Assessment of the Performance of Zener References of the Highest Quality

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Abstract—**Zener diodes are now playing an important part in the development of transfer voltage standards. The computer-controlled equipment that is described is capable of measuring these devices to 1 part in 10^7 at the 6-V level. A technique is described for characterizing the data obtained at various currents and temperatures in order to produce quantitative figures for the important parameters of zener diodes. The results and application of this method are discussed.**

I. Introduction

IMPROVEMENTS IN digital voltmeters and the general trend towards increased resolution and performance of analog/digital processing schemes continually raise the demands on local and national calibration centres for accuracy and confidence. Although developments in the Josephson voltage standard have meant a significant advance in confidence at the national level, to the extent that national alterations in the legal volt are being contemplated, this resolution is not available on a commercial basis, due to lack of portability. Transfer standards, once wholly the domain of standard cells and later, that of zener diodes and other semiconductor devices, need to be developed for some years yet to meet industry's requirements in calibration.

The compensated zener diode is one of the most popular types of device for use as a reference element (or one of a group of elements) in a standard. Together with an amplifier and some scaling and current setting resistors, they form the basis of standards that have been demonstrated to give good performance—typically less than 1 ppm of noise or drift even after transportation.

Unfortunately this, and the other types of semiconductor device used can exhibit serious defects in relation to their use as potential reference elements. Extensive testing of devices is necessary before they can be considered for building into standards. Work has been going on for over a decade at Cambridge University, England, to investigate and characterize the properties of semiconductor reference elements and this paper presents one aspect of recent work carried out.

II. Routine Measurement of Zener Voltage

Equipment has been constructed to allow investigation of the deficiencies of zener diodes, in particular temperature coefficient (and changes in relation to bias current), long-term voltage change with time (ageing), noise and non-repeatable change of voltage with temperature or current (hysteresis). In order to resolve small aging effects in a reasonable time, a design goal of repeatable measurement to an accuracy of 1 μV at the 6-V level was chosen. This is beyond the level at which calibration is available, and so all results are relative to standards maintained at the University.

Up to 40 devices may be on test at any one time, 20 of them maintained in an environment accurate to +/− 0.01°C and adjustable in temperature from 10 to 60°C, this being maintained by 3-term controller and Peltier effect heat pumps. Devices are selected for measurement by mechanical switching arrangements. Their current is set by a precision current calibrator during testing, and by a "standby" source at other times, depending upon whether the operator has selected (via software) that the device be continuously run or not. Voltage is measured in a standard 4-terminal way, being compared using a commercial nanovoltmeter to one of four possible backoff sources. All crucial areas in the experiment are continuously powered by rechargeable batteries on float charge so that there is no danger of unforeseen current or temperature hysteresis due to mains supply failure.

All of the experiment is under microcomputer control, and extensive software has been written to allow routine measurements to be made simply yet with the greatest level of confidence. The software provided allows for routine measurement of voltage, slope resistance and temperature three times per day together with data storage and preliminary analysis of results. Other interactive procedures allow direct measurement, comparison with expected data, plotting and "housekeeping" functions, and other research programs, such as temperature test cycles, to be automatically loaded and executed at a defined time.

Results show daily noise figures of less than 5 parts in 10^8 (RSS) for some devices, this figure being made up of noise contributions from the device, backoff, DVM, and current source. It should be noted that the equipment is not in an air conditioned room and that the typical weekly range of temperature is several degrees Celsius. Longer term errors are typically of the order of a few parts in 10^7 for the better devices, and parts in 10^6 for the "rogue" devices. Fig. 1 shows specimen results for 4 devices over 1 month; device 3 is "good," devices 6 and 18 are "aver-

Manuscript received April 28, 1987.
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IEEE Log Number 8716862.

0018-9456/87/1200-0913$01.00

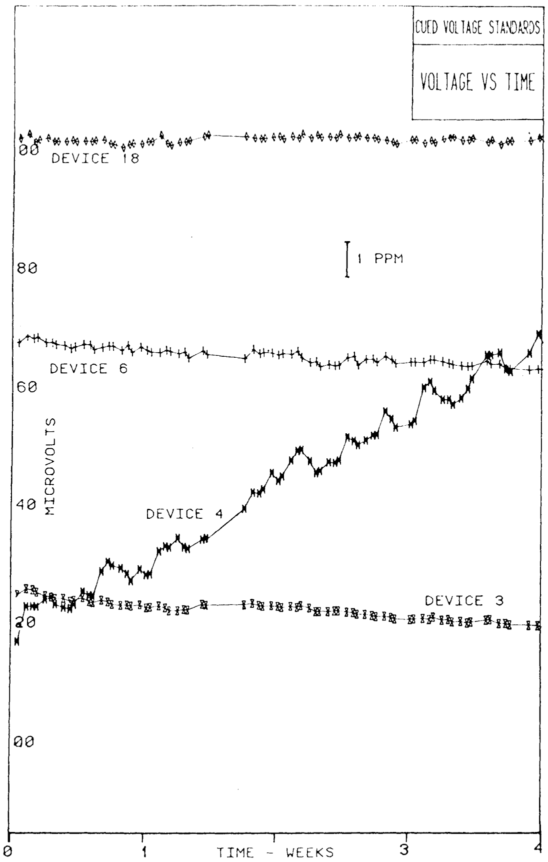

Fig. 1. Voltage versus time for 4 typical devices over 1 month.

age'' and device 4 is definitely ''rogue'' both with respect to noise and ageing.

III. Location of Optimum Working Current

Compensated zener diodes (and simple zeners for a voltage of approximately 5.1 to 5.6 V) have an optimum working current which yields the lowest or zero temperature coefficient (TC). Reference [1] is one of the many articles on this subject. This current must always be found empirically. Normally the temperature of the device must be repeatedly altered and its current adjusted in such a way as to successively reduce the TC to zero. This is usually a lengthy process, even when under computer control. Each current interpolation suffers inaccuracy due to the noise involved in the voltage measurement; also the relationship between the TC and current is nonlinear, so only an approximation for the new working current can be made at each stage.

IV. Development of a Mathematical Model

Any zener diode has a terminal voltage which is characterized by $V = F(I, T, t)$ where

V voltage,
I current,
T temperature,
t time. (1)

Given that its environmental conditions (such as lead resistance, thermal resistance junction/ambient etc.) remain constant. There are problems in devising a simple model for the function F. These are as follows:

As yet there is no accurate model for a zener diode based on fundamental theory and including parameters such as dopant concentrations.

Devices can exhibit voltage changes in the form of random steps.

The parameters such as TC have been found to change slowly with time.

The simplest model for the voltage dependence on current, a logarithmic function, prevents an analytic method of fitting test data to the model.

In setting up the equations that follow, early sets of trial data obtained by cycling a device through normally 6 currents and 30 temperatures were used; Fig. 2 shows one such set of results. Temperatures were chosen so as to be close enough for numerical differentiation to be meaningful. An experimental model was chosen to fit the data and the residuals examined at each stage to assess whether any improvement in fit would result from extending the model.

The following expression was obtained:

$$V = C_0 + C_1 I + C_2 I^2 + C_3 I^3 + C_4 IT + C_5 I^4 + C_6 I^2 T + C_7 T^2 + C_8 T + C_9 I T^2. \quad (2)$$

This generally has residuals of the order of the noise of the original data. Since the expression is analytic, it can be differentiated:

$$\left(\frac{\partial V}{\partial T}\right)_I = C_8 + 2C_7 T + I(C_4 + 2C_9 T) + C_6 I^2 \quad (3)$$

$$\left(\frac{\partial V}{\partial I}\right)_T = (C_1 + C_4 T + C_9 T^2) + 2I(C_2 + C_6 T) + 3C_3 I^2 + 4C_5 I^3 \quad (4)$$

$$\left(\frac{\partial^2 V}{\partial I\,\partial T}\right)_{I,T} = C_4 + 2C_6 I + 2C_9 T \quad (5)$$

$$\left(\frac{\partial^2 V}{\partial T^2}\right)_I = 2(C_7 + C_9 I). \quad (6)$$

Equation (3) represents the TC: after finding the coefficients C_0–C_9 the expression yields the working current for zero or minimum TC.

Equation (4) represents the slope resistance and a device's sensitivity to changes in operating current.

Equation (5) represents the change in TC for a change in operating current. A device for which this parameter is low will be more tolerant in current setting to achieve lowest TC (however a stable current is always essential as the devices have a slope resistance of around 10 Ω).

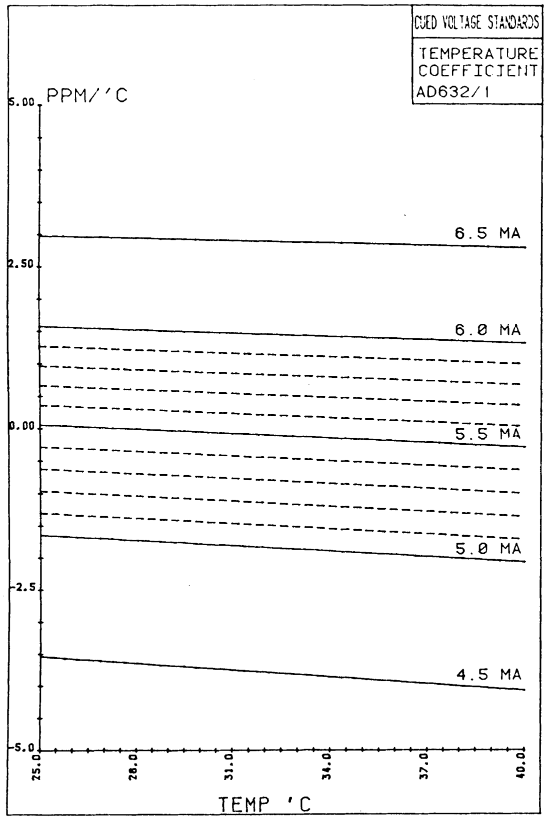

Fig. 2. Temperature coefficient versus temperature for a typical compensated zener.

Equation (6) represents the change in TC with respect to temperature. This is an important measure of a device's suitability as a reference element since the TC must remain low over a suitable range of temperatures.

Additionally, the change in terminal voltage to be expected if current or temperature or both are changed can be easily produced. This is helpful in research if, for example, a new working current is tried for a few days or weeks. The change in voltage arising from this change can be compared with that predicted, and the changed voltage can still be added to the long-term history of the device with confidence, despite perhaps being hundreds of ppm different.

V. Data Collection and Processing

Software has been written to allow the collection of data from a device being operated at a predetermined number of temperatures and currents. A normal measurement cycle takes about 12 hours to test 20 devices at 25 I/T combinations, including time for the oven temperatures to stabilize. It is important when using a small number of data points that they be well spread across the device operating area, or an ill-conditioned data set results.

Further software processes the data by normalizing it, and solving the regression matrix by Gauss–Jordan elimination in the usual way. Results recorded are discussed in the next section; solved coefficients are stored on disk for further use. Printouts can be requested in order that a comparison be made with earlier results.

VI. Results

Space only permits a few of the results obtained from the experiment to be shown; further results were presented at the conference.

Table I shows computed results based on the 231 point data set used to produce figure [2]. Careful measurements from Fig. 2 give results as follows: TC at 5.5 mA, −0.09 ppm/°C; best operating current 5.52 mA; sensitivity of TC to change in current approximately 3.3 ppm/°C/mA and rate of TC change −0.02 ppm/°C/°C. Slope resistance was measured on the original experiment as 8.918 Ω at 5.5 mA and 30°C. These figures are close to the computed results in Table I.

Table II shows the normal printout of results, giving the reader some feel for the magnitude of figures encountered. Temperatures chosen were 20°C +/− 1.5°C and despite this small change in temperature the larger variance figures for devices 1, 5, 7, 8, 16, and 17 indicate that some hysteresis has taken place. Devices 1, 8, 16, and 17 are known to be bad in this respect and are kept in the equipment for research purposes.

Two further independent experiments have sought to test the validity of the computer modelling. In test 1, the working current is raised by 200 μA and the resulting voltage for each device is compared with that predicted (a) by the computer model and (b) by a calculation from the best measure of slope resistance. Since the original data for the computer model was obtained at 500-μA intervals, this test shows how well the current terms model the interval between the sample data points (Table III).

For the second test the device voltage has been plotted against the oven temperature by analog means. Fig. 3 shows the results of this temperature cycling at three different currents (zero has been reset for each current). Software exists to manipulate the equipment by means of simple English commands such as TEMP. 20 TO 22 BY .4. The "lumpy" nature of the lines is caused by the temperature steps being too large, done to reduce the test time to around three hours. The best working current is clearly close to 7.25 mA and the sensitivity of TC to current can be estimated at 2.6 ppm/°C/mA from the graph. The same best current is shown in the computed results (Table II device 3) and 2.7 ppm/°C/mA is given as the TC sensitivity to current.

The two methods are quite independent, and are a useful check on the validity of the mathematical model.

VII. Applications

A. Location of the Zero TC Current

This becomes a trivial task after one measurement set. Further measurements can be made to increase confidence and to allow tracking of possible parameter changes with time.

B. Elimination of "Rogue" Devices

Voltage hysteresis during the small temperature cycle needed to perform this test would generally render a de-

TABLE I
TEMPERATURE TEST RESULTS ANALYSIS

Date of test :13/12/84
33 test temperatures, 7 test currents
10 fit coefficients, parameters specified at (Td) 30 °C
Test currents were 4, 4.5, 5, 5.5, 6, 6.5, 7 mA

Device	Fit variance ppm	d²V/dt² ppm/°C/°C	d²V/dIdT ppm/°C/mA	Present TC @ Td ppm/°C	Present slope res ohms	New current mA	Action required
Model							
ad642:1	0.28	- .02	3.25	- .05	8.9215	5.52	up 20 μA
Measured:							
ad642:1		- .02	3.3	- .09	8.918	5.52	up 20 μA

TABLE II
TEMPERATURE TEST RESULTS ANALYSIS

Date of test :Monday 10th November 1986
5 test temperatures, 5 test currents
10 fit coefficients, parameters specified at (Td) 20 °C
Test currents were iz nom + 1 , .5 , 0 ,-.5 , -1 mA

Device No.	Fit variance ppm	Present current mA	d²V/dt² ppm/°C/°C	d²V/dIdT ppm/°C/mA	Present TC @ Td ppm/°C	Present slope res ohms	New current mA	Action required
1	.72	4.84	- .07	4.7	- .10	14.38	4.86	up 20 μA
2	.09	4.38	+ .12	4.4	+ .01	15.14	4.38	
3	.06	7.25	+ .04	2.7	+ .03	6.60	7.24	
4	.08	4.86	+ .12		+ .03	14.55	4.66	dn 200 μA
5	.47	5.28	+ .09	4.6	- .46	14.50	5.38	up 100 μA
6	.06	5.65	+ .06	3.5	+ .00	8.24	5.65	
7	.41	5.17	+ .16	5.6	- .19	13.57	5.20	up 30 μA
8	.37	5.55	+ .26	3.9	+ .02	15.95	5.46	
9	.15	4.33	+ .02	4.2	+ .01	10.41	4.32	
10	.07	5.92	+ .04	3.5	+ .16	8.71	5.87	dn 50 μA
14	.11	4.70	- .04	3.3	+ .01	11.01	4.69	
15	.03	3.76	+ .01	5.1	+ .04	11.61	3.75	
16	.46	5.00	+ .39	8.3	-14.24	12.91		
17	.82	5.79	- .07	7.1	+1.20	8.54	5.62	dn 170 μA
18	.10	6.00	- .02	3.4	+ .09	7.72	5.97	dn 30 μA
19	.10	5.78	+ .02	3.3	- .01	8.11	5.78	
20	.07	4.93	+ .02	4.0	- .02	9.17	4.93	
21	.13	6.12	+ .19	4.8	- .04	8.11	6.12	
22	.02	10.23	+ .15	3.5	+ .06	5.74	10.21	

TABLE III
VOLTAGE CHANGE FOR A 200-μA CHANGE IN WORKING CURRENT

Device No.	Measured Change in Voltage	Expected Change in Voltage			
		Computed from Model		Derived from slope resistance	
		Predicted	Error	Predicted	Error
	μV	μV	μV	μV	μV
2	2981.9	2980.4	- 1.5	3025	+ 43
3	1307.0	1306.9	- .1	1319	+ 12
4	2875.2	2874.8	- .4	2907	+ 32
6	1626.1	1626.1	+ .0	1645	+ 19
7	2613.0	2652.8	+39.8	2654	+ 41
14	2162.8	2163.2	+ .4	2201	+ 38
15	2268.8	2269.4	+ .6	2321	+ 52
18	1525.3	1525.4	+ .1	1543	+ 18
20	1804.5	1805.6	+ 1.1	1835	+ 31

vice unsuitable for standards work. Also, those showing large changes in TC with respect to temperature would also be rejected. Slope resistance and sensitivity of TC to changes in current are factors to take into account and together with noise are particularly important in an assessment of a manufacturer's new products.

C. Computer Model

Production of an analytic model allows the designer to use a computer program to model any zener's behavior in a reference circuit very accurately (subject to the proviso that the diode's environmental conditions are not changed). Programs such as SPICE are well established in this role, but lack a detailed model of the zener's behavior. Reference [3] gives a basic model. Other models also have been used [4] but the analytic model described has been proved fully by the range of conditions investigated.

VIII. CONCLUSIONS

Our results show that with careful measurements in controlled conditions, accuracies of 1 part in 10^7 are achievable. A method is proposed that simplifies the characterization process and provides a means of tracking pa-

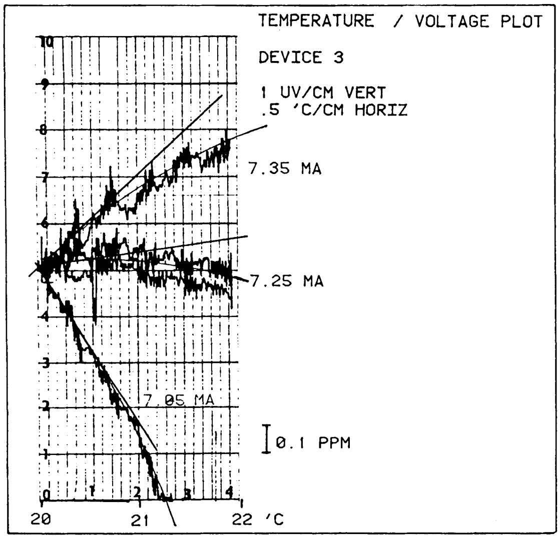

Fig. 3. Temperature coefficient versus temperature (at 3 currents) plotted by analog means.

rameters which, though small, may yield important information about the long-term stability of zener diodes and their selection for use in a voltage standard.

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