SAND2017-7761C

Power Spectrum Analysis (PSA)

Paiboon Tangyunyong, Edward I. Cole Jr., Guillermo M. Loubriel, Joshua Beutler, Darlene M. Udoni, Biliana S. Paskaleva, and Thomas E. Buchheit
Sandia National Laboratories, Albuquerque, New Mexico, USA
e-mail address: ptangyu@sandia.gov

Abstract

We present a new, non-destructive electrical technique, Power Spectrum Analysis (PSA). PSA as described here uses off-normal biasing, an unconventional way of powering microelectronics devices. PSA with off-normal biasing can be used to detect subtle differences between microelectronic devices. These differences, in many cases, cannot be detected by conventional electrical testing. In this paper, we highlight PSA applications related to aging and counterfeit detection.

Introduction

PSA measures the dynamic frequency-domain responses of a microelectronics device when subjected to dynamic stimuli. Unique PSA signatures exist in the power spectrums associated with each device, and these signatures are found to be sensitive to subtle device changes.

We present a new electrical technique based on PSA that uses off-normal biasing to stimulate devices [1]. Off-normal biasing refers to powering conditions that are not used in conventional electrical testing. There are several ways of implementing off-normal biasing. An example is to bias a device with a square-waveform voltage (Fig. 1) between the power (V_{DD}) and ground (V_{SS}) pins, with all the other input and output pins floating. The magnitude of the square-waveform voltage is typically less than or equal to the device operating voltage. The example in Fig. 1 shows the square-waveform pulses (from 0 to 4.5 V) for a 5 V microcontroller. The device responds to these pulses by loading on the square-waveform voltage. The amount of loading depends on the device's dynamic impedance. The frequency of the square-waveform voltages depends on the device and ranges from 1 kHz to 1 MHz.

The top left plot in Figure 1 shows the time-domain, voltage waveforms before (top black curve) and after (bottom red curve) they are connected to a 40-pin microcontroller; the top black curve is taken with no device in the test fixture. The two waveforms are offset for display on the plot. The corresponding frequency-domain PSA spectra are shown in the bottom two plots. After the square-waveform voltage is connected to the device, there is a slight distortion in the voltage waveform (denoted by the blue dashed circle in the top left plot of Fig. 1). This slight distortion creates a distinct fingerprint in the PSA spectra (bottom right plot of Fig. 1).

Off-normal biasing does not require detailed electrical knowledge of the test device. The package pin layout and the normal operating voltage are the requirements needed to bias the device shown in Fig. 1.

PSA is non-destructive and has short acquisition times (typically less than 15 seconds). PSA is a comparative technique; comparing the spectra of a test sample to those of a single or population of standard or control samples. PSA can be used to detect subtle differences between microelectronics devices. These differences, in many cases, cannot be detected by conventional electrical testing.

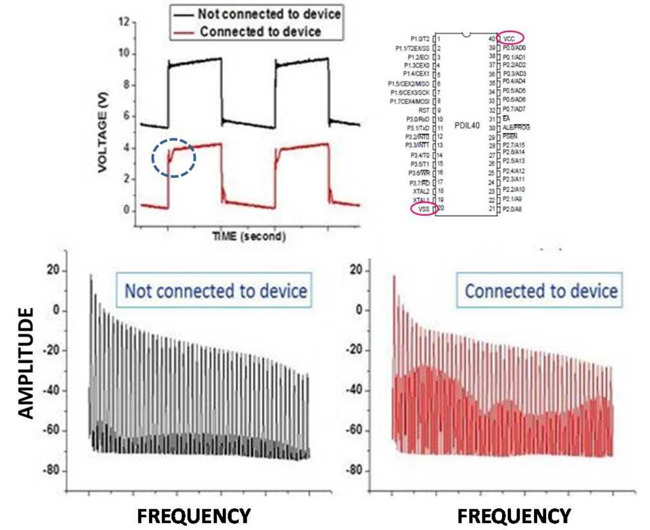

Figure 1: Time-domain, square-waveform voltages (top left image) with offsets for display before (top black curve) and after (bottom red curve) connecting to the microcontroller pins shown in the top right image; only power (V_{DD}) and ground (V_{SS}) pins are connected with all the input and output pins floating. Corresponding frequency-domain PSA spectra are shown in the bottom two plots.

PSA has successfully been used to characterize various devices ranging from discrete components (e.g., diodes and transistors) to complex integrated circuits (ICs) such as microcontrollers, FPGAs and high-density memory devices. PSA has been used for digital, analog, and mixed-signal ICs; analog and mixed-signal devices may require a different off-normal biasing scheme with more than power and ground pins connected to the device.

Statistical methods such as principal component analysis (PCA) has been used in conjunction with PSA to analyze measurements. PCA [2] is a long-established statistical method for data sets with a large number of variables such as those in PSA spectra. Applying PCA to PSA data facilitates visual representation of PSA in 3-D distribution plots. Other data visualizations such as histogram distribution (HD) and cumulative distribution (CD) plots have also been used to analyze PSA data. Examples of data analysis using PCA distributions, CD and HD plots are shown in later sections of this paper.

PSA Application Examples

Differences in Manufacturers

Functionally equivalent operational amplifiers from three different manufacturers were tested with conventional electrical testing. All the test parameters show similar values for devices from these three manufacturers.

PSA spectra of operational amplifiers from the three different manufacturers are shown in Figs. 2 and 3. Figs. 2 and 3 show the normalized spectra with offsets for display of the test devices using two different off-normal biasing configurations with different pin connections to the devices.

The normalized spectra are generated by dividing the PSA spectrum of the biased test device by the spectrum of the experimental setup (no device in the fixture). The reason for generating the ratio plot is that differences between devices are more easily discernible in the normalized spectra compared to the raw data.

For both biasing configurations, PSA spectra from the same manufacturer are similar (compare the red and black curves), but different manufacturers clearly show distinct PSA signatures.

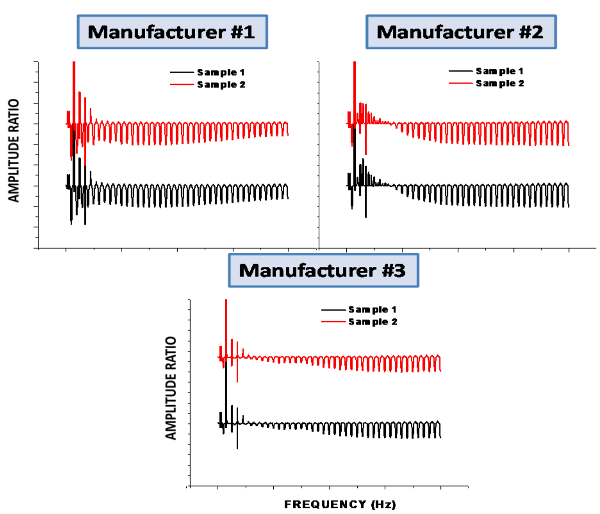

Figure 2: Normalized PSA spectra of operational amplifiers from three different manufacturers using off-normal biasing configuration 1. The PSA plots for two different samples of each manufacturer are offset for display.

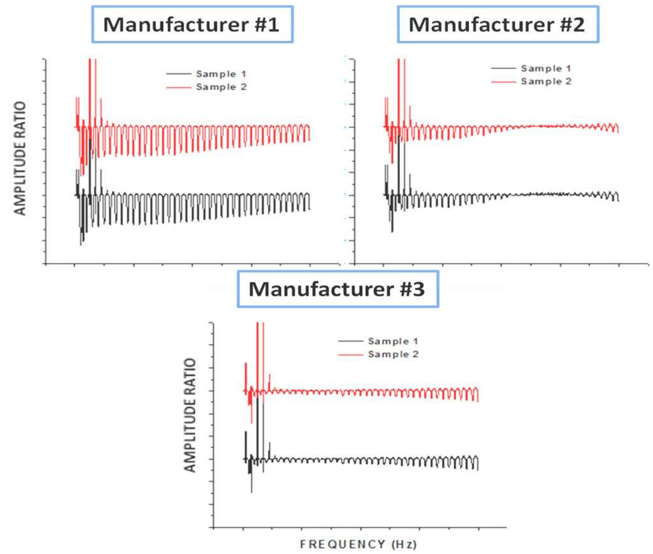

Figure 3: Normalized PSA spectra of operational amplifiers from three different manufacturers using off-normal biasing configuration 2. The PSA plots for two different samples of each manufacturer are offset for display.

Differences in Features (Memory Sizes)

Raw and normalized PSA microcontroller spectra with different memory sizes (32 kB and 64 kB) from the same manufacturer are shown in Fig. 4 and 5 respectively. The normalized spectra in Fig. 5 were generated by dividing the raw spectra shown in Fig. 4 by the spectrum of a reference (32 kB, Sample 1, top left plot in Fig. 4). The normalized PSA spectrum of the reference (top left plot in Fig. 5) was generated by taking a ratio of two successive PSA spectra of the reference. The microcontroller PSA spectra with different memory sizes clearly show distinct PSA signatures.

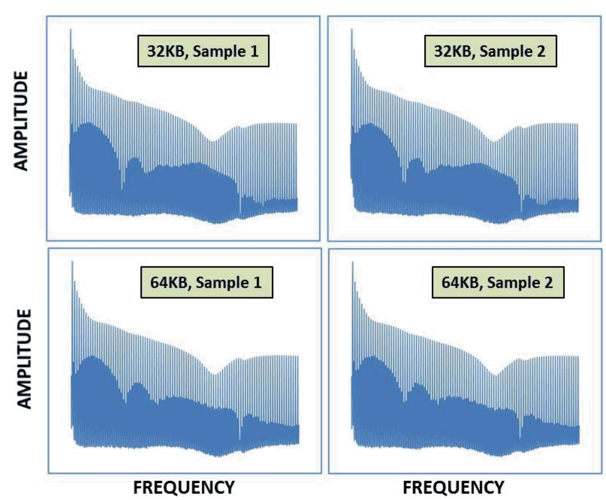

Figure 4: Raw PSA spectra of microcontrollers from the same manufacturer with different memory sizes: 32 kB (top two plots) and 64 kB (bottom two plots).

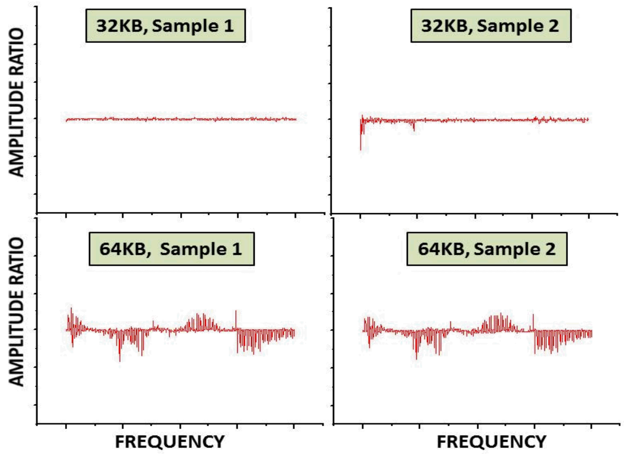

Figure 5: Corresponding normalized PSA microcontroller spectra from the raw spectra shown in Fig. 4: 32 kB (top two plots) and 64 kB (bottom two plots). The normalized spectrum was generated by dividing the PSA device spectra by the PSA spectrum of a reference (32kB sample-1 microcontroller).

Differences in Date Codes

Raw and normalized PSA spectra of "identical" 32 kB microcontrollers from the same manufacturer with two different date codes are shown in Figs. 6 and 7 respectively. The normalized spectra in Fig. 7 were generated by dividing the raw spectra shown in Fig. 6 by the spectrum of a reference (32 kB, date-code-1, sample-1 microcontroller, top left plot in Fig. 6). The normalized PSA spectrum of the reference (top left plot of Fig. 7) was generated by taking a ratio of two successive PSA spectra of the reference device.

The PSA microcontroller spectra from the same date code look similar, but are slightly different from the ones with a different date code. In contrast, conventional electrical testing cannot differentiate the devices from these two date codes; all the test-parameter values are similar for the devices of both date codes.

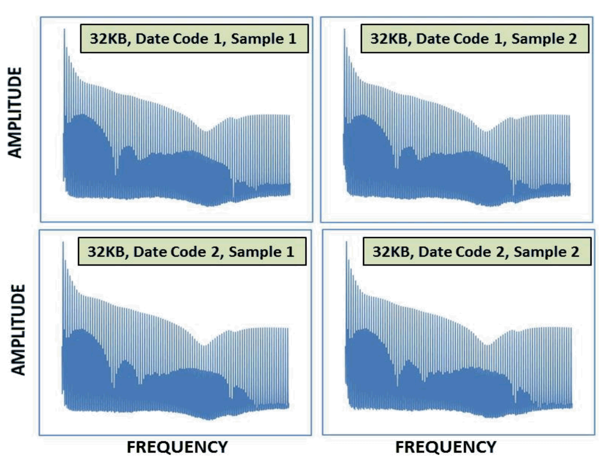

Figure 6: Raw PSA spectra of "identical" 32 kB microcontrollers from two different date codes: date code 1 (top two plots) and date code 2 (bottom two plots).

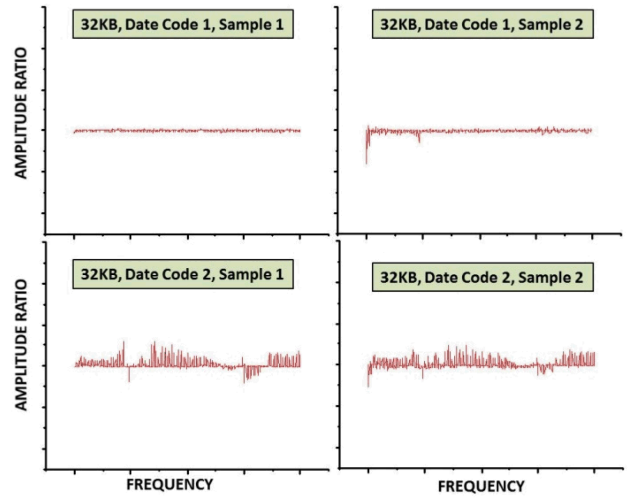

Figure 7: Normalized PSA spectra of 32 kB microcontrollers from the raw spectra shown in Fig. 6: date code 1 (top two plots) and date code 2 (bottom two plots). The normalized spectrum was generated by dividing the PSA device spectrum by the PSA spectrum of a reference (32 kB, date-code-1, sample-1 microcontroller).

PCA Distributions of Microcontrollers

PSA measurements were performed on multiple NXP microcontrollers with different memory sizes (16, 32 and 64 kB). PCA distributions of these microcontrollers were then generated from the PSA data; the PCA distributions are shown in Fig. 8.

All the 64 kB samples (filled stars) are clustered together with a slight separation between 3 different date codes (different colors: black, red, and blue). The 32 kB samples show a bi-modal distribution with samples from date code 1014 (red filled circles) appearing in a separate cluster; 32 kB samples from 4 other date codes (black, blue, purple, and dark green filled circles) appear in another cluster.

Interestingly, the 16 kB samples (open black circles) lie in the same cluster as the 32 kB samples with 1014 date code (red filled circles). Representative samples from 16 kB and 32 kB samples from each date code were jet etched to remove the packaging materials and expose the underlying dice. The optical images of representative 16 kB and 32 kB samples are shown in Fig. 9. The optical images show that the same die type is used for both 32 kB and 16 kB devices. The "labeled" 16 kB devices were actually 32 kB devices that were sold as 16 kB devices. The only difference between 32 kB and 16 kB devices was that different ID codes were programmed into the device memories. Ignoring the ID code verification, 16 kB devices can be used as 32 kB devices.

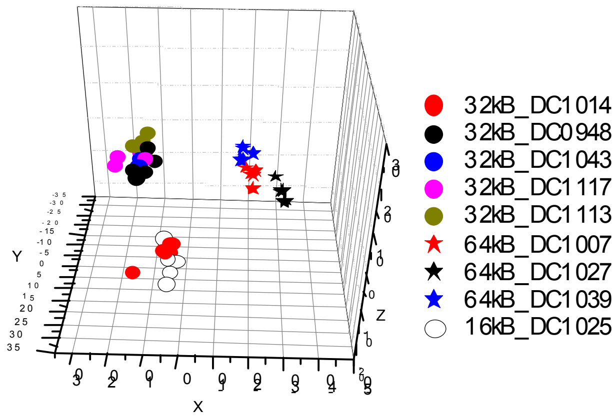

Figure 8: PCA distributions of microcontrollers with different memory sizes and date codes.

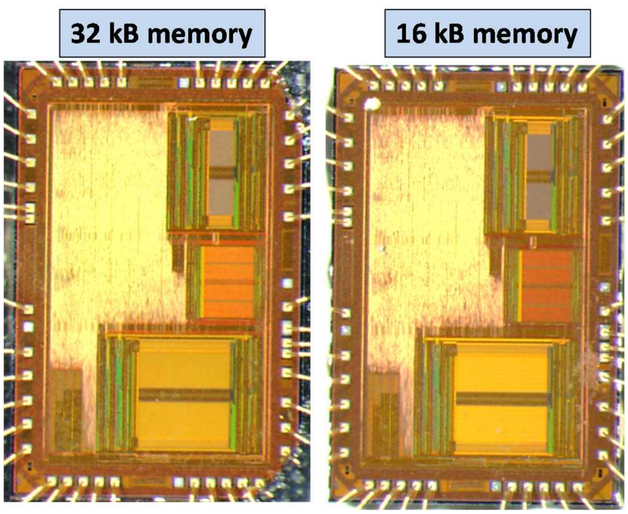

*Figure **9:** Optical images of 32 kB and 16 kB NXP microcontrollers; the same die type is used for both microcontrollers.*

Aging Detection

Fig. 10 shows the normalized PSA spectra of a representative Zener diode before and after two successive 500-hour unbiased bakes at 140 °C. Significant changes occur primarily between pre-bake and post-500-hour PSA spectra. The changes between post-500-hour and post-1000-hour spectra are much smaller. Fig. 11 shows the corresponding PCA of PSA data from multiple test samples.

The PCA distribution plots shown in Fig. 11 were generated by first extracting the PCA parameters (principal axes) of pre-bake distributions from all samples. These initial PCA parameters were then used to project and plot the subsequent distributions after two successive 500-hour unbiased bakes.

As a comparison, the distributions of the control samples are included in right image of Fig. 11. The control samples were not aged and PSA spectra of these samples were taken at the same time as the test samples during the aging processes. The PSA spectra of the control samples were used to monitor the experimental variations of PSA measurements. As shown in Fig. 11, PCA distributions of the control samples exhibit minor variations before and after the unbiased bakes, indicating stability in PSA measurements.

The PCA distribution plot in Fig. 11 indicates that most of the aging occurs within the first 500-hour bake; there is a significant shift in the distributions between the unaged population (filled black circles) and the aged population after 500-hour bake (blue filled circles). No significant changes were observed between aged populations after the 500-hour bake (blue filled circles) and those after a 1000-hour bake (pink filled circles).

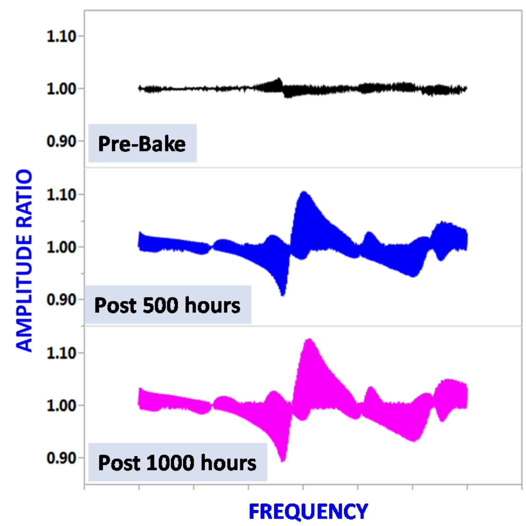

Figure 10: Normalized PSA spectra of a representative Zener diode before aging (top) and after two successive unbiased 500-hour bakes (middle and bottom).

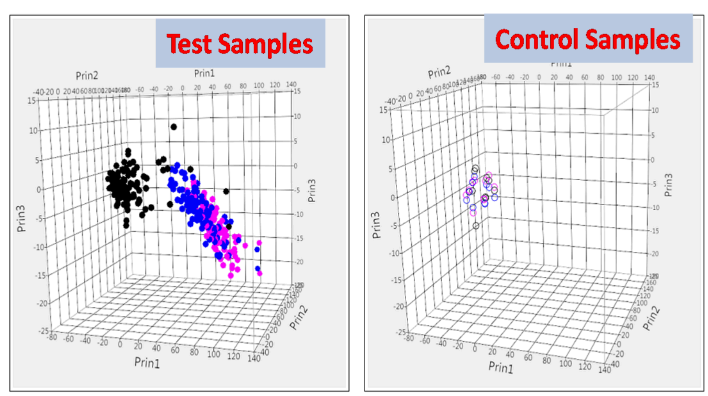

Figure 11: PCA distribution plot of Zener diodes before bake (black circles), after a 500-hour bake (blue circles), and after a 1000-hour bakes (pink circles). The distributions of both test (filled circles, left image) and control (open circles, right image) are shown.

In addition to PCA distributions, statistical parameters such as standard deviation were also calculated for each normalized PSA spectrum of the Zener diodes. Standard deviation calculation of a normalized PSA spectrum provides a quick means to determine the areas of peaks and valleys in each spectrum. The standard-deviation values were then used to generate both cumulative distribution (CD) and histogram distribution (HD) plots. Fig. 12 (left image) shows the standard-deviation CD plot of test samples' PSA spectra before and after two 500-hour unbiased bakes. There is a significant shift in the cumulative distributions between pre- and post-500-hour bake data. The shift is much smaller between post-500-hour and post-1000-hour data. As a comparison, the CD plots of 10 unaged control samples are also shown in Fig. 12 (right image); there are virtually no changes in the cumulative distributions for the control samples. Fig. 13 shows the histogram distribution (HD) plots of the standard deviation values of test samples' PSA spectra before and after two 500-hour unbiased bakes. Similar to CD plots, there is a large shift in the distributions between pre- and post-500-hour bake data, with a much smaller shift between post-500-hour and post-1000-hour data. Several outlier test diodes were also observed in the pre-bake distribution; these diodes remained outliers after the bakes.

Fig. 14 shows corresponding conventional electrical test parameters of the Zener diodes taken before and after the bakes; the test parameters include Zener voltages (VZ), forward voltages (VF), Zener impedances (ZZK and ZZT), and reverse leakage currents. In contrast to PSA results, no significant changes were observed in the test data before and after the bakes.

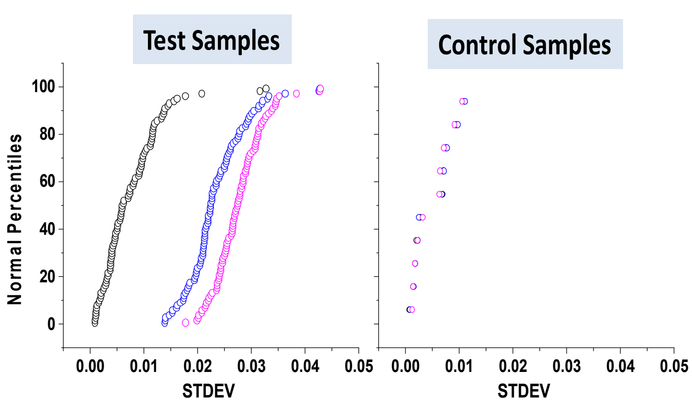

Figure 12: CD plots of standard deviation values in test Zener diodes' PSA spectra before (black circles) and after two 500-hour unbiased bakes (blue and pink circles). The distributions of both test (left image) and control (right image) samples are shown.

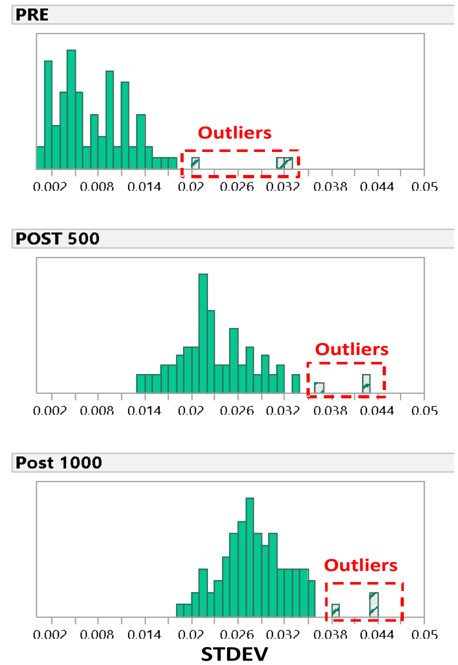

Figure 13: HD plots of standard deviation values in test Zener diodes' PSA spectra before (top plot) and after two 500-hour unbiased bakes (middle and bottom plots).

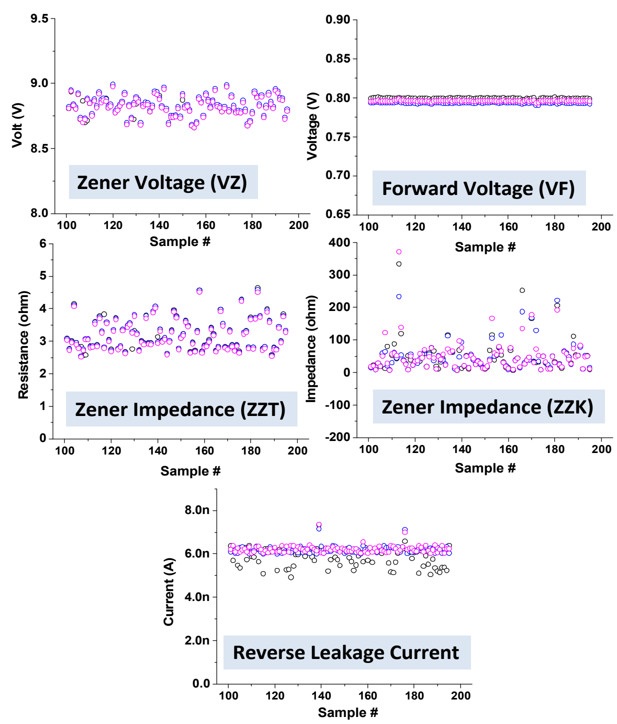

Figure 14: Electrical test data of Zener diodes before aging (black open circles) and after two unbiased 500-hour bakes (blue and pink open circles). No significant changes are observed before and after the bakes.

Physical analysis was performed on representative unaged and aged samples using mechanical polishing to expose the bond-pad areas. The SEM images of represenative unaged and aged samples are shown in Fig. 15. The preliminary results show a good correlationship between PSA data and results from physical analysis; the aged sample in Fig. 15 shows growth of Cu-Al intermetallic layer at the bond-pad area, corresponding to a large shift in PCA distributions (Fig. 11) after aging. The growth of Cu-Al intermetallic layer may be the reason for the observed PSA changes.

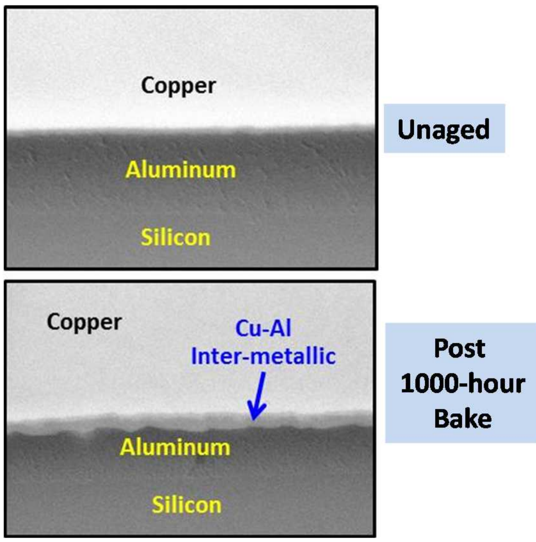

Fig. 15: SEM images of cross sections of bond-pad areas of unaged (top) and aged (bottom) of Zener diode. The aged sample shows growth of a Cu-Al inter-metallic layer at the bond pad.

Summary

A new, non-destructive electrical technique, Power Spectrum Analysis (PSA) with off-normal biasing was presented. Off-normal biasing refers to powering conditions that are not used in conventional electrical testing. PSA with off-normal biasing can be used to detect subtle differences between microelectronics devices. These differences, in many cases, cannot be detected by conventional electrical testing. We have highlighted applications related to aging and counterfeit detection.

References

[1] P. Tangyunyong, E. I. Cole, Jr., and D. J. Stein, *"Power Spectrum Analysis for Defect Screening in Integrated Circuit Devices.*" US patent 9,188,622, issued November 17, 2015.

[2] I.T. Jolliffe, *Principal Component Analysis: Springer Series in Statistics, 2nd* ed., Springer (New York, 2002).

Acknowledgements

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.