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Characterization of MOSFET temperature sensors for on-chip dynamic thermal measurements

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Abstract

This work analyses the performance of MOSFETs as a temperature sensor for the measurement of AC on-chip thermal signals caused by a power-dissipating circuit under test (CUT). First, we characterize how the CUT-sensor thermal coupling depends on the frequency of the AC thermal signal and the CUT-sensor distance. Second, we characterize how the thermal sensitivity of the sensor depends on the bias current and the dimensions of the MOSFET. Such characterizations are carried out through a chip fabricated in CMOS technology with heaters and sensors integrated, and an infrared (IR) camera. The knowledge extracted from this work is expected to provide guidelines for a better design of thermal sensors intended for IC testing applications.

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Keywords: IC testing; MOSFET; temperature sensor; thermal coupling; thermal testing.

1. Introduction

Among many other applications [1], integrated thermal sensors are employed as built-in testers (BIT) of other blocks (so-called CUT) embedded into the same integrated circuit (IC). The thermal sensor measures on-chip thermal variations caused by the CUT-dissipated power with the aim of extracting electrical information, for instance: failure or hot-spots in digital ICs [2], and the centre frequency or the 1-dB compression point of analogue radio frequency (RF) ICs [3]. To do so, the sensor is placed near the CUT so that they are thermally coupled through

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the semiconductor substrate. For such applications, the simplest thermal sensor that can be used is a diode-connected transistor, with either a bipolar junction transistor (BJT) or a metal-oxide-semiconductor field-effect transistor (MOSFET). According to the comparative analysis reported in [4,5], which was carried out through static on-chip thermal measurements, MOSFET-based sensors offer attractive advantages for those applications: (i) fully compatibility with the fabrication process, (ii) less layout area required around the CUT, and (iii) more sensitivity (especially, in strong inversion [4]) to on-chip thermal variations caused by the CUT.

Some IC testing techniques involve dynamic on-chip thermal measurements, i.e. the sensor has to measure an AC on-chip thermal signal whose amplitude (and/or phase) has information about the CUT performance. An example is the heterodyne technique applied to RF-ICs [3,6], which relies on applying two tones of high frequency f_1 and $f_2 = f_1 + \Delta f$ (Δf being, for instance, 1 kHz) to the CUT input. Then, as a consequence of the frequency mixing generated by Joule effect, the RF circuit dissipates power at low frequency (i.e. at Δf) that generates an on-chip thermal signal at the same frequency with information about the performance at high frequency (i.e. at f_1). Of course, the CUT also dissipates power at other spectral components (i.e. at $f_1, f_2, f_1+f_2, \ldots$) but these are filtered out by the low-pass filter (LPF) response of the thermal coupling. In such AC thermal measurements, the frequency of the AC thermal signal and the CUT-sensor distance play a significant role in the thermal coupling, as reported in [7] for BJT-based sensors fabricated on a silicon-on-insulator substrate.

With the final aim of using MOSFETs as a thermal sensor in the heterodyne test of CMOS-ICs, this work analyses their performance when measuring AC on-chip thermal signals. The characterisation is carried out with MOSFETs fabricated in a silicon substrate using a commercial 0.35 μm CMOS technology.

2. Theoretical background

2.1. Heat conduction

The heat dissipated by the CUT at the top of the substrate, which is here a harmonic function of frequency f, is transferred by conduction through the silicon of the IC, thus generating a gradient of temperatures on its neighborhood. This temperature change is then monitored by a thermal sensor that is also located at the top of the substrate at a distance d from the CUT. This scenario can be treated, in a first approximation, as a semi-spherical heat source in a semi-infinite homogeneous media and, therefore, the amplitude and phase shift of the thermal oscillation (T) can be expressed, using phasor notation, as [3]:

$$T(d, f) = Ae^{-d/\delta_p} e^{-jd/\delta_p}, \tag{1}$$

where A is the amplitude at $d = 0$, and $\delta_p = (D/\pi f)^{1/2}$ is the thermal penetration depth, D being the thermal diffusivity of the media. From (1), the higher d and/or f, the lower the amplitude and the higher the phase shift. Accordingly, the CUT-sensor thermal coupling can be modeled by a transfer function with a LPF behavior.

2.2. Thermal sensitivity of the sensor

A diode-connected n-type MOSFET operating in strong inversion and biased with a DC current source I_B has the following sensitivity to temperature [4]:

$$S_T = \beta - \frac{\alpha}{2}\frac{1}{T_0}\sqrt{2I_B\left(\mu_0 C_{OX} W/L\right)^{-1}}, \tag{2}$$

where β is the temperature coefficient of the threshold voltage, α is the exponent of the temperature dependence of the mobility, T_0 is a reference temperature, μ_0 is the carriers mobility at T_0, C_{ox} is the gate oxide capacitance per unit area, and W and L are the width and length of the channel, respectively. Since $\alpha < 0$ and $\beta < 0$, we can achieve a high (positive) sensitivity by means of a high value of I_B and/or a low value of W/L. Values of S_T up to +6.6 mV/K (which is three times higher than that of BJTs) were reported in [4] for static on-chip thermal measurements.

3. Experimental results

The setup to characterize the performance of MOSFET sensors for dynamic on-chip thermal measurements is shown in Fig. 1 and has three main blocks:

(a) A heater implemented by a diode-connected MOSFET (with W_h= 450 µm, L_h= 1 µm and 15 fingers) that was excited by a signal generator providing a sine wave signal with a frequency f, an amplitude (A_h) of 0.2 V and a DC level (V_{dc}) of 1.2 V. With this excitation, the heater dissipated power mainly at DC and f, i.e. $P(t) \approx P_{DC} + P_p \cdot \cos(2\pi f t)$, where P_p = 10 mW. The dynamic resistance of the heater was constant up to 1 MHz, which is higher than the frequencies under test.

(b) A thermal coupling, through the semiconductor substrate, that transforms the power signal at f generated by the heater into a thermal signal at f.

(c) A thermal sensor implemented by a diode-connected n-type MOSFET biased with I_B that converts the thermal signal at f into a voltage signal at f whose amplitude (A_s) was measured by a lock-in amplifier (Signal Recovery 7265). Three MOSFET sensors (M1, M2 and M3) with different W/L ratios (1/1, 1/4, 1/16 µm, respectively) placed at different distances d from the heater were tested.

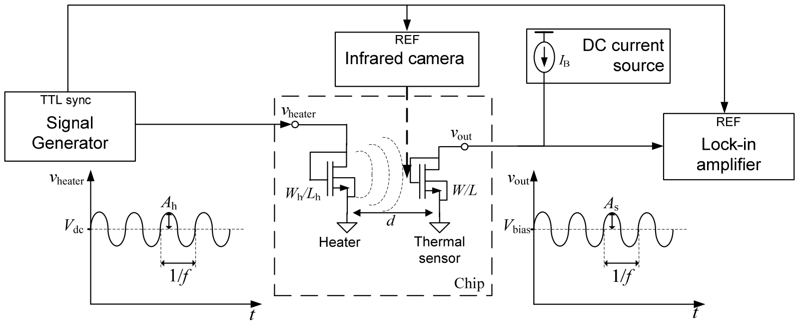

Fig. 1. Setup to characterize the performance of MOSFET sensors for dynamic on-chip thermal measurements.

Experimental results of A_s versus f and for different values of d are represented in Fig. 2a. The higher f, the lower A_s due to the LPF response of the thermal coupling, as suggested by (1). Moreover, A_s decreased with increasing d. Note that for d = 35 µm and $f \geq$ 20 kHz, A_s was really low since δ_p became smaller than d. Such results using the MOSFET sensor were then validated through an IR camera (FLIR SC5500) including a lock-in processing module [8] in the frequency range from 10 Hz to 2 kHz, as shown in Fig. 2b.

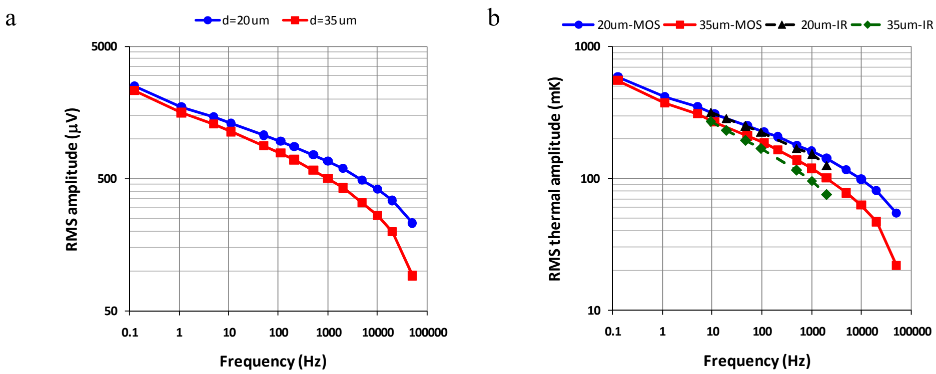

Fig. 2. (a) Experimental results versus frequency for different heater-sensor distances (d) using M2 at I_B = 40 µA. (b) Results from Fig. 2a (expressed in mK assuming S_T = 4.2 mV/K [4]) compared to those obtained with an IR camera.

More experimental results for different values of I_B and W/L are shown in Figs. 3a and 3b, respectively. Besides the LPF effects of the thermal coupling indicated before, we can see how A_s increases as I_B increases (Fig. 3a) and as W/L decreases (Fig. 3b), which agrees with (2). The flat frequency response of M1 at $I_B = 10$ µA represented in Fig. 3b is due to a thermal insensitivity caused by a mutual compensation of mobility and threshold voltage thermal effects, which was also reported in static thermal measurements [4].

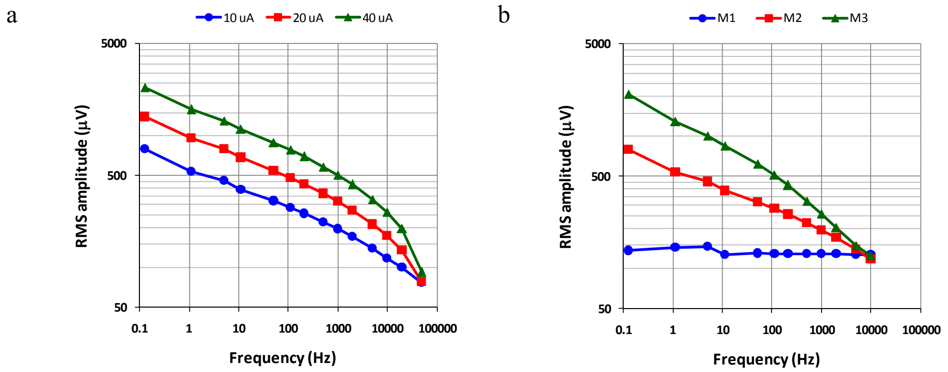

Fig. 3. Experimental results versus frequency for (a) different bias currents using M2 at $d = 35$ µm, and (b) for different MOSFET dimensions at $I_B = 10$ µA and $d = 35$ µm.

4. Conclusions

After conducting this experimental characterization of MOSFETs as a thermal sensor for the measurement of AC on-chip thermal signals, a better design of thermal sensors for IC testing applications can be carried out. In terms of the sensor itself, we have seen that the rules for increasing the thermal sensitivity in dynamic measurements are the same that those in static measurements, i.e. high bias current and low W/L ratio. In terms of the CUT-sensor thermal coupling, high operating frequencies (say, higher than 10 kHz) do not seem advisable since the resulting thermal signal is really low. Of course, this can be compensated by locating the sensor closer to the CUT as long as there is available layout area around it. On the other hand, low operating frequencies (say, lower than 100 Hz) provide high-amplitude thermal signals, but the response depends more on the boundary conditions (such as the package type) because δ_p becomes longer than the substrate thickness.

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