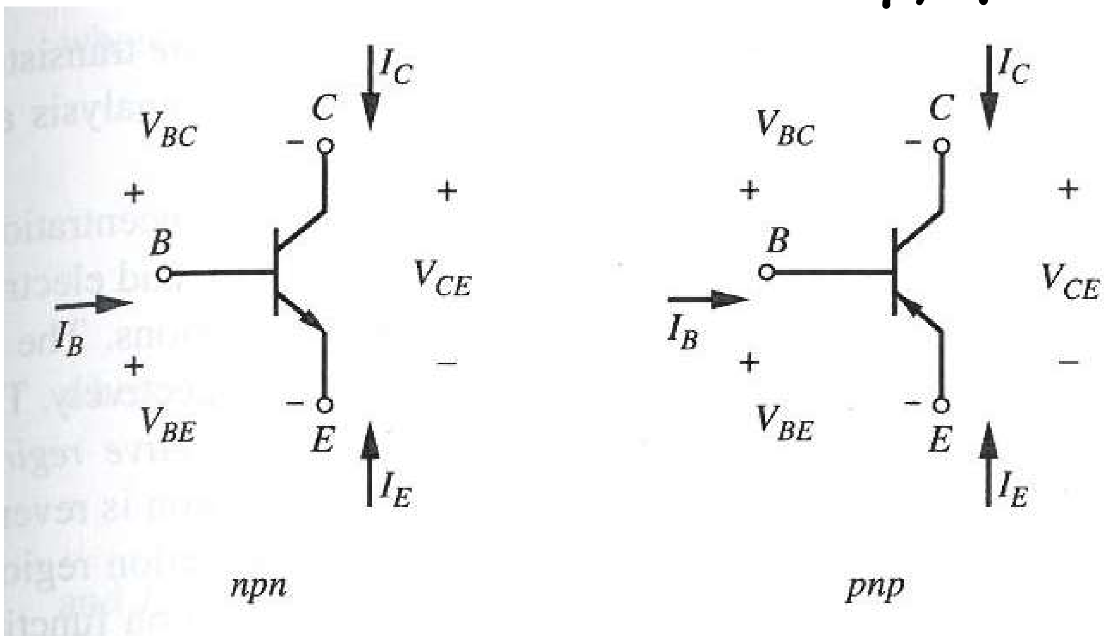
Lecture #10, Jan 31st, 2022

- Read Chapter 12.
- Will be on campus for the rest of the quarter.
- CAD 3 Assigned
- Today: Continue Reference Voltage Design.
  - Current References
  - Process Voltage and Temperature Dependence.
  - Constant Voltage (Temp)
  - Proportional to Absolute Temperature (PTAT)
  - Constant Gm (Temp).

Bipolar Primer

NPN PNP



$$I_C = -(I_E + I_b) \qquad I_C = -(I_E + I_B)$$

LARGE SIGNAL DC CURRENT

$$I_C = \frac{q A D_n n_{po}}{W_B} \exp\left(\frac{V_{BE}}{V_T}\right)$$

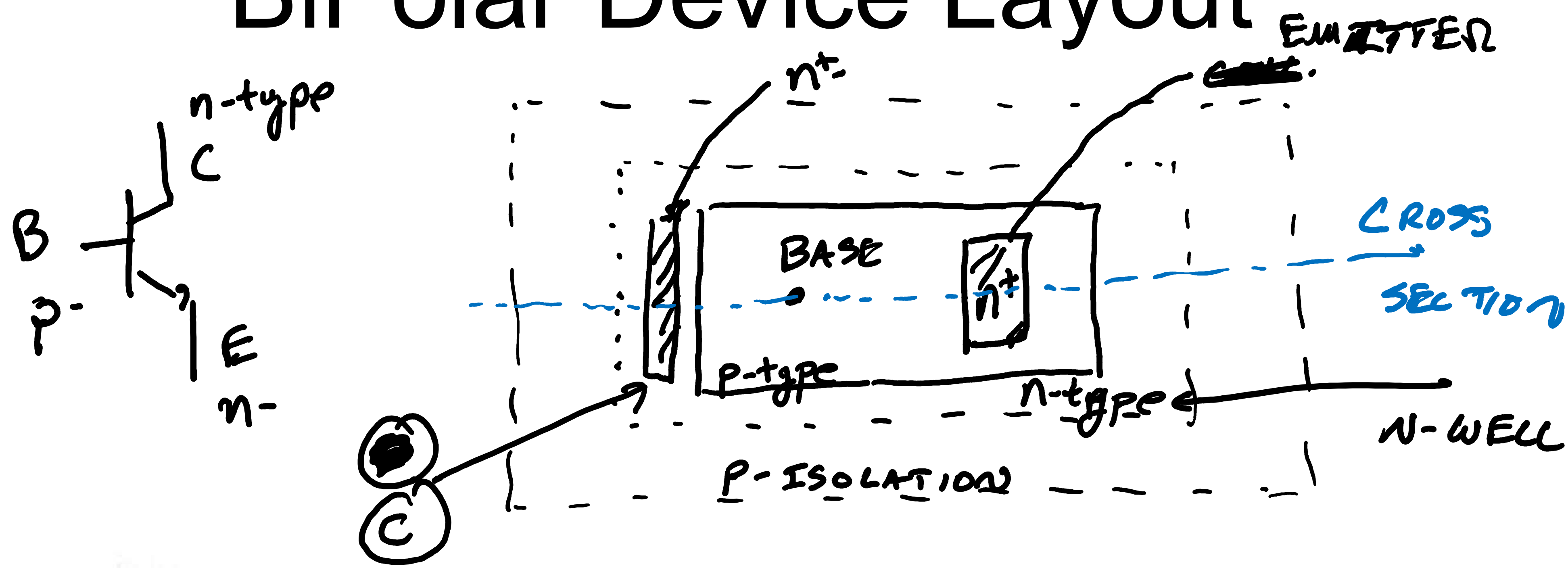
$$I_S = \frac{q A D_n n_{po}}{W_B}$$

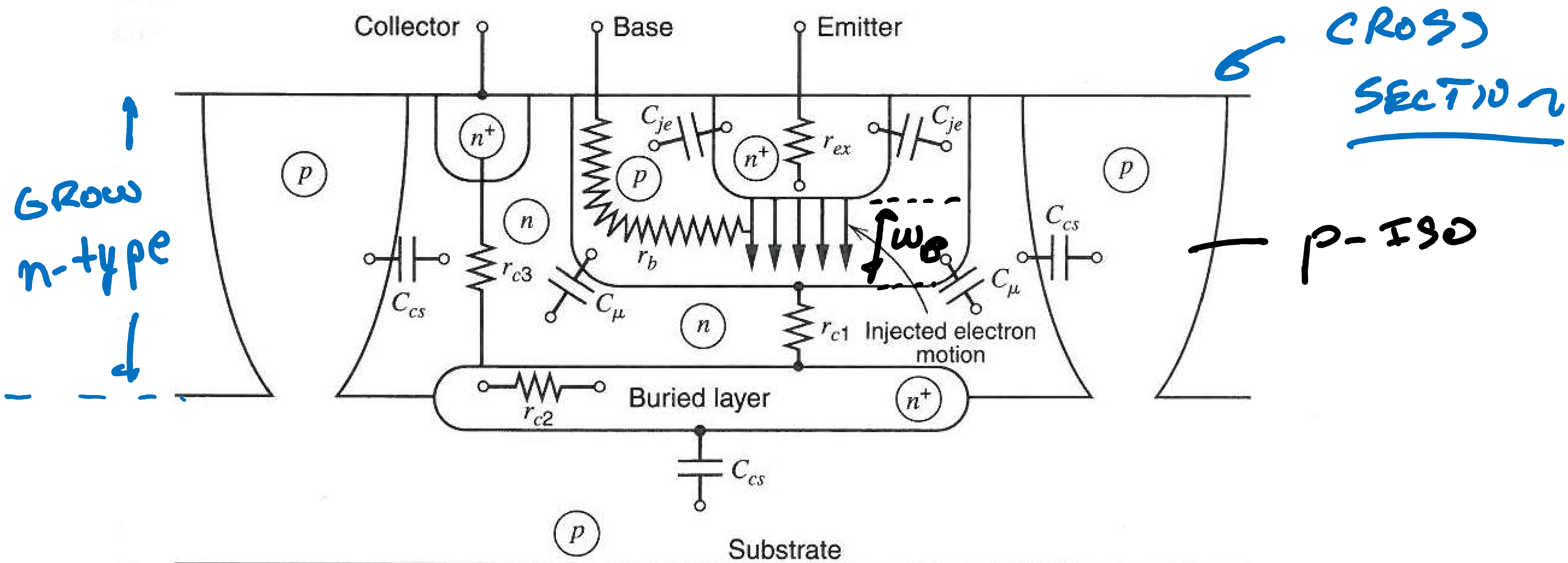
MINORITY CARRIERS IN BASE

$V_T = KT/q$

V_T @ ROOM TEMP $\approx 25mV$

BiPolar Device Layout





Razavi Expressions for BJT Collector Current

FORWARD ACTIVE REGION.

$$I_c = I_s \exp\left(\frac{V_{BE}}{V_T}\right)$$

$V_T = \frac{kT}{q} \approx 25\,mV$ @ ROOM TEMP. 300K

THERMAL VOLTAGE

$$I_s = \mu k T n_i^2$$

- μ: MOBILITY OF MINORITY CARRIERS

  T: TEMP KELVIN

  K: BOLT. CONSTANT

  n_i^2: INTRINSIC CARRIER CONCENTRATION

- $\mu \propto \mu_0 T^m$ $\quad m \approx -3/2$

- $n_i^2 \propto T^3 \exp\left(-E_g/kT\right)$

  NOTE: T DEP.

$E_g \approx \underline{1.12eV}$

BAND GAP ENERGY IN SILICON.

Expressing V_{BE} and Temp Dependence

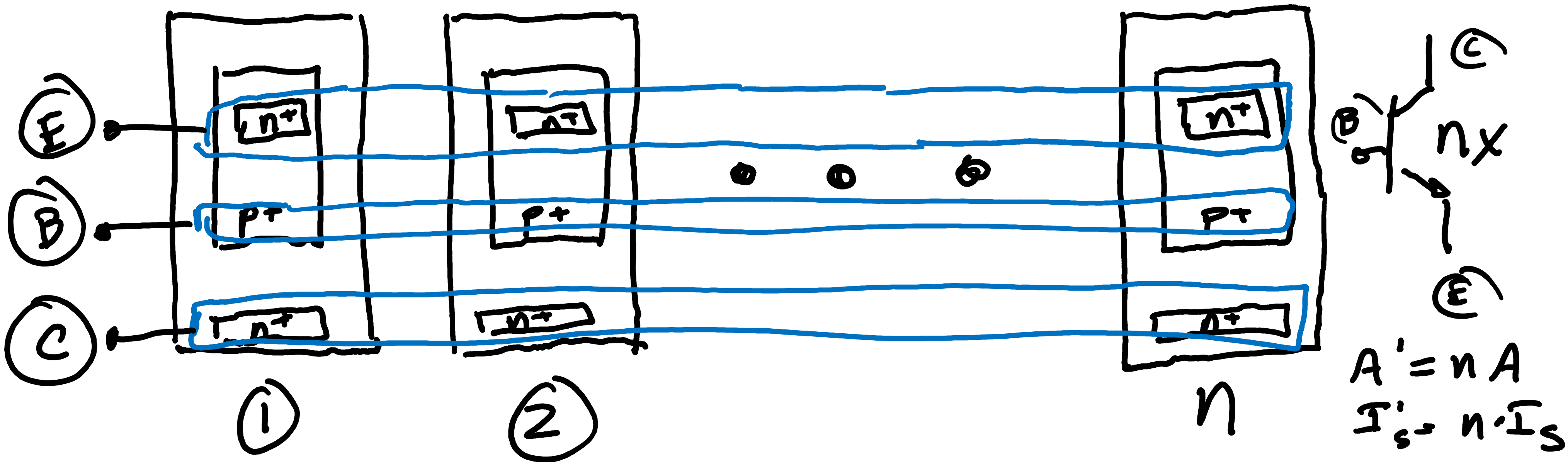
$$I_s = bT^{4+m} \exp\left(\frac{-E_g}{kT}\right)$$

b constant.

$$\boxed{I_C = I_s \exp\left(\frac{V_{BE}}{V_T}\right)}$$

$$\boxed{\underline{V_{BE}} = V_T \ln\left(\frac{I_C}{I_s}\right)}$$

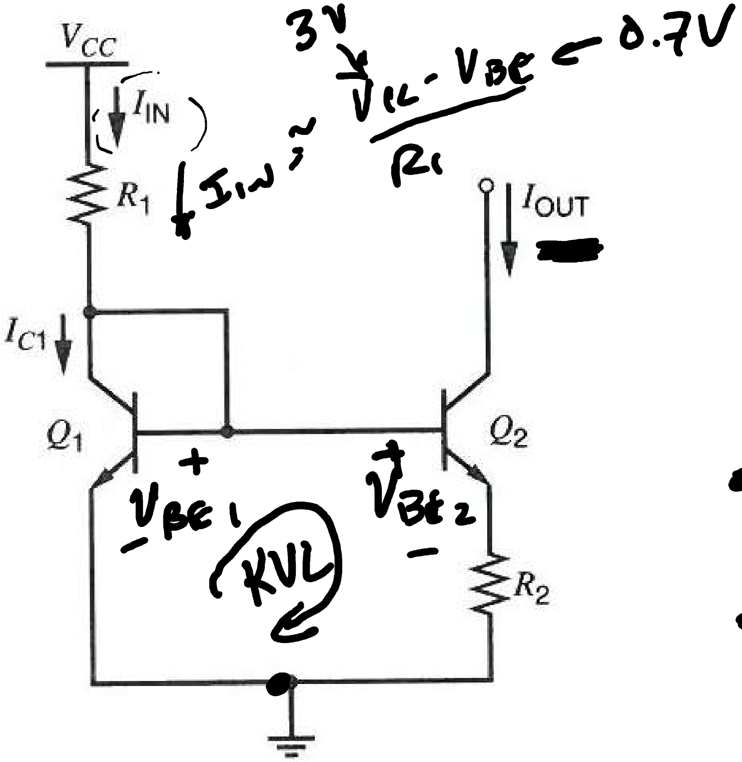
BJT Device Layout



- **No Control over area of a BJT Transistor (A) and width of the base (W). The device size and layout are fixed and part of your Process and Design Kit (PDK).**

w_B

- **Can layout multiple devices in parallel, then short the collector, base and emitters.**



$V_{BE2} < V_{BE1}$

$$V_{BE1} - V_{BE2} - \underbrace{\frac{\beta_F + 1}{\beta_F} I_{OUT}}_{I_E} R_2 = 0$$

- CANNOT ASSUME $V_{BE_{ON}} = 0.7V$
- CAN ASSUME β LARGE $\approx$ 150

$$V_T \ln\left(\frac{I_{IN}}{I_{S1}}\right) - V_T \ln\left(\frac{I_{OUT}}{I_{S2}}\right) - I_{OUT} R_2 = 0$$

- ASSUME $I_{S1} = m \cdot I_{S2}$, IN THIS CASE $m = 1$.

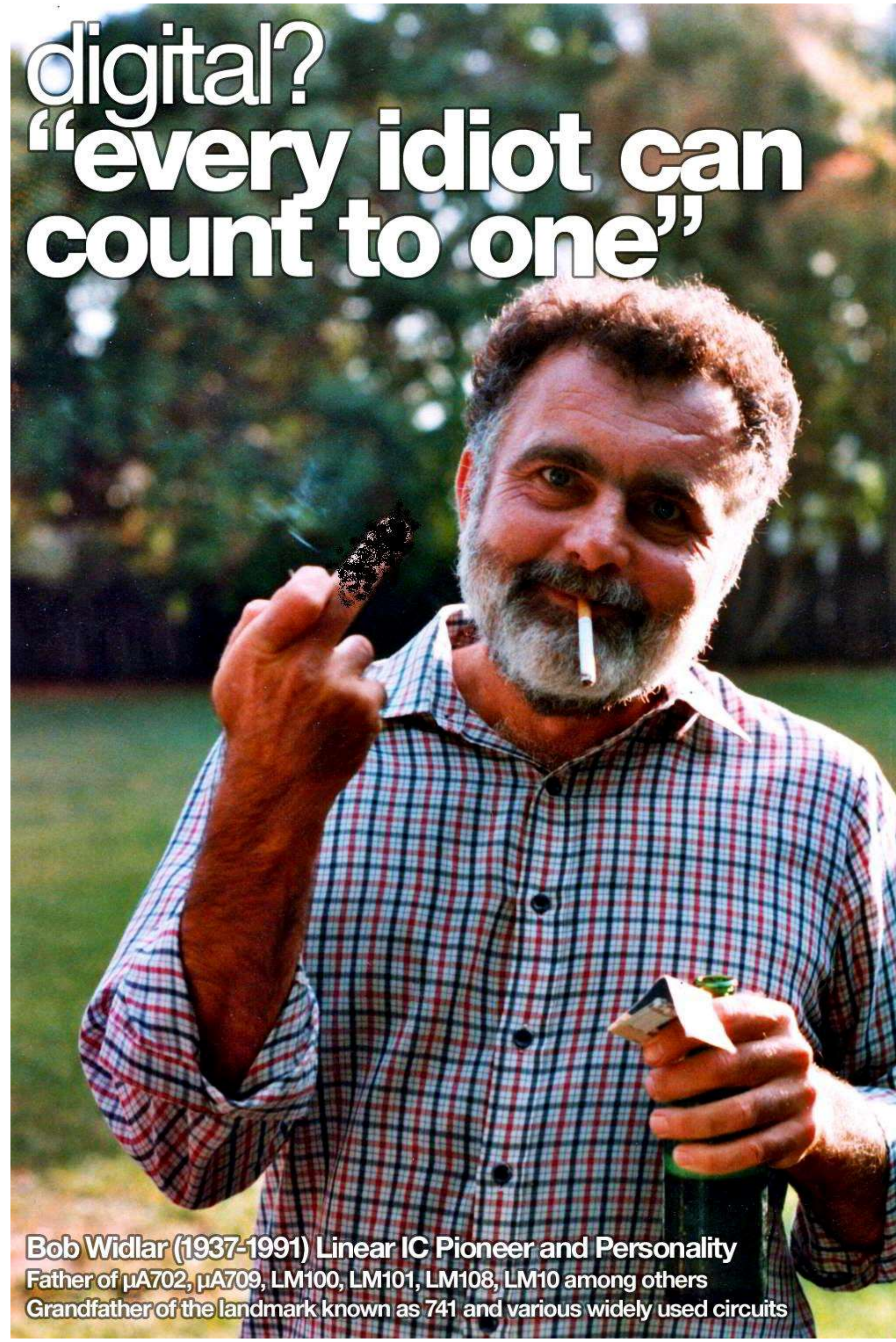
$$I_{OUT} = \frac{V_T}{R} \ln\left(\frac{I_{IN}}{I_{OUT}}\right)$$

Widlar Current Mirror Characteristics

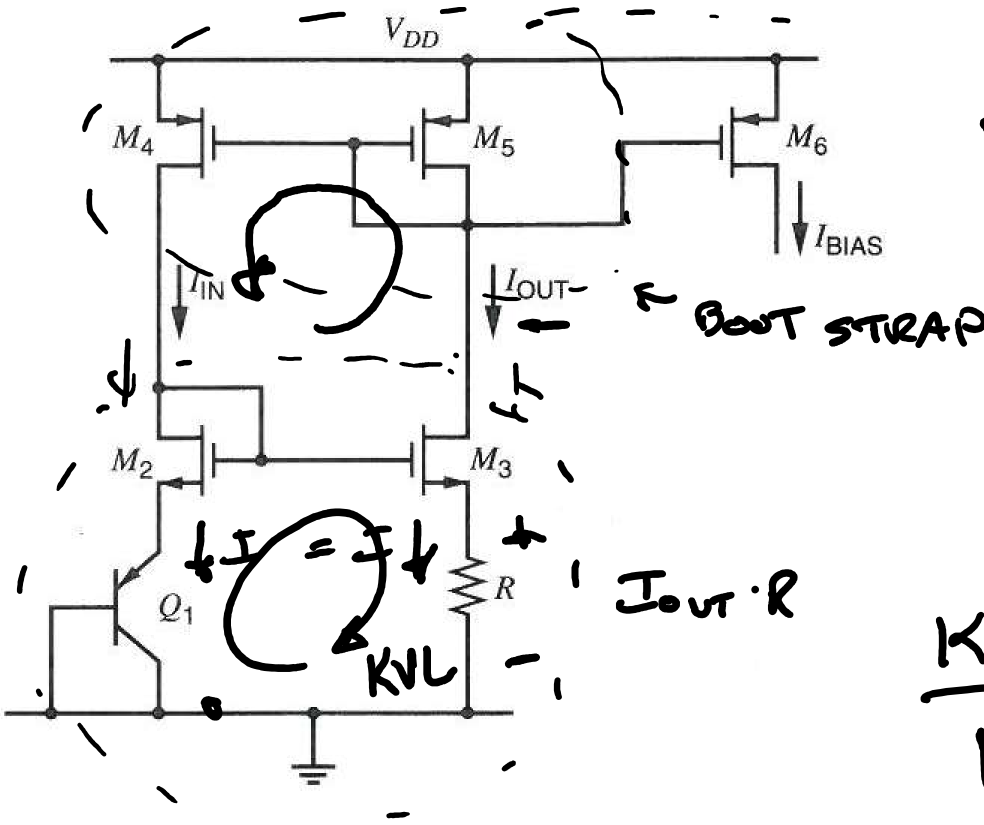
$$I_{out} = \frac{V_T}{R_2} \cdot \ln \frac{I_{IN}}{I_{OUT}}$$

- “Transcendental” Equation in I_{OUT}. Process of trail and error to find a solution for R_2, I_{IN}, and I_{OUT}.
- Usually have a desired I_{IN} and I_{OUT}, want to find R_2.
- Can easily generate a low value of current in the μA range with reasonable resistor sizes.

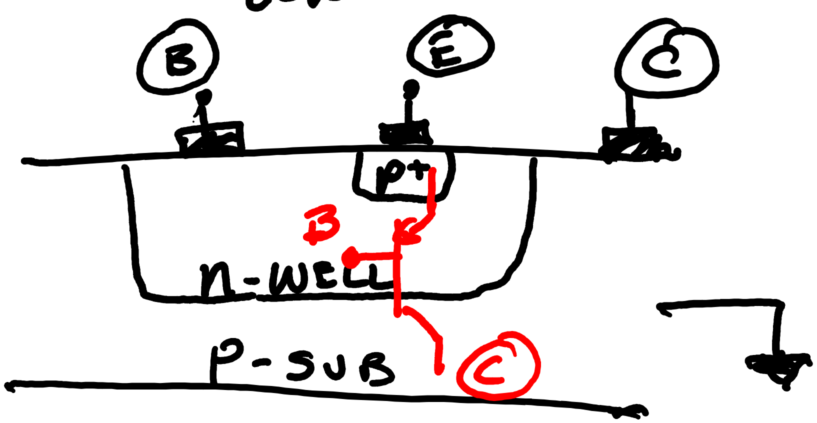
Bob Widlar (1937-1991)



CMOS Version of V_{BE} Referenced C-Source



CORE C-SOURCE



• IF $I_{OUT} = I_{IN}$ & $\left(\frac{W}{L}\right)_{M2} = \left(\frac{W}{L}\right)_{M3}$

$\Downarrow$

$$V_{GS2} = V_{GS3}$$

$\Downarrow$

KVL

$$V_{BE1} + \cancel{V_{GS2}} - \cancel{V_{GS2}} - I_{OUT} \cdot R = 0$$

$$\boxed{I_{OUT} = \frac{V_{BE1}}{R}}$$

SUBSTRATE PNP

Temperature-Independent References

- Reference voltages or currents exhibiting little dependence of temperature are useful in analog circuits
- If two quantities having opposite temperature coefficients (TCs) are added with proper weighting, the result displays a zero TC
- For two voltages V_1 and V_2 that vary in opposite directions with temperature, we choose α_1 and α_2 such that $\alpha_1\partial V_1/\partial T + \alpha_2\partial V_2/\partial T = 0$, obtaining a reference voltage, $V_{REF} = \alpha_1 V_1 + \alpha_2 V_2$, with zero TC
- Characteristics of bipolar transistors have proven the most reproducible and well-defined quantities that can provide positive and negative TCs

Negative-TC Voltage

- The base-emitter voltage of bipolar transistors, or more generally, the forward voltage of a *pn*-junction diode exhibits a negative TC
- For a bipolar device, $I_C = I_S \exp(V_{BE}/V_T)$, where $V_T = kT/q$
- Saturation current I_S is proportional to μkTn_i^2, where μ denotes the mobility of minority carriers and n_i is the intrinsic carrier concentration of silicon
- The temperature dependence of these quantities is expressed as $\mu \propto \mu_0 T^m$, where $m \approx -3/2$, and $n_i^2 \propto T^3 \exp[-E_g/(kT)]$, where $E_g \approx 1.12\ eV$ is the bandgap energy of silicon
- Thus,

$$I_S = bT^{4+m} \exp \frac{-E_g}{kT}$$

where *b* is proportionality factor