Assessing Zener-Diode-Structure Reliability From Zener Diodes' Low-Frequency Noise

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Assessing Zener-Diode-Structure Reliability From Zener Diodes' Low-Frequency Noise

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***Abstract*—An electrical-stress test has been conducted on 98 Zener conventional reference diode structures, and it has been observed that 45% of these devices failed after 3000 h. However, this high failure ratio can be reduced to below 25%, or less, provided that an appropriate low-frequency-noise (LFN) characterization is initially performed and that all the devices exhibiting a larger LFN are subtracted from the lot subjected to electrical-stress test. Further results obtained after a 4500-h electrical-stress test conducted on a reduced number of diodes fully validate this finding.**

***Index Terms*—Low-frequency-noise (LFN) measurement, reliability testing, Zener diode.**

I. Introduction

In SPACE or military electronic equipment, high-reliability specially processed qualified active devices are more and more widely replaced today by more standard devices in order to cut the cost. Consequently, these devices can suffer from unexpected reliability problems, and there is a need for a nondestructive and easy-to-implement cost-effective technique that is able to predict which devices among others are more likely to experience failures in order to achieve an appropriate screening. Such a technique could also be useful to achieve an extra screening on well-qualified devices.

Following the pioneering work of Kim and Misra *et al.* [1], many authors have already reported on low-frequency noise (LFN) as a valuable diagnostic tool for the reliability of semiconductor active devices [2]–[5] .... However, too little has yet been done on the applicability of this technique to industrial needs.

We therefore have addressed this issue from the investigation of a lot of hundred commercial 1N4584 Zener structures. In fact, these structures are made of a series back-to-back assembly of two different chips: a Zener diode featuring a 5.6-V Zener voltage with a positive 2-mV/°C temperature coefficient and a conventional p-n junction featuring a negative temperature coefficient of about -2 mV/°C. The advantage of such a structure is twofold: First, it features an overall very small temperature coefficient (the device is said to be compensated), and second, it cannot conduct any current if the Zener diode is fortuitously forward-biased since, in this case, the p-n junction is reverse-biased. The drawback of such an assembly lies not only in an increased reverse voltage (which is about $5.6 + 0.7 = 6.3$ V) but also, more particularly, in an enhanced failure rate with respect to a single Zener diode. Indeed, failure events can now possibly take place not only at the Zener-diode chip but also at the p-n junction chip or at the defects possibly induced by the processing of the bonding between the two devices.

Any defect in a semiconductor device is likely to induce some excess noise, i.e., some noise in excess with respect to the normal expected noise: thermal noise for a resistor, shot noise for a conventionally biased diode, multiplication noise for a diode biased in avalanche breakdown conditions, etc. Therefore, as soon as an excess noise is present in a device, a defect should be present too, and a reduced reliability can be expected. However, this situation is not as simple as it could be since, first, not all the defects that contribute to the LFN impact on reliability too, and second, not all the defects that could impact on reliability, would, in turn, influence the measured LFN too.

Nevertheless, any defect creates a state in the semiconductor band gap which is likely to trap and detrap some of the carriers and has therefore a possible impact on the LFN (number fluctuation noise) as soon as a current flows across the device. However, trapping and detrapping are effective only if the defect state energy matches ($\pm kT$, i.e., the product of the Boltzmann constant by the device temperature in kelvin) the Fermi (pseudo-Fermi) level which is temperature (and bias)-dependent. Therefore, room-temperature LFN measurements, which are the most easy to conduct, will reveal some of the defects only. However, in a reverse-biased diode, the pseudo-Fermi level position varies across the junction, and therefore, a large range of defects featuring different energy levels impact the observed LFN. Additionally, the frequency range of the LFN measurements must be carefully taken as low as possible (the measurement time severely increases when the measurement frequency decreases) since no defect-related noise can be detected at frequencies well beyond the defect-noise corner frequency which depends on the lifetime of the carriers trapped and detrapped by this defect. All these considerations provide guidelines for the noise-measurement conditions and setup implementation.

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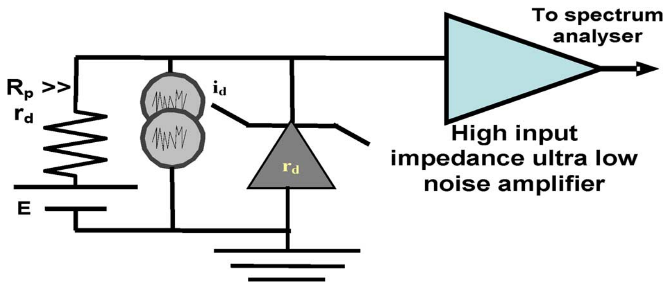

Fig. 1. LFN measurement setup showing the diode noise equivalent current generator i_d that has to be measured.

II. Noise Measurements

Fig. 1 shows the room-temperature noise-measurement setup. It is a very basic one, well shielded, and battery-operated with R_p, which is the bias resistor that needs to be large with respect to the dynamic resistance r_d of the device under test (DUT) in order to prevent any contribution of R_p to the measured noise. If R_p is large enough, the DUT current noise generator spectral intensity Si_d at a given frequency f is simply given by

$$\mathrm{Si}_d(f) = (\mathrm{Sv}_s - \mathrm{Sv}_{s0})/(Gr_d)^2 \tag{1}$$

where G is the amplifier voltage gain at f, and r_d is the device dynamic resistance which can be easily obtained from the derivative of the $I(V)$ at a given current I where the noise is measured. Sv_s and Sv_{s0} are the voltage spectral intensities displayed on the spectrum analyzer, respectively, either with the DUT or with a short substituted for the DUT.

A measurement averaged over 100 samples can be taken in less than 15 s with a modern fast-Fourier-transform analyzer and can therefore be conducted on a large number of devices. Finally, S_i, which is the averaged noise current spectral density that will be considered in this paper, is obtained from an average of Si_d over 201 points from 20 to 30 Hz. A higher frequency would not allow one to easily discriminate between the white noise and the defect-induced noise and would make it more difficult to get rid from the possible line-induced noise. A lower frequency could be more efficient for defect detection but is more cumbersome due to the necessary increased measurement time (2 min for 100 averaged samples at 1 Hz).

The bias conditions for noise measurements need also to be carefully selected. Based on Fig. 2, at least three different situations (A to C) are possible. A: If biased at the Zener voltage, our devices (in contrast to the situation reported in [5]) essentially exhibit a multiplication noise much larger than the shot noise and also larger than the defect-induced noise which can no more be detected. B: If the device is biased with the p-n junction reverse-biased and the Zener diode forward-biased, it operates very differently than in normal Zener operation. Hence, it can be anticipated that the defects that could be detected in this way do not directly impact on the reliability of the device operating as a reference-voltage diode. Hence, we have retained situation C (small reverse bias) where the multiplication noise is weak and where it is anticipated that the electrically active defects are the same as the ones that could impact on the reliability of the device operating at normal reverse-bias Zener conditions.

All the devices, as received from the manufacturer, show very similar $I(V)$ reverse characteristics. They have been numbered from 1 to 101, and the noise data have been taken in small reverse-bias conditions ($V = -5.3$ V, $I = -3.8$ μA). These data are shown in Fig. 3. The excess noise ratio N is given by $N = S_i/2qI$. Hence, a device with no multiplication or defect-induced noise should feature an N which is equal to one. Fig. 3 shows that such a situation never occurs and that a lot of 39 diodes features an N that does not exceed eight. Additional measurements on these diodes up to 2000 Hz show that, for most of them, N is frequency-independent. Therefore, it can be stated that the dominant noise superimposed on the shot noise is, in this case, essentially a large multiplication noise which is known to be frequency-independent [6], [7].

Fig. 3, therefore, also shows that a lot of 62 diodes features an N that is larger than eight and ranging up to 18 or more. Additional measurement up to 2000 Hz indicates that, for most of these noisy diodes, N decreases down to eight or less as the frequency increases from 20 to 2000 Hz. This denotes that the excess noise contributing to an N larger than eight in the second lot is essentially a defect-induced noise that is known to vary as $f^{-\alpha}$ with $1 \leq \alpha \leq 2$. Therefore, Fig. 3 shows that the LFN-generating defects are present at least in 62 diodes among 101 (some excess noise can also exist in the other device but is much less than the multiplication noise which denotes a reduced defect density), and the issue now is to investigate if these defects have an impact on the lifetime of the corresponding devices.

III. Electrical-Stress Test

In order to conduct an electrical-stress test at room 295-K ambient temperature, 98 diodes (the three other diodes have been used as control devices) have been biased at a constant current of 100 mA which results in a dissipated power of 630 mW which exceeds by 25% of the 500-mW maximum rating for this kind of device. It also turns out that the effective junction temperature during stress is well above room temperature and that a 450-K chip temperature is anticipated from an estimated 300-$^{\circ}\mathrm{C/W}$ thermal resistance.

After 3000 h, only two catastrophic failures have been observed. All other 96 diodes only exhibit some drift of their Zener voltage at a given constant current. In order to quantify this drift, we have used a cumulated-drift DVzi in percent which is defined as

$$\mathrm{DVzi} = |\Delta\mathrm{Vzi}_1|/4 + |\Delta\mathrm{Vzi}_2| + 2|\Delta\mathrm{Vzi}_3| \tag{2}$$

where $\Delta\mathrm{Vzi}_1$, $\Delta\mathrm{Vzi}_2$, and $\Delta\mathrm{Vzi}_3$ are the voltage drifts in percent observed at constant currents of 11 and 550 μA and 10 mA, respectively. The phenomenological weighting coefficients 2 and 1/4 in (2) have been taken in order to ensure that a drift observed at a given current has a similar impact on the cumulated drift whatever the current is. Therefore, the reported drift data will be useful for any possible further application whatever the diode-bias operating conditions are.

Fig. 4 shows the cumulated drift of each of the 98 devices observed after a 3000-h electrical-stress test. From this plot, it

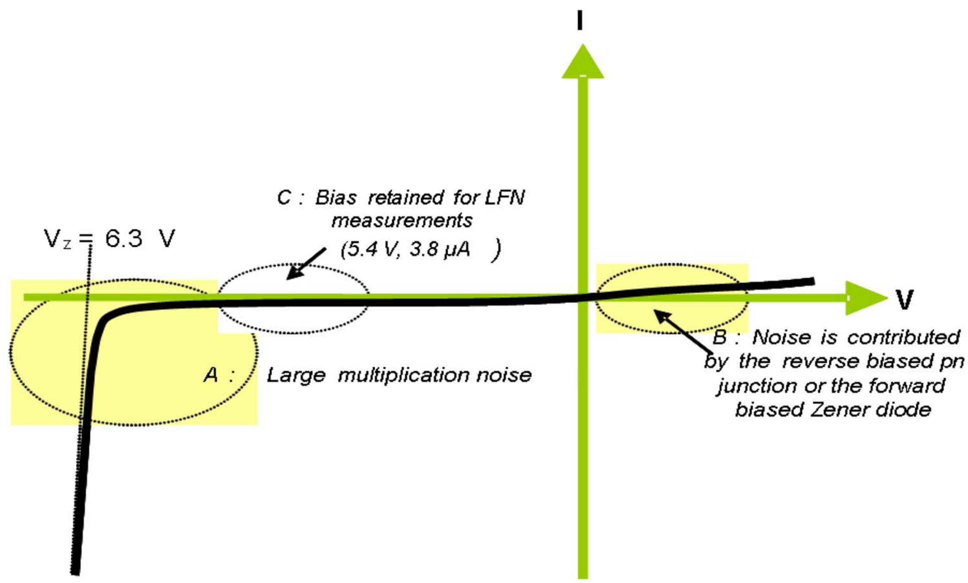

Fig. 2. $I(V)$ characteristic of a Zener diode back to back connected with a p-n junction, showing the different possible regions for the LFN measurement.

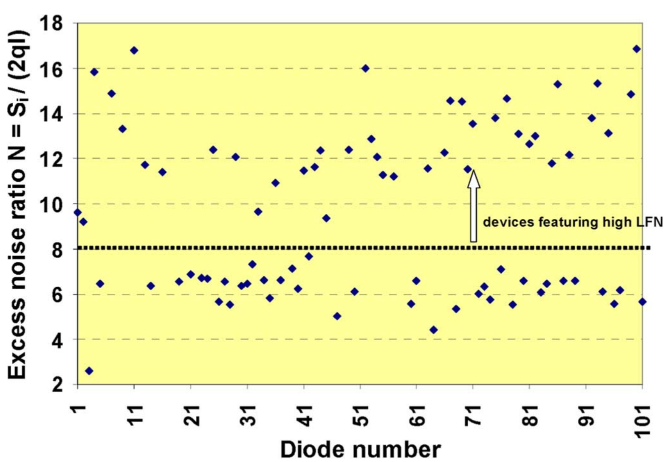

Fig. 3. Different excess noise ratios N at 20 Hz observed on a set of 101 compensated Zener diodes as received from the manufacturer. An N less than eight denotes a dominant multiplication noise, whereas an N more than eight denotes some extra defect-related noise. The few devices showing an N in excess of 18 are not shown. The black dashed line splits the graph between those devices featuring an N larger than eight and the others.

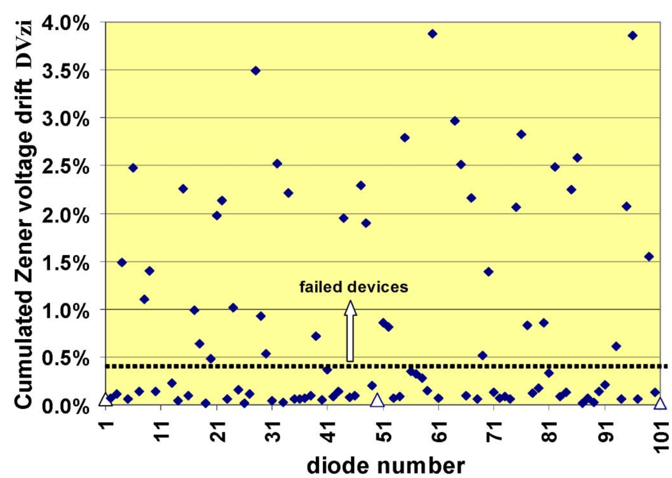

Fig. 4. Different Zener-voltage-observed cumulated-drift DVzi at 11 and 550 μA and 10 mA measured on 98 diodes after a 3000-h electrical-stress test. The three open triangles stand for the three control devices. The few devices featuring a DVzi larger than 4% are not shown. Every device featuring a DVzi more than 0.4% (dashed black line) is considered to have failed.

can first be observed that the cumulated drifts scatter between less than 0.1% and more than 4% (only the cumulated drifts less than 4% are shown on the plot, but drifts up to 50% have marginally been observed). The average drift (excluding the five more severe drifts larger than 10%) observed over 93 devices is 0.9%. The three open rectangles near the x-axis of Fig. 4 correspond to the three control devices.

We have decided that a cumulative drift less than 0.4% is the maximum that can be accommodated at the user level by a proper circuit design. This corresponds to the maximum end-of-life Zener voltage drift that is usually considered for a device operated at 85 °C for 18 years in a space-qualified assembly [8]. Therefore, all the diodes featuring a cumulative drift in excess of 0.4% are considered to have failed. Following this criterion, only 52 diodes do not fail which results in a $(98 - 52)/98 = 47\%$ failure rate after the stress.

IV. Failure-Rate Reduction From Noise Assessment

Suppose now that a lot made only of those diodes featuring an excess noise ratio N less than eight is considered: 36 diodes (39 initially but three of them have been used as the control devices and, hence, have not been submitted to the electrical-stress test) fulfill this condition. At the end of the electrical-stress test, only nine of them would have failed, and the failure rate for this lot would have therefore decreased down to 9/36 $= 25\%$. Additionally, a benefit of the proposed technique is that it allows the subtraction from the initial lot of the two diodes having experienced a catastrophic failure since they were both featuring an N in excess of eight.

Finally, the average-cumulated Zener voltage drift of these 36 “noiseless” diodes is only 0.2%, which is more than a four-fold improvement over the average drift (0.9%) of the whole

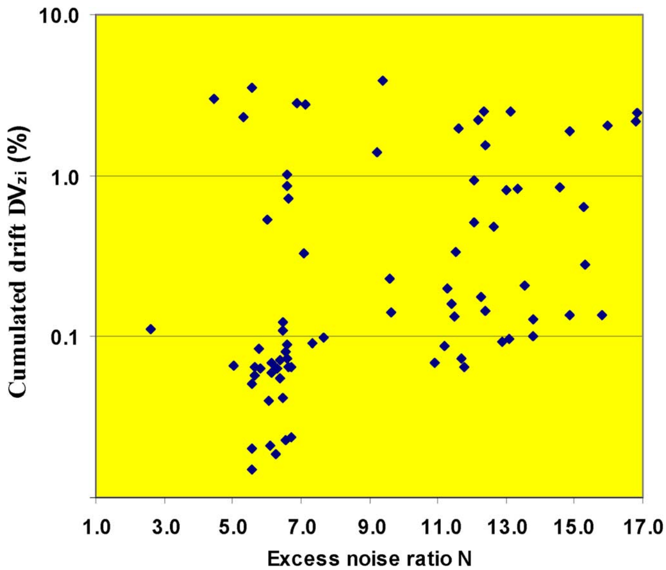

Fig. 5. Different Zener-voltage cumulated-drift DVzi after a 3000-h electrical stress versus the initial excess noise ratio N. The few devices featuring a DVzi larger than 10% are not shown.

93 devices (among 98) which have experienced a drift less than 10%. Therefore, all these data show a serious improvement of the reliability of a lot of diodes screened from straightforward LFN measurements. Fig. 5 shows that those diodes featuring an N below eight are less prone to a stress-induced Zener voltage drift than the others.

Additionally, a lot of 34 diodes has been electrically stressed up to 4500 h. At the end of the stress, only 16 diodes among the 34 ones exhibit a cumulated drift less than the 0.4% retained as the failure criterion. It results in a $(34 - 16)/34 = 53\%$ failure rate for this lot.

Among these 34 diodes, only seven were initially featuring a noise ratio less than eight, and none, among these seven diodes, was featuring a cumulated drift more than 0.4% after a 4500-h electrical-stress test: Therefore, the failure rates of a lot of diodes, which could have been made with only these seven diodes selected from the initial LFN measurements, would have been reduced down to 0%.

Finally, the question is which mechanism and which kind of defects could be invoked in order to explain the observed data. A drift of the Zener voltage in a diode subjected to a large current density over a large time period could be the consequence of some metal migration. Additionally, it has already been reported [9] that metal migration could be accelerated along defect tubes. Therefore, a diode featuring more defects, as evidenced by a higher excess-noise level, could be more prone to metal migration and, hence, to a higher Zener voltage drift induced by an electrical stress. The dislocations in space-charge region could possibly [8] be the invoked defects.

V. Conclusion

From either a 3000- or a 4500-h electrical-stress test, it has been observed that screening the compensated Zener diodes from their LFN properties can dramatically improve the observed average failure rate of a given lot (a 0% average failure rate is anticipated after a 4500-h life compared with an observed 53% without any screening test). The proposed technique consists in a 20–30-Hz room-temperature moderate reverse-bias noise characterization of all the devices from a lot and in subtracting from this lot all the devices featuring an observed defect-induced LFN. This technique can be easily implemented at the end of the device process and test flow and can therefore contribute to the production of high-reliability devices at a reduced cost.

Based on the aforementioned results and on the previously reported ones [1, 5,...,] it can therefore be stated that the very basic and straightforward $1/f$ noise measurements can efficiently screen different types of diodes and more specially different types of Zener diodes in high-reliability applications. Our results show that these noise measurements can efficiently be conducted at bias levels different from the normal operating ones in order to enhance the observed-induced defect noise over the regular noise or to prevent any possible device stress during the noise measurements. They also show that they are still effective in a structure that is more complex than a single diode.

Nevertheless, it must be stated that such a result can be obtained only if the LFN noise-measurement conditions are carefully selected; they depend on the active-device structure and on the active-device future use. By way of example, they probably will not be the same for a diode to be used as a reference voltage or for a diode to be used as a nonlinear device. Therefore, in-depth preliminary investigations are needed for each new active structure that is intended to be screened with this technique.

Its applicability to two-port devices needs also to be investigated.

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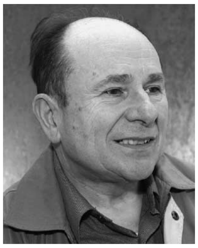

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