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REDUCING OF THE TIME DRIFT OF ZENER STABILIZATION VOLTAGES

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A technology is described that decreases the time drift of the Zener stabilization voltage, shortens the run-in time, and reduces the low-frequency noise amplitude.

Solid-state standards are used to transfer the dc voltage unit from primary standards, based of the Josephson effect, to standard cells (SC) that maintain the unit. These devices are based on Zener diodes. Zener diodes are also used to provide reference voltages in precision measuring instruments (MI) such as calibrators, first and second class voltmeters, and others.

The high stability of solid-state standards and reference voltage sources is a result of a unique Zener fabrication technology and special run-in procedures. Specialists of the DATRON company [1] have devised a technique to reduce to minimum the Zener diode error due to time drift ("settling down" of the stabilization voltage, drift, and diode degradation) based on a system in which four thousands Zener diodes are "processed" (run in) simultaneously under operating conditions. At first, a current is selected for each diode so that the voltage stabilization temperature coefficient is zero and then the diodes are maintained under operating conditions for four to five years (Fig. 1). The stabilization voltage of each Zener diode is periodically measured every three months and stored in the computer memory. The measured results are then plotted as degradation (trend) curves from which are calculated the values $\Delta U \cdot \Delta t$, where Δt is the Zener diode conditioning time during the last three months of processing. Any diode whose stabilization voltage change ΔU for the time Δt exceeds or is equal to $3 \cdot 10^{-6} U_{st}$ is assumed to be unsuitable for application in precision instruments with stable metrological characteristics, e.g., in 4000 AUTOCAL STANDARD calibrators.

A significant disadvantage of this method is the long aging time needed. To reduce this time we propose an accelerated technology for settling down the Zener diode stabilization voltage (Fig. 2). The diodes are subjected under operating conditions to "soft" thermal shocks with ambient temperature drops of 70 to 100°C. The Zener diodes are heated for a time $t_1 - t_0$ and maintained at this temperature for a time $t_2 - t_1$. They are then subjected to a soft thermal shock by cooling them for a time $t_3 - t_2$ (2-5 min) to room temperature T_0 or slightly above. The diodes are next heated during for a time $t_4 - t_3$ to a temperature T_2 that remains constant during the entire aging time, at which the stabilization voltage of the diodes is measured. This time corresponds in Fig. 2 to the interval $t_5 - t_4$. The measured stabilization voltages of each Zener diode are recorded in a long-term memory.

The laboratory equipment used to test the proposed technology of accelerated settling down of the diode stabilization voltage consists of a power supply, a switching unit, measuring instruments, and two thermostats.

At the beginning of each cycle the diodes, with a dc current flowing through them, are placed in thermostat 1. Stable resistors that control the current are placed in thermostat 2 in which the temperature is maintained at exactly 35 ± 0.1°C throughout the aging time. The Zener diodes in thermostat 1 are heated to 100 ±2°C, held at this temperature for 3-4 h, and subjected to a soft thermal shock. The diodes are cooled at a rate v = 0.25 to 0.6 K/sec. The diodes are then placed in thermostat 2 where they are held at a temperature of 35 ± 0.1°C for 2-3 h after which the stabilization voltage of each diode is measured against a battery of standard cells (SC). The entire cycle takes 8-10 h.

The measured differential stabilization-voltage differences have systematic and instrumental error components due to the errors of class 0.05 measuring instruments, in particular of the Shch31 digital voltmeter, the errors of the reference source consisting of class 0.001 standard cells, the errors introduced by the commutator contact resistance and the current-control resistors R_1-R_n, and also to power supply instability.

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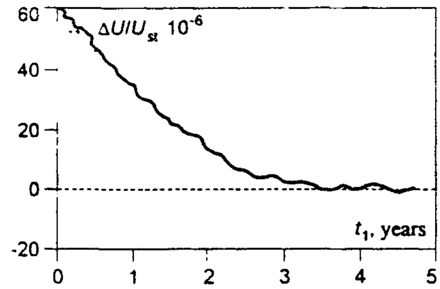

Fig. 1. Empirical trend curve of Zener diode stabilization voltage obtained by the DATRON Company.

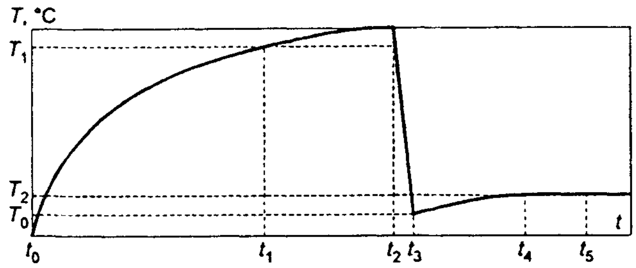

Fig. 2. Diagram of one accelerated Zener diode stabilization cycle.

To find the stabilization voltage variations $U(t)$ it is sufficient, instead of U_{st} and $\Sigma U_{sc\ i}$ (U_{st} and $U_{sc\ i}$ being the absolute diode stabilization voltage and the emf of the i-th standard cell), to know the deviation ΔU_i from the first measurement ΔU_{i_1},

$$\Delta U_{j1} = \left(\sum_{i=1}^{m} U_{sc\ i} - U_{st\ j} \right),$$

where i is the serial number of the Zener diode, and m is the number of standard cells.

Using the measuring procedure described above, and considering all measurement error components, we have for the i-th diode:

$$\Delta U_j = \left(\sum_{i=1}^{m} U_{sc\ i} \pm \Delta U_{cs} \right) - \left[U_{st\ j} - U(t) \right] \pm \sum_{1}^{k} \Delta U_k, \tag{1}$$

where ΔU_{sc} is the absolute error of the SC battery, $U(t)$ is the degradation voltage of the j-th diode, and ΔU_k is the instrumental error mentioned above.

It is known that according to [2], the absolute error limit is found from

$$\Delta U_{sc} = \pm K \sqrt{\sum_{i=1}^{m} \Delta U_{sc\ i}^2}$$

assuming $K = 1.1$ with a confidence coefficient $p = 0.95$.

The deviation of the emf of a battery of nine SCs does not exceed $\pm 10\ \mu$V in three months and $\pm 33\ \mu$V in one year.

The error component due to the change of the resistance of closed switches is insignificant since the input current strength of the Shch31 voltmeter does not exceed 1-2 nA in the 1 V measurement range, and the change of the resistance of a closed switch $\Delta R << 100\ \Omega$.

The voltmeter error consists, essentially, of an additive component, the zero drift, and a multiplicative component, the variations of the conversion slope. Zero drift can be neglected since the instrument is set to zero before every measurement.

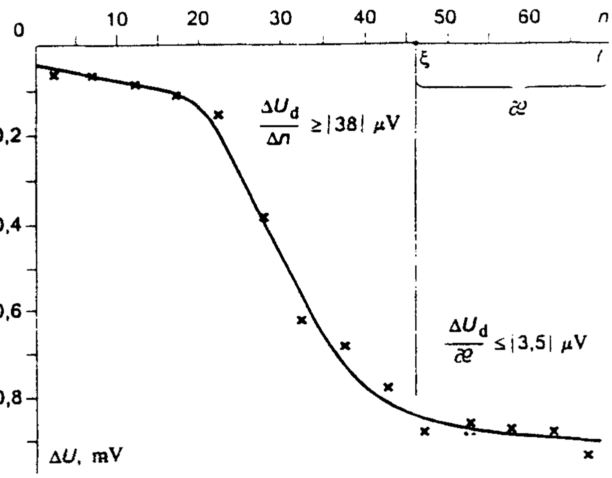

Fig. 3. Typical empirical trend curve of Zener diode stabilization voltage (diode No. 18).

In relative measurements of differential voltage differences, the conversion slope varies markedly less at the beginning of the measurement scale than at the end of the scale so that, correspondingly, the multiplicative error component of relative measurements is K_1 times smaller [3]:

$$K_1 = \Delta A_k / \Delta A_c \approx A_k / A_c,$$

where ΔA_k is the change of the slope of the digital voltmeter conversion characteristic at the end of the measurement range, and ΔA_c is the change of the conversion characteristic slope at the point of measurement in the given range.

The diode supply source and the stable current-control resistors are placed in a thermostat whose internal temperature does not change by more than $\pm 0.1°C$ during the entire experiment. The error component $\Sigma \Delta U_k$ in Eq. (1) then becomes insignificant in comparison with settling down of the diode stabilization voltage during the active aging time. Equation (1) is then simplified to

$$\Delta U_j = \sum_{i=1}^{m} U_{sc\,i} - \left[U_{st\,j} - U(t)\right].$$

The sequence of ΔU_i values, measured after γ thermal cycles, is filtered mathematically. Linear filtration of the sequence of empirical ΔU_i data obtained for each Zener diode is carried out with the aid of the system of equations cited in [4].

Since the degradation of Zener diodes is very slow, it is advisable to divide the sequence of filtered data into k groups of five to seven ΔU_{ji} values per group and to take their average value $\overline{\Delta U_{jk}}$. The obtained data are used to plot for each Zener diode an empirical trend curve (Fig. 3) in which the x axis shows the number of thermal cycles n and the y axis, the calculated diode degradation voltage

$$\Delta U_{dj} = \Delta U_{j1} - \Delta \overline{U}_{jk}.$$

Linear filtration somewhat levels down the trend curve in the region of transition to steady-state conditions. Linear filtration also levels down high-frequency noise. The slope of the degradation curve is found from plotted trend curves:

$$\Delta \overline{U}_j = \left(\Delta \overline{U}_{d\gamma} - \Delta \overline{U}_{d\xi}\right) / \kappa = \Delta U_d / \kappa,$$

where $\Delta \overline{U}_{j\gamma}$ and $\Delta \overline{U}_{j\xi}$ are increments of the j-th diode voltage read from the trend curve along the y axis near the steady-state degradation conditions, and $\kappa = \gamma - \xi$ is the number of thermal cycles counted from the cycle at which the trend curve begins to change almost linearly to the end cycle γ.

TABLE 1

Serial number of Zener diode	Maximum degradation, $-\Delta U_{dj}$, mV	Steep section of degradation curve, $\Delta U_d/\Delta n$, µV	Steady-state conditions, $-\bar{U}_j$, µV
1	0,80	44	8,0
2	1,37	13	3,0
3	1,17	23	15,0
4	1,08	33	13,0
5	0,85	23	9,0
6	0,46	21	4,0
7	0,26	9	1,7
8	1,25	28	2,8
9	0,41	22	3,7
10	0,49	20	3,6
11	0,62	19	4,5
12	0,90	19	5,0
13	0,48	14	5,0
14	0,42	28	4,0
15	0,91	25	3,0
16	0,93	40	3,0
17	0,80	25	4,0
18	0,88	37	3,5
19	0,51	25	3,5
20	0,78	32	5,0
21	1,51	68	12,0
22	0,67	27	2,0
23	0,57	37	2,5
24	0,40	21	2,5
25	0,87	25	3,0
26	0,57	30	3,0
27	0,65	30	8,0
28	0,97	29	3,5
29	0,92	19	3,0
30	0,49	50	3,5
31	0,58	40	4,0
32	0,92	45	3,5
33	0,93	33	3,5
34	1,10	36	4,5
35	0,91	20	2,5
36	0,97	36	3,0
37	1,13	50	7,5
38	0,52	26	2,5
39	1,03	40	4,5
40	0,62	18	3,0
41	0,69	22	3,0
42	0,80	37	3,0
43	1,15	50	7,0
44	0,74	45	2,0
45	0,57	20	2,0
46	9,32	263	30,0

Zener diodes with $\Delta\bar{U}_j \leq |3.0\text{-}3.5|$ µV in a single cycle are suitable for use in high-stability instruments.

The described technology was used to accelerate the aging of two batches of KS191F Zener diodes.

Of the first batch of 24 diodes that have been subjected to 56 thermal cycles eight had minimum time drift. The second batch consisted of 46 Zener diodes and 11 control diodes. The diodes were subjected to 70 thermal cycles of accelerated aging. After processing the results of measurement and plotting trend curves the data were listed in Table 1.

The control Zener diodes where aged under operating condition at an ambient temperature of 35 ± 0.1°C during the entire experiment. In most diodes of the control batch the stabilization temperature varied nearly linearly. The average rate of change of the stabilization voltage was 6-10 µV in 9-10 h. In two diodes, the first and sixth, the stabilization voltage increased by 0.5 and 0.25 mV respectively during the first 16-20 days and then, after a certain maximum, the stabilization voltage was observed to drop. None of the Zener diodes had a degradation curve with a segment that could be attributed to steady-state conditions.

The minus sign in front of $\Delta\bar{U}_j$ indicates that the Zener stabilization voltage decreases with time, agreeing with the data presented by the DATRON company (see Fig. 1).

After active run-in for the fabrication of precision and high-stability instruments, the yield of satisfactory Zener diodes was about 50%. It can be thus said that the yield of Zener diodes with minimum variation of stabilization voltage with time can be raised by increasing the number of thermal cycles to 80-100.

After active run-in, practically all Zener diodes, except for a few individual specimens, were suitable for use in the manufacture of electronic equipment.

Figure 3 shows a typical trend curve of a Zener diode listed in Table 1 and used in a bipolar current strength stabilizer [5, 6] in which the trend was less than 3.5 μV per cycle near the state-state region. Investigation of the current stabilizer performance during six months of operation proved that the integral error did not exceed $\pm 5 \cdot 10^{-4}\%$.

In comparison with the current technology [1], the proposed procedure makes it possible significantly to reduce the Zener diode run-in time, to plot a trend curve for each individual diode, to select diodes with minimum degradation voltage, and to predict the stabilization voltage time drift for a time of up to 5000-10,000 h. Moreover, investigation of the noise characteristics of a reference current source [5-7] indicated that such aging reduces the amplitude of the internal Zener diode low-frequency noise in the 0.001-10 Hz range by at least one order of magnitude.

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