# IC Voltage Reference has 1 ppm per Degree Drift

A new linear IC now provides the ultimate in highly stable voltage references. Now, a new monolithic IC the LM199, out-performs zeners and can provide a 6.9V reference with a temperature drift of less than 1 ppm/° and excellent long term stability. This new IC, uses a unique subsurface zener to achieve low noise and a highly stable breakdown. Included is an on-chip temperature stabilizer which holds the chip temperature at 90°C, eliminating the effects of ambient temperature changes on reference voltage.

The planar monolithic IC offers superior performance compared to conventional reference diodes. For example, active circuitry buffers the reverse current to the zener giving a dynamic impedance of 0.5Ω and allows the LM199 to operate over a 0.5 mA to 10 mA current range with no change in performance. The low dynamic impedance, coupled with low operating current significantly simplifies the current drive circuitry needed for operation. Since the temperature coefficient is independent of operating current, usually a resistor is all that is needed.

Previously, the task of providing a stable, low temperature coefficient reference voltage was left to a discrete zener diode. However, these diodes often presented significant problems. For example, ordinary zeners can show many millivolts change if there is a temperature gradient across the package due to the zener and temperature compensation diode not being at the same temperature. A 1°C difference may cause a 2 mV shift in reference voltage. Because the on-chip temperature stabilizer maintains constant die temperature, the IC reference is free of voltage shifts due to temperature gradients. Further, the temperature stabilizer, as well as eliminating drift, allows exceptionally fast warm-up over conventional diodes. Also, the LM199 is insensitive to stress on the leads—another source of error with ordinary glass diodes. Finally, the LM199 shows virtually no hysteresis in reference voltage when subject to temperature cycling over a wide temperature range. Temperature cycling the LM199 between 25°C, 150°C and back to 25°C causes less than 50 $\mu$V change in reference voltage. Standard reference diodes exhibit shifts of 1 mV to 5 mV under the same conditions.

## SUB SURFACE ZENER IMPROVES STABILITY

Previously, breakdown references made in monolithic IC's usually used the emitter-base junction of an NPN transistor as a zener diode. Unfortunately, this junction breaks down at the surface of the silicon and is therefore susceptible to surface effects. The breakdown is noisy, and cannot give long-term stabilities much better than about 0.3%. Further, a surface zener is especially sensitive to contamination in the oxide or charge on the surface of the oxide which can cause short-term instability or turn-on drift.

The new zener moves the breakdown below the surface of the silicon into the bulk yielding a zener that is stable with time and exhibits very low noise. Because the new zener is made with well-controlled diffusions in a planar structure, it is extremely reproducible with an initial 2% tolerance on breakdown voltage.

A cut-away view of the new zener is shown in *Figure 1*. First a small deep P+ diffusion is made into the surface of the silicon. This is then covered by the standard base diffusion. The N+ emitter diffusion is then made completely covering the P+ diffusion. The diode then breaks down where the dopant concentration is greatest, that is, between the P+ and N+. Since the P+ is completely covered by N+ the breakdown is below the surface and at about 6.3V. One connection to the diode is to the N+ and the other is to the P base diffusion. The current flows laterally through the base to the P+ or cathode of the zener. Surface breakdown does not occur since the base P to N+ breakdown voltage is greater than the breakdown of the buried device. The buried zener has been in volume production since 1973 as the reference in the LX5600 temperature transducer.

### CIRCUIT DESCRIPTION

The block diagram of the LM199 is shown in *Figure 2*. Two electrically independent circuits are included on the same chip—a temperature stabilizer and a floating active zener. The only electrical connection between the two circuits
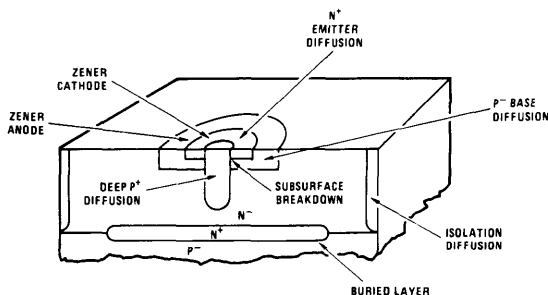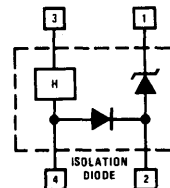


FIGURE 1. Subsurface Zener Construction



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FIGURE 2. Functional Block Diagram

is the isolation diode inherent in any junction-isolated integrated circuit. The zener may be used with or without the temperature stabilizer powered. The only operating restriction is that the isolation diode must never become forward biased and the zener must not be biased above the 40V breakdown of the isolation diode.

The actual circuit is shown in *Figure 3*. The temperature stabilizer is composed of Q1 through Q9. FET Q9 provides current to zener D2 and Q8. Current through Q8 turns a loop consisting of D1, Q5, Q6, Q7, R1 and R2. About 5V is applied to the top of R1 from the base of Q7. This causes 400 $\mu$A to flow through the divider R1, R2. Transistor Q7 has a controlled gain of 0.3 giving Q7 a total emitter current of about 500 $\mu$A. This flows through the emitter of Q6 and drives another controlled gain PNP transistor Q5. The gain of Q5 is about 0.4 so D1 is driven with about 200 $\mu$A. Once current flows through Q5, Q8 is reverse biased and the loop is self-sustaining. This circuitry ensures start-up.

The resistor divider applies 400 mV to the base of Q4 while Q7 supplies 120 $\mu$A to its collector. At temperatures below the stabilization point, 400 mV is insufficient to cause Q4 to conduct. Thus, all the collector current from Q7 is provided

as base drive to a Darlington composed of Q1 and Q2. The Darlington is connected across the supply and initially draws 140 mA (set by current limit transistor Q3). As the chip heats, the turn on voltage for Q4 decreases and Q4 starts to conduct. At about 90°C the current through Q4 appreciably increases and less drive is applied to Q1 and Q2. Power dissipation decreases to whatever is necessary to hold the chip at the stabilization temperature. In this manner, the chip temperature is regulated to better than 2°C for a 100°C temperature range.

The zener section is relatively straight-forward. A buried zener D3 breaks down biasing the base of transistor Q13. Transistor Q13 drives two buffers Q12 and Q11. External current changes through the circuit are fully absorbed by the buffer transistors rather than D3. Current through D3 is held constant at 250 $\mu$A by a 2k resistor across the emitter base of Q13 while the emitter-base voltage of Q13 nominally temperature compensates the reference voltage.

The other components, Q14, Q15 and Q16 set the operating current of Q13. Frequency compensation is accomplished with two junction capacitors.



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**FIGURE 3. Schematic Diagram of LM199 Precision Reference**

## PERFORMANCE

A polysulfone thermal shield, shown in *Figure 4,* is supplied with the LM199 to minimize power dissipation and improve temperature regulation. Using a thermal shield as well as the small, high thermal resistance TO-46 package allows operation at low power levels without the problems of special IC packages with built-in thermal isolation. Since the LM199 is made on a standard IC assembly line with standard assembly techniques, cost is significantly lower than if special techniques were used. For temperature stabilization only 300 mW are required at 25°C and 660 mW at −55°C.
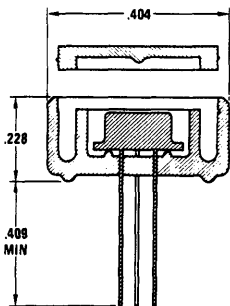


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**FIGURE 4. Polysulfone Thermal Shield**

Temperature stabilizing the device at 90°C virtually eliminates temperature drift at ambient temperatures less than 90°C. The reference is nominally temperature compensated and the thermal regulator further decreases the temperature drift. Drift is typically only 0.3 ppm/°C. Stabilizing the temperature at 90°C rather than 125°C significantly reduces power dissipation but still provides very low drift over a major portion of the operating temperature range. Above 90°C ambient, the temperature coefficient is only 15 ppm/°C.

A low drift reference would be virtually useless without equivalent performance in long term stability and low noise. The subsurface breakdown technology yields both of these. Wideband and low frequency noise are both exceptionally low. Wideband noise is shown in *Figure 5* and low frequency noise is shown over a 10 minute period in the photograph of *Figure 6.* Peak to peak noise over a 0.01 Hz to 1 Hz bandwidth is only about 0.7 μV.

Long term stability is perhaps one of the most difficult measurements to make. However, conditions for long-term stability measurements on the LM199 are considerably more realistic than for commercially available certified zeners. Standard zeners are measured in ±0.05°C temperature controlled both at an operating current of 7.5 mA ±0.05 μA. Further, the standard devices must have stress-free contacts on the leads and the test must not be interrupted during the measurement interval. In contrast, the LM199 is measured in still air of 25°C to 28°C at a reverse current of 1 mA ±0.5%. This is more typical of actual operating conditions in instruments.

When a group of 10 devices were monitored for long-term stability, the variations all correlated, which indicates changes in the measurement system (limitation of 20 ppm) rather than the LM199.
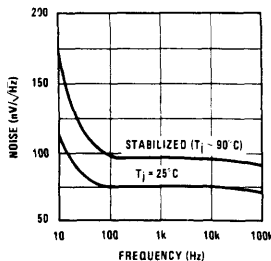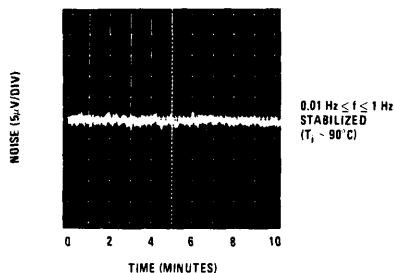


**FIGURE 5. Wideband Noise of the LM199 Reference**



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**FIGURE 6. Low Frequency Noise Voltage**

Because the planar structure does not exhibit hysteresis with temperature cycling, long-term stability is not impaired if the device is switched on and off.

The temperature stabilizer heats the small thermal mass of the LM199 to 90°C very quickly. Warm-up time at 25°C and −55°C is shown in *Figure 7.* This fast warm-up is significantly less than the several minutes needed by ordinary diodes to reach equilibrium. Typical specifications are shown in Table I.
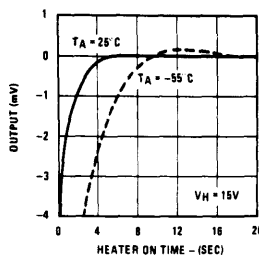


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**FIGURE 7. Fast Warmup Time of the LM199**

**Table I. Typical Specifications for the LM199**

| | |
|---|---|
| Reverse Breakdown Voltage | 6.95V |
| Operating Current | 0.5 mA to 10 mA |
| Temperature Coefficient | 0.3 ppm/°C |
| Dynamic Impedance | 0.5Ω |
| RMS Noise (10 Hz to 10 kHz) | 7μV |
| Long-Term Stability | ≤20 ppm |
| Temperature Stabilizer Operating Voltage | 9V to 40V |
| Temperature Stabilizer Power Dissipation (25°C) | 300 mW |
| Warm-up Time | 3 Seconds |

## APPLICATIONS

The LM199 is easier to use than standard zeners, but the temperature stability is so good—even better than precision resistors—that care must be taken to prevent external circuitry from limiting performance. Basic operation only requires energizing the temperature stabilizer from a 9V to 40V power source and biasing the reference with between 0.5 mA to 10 mA of current. The low dynamic impedance minimizes the current regulation required compared to ordinary zeners.

The only restriction on biasing the zener is the bias applied to the isolation diode. Firstly, the isolation diode must not be forward biased. This restricts the voltage at either terminal of the zener to a voltage equal to or greater than the V⁻.

A dc return is needed between the zener and heater to insure the voltage limitation on the isolation diodes are not exceeded. *Figure 8* shows the basic biasing of the LM199.

The active circuitry in the reference section of the LM199 reduces the dynamic impedance of the zener to about $0.5\Omega$. This is especially useful in biasing the reference. For example, a standard reference diode such as a 1N829 operates at 7.5 mA and has a dynamic impedance of $15\Omega$. A 1% change in current (75 $\mu$A) changes the reference voltage by 1.1 mV. Operating the LM199 at 1 mA with the same 1% change in operating current (10 $\mu$A) results in a reference change of only 5 $\mu$V. *Figure 9* shows reverse voltage change with current.

Biasing current for the reference can by anywhere from 0.5 mA to 10 mA with little change in performance. This wide current range allows direct replacement of most zener types with no other circuit changes besides the temperature stabilizer connection. Since the dynamic impedance is constant with current changes regulation is better than discrete zeners. For optimum regulation, lower operating currents are
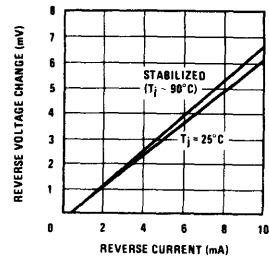


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### FIGURE 9. The LM199 Shows Excellent Regulation Against Current Changes

preferred since the ratio of source resistance to zener impedance is higher, and the attenuation of input changes is greater. Further, at low currents, the voltage drop in the wiring is minimized.

Mounting is an important consideration for optimum performance. Although the thermal shield minimizes the heat low, the LM199 should not be exposed to a direct air flow such as from a cooling fan. This can cause as much as a 100% increase in power dissipation degrading the thermal regulation and increasing the drift. Normal conviction currents do not degrade performance.

Printed circuit board layout is also important. Firstly, four wire sensing should be used to eliminate ohmic drops in pc traces. Although the voltage drops are small the temperature coefficient of the voltage developed along a copper trace can add significantly to the drift. For example, a trace with $1\Omega$ resistance and 2 mA current flow will develop 2 mV drop. The TC of copper is 0.004%/°C so the 2 mV drop will change at 8 $\mu$V/°C, this is an additional 1 ppm drift error. Of course, the effects of voltage drops in the printed circuit traces are eliminated with 4-wire operation. The heater current also should not be allowed to flow through the voltage reference traces. Over a −55°C to +125°C temperature



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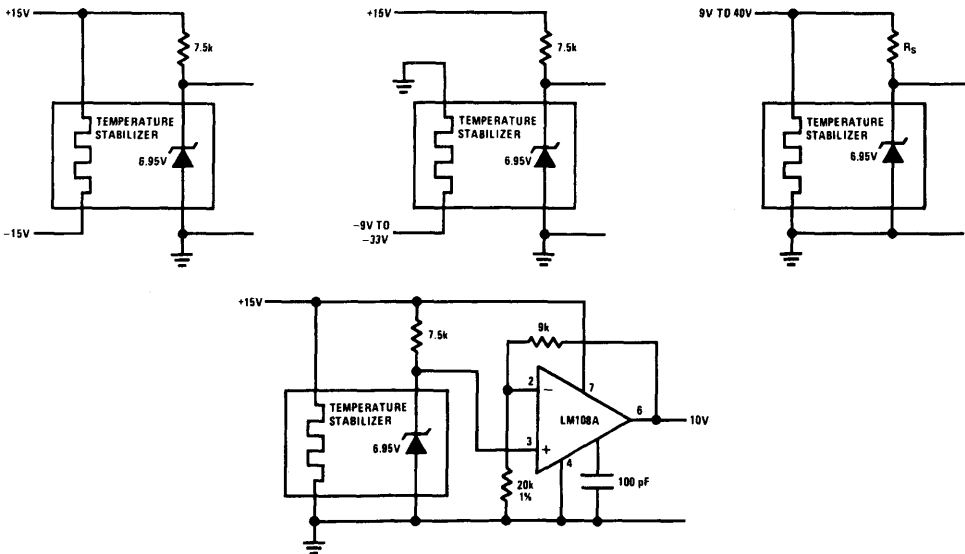### FIGURE 8. Basic Biasing of the LM199

range the heater current will change from about 1 mA to over 40 mA. These magnitudes of current flowing reference leads or reference ground can cause huge errors compared to the drift of the LM199.

Thermocouple effects can also use errors. The kovar leads from the LM199 package from a thermocouple with copper printed circuit board traces. Since the package of the 199 is heated, there is a heat flow along the leads of the LM199 package. If the leads terminate into unequal sizes of copper on the p.c. board greater heat will be absorbed by the larger copper trace and a temperature difference will develop. A temperature *difference* of 1°C between the two leads of the reference will generate about 30 $\mu$A. Therefore, the copper traces to the zener should be equal in size. This will generally keep the errors due to thermocouple effects under about 15 $\mu$V.

The LM199 should be mounted flush on the p.c. board with a minimum of space between the thermal shield and the boards. This minimizes air flow across the kovar leads on the board surface which also can cause thermocouple voltages. Air currents across the leads usually appear as ultra-low frequency noise of about 10 $\mu$V to 20 $\mu$V amplitude.

It is usually necessary to scale and buffer the output of any reference to some calibrated voltage. *Figure 10* shows a simple buffered reference with a 10V output. The reference is applied to the non-inverting input of the LM108A. An RC rolloff can be inserted in series with the input to the LM108A to roll-off the high frequency noise. The zener heater and op amp are all powered from a single 15V supply. About 1%

regulation on the input supply is adequate contributing less than 10 $\mu$V of error to the output. Feedback resistors around the LM308 scale the output to 10V.

Although the absolute values of the resistors are not extremely important, tracking of temperature coefficients is vital. The 1 ppm/°C drift of the LM199 is easily exceeded by the temperature coefficient of most resistors. Tracking to better than 1 ppm is also not easy to obtain. Wirewound types made of Evenohm or Mangamin are good and also have low thermoelectric effects. Film types such as Vishay resistors are also good. Most potentiometers do not track fixed resistors so it is a good idea to minimize the adjustment range and therefore minimize their effects on the output TC. Overall temperature coefficient of the circuit shown in *Figure 10* is worst case 3 ppm/°C. About 1 ppm is due to the reference, 1 ppm due to the resistors and 1 ppm due to the op amp.

*Figure 11* shows a standard cell replacement with a 1.01V output. A LM321 and LM308 are used to minimize op amp drift to less than 1 $\mu$V/°C. Note the adjustment connection which minimizes the TC effects of the pot. Set-up for this circuit requires nulling the offset of the op amp first and then adjusting for proper output voltage.

The drift of the LM321 is very predictable and can be used to eliminate overall drift of the system. The drift changes at 3.6 $\mu$V/°C per millivolt of offset so 1 mV to 2 mV of offset can be introduced to minimize the overall TC.
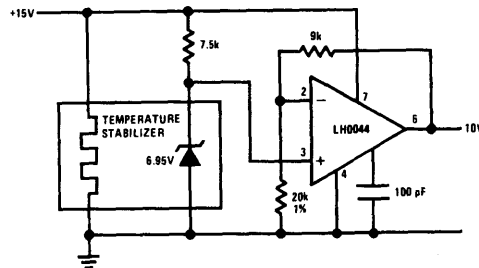


FIGURE 10. Buffered 10V Reference



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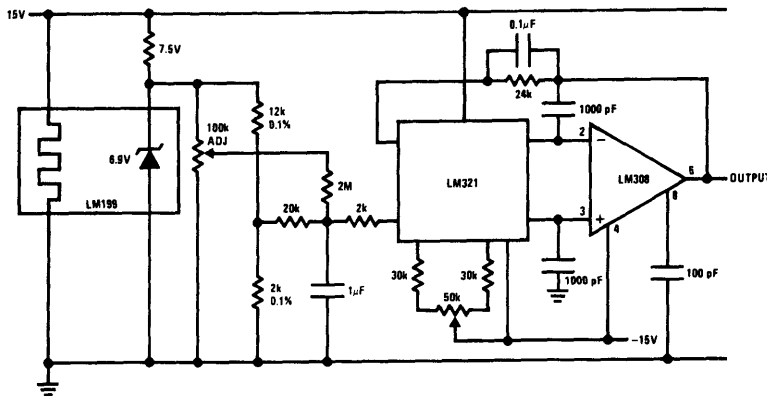
FIGURE 11. Standard Cell Replacement

For circuits with a wide input voltage range, the reference can be powered from the output of the buffer as is shown in *Figure 12*. The op amp supplies regulated voltage to the resistor biasing the reference minimizing changes due to input variation. There is some change due to variation of the temperature stabilizer voltage so extremely wide range operation is not recommended for highest precision. An additional resistor (shown 80 kΩ) is added to the unregulated input to insure the circuit starts up properly at the application of power.

A precision power supply is shown in *Figure 13*. The output of the op amp is buffered by an IC power transistor the LM395. The LM395 operates as an NPN power device but requires only 5 μA base current. Full overload protection inherent in the LM395 includes current limit, safe-area protection, and thermal limit.

A reference which can supply either a positive or a negative continuously variable output is shown in *Figure 14*. The reference is biased from the ±15 input supplies as was shown

earlier. A ten-turn pot will adjust the output from +$V_Z$ to −$V_Z$ continuously. For negative output the op amp operates as an inverter while for positive outputs it operates as a non-inverting connection.

Op amp choice is important for this circuit. A low drift device such as the LM108A or a LM108-LM121 combination will provide excellent performance. The pot should be a precision wire wound 10 turn type. It should be noted that the output of this circuit is not linear.

## CONCLUSIONS

A new monolithic reference which exceeds the performance of conventional zeners has been developed. In fact, the LM199 performance is limited more by external components than by reference drift itself. Further, many of the problems associated with conventional zeners such as hysteresis, stress sensitivity and temperature gradient sensitivity have also been eliminated. Finally, long-term stability and noise are equal of the drift performance of the new device.
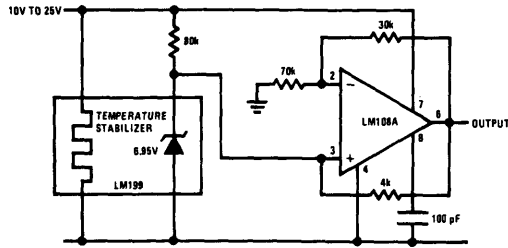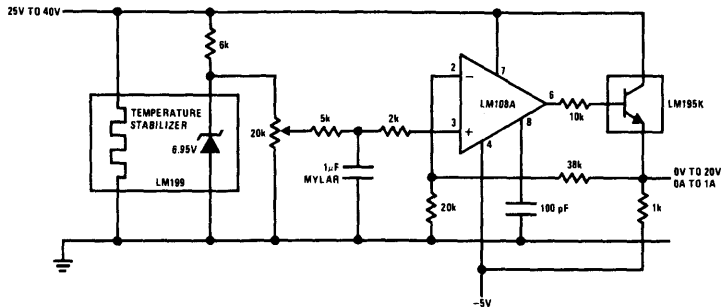


FIGURE 12. Wide Range Input Voltage Reference
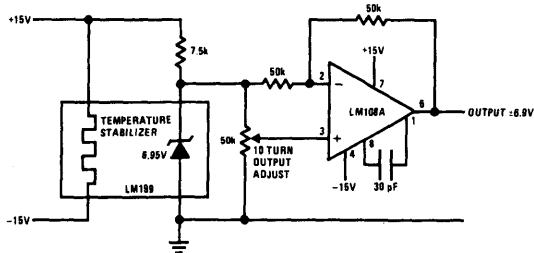


FIGURE 13. Precision Power Supply



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FIGURE 14. Bipolar Output Reference