EE 435
Lecture 40

References
Types of References

• Voltage References
• Current References
• Time References
• ....
Voltage Reference

$V_{BIAS}$ → Voltage Reference Circuit → $V_{REF}$

$V_{REF}$
Current Reference

Current Reference Circuit

$V_{BIAS}$

$I_{REF}$

$I_{REF}$
Desired Properties of References

- Accurate
- Temperature Stable
- Time Stable
- Insensitive to $V_{BIAS}$
- Low Output Impedance (voltage reference)
- Floating
- Small Area
- Low Power Dissipation
- Process Tolerant
- Process Transportable
Desired Properties of References

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Similar properties desired in other references
Consider Voltage References

**Voltage Reference Circuit**

\[
I_{D1} = \frac{\mu C_{OX} W_1}{2 L_1} (V_{GS1} - V_{T1})^2 \\
I_{D2} = \frac{\mu C_{OX} W_2}{2 L_2} (V_{GS2} - V_{T2})^2 \\
V_{T1} = V_{T0} + \gamma \left( \sqrt{\phi + V_{REF}} - \sqrt{\phi} \right) \\
V_{DD} - V_{REF} - V_{T1} = \frac{W_2 L_1}{W_1 L_2} (V_{REF} - V_{T2})
\]

If matching assumed and \( \gamma \) effects neglected

\[
V_{DD} - V_{T0} \left( 1 - \frac{W_2 L_1}{\sqrt{W_1 L_2}} \right) \\
V_{REF} = \frac{1 + \frac{W_2 L_1}{\sqrt{W_1 L_2}}}{\frac{W_2 L_1}{\sqrt{W_1 L_2}}}
\]

**Popular Voltage “Reference”**

- \( V_{DD} \)
- \( M_1 \)
- \( V_{REF} \)
- \( M_2 \)
Consider Voltage References

Popular Voltage “Reference”

Uses as a reference limited to biasing and even for this may not be good enough!

If matching assumed and $\gamma$ effects neglected

$$V_{REF} = \frac{V_{DD} - V_{T0} \left(1 - \sqrt{\frac{W_2 L_1}{W_1 L_2}}\right)}{1 + \sqrt{\frac{W_2 L_1}{W_1 L_2}}}$$

Dependent upon $V_{DD}$, $V_{T0}$, matching, process variations, $\gamma$

Termed a $V_{DD}, V_T$ reference

Does not satisfy key properties of voltage references
Consider Voltage References

\[ V_{DD} - V_T \left( 1 - \frac{W_2 L_1}{W_1 L_2} \right) \]

\[ V_{REF} = \frac{V_{DD} - V_T}{\sqrt{\frac{W_2 L_1}{W_1 L_2}}} \]

Observation – Variables with units Volts needed to build any voltage reference
Voltage References

Observation – Variables with units Volts needed to build any voltage reference

What variables available in a process have units volts?

What variables which have units volts satisfy the desired properties of a voltage reference?

How can a circuit be designed that “expresses” the desired variables?
Voltage References

Observation – Variables with units Volts needed to build any voltage reference

What variables available in a process have units volts?

\( V_{DD}, V_T, V_{BE \ (diode)}, V_Z, V_{BE}, V_t \) ???

What variables which have units volts satisfy the desired properties of a voltage reference?

How can a circuit be designed that "expresses" the desired variables?
Voltage References

Consider the Diode

\[ I_D = J_S A e^{\frac{V_D}{V_t}} \]

\[ J_S = \tilde{J}_{SX} \left[ T^m e^{\frac{-V_{G0}}{V_t}} \right] \]

\[ V_t = \frac{kT}{q} \]

\[ k = \frac{1.38 \times 10^{-23}}{1.602 \times 10^{-19}} \text{ V } \text{K} = 8.614 \times 10^{-5} \text{ V } \text{K} \]

\[ V_{G0} = 1.206 \text{V} \]

termed the bandgap voltage

pn junction characteristics highly temperature dependent through both the exponent and \( J_S \)

\( V_{G0} \) is nearly independent of process and temperature
Voltage References

Observation – Variables with units Volts needed to build any voltage reference

What variables available in a process have units volts?

$V_{DD}$, $V_T$, $V_{BE}$ (diode), $V_Z$, $V_{BE}$, $V_t$, $V_{G0}$, ??

What variables which have units volts satisfy the desired properties of a voltage reference? $V_{G0}$ and ??

How can a circuit be designed that “expresses” the desired variables?

$V_{G0}$ is deeply embedded in a device model with horrible temperature effects! Good diodes are not widely available in most MOS processes!
Good diodes are not widely available in most MOS processes!
Voltage References

Good diodes are not widely available in most MOS processes!

These diodes interact and actually form substrate pnp transistor.

Not practical to forward bias junction.
Good diodes are not widely available in most MOS processes!
Voltage References

\[ I_C = J_S Ae^{\frac{V_{BE}}{V_t}} \]

\[ J_S = J_{Sx} \left[ T^m e^{\frac{-V_{G0}}{V_t}} \right] \]

\[ I_C(T) = \left( J_{Sx} A \left[ T^m e^{\frac{-V_{G0}}{V_t}} \right] \right) e^{\frac{V_{BE}(T)}{V_t}} \]

Bandgap Voltage Appears in BJT Model Equation as well
Voltage References

Voltage references that “express” the bandgap voltage are termed “Bandgap References”

$V_{G0}$ is deeply embedded in a device model with horrible temperature effects!

Good BJTs are not widely available in most MOS processes but the substrate pnp is available!
Standard Approach to Building Voltage References

Pick $K$ so that at some temperature $T_0$, 
\[ \left. \frac{\partial (X_N + KX_P)}{\partial T} \right|_{T=T_0} = 0 \]
Standard Approach to Building Voltage References

![Diagram showing voltage (V) as a function of temperature (T), with curves indicating positive and negative temperature coefficients.]

- Positive Temperature Coefficient
- Negative Temperature Coefficient
Standard Approach to Building Voltage References

\[ V = X_N + KX_P \]

\[ \left. \frac{\partial (X_N + KX_P)}{\partial T} \right|_{T=T_0} \]
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
I_C(T) = \left( \tilde{I}_{SX} \left[ T^m e^{-\frac{V_G}{V_t}} \right] \right) e^{\frac{V_{BE}(T)}{V_t}}
\]

\[
V_{BE} = V_t \ln(I_C) + \left[ V_{G0} - V_t \left( \ln \left( J_{SX} A_e \right) + m \ln T \right) \right]
\]

\[
V_{BE2} - V_{BE1} = \Delta V_{BE} = \left[ k \ln \left( \frac{I_{C2}}{I_{C1}} \right) \right] T
\]

If the $I_{C2}/I_{C1}$ ratio is constant, the TC of $\Delta V_{BE}$ is positive

$\Delta V_{BE}$ is termed a PTAT voltage (Proportional to Absolute Temperature)

This relationship applies irrespective of how temperature dependent $I_{C1}$ and $I_{C2}$ may be provided the ratio is constant !!
Consider two BJTs (or diodes)

\[ V_{BE2} - V_{BE1} = \Delta V_{BE} = \left[ \frac{k}{q} \ln \left( \frac{I_{C2}}{I_{C1}} \right) \right] T \]

\[ \frac{\partial (V_{BE2} - V_{BE1})}{\partial T} = \frac{k}{q} \ln \left( \frac{I_{C2}}{I_{C1}} \right) \]

At room temperature

\[ V_{BE2} - V_{BE1} = \left[ 8.6 \times 10^{-5} \times 300 \right] = 25.8 \text{mV} \]

If \( \ln(I_{C2}/I_{C1}) = 1 \)

\[ \left. \frac{\partial (V_{BE2} - V_{BE1})}{\partial T} \right|_{T = T_0 = 300^\circ K} = 8.6 \times 10^{-5} = 86 \mu V/\circ C \]

The temperature coefficient of the PTAT voltage is rather small
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
\frac{\partial (V_{BE2} - V_{BE1})}{\partial T} = \frac{k}{q} \ln \left( \frac{I_{C2}}{I_{C1}} \right)
\]

At room temperature

The temperature coefficient of the PTAT voltage is rather small even if large collector current ratios are used
Bandgap Voltage References

Consider two BJTs (or diodes)

\[
\begin{align*}
    I_C(T) &= I_{SX} \left[ T^m e^{-\frac{V_{G0}}{V_T}} \right] e^{\frac{V_{BE}(T)}{V_T}} \\
    V_{BE} &= V_t \ln(I_C) + \left[ V_{G0} - V_t \left( \ln(\tilde{J}_{SGA}) + m \ln(T) \right) \right]
\end{align*}
\]

If \( I_C \) is independent of temperature, it follows that

\[
\frac{\partial V_{BE}}{\partial T} = \frac{k}{q} \left[ -m + \left( \frac{V_{BE} - V_{G0}}{V_T} \right) \right] = 8.6 \times 10^{-5} \left[ -2.3 + \left( \frac{0.65 - 1.2}{25 \text{mV}} \right) \right] \approx -2.1 \text{mV/°C}
\]
Bandgap Voltage References

Consider two BJTs (or diodes)

\[ V_{BE1} - Q_1 - V_{BE2} - Q_2 \]

If \( I_C \) is independent of temperature, it follows that

\[
\frac{\partial V_{BE}}{\partial T} \bigg|_{T=T_0=300^\circ K} \approx 8.6 \times 10^{-5} \left[ -2.3 + \left( \frac{0.65-1.2}{25mV} \right) \right] \approx -2.1mV/^{\circ}C
\]

If \( \ln(I_{C2}/I_{C1})=1 \)

\[
\frac{\partial (V_{BE2} - V_{BE1})}{\partial T} \bigg|_{T=T_0=300^\circ K} = 8.6 \times 10^{-5} = 86\mu V/^{\circ}C
\]

Magnitude of TC of PTAT source is much smaller than that of \( V_{BE} \) source

If \( \frac{\partial (X_N + KX_P)}{\partial T} \bigg|_{T=T_0} = 0 \) \( K \) will be large

\[ X_{OUT} = X_N + KX_P \]