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Thermal characterization of silicon integrated spiral inductors by thermal impedance using transient thermography

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Abstract

IR thermography was used for thermal characterisation of the heating and cooling process of the silicon integrated spiral inductors. Four different inductors were powered and their temperature response to a heat step function was measured using an infrared camera. Based on these measurement results, for each of the spirals their complex thermal impedance was calculated to evaluate if there is a difference in the heat removal from the device to the substrate and environment.

1. Silicon integrated spiral inductor

Spiral inductors are a special case of on-chip interconnects used in integrated circuits [4-6]. They are allowing direct integration of inductances in semiconductor structures, in standard CMOS/BiCMOS technologies, without the need of additional technological processes. Because of their relatively important sizes compared to other elements integrated on a semiconductor wafer, spiral inductors can became a source of non negligible interferences for neighboring circuits located on the same semiconductor structure. According to the Joule-Lenz law, a current flowing through a metal produces heat. A spiral inductor is a metal interconnect conveying current, thus one can expect, that the current flowing through the spiral will heat it, changing its series resistance and changing one of the inductor key design parameters – its quality factor *Q*. The goal of the research was to investigate the thermal behavior of silicon integrated spiral inductors under current stress.

Four different layouts of the integrated spiral inductors were taken for the investigation. The standard spiral coil was used as a reference one to be compared with a coil with tiles, metal core and shield. The main aim of this paper is to confirm the possibility of integrated inductor characterization by thermal modeling and measurement. We assume that the temperature rise (or decay) versus time could be use for differentiating the coils with different internal layers and /or the substrate.

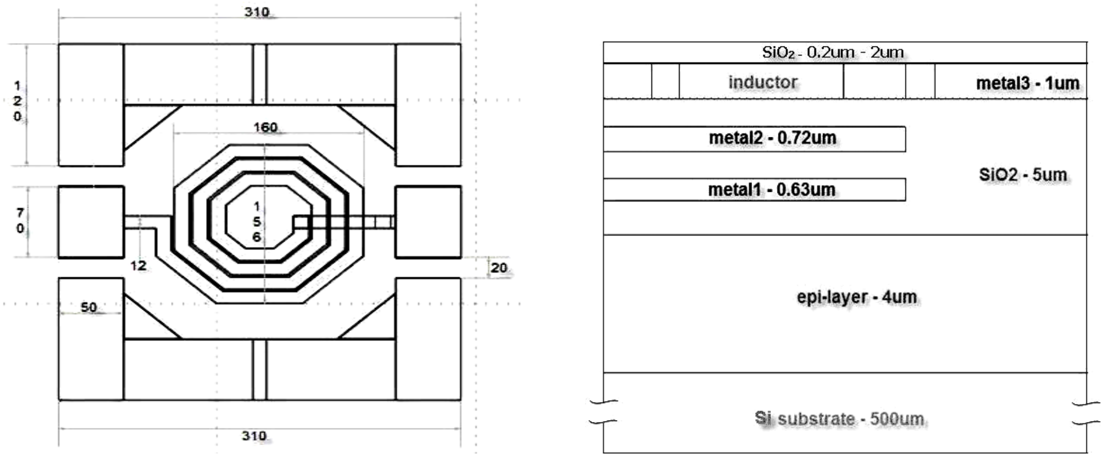

Fig. 1. *An octagonal integrated inductor (all dimensions in μm)*

2. Thermal impedance concept and *Nyquist* plot

The thermal impedance Z_{th} is a convenient parameter for thermal characterization of electronic integrated circuits [1-3]. The temperature response to a heating step function $T_{step}(t)$ was used to evaluate the thermal impedance versus frequency. The complex thermal impedance can be express by eqn. (1).

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$$Z_{th}(j\omega)=\frac{T(j\omega)}{P(j\omega)}=\frac{T_{step}(j\omega)}{P_0F\{1(t)\}}=\frac{j\omega}{P_0}T_{step}(j\omega)=\frac{j\omega}{P_0}\int_{-\infty}^{\infty}T_{step}(t)e^{-j\omega t}dt \tag{1}$$

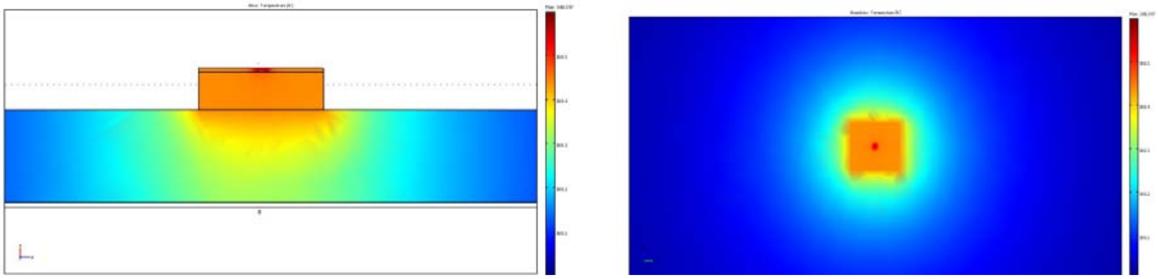
where *F* denotes Fourier transform, T_{step} is the heat step function temperature response, ω the angle frequency and P_0 is the power delivered to the inductor in steady state.

For getting the thermal impedance, the temperature is typically measured in the heat source. In some cases it is impossible to get the temperature of a heat source, in particular if it is below the upper surface of the device, or there is no direct access to the heating area. In these cases one can measure so called transfer thermal impedance. Such measurements can lead to the results that can be used for characterisation the material properties of a thermal interface between the heat source and the measuring point.

The thermal resistance of an electronic device is presented in the form of a *Nyquist* plot which represents the real versus imaginary part of thermal impedance. Typically, the curve is a part of a circle which directly approaches the origin of *Oxy* coordinate system. If the plot represents a transfer thermal impedance, the phase shift is larger than *45°* or even *90°* (Fig. 6). It means that the plot can have the negative real part. In this case the interpretation of the obtained results is much more difficult, and should be precisely correlated with the technological data, dimensions of the layers and their thermal parameters.

3. Thermal modelling

In order to start the thermal investigations of an integrated inductance, a *2D* and a *3D* modeling of the multilayer structure of the device was performed using COMSOL® software. The model was created with simplifying assumptions. We have modeled the inductor mounted on *2* different substrates. Alumina (AL_2O_3), ceramic substrate was chosen as a highly conductive material ($k=25W/m\cdot K$). The next modeling was performed for a weak thermal conductor used as the device substrate – the epoxy layer of *1mm* thickness ($k=1W/m\cdot K$). The convective cooling boundary conditions were assumed at all outer surfaces of the structure, Heat transfer coefficient $h=20W/m^2K$ was chosen for modeling. It corresponds to the weak forced convection, which was observed during the experiments. The inductor was covered by the thin $40\mu m$ layer of paint on top of the structure. Its thermal conductivity was as low as of the substrate, i.e. $k=1W/m\cdot K$. Fig. 2 and 3 present the simulation results.



a) b)

Fig. 2. *Temperature distribution of the standard integrated inductor using 3D modeling, a) cross-section, b)upper view*

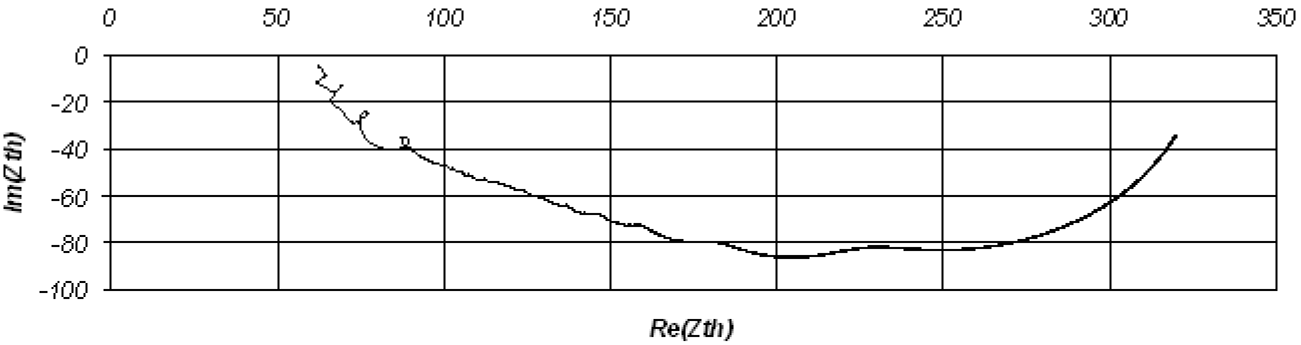


Fig. 3. *Thermal impedance obtained by 3D modeling*

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The result of the thermal impedance confirms the theoretical expectations. It is a curve with negative imaginary part corresponding to the negative phase shift between temperature generated in the structure and the power excitation. The high value of the impedance, especially in the low frequency range is due to the low thermal conductivity. In such a case, the heat removal to the ambient by the convection from the upper side of the structure is very important. The modulus of thermal impedance in this range is approximately equal to *300 K/W*.

4. Thermographic measurements

A test circuit containing several octagonal and rectangular spiral inductors was designed and manufactured in a *3* metal layer *CMOS AMIS 0,5* µm technology (Fig. 5). To reduce the parasitic capacitances between the silicon substrate and the spirals, inductors were designed in the last, third metal layer. Semiconductor test dies were next glued onto a substrate. Two different substrates were used in the research. The white ceramic plate made of alumina (AL_2O_3) was the first one as the highly conductive material. The second experiment was carried out for low thermal conductive epoxy substrate with a thickness of *1mm*. For the alumina substrate the inductor was powered by a *150mA* electrical current, while during the experiment with the die on epoxy layer, the current was *80mA*.

Four of the octagonal inductors were chosen for the experiment, all having the same geometry: external dimensions *160* µm x *156* µm, metal width *12* µm, adjacent turns edge to edge distance *2* µm and metal thickness of *1* µm. The first spiral was a standard octagonal inductor. The second spiral had a thin polysilicon shield added between the inductor and the semiconductor substrate. In the third spiral, the polysilicon shield was replaced by a series of metal tiles made of aluminum. The last of the inductors had the same geometry as the first one, but a metal core was added in its center.

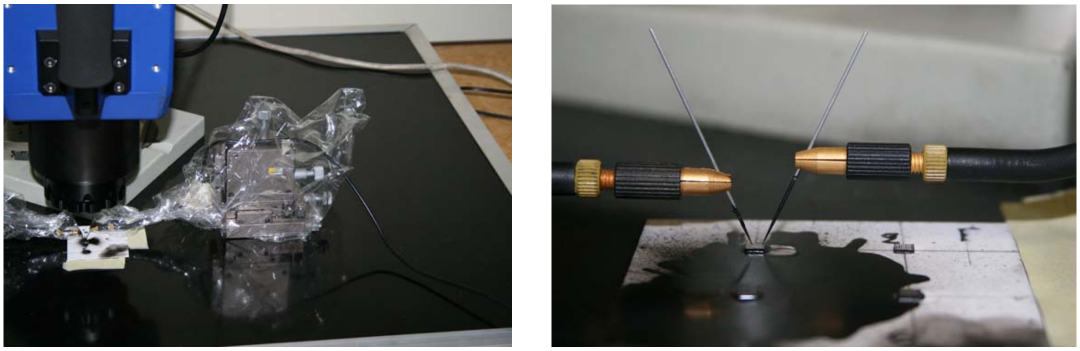

Fig. 4. *Measurement setup*

For each of the inductors, their temperature response to a heat step function was measured – both for heating and for cooling, using a DC current source and a *150 mA* current value. Because of the small sizes of the spiral's contact pads (*50 x 70* µm), XYZ micromanipulators with tungsten probes were used to make the connections (Fig. 4). To overcome the problem of low emissivity of aluminum interconnects, after connecting the circuit, the test circuit was covered with black mate paint. The measurements were made using a *MWIR Cedip Titanium* camera with a cooled *InSb 640 x 512* pixels detector matrix (*15* µm pixel pitch). A *60 mm* extension tube was added between the lens and the camera housing, allowing increasing the resolution from about *88 µm/pixel* (without the extension tube) to about *15* µm/pixel (with the tube).

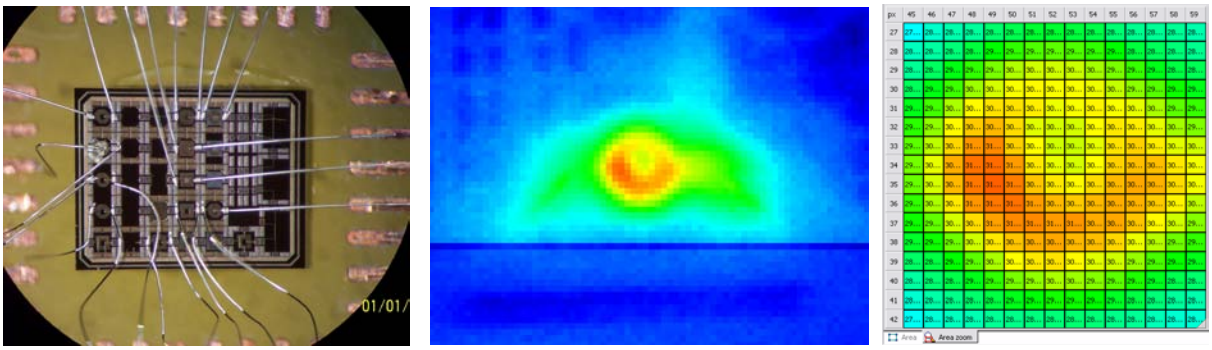

Fig. 5. *Photo of the IC containing the inductors and Thermal image of an octagonal spiral inductor under current stress (DC current 150mA for die on alumina substrate)*

Based on equation (1) and thermographic measurements made for the 4 octagonal spiral inductors, their thermal impedance was calculated. The results of the calculation are presented in the form of *Nyquist* plot in Fig. 6 and 7.

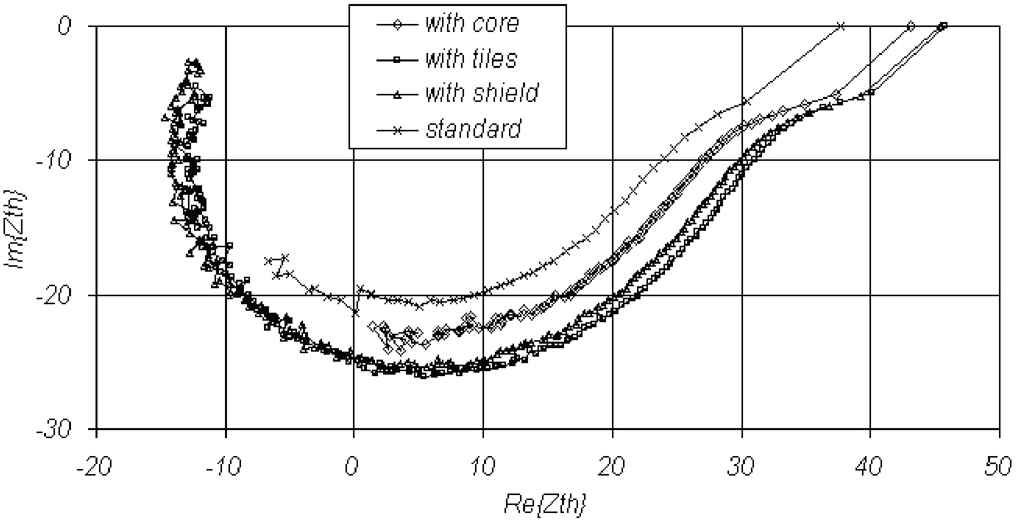

Fig. 6. *Nyquist plot of the complex thermal impedance Z_{th}[K/W] of the four measured integrated spiral inductors mounted on a ceramic substrate*(*k=25W/m·K*)

The standard coil is cooled the most, while the inductor with the polysilicon shield between the spiral and the silicon substrate and the inductor with metal tiles beneath the spiral are having the highest value of the thermal impedance in the entire frequency range. Both of these spiral inductors are giving results very close one to another. The measurements of the thermal impedance Z_{th} for the fourth spiral inductor with the aluminium core in its center gave intermediate values, between the standard octagonal inductor and inductors having a metal or polysilicon structure separating the spiral from the semiconductor structure.

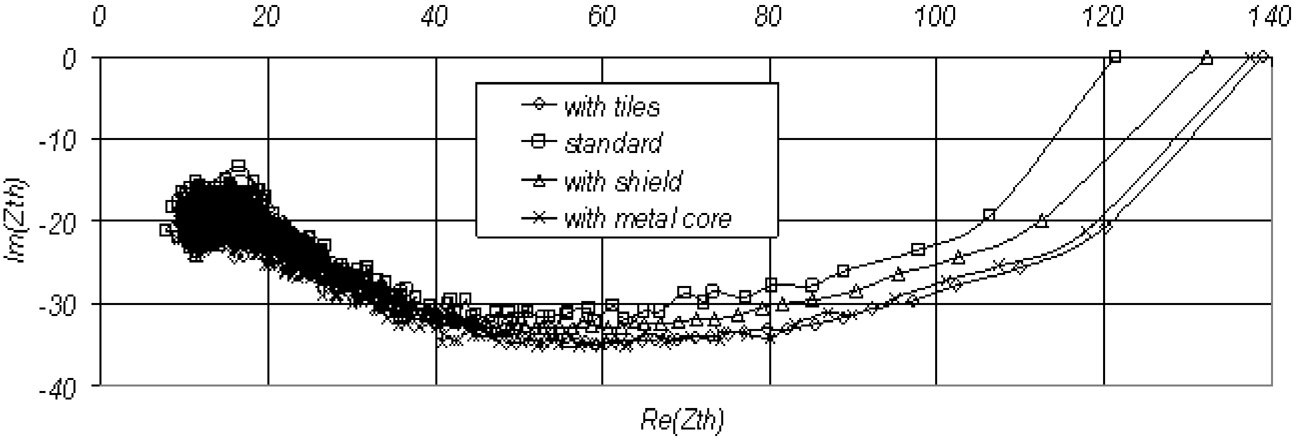

Fig. 7. *Nyquist plot of the complex thermal impedance Z_{th}[K/W] of the four measured integrated spiral inductors mounted on an epoxy substrate* (*k=1W/m·K*).

For the inductor mounted on top of the low thermal conductor, such as epoxy layer, the thermal impedance mainly depends on the convective cooling at upper side of the structure. The thermal camera generated images at the rate of *200frames/s*. Such low rate did not allowed to observe the high frequency components of thermal impedance. The thermal impedance at high frequency range varies due to the thermal properties of the silicon die and the inductor. The low frequency part of the *Nyquist* plot represents the cooling conditions of the entire structure. In the case on low thermal conductivity of the epoxy layer, thermal impedance obtained by the thermography measurements, depends on the convective cooling parameters only.

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5. Conclusions

In this paper we presented the measurement and simulation results of integrated inductors. The main aim of the research was partly achieved. We wanted to use thermography measurements for characterisation the technological process of fabrication such coils. In the research, we used the standard octagonal inductors, the inductors with/without the shield, as well as with metal core in the middle. Two experimental setups were chosen. At first, we measured the devices placed on the alumina substrate, highly conductive material, with $k \approx 25 W/m \cdot K$. Then, the epoxy substrate was used ($k<1W/m \cdot K$). On top of it, the silicon chip was glued with bounded connectors. In the first experiment, the electrical current was supplied through the needle probes. They had worse electrical contacts then the bounded wires in the second measurement. The most probably, we introduced the extra heat sources at both sides of the inductor. It could change the expected results of the experiment.

In the first measurement with alumina substrate, it was possible to differentiate the inductor's structure using the the thermal impedance method. It was due to the heat flow to the substrate. In this case any small change of the material properties or/and layers' thicknesses caused the change of the thermal impedance, both in high and low frequency range.

In the second experiment with the epoxy substrate, the simulations did not confirm the possibility of inductor characterisation. However, we obtained the different shapes of thermal impedance plots, due to the different positions of the coils on the substrate. The thermal impedance *Nyquist* plot mainly depends on convective cooling on the upper side of the structure.

The main conclusion of this paper one can draw, is that the thermal impedance is an easy method for thermal characterisation of microelectronic devices. Thermography can be used in such measurements, but in order to differentiate the devices according their structures it is necessary to record the thermal process at high sampling rate, which should be at least at the level of *kHz*. The thermal impedance varies much more in high frequency range due to the change of technological process parameters.

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