Leakage Current Analysis for Intra-Chip Wireless Interconnects

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***Abstract*—A simulation-based feasibility study of an intra-chip wireless interconnect system is presented. The wireless interconnect system is modelled in a 250 nm standard complementary metal-oxide semiconductor (CMOS) technology operating at typical conditions. A finite element method (FEM) based 3-D full-wave solver is used to perform the electromagnetic field analysis. In the field analysis, the effects of the radiation of an intra-chip wireless interconnect system operating at 16 GHz on the circuit devices and local metal interconnects at arbitrary distances from the antennas are investigated. It is shown that the transmission gain between the antennas is mostly unaffected by the presence of local metal interconnects. The transmission scattering parameter (s-parameter) between the radiating antenna and the metal interconnects is below -31.66 dB. The leakage current in the sub-threshold region of the transistors, caused by the antenna radiation induced voltages, is shown to be below 2.2 fA and decreasing with distance from the radiating antenna.**

I. Introduction

Reduction in device sizes in semiconductor technologies has increased the speed and performance of integrated circuits. However with the reduction in device sizes, there has also been a proportional reduction in the cross-sectional area of the interconnects between these devices. The global interconnect lines have become a bottleneck to the increase in speed, as the delay due to these interconnects is becoming higher than the gate delay [1]. In addition, the system complexity and the die size of a typical integrated circuit have increased significantly. Hence, global interconnect networks such as the clock distribution network will suffer from skew, jitter, power dissipation and area consumption in future generations of integrated circuits [2].

Changes to materials of the chip such as low κ dielectrics and high conductivity metals have been introduced to mitigate the effect of the interconnect delay but these changes can increase the scaling of the global interconnect system only by a few technology generations [1]. These considerations have necessitated the need for an alternative global interconnect system to address the growing concerns of timing, power and area overheads of global interconnect networks.

One possible alternative for the global interconnects is to use wireless interconnects operating in the radio-frequency (RF) range, as proposed in [3]. Despite not being fully-functional, the study in [3] demonstrates the feasibility of establishing an intra-chip wireless communication channel. The signal coupling for the wireless communication channel between the transmitting and receiving antennas is shown to be due to wave propagation, and not due to conduction through the substrate, demonstrating the true wireless behavior of an intra-chip communication system.

In this paper, the effects of the radiation from the antennas of the wireless interconnect system are investigated on:

1) The circuit devices,
2) The local metal interconnects.

In order to study the effect of the antenna radiations on the circuit devices, the electric field created over the metal-oxide semiconductor field-effect transistor (MOSFET) devices at varying distances from the antenna is studied. Particularly the effect of the antenna radiations on the sub-threshold region of operation for leakage power is studied. The effect of the antenna radiations on the local metal interconnects is presented using the transmission scattering parameter (s-parameter) between the metal interconnects and the transmitting antenna as a basis. The effect of the presence of local metal interconnects on the same metal layer and in proximity of the intra-chip communication antennas are investigated. Experimental results depict no significant effect on the radiation patterns.

II. Literature Review

There is a limited body of work on designing, simulating and manufacturing on-chip antenna pairs for intra-chip communication. The previous body of work can be categorized into three items in relevance to the work presented in this paper:

1) Different antenna topologies [4–6],
2) Design principles of wireless interconnects in multi metal layer semiconductor technologies [7, 8],
3) Analysis of wave propagation on an IC die [4, 9].

It is shown in [4–6] that the transmission gain between the transmitting and receiving antennas can be improved by using different antenna topologies. In [4], it is shown that among the various dipole antenna topologies, the zigzag antenna with a bend angle of 30 deg. provides relatively high gains. In [6], it is shown that the presence of metal interconnects placed on the same layer as that of the antenna in parallel orientation to the antenna decreases the antenna gain in the lower frequency range and increases it in the mid-band and high frequency ranges. However, the change in the gain is not very large and does not have a major influence on the transmission gain. In other words, the presence of the metal interconnects shifts the response to a higher frequency range.

In [7] and [8], it is shown that the presence of metal interconnects directly above or below the antenna structures tremendously reduces the transmission gain between the antenna pairs. This is because of the reflection of the dipole antenna formed in these metal layers, which is not desirable for a dipole antenna. In [4] and [9], it is shown that the majority of the wave propagation happens in the substrate and through surface waves. This emphasizes the criticality of the analysis of the effect of the antenna radiations on the metal interconnects in the same metal layer as that of the antenna and on the circuit elements. The intensity of the antenna radiations is the highest on the surface containing the antenna (the metal interconnects are on this layer) and through the substrate which contains the transistors.

Aforementioned previous work establishes facts and considerations in the implementation of an intra-chip wireless communication system by

1) Demonstrating the feasibility of using on-chip antennas for intra-chip communication,
2) Analyzing the effect of the presence of physical interconnects on the transmission gain between the antenna pairs.

However, the effect of the radiations from the antenna on the local metal interconnects and devices in the physical proximity is not considered in [4–6]. The effect of the antenna radiations on the local metal interconnects and circuit devices is important as it can greatly influence the overall behavior of an IC system using wireless interconnects for intra-chip communication. In particular, the effect of the antenna radiations on the metal interconnects can interfere with the integrity of the signals on the metal interconnects. The effect of the antenna radiations on a device (e.g. at the gate oxide and the channel of the MOSFETs) can affect the operation mode of the device. The criticality of the effect of the antenna radiations on the metal interconnects and circuit devices significantly increases for deep sub-micron technologies as V_{DD} and noise margins for these technologies are much smaller.

In [6], the effect of the presence of the local metal interconnects on the transmission gain of the antenna pair is analyzed. However, the effect of the antenna radiations on the local metal interconnects (there is mutual interaction) has not been critically analyzed. Since the local interconnect is in the same metal layer as that of the antenna, substantial amount of power can be transmitted to it from the antenna radiations. Hence, it is critical to analyze the transmission gain between the antenna and the local interconnects. In this paper, the effect of the antenna radiations on specifically the gate oxide and the channel of MOSFET devices is analyzed in detail. The effect of the antenna radiations is simulated at varying distances from the transmitting antenna. The effect of the antenna radiations on the local metal interconnects and the effect of the presence of metal interconnects on the transmission gain between the transmitting and the receiving antennas is also discussed in tradition of the previous work.

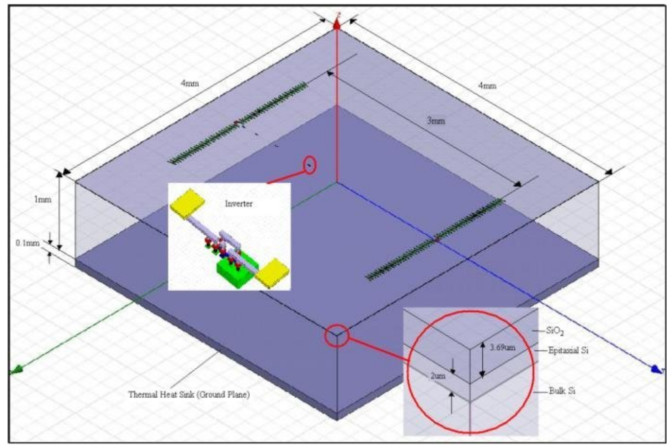

Fig. 1. Simulated structure for a wireless interconnect system. Design dimensions are according to a 250 nm design technology.

III. Experimental Setup

The simulation of the wireless interconnect system is performed in Ansoft HFSS (High Frequency Structure Simulator), a 3-D FEM based simulator [10]. A 250 nm CMOS technology is selected for metal interconnects and circuit device integration. Without loss of generality, nominal operating conditions are assumed. The simulated structure is constructed as shown in Figure 1. The die size is 4 x 4 mm^2. Note that, the die size and the size of the antennas are interdependent. In smaller sized chips, the overhead in terms of the footprint and the complexity of using a wireless system is much higher than using metal interconnects. This does not rule out the possibility of wireless inter-chip communication; although the chip size would still have to be limited by the antenna dimensions.

The transmitting and receiving antennas are separated at a distance of 3 mm from each other. According to the results shown in [3] and the discussion in Section II, two (2) half-wave zig-zag dipole antennas with a bend angle of 30 deg. and a total arm length (including the length of the bent segments) of 3.9 mm are designed to operate at 16 GHz. The metal thickness of the antennas is 10 μm. In the 3-metal layer 250 nm process, the antennas are placed in the third metal layer to have maximum separation of the antenna from the lossy silicon substrate. The conductivity of the bulk substrate used in the model is 20 Ω-cm.

In order to simulate the effect of the radiation from the antenna on the local metal interconnects, and the effect of the metal interconnects on the antenna gain, several interconnects are placed in the third metal layer (same layer as the antenna). Note that, M3 interconnects are chosen because the effect of the antenna radiations is expected to be the highest on the same metal layer as that of the antenna. The metal interconnects are placed at distances ranging from 1 μm to 2.0 mm from the transmitting antenna. The metal interconnects are 100 μm long, 0.5 μm wide and are placed parallel to the antenna. In order to simulate the effect of the radiation from the antenna on the circuit devices, inverters are placed at distances ranging from 1 μm to 1.5 mm from the transmitting antenna. Note that the inverter are designed in the standard 250 nm process technology design rules utilizing all three metal layers.

The metal interconnects and inverter devices are placed perpendicular to the center of the antenna. This is such, as the gain for the dipole antenna is highest in the direction perpendicular to the antenna and at the center of the antenna structure. Experimentally, the highest antenna gain leads to the modelling of the worst case of the interference effects for selected device sizes and interconnect lengths. The simulations are performed in the frequency range from 10 GHz to 30 GHz as the target operating frequency is at 16 GHz.

IV. Results and Discussions

In experimentation, four primary sets of data are collected:

1) The scattering parameter (s-parameter) matrix between the antenna pair, $\overline{S}$,
2) The transmission s-parameter between the transmitting antenna and the metal interconnects, S_{31},
3) The electric field due to the antenna radiations in the gate oxide region of MOSFETs, $[E_{f(gate)}]_{RAD}$,
4) The electric field due to the antenna radiations in the channel of the MOSFETs, $[E_{f(channel)}]_{RAD}$.

The scattering parameter (s-parameter) matrix of a network characterizes the coupling between the ports of a network. An element, S_{ij} of the s-parameter matrix, $\overline{S}$, is the ratio of the normalized output power at port i due to the normalized input power at port j [11]. Hence, the s-parameter matrix is used to characterize the operation and efficiency of the intra-chip wireless communication system. Note that, the electric fields measured on the transistors are only those created by the antenna radiations. These electric fields superimpose with the electric fields due to conventional transistor operation.

The simulation model is a three (3) port network, with the transmitting and receiving antennas designated as ports 1 and 2, respectively, and the interconnect designated as port 3. The s-parameter S_{11}, also defined as the radiation loss, is used to determine the radiation frequency of the transmitting antenna. The s-parameter S_{21} characterizes the signal coupling between the radiating and the transmitting antennas. Hence, the s-parameter S_{21} is used to characterize the strength of the wireless link between the transmitting and receiving antennas. The transmission s-parameter S_{31} characterizes the signal coupling between the transmitting antenna and the interconnect. Hence, the s-parameter S_{31} gives the amount of power transferred to the interconnect from the antenna radiations.

The radiation frequency of 16 GHz for the antenna is verified from the s-parameter S_{11} as shown in Figure 2. It is also shown, in Figure 2, that the presence of 0.5 μm wide interconnects shifts the radiation frequency to a higher value and is consistent with the results in [6].

The figure of merit for the antenna pair is the transmission gain between the transmitting and receiving antenna. Hence,

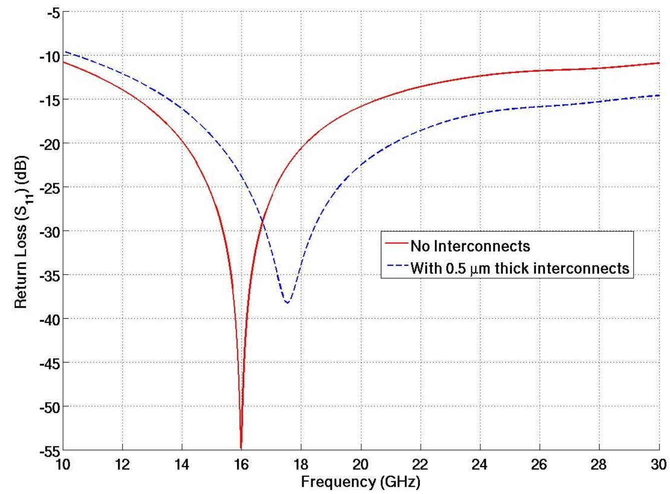

Fig. 2. Return loss S_{11} at the transmitting antenna.

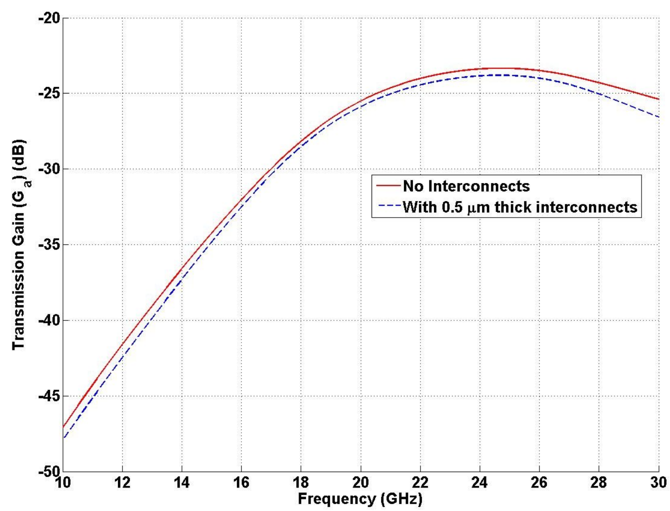

Fig. 3. Transmission gain G_a between transmitting and receiving antenna.

the transmission gain of the antennas is analyzed in order to study the effect of the local metal interconnects on the antenna performance. The transmission gain, G_a of the antenna pair is computed using (1) :

$$G_a = \frac{|S_{21}|^2}{(1 - |S_{11}|^2)(1 - |S_{22}|^2)} \tag{1}$$

where S_{21} is the forward transmission, S_{11} is the reflection of the electric field at the transmitting antenna and S_{22} is the reflection of the electric field at the receiving antenna. All three parameters S_{11}, S_{21}, and S_{22} are obtained from the s-parameter matrix $\overline{S}$.

In Figure 3, the transmission gain for the two cases, with and without the metal interconnects, are shown. It is observed that the transmission gain remains unaffected by the presence of the metal interconnects in the same metal layer as that of the antennas (M3). Note that, in [6] the transmission gain is higher than that shown in Figure 3. It is also shown in [6] that the presence of metal interconnects increases the transmission gain

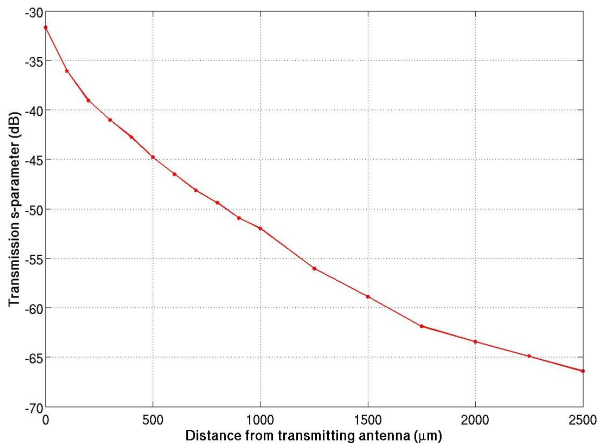

Fig. 4. Transmission s-parameter S_{31} between transmitting antenna and local metal interconnects.

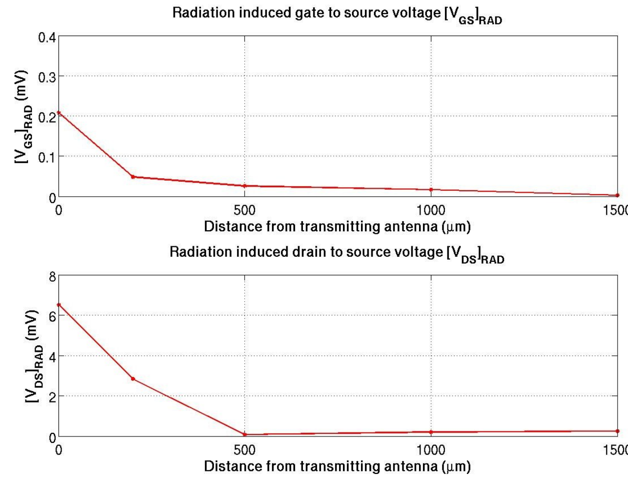

Fig. 5. Radiation induced gate to source voltage and drain to source voltage with distance from the transmitting antenna.

in the mid-band and high frequency ranges. However, in [6] no information about the conductivity of the bulk substrate is provided. This potential difference in the conductivity of the bulk substrate is the primary reason for the discrepancy in the results provided in [6] and in this work. The substrate conductivity is important and can substantially change the transmission gain between the antenna pair [4].

In Figure 4, the transmission s-parameter S_{31} between the M3 interconnects and the transmitting antenna is shown at varying distances from the transmitting antenna and is measured at a frequency of 16 GHz. The transmission s-parameter S_{31} between the M3 interconnects and the transmitting antenna characterizes the amount of antenna radiations picked up by the metal interconnects. A monotonous decrease, from an already very low value of -31.66 dB to an even lower value of -66.42 dB, is observed.

The antenna radiations picked up by metal interconnects is also picked up by the circuit devices on the die. The circuit devices, which are modelled as MOSFETs, operate under the principle that a voltage applied at the gate of the device causes a strong electric field across the gate oxide. This electric field causes a strong inversion and forms the channel under the gate oxide. Similarly, the radiation from the antenna also creates an electric field across the gate oxide, which might change the operating condition of the device. Consequently, the effect of the antenna radiations on the MOSFET device is studied by obtaining the electric field across the gate oxide and the channel. The near field radiation is considered as the distance of the devices, from the transmitting antenna in this simulation, is much smaller than the wavelength of the radiation. While the radiation induced voltage affects all modes of operation it is considered most critical at the cut-off stage, where sub-threshold leakage might occur. Hence, the near field radiation effect is analyzed in the sub-threshold region.

First, the magnitude of the electric field, $[E_{f(channel)}]_{RAD}$, across the channel and the electric field $[E_{f(gate)}]_{RAD}$ at the gate oxide due to the antenna radiations is obtained (in units of V/m). In general a voltage difference due to an electric field over any region is given by (2):

$$V_{RAD} = [E_f]_{RAD} \times L \tag{2}$$

where $[V]_{RAD}$ is the radiation induced voltage, $[E_f]_{RAD}$ is the electric field due to the radiation and the L is the length of the element across which the electric field is considered. This general equation, (2), for the induced voltage is used to determine the radiation induced voltages $[V_{DS}]_{RAD}$ and $[V_{GS}]_{RAD}$ over a MOSFET channel and gate, respectively, as given by (3):

$$[V_{DS}]_{RAD} = [E_{f(channel)}]_{RAD} \times L_{channel} \tag{3a}$$

$$[V_{GS}]_{RAD} = [E_{f(gate)}]_{RAD} \times t_{OX} \tag{3b}$$

In (3a) and (3b), $[V_{DS}]_{RAD}$ is the radiation induced voltage across the drain-source region, $L_{channel}$ is the channel length, $[V_{GS}]_{RAD}$ is the radiation induced voltage across the gate-source region and t_{OX} is the gate oxide thickness. In the target 250 nm semiconductor technology, the gate oxide thickness, t_{OX} is 10 nm and the MOSFET device channel length, $L_{channel}$ is 0.5 μm.

In Figure 5, $[V_{DS}]_{RAD}$ and $[V_{GS}]_{RAD}$ are plotted for increasing distance from the radiating antenna with a 1 W input power at the transmitting antenna. It is observed from Figure 5 that the radiation induced voltages $[V_{DS}]_{RAD}$ and $[V_{GS}]_{RAD}$ decrease non-monotonously with increasing distance from the transmitting antenna. It is also noted that there is a slight increase in the value of the induced voltages after a distance of 500 μm. However, this increase is very small compared to the radiation induced voltages at a distance of 1 μm. This increase in radiation induced voltages is attributed to the asymmetrical radiation pattern of the transmitting antenna.

The leakage current in the sub-threshold region of operation of the transistor is given by (4) [12]:

$$I_D = I_S e^{qV_{GS}/nkT}(1 - e^{-qV_{DS}/kT})(1 + \lambda V_{DS}) \tag{4}$$

where, I_S is the reverse saturation current, q the charge of an electron, k the Boltzmann constant, T the temperature in

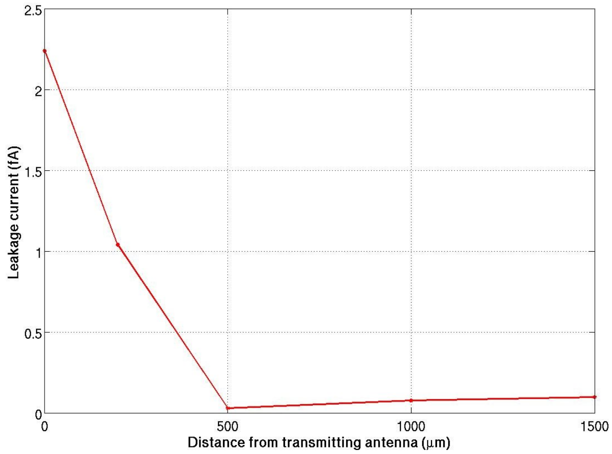

Fig. 6. Leakage current vs. distance from transmitting antenna, in sub-threshold region of operation caused due to radiation induced voltages.

Kelvin, λ the channel length modulation factor, n the empirical constant, V_{GS} the gate to source voltage and V_{DS} is the drain to source voltage. I_S and n are empirically measured values. It is reported in [12] that typical values for I_S range from 10^{-13} to 10^{-15}, therefore I_S is taken as 10^{-14} as an approximation for the selected 250 nm technology. For an ideal transistor $n = 1$ and for a non ideal transistors $n > 1$; the value of $n = 1$ is chosen to obtain the worst case scenario. Without loss of generality, the channel length modulation is ignored, thus $\lambda = 0$.

The leakage current equation in (4) and the radiation induced voltage on the devices shown in Figure 5 are used to estimate the leakage current due to antenna radiation at varying distances from the transmitting antenna. In Figure 6, the leakage current due to the radiation induced voltages $[V_{DS}]_{RAD}$ and $[V_{GS}]_{RAD}$ is shown. It is observed that the leakage current due to the radiation induced voltages is very small at 2.2 fA. For comparison note that a noise spike of 100 mV at the drain, gate and source of the MOSFET would create a leakage current of 22.7 pA, which is four (4) orders of magnitude larger. Therefore, very little power is dissipated in the transistors due to the leakage current caused by the presence of the radiation. The leakage current is also seen to decrease with increasing distance from the transmitting antenna while still reflecting the non-monotonicity of the voltages induced due to the radiation.

V. Conclusion

The effect of the radiations from the antennas integrated on chip for intra-chip communication with the circuit elements and the local metal interconnects is demonstrated for a 250 nm standard CMOS technology. The effect of the antenna radiations on the transistors is investigated by calculating the leakage current in the sub-threshold region of operation. The leakage current is found to be less than 2.2 fA. This value of leakage current (< 2.2 fA) is at least four orders of magnitude smaller than the typical leakage currents experienced by the MOSFET devices in an IC. The leakage current due to the antenna radiation induced voltages also reduces with increasing distance from the transmitting antenna. Such a low value of leakage current implies that the intra-chip wireless interconnect system is realizable and does not dissipate a large amount of power due to the leakage current. It is also to be noted that this value of leakage current is for sparse metal layers. On an actual chip the density of metal in the different metal layers would provide shielding to the transistors from the antenna radiations. The shielding effect of the different metal layers is expected to decrease the electric field across the channel and the gate oxide regions of the MOSFET. This decreased electric field implies a reduction in the radiation induced voltages and hence the leakage current, which are already very low.

It is also shown that the presence of local metal interconnects in the same metal layer as that of the antenna does not have any significant effect on the transmission gain between the antennas. Further, the return loss between the transmitting antenna and the local metal interconnects is below -31.66 dB and decreases with an increasing distance from the transmitting antenna. The radiation from the on-chip antennas has very little effect on the circuit elements and the local interconnects and therefore such a system is realizable without any detrimental effects on system operation. The benefits of an intra-chip wireless communication system still need to be investigated further for synchronization, area and power concerns.

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