CHAPTER 2
MODELING OF SELF-HEATING IN IC INTERCONNECTS AND INVESTIGATION ON THE IMPACT ON INTERMODULATION DISTORTION

2.1 CONCEPT OF SELF-HEATING

As the frequency of operation increases, especially in the RF and microwave range (MHz - GHz), current that flows through resistive elements in ICs causes collision of charge carriers, resulting in an increase in the temperature of the IC.

The physics of self-heating can be given as follows: when a current at RF frequencies passes through a resistive element, collision of charge carriers occurs that causes a change in the temperature of resistive element. This is independent of ambient temperature and hence, appropriately called “self” heating. This heating then causes a change in resistivity, which then affects the time constants of the model, and hence causes undesired frequency components to appear in the output.

This is an undesired effect because of appearance of undesired frequency components, and self heating effects become more prominent as the devices are scaled down, especially towards 90nm and smaller technologies.

The problem of self heating can be accounted for, by coupling thermal and electrical domains and then developing a comprehensive model.

2.2 INTERCONNECTS AND TRANSMISSION LINE MODELS

In today’s VLSI circuits, in order to minimize chip size, we often go for multilayered interconnects, a typical example of which is shown below.
As seen above, there are various metal layers one above the other, separated with insulators in between. These interconnects can be modeled using standard transmission line models.

The transmission line models used most commonly to represent interconnects are:

1. The coplanar model (within a metal layer)
2. The microstrip model (between two metal layers of different heights).

The model parameters used in this work are as given below:
2.3 EQUIVALENT CIRCUITS OF TRANSMISSION LINE MODELS

Both coplanar and microstrip models can be modeled using passive RLC (resistor – inductor – capacitor) elements. The values of R, L, and C can be found out from the device dimensions using certain relations. These are lossy line models, including the resistive losses. As will be seen later, it is in the resistor that self-heating plays a vital role.
2.4 TWO TONE TEST AND INTERMODULATION DISTORTION

Usually, to test for nonlinear effects in line models, we use certain test signals. One such signal that is commonly used is the 2-tone signal which is the sum of 2 sinusoids of different frequencies. This is represented as follows:

\[ x(t) = a_1 \cos [f_1 t + u(t)] + a_2 \cos (f_2 t) \]

In our model, we used this 2 tone signal with the frequency of separation ranging from tens of Megahertz to tens of Gigahertz. When the 2 tone signal is passed through a nonlinear model a wide range of frequencies, created by the sum and difference of the fundamental frequencies and their harmonics are formed.

Hence if the input tones are \( f_1 \) and \( f_2 \), we have \( f_1, f_2, 2f_1, 2f_2, f_1-f_2, f_1+f_2, 3f_1, 3f_2, 2f_1-f_2, 2f_1+f_2, 2f_2-f_1 \) and \( 2f_2+f_1 \) (approximated third order). Out of these, all frequencies except \( f_1, f_2, 2f_2-f_1, \) and \( 2f_1-f_2 \) are called “out-of-band” products and can be easily filtered out. The in-band frequencies are \( f_1, f_2, 2f_1-f_2, \) and \( 2f_2-f_1 \). Out of these \( f_1 \) and \( f_2 \) are the desired output frequencies. The distortion caused by the remaining frequencies (\( 2f_1-f_2, \) and \( 2f_2-f_1 \)) are called “intermodulation distortion” (IMD)
Hence IMD is the most critical form of distortion as these frequencies can neither be filtered out nor be ignored. As will be seen later, it is the Third Order IMD (IMD3) i.e. \(2f_2-f_1\) and \(2f_1-f_2\) that cause much of the problem with regards to self heating.

### 2.5 CHARACTERIZATION AND MEASUREMENT OF IMD3

The 2 means of characterizing IMD3 are intercept point (IP3) and intermodulation ratio (IMR). The means of determining them is as shown.

![Figure 7 Computation of third order intercept point](image)

Here output power is measured as a function of input power, and the intersection of the extrapolated Pinput and PIMD gives IP3.

\[
IMR = \frac{P_{fund}}{P_{IMD}} = \frac{P(\omega_1)}{P(2\omega_1 - \omega_2)} = \frac{P(\omega_2)}{P(2\omega_2 - \omega_1)}
\]

![Figure 8 Computation of IMR](image)

Shown below is the most commonly used setup for measuring IMD3.
2.6 MULTISIM IMPLEMENTATIONS OF LINEAR AND NONLINEAR TRANSMISSION LINES

To better understand the effects of IMD due to line nonlinearity, we simulated first a linear transmission line (microstrip) based on the equivalent circuit in MultiSim and then observed the Waveforms and Fourier Spectrum. The results are as shown below:
2.6 MULTISIM IMPLEMENTATIONS OF LINEAR AND NONLINEAR TRANSMISSION LINES

Figure 10 Linear Transmission line

Figure 11 Output Fourier Spectrum
Next we repeated the simulations, but this time with a nonlinear transmission line obtained by replacing the capacitors with the varactors.

Figure 12 Nonlinear transmission line waveform

Figure 13 Output spectrum
As can be seen the nonlinear transmission line shows a lot of other components other than the input frequencies, and these components contain both inband and out-of-band distortion components. Thus the intermodulation distortion was effectively understood using the equivalent circuits.

2.7 ELECTRO-THERMAL THEORY OF SELF-HEATING

Self-heating causes Intermodulation distortion and this is called ET-PIM (electro-thermal passive intermodulation distortion). This is explained in the paper by Wilkerson et al. and is outlined briefly here:

THE COLLISION OF CHARGE CARRIERS IN A RESISTIVE ELEMENT CAUSES CHANGE IN TEMPERATURE AND THIS CHANGE IS PERIODIC, WITH A BASEBAND RANGE. NOW, WHEN A 2 TONE INPUT SIGNAL IS GIVEN AS INPUT, THE POWER SPECTRUM CONSISTS OF THE SUM (F1+F2) AND THE DIFFERENCE (F1-F2, ALSO CALLED ENVELOPE OR BEAT FREQUENCY). IF THE BEAT FREQUENCY HAPPENS TO FALL IN THIS BASEBAND RANGE, THE THERMAL EFFECTS BECOME PROMINENT, PERIODICALLY VARYING THE RESISTANCE. IN EFFECT, THIS CREATES A PASSIVE MIXER PRODUCING INTERMODULATION DISTORTION THROUGH UPCONVERSION OF THE ENVELOPE FREQUENCIES AT BASEBAND TO RF FREQUENCIES. THESE FREQUENCIES ARE NOTHING BUT THOSE ARISING IN IMD3 (THIRD ORDER INTERMODULATION DISTORTION).

This is clearly illustrated in the following diagram:
Mathematically the expressions denoting the process are as follows:
2.8 COMPACT MODELING OF SELF HEATING

The equations and resulting changes can be given as an equivalent circuit which acts as a replacement of the resistor in the transmission line models.

![Figure 16 Equivalent circuit of resistor](image)
Here, $Q$ is the input to the model and this is the power dissipated through the resistor, $T_a$ represents ambient temperature. The expressions for the $R_{th}$ and $C_{th}$ are as follows:

\[
R_{th} = \frac{\Delta T}{P} = \frac{\Delta T}{T^2R}
\]

AND THE THERMAL CAPACITANCE CAN BE CALCULATED USING THE FOLLOWING:

\[
C_{th} = C_v R_{th}
\]

HERE $C_v$ IS THERMAL CAPACITY, $p_d$ IS DENSITY, $V$ IS VOLUME, AND $k$ IS THERMAL DIFFUSIVITY

**Figure 17 Rth and Cth for self heating equivalent circuit**

### 2.9 TRANSMISSION LINE MODELS INCLUDING SELFHEATING EFFECTS

Next, we implement Transmission line models including the effects of self heating. To start with, we implement Microstrip made of Aluminium SOI as a model including self heating effects, and set the 2 tones at 600MHz and 700MHz. The results are as follows:

**Figure 18 Aluminium microstrip waveforms**
Figure 19 Input Fourier Spectrum

Figure 20 Output spectrum
As we can see in Fourier analysis of output, there is significant amplitude of the desired components, 600 and 700 MHz (the 2 tones). In addition we have components at 800 and 500 MHz which are the IMD3 frequencies. There are components in other frequencies as well. For example, 400 and 900 MHz But these are far apart from the desired frequency (600 and 700 MHz) and hence can be easily filtered out using appropriate band pass filters.

Next we repeat the same but with the 2 tones at 300 and 400MHz. The results are as follows:

*Figure 21 Aluminium Microstrip Waveforms*
2.9 Transmission Line Models Including Selfheating Effects

Figure 22 Input spectrum

Figure 23 Output spectrum
As we can see in Fourier analysis of output, there is significant amplitude of the desired components, 300 and 400 MHz (the 2 tones). In addition we have components at 500 and 200 MHz which are the IMD3 frequencies. There are components in other frequencies as well. For example, 100, 600, 700 MHz But these are far apart from the desired frequency (300 and 400 MHz) and hence can be easily filtered out using appropriate band pass filters.

From the equations regarding self-heating that were described earlier, we could observe that resistance changes as a function of temperature which in turn varies with time. So we can conclude that resistance varies with temperature. The plot of resistance (ohm) as a function of time (us) for a frequency separation of 999MHz is shown below:

![Resistance variations](image1)

**Figure 24 Resistance variations**

### 2.10 VERIFICATION OF THE COMPACT MODEL

The compact model has to be verified and checked for consistency. For this we considered a similar model was devised by Eduard Rocos et al. Mentioned in their paper titled “third order intermodulation distortion due to self-heating in gold coplanar waveguides” and they had simulated the model and also verified the results experimentally. Hence in order to verify our model, we tried to reproduce the results by simulating a gold coplanar transmission line of the dimensions specified by them. The model parameters used by them are as follows:
MODEL PARAMETERS

- **COPLANAR:**
  - SUBSTRATE: Sapphire
  - CONDUCTOR: Gold
  - CONDUCTOR WIDTH: 30\,\text{um}
  - SLOT SPACING: 15\,\text{um}
  - CONDUCTOR THICKNESS: 480\,\text{nm}
  - SUBSTRATE HEIGHT: 200\,\text{um}
  - LINE LENGTH: 9.933\,\text{mm}

The results are as follows:

Figure 25 Model parameters of Gold Coplanar Waveguide

Figure 26 Waveforms for 700 and 800\,\text{MHz}
As we can see in Fourier analysis of output, there is significant amplitude of the desired components, 700 and 800 MHz (the 2 tones). In addition we have components at 600 and 900
MHz which are the IMD3 frequencies. There are components in other frequencies as well. For example, 300, 1000, and 1100 MHz. But these are far apart from the desired frequency (700 and 800 MHz) and hence can be easily filtered out using appropriate band pass filters.

Shown below is the frequency separation (MHz) vs. IMD3 (dBm) of the simulated gold CPW model, shown alongside the corresponding curve obtained by Eduard Rocos et al (denoted as A-CPW).

![Figure 29 Curves of Edouard](image_url)
Figure 30 Curves for our model

Figure 31 Curves overlaid
Thus the above curves assert without doubts the validity and accuracy of the compact model, thus making it as good as measuring the values in the lab and asserting it.

**2.11 COMPACT MODELING OF BEOL INTERCONNECTS**

**Back-end-of-line (BEOL)** denotes the second portion of IC fabrication where the individual devices (transistors, capacitors, resistors, etc.) get interconnected with wiring on the wafer. BEOL generally begins when the first layer of metal is deposited on the wafer. It includes contacts, insulating layers (dielectrics), metal levels, and bonding sites for chip-to-package connections.

The next step is to model the self heating in back end of line (BEOL) interconnects. These are usually made of tantalum which has a negative temperature coefficient of resistance. Thus beol can be modeled as microstrip with the same geometry given earlier but with the conductor replaced by tantalum. The results will now be shown.
Figure 33 Waveforms of tantalum at 300 and 400 MHz

Figure 34 Input spectrum
2.12 IMPACT OF SELF HEATING ON INTERMODULATION DISTORTION

As the MultiSim comprehensive model is now validated with the verification of results with gold coplanar waveguide, the next step is to simulate the self heating effects observed in real time in back end of line interconnects., where the material is either aluminium or tantalum and substrate is SiO2 (SOI technology). Such self heating depends on a number of factors as follows:

1. Whether the model is coplanar strip / microstrip

2. Whether the transmission line is linear or nonlinear (varactor induced nonlinearity)

3. Whether the conductor is aluminium / tantalum.

4. Whether self heating is included or not.
This gives a total of 16 combinations, all of which are simulated with the dimensions specified earlier, and a graph of IMD3 power (dBm) vs. separation frequency (w2-w1) is overlaid and plotted as follows.
2.12 Impact of Self Heating on Intermodulation Distortion
To understand the curves better we isolate 3 cases, involving aluminium microstrip and plot them as follows:
We can infer the following points from these curves:

1. Self heating does have an impact on IMD as the IMD3 values of aluminium microstrip under varactor induced nonlinearity show a significant increase when self heating is present.
2. Hence self heating is very important.
3. There is a nonlinear region in the curve at high frequencies (around 10 to 1000 MHz). But in this region aluminium microstrip show much better performance than their tantalum counterparts.

2.14 SUMMARY

Thus we conclude by stating that we have obtained an equivalent circuit that explains self-heating effects and have tested the presence of nonlinearity and IMD using simulation.

The significance of the approach lies in successfully modeling thermal effects in interconnects in ICs using SOI technology with al conductors.

Future work: proposing of circuits and techniques that can be used for compensation of self-heating effects.

2.15 REFERENCES

