Study of electromigration mechanisms in 22nm half-pitch Cu interconnects by 1/f noise measurements

S. Beyne[1,2], K. Croes[2], M. H. van der Veen[2], O. Varela Pedreira[2], Q. Qi[1], I. De Wolf [1,2] and Zs. Tőkei[2]
[1]MTM, KU Leuven, Kasteelpark Arenberg 44 bus 2450, B-3001, Leuven, Belgium
[2]imec, Kapeldreef 75, B-3001, Leuven, Belgium
E-mail: Sofie.beyne@imec.be

Abstract— **The electromigration (EM) performance of Cu interconnects with different barrier/liner combinations is studied by means of 1/f (or generally known as low-frequency) noise measurements. It is shown that Cu interconnects with a TaN barrier and Co liner have lower EM activation energies for 22nm half-pitch line-widths than Ru based liners. Indeed, interconnects with a 1nm Ru liner (both with TaN and Mn-based barriers) are found to outperform lines with a Co liner in terms of EM reliability. A possible explanation for this is a less defective Cu/Ru interface as compared to Cu/Co.**

Keywords —interconnects; electromigration; low-frequency noise; activation energy; barriers; liners; TaN barrier; Ru liner; Co liner; Mn barrier

I. INTRODUCTION

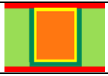
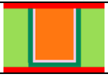
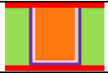
One of the main reliability issues arising from scaling interconnect line-widths is electromigration (EM)[1]. EM occurs along fast diffusion paths such as grain boundaries, the Cu/dielectric cap- or the Cu/barrier interface. Identifying these diffusion paths and understanding the EM mechanisms are key as this allows introducing new materials that can decrease EM along certain diffusion paths by increasing their activation energy. Classic EM tests are time-consuming and provide limited physical understanding. Recently it has been demonstrated that 1/f or low-frequency (LF) noise measurements are a promising technique for EM characterization in scaled interconnects [2-5]. The main advantages of the LF noise measurements as compared to standard EM tests are that a) EM activation energies can be calculated for individual samples in a fast and non-destructive way, b) it is possible to separate different activation energies whereas standard accelerated test methods only estimate an average of several mechanisms occurring simultaneously, c) the magnitude of the noise in each sample gives an indication of its defect density, thus providing a link to its EM lifetime [5] and d) noise measurements can be done much closer to the actual use conditions of the interconnects where thermal stresses may be lower or the dominant diffusion mechanisms might differ from the ones seen in high temperature accelerated tests. In this paper, LF noise measurements are used to investigate the EM activation energies of 22nm half pitch Cu low-k interconnects with different barrier (Mn-based or TaN) and liner (Co or Ru) stacks. Encouraging results in terms of their resistivity, resistance scaling and initial EM performance were shown in [6]. Using our LF noise measurements, we provide a more thorough comparison of the EM performance of the different barrier/liner stacks as well as a better understanding of why certain barrier/liner stacks lead to longer EM lifetimes. Additionally, the effect of a Co cap on the EM performance is studied. For the LF noise measurements, it suffices to measure single damascene (SD) lines, since we want to compare the effect of different interfaces on EM, rather than stress-related phenomena around the flux divergence point. Moreover, measurements on Dual Damascene (DD) structures were consistent with the results on SD lines and EM experiments.

II. METHODOLOGY

A. Sample description

The details of our 22nm ½pitch samples are shown in table 1, where the details of processing and integration can be found in [6]. The color coding is shown in table 2. The samples "TaNCo" and "TaNCo-Co" allow studying the effect of a Co cap on the EM performance in these dimensions, where the samples "TaNCo", "TaNRu" and "Mn-based-Ru" allow a benchmark of Co vs Ru liners. The "Mn-based-Ru" samples are investigated because Mn is an interesting alternative for the TaN barrier; it forms a silicate and can be scaled to lower dimensions, which greatly improves the line resistance [6]. Note that for one type of "Mn-based-Ru" sample, an in-situ post-deposition Ru anneal (5min in H2/Ar at 350°C) was performed prior to the Cu plating.

TABLE I. SAMPLE DESCRIPTION.

	TaNCo	**TaNCo-Co**	**TaNRu**	**Mn-based Ru**
Barrier	3nm TaN	3nm TaN	3nm TaN	1nm Mn-based
Liner	1nm Co	1nm Co	1nm Ru	1nm Ru (*)
Cap	SiC(N)	Co + SiC(N)	SiC(N)	SiC(N)
Cross Section				

*In one type of Mn-based Ru samples, a post-deposition Ru anneal (5min in H2/Ar at 350°C) was performed prior to the Cu plating.

TABLE II. COLOR CODING USED IN TABLE 1.

Co	**Ru**	**Cu**
TaN	**Mn-based**	**SiC(N)**

Research funded by the fund for scientific research in Flanders, FWO (Fonds voor Wetenschappelijk Onderzoek, www.fwo.be) .

B. Low-frequency noise measurements

LF noise measurements recently have been shown to be an excellent tool for potentially assessing EM lifetime of copper interconnects at wafer level. Because the technique is sensitive to point defects it is well-suited to assess EM in an early phase at relatively low current density level. A detailed description of the LF noise measurements technique is out of the scope of the present paper. For a detailed description of the technique the reader is referred to our previous publications [2-3]. The current density applied during the noise measurements was between 0.11MA/cm^2 and 1.1MA/cm^2. Activation energies were calculated from the temperature dependence of the noise power spectral density (PSD) [7] and were shown to coincide with values found in classic EM tests [2,3], which implies that they correspond to diffusion mechanisms in the interconnect. Indeed, when the PSD of the LF noise shows a maximum at a certain temperature, this temperature can be linked with the activation energy through the following formula [7]:

$$E_A = -k_B T\log(\omega\tau_0) \qquad (1)$$

where k_B is the Boltzmann constant, $\omega=2\pi f$ the radial frequency, T the temperature at which the PSD peak is observed and τ_0 is the inverse attempt frequency that is approximated for Cu as 10^{-13}s. In this paper the noise temperature dependence was investigated between 20 and 200°C, which allows to study activation energies between 0.7 and 1.1eV.

An example is shown in Fig. 1 (a) for the TaNCo sample with SiC(N) cap, where the normalized PSD (=PSD/I^2) at 2Hz is plotted as a function of temperature. A peak in PSD at 80-85°C can be distinguished. Following eq. (1) this peak indicates an activation energy of 0.84eV. In some samples, the PSD peak was not observable in the measured frequency range so the method has been improved to account for this.

It was found that the temperature at which the peak PSD occurs, marks a change in the PSD's temperature dependence. In this way, rather than identifying the peak PSD, it is sufficient to investigate graphs of log(PSD) vs. $1/k_BT$ and define the temperature that separates two different temperature regimes. In all cases, both methods resulted in identical activation energies, as shown in Fig. 1 (b) for the TaNCo sample; here the temperature marking a difference in PSD behavior occurs at 80-85°C, corresponding to 0.84eV.

III. RESULTS AND DISCUSSION

A. TaNCo with and without Co-cap

The temperature dependence of the LF noise measurements on the TaNCo samples is shown in Fig. 1. A low and high activation energy of 0.84eV and 1.02-1.05eV are found, respectively. After several measurements on the same sample both noise magnitude and activation energies remained constant, which is expected given their non-destructive nature.

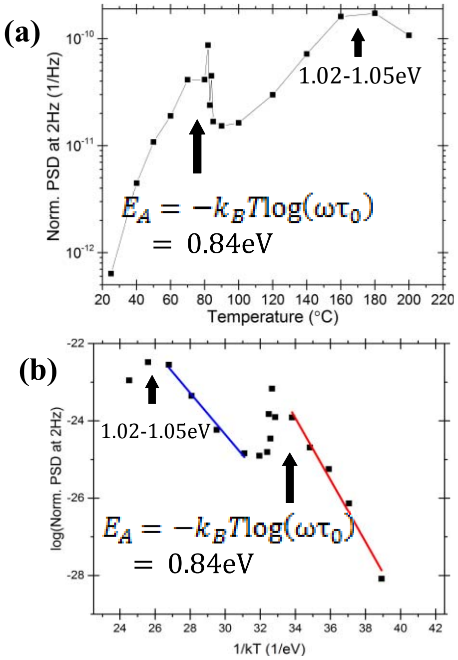


Fig. 1. Demonstration of the equivalence of both methods for the TaNCo sample. (a) Shows the temperature dependence of the normalized noise PSD at 2Hz. (b) Demonstrates that the peak temperature separates two different temperature dependencies of the PSD.

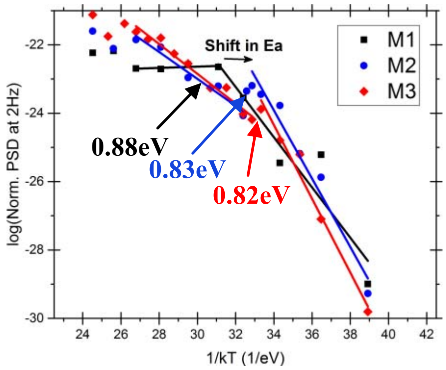


Fig. 2. Logarithm of the normalized PSD at 2Hz as a function of $1/k_BT$ for TaNCo with additional Co cap. M1, M2 and M3 are consecutive measurements on the same sample. The activation energy decreased from 0.88 to 0.83 to 0.82eV.

SD EM data are not available for these samples, but EM tests on DD structures with TaNCo and SiC(N) cap on both M1 and M2 indicated an activation energy of 0.85eV with 95% confidence bounds (0.78, 0.92)eV for line failures, corresponding well with the LF noise measurements.

An example of the results on TaNCo-Co are shown in Fig. 2. In this case, both the noise PSD and activation energy decreased for consecutive measurements by one order of magnitude at 5Hz and from 0.88 to 0.82eV respectively. A second, higher activation energy is not clearly discernible. Fig. 2 is representative for the other TaNCo-Co samples as well. The decreasing PSD and E_A is attributed to thermal effects (a maximum temperature of 200°C is reached during one measurement cycle) because this was also observed in samples that only went through the thermal cycle of the measurement, without applying any current. The decreasing PSD and E_A

could be related to mobility of Co from the cap, because it was not observed for the TaNCo samples. One hypothesis is that Co moves to Cu-deficient areas [6], another is that the thin TaN barrier (2nm observed thickness on the sidewalls) allows for free oxygen to preferentially move to Co that gets thereby oxidized. A combination of both hypotheses is also plausible. EM data of the activation energy are not available, but the lifetime of the TaNCo-Co wafer was found to be indeed considerably lower than for the TaNCo wafer. The following conclusions are then drawn: 1) TaNCo with and without an additional Co cap cannot effectively suppress the low activation energy ≈0.85eV. An additional Co cap might increase the second activation energy to higher values, but if the dominant diffusion path is the one corresponding to 0.85eV (which would be the case at operating conditions), this improvement becomes irrelevant. Thus, Co cap alone will no longer be effective in deeply scaled copper interconnects; 2) The LF noise measurements revealed a thermal effect causing a decrease in activation energy that could be related to mobility of Co from the cap.

B. *TaNRu*

In the majority of the tested TaNRu samples the activation energy was found to be 0.94-0.98eV. Higher activation energies could not be observed within this measurements' temperature range. Standard EM tests on the DD TaNRu structures revealed an activation energy of 0.96 (0.83,1.09)eV. It can thus be concluded that the TaNRu system generally inhibits the low activation energy close to 0.80eV and increases it to values in the range above 0.90eV, whereas this was not the case for the TaNCo system. Therefore, TaNRu systems are more promising for scaled Cu interconnects. The reason for the enhanced EM performance is likely related to a less defective Cu/Ru interface, although a full analysis and understanding of the observation is still necessary.

C. *Mn-based Ru with and without Ru post-deposition anneal*

For the Mn-based Ru samples *without* post deposition Ru anneal, a first activation energy ranging from 0.80-0.85eV and a second activation energy ≈1.03eV was observed.

The Mn-based Ru samples *with* post deposition Ru anneal showed a significant increase in first activation energy, with values between 0.90 and 0.94eV. The second activation energy remained ≈1.03eV for most samples and was not observable in others. Also the magnitude of the noise PSD was significantly lower in all the samples with the anneal as compared to the ones without. The best Mn-based Ru split (with anneal) is thus comparable to TaNRu, making it a potential attractive future barrier/liner candidate.

The LF noise measurements were particularly interesting in this case, since standard EM tests could not provide an activation energy because there were no failures due to the absence of a flux divergence point in these samples.

IV. CONCLUSIONS

The activation energies obtained with the LF noise measurements are summarized in Fig. 3. In the TaNCo stack (both with and without additional Co cap) the low activation energy around 0.80-0.85eV is present, whereas the TaNRu and Mn-based Ru stacks do increase this activation energy to values above 0.90eV. For the latter, an additional post-deposition Ru anneal proves to be desirable from reliability point of view. A possible explanation is a less-defective Ru/Cu interface. A metal Co cap could further increase the second activation energy that lies in the range of 1.00-1.10eV for the other samples, but this is irrelevant as the lower activation energy will be dominant in EM failure at use conditions. Fig. 4 shows the maximum PSD for the different sample types. The lower these values, the higher the expected EM lifetime [4], TaNRu and Mn-based Ru (with anneal *) being the best. From an EM reliability perspective, the TaNRu and Mn-based Ru (with post-deposition Ru anneal *) seem therefore the most promising candidates for barrier/liner combinations in future interconnect generations.

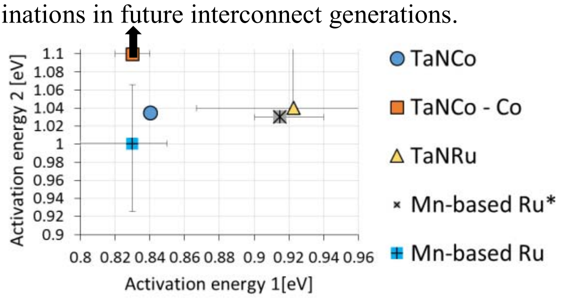


Fig 3. Summary of the low (x-axis) and high (y-axis) activation energy obtained for the sample types in table 1. When the higher activation energy was not observable within the temperature range, it was placed at the upper border with an upward arrow.

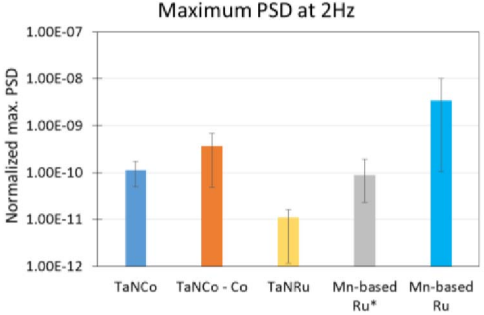


Fig.4. Maximum PSD at 2Hz for the different Cu barrier/liner options tested. The larger the maximum PSD the lower the expected EM lifetime [4].

REFERENCES

[1]Croes, K.,*et al.*"Electromigration study of ultra narrow copper lines in low-k dielectric."Proc. Advanced Metallization Conference.2007.p.711-715.

[2] Beyne, S., *et al.* "1/f noise measurements for faster evaluation of electromigration in advanced microelectronics interconnections." Journal of Applied Physics 119.18 (2016): 184302.

[3]Beyne, S., *et al.* "1/f Noise measurements for faster electromigration characterization." Reliability Physics Symposium (IRPS), 2016 IEEE International. IEEE, 2016.

[4]Beyne, S., *et al.* "Direct Correlation between Low Frequency Noise Measurements and Electromigration Lifetimes", Reliability Physics Symposium (IRPS), 2017, unpublished.

[5]Beyne, S., *et al.*, "Demonstration of low frequency noise measurements for studying electromigration mechanisms in advanced nano-scaled interconnects." International Conference on Noise and Fluctuations (ICNF), (2017), unpublished

[6]van der Veen, M. H., *et al.* "Barrier/liner stacks for scaling the Cu interconnect metallization." Interconnect Technology Conference/Advanced Metallization Conference (IITC/AMC), 2016 IEEE International. IEEE, 2016

[7]Dutta, P., P. Dimon, and P. M. Horn. "Energy scales for noise processes in metals." Physical Review Letters 43.9 (1979): 646