Introduction to Bandgap Reference Generators

Lecture Notes for

ELEN 689-602

by

Fikret Dülger

Temperature-Independent References

- Reference voltages and/or currents with little dependence to temperature prove useful in many analog circuits.

- As many process parameters vary with temperature, if a reference is temperature-independent, it is usually process-independent, as well.

- If two quantities with opposite temperature coefficient are added with proper weighting, the resultant quantity theoretically exhibits zero temperature coefficient.

Temperature-Independent References

- For V_1 and V_2 with opposite temperature dependence, the coefficients c_1 and c_2 can be chosen in such a way that

$$c_1 \frac{\partial V_1}{\partial T} + c_2 \frac{\partial V_2}{\partial T} = 0.$$

  Thus, the reference voltage $V_{ref}=c_1V_1+c_2V_2$ exhibits zero temperature coefficient.
- Among various devices in the semiconductor technology, the characteristics of the bipolar transistors have proven the most reproducible and well-defined quantities that provide positive and negative temperature coefficients.

Bandgap Voltage Reference

- The most popular technique for both Bipolar and CMOS technologies.

- Generates a fixed dc reference voltage that does not change with temperature.

- Cancels the negative temperature dependence of a PN junction with a positive temperature dependence from a PTAT (proportional-to-absolute-temperature) circuit.

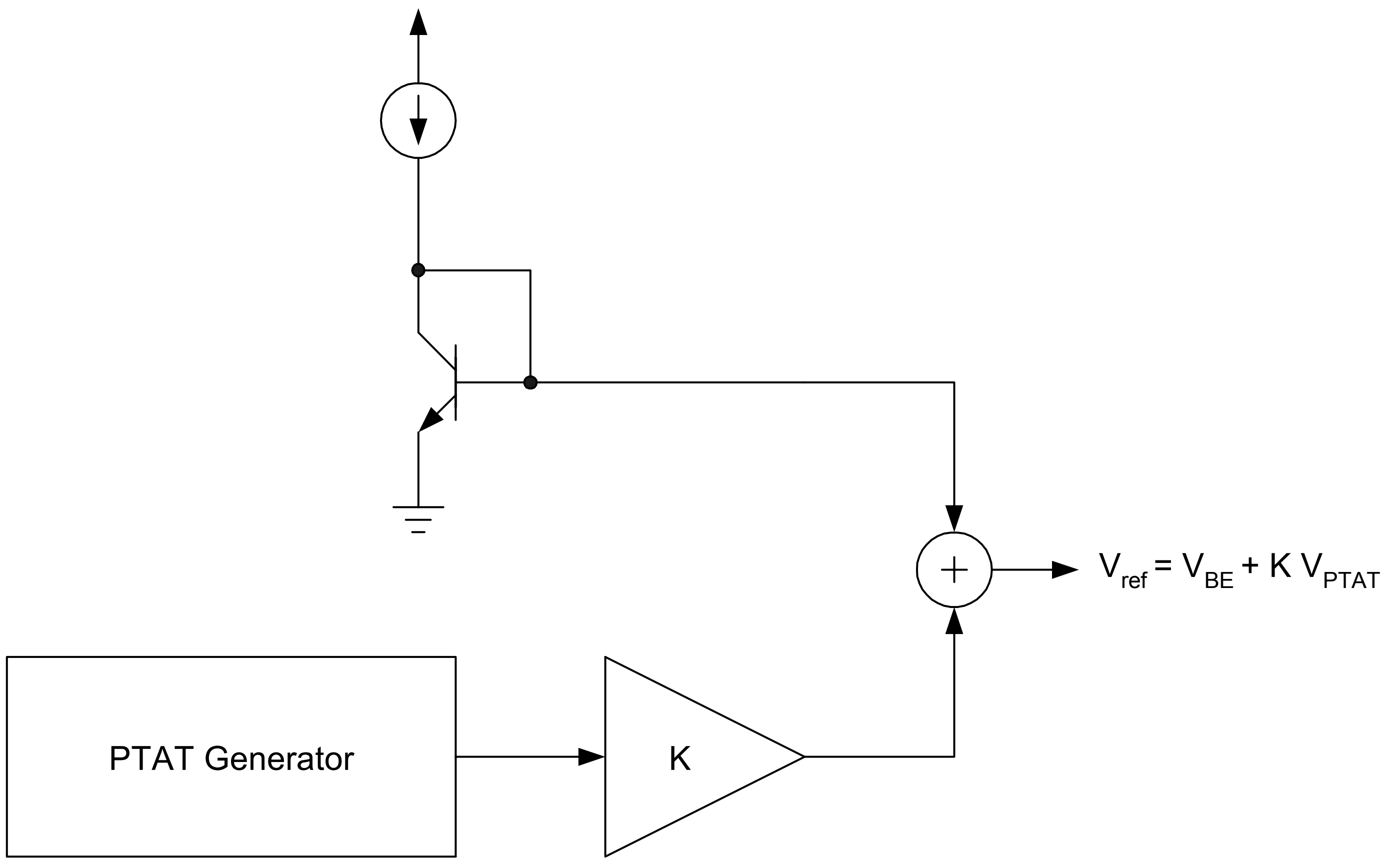
Bandgap Voltage Reference

- The term with negative temperature dependence is the forward-biased voltage of a diode (usually base-emitter junction).
- The PTAT term is realized by amplifying the voltage difference of two forward-biased diodes (i.e., base-emitter junctions).

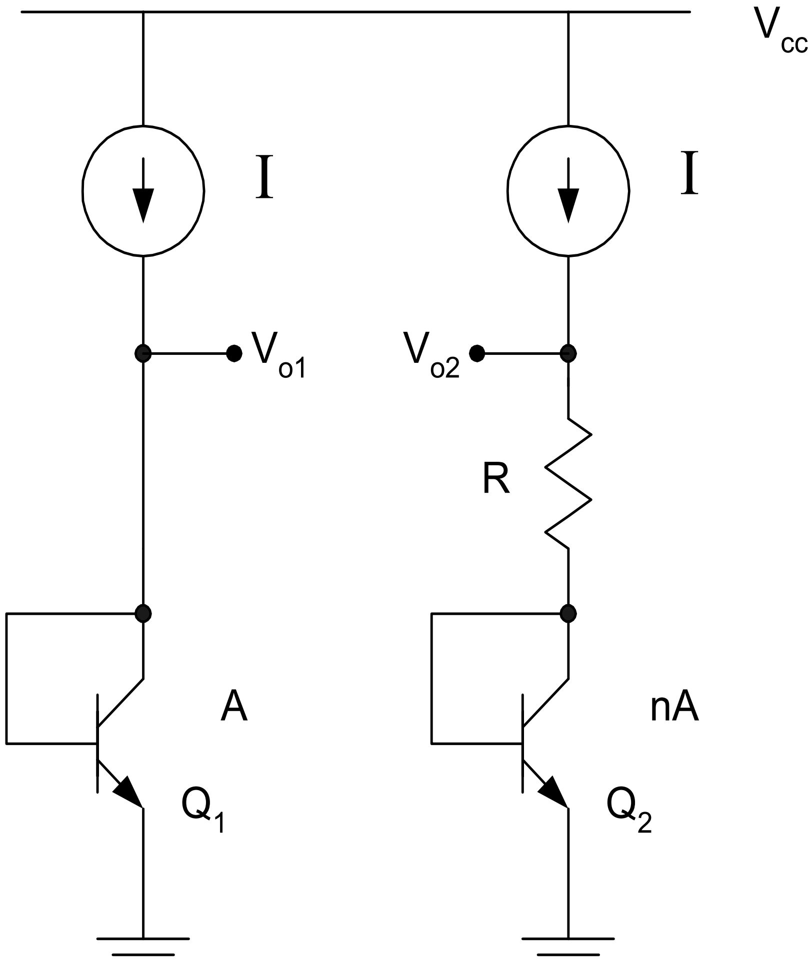
$$V_{ref} = V_{BE} + K.V_{PTAT}$$

- Exact Cancellation of the dependence of V_{ref} to temperature is not possible because of component tolerances and second order effects such as the nonlinearity of the dependence of VBE on temperature.

Bandgap Voltage Reference

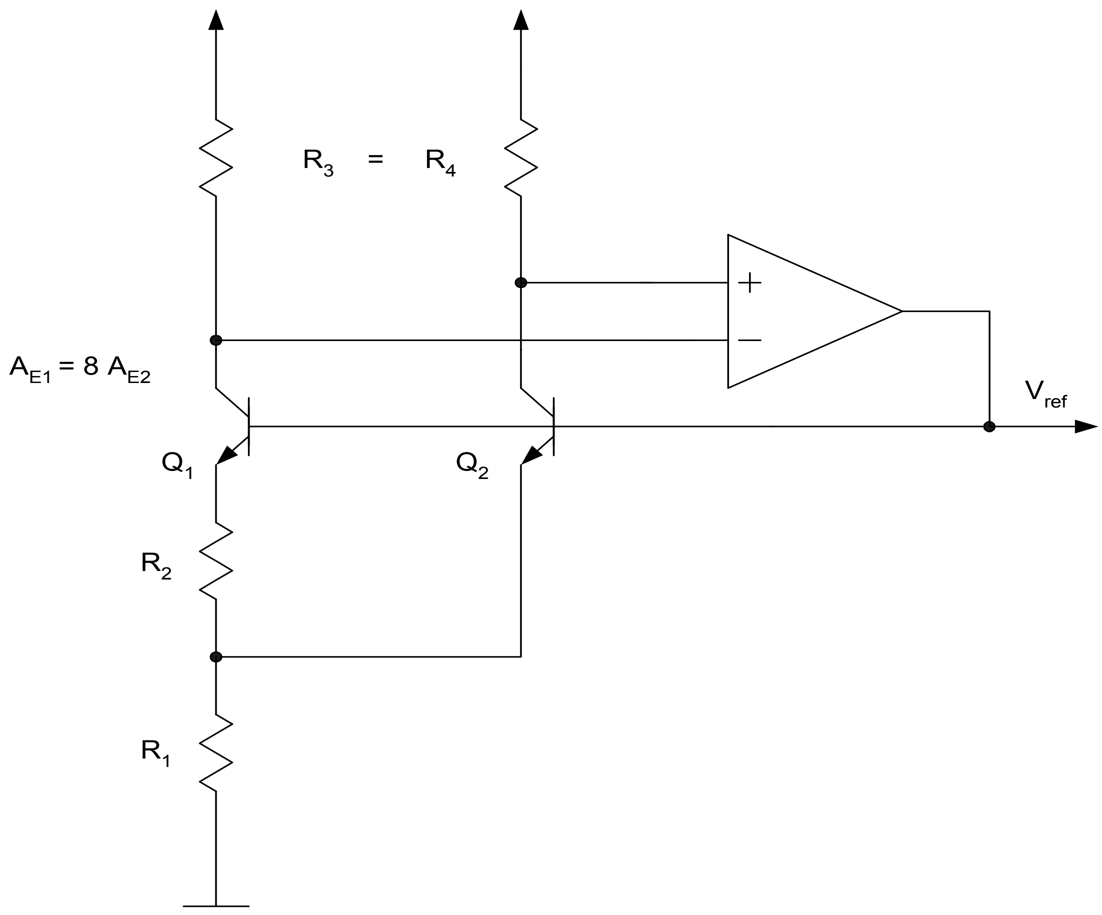


Bandgap Voltage Reference



- Conceptual generation of temperature-independent voltage, [3].
- Q_2 consists of n unit transistors in parallel, whereas Q_1 is a unit transistor.
- Somehow forcing V_{o1} to be equal to V_{o2}, the voltage drop on R is determined with the difference of the V_{BE} voltages of the transistors. This suggests that V_{o2} can serve as a temperature-independent reference with proper design.

Bandgap Voltage Reference
Brokaw's Circuit



Bandgap Voltage Reference

- The analysis follows:

$$V_{CQ_1} = V_{CQ_2},\ R_3 = R_4,\ A_{EQ_1} = 8\,A_{EQ_2} \Rightarrow \frac{J_{C1}}{J_{C2}} = \frac{1}{8}$$

$$V_{ref} = V_{BE2} + V_{R1}$$

$$V_{R1} = I_{R1}R_1 = 2I_{R2}R_1 = 2\frac{V_{R2}}{R_2}R_1$$

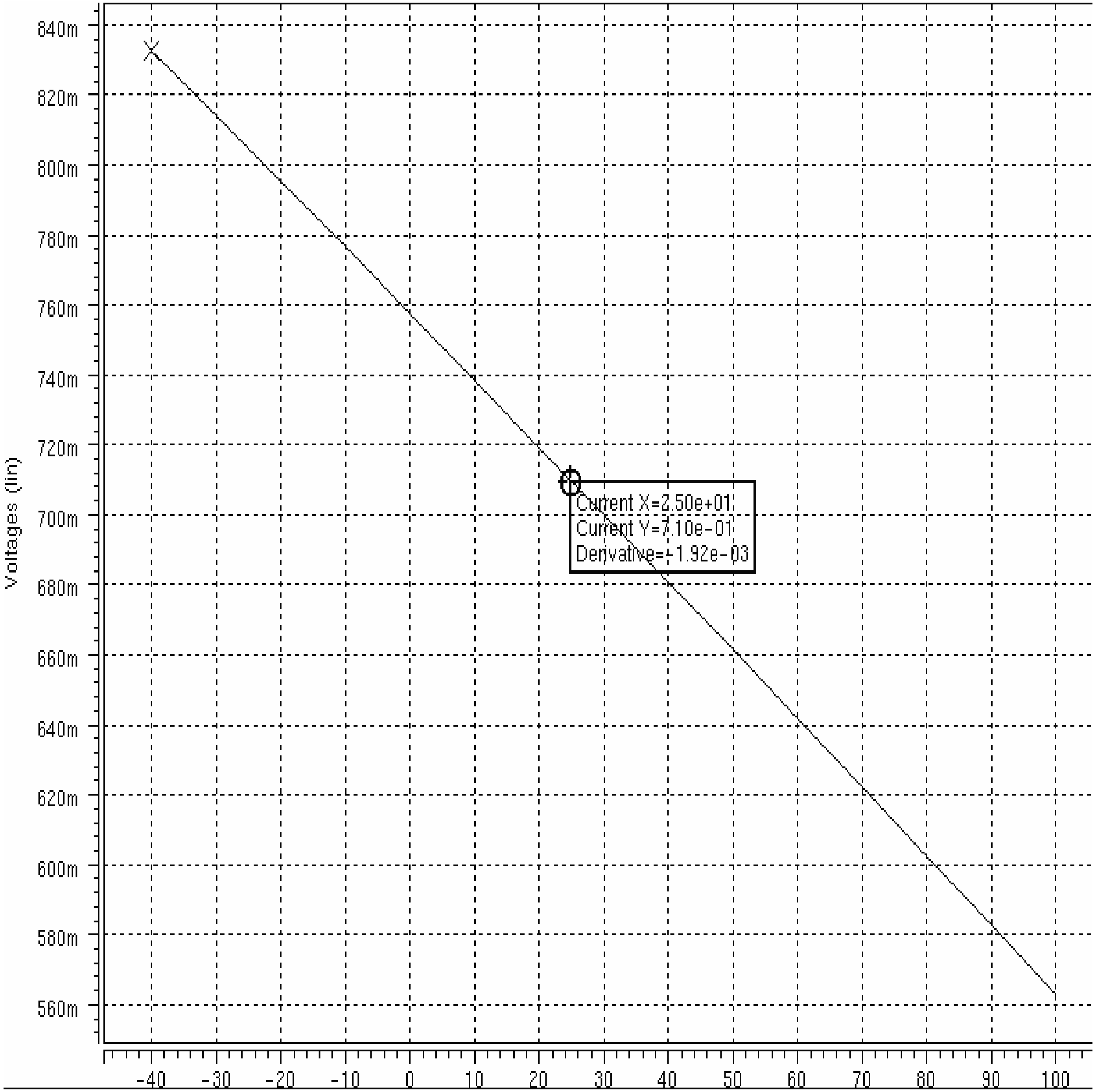
$$V_{R2} = V_{BE2} - V_{BE1} = \Delta V_{BE} = V_T \ln\left(\frac{J_{C2}}{J_{C1}}\right)$$

$$\Rightarrow V_{ref} = V_{BE2} + 2\frac{R_1}{R_2}V_T \ln\left(\frac{J_{C2}}{J_{C1}}\right)$$

Bandgap Voltage Reference

- In CMOS technologies, where the independent bipolar transistors are not available, parasitic bipolar transistors are used.
- Vertical well transistors are preferred, but lateral transistors (with lower β_F) can also be used. High base resistance limits the maximum collector currents through the transistors to be less than 0.1mA.
- Realization of PTAT voltage from the difference of the source-gate voltages of two MOS transistors biased in weak inversion is also reported in the literature.

Hspice Simulations

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* HSPICE deck for Vbe Temperature
* Coefficient at constant Ic=100uA

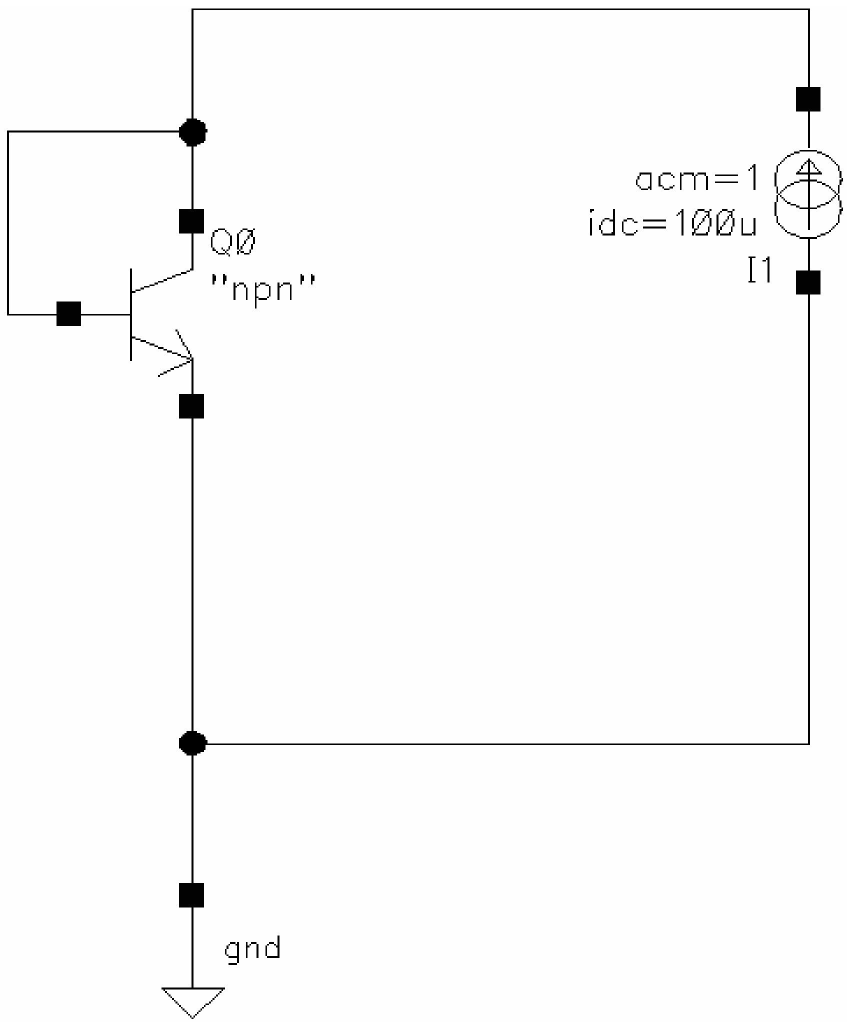
Q1 c c gnd gnd mod

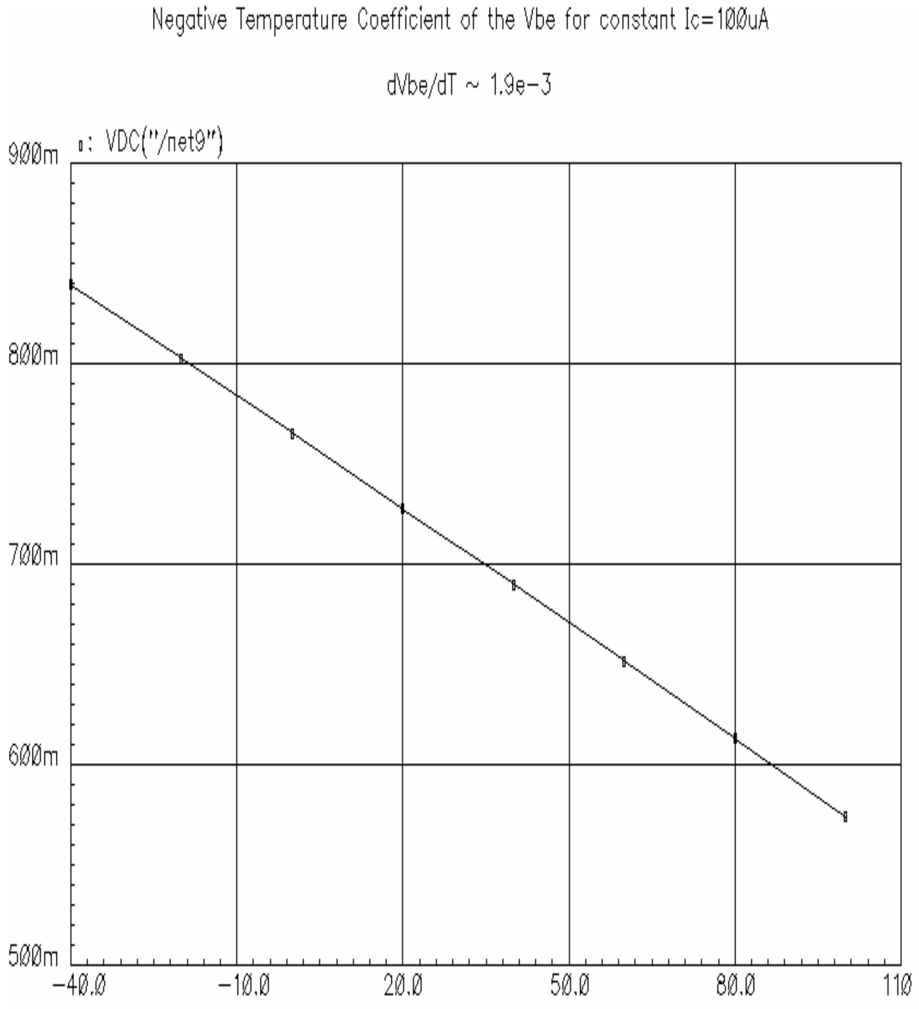
Ic vdd c dc 100e-6

Vdd vdd gnd 2.5

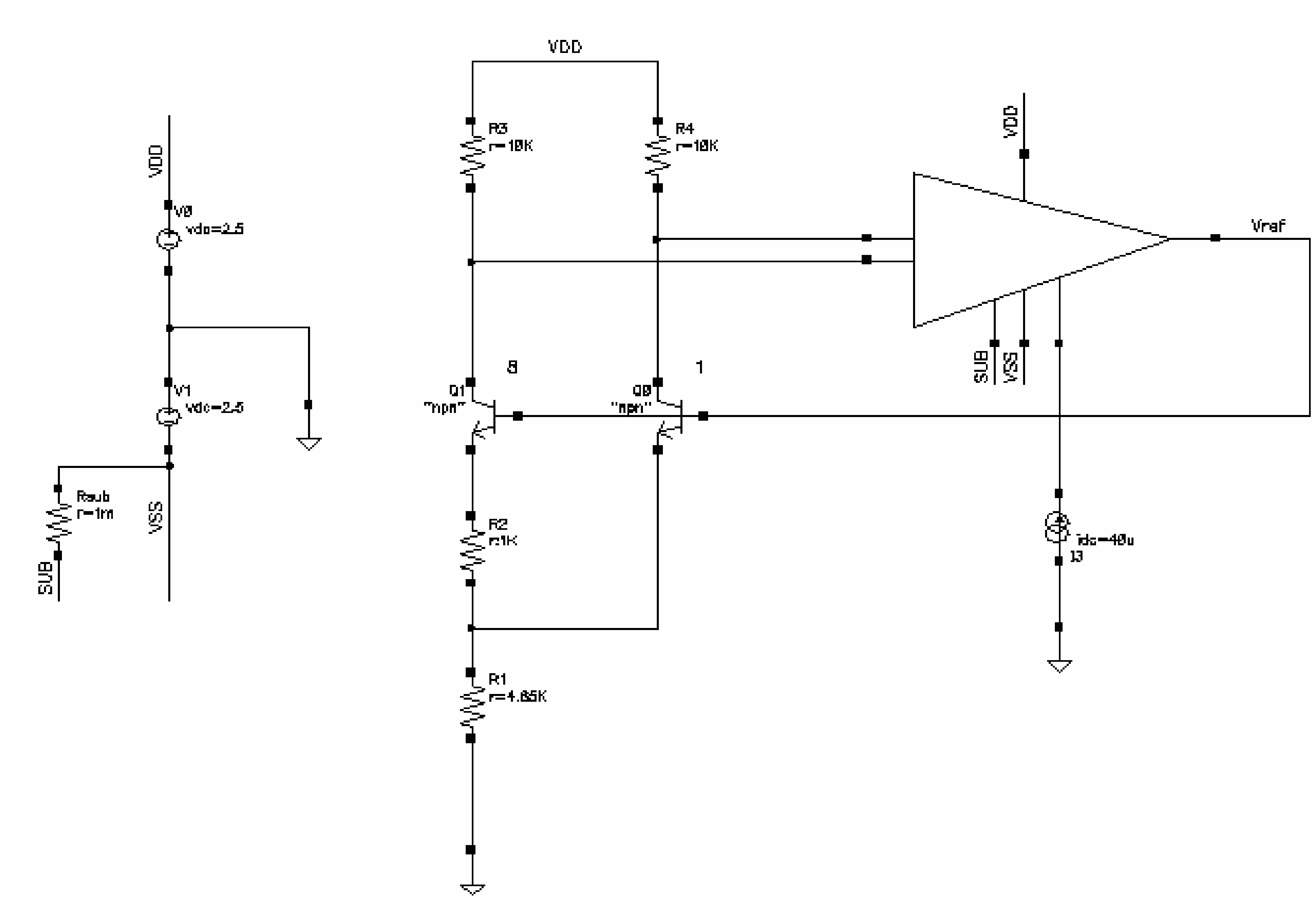
.model mod npn BF=111 VAF=74 EG=1.2058
.option post
.op
*.dc Ic 10e-6 200e-6 10e-6
.dc sweep temp -40 100 10
.end
```

SpectreS Simulations

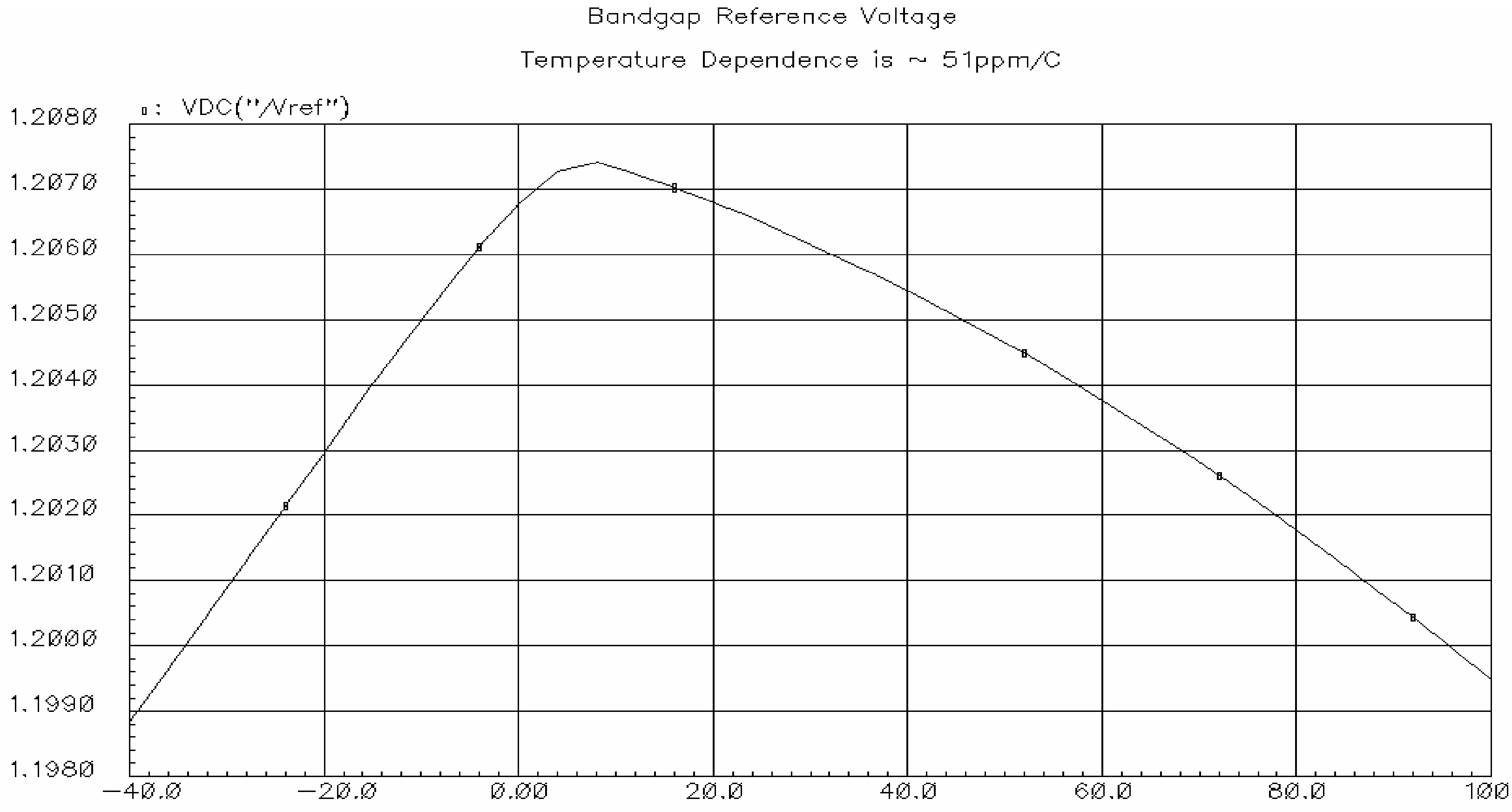




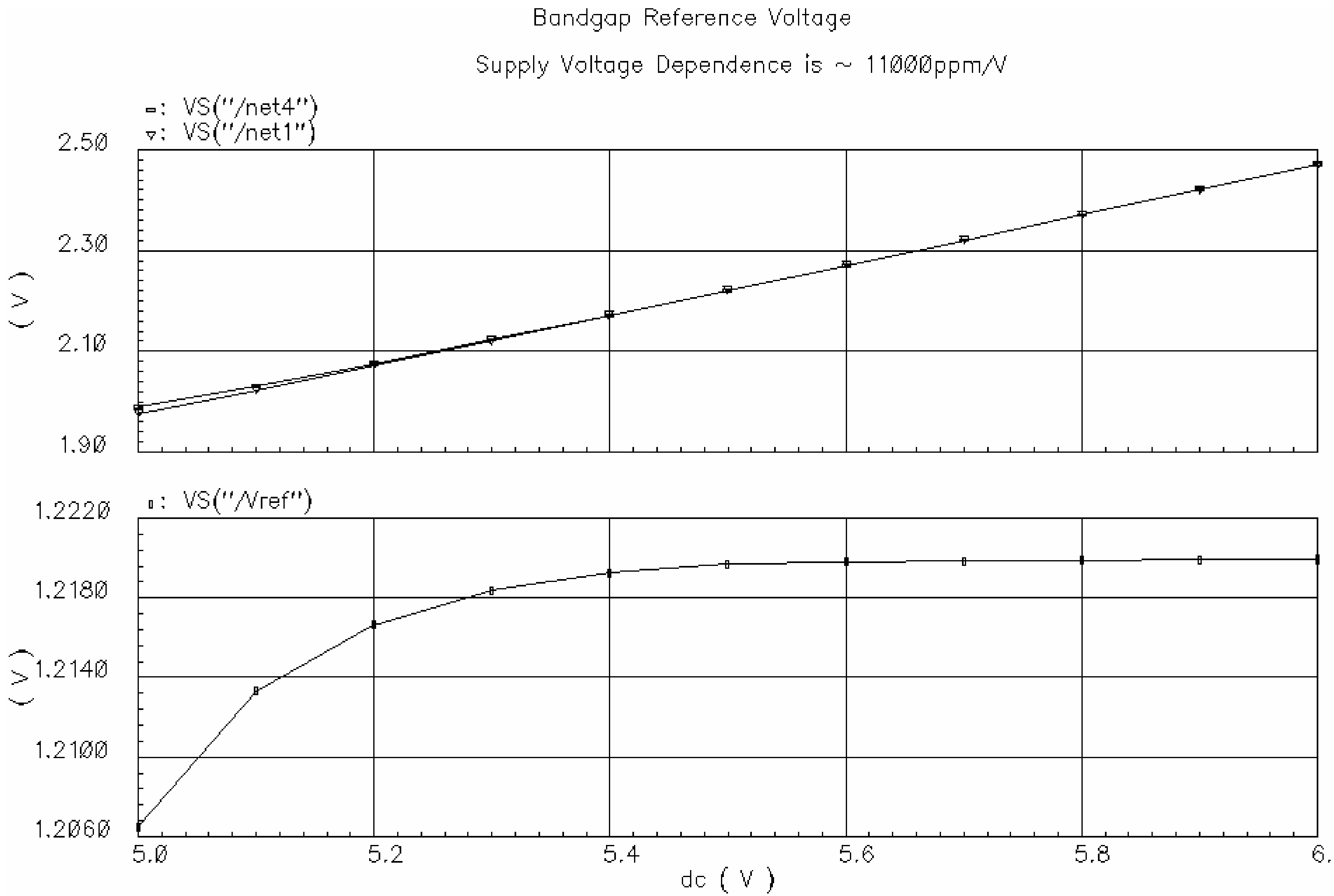
SpectreS Simulations



SpectreS Simulations



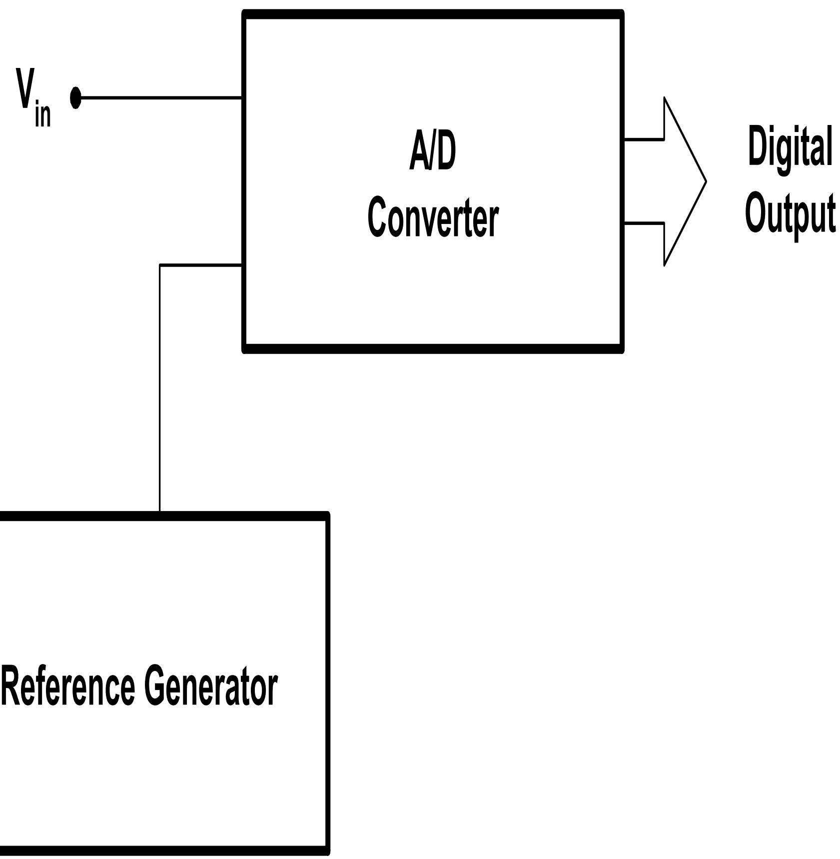
SpectreS Simulations



Noise Considerations

- Bandgap reference generator introduces noise, as it is the case for all the electronic circuits.
- Noise can be reduced by minimizing the number of components and using small value resistors.
- If MOS devices operating in weak inversion are used, p-channel MOS devices should be preferred due to their lower *1/f* noise. Increasing the area of the devices also helps.

Noise Considerations



- Conceptual illustration of effect of reference generator noise on the performance of an analog circuit, [3].
- The performance of a high-precision A/D converter, which uses references generated from a bandgap reference to compare its analog input, may considerably be degraded by the output noise of the bandgap reference generator.

References

- [1] D.A.Johns, K.Martin, Analog Integrated Circuit Design, John Wiley & Sons, Inc., 1997.
- [2] R. L. Geiger, P. E. Allen, N. R. Strader, VLSI Design Techniques for Analog and Digital Circuits, McGraw-Hill, Inc., 1990.
- [3] B.Razavi, Design of Analog CMOS Integrated Circuits, McGraw-Hill, Inc., 2000.
- [4] T.H.Lee, The Design of CMOS Radio-Frequency Integrated Circuits, Cambridge University Press, 1998.