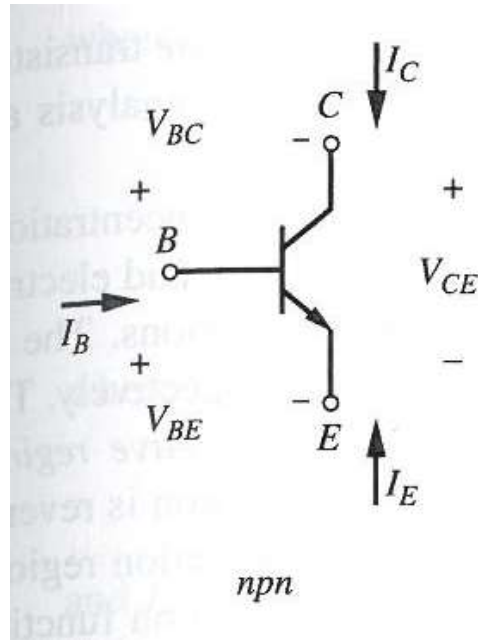


Lecture #10, Jan 31st, 2022

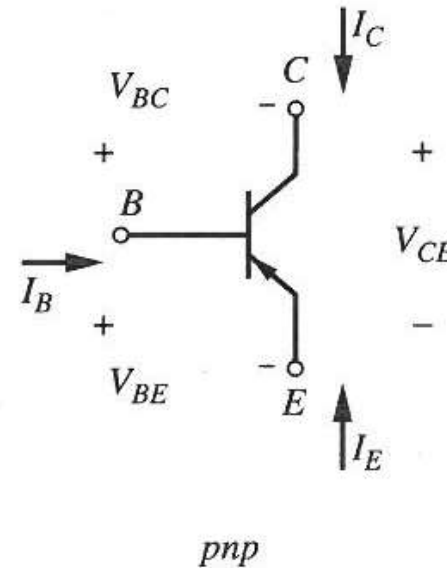
- Read Chapter 12.
- Will be on campus for the rest of the quarter.
- CAD 3 Assigned
- Today: Continue Reference Voltage Design.
 - Current References
 - Process Voltage and Temperature Dependence.
 - Constant Voltage (Temp)
 - Proportional to Absolute Temperature (PTAT)
 - Constant Gm (Temp).

Bipolar Primer

NPN



PNP



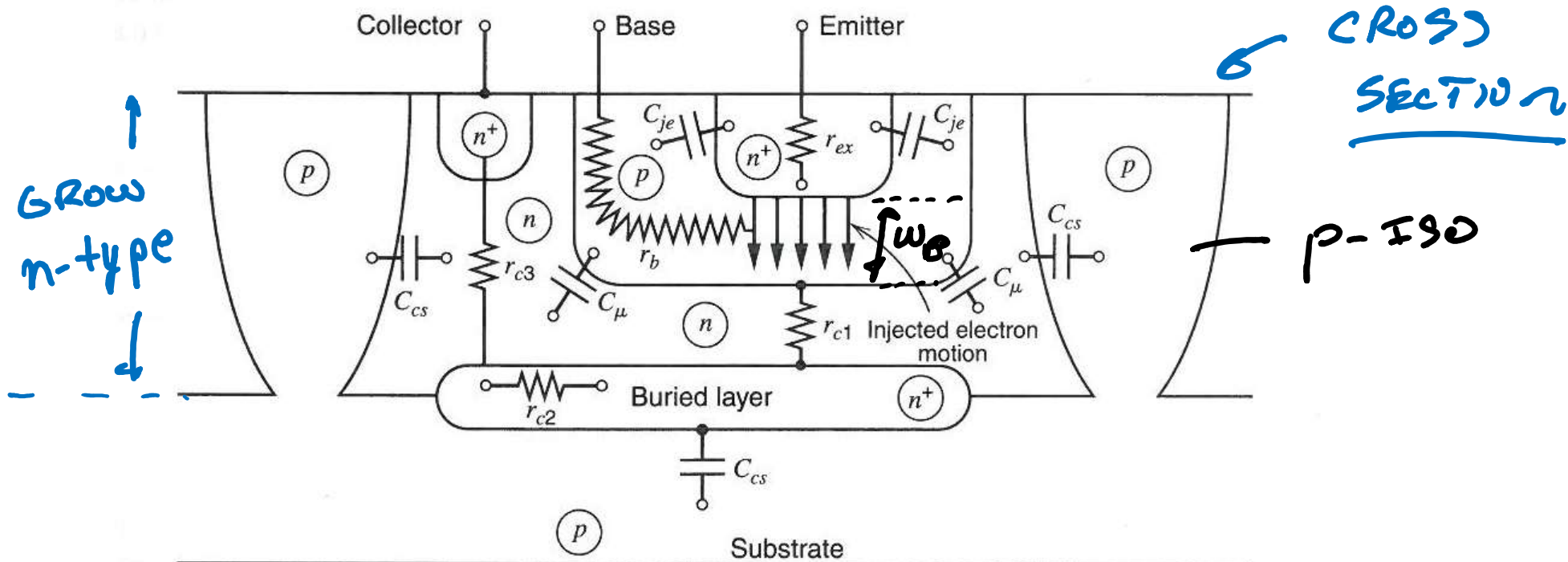
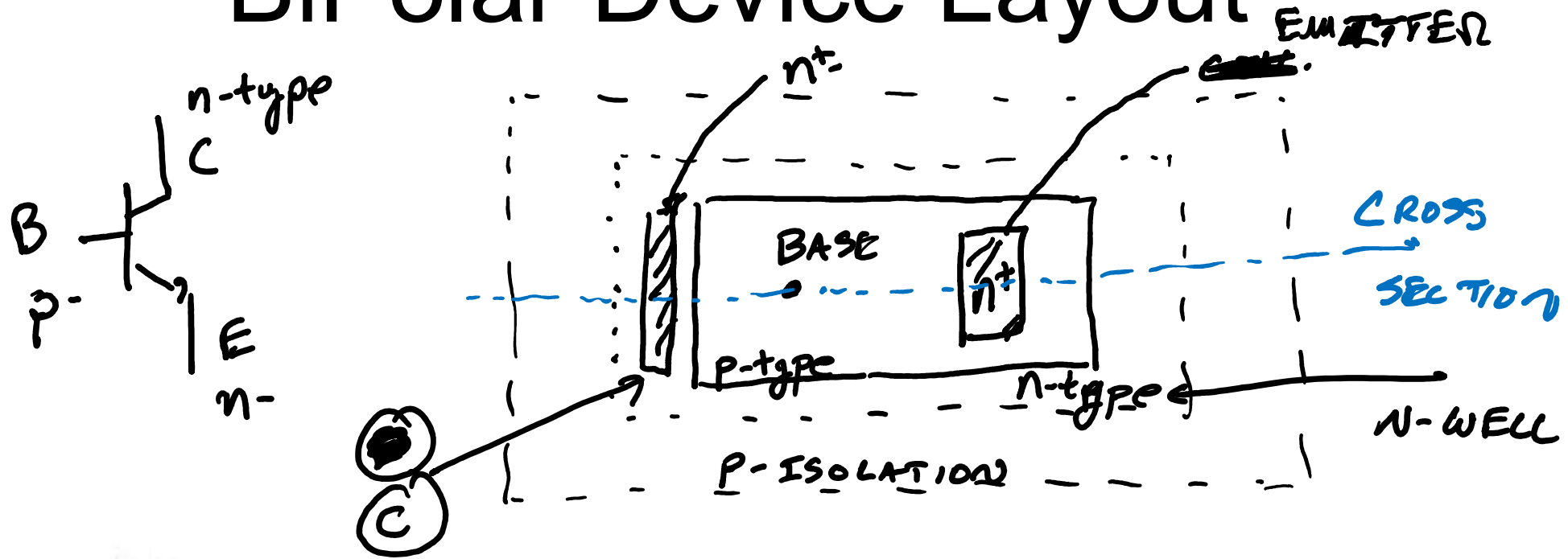
$$I_C = -(I_E + I_B) \quad I_C = -(I_E + I_B)$$

LARGE SIGNAL DC CURRENT

$$I_C = \frac{q A D_n n_{p0}}{W_B} \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$I_S = \frac{q A D_n n_{p0}}{W_B} \quad \begin{array}{l} \text{MINORITY} \\ \text{CARRIERS} \\ \text{IN} \\ \text{BASE} \end{array} \quad \left| \begin{array}{l} V_T = KT/q \\ V_T \approx 25 \text{ mV} \\ \text{at room} \\ \text{TEMP} \end{array} \right.$$

BiPolar Device Layout



Razavi Expressions for BJT Collector Current

FORWARD ACTIVE REGION.

@ ROOM TEMP.
300K

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

$$V_T = \frac{kT}{q} \approx 25 \text{ mV}$$

THERMAL VOLTAGE

$$I_s = \mu kT n_i^2$$

- μ : MOBILITY OF MINORITY CARRIERS

T : TEMP KELVIN

k : BOLT. CONSTANT

n_i^2 : INTRINSIC CARRIER CONCENTRATION

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

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

NOTE : T DEP.

$$E_g \approx \underline{1.12 \text{ eV}}$$

BAND GAP ENERGY IN SILICON.

Expressing V_{BE} and Temp Dependence

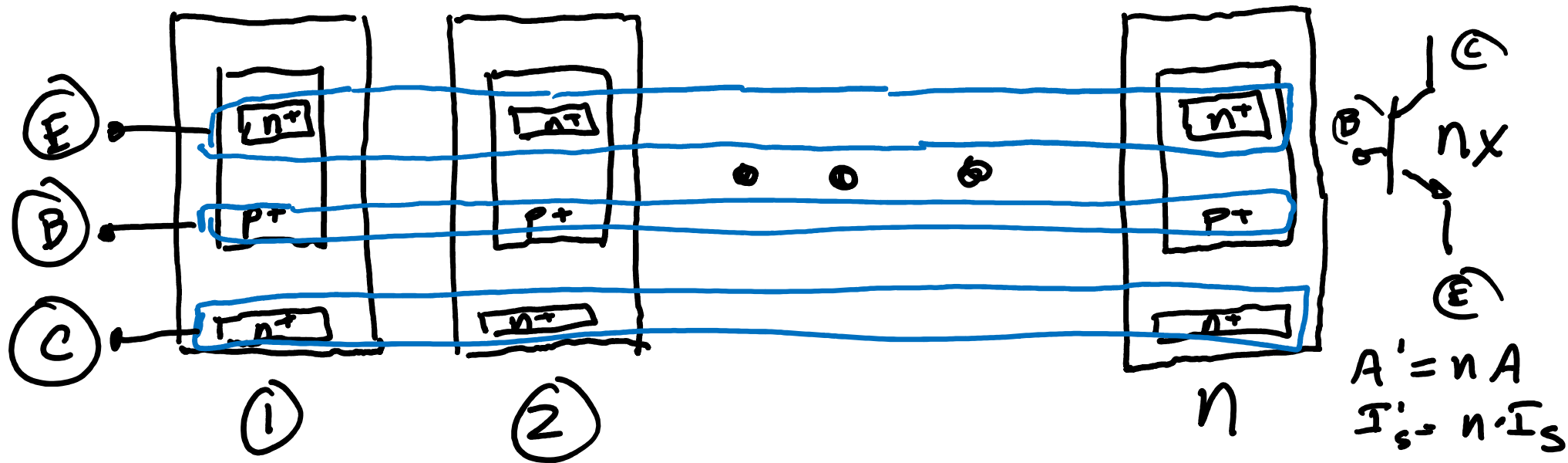
$$I_s = b T^{4+m} \exp\left(\frac{-E_g}{kT}\right)$$

\uparrow
constant.

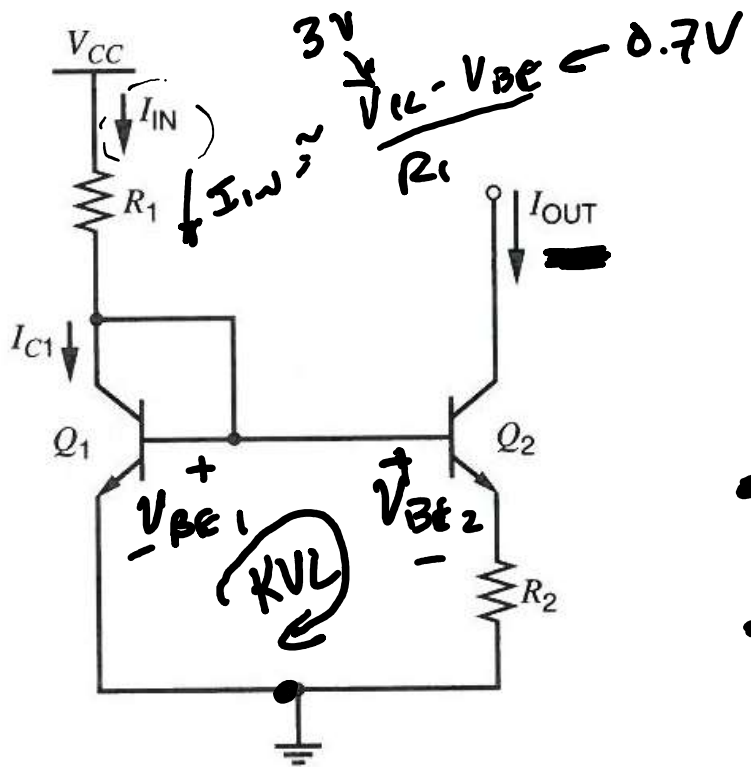
$$I_c = I_s \exp\left(\frac{V_{BE}}{V_T}\right)$$

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

BJT Device Layout



- No Control over area of a BJT Transistor (A) and width of the base (w_B). The device size and layout are fixed and part of your Process and Design Kit (PDK).
- Can layout multiple devices in parallel, then short the collector, base and emitters.



$$V_{BE2} < V_{BE1}$$

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

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

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

- ~~DO~~ 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 trial 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)

Our message to the competition is simple and straightforward.

We've had 11 years of quality, blue sky advertising. From now on, National Semiconductor is going to take on the rest of the semiconductor industry and let the chips fall where they may.

We're the second largest manufacturer by unit volume of every product category and we're going to let everyone know it.

We're also going to introduce some new products that will knock the competition right on their profit margins.

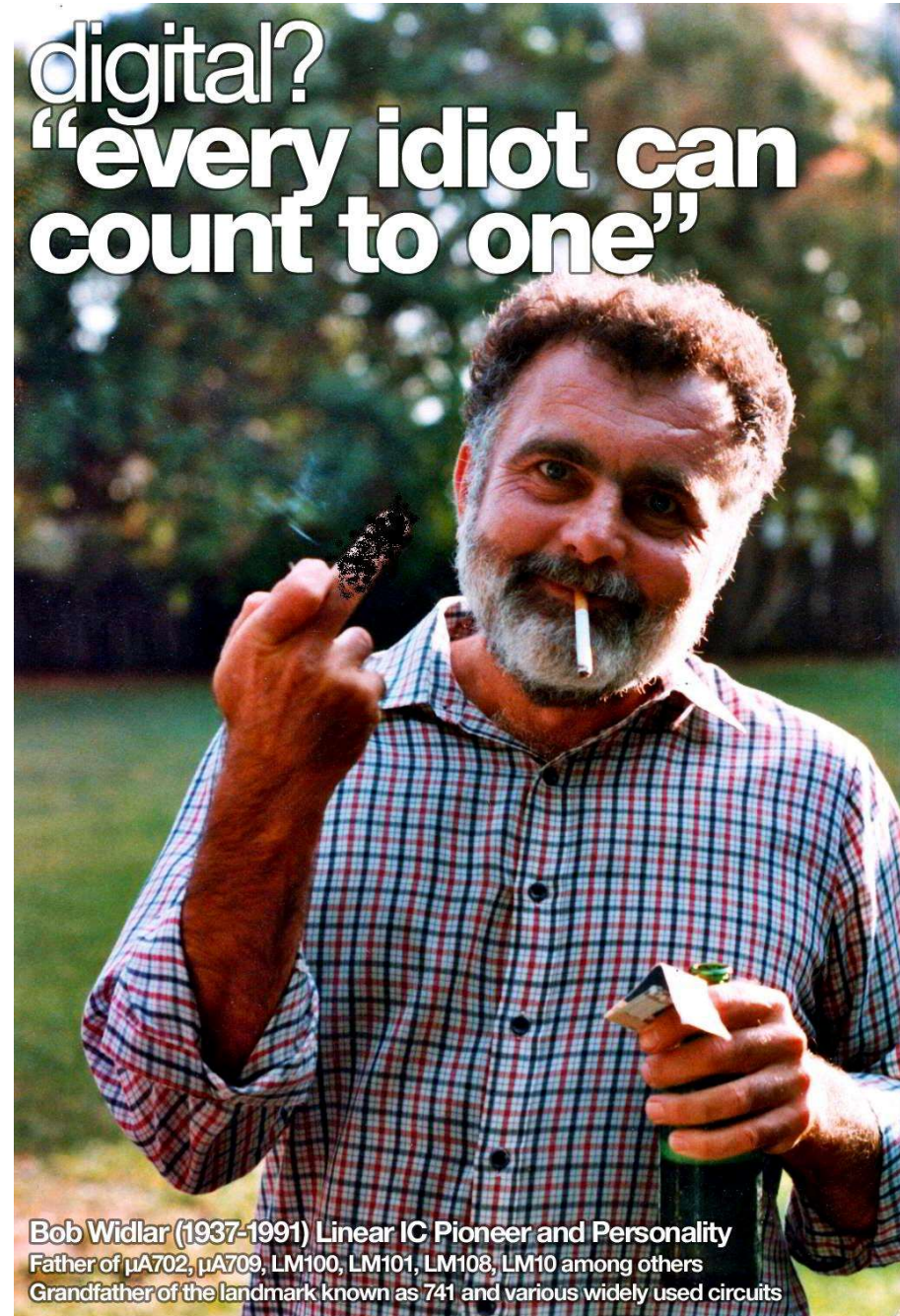
There are also a few things we're not going to do. We're not going to make a lot of products nobody needs. That's a guarantee.

We're not going to introduce a new line that doesn't get at least 100,000 units in the first year. That's a guarantee.

We're not going to introduce a product that's not going to be a market leader. That's a guarantee.

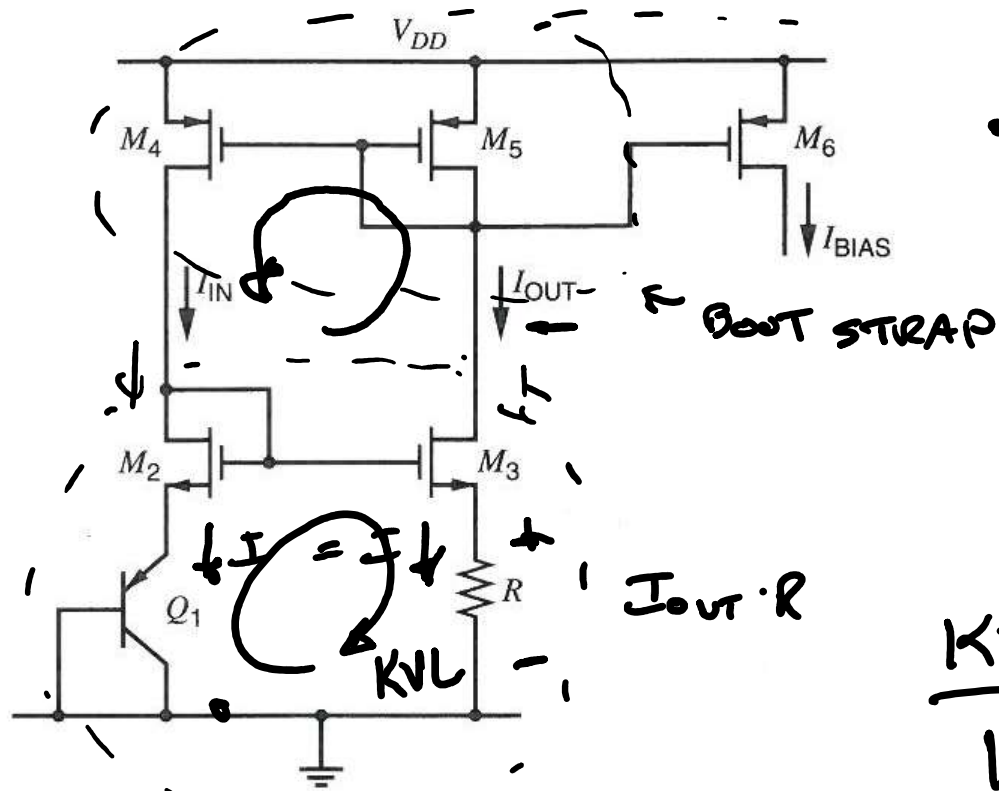
We're not going to introduce a product that's not going to be a market leader. That's a guarantee.

National



Bob Widlar (1937-1991) Linear IC Pioneer and Personality
Father of μ A702, μ A709, LM100, LM101, LM108, LM10 among others
Grandfather of the landmark known as 741 and various widely used circuits

CMOS Version of V_{BE} Referenced C-Source



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

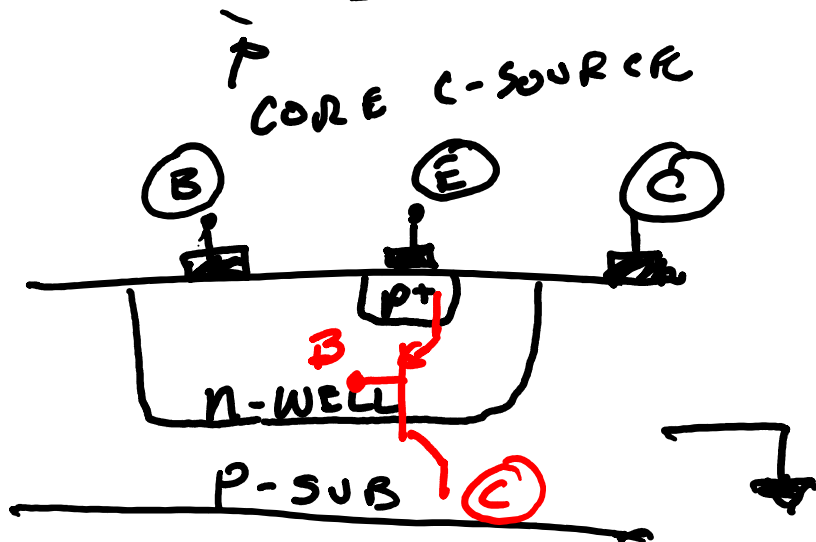
$$\underline{V_{GS2} = V_{GS3}}$$

KVL

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

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

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 $\mu k T n_i^2$, 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,

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

where b is proportionality factor