Clocked Comparator

Preamplifier with offset compensation and regenerative latch

Gain of preamplifier may still not be large enough
ADC Types

Nyquist Rate
- Flash
- Pipeline
- Two-Step Flash
- Multi-Step Flash
- Cyclic (algorithmic)
  - Successive Approximation
  - Folded
  - Dual Slope

Over-Sampled
- Single-bit
- Multi-bit
- First-order
- Higher-order
- Continuous-time

All have comparable conversion rates
Basic approach in all is very similar

Review from last lecture
Pipelined ADC Stage $k$

Pipeline Stage

$X_{IN_k} \rightarrow \text{ADC}_k \rightarrow \text{DAC}_k \rightarrow A_k \rightarrow S/H_k \rightarrow X_{OUT_k}$

$V_{REF} \rightarrow d_k \rightarrow n_k \rightarrow C_{LK}$
Pipelined ADC Stage $k$

Pipeline Stage

$X_{INk}$

$A_k$

$S/H_k$

$C_{LK}$

$X_{OUTk}$

Usually Realized as Single SC Block
1-bit/Stage Pipeline Implementation

\[ V_O = \begin{cases} 
2V_{IN} + \frac{V_{REF}}{2} & V_{IN} < 0 \\
2V_{IN} - \frac{V_{REF}}{2} & V_{IN} > 0 
\end{cases} \]
Cyclic (Algorithmic) ADC

- Re-use Pipelined Stage
- Small amount of hardware
- Effective thru-put decreases
References
Types of References

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

$X_{BIAS}$

$X_{REF}$
Voltage Reference

Voltage Reference Circuit

$V_{\text{BIAS}}$ $\rightarrow$ Voltage Reference Circuit $\rightarrow V_{\text{REF}}$

$V_{\text{REF}}$
Current Reference

\[ V_{BIAS} \rightarrow \text{Current Reference Circuit} \rightarrow I_{REF} \]
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

- Accurate
- Temperature Stable
- Time Stable
- Insensitive to $V_{\text{BIAS}}$
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- Small Area
- Low Power Dissipation
- Process Tolerant
- Process Transportable

Similar properties desired in other references
Consider Voltage References

![Diagram showing a Voltage Reference Circuit with transistors M1 and M2, and equations for current and voltage calculations.]

\[ I_{D1} = \frac{\mu C_{OX} W_1}{2L_1} (V_{GS1} - V_{T1})^2 \]
\[ I_{D2} = \frac{\mu C_{OX} W_2}{2L_2} (V_{GS2} - V_{T2})^2 \]
\[ V_{T1} = V_{T0} + \gamma \left( \sqrt{\phi + V_{REF}} - \sqrt{\phi} \right) \]
\[ V_{DD} - V_{REF} - V_{T1} = \frac{W_2L_1}{W_1L_2} (V_{REF} - V_{T2}) \]

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

\[ V_{DD} - V_{T0} \left( 1 - \sqrt[4]{\frac{W_2L_1}{W_1L_2}} \right) \]

\[ V_{REF} = \frac{1}{1 + \sqrt[4]{\frac{W_2L_1}{W_1L_2}}} \]
Consider Voltage References

If matching assumed and $\gamma$ effects neglected,

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

$$V_{REF} = \frac{1 + \sqrt{W_2 L_1}}{1 + \sqrt{W_1 L_2}}$$

Popular Voltage “Reference”

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

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

\[ V_{DD}, V_T \text{ reference} \]

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

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

What variables available in a process have units volts?

\[ V_{DD}, V_T, V_{BE \text{ (diode)}}, V_Z, V_{BE}, V_t, \ldots \]

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?
Consider the Diode

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

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

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

\[ k = 1.38 \times 10^{-23} \] \( \text{J/K} \)
\[ q = 1.602 \times 10^{-19} \] \( \text{C} \)
\[ V = 8.614 \times 10^{-5} \] \( \text{V/°K} \)

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

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?

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

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!
Voltage References

Good diodes are not widely available in most MOS processes!
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

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

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

\[ I_C(T) = \left( \tilde{J}_{SX} A \left[ T^m e^{\frac{-V_{G0}}{V_t}} \right] \right) e^{\frac{V_{BE}(T)}{V_t}} \]

Bandgap Voltage Appears in BJT Model Equation as well
Voltage references 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 $T_0$, \[ \frac{\partial (X_N + KX_P)}{\partial T} \bigg|_{T=T_0} = 0 \]
Standard Approach to Building Voltage References

![Diagram showing the relationship between voltage (V) and temperature (T). The curve indicates a negative temperature coefficient at lower temperatures and a positive temperature coefficient at higher temperatures, with a reference temperature (T₀).]
Standard Approach to Building Voltage References

\[ V(T) = X_N + K X_P \]

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

Consider two BJTs (or diodes)

\[ I_c(T) = \left( \tilde{I}_{sx} \left[ T^m e^{\frac{-V_{G0}}{V_t}} \right] e^{\frac{V_{BE}(T)}{V_t}} \right) \]

\[ V_{BE} = V_t \ln(I_c) + [V_{G0} - V_t \left( \ln(\tilde{J}_{sx} A_e) + m \ln T \right)] \]

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

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 !!
Bandgap Voltage References

Consider two BJTs (or diodes)

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

At room temperature

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

If \( \ln \left( \frac{I_{C2}}{I_{C1}} \right) = 1 \)

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

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)

\[
I_C(T) = I_{SX} \left[ T^m e^{\frac{-V_G_0}{V_t}} \right] e^{\frac{V_{BE}(T)}{V_t}}
\]

\[
V_{BE} = V_t \ln(I_C) + \left[ V_{G_0} - V_t \left( \ln(\tilde{J}_{SX} A_e) + m \ln T \right) \right]
\]

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

\[
\frac{\partial V_{BE}}{\partial T} = \frac{k}{q} \left[ -m + \left( \frac{V_{BE} - V_{G_0}}{V_t} \right) \right]
\]

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

Consider two BJTs (or diodes)

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

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

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

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

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

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

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

\[ X_{OUT} = X_N + KX_P \]
Bandgap Voltage References

Consider two BJTs (or diodes)

\[ V_{BE} = V_t \ln(I_C) + \left[ V_{G0} - V_t \left( \ln \left( \tilde{J}_{SX} A_E \right) + m \ln T \right) \right] \]

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

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

Rewriting \( V_{BE} \) equation

\[ V_{BE} = V_{G0} + \left( V_t \ln(I_C) + \left[ m \ln T - V_t \left( \ln \left( \tilde{J}_{SX} A_E \right) \right) \right] \right) \]

If \( I_C \) is reasonably independent of temperature, \( V_{BE} \) will still provide a negative TC
Bandgap Reference Circuits

- Circuits that implement $\Delta V_{BE}$ and $V_{BE}$ or $\Delta V_D$ and $V_D$ widely used to build bandgap references
$V_{BE}$ and $\Delta V_{BE}$ with constant $I_C$
$V_{BE}$ plot for constant $I_C$
Comparison of $V_{BE}$ with constant current and PTAT current

![Graph showing comparison of $V_{BE}$ with constant current and PTAT current.](attachment:image.png)
First Bandgap Reference (and still widely used!)

End of Lecture 43