Fluctuation Scaling in Nano-Interconnects and its Application to Electromigration

Sofie Beyne[1,2]
[1]*Department of Materials Engineering, MTM*
[1]KU Leuven and [2] imec
Leuven, Belgium
sofie.beyne@imec.be

Tim Beyne[3]
[3]*Department of Electrical Engineering, ESAT*
KU Leuven
Leuven, Belgium
tim.beyne@esat.kuleuven.be

***Abstract*—The output current fluctuations in metallic interconnects exhibit fluctuation scaling. The temperature dependence of the scaling exponent is analyzed and found to increase up to a specific temperature, above which it remains constant. This temperature corresponds to the temperature at which a maximum in low-frequency noise (LFN) power spectral density (PSD) is observed. The model of Dutta et al. is applied to calculate the activation energy of the defect mechanisms contributing to the noise spectrum. This LFN activation energy is found to correspond to the electromigration activation energy, indicating that both phenomena depend on the same defect mechanisms. Studying the temperature dependence of the fluctuation scaling behavior of output current fluctuations can thus be used to study electromigration in advanced nano-electronic interconnects, in a fast and non-destructive way.**

I. Introduction

We previously reported that the output current fluctuations of metallic nano-interconnects follow Taylor's law [1], [2]. This empirical law was originally obtained by studying the distribution of animal populations in a habitat, relating the variance of the population density to its mean by the following power function relationship:

$$\sigma^2 = a\mu^p, \tag{1}$$

with a and p positive constants. In physics, this phenomenon is known as Fluctuation Scaling (FS) [3].

The scaling exponent, p, of the current fluctuations in nano-interconnects was calculated, thereby studying temporal instead of spatial distributions. The scaling exponent was found to be approximately 2 on pristine interconnect samples at $200°$C. Inducing voids in the samples, caused a sudden change in fluctuation scaling, indicated by the drop in p-exponent from 2 to ≈ 1. Our previous study thus established the potential of using the scaling exponent of current fluctuations for defect characterization purposes in nano-interconnects.

In this paper, we study the temperature dependence of the scaling exponent and demonstrate how the results can be used for electromigration (EM) characterization.

Electromigration is the mass transport due to the momentum exchange between the electrons and metal ions of the conductor. It can lead to voiding and/or hillock formation, eventually resulting in failure of the entire component. Electromigration is indeed one of the main reliability issues in interconnects and becomes increasingly problematic as scaling of the line-width continues. It is of foremost importance for the semiconductor industry to test the EM reliability of new interconnect structures, materials, etc. The presently accepted EM test method is based on accelerated testing (high current densities and elevated temperatures speed up electromigration failure), but is nevertheless still too time-consuming and limited in providing sufficient fundamental understanding [4], [5]. As a solution, low-frequency noise measurements have been proposed to characterize the EM activation energy [4], [6], [7]. We will briefly explain this methodology and demonstrate how this solution can be further simplified, by directly analyzing the output current fluctuations and their fluctuation scaling behavior. Other than being a fast characterization method and providing more fundamental understanding, the additional benefit of the methodology is that it is non-destructive.

II. Methodology

A. Sample description

The interconnects studied in this work are 100μm long and 22nm wide Cu lines without vias (aspect ratio 2). They have a 3nm TaN barrier and 1nm Co liner at the Cu/low-k dielectric interface. The lines are capped with 30nm SiCN and passivated with 300nm SiO_2 and 500nm SiN. The line resistance at room temperature is approximately $4.5\mathrm{k}\Omega$.

B. Measurements

The electrical measurements are performed using a commercial Keysight E4727A Low-frequency noise analyzer and a B1500 semiconductor device analyzer.

1) Current fluctuations: To measure the output current fluctuations, a constant voltage is applied to the metal line, resulting in a current density of $\approx 1\mathrm{MA/cm^2}$. The measured output current $\mathrm{I_{out}}$ is composed of the average current $\mathbf{E}[\mathrm{I_{out}}]$ and (small) fluctuations $\Delta\mathrm{I}$. We are interested in studying these fluctuations because they are the result of electron scattering mechanisms in the conductor and as such elicit insights into the defects present in the metal line. The time-domain fluctuations were recorded taking 4096 samples with a sampling frequency of 190.7Hz. A bandstop filter was applied to the data to remove the 50Hz contamination. The temperature dependence was studied between 25 and $100°$C.

2) Low-frequency noise masurements: The Low-frequency noise (LFN) Power Spectral Density (PSD) is calculated based on the recorded current fluctuations and is obtained from the spectrum analyzer.

Based on the temperature dependence of the low-frequency noise PSD (in the equations below denoted as $S(\omega)$), the activation energy (E_A) of defect mechanisms in metal films can be calculated by application of the model of Dutta et al. [8]. They show that the activation energy E_A can be calculated as

$$E_A = -k_B T \ln(\omega \tau_0), \tag{2}$$

with k_B the Boltzmann constant, ω the radial frequency, T the temperature and τ_0 an inverse attempt frequency, which for Cu is $\approx 10^{-13}$s. They then derive a distribution of activation energies $D(E_A)$ from $S(\omega)$, for which

$$D(E_A) \propto \frac{k_B T}{\omega} S(\omega, T). \tag{3}$$

The maximum in distribution function $D(E_A)$ indicates the activation energy.

This activation energy has previously been linked to diffusion mechanisms in aluminum [6], [9] and more recently we have shown that the activation energies obtained by LFN measurements correspond well with the values found for electromigration in nano-electronic interconnects consisting of copper and even alternative metals such as tungsten and ruthenium [4], [10], [11].

C. Fluctuation Scaling

As mentioned in the introduction, in this paper we will study the fluctuation scaling behavior of the output current fluctuations. To this aim, the scaling exponent p will be calculated using the method of expanding bins [12]. This methodology works as follows: a wide-sense stationary discrete-time stochastic process, given by $(X_i)_{i=1}^N$, with length N can be divided into subsequent bins of equal length. The absolute current fluctuations in each of the bins are summed and the variance and mean of this sum are estimated. This procedure is repeated for successively expanding bin sizes, until $N/2$ pairs of variance and mean are obtained. The sum of the values in bin i is thus equal to

$$Z_i^{(m)} = \sum_{k=(i-1)m+1}^{im} X_k, \tag{4}$$

which can be shown to have variance

$$\mathbf{Var}\left[Z_i^{(m)}\right] = \sigma^2 \sum_{k=1-m}^{m-1} (m - |k|)\,\gamma(k), \tag{5}$$

with μ and σ^2 the mean and variance of X_i respectively and γ its autocorrelation function. For processes exhibiting fluctuation scaling, one expects a variance-to-mean relationship as in eq. (1):

$$\mathbf{Var}\left[Z_i^{(m)}\right] = a\,(m\mu)^p. \tag{6}$$

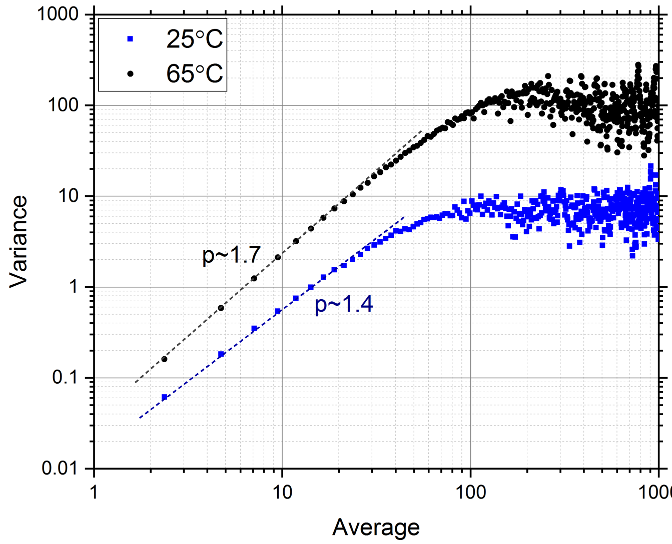

Fig. 1: Method of expanding bins at 25 and 65°C.

From the equalities (5) and (6), one can deduce that

$$\gamma(k) \sim \frac{(2-\beta)(1-\beta)}{2a\mu^p} k^{-\beta}, \tag{7}$$

as $k \to \infty$ and with $\beta = 2 - p$. Constructing a log-log plot of the variance-to-mean pairs allows estimating p (hence β).

As β is directly linked to the shape of the autocorrelation function, it allows one to identify whether the underlying stochastic process of electron scattering exhibits long-range-dependence (LRD), which is closely related to self-similarity and $1/f$ noise [13]. Specifically, a stationary stochastic process is said to exhibit long-range-dependence and therefore also $1/f$ noise, if the autocorrelation function γ is of the form

$$\gamma(k) = k^{-\beta} L(k), \tag{8}$$

with $0 < \beta < 1$ and $L(k)$ a slowly varying function as $k \to \infty$ [13]. The lower β, the stronger the LRD.

The evolution of p (or β) with temperature, will be studied in this paper because it directly provides information about the underlying stochastic processes; a sudden change in the fluctuation scaling behavior relates to a change in the stochastic process of the output current fluctuations.

III. Results and Discussion

The p-exponent was calculated using the method of expanding bins, as explained above. An example of the application of the method is shown in Fig. 1. The p-exponent of the current fluctuations at 25°C is 1.7 and 1.4 at 65°C. This procedure is repeated to calculate the temperature dependence of p and the results are given in Fig. 2. Note that $\beta = 2 - p$, such that a larger p corresponds to a lower β and whilst $1 < p < 2$, $0 < \beta < 1$. A strong drop in β is observed above 65°C, which is an indication of increased long-range dependence. To confirm this, the autocorrelation functions of the time domain data are studied. They were calculated based on the filtered time domain data, in the temperature range 25 to 100°C, as

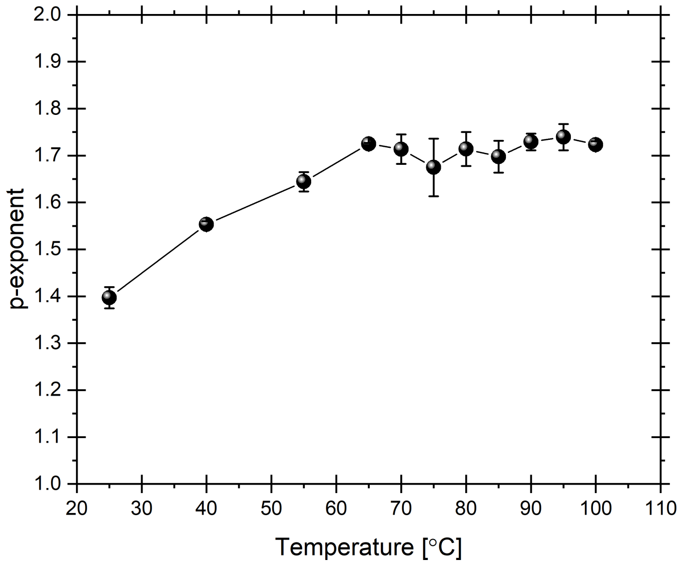

Fig. 2: p from 25 to 100°C.

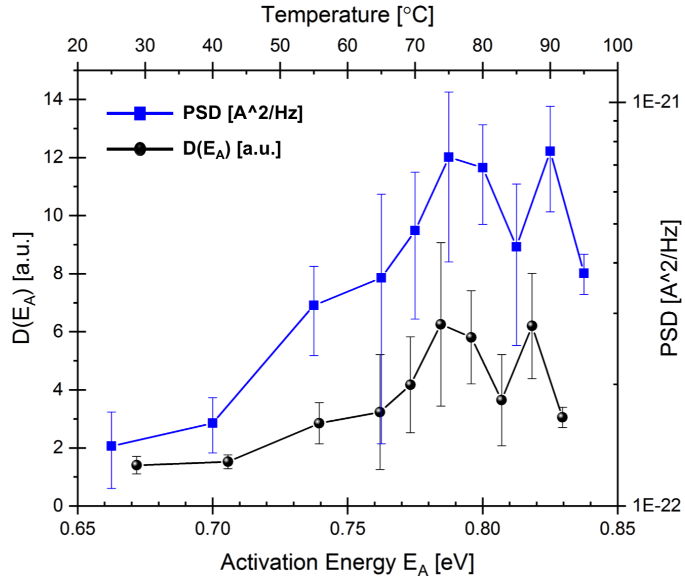

Fig. 4: Calculation of $\mathrm{E_A}$ by the model of Dutta et al.

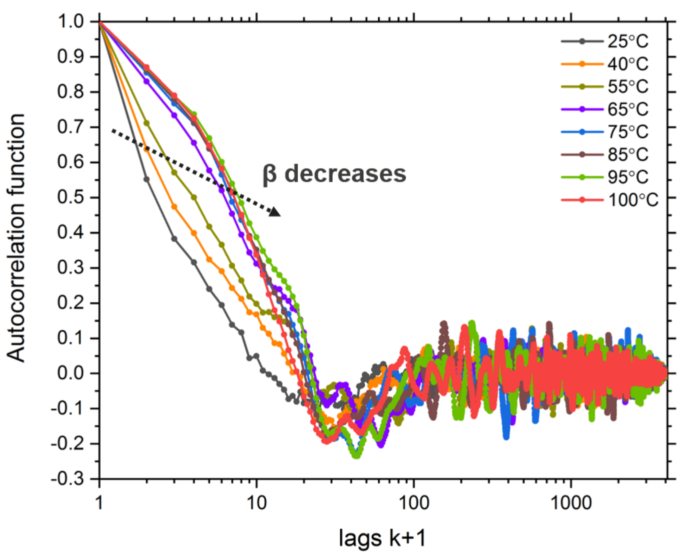

Fig. 3: Autocorrelation functions from 25 to 100°C.

shown in Fig. 3. The autocorrelation functions displayed in Fig. 3 indeed decrease with k roughly as $k^{-\beta}$. Above 65°C, the autocorrelation function decreases more slowly, which conforms to the observation of an increased p-exponent.

The change in fluctuation scaling behavior up to 65°C, as seen in Fig. 3 and 2 reveals a gradual change in the stochastic process of the electron scattering.

This result can be directly compared with the temperature dependence of the LFN in these interconnects. Fig. 4 shows the temperature dependence of the LFN PSD (evaluated at 5Hz) and corresponding $\mathrm{D(E_A)}$ for the Cu interconnect described in Section II-A. The PSD is maximal between 75 and 95°C, which, by application of the model of Dutta et al. (eq. (2)), corresponds to an $\mathrm{E_A}$ of 0.80 ± 0.02eV. We previously showed that this value is in line with the electromigration activation energy [4], which in these samples was found to be 0.85 ± 0.07eV.

The temperature at which the scaling exponent p reaches a 'plateau' and the temperature of the peak in LFN power spectral density, are indeed observed to almost coincide.

If we now use the temperature at which the p-exponent first becomes maximal (β reaches a local minimum), in eq. (2), with $\omega = 2\pi f$ and f evaluated between 1 and 5Hz (because this is the frequency range where maxima are typically visible in the PSD), an activation energy of $0.77 - 0.82$eV is found, which is in line with the value found using the LFN measurements and the standard electromigration tests.

Electromigration activation energies correspond to the activation energy of a diffusion mechanism. For Cu, surface diffusion is typically dominant, but in sub-30 nm interconnects grain boundary diffusion becomes also important due to the increased polycrystallinity of the metal [14], [15]. These diffusion mechanisms are vacancy-assisted and it is our understanding that the LFN spectra are impacted by the interaction of electrons with vacancies. The temperature dependence of p indicates that the contribution of these vacancies to the current fluctuations, keep gaining importance up to 65°C and then remains constant at higher temperatures. This corresponds to the observation of a constant shape in autocorrelation functions above $65 - 75$°C (Fig. 3). Based on the PSD data alone, this is not evident because the PSD peaks around a specific temperature and is then seen to decrease again.

Additionally, studying fluctuation scaling is much easier and faster than a full low-frequency noise analysis. For the fluctuation scaling analysis presented in this paper, one measurement point only requires 21 seconds, whereas low-frequency noise measurements can easily take up to several minutes, especially when a very accurate noise spectrum is desirable at low-frequencies (increased amount of averaging is needed).

One possible drawback of the fluctuation scaling method, is that it remains unknown how concurrent diffusion mechanisms affect the temperature dependence of the p-exponent.

IV. Conclusions

This paper demonstrates that the time-domain current fluctuations in nanoelectronic interconnects exhibit fluctuation scaling and that studying the temperature dependence of the scaling exponent can be used to calculate the activation energy of defects that are important during electromigration failure. Moreover, the activation of these defect mechanisms is found to correspond to increased long-range dependence in the autocorrelation functions of the output current fluctuations.

V. Acknowledgement

The authors would like to thank Kristof Croes, Ingrid De Wolf and Zsolt Tőkei for enabling this research, as well as the fund for scientific research in Flanders, FWO (Fonds voor Wetenschappelijk Onderzoek, www.fwo.be) for funding it.

References

[1] S. Beyne, and T. Beyne, (2017). In 2017 International Conference on Noise and Fluctuations, ICNF 2017.
[2] L. Taylor, Nature, 169, 732-735, 1961.
[3] Z. Eisler, et al., Advances in Physics, 57(1), 89-142, 2008.
[4] S. Beyne, et al., Journal of Applied Physics, 2016.
[5] S. Beyne, et al., Applied Physics Letters, 111(8), 2017.
[6] M. van den Homberg, et al., Physical Review B, 57(1), 53-55, 1998.
[7] S. Beyne, et al., In 2017 International Conference on Noise and Fluctuations, ICNF 2017.
[8] P. Dutta, et al., Physical Review Letters, 43(9), 646–649, 1979.
[9] R.H. Koch, et al., Physical Review Letters, 55(22), 2487, 1985.
[10] S. Beyne, et al., Semiconductor Science and Technology, 2019.
[11] S. Beyne, et al., in 2019 International Interconnect Technology Conference (IITC), 2019.
[12] W. S. Kendal and B. Jorgensen, Physical Review E, 84, 066120, (2011).
[13] P. Doukhan, G. Oppenheim, and M. Taqqu, Springer Science & Business Media, 2002.
[14] A. S. Oates, ECS Journal of Solid State Science and Technology, 4(1), N3168–N3176, 2014.
[15] S. Beyne, et al., In 2019 International Reliability Physics Symposium (IRPS), 2019.