SAND2016-12238C

Various Applications of Power Spectrum Analysis (PSA)

Paiboon Tangyunyong, Darlene M. Udoni, and Guillermo M. Loubriel
Validation and Failure Analysis Department
Sandia National Laboratories, Albuquerque, NM 87112

Abstract: *Power Spectrum Analysis (PSA) is being studied as a counterfeit detection tool. We describe other possible applications: process monitoring, tracking changes in packaging, and changes due to gamma-ray exposure.*

Keywords: Power Spectrum Analysis; PSA; Process Monitoring; Package; Gamma-ray Exposure

Introduction

Power spectrum analysis (PSA) measures the dynamic frequency-domain responses of an integrated circuit (IC) when subjected to dynamic stimuli. Unique PSA signatures exist in the power spectrum associated with each IC, and these signatures are found to be sensitive to subtle changes in the IC. PSA has been an effective tool in detecting differences between genuine and counterfeit devices once differentiating signatures have been identified [1]. PSA has also been used to study the aging effects when devices are subjected to accelerated aging [2].

In this paper, we describe other applications of PSA that are not directly related to counterfeit and aging detection. We describe the use of PSA as a monitor tool to track changes resulting from process variations in IC fabrication. By changing the biasing conditions, we show that PSA can differentiate changes that originate from package. We also show that changes due to radiation (gamma-ray) exposure can also be detected by PSA.

PSA Basics

PSA uses off-normal biasing to stimulate devices. Off-normal biasing refers to powering conditions that are not used in regular testing. One of the off-normal biasing conditions is to pulse the device with periodic waveform voltages between the power (VDD) and ground (VSS) pins with all the input and output pins floating. The device responds to these pulses by loading on the periodic waveform voltage. The amount of loading depends on the device dynamic impedance. Figure 1 shows an example of the off-normal biasing on a device with square-waveform voltages; the top plot in Figure 1 shows the voltage waveforms before (top black curve) and after (bottom red curve) they are connected to a device. The corresponding 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). This slight distortion creates a distinct fingerprint in the PSA spectra (right bottom plot of Fig. 1).

PSA is non-destructive and the dynamic stimuli used in PSA measurements are within the normal device operating conditions. PSA has short acquisition times (typically less than 20 seconds). PSA normally uses a "gold" standard as a reference for comparison.

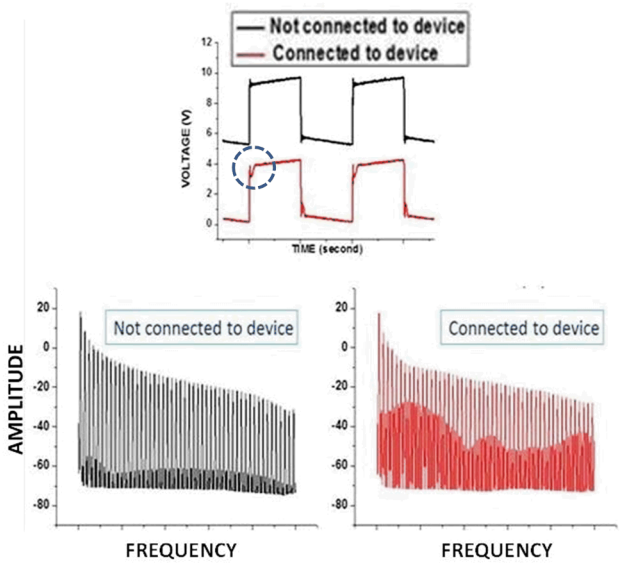

Figure 1. Square-waveform voltage (top plot) before (top black curve) and after (bottom red curve) connecting to a device under test. Corresponding PSA spectra of the waveform voltages are shown in the bottom two plots.

Process Monitoring

Figure 2 shows the PSA spectra of a Sandia-manufactured ASIC from two different lots (Lot 1 and Lot 2). Figure 3 shows the corresponding Principal Component Analysis (PCA) analysis of PSA data from multiple devices of these two lots. PCA [3] is a long-established statistical analysis method that reorganizes a data set with a large number of variables such as in PSA spectra. Applying PCA to PSA data allows the visual representation of PSA data in 3-D distribution plots.

There are some minor processing differences between Lot 1 and Lot 2 and these differences are not observed with conventional electrical testing. PSA can, however, detect differences between these two lots. PCA analysis produces

two separated clusters as shown in Figure 3 corresponding to these two lots. We believe that the observed differences in PSA are most likely the result of the difference in contact etch. There is no in-situ clean in Lot 1, but there is an in-situ clean in Lot 2; this difference in contact etch may result in minor differences in contact resistance that is observable by PSA.

In Lot 2, there is also a process split between odd and even wafers; the difference between the split is in the metal-etch step. Figure 4 shows the PCA distributions of both even and odd wafers for Lot 2. There is a slight separation between even-wafer (open blue squares) and odd-wafer distributions (open pink squares). The odd-wafer distribution is situated closer to the Lot-1 distribution, compared to the even-wafer distribution.

Figure 5 shows the edge-die and non-edge-die distributions of Lot 2. Most of the edge dice (filled blue squares) are located near the edge of the Lot-2 distribution. In addition, the large majority of the outliers (circled in the figure) are from the edge-die population. Even though electrical testing does not show any significant differences between edge-die and non-edge-die samples, PSA results appear to indicate there are subtle process variations during fabrication for the edge-die devices compared to the non-edge-die devices, resulting in differences in the spectra that produce both edge distributions and outliers.

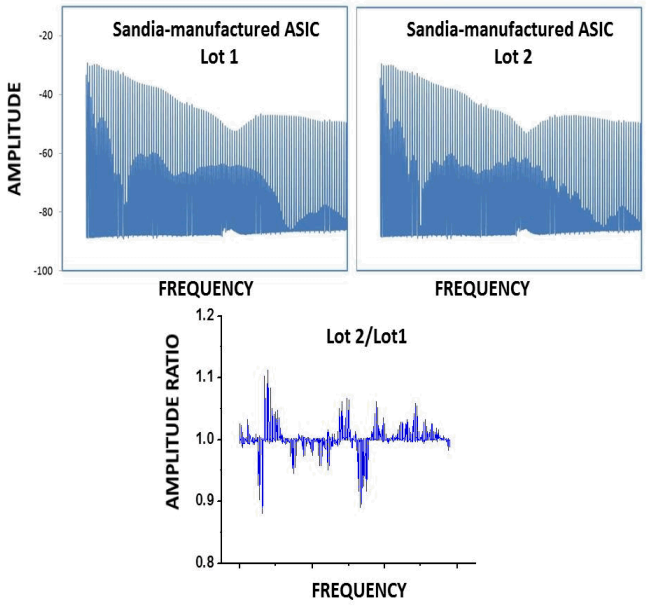

Figure 2. Representative PSA spectra of Sandia-manufactured ASICs from two different wafer lots, Lot 1 and Lot 2 (top two plots). The differences between PSA spectra of these two lots are much more discernible in the normalized or ratio plot shown in the bottom plot.

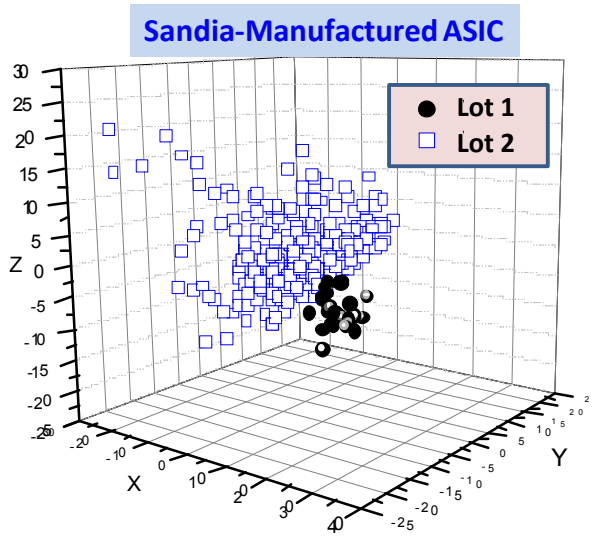

Figure 3. Corresponding Principal Component Analysis (PCA) analysis of PSA data from multiple devices from Lot 1 and Lot 2 shown in Figure 1.

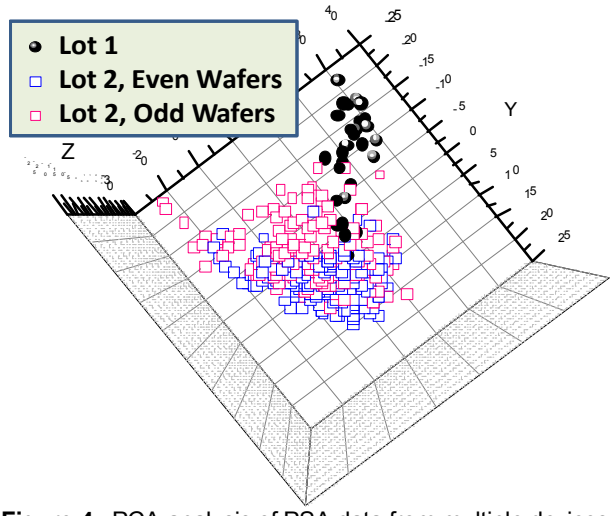

Figure 4. PCA analysis of PSA data from multiple devices of Lot 2 showing a slight separation between even-wafer and odd-wafer distributions.

Figure 6 shows the PCA distribution of multiple devices of an additional lot, Lot 3. The distributions of both Lot 1 and Lot 2 are also shown in Figure 6 as a comparison. As expected, there is a significant overlap between Lot-2 and Lot-3 populations. This was not surprising since the devices from Lot 2 and Lot 3 were fabricated with similar processing steps.

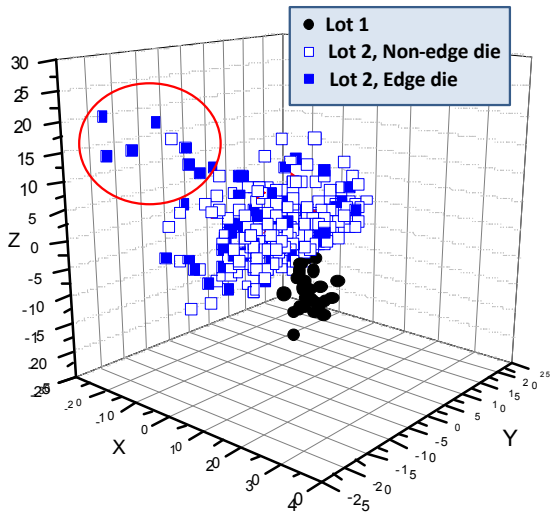

Figure 5. PCA analysis of PSA data from multiple devices from Lot 1 and Lot 2. The distributions of edge-die (filled blue squares) and non-edge-dice (open blue squares) devices are shown in the Lot-2 population.

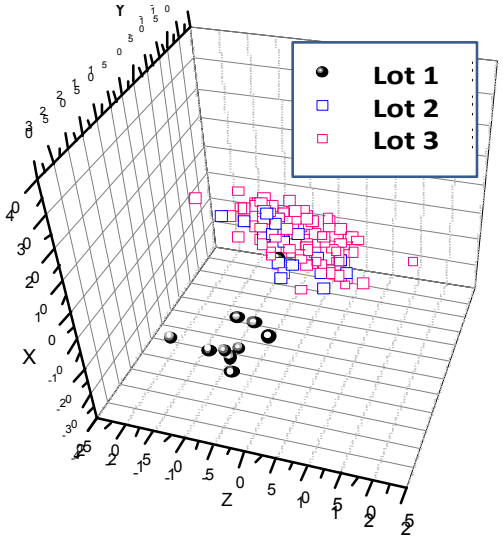

Figure 6. PCA analysis of PSA data from multiple devices of 3 different lots: Lot 1, Lot 2, and Lot 3; there is a significant overlap between Lot-2 and Lot-3 populations.

Package Differentiation

In the previous sections, PSA biasing conditions (voltage levels and frequency of the square waveforms) are tailored to bring out difference in the die. PSA biasing conditions can also be tailored specifically to detect differences that are originated in the package. An example of package differentiation is shown in Figure 7. Figure 7 shows the PCA distributions from Sandia-manufactured devices from Lot 1 and Lot 2 using two different types of packages (Package 1 and Package 2). Lot 1 and Lot 2 are the same two lots described in previous sections. PCA analysis in Figure 7 shows two distinct distributions corresponding to Package 1 (open circles) and Package 2 (filled circles). The physical differences between these two types of packages are shown in Figure 8. Interestingly, electrical acceptance testing (focusing on functional, and AC/DC parametric test) does not show any differentiation between devices from these two types of packages.

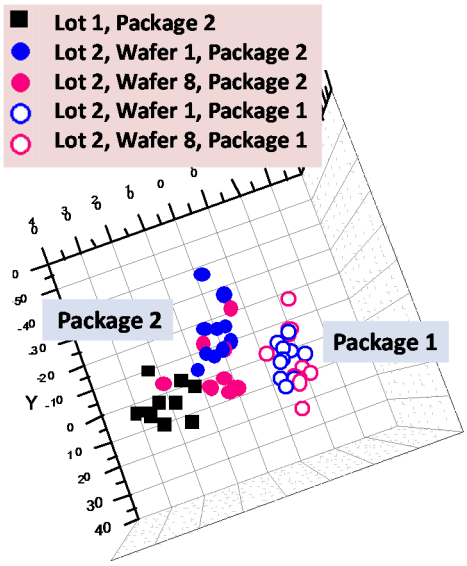

Figure 7.

Figure 7. PCA analysis of PSA data from multiple devices of 2 different lots (Lot 1, Lot 2) showing two distinct populations corresponding to Package 1 and Package 2.

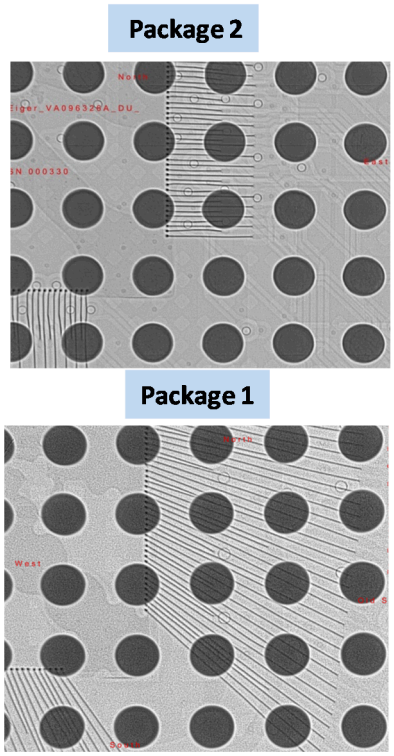

Figure 8. Optical images showing differences between Package 1 and Package 2 that were used for Sandia-manufactured ASICs.

Detection Changes due to Gamma-ray Exposure

PSA can also be used to detect changes due to gamma-ray exposure. Figure 8 shows the PSA spectra and distributions of Sandia-manufactured ASICs before and after 1-Mrad gamma-ray exposure. No significant changes were observed in conventional electrical testing for exposed and unexposed sample, but significant differences were observed in PSA before and after exposure.

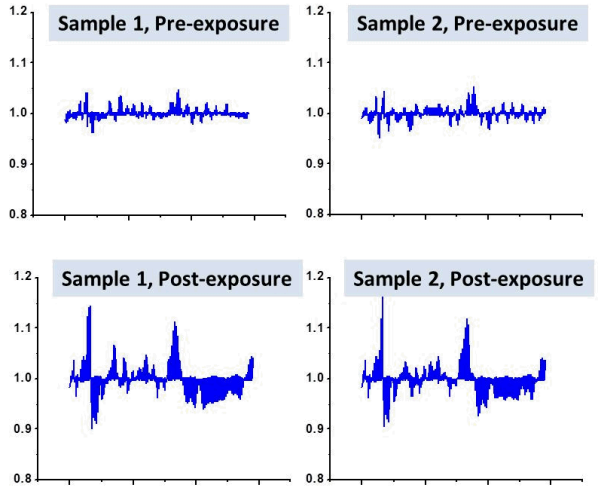

Figure 9. Normalized PSA spectra for Sandia-manufactured devices before and after 1-MRAD, gamma-ray exposure.

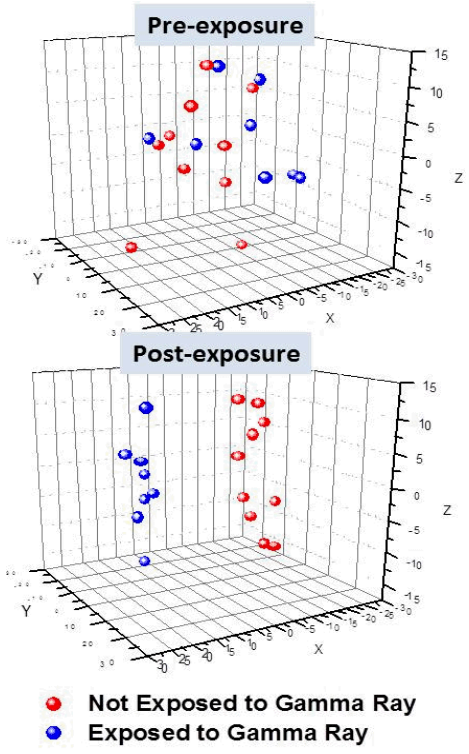

Figure 9. PCA distributions for Sandia-manufactured devices before and after 1-MRAD, gamma-ray exposure.

Conclusion

We have shown that PSA can be applied to other applications that are not directly related to counterfeit and aging detection. PSA can be used as a monitor tool to track changes resulting from process variations in IC fabrication. PSA can be tailored to differentiate changes that originate from package by using specific biasing conditions. Changes due to gamma-ray exposure can also be detected with PSA.

References

1. Tangyunyong, P., Cole, Jr., E. I., Loubriel, G. M., and Beutler, J., "Counterfeit Detection Using Power Spectrum Analysis (PSA)," *Proceedings of GOMACTech 2015*, St. Louis, Missouri, March 2015, pp. 29-32.
2. Tangyunyong, P., Paskaleva, B., Udoni, D. M., Buchheit, T. E., Loubriel, G. M., Stinnett, R. W., and Cole, Jr., E. I., "Aging Detection in Zener Diodes Using Power Spectrum Analysis (PSA)," *Proceedings of GOMACTech 2016*, Orlando, Florida , March 2016, pp. 81-84.
3. Jolliffe, I.T. *Principal Component Analysis, Series: Springer Series in Statistics, 2nd* ed., Springer, NY, 2002.

Acknowledgements

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL8500.