Temperature Controlled Oven for Low Noise Measurement Systems

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***Abstract*—Low-frequency noise (LFN) measurements are often applied to the characterization of electron devices. When such measurements have to be performed on electronic components maintained at a given temperature, the thermal stability of the oven which is used for this purpose becomes a major concern, because of the high sensitivity of electron devices to temperature fluctuations (TF's).**

In this paper, we present the realization of a high-stability temperature-controlled oven, purposely designed for the characterization of electromigration in metal interconnections of integrated circuits by means of low-frequency noise measurements.

The prototype which has been realized demonstrates that the contribution of the thermal fluctuations of the oven to the background noise of the measurement system is negligible down to frequencies as low as 10 mHz in the entire range of operating temperatures (25–250 °C).

***Index Terms*—Low pass filters, noise, temperature control, thermal variables measurements.**

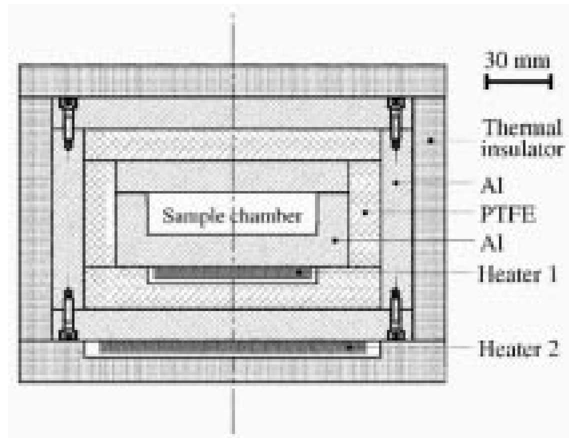

Fig. 1. Simplified structure of the oven. The internal heater (Heater 1) is used only during the warming up in order to reduce the time needed to reach the steady state temperature in the sample chamber.

I. Introduction

In order to characterize the low-frequency noise (LFN) behavior of materials and devices used for the realization of integrated circuits, it is often necessary to employ a temperature-controlled oven in order to maintain the device under test (DUT) at a given temperature. The performances of the oven, in terms of short-term temperature fluctuations, can be quite critical if a high sensitivity is required and/or the quantity under investigation has a strong dependence on the environment temperature. This is what happens, for instance, when the spectral analysis of resistance fluctuation (SARF) [1] technique is used to characterize the electromigration (EM) in the metallic lines used for interconnections in the integrated circuit. The SARF technique consists of supplying the metallic stripe with a current density in the range of a few MAcm^{-2} and recording the voltage fluctuations at its ends. The sensitivity required in this measurement is very high: the background noise (BN) of the entire measurement system must be kept as low as possible down to frequencies as low as a few mHz. In fact, most of the information about the investigated phenomenon can be obtained from the spectral analysis of the acquired data in the frequency range 10 mHz–1 Hz. Acceptable values of BN are below 30, 10, and 3 nVHz$^{-1/2}$ at 0.01, 0.1, and 1 Hz, respectively [2].

In this case, the effect of the temperature fluctuations (TF's) of the oven on the BN of the system can be evaluated by means of the thermal coefficient of resistance (TCR) of the investigated stripe. It is therefore possible to calculate the maximum value of the power spectral density of the TF that does not cause a significant increase of the BN, with respect to the values reported above. On the basis of these considerations, we have been able to design a temperature-controlled oven that satisfies the required specifications. The guidelines for the design and the realization of this piece of instrumentation, as well as the results of the characterization of a prototype which has been realized and tested, will be reported in this paper.

II. Design Guidelines and Realization

In a thermostatic chamber, the residual thermal fluctuations are primarily due to two sources: 1) the environmental perturbations and 2) the fluctuation of the power source which supplies the heater. These perturbations are partially filtered out by the combined effect of the thermal capacity C of the oven and of the thermal resistance R between the oven and the source of fluctuations. In our case, in order to improve this effect, the choice has been made to use a two stage thermal structure in which two coaxial aluminum vessels are separated by a thermal insulating layer (PTFE). This structure, shown in Fig. 1, acts as a second-order low-pass filter, effectively reducing the effects of environmental perturbations. Moreover, if only the external vessel is heated, the TF's induced by the heater power supply are filtered by the thermal mass of the internal chamber and the insulator resistance which act as a low-pass filter. When compared with the single-stage traditional structure, this solution has proven to be much more effective. In fact, as it will be shown in the following, the choice of a two-stage chamber allows an

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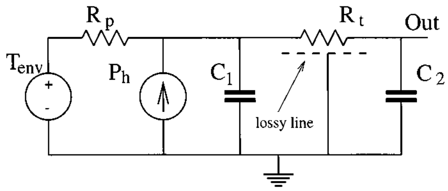

Fig. 2. Electrical equivalent for the estimation of the thermal fluctuations induced by the power fluctuation of the heating power P_h. Only Heater 2 in used in steady state operation.

acceptable trade off between the thermal stability and time necessary for obtaining the steady-state temperature.

The proposed structure is composed of two aluminum coaxial vessels separated by a PTFE thermal insulator, which can withstand, without damage, a temperature as high as 270 °C. The thermal equivalent circuit of this structure is shown in Fig. 2 in which R_p is the thermal resistance between the external vessel and the environment, R_t is the thermal resistance between the two stages, $T_{\rm env}$ represents the fluctuations of the environment temperature, P_h the heating power (in normal operation only the external vessel heater is operated) and C_1 and C_2 are the thermal capacities of the two vessels. We assume that the thermal time constants τ_1 and τ_2 of the system are so high that the corresponding pole frequencies f_1 and f_2 result well below the frequency range (0.01–1 Hz) of interest in our application. In this range, the modulus of the transfer function $H(f) = T/P$, where T is the fluctuation of the temperature inside the oven and P the fluctuation of the heating power, can be approximated (from the equivalent circuit of Fig. 2) as

$$|H(f)| \simeq \frac{1}{(2\pi f)^2 C_1 C_2 R_t} \tag{1}$$

where f is the frequency. This estimate of the transfer function has been carried out under the concentrated parameter hypothesis, supposing that the thermal flux Φ through the insulator layer can be evaluated with the following relation, valid for steady-state:

$$\Phi_{\rm conc} = \frac{S K_{\rm th}}{L} A \tag{2}$$

where S is the cross section of the insulator, $K_{\rm th}$ its thermal conductivity and L its length, and A is the amplitude of the temperature stimulus.

However, the thermal flux in a material under sinusoidal excitation drops exponentially with distance [4], according to the equation

$$\Phi_{\rm dist}(\omega) = \sqrt{1/2}\, A \frac{S K_{\rm th}}{L_0} \exp(-L/L_0) \tag{3}$$

where L_0 is the thermal wavelength calculated at the frequency of interest ω

$$L_0 = \sqrt{\frac{2K_{\rm th}}{C_p \rho \omega}} \tag{4}$$

in which C_p is the mass specific heat and ρ the density. It is worth noting that for PTFE (assuming $C_p = 900$ JKg^{-1}K^{-1}, $\rho = 2160$ Kgm^{-3}) at the frequency of $\omega = 0.01$ Hz we have $L_0 = 1.92$ mm while the physical length L is in our case 15 mm. As a consequence of that, the PTFE layer behaves as a lossy line which introduces an attenuation in the signal path. This can be taken into account by introducing an additional attenuation term ("lossy line attenuation")

$$A_{\rm add} = \frac{\Phi_{\rm dist}}{\Phi_{\rm conc}} = \sqrt{1/2} \frac{L}{L_0} \exp(-L/L_0). \tag{5}$$

The TF's caused by the heater can be estimated by assuming that they are mainly due to the fluctuations of the power P supplied to the heater itself. Supposing a 1% heating power regulation [3] and a mean power of 30 W, which corresponds to an oven temperature of 170 °C, and assuming a white noise spectrum between 0 and 1 Hz (since in a power supply high frequency noise can easily be avoided), we can estimate the sample chamber temperature noise spectrum as

$$S_T = N_0 |H(f)|^2 A_{\rm add}^2 \tag{6}$$

where $N_0 = 0.09$ W^{2}Hz^{-1} (-10.5 dB) is the heating power noise spectrum. In our case, $S_T \simeq 40$ nKHz$^{-1/2}$ at 0.01 Hz (-148 dB).

The thermal fluctuations induced by environmental temperature variations have a very similar effect on the internal temperature, since the $T_{\rm env}$ thermal generator can be converted, by means of Norton's theorem, into a thermal flux (current) generator in parallel with S_p. However, since the environmental fluctuations tend to fall under the band of interest (environmental thermal fluctuations are usually longer than 100 s), their effect can be neglected.

Finally, we assume that the resistance R_s of the stripe which has to be characterized by means of the SARF technique can be written as

$$R_s = R_0(1 + \alpha(T - T_0)) \tag{7}$$

where T is its temperature, R_0 is the resistance at the reference temperature T_0 ($T_0 = 0$ °C), and α is the TCR. Using the previous equations, we may calculate the spectrum of the voltage fluctuations S_v induced by the temperature at the end of the stripe supplied with a current I

$$S_v = S_T \alpha^2 R_0^2 I^2. \tag{8}$$

Evaluating (8) with $R_0 = 100\ \Omega$, $I = 100$ mA assuming a typical value of α of 4×10^{-3} K^{-1} we obtain a noise level estimate of 1.6 nVHz^{-1} at 0.01 Hz (-176 dB).

A similar analysis can be carried out for a single-stage oven with an equivalent thermal mass. In this case, the filtering action is much lower, due to the absence of the second low-pass RC cell and of the lossy line attenuation introduced by the intermediate PTFE insulator. As a consequence of that the noise level induced by heating power fluctuations can be estimated to be 90 dB higher (1.3 mKHz^{-1}).

The use of the two stage configuration has one major drawback, that is, the unacceptably long time which is required for the internal vessel to reach the operating temperature. In order to shorten this time, a supplementary heater (marked as "1" in Fig. 1) has been mounted onto the internal vessel which is

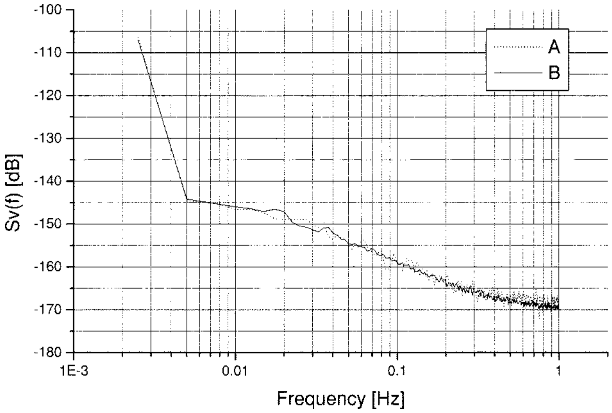

Fig. 3. Background noise of amplifier and current generator closed on (A) a low noise resistor and (B) on the PT100 test sample without heating.

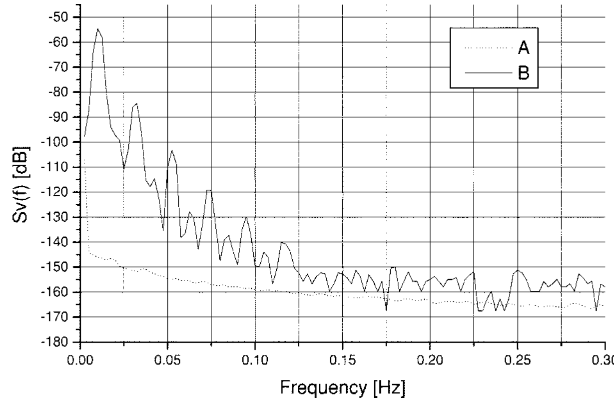

Fig. 4. (A) Spectrum recorded without stimulation and (B) with a square wave heating power stimulus of 2 W amplitude applied to the internal vessel.

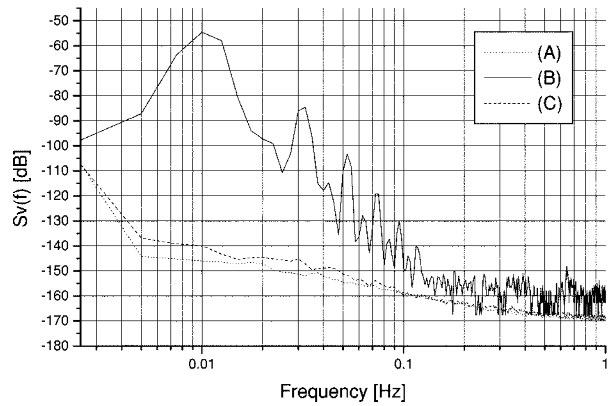

Fig. 5. (A) Spectrum recorded without stimulation, with (B) a square wave heating power stimulus of 2 W amplitude applied to the internal vessel, and (C) with the same stimulus applied to the external vessel.

used during the warming up of the system, and it is left unconnected when the steady-state temperature is approached. To this purpose, two standard PT100 temperature sensors have been used, one mounted in the external vessel, the other mounted in the internal one. A microcontroller based board implements all the operations needed for the warming-up procedure and for a closed-loop control of the temperature of the external vessel in steady-state conditions. Particular care has been devoted to the cabling of the different components in order to minimize the EMI interferences of the power circuitry (heaters power supply) on to the noise measurement chain.

III. Results and Conclusions

The tests which have been performed on the realized prototype are aimed at measuring the spectral density of the temperature fluctuation in the sample chamber of the oven in the frequency range of interest. The measurement was performed in two steps. In the first step, we used a dummy sample (a 160 Ω thin film resistor by Vishay) with a very low TCR (a few ppm°C^{-1}) in order to measure the BN of the system excluding the influence of the TF's. The test current was about 30 mA. This measurement was performed at 150 °C because this was the maximum operating temperature of the resistors we used. When the steady-state condition was reached, after a transient of about 3 h, a spectrum measurement was started by using the instrumentation described in [2]. The spectrum which was obtained in this way was coincident with that due to the BN introduced by the input preamplifier, thus confirming that no excess noise was introduced in the measurement chain because of EMI interferences due to the power supply and the temperature control system of the oven. A second set of measurements was performed using a dummy sample made of a set of 16 PT100 resistors connected to have an equivalent resistance of a single PT100 sensor, but with the capability of withstanding a test current of about 40 mA with negligible self heating. The TCR of the PT100 is similar to that of the samples used during the elctromigration tests. In particular, at 150 °C the resistance of the PT100 sensor is equivalent to that of the dummy sample used in the previous experiment. The spectrum which was recorded with the oven at 150 °C in the same conditions used for the first experiment was practically coincident with the first one (see Fig. 3), thus confirming that the thermal fluctuations inside the oven chamber are so low that they cannot be detected with the available instrumentation.

Another set of tests was performed by superimposing a square wave stimulus to the voltage applied to the heater. In a first test the stimulus, with a frequency of 10 mHz and an amplitude of 2 W, was applied to the internal heater (the one applied to the internal vessel and usually operated only for faster warmup). The typical square wave spectrum obtained is clearly visible in Fig. 4. It is worth noting that while the fundamental frequency exhibits the correct amplitude, the decay of the higher harmonics is faster than expected for a first order filter. This is due to lossy line attenuation in the internal aluminum vessel itself, which affects the high-frequency harmonics that have a shorter thermal wavelength [see (4)] In a second test, the same stimulus was applied to the external heater. No square wave spectrum lines were visible, even if a slight increment of the noise level is present (see Fig. 5).

Very low noise measurements and testing require an accurate control of many noise generation mechanisms. Since electrothermal effects usually play a major role in noise generation, accurate thermal filtering must be provided in most measuring instruments. The present analysis has shown how a simple solution can be effective in improving the thermal performances of a piece of instrumentation.

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