

1.2V Reference

National Semiconductor
Application Note 56



INTRODUCTION

Temperature compensated zener diodes are the most easily used voltage reference. However, the lowest voltage temperature-compensated zener is 6.2V. This makes it inconvenient to obtain a zero temperature-coefficient reference when the operating supply voltage is 6V or lower. With the availability of the LM113, this problem no longer exists.

The LM113 is a 1.2V temperature compensated shunt regulator diode. The reference is synthesized using transistors and resistors rather than a breakdown mechanism. It provides extremely tight regulation over a wide range of operating currents in addition to unusually low breakdown voltage and low temperature coefficient.

DESIGN CONCEPTS

The reference in the LM113 is developed from the highly-predictable emitter-base voltage of integrated transistors. In its simplest form, the voltage is equal to the energy-band-gap voltage of the semiconductor material. For silicon, this is 1.205V. Further, the output voltage is well determined in a production environment.

A simplified version of this reference¹ is shown in Figure 1. In this circuit, Q₁ is operated at a relatively high current density. The current density of Q₂ is about ten times lower, and the emitter-base voltage differential (ΔV_{BE}) between the two devices appears across R₃. If the transistors have high current gains, the voltage across R₂ will also be proportional to ΔV_{BE} . Q₃ is a gain stage that will regulate the output at a voltage equal to its emitter base voltage plus the drop across R₂. The emitter base voltage of Q₃ has a negative temperature coefficient while the ΔV_{BE} component across R₂ has a positive temperature coefficient. It will be shown that the output voltage will be temperature compensated when the sum of the two voltages is equal to the energy-band-gap voltage.

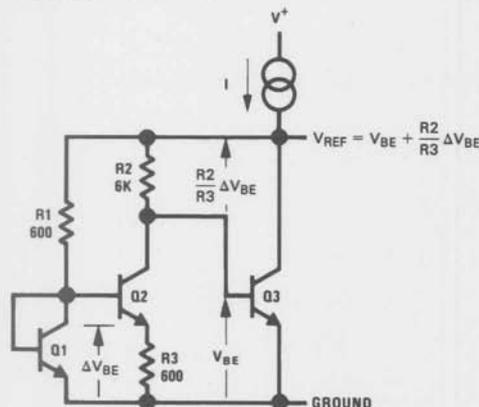


FIGURE 1. The Low Voltage Reference
in One of Its Simpler Forms

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Conditions for temperature compensation can be derived starting with the equation for the emitter-base voltage of a transistor which is²

$$V_{BE} = V_{g0} \left(1 - \frac{T}{T_0} \right) + V_{BE0} \left(\frac{T}{T_0} \right) + \frac{nkT}{q} \log_e \frac{T_0}{T} + \frac{kT}{q} \log_e \frac{I_C}{I_{C0}} \quad (1)$$

where V_{g0} is the extrapolated energy-band-gap voltage for the semiconductor material at absolute zero, q is the charge of an electron, n is a constant which depends on how the transistor is made (approximately 1.5 for double-diffused, NPN transistors), k is Boltzmann's constant, T is absolute temperature, I_C is collector current and V_{BE0} is the emitter-base voltage at T_0 and I_{C0} .

The emitter-base voltage differential between two transistors operated at different current densities is given by

$$\Delta V_{BE} = \frac{kT}{q} \log_e \frac{J_1}{J_2} \quad (2)$$

where J is current density.

Referring to Equation (1), the last two terms are quite small and are made even smaller by making I_C vary as absolute temperature. At any rate, they can be ignored for now because they are of the same order as errors caused by non-theoretical behavior of the transistors that must be determined empirically.

If the reference is composed of V_{BE} plus a voltage proportional to ΔV_{BE} , the output voltage is obtained by adding (1) in its simplified form to (2):

$$V_{ref} = V_{g0} \left(1 - \frac{T}{T_0} \right) + V_{BE0} \left(\frac{T}{T_0} \right) + \frac{kT}{q} \log_e \frac{J_1}{J_2} \quad (3)$$

Differentiating with respect to temperature yields

$$\frac{\partial V_{ref}}{\partial T} = -\frac{V_{g0}}{T_0} + \frac{V_{BE0}}{T_0} + \frac{k}{q} \log_e \frac{J_1}{J_2} \quad (4)$$

For zero temperature drift, this quantity should equal zero, giving

$$V_{g0} = V_{BE0} + \frac{kT_0}{q} \log_e \frac{J_1}{J_2} \quad (5)$$

The first term on the right is the initial emitter-base voltage while the second is the component proportional to emitter-base voltage differential. Hence, if the sum of the two are equal to the energy-band-gap voltage of the semiconductor, the reference will be temperature-compensated.

Figure 2 shows the actual circuit of the LM113. Q₁ and Q₂ provide the ΔV_{BE} term and Q₄ provides the V_{BE} term as in the simplified circuit. The additional transistors are used to decrease the dynamic resistance, improving the regulation of the reference against current changes. Q₃ in conjunction with current inverter, Q₅ and Q₆, provide a current source load for Q₄ to achieve high gain.

Q₇ and Q₉ buffer Q₄ against changes in operating current and give the reference a very low output resistance. Q₈ sets the minimum operating current of Q₇ and absorbs any leak-

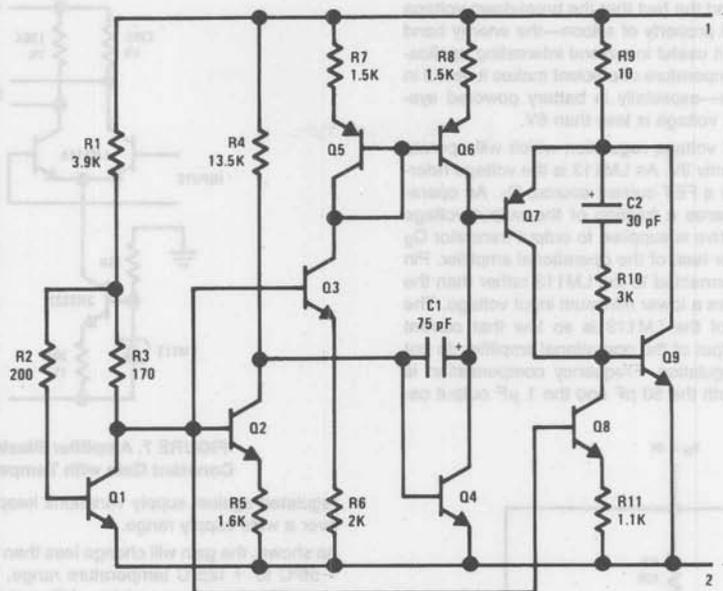


FIGURE 2. Schematic of the LM113

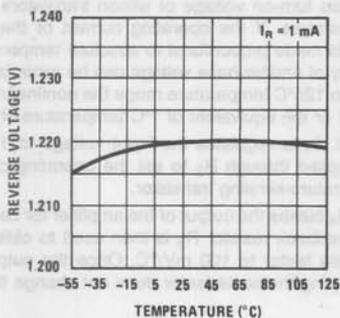
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age from Q₉. Capacitors C₁, C₂ and resistors R₉ and R₁₀ frequency compensate the regulator diode.

PERFORMANCE

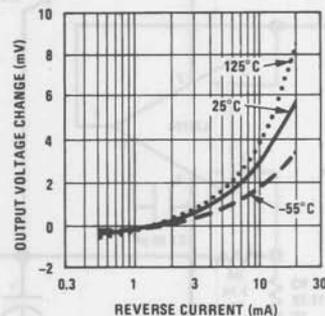
The most important features of the regulator diode are its good temperature stability and low dynamic resistance. Figure 3 shows the typical change in output voltage over a -55°C to +125°C temperature range. The reference voltage changes less than 0.5% with temperature, and the temperature coefficient is relatively independent of operating current.

Figure 4 shows the output voltage change with operating current. From 0.5 mA to 20 mA there is only 6 mV of change. A good portion of the output change is due to the resistance of the aluminum bonding wires and the Kovar leads on the package. At currents below about 0.3 mA the diode no longer regulates. This is because there is insufficient current to bias the internal transistors into their active region. Figure 5 illustrates the breakdown characteristic of the diode.



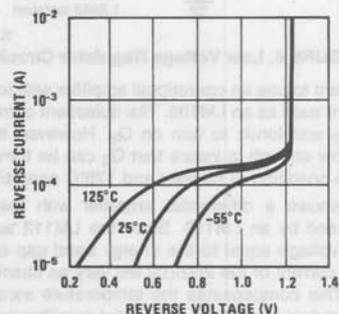
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FIGURE 3. Output Voltage Change with Temperature



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FIGURE 4. Output Voltage Change with Current



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FIGURE 5. Reverse Breakdown Characteristics

APPLICATIONS

The applications for zener diodes are so numerous that no attempt to delineate them will be made. However, the low

breakdown voltage and the fact that the breakdown voltage is equal to a physical property of silicon—the energy band gap voltage—makes it useful in several interesting applications. Also the low temperature coefficient makes it useful in regulator applications—especially in battery powered systems where the input voltage is less than 6V.

Figure 6 shows a 2V voltage regulation which will operate on input voltages of only 3V. An LM113 is the voltage reference and is driven by a FET current source, Q_1 . An operational amplifier compares a fraction of the output voltage with the reference. Drive is supplied to output transistor Q_2 through the V^+ power lead of the operational amplifier. Pin 6 of the op amp is connected to the LM113 rather than the output since this allows a lower minimum input voltage. The dynamic resistance of the LM113 is so low that current changes from the output of the operational amplifier do not appreciably affect regulation. Frequency compensation is accomplished with both the 50 pF and the 1 μ F output capacitor.

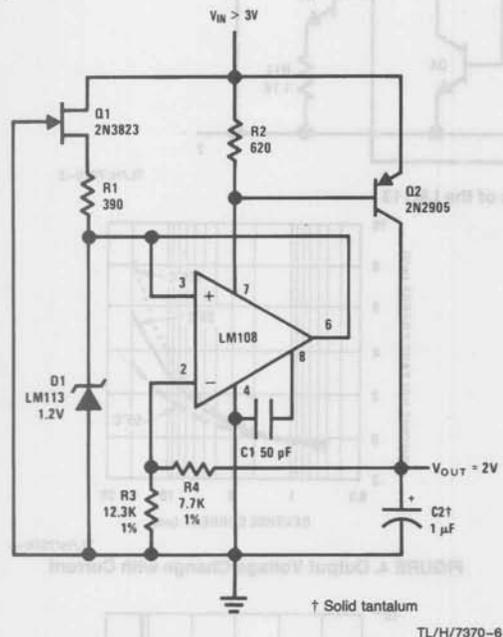


FIGURE 6. Low Voltage Regulator Circuit

It is important to use an operational amplifier with low quiescent current such as an LM108. The quiescent current flows through R_2 and tends to turn on Q_2 . However, the value shown is low enough to insure that Q_2 can be turned off at worst case condition of no load and 125°C operation.

Figure 7 shows a differential amplifier with the current source biased by an LM113. Since the LM113 supplies a reference voltage equal to the energy band gap of silicon, the output current of the 2N2222 will vary as absolute temperature. This compensates the temperature sensitivity of the transconductance of the differential amplifier making the gain temperature stable. Further, the operating current is

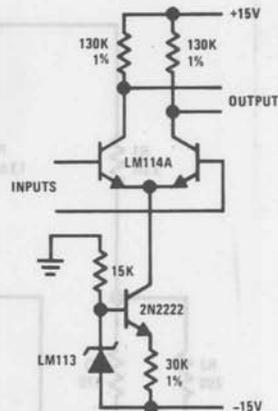


FIGURE 7. Amplifier Biasing for Constant Gain with Temperature

regulated against supply variations keeping the gain stable over a wide supply range.

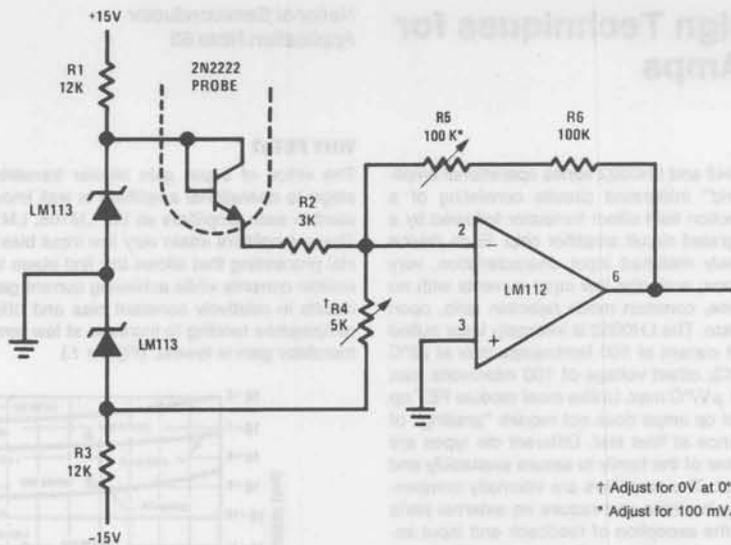
As shown, the gain will change less than two per cent over a -55°C to $+125^{\circ}\text{C}$ temperature range. Using the LM114A monolithic transistor and low drift metal film resistors, the amplifier will have less than 2 $\mu\text{V}/^{\circ}\text{C}$ voltage drift. Even lower drift may be obtained by unbalancing the collector load resistors to null out the initial offset. Drift under nulled condition will be typically less than 0.5 $\mu\text{V}/^{\circ}\text{C}$.

The differential amplifier may be used as a pre-amplifier for a low-cost operational amplifier such as an LM101A to improve its voltage drift characteristics. Since the gain of the operational amplifier is increased by a factor of 100, the frequency compensation capacitor must also be increased from 30 pF to 3000 pF for unity gain operation. To realize low voltage drift, case must be taken to minimize thermoelectric potentials due to temperature gradients. For example, the thermoelectric potential of some resistors may be more than 30 $\mu\text{V}/^{\circ}\text{C}$, so a 1°C temperature gradient across the resistor on a circuit board will cause much larger errors than the amplifier drift alone. Wirewound resistors such as Evenohm are a good choice for low thermoelectric potential.

Figure 8 illustrates an electronic thermometer using an inexpensive silicon transistor as the temperature sensor. It can provide better than 1°C accuracy over a 100°C range. The emitter-base turn-on voltage of silicon transistors is linear with temperature. If the operating current of the sensing transistor is made proportional to absolute temperature the nonlinearity of emitter-base voltage can be minimized. Over a -55°C to 125°C temperature range the nonlinearity is less than 2 mV or the equivalent of 1°C temperature change.

An LM113 diode regulates the input voltage to 1.2V. The 1.2V is applied through R_2 to set the operating current of the temperature-sensing transistor.

Resistor R_4 biases the output of the amplifier for zero output at 0°C . Feedback resistor R_5 is then used to calibrate the output scale factor to 100 mV/ $^{\circ}\text{C}$. Once the output is zeroed, adjusting the scale factor does not change the zero.



† Adjust for 0V at 0°C
 * Adjust for 100 mV/°C

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FIGURE 8. Electronic Thermometer

CONCLUSION

A new two terminal low voltage shunt regulator has been described. It is electrically equivalent to a temperature-stable 1.2V breakdown diode. Over a -55°C to 125°C temperature range and operating currents of 0.5 mA to 20 mA the LM113 has one hundred times better reverse characteristics than breakdown diode. Additionally, wideband noise and long term stability are good since no breakdown mechanism is involved.

The low temperature coefficient and low regulation voltage make it especially suitable for a low voltage regulator or battery operated equipment. Circuit design is eased by the

fact that the output voltage and temperature coefficient are largely independent of operating current. Since the reference voltage is equal to the extrapolated energy-band-gap of silicon, the device is useful in many temperature compensation and temperature measurement applications.

REFERENCES

1. R.J. Widlar, "On Card Regulator for Logic Circuits," National Semiconductor AN-42, February, 1971.
2. J.S. Brugler, "Silicon Transistor Biasing for Linear Collector Current Temperature Dependence," IEEE Journal of Solid State Circuits, pp. 57-58, June, 1967.