Journal of
INDUSTRIAL
TECHNOLOGY

Volume 18, Number 2 - February 2002 to April 2002

Investigating Electrical Noise Signals in Metal Thin Films with Different Geometry

By Dr. Gholam H. Massiha & Mr. Kuldeep S. Rawat

KEYWORD SEARCH

Electricity
Electronics
Materials & Processes
Materials Testing
Research

Reviewed Article

The Official Electronic Publication of the National Association of Industrial Technology • www.nait.org

Investigating Electrical Noise Signals in Metal Thin Films with Different Geometry

By Dr. Gholam H. Massiha & Mr. Kuldeep S. Rawat

Dr. Gholam H. Massiha is an Elio Girard/BORSF professor in engineering in the Department of Industrial Technology at University of Louisiana at Lafayette. He has ten years of full-time faculty teaching experience. His areas of expertise are in experimental and theoretical microelectronics, VLSI, microprocessor and control systems, and solar energy research. He has designed, built and investigated VLSI, IC semiconductor devices, and electronic circuits for reliability measurements.

Mr. Kuldeep S. Rawat is currently working towards his Ph.D Degree in Computer Engineering at Center for Advanced Computer Studies (CACS), University of Louisiana at Lafayette. He received the Bachelor degree in Electronics Engineering from Bombay University, India, in 1997, and the Master Degree in Computer Science from University of Louisiana at Lafayette, in 2001. He also worked for two years in the R&D division of Procter & Gamble in Bombay, India. His research interests are in low power VLSI design, image and video compression, digital signal processing and data acquisition systems.

Abstract

The demands for reducing the size of integrated circuits (IC) at higher operating speeds are driving the semiconductor industry to reduce feature dimensions of circuit components and metallic interconnections. As device sizes on the chip become smaller, the reliability of the integrated circuit becomes limited by the performance of these metallic interconnections. The excess noise measurement is a fast and non-destructive method in studying reliability problems related to thin metal films. Low frequency (LF) noise measurements were performed on thin metal films of three different geometries. These measurements were carried out under stressing current densities and at different ambient temperatures up to 200 ^{o}C. Noise spectra measurements were found to be a function of ambient temperature and current density. Under these conditions thin metal films exhibited to have a $1/f^{\alpha}$ type noise component. Studying $1/f^{\alpha}$ noise measurements as a function of temperature showed that the value of α closely resembled the same pattern as that of the excess noise magnitude. Furthermore, a discussion of the measurement system and technique to investigate excess noise in thin metal films is presented. It was found that the thin metal film with higher resistance is more reliable and its results are analyzed in the paper. The excess noise measurement on the metal thin films of different geometry helps in understanding reliability problems related to film structure and dimensions.

***Keywords**: Excess noise, Metal thin films, reliability, and measurement system.*

Introduction

Metal thin films form a major part of modern technology. They are widely and successfully used in all-pervasive semiconductor technologies. In the extremely competitive international integrated circuit (IC) market, companies are driven to produce ever more complex IC designs at an ever lower cost per function. This compulsion has been the force behind the continual scaling down of device dimensions while increasing reliability against device failure. As a result, production becomes economically feasible only if defect densities and process variability are steadily reduced. The decrease in the thin film dimension has caused a rise in current density and has led to a reliability problem of metallic thin films. Several techniques have been introduced to study defects in metal thin films. These defects can be grouped into electromigration, aluminum micro cracks, contact alloying problems, and bonding problems. The phenomenon of the electromigration, the mass transport of metal ions in the thin metal films under high current density, was recognized in early 80's as the most prominent device failure mode (Fleetwood & Giordano, 1985).

The excess noise measurement technique is much faster than the conventional median-time-to-failure (MTF) method and is non-destructive in nature, which makes this technique an ideal tool for the study of electromigration phenomenon in thin films (Ghate, 1982). There are several well-known competing theories regarding the properties of excess noise in metal thin films. In general, depending on the spectral shape of the noise power, these studies can be divided into two groups: one that concentrates on 1/*f* (one-over-f) noise and other on $1/f^2$ noise. We refer to $1/f^{\alpha}$ noise with $0.7 \leq \alpha < 1.4$ as 1/*f* noise or low-frequency noise. This project was carried out as a part of grant Dr. Massiha received from Louisiana Board of Regent, grant number: LEQSF (1999-02)-RD-A-54. This project was sponsored to introduce undergraduate and graduate students in the Department of Industrial Technology at the University of Louisiana at Lafayette to study electrical noise measurement as a tool to understand device failure mechanism and the effect of structural geometry of device on its reliability. Industrial Technology in 21st century covers wide range of fields in technology. As the subject of reliability in semiconductor devices has gained importance more and more students take keen interest in learning it. This research project gives them the hands-on experience with the latest equipment, research techniques and testing methods used in semiconductor industry. In this paper we report, the 1/*f* noise measurements in metal thin films of different geometry. In the next section a brief introduction about the electrical noise and the noise measurement system will be presented. The later part of the paper will focus on the samples used and the investigation of 1/*f* noise in these samples. Finally, we conclude with results obtained and the relevant conclusion drawn.

Electrical Noise Theory

Noise in a broad sense can be defined as an unwanted signal or disturbance. Three main types of noise mechanisms are referred to as the thermal noise, shot noise, and low-frequency excess noise. Thermal noise is caused by the random thermally excited vibration of the charge carriers in a conductor. Shot noise is found in tubes, transistors, and diodes. Shot noise is associated with current flow across a potential barrier. Low frequency or excess noise was first observed in vacuum tubes; this noise was called flicker noise (Herman, 2000). The excess noise has also been observed in non-electrical and physiological phenomenon. Studies of 1/*f* noise have shown that the major cause of 1/*f* noise in semiconductor devices is traceable to the surface of the material (Ciofi, Dattilo & Neri, 1999).

The noise power spectral density of a DC biased metal thin film consists of the thermal noise and excess noise components. The thermal noise power spectral density term can be measured without applying current or it can be easily estimated using $S_v = 4k_BRT$, where S_v is the spectral density due to the fluctuation in the voltage across the terminals of the conductor, k_B is the Boltzmann's constant, if temperature T and resistance R of the sample is known. The thermal noise exists in all devices with finite conductivity at temperatures above absolute zero, and it determines the minimum level of noise in the test sample. However, when the noise measurement system is used, an additional noise can be generated through the preamplifier, biasing circuit, multimeters, power supplies, and connecting wires. This noise is called the system noise $S_{v\,system}$. The sum of the test sample thermal noise and the system noise determines the minimum level or background noise, $S_{v\,bgn}$.
The total noise $S_{v\,total}$ can be written as:

$$S_{v\,total}(f) = 4k_BRT + S_{v\,system}(f) + \frac{KV^{\beta}}{f^{\alpha}}$$

$$= S_{v\,bgn}(f) + \frac{KV^{\beta}}{f^{\alpha}} \qquad (1)$$

Where K and ^{2} are constants, *f* is the frequency, and V is the voltage across the conductor.

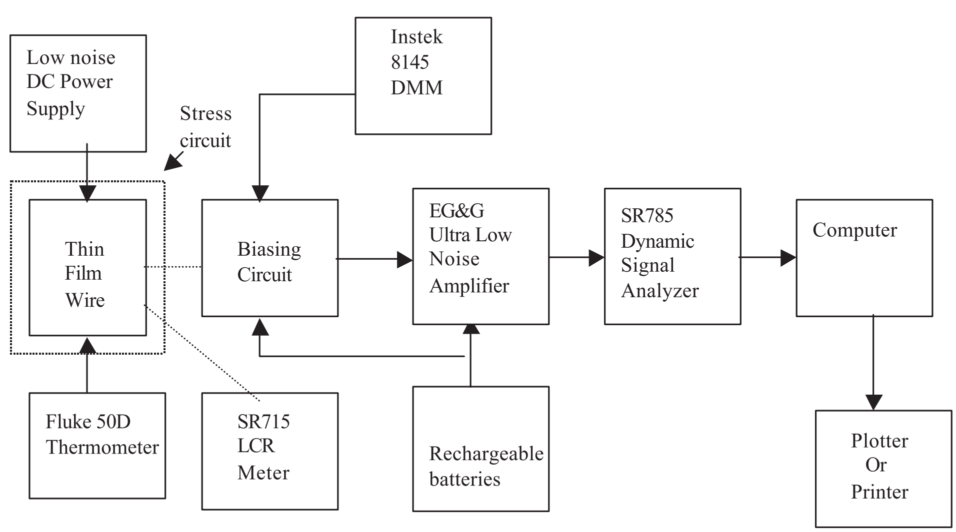
In this project the $S_{v\,bgn}$ was measured when the entire system was operating with no DC current passing through the thin film.

Electrical Noise Measurement System

A typical low-frequency electrical noise measurement system has a set-up consisting of four important parts: SR785 Dynamic Signal Analyzer, EG&G 5184 Ultra Low Noise Voltage Preamplifier, and SR715 LCR meter and Biasing circuit. The function and characteristics of each part will be described next. A block diagram of complete noise measurement system is shown in Figure 1.

1. SR785 Dynamic Signal Analyzer: The SR785 is dual channel and performs Fast Fourier Transform (FFT) to obtain the spectral density of an input voltage signal. One important feature of

Figure 1: Electrical Noise Measurement System.



this is different types of averaging modes, which are necessary in a given frequency range to reduce the variance of the final plot. Furthermore, the trace storage, retrieval, capture buffer and the math function are used to save and subtract background noise from the final measurement.

2. EG&G Ultra Low-Noise Voltage Preamplifier:
The excess noise generated by a resistance sample used is in the ρV to ηV range. The sensitivity of a SR785 signal analyzer is limited to detect input noise of about 10ηV/√Hz at 200 Hz. For this reason a very low noise preamplifier is needed to amplify the noise signal to drive an input of the signal analyzer. The gain provided by the preamplifier is a fixed 60 dB.

3. SR720 LCR Meter:
The LCR meter is capable of measuring the resistance, inductance and capacitance while the current flows through the sample. The resistance of a sample changes when an electric current flows through it. In noise measurement we have to keep track of the resistance of the metal thin films when the current is flowing through it.

4. Biasing Circuit:
To achieve a fixed range of current density across the sample, a biasing circuit was designed and fabricated. Depending on the required current density, a few batteries in series with resistances were connected to provide the biasing voltage. The batteries are used instead of a power supply to avoid electrical noise, which adds to the 1/*f* noise to be measured. This can induce an error in the measurement of the actual electrical noise generated when the current is passed through the sample. Very low noise power supplies, can also be used, if available. For more detailed description on electrical noise measurement system, refer to http://electricalnoise.net for detailed description on how to use this measurement system.

Figure 2: Schematic Layout of the Thin Metal Film Sample.

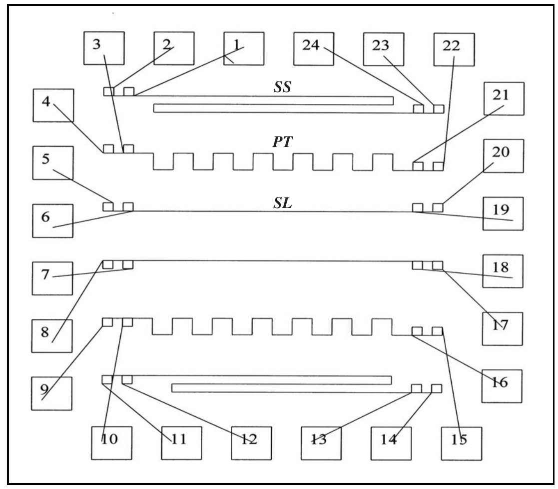


Figure 3: Scanning Electron Microscope Picture of the Sample.

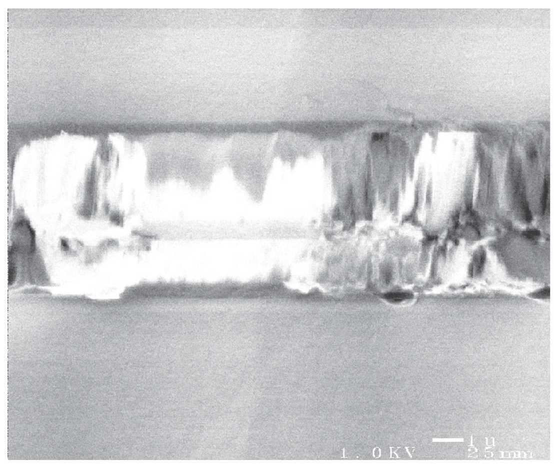


Table 1: Average Dimensions and Resistance of the Thin Metal Samples.

Thin Film Type	Parameter (mm)	Resistance (Ohms)
Single Step (ST)	Thickness = 3.55	81.4
Pulse Train (PT)		59.7
Straight Line (SL)	Height = 2.44	37.2

Metal Film Sample Characteristics

The 1/*f* measurements were carried out on two samples. The layout of the selected sample with metal thin film contacts is shown in Figure 2. Each sample has two sets of three metal thin film contacts. Each metal film has different geometry. Metal thin films on the sample are categorized as straight line (SL), pulse train (PT), and single step (SS). Samples for the project were fabricated by Dr. Wilferdo Moreno at University of South Florida. The selected samples were inspected using a Scanning Electron Microscope (SEM) for dimensions and any damage. Figure 3 shows the SEM picture of the sample used. Table 1 shows the average dimension and resistance of the set of three Metal thin films samples.

After we made sure that the samples were of appropriate quality we studied the changes in the resistance of the metal thin film sample with the increase in the temperature. This temperature versus resistance data was collected on all types of VLSI samples used in the project. This data has significance because it was reported that the magnitude of excess noise in metal thin films is temperature dependent (Scofield & Mantese, 1986). A drift in resistance during the measurement implied that the metal thin film is damaged.

Investigating 1/f Noise

The Figures 4a, 4b, 4c show a noise power spectral density S*v* (f) for some selected frequencies in the range 3-80 Hz obtained from all the three different shaped thin metal films biased at current density 1.0 x 10^6 A/cm^2 at 190 ^{o}C. To capture 1/*f* noise spectra we first measured the thermal and system noise ($S_{v\ bgn}$) when the entire system was operating with no DC current passing through the thin metal film. This spectrum was captured and stored in the spectrum analyzer. Next the thin metal film was biased at current densities between 1.0 x 10^6 A/cm^2 and 2.2 x 10^6 A/cm^2 and the ambient temperature was raised from 23 ^{o}C to 200 ^{o}C. These spectra were again captured and stored. Using features of the SR785 dynamic signal analyzer, back-

Figure 4a. Noise Power Spectral Density (Sv) vs. Frequency for Straight Line

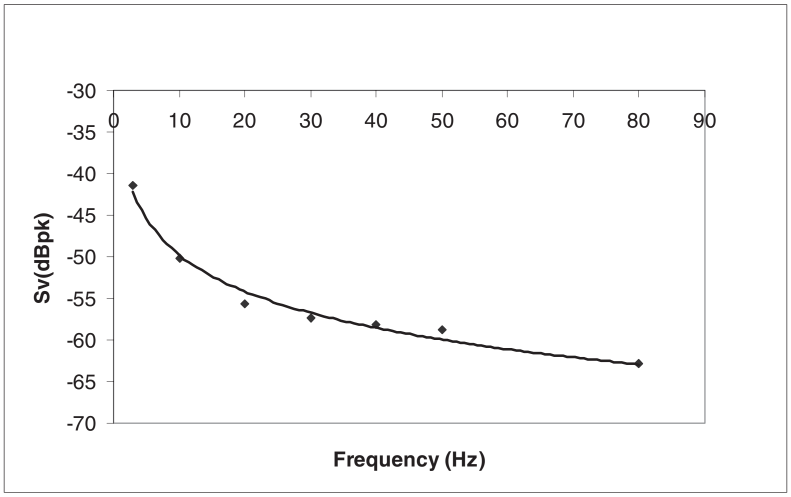


Figure 4b. Noise Power Spectral Density (Sv) vs. Frequency for Pulse Train

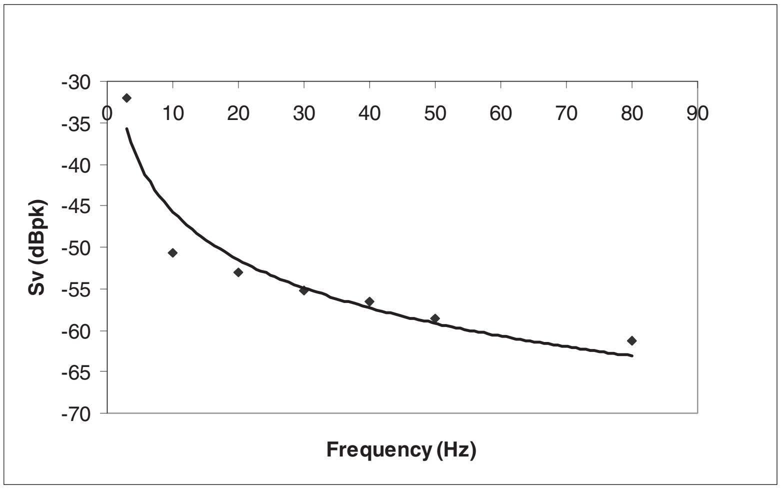
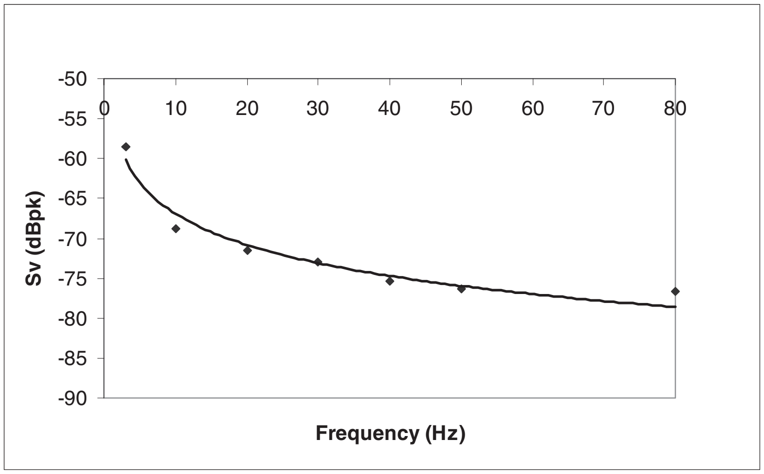


Figure 4c. Noise Power Spectral Density (Sv) vs. Frequency for Single Step



ground noise was subtracted from the total noise with the remainder being the excess noise of the metal thin film. The details of measurement technique and the measurement system can be found elsewhere (Zeynep, Wiyi, Hoang, William, 1990). We should still note here, however, that the measured noise was in the form of 1/*f*, and the resistance of samples was monitored during the measurements to check against any resistance drift. The time period for each set of noise measurement was also documented, so that the changes in the level and slope of the spectrum of excess noise could be traced as a function of test time duration.

Experimental Results

While the single step thin metal films sustained high current densities even up to 2.2 x 10^6 A/cm ^{2} and higher than 200 ^oC heating temperatures, the other two thin metal films failed at a current density 1.1 x 10^6 A/cm ^{2} at 200 ^oC heating temperatures. The frequency exponent (a) was found by taking a slope on spectral power density curve. All three thin metal films exhibited a 1/*f* noise spectrum as shown in the Figures 4a, 4b, and 4c. We also observe in Figure 4c that the single step thin metal film shows higher magnitude of noise power compared to other two, which is expected due to higher resistance of the single step thin metal film. Figure 5 shows the noise power at 30Hz versus temperature for all three thin metal films. There is negligible change in the noise power in case of pulse train and single step thin metal films up to 200 ^oC as seen in Figure 5. For the straight-line thin metal film, there is increase in the noise power initially but levels off after 100 ^oC ambient temperature to the same level as single step (SS) and pulse train (PT). Figure 6 shows noise power versus current density for single step thin metal film. As seen the noise power is relatively constant till 200 ^oC, but increases considerably depicting the reliable limit of the thin metal film. The noise magnitude of single step (SS) metal thin film did not show significant variation while biased below current density of 1.8 x 10^6 A/cm ^{2}.

Figure 5. Noise Power Spectral Density (Sv) vs. Temperature for all three metal thin films at 30Hz.

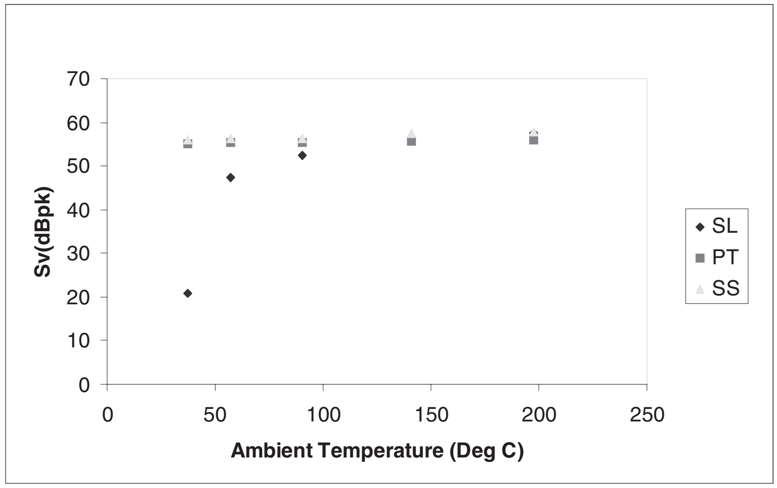


Figure 6. Noise Power Spectral Density (Sv) vs. Current Density for single step at 30Hz.

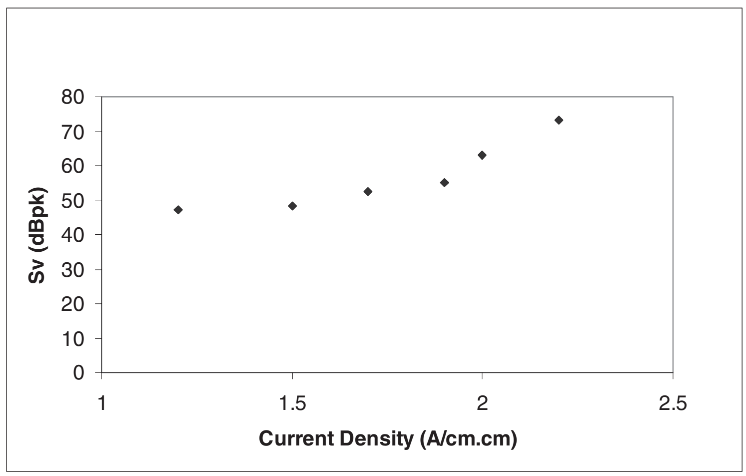
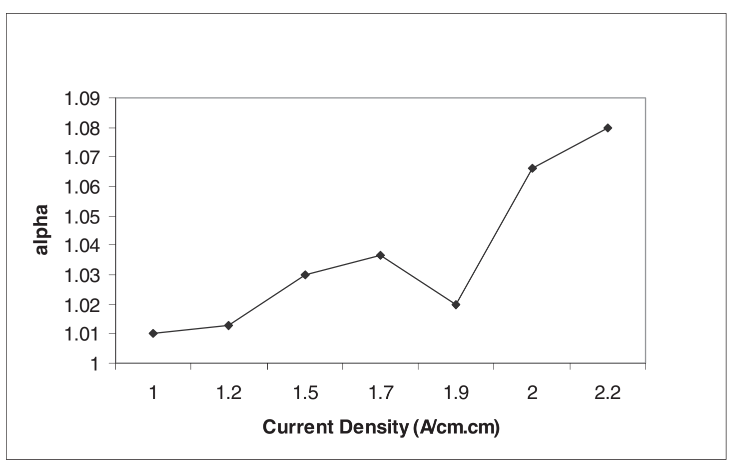


Figure 7. Alpha (Frequency exponent) vs. Current Density at 30Hz.



The current dependency of the spectral shape, namely the frequency exponent a, was also investigated for single step thin metal film. Values of a were found to increase with increase in current density as shown in Figure 7. As with the noise magnitude in all the three geometries, the slope of the spectral density curve seems to possess a threshold below which it is insensitive to increase in the biasing current density and hence do not exhibit 1/*f* pattern. Above this threshold, the sample undergoes structural defect leading to higher noise magnitudes.

Industrial Ramifications

The 1/*f* noise analysis technique has been widely applied, in order to investigate the dynamics of metal defects. With the help of this technique, semiconductor industries have found better ways to design chips. These integrated circuits are reliable and can sustain high stress conditions. Metal interconnects form one of the important part of a VLSI circuit. Our experiment deals with the different geometry of the metal thin films and confirms that the geometry of the metal interconnects is one of the important factor in deciding the reliability. The metal thin films with different geometry behave differently when subjected to stress condition. This criterion can be used while manufacturing a chip so that it can handle high stress (heat and current density) conditions and have a low chance of failure. These initial considerations can save cost and can provide better and reliable devices.

Conclusion

Low frequency electrical noise in thin metal films with different geometry was measured. These noise spectra measurements were found to be function of ambient temperature. Our results showed that the 1/*f* pattern was repeated in all the three different thin metal films. At high current density ($> 1.1 \times 10^{6}$ A/cm^{2}) two of the thin metal films straight line and pulse train were damaged whereas one with higher resistance, single step exhibited 1/*f* pattern even on being subjected to high temperatures. This shows that the thin film with single step (SS) geometry is more reliable as compared to the other two. Higher values of noise magnitude were observed in case of single step thin metal film, which has the highest resistance. This result was expected and confirms the resistance dependency of the noise power. Also, temperature dependence of the 1/*f* noise was taken into consideration. We measured the current dependency of noise power and frequency exponent for the single step. The results showed us the increase in these values with increase in the current densities. Also the thin metal films showed slight resistance drift when subjected to higher temperatures. The average 1/*f* noise spectrum measurement and capture takes 15 minutes as compared to several hours needed in other techniques to study reliability issues in metal thin films. Hence this technique is found to be faster and less destructive than methods in use in industry. The excess noise measurement on the metal thin films of different geometry helps in understanding reliability problems related to film structure and dimensions.

References

Kogan, S.M., (1985, Feb), *Low-frequency Current Noise with 1/f Spectrum in Solids*, Sov. Physics. Usp, vol. 28.

Cottle, J.G. & Gutt, G. *Noise and Reliability Lab*, Elec. Eng. Dept., USF, Tampa, Florida 33620.

Massiha, G.H., Chen, T.M. & Scott, G.J., (1989, Feb), *Detection of Hot Spots in Thin Metal Films via Thermal Noise Measurements*, Electron Dev. Lett., vol. 10, no. 2.

Fleetwood, D.M. & Giordano, (1985, Jan), *Direct Link Between 1/f Noise and Defects in Metal Films*, Phys. Rev. B, vol. 31, no.2, p. 1157.

Zeynep, C.B. & Min, Y. (1992, Jan), *Prediction of Electromigration Failure in W/Al-Cu Multilayered Metallization by 1/f Noise Measurement,* Solid-State Electronics, Vol.35, No.9, pp. 1209-1212.

Hermann A. Haus, (2000), *Electromagnetic Noise and Quantum Optical Measurements*, Springer-Verlag Berlin Heidelberg New York, pp. 127-312.

Ciofi, C., Dattilo, V., & Neri, B., (1999, July), *Open Questions on Noise in Metal Lines Subjected to High Current Densities*, Proceedings of 2nd International Conference on Unsolved Problems of Noise in Physics, High Technology, and Information Technology, Adelaide, Australia.

Zeynep, C.B. & Wiyi Y., (1990 July), *Characterization of Electromigration Parameters in VLSI Metallizations By 1/f Noise Measurements,* Solid-State Electronics Vol.34, No. 2, pp. 185-188.

Scofield, J. H. & Mantese, J. V., (1986, July), *Temperature Dependence of Noise Processes in Metals*, Phys. Rev. B, vol. 34, no. 2, p. 723.

Ghate, P. B., (1982), Proc. IEEE International Reliability Physics Symp., p. 292.