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ON THE DESIGN OF AN AUTOMATED SYSTEM FOR THE CHARACTERIZATION OF THE ELECTROMIGRATION PERFORMANCE OF ADVANCED INTERCONNECTS BY MEANS OF LOW-FREQUENCY NOISE MEASUREMENTS

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Abstract

Low-frequency noise measurements have long been recognized as a valuable tool in the examination of quality and reliability of metallic interconnections in the microelectronic industry. While characterized by very high sensitivity, low-frequency noise measurements can be extremely time-consuming, especially when tests have to be carried out over an extended temperature range and with high temperature resolution as it is required by some advanced characterization approaches recently proposed in the literature. In order to address this issue we designed a dedicated system for the characterization of the low-frequency noise produced by a metallic line vs temperature. The system combines high flexibility and automation with excellent background noise levels. Test temperatures range from ambient temperature up to 300°C. Measurements can be completely automated with temperature changing in pre-programmed steps. A ramp temperature mode is also possible that can be used, with proper caution, to virtually obtain a continuous plot of noise parameters vs temperature.

Keywords: low-frequency noise measurements, electron devices reliability, electro-migration, dedicated instrumentation.

1. Introduction

Electro-migration (EM) is a degradation mechanism of metallic interconnections in integrated circuits and as such it is a major concern when assessing reliability of microelectronic processes [1]. EM consists in a mass transport caused by the momentum exchange between electrons accelerated by an electric field and the metal ion within the conductor. It can cause the formation of voids along the conduction lines that eventually lead to the formation of open paths. On the other hand, depleted material can accumulate and protrude through insulation layers until a short occurs between neighbouring lines. Reaching a catastrophic failure in nominal operating conditions can take years, and therefore accelerated stress tests are normally used to assess reliability of a given metallization process in a reasonable time. By increasing the operating temperature and/or the current density, EM damage rate can be increased significantly and failure

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can be made to occur in days or weeks. Typically, such destructive tests are repeated at different stress levels (temperature/and or current density) and proper models are used to extrapolate the expected failure rate at nominal operating conditions. The issue of the model to be used is, however, anything but settled. Besides the huge simplification in the models in respect of the high complexity of modern metallization schemes, there is always a possibility that highly accelerated stress conditions may trigger failure mechanisms that may never occur in nominal operating conditions [2]. It is for this reason that non-destructive examination techniques that can provide information about EM without resorting to extreme combinations of temperature and current stresses are of great interest. *Low-Frequency Noise Measurements* (LFNM) have long been recognized as the most sensitive tools for examination of the EM in low/moderate stress conditions [3–5]. A typical setup for LFNM on metallic interconnections is shown in Fig. 1. A test line kept at constant temperature is supplied with a constant current and the voltage fluctuations at the ends of the line are amplified and sent to a spectrum analyser for spectral estimation.

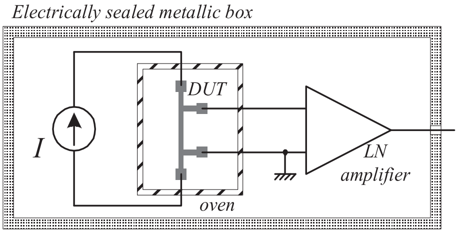

Fig. 1. A simplified diagram of typical measurement setup for the characterization of EM by means of LFNM.

Information about EM is extracted from the flicker noise ($1/f$ noise) that is however superimposed on the thermal noise that carries no useful information. Ideally, whatever the level of flicker noise, a frequency can always be found below which the flicker component is predominant. However, the measurement time required to reliably estimate the *Power Spectral Density* (PSD) is inversely proportional to the frequency at which it has to be estimated, so that there exists a practical limitation of the lowest frequency that can be observed [6]. On the other hand, the instrumentation itself introduces flicker noise that may mask the noise coming from the DUT. For these reasons, stress to DUT must be risen until its flicker noise overcomes the background noise of the system. This means that the sensitivity of the technique is strongly affected by the noise introduced by each piece of instrumentation in the measurement chain (bias system, temperature control system, pre-amplifier) and efforts to improve the instrumentation noise performance are worthwhile as they result in a possibility of extracting useful information at lower stress levels [7–8]. Another important issue that needs to be carefully addressed when performing LFNM is the fact that LFNM setups are extremely sensitive to *Electro-Magnetic Interferences* (EMI) coming from the environment. Even high-frequency disturbances, that can couple with the measurement chain and be rectified by non-linearities in the circuits, can result in a significant increase in the spectrum at low frequency that may completely mask the noise spectra of interest [7]. It is for this reason that accurate shielding from EMI must be guaranteed and this is why, whenever possible, the entire measurement chain is enclosed in a shielding box and no cables, other than the ones required to connect the output of the low noise preamplifier to the input of the spectrum analyser, are used to cross the shield (Fig. 1). Clearly, this is only possible if all the systems are battery-supplied and the batteries are located within the very same shielded enclosure that contains the DUT, the bias system and the amplifiers. This requirement, however, is at odds with the possibility of introducing some degree of automation that could greatly simplify the implementation of otherwise significantly time-consuming measurement procedures. The subject of this work is indeed the design of a system capable of overcoming these difficulties in the case of a quite promising approach to the characterization of EM by means of LFNM [9]. This approach, that could be extremely useful in the design of new generations of metallization systems aimed at overcoming the limitation of current copper-based interconnection schemes, is based on the observation of the dependence of the flicker noise produced by a constant-current biased test line on temperature. Information about the activation energy of the electro-migration phenomenon can be obtained in a relatively short time and with the test specimens operating in moderate stress conditions. The overall test time depends on the time required for measuring the flicker noise spectra at any temperature to be explored. Depending on the level of flicker noise (*i.e.* the frequency at which it becomes detectable), once temperature stabilization is obtained, the measurement time typically ranges from a few minutes to a few tens of minutes. However, without automation in obtaining a new temperature set-point, one is forced to either limit the examination to a small number of widely spaced temperature set-points, or to prolong measurements over several days to cover with high resolution the entire temperature range of interest that goes from room temperature up to 300°C, depending on the metallization technology being examined.

In the remainder of the paper we will discuss the design choices and the relevant features of the system we have developed and tested for combining a high level of automation while maintaining a very low background noise in performing LFNM on metallic lines.

2. System design and testing

As it has been noted above, the ideal situation from a point of view of obtaining the lowest level of background noise would be to use batteries for supplying all pieces of instrumentation in Fig. 1. As far as the bias system and the low-noise preamplifier are concerned, employing batteries with a capacity in the order of a few Ah can assure continuous operation for several days (test currents are often well below 1 mA). The main issue lays with the oven that is needed to keep temperature of the DUT constant. Designing a battery y-supplied oven capable of unattended operation for several hours or even days would require a very large battery capacity resulting in unmanageable size and weight. In order to address this issue we came out with a relatively simple and yet extremely effective design shown in Fig. 2. The oven presented in Fig. 1 is obtained as a hot

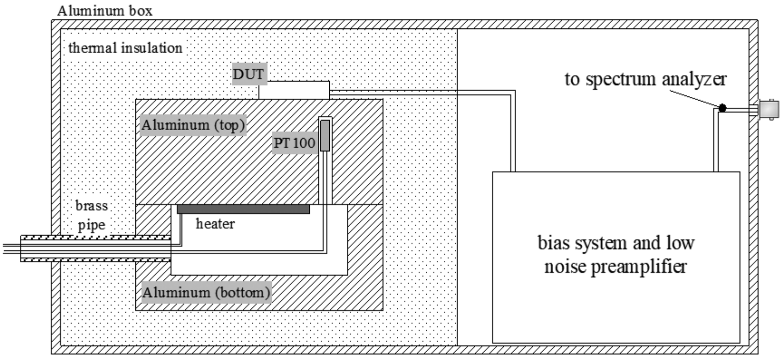

Fig. 2. A schematic diagram of the test chamber. The void space where the heater and the PT100 are located is completely surrounded by thick aluminium walls.

plate surrounded by insulating material. The hot plate is made of two sections (top and bottom). The top section is a solid aluminium cylinder save for a small dead hole (3 mm in diameter) that hosts a PT100 temperature sensor so that it is located in close proximity to the DUT. The bottom section is still a cylinder but with a void space that enables positioning a high-temperature heater in contact with the top section. A brass pipe enables the wires connected to the heater and the temperature sensor to leave the test chamber. The brass pipe is tightly screwed to both the bottom section of the hot plate and to the wall of the external aluminium box that is used to shield the system from external interferences.

The key aspect of the configuration from Fig. 2 is the fact that the inner surface of the brass pipe as well as the inner surface of the empty space in the bottom section of the hot plate topologically belong to the external surface of the shielding box. In this way, we have obtained that both the cables supplying the heater and the cables connected to the PT100 sensor do not cross the shielding surface. With this arrangement, the conventional laboratory instrumentation can be used to supply the heater and obtain a readout from the temperature sensor (namely a programmable power supply and a digital multi-meter) without introducing significant levels of EMI that could otherwise degrade sensitivity of the measurement chain. In particular, as it will be discussed in more detail in the following, the programmable power supply and the multi-meter can be controlled by a personal computer to implement a quite flexible digital temperature control system. In order to demonstrate effectiveness of the design, we performed test measurements with the hot plate temperature set at 150°C. We employed an *Ultra-Low Noise Amplifier* (ULNA) described in [10] as the LN amplifier of Fig. 1. The spectrum "A" shown in Fig. 3 is obtained with the input of the ULNA shorted and represents the background noise of the system with the temperature control system in operation. EMI effects are limited to a few lines at integer multiples of the mains frequency (50 Hz) that do not disappear when the temperature control system is turned off. Such lines can come from interferences coupling with the cable outside the shielded box and directly with the acquisition board installed inside the PC. The spectrum "B" is obtained when a test specimen (a copper metallization line with a resistance of about 4 kΩ at room temperature) is connected to the input of the LN amplifier as in Fig. 1 with $I = 0$. The only noise generated by the specimen is, in this case, its thermal noise. Note that below 500 mHz we notice the effect of the noise introduced by the amplifier. The spectrum "C" is obtained with the specimen kept at 150°C and a current $I = 30$ µA. In this case we can clearly estimate the low-frequency noise component due to the bias.

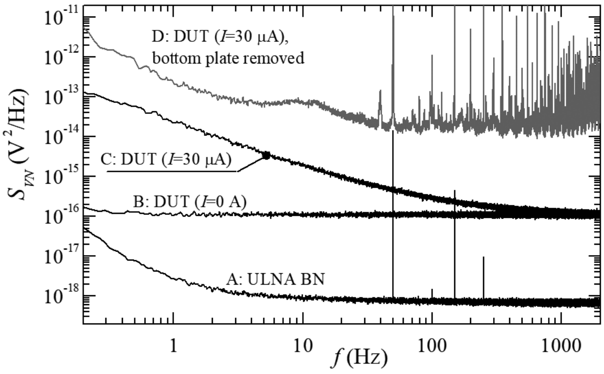

Fig. 3. Spectra obtained while testing the system from Fig. 2 with temperature set to 15°C (A, B, C). The spectrum "D" is obtained with the bottom section of the hot plate from Fig. 2 removed to demonstrate the need for accurate shielding of the cables connected to the heater and to the PT100 sensor.

Finally, the spectrum "D" represents what is obtained if, with the same test temperature and current as in the case of the spectrum "C", the bottom plate from Fig. 2 is removed so that the wires connecting the heater and the temperature sensor cross the shielding surface. It is apparent that the level of interferences in this situation prevents any sensible estimation of the noise produced by the specimen.

In a typical application for which this system is intended, the temperature is typically made to change in steps of 10°C or less in a range from 30°C to 250°C or 300°C (depending on the nature of the DUT) while the bias current is maintained constant. While with the ability to supply the oven from outside the box and to control the temperature with high accuracy we obtain a significant reduction in the time and efforts required to complete the measurements, a complete temperature sweep may still take several tens of hours to be completed and therefore we deemed unnecessary, at this stage, to integrate a programmable low-noise current source as part of the system. The bias current, generally below 1 mA, can be simply obtained by resorting to a battery with a large resistance in series to approximate the behaviour of the current source. With this level of bias current and with the low-noise amplifier we employ [10], supply-batteries with a capacity of a few Ah are sufficient to insure continuous operation for a few days. Programmable current sources such as the one in [11] can be however integrated in the system to extend the range of possible applications.

As far as the data acquisition and spectral estimation are concerned, we resort to a two channel PCI-4451 dynamic signal acquisition board and to dedicated software in order to completely automate the operation of the system. A block diagram of the entire system is presented in Fig. 4. The multi-meter is used to read the resistance of the PT100 temperature sensor shown in Fig. 2.

One of the two input channels of the PCI-4451 is connected to the output of the low-noise amplifier, while the other input can be connected to the output of a DA board (USB6602) that produces a voltage proportional to the oven temperature continuously monitored by the temperature control system. The temperature control system consists of a dedicated software module that interfaces with the multi-meter and a programmable power supply connected to the heater. The software module implements a digital temperature controller capable of stability better than 0.01°C.

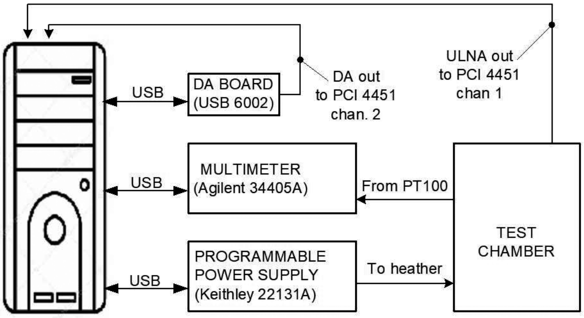

Fig. 4. A block diagram on the test system. The dual-channel National Instruments PCI 4451 dynamic signal acquisition board is installed in the PCI bus of the personal computer.

The signals acquired by the PCI-4451 are processed in real time for spectral estimation but are also saved to enable their post processing. The fact that the instantaneous temperature is also recorded means that all data required for post processing are present in the saved file. While clearly simplifying post processing, saving the temperature data with the same sampling rate as used for the noise signal may appear to be a waste of resources. It must be noted, however, that even assuming that 4 bytes per channel and per sample are saved, with a sampling rate of 100 kHz, the disk space required by 10 hours of measurement time is less than 30 GB.

The system software enables programming a measurement session by specifying the temperature range, the temperature interval, the hold time upon reaching any new temperature set-point and the actual measurement time at the set-point. The temperature control system assumes that a new set-point has been reached when the temperature remains within ±0.2°C in respect of the target temperature. After a temperature set-point is reached, the system waits the programmed hold time before starting the actual measurement (spectrum estimation). The hold time (typically in the order of 10 minutes) is required to enable the microstructure of the DUT to completely reset any stress induced by the fast temperature step to which it was subjected. The measurement finally starts and spectral estimation proceeds for the pre-programmed time before the temperature is stepped once again toward a new set-point. The duration of the measurement during spectral estimation depends on the minimum frequency to be observed [6] and it is typically in the order of half an hour, enabling to explore frequencies down to a few hundred of mHz with a sufficient number of spectrum averages.

Once the DUT is placed onto the hot plate, the bias system is connected and the measurement parameters are set, the system can run completely unattended for as long as required to complete the pre-programmed steps.

Typical spectra recorded on a tungsten-based experimental metallization process with a bias current of 100 μA are shown in Fig. 5. Only three of 28 spectra obtained as part of a test run of the instrumentation (from 30°C to 300°C in 10°C steps) are shown.

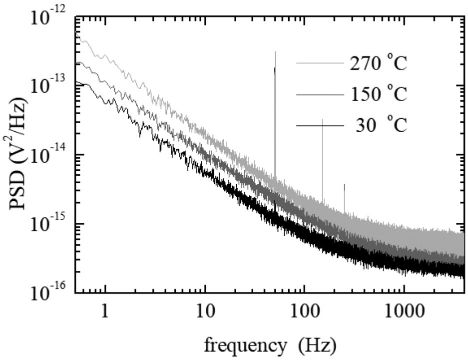

Fig. 5. Typical spectra recorded on a tungsten-based DUT. Only three of the spectra corresponding to over 20 pre-programmed set-points (from 30°C to 300°C) are shown.

When accounting for the time required to reach each new set-point (about 40 minutes for a temperature step of 10°C), for the hold time (about 10 minutes) and for the time required for spectral estimation (about 30 minutes), the time required to complete the characterization of a single specimen in the maximum temperature range from 30°C to 300°C with 10°C steps, is in the order of 40 hours. While this performance can be considered as quite satisfactory, it must be remarked that the useful measurement time (the time in which power estimation is active) is typically less than 40% of the entire test duration. Moreover, if the temperature resolution is reduced (say from 10 to 5°C) the test duration increases accordingly since twice as many set-points need to be explored.

These observations, coupled with the flexibility offered by the system we have designed, led us to the examination of a new measurement procedure consisting in continuously monitoring the evolution of the noise spectra while the temperature of the specimen is made to change linearly with time instead of that in discrete steps.

3. Temperature ramp measurement approach

Let us assume that we can force the temperature of the DUT to change linearly with time. If the temperature change rate is sufficiently small, it is reasonable to expect that the power spectrum estimated in any time interval from t_1 to t_2 would be representative of the power spectrum measured at the average temperature between time t_1 and time t_2. Let us assume now that we employ exponential averaging in the estimation of the power spectrum. In this case after an initial transient, at any new spectral estimation, we would obtain an averaged spectrum representative of the spectrum at a temperature somewhere between the one at which the last estimate was done and the one a few time constants before (the time constant corresponding to the exponential averaging process). This would mean that we could obtain a virtually continuous plot of any relevant noise parameter vs temperature. Clearly, the key factor to be determined is how small the temperature change rate should be in order not to introduce artefacts in the measurements. For instance, the resistance of the EM test line depends on temperature and in the presence of a temperature ramp this translates in the presence of a deterministic voltage ramp across the specimen (that is supplied with constant current). Moreover, the temperature stress can result in fluctuations in the resistance of the specimen that are not directly related to the process under examination. For some of these artefacts there could be a way to estimate their effect on the measured spectra (this is the case for instance of the effect due to the dependence of resistance on temperature), while for others we just do not have enough information to assess a priori their influence (this is the case of thermal stress).

With the system we have designed, we have an advantage that we can perform measurements both using the standard approach (discrete temperature steps) and using a temperature ramp. We can therefore experimentally verify whether the temperature ramp approach may enable to obtain the same results as in the standard approach but with an added advantage of a finer temperature resolution in a reduced measurement time. In the case of the temperature ramp approach the measurement time clearly depends on the temperature change rate. We decided to experiment with a temperature change rate of 0.5°C/minute since it is the lowest rate that enables to complete a temperature sweep from 30°C up to 300°C within about one full day of work in the laboratory. We used the same specimen for performing a standard test (from 30°C to 300°C in 10°C steps) and the test with the temperature ramp approach just described. Estimation and averaging of spectra lasted 20 minutes per each temperature set-point in the standard approach, while in the case of the temperature ramp approach exponential averaging was set to obtain a time constant of 6 minutes. With a temperature rate of 0.5°C/minute the temperature changes by 3°C within one time constant. In order to obtain an objective and unbiased "effective" temperature to refer the estimate spectra along time, we subjected the temperature signal (sampled by one of the channels of the acquisition board used for spectral estimation in Fig. 4) to the very same filtering process to which spectral data points are subjected.

In order to easily compare the results obtained with the two approaches, we fitted each spectrum to:

$$S_N = \frac{A}{f^{\gamma}} + W_N\,, \tag{1}$$

where S_N is the total noise across the DUT, W_N is the white noise component and A and the frequency exponent γ are parameters defining the flicker noise components.

The values of A and γ vs temperature as extracted from the two measurement procedures are presented in Figs. 6a and 6b, respectively. As it can be noticed, we obtain essentially the same results with both approaches, but with important differences. In the first place, temperature resolution in the case of the temperature ramp approach (small circles) is much finer than in the temperature step approach. Moreover, the entire measurement time was slightly less than 9 hours in the case of the temperature ramp approach while it was almost two full days in the case of the conventional approach.

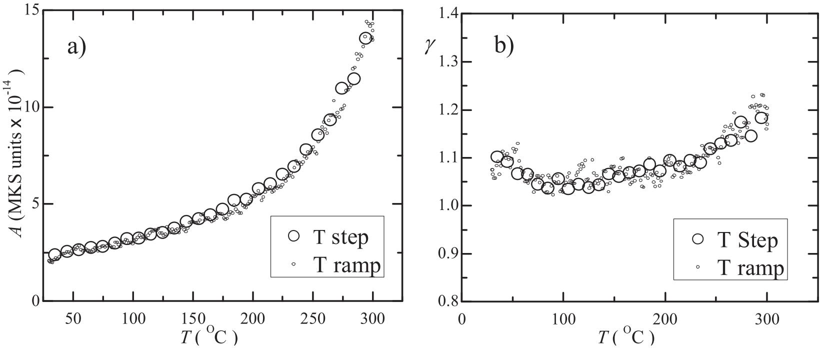

Fig. 6. Comparison of the results obtained with the conventional approach (large circles) and with the temperature ramp approach (small circles) on the same specimen. Comparable results are obtained in the two cases, with the ramp temperature approach resulting in better temperature resolution and much shorter measurement time.

4. Unsolved problems and future work

While the experimental results obtained so far are encouraging and appear to support the idea that noise measurements for the characterization of EM can be successfully performed imposing a temperature ramp to the DUT, we have no clear criterion to establish, for any given metallization process, what is the maximum temperature change rate that can be used without introducing artefacts in the results. Actually, we suspect that, since potential artefacts caused by thermal stress build-up and relaxation are expected to be strongly dependent on the metallization process, finding a general criterion is going to be quite difficult. On the other hand, potential advantages of the temperature ramp mode (higher temperature resolution and shorter overall test time) can be impressive, thus justifying further examination of this issue. It is worth noting that, even using the ramp temperature test mode, the EM characterization remains a costly process in terms of the time required to obtain statistically significant results on a number of specimens. It is for this reason that the future work will have to include the design of a system capable of performing noise measurements on more than one specimen at a time.

5. Conclusions

We have designed and tested a system dedicated to the examination of electro-migration in metallic lines by means of low-frequency noise measurements. The design choices that have been made have resulted in excellent background noise performance combined with a high level of system automation that simplifies the characterization of the dependence of the low-frequency noise on temperature and reduces the time required for it. Besides enabling unattended tests on predefined and closely spaced temperature set-points from room temperature up to 300°C, the system can work in the ramp temperature measurement mode that enables to further speed up the extraction of the relevant data.

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