Noise Coupling between TSVs and Active Devices: Planar nMOSFETs vs. nFinFETs

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Abstract

Through Silicon vias (TSVs) are a key breakthrough in 3D technology to shorten global interconnects and enable the heterogeneous integration. However, TSVs also introduce an important source of noise coupling arising from electrical coupling between TSVs and the active devices. This paper investigates the TSV noise coupling to active devices including both FinFETs and planar transistors based on two-port S-parameter measurements up to 40 GHz. The measurements clearly show that nFinFETs have better noise coupling immunity than planar nMOSFETs. The dominant coupling mechanisms were also identified for both types of active devices.

Moreover, calibrated TCAD models were developed. We show that via-last TSV architectures with thick liners (“donut TSVs”) and scaled TSV diameters reduce the noise coupling to active devices. Finally, both coupling and stress induced saturation current variations as a function of TSV to active devices distance were investigated. This allows us to propose a novel model for the TSV Keep Out Zone (KOZ) including electromagnetic coupling effects.

Introduction

3D technologies provide promising solutions to meet the needs of today’s high performance and high speed ICs. Amongst these 3D technologies, the through silicon via (TSV) process has become a key breakthrough in 3D technology to shorten global interconnects. Moreover, TSVs enable the heterogeneous integration of different technologies into advanced systems-in-package enabling “More than Moore” applications. However, TSVs are also an important source of noise coupling: high speed signals on TSVs can interact with the active devices through the TSV oxide liner and the bulk silicon substrate as shown in Figure 1.

Figure 1. Noise coupling between TSV to active device.

This noise coupling can cause circuit malfunctioning and signal integrity problems. Therefore, it is essential to analyze

and understand the impact of TSV high frequency noise on active devices. Most publications in the literature address the noise coupling through electromagnetic simulations and modeling without experimental verification [1,2,3,4]. This paper focusses on an experimental coupling study based on RF S-parameter measurements up to 40 GHz. This is complemented by calibrated TCAD models. This approach allows for a complete analysis of the coupling mechanisms between TSVs and different active devices, both planar and FinFET based.

In the first part of this paper, the TSVs to active devices test structure and RF measurement set up are presented. DC and two-port (Drain-to-TSV) S-parameter measurements were performed under different biasing conditions of the TSV as well as of gate and drain of the transistors. Secondly, the measured coupling coefficients (S12) were analyzed for both types of active devices in both their ON and OFF states and the dominant coupling mechanisms were identified. Furthermore, TCAD models were developed and calibrated against S-parameter measurements. The impact of TSV diameter, liner material and thickness, substrate contact location on the coupling level were investigated using the calibrated TCAD model. Finally, we show that the coupling induced variation of the transistor current should be considered together with the thermo-mechanical stress impact for the KOZ extraction.

Test structure description and RF measurements setups

The RF noise coupling test structures were built using state of the art 5 μm / 50 μm TSV technology and two types of active devices: 65 nm planar nMOSFETs and 32 nm nFinFETs. The specifications of these two types of transistors are given in Table 1.

Table 1. FinFET and planar transistor specifications based on RF test structures

Parameter	Planar	FinFET
TSV-active spacing	10 μm	10 μm
TSV diameter/height/liner	5/50/0.2 μm	5/50/0.2 μm
W _{total}	15 μm	6.4 μm
L	50 nm	40 nm
#	5 fingers	80 fins

The layout of the RF test structures is shown in Figure 2. The distance between the TSV centers and the active devices is 10 μm. Two-port (Drain-to-TSV) S-parameter measurements were performed using an Anritsu 37369A 40 GHz Vector Network Analyzer. The measurement setup for

the RF probe connection is shown in Figure 3. The noise coupling measurements were performed under different biasing conditions of the TSV (-15 V to 10 V) as well as of the gates and drains of the transistors.

Figure 2. RF test structures for Noise coupling between TSV to active device.

Figure 3. RF S-parameter measurements setup.

Experimental coupling study for TSV-planar nMOSFETs

In a first step, DC measurements for planar nMOSFETs under different TSV biasing condition have been performed. The initial DC measurements (Figure 4) showed that biasing the TSVs (-15 V to 10 V) had no impact on the DC behavior of planar nMOSFETs.

Figure 4. TSV bias impact on DC behavior of planar nMOSFETs.

In a next step, RF measurements of the noise coupling coefficients (S_{12}) between the TSVs and the drains of planar device were analyzed. This coupling coefficient represents the

noise that can be coupled from an RF signal in the TSV to the active devices through the TSV oxide liner and the bulk silicon substrate. Two coupling mechanisms exist between TSVs and active devices: noise amplification through the bulk transconductance (g_{mb}) as well as capacitive coupling to the drain/source through the substrate. For planar nMOSFETs, the first mechanism dominates for the ON state, leading to large noise coupling with respect to the OFF state. As shown in Figure 5, up to 25dB in difference is observed for transistors in the ON and OFF states.

Figure 5. TSV - planar nMOSFETs noise coupling measurement: transistors in on and off state (TSV biasing = 0V).

Moreover, S_{12} was also investigated as a function of V_{gate} both in the linear (Figure 6) and the saturation region (Figure 7). Above 0.4 V, the increase of V_G decreases the coupling in the linear region because it turns on the inversion channel in the transistor, creating a resistive path from drain to source (R_{on}). The TSV signal that coupled to the drain can thus be sunk through this resistive channel to the source which is connected to ground. This reduced the noise coupling coefficient.

Figure 6. Measured TSV - Planar NMOSFET coupling vs. V_G bias in the linear region.

As shown in the Figure 7, gate biases above 0.4V strongly impact the substrate coupling between TSV and planar device in the saturation region because the bulk transconductance (g_{mb}) amplifies the TSV noise signal propagating through the Si substrate and reaching the transistor.

Figure 7. Measured TSV - Planar nMOSFETS coupling vs. V_G bias in the saturation region.

Experimental coupling study for TSV- nFinFET

Similar to planar devices, DC measurements for nFinFET transistors under different TSV biasing condition have been performed. The initial DC measurements in Figure 8 showed that biasing the TSVs (-15 V to 10 V) had no impact on the DC behavior of nFinFETs.

Two port RF measurement of the noise coupling coefficients (S_{12}) between the TSV and the drain of an nFinFET device were also performed. As shown in Figure 9, the noise coupling level is similar in the ON and OFF state of the transistors and even slightly smaller for ON state than the OFF state. This phenomenon can be explained by the small g_{mb} of nFinFETs. Hence, the dominant coupling mechanism between TSVs and nFinFETs is the capacitive coupling to the drain in both ON and OFF states. When the nFinFET is on, the depletion region increases as shown in Figure 1 and the capacitance decreases which reduces the capacitive coupling to the drain.

Figure 8. Measured TSV bias impact on the DC behavior of nFinFET transistors.

Moreover, S_{12} was also investigated as a function of V_{gate} both in the linear (Figure 10) and the saturation region (Figure 11). Increasing V_G decreases the coupling in the linear region

because it turns on the inversion channel in the transistor, as in the case of planar nMOSFET. Again, this connects the drain through this resistive channel to the grounded source and thus reduces the noise coupling coefficient.

Figure 9. TSV - nFinFET coupling measurement: transistors in on and off state.

Figure 10. TSV - nFinFET coupling measurements vs. V_G bias in linear region.

As shown in the Figure 11, increasing V_G in the saturation regime increases the coupling because of the bulk transconductance (g_{mb}). However, the increase of the coupling is insignificant because of the small g_{mb} of FinFETs.

Figure 11. TSV - nFinFET coupling vs. V_G bias in the saturation region.

TSV – active device coupling mechanisms: planar nMOSFETs vs. nFinFETs

By analyzing and comparing the impact of TSV noise on FinFET and planar device performance, the dominant coupling mechanisms were identified for both types of active devices. A summary of the TSV to active device coupling mechanism is given in Table 2. For planar nMOSFETs, noise amplification through the bulk transconductance (g_{mb}) dominates for the ON state, leading to large noise coupling. For FinFETs, this mechanism was however negligible due to the small g_{mb} and the main coupling mechanism was capacitive even in the ON state. Moreover, the increased bulk depletion around the FinFET in the ON state led to a reduced capacitive noise coupling. In this case, the coupling was even lower in the ON state than in OFF state, in contrast to the planar device. This clearly demonstrates that nFinFETs have better noise coupling immunity than planar nMOSFETs: TSV noise coupling to FinFET device is 20dB smaller than planar device at 1GHz and 4-8dB smaller at 40 GHz. The main reason for improved FinFET noise immunity is that the FinFETs are less sensitive to substrate bias due to the stronger gate control w.r.t. planar MOSFET.

Table 2. TSV-active devices coupling mechanism summary

Parameter	Planar nMOSFET		nFinFET	
	OFF	ON	OFF	ON
g_{mb} values		big		small
Dominant coupling mechanism	Capacitive coupling	g_{mb}	Capacitive coupling	Capacitive coupling (g_{mb} is too small)
Coupling level	small	big	small	smaller

TCAD Modeling of TSVs to Active devices noise coupling

In order to have a complete overview of the coupling mechanisms between TSVs and different active devices, the Synopsys TCAD models were developed as shown in Figure 12. The specifications for FinFET and planar devices are listed in Table 1.

In a first step, the TCAD models were calibrated with RF measurements of the TSV-active noise coupling test structure. Secondly, the calibrated TCAD models are used to investigate the impact of the substrate contact location and TSV architectures on the noise coupling level to active devices. Finally we will discuss the coupling induced Keep Out Zone for the TSVs to active devices.

A. TCAD model calibration

The Synopsys Technology Computer Aided Design (TCAD) device simulator can assess the substrate coupling effect between TSVs and active devices by performing transient analysis of transistor behavior [5]. A time domain analysis was performed by applying high frequency sine signals to TSV and extracting the active device saturation current variations. These variations are converted to S parameter and compared with 2-port (Drain-to-TSV) S parameter measurements of the RF test structures.

Figure 12. TCAD simulation structure for FinFET (a) and planar FET (b).

The good agreement between the TCAD simulation and RF measurements in Figure 13 verifies our understanding of the mechanisms responsible for the TSV noise coupling. In general, FinFET device shows a better TSV noise immunity compared to equivalent planar device.

Figure 13. TCAD Simulation vs. measurements for planar and FinFET devices: $V_g=1V$, $V_d=1V$, $V_{TSV}=0V$.

B. Impact of TSV architectures on the noise coupling

Based on the calibrated TCAD model, we have also investigated four different TSV architectures to predict their impacts on the noise coupling: 5 μ m/50 μ m via-middle TSVs with 200nm oxide liner; scaled 3 μ m/50 μ m via-middle TSVs with 200nm oxide liner; 5 μ m/50 μ m via-middle TSVs with 400nm oxide liner; and via-last TSV architecture with thick (3 μ m) polymer liner (“Donut” TSV).

As shown in Figure 14, scaling the TSV diameter, using thicker liner materials, and polymer based liner materials with smaller dielectric constant all reduce the coupling level mainly at low frequencies where TSV liner capacitance is the dominant factor on noise coupling. At 100 MHz, for the 3/50 μ m and “Donut” TSVs, the noise coupling reduces by about 4dB and 20dB respectively.

Figure 14. TCAD simulation: impact of TSV architectures on noise coupling.

C. Impact of substrate contact location on the noise coupling

The grounded substrate contact offers a resistive path for the substrate noise to be sunk to the ground, reducing the noise coupling level. The location of the substrate contact with respect to the active device determines the values of this resistive path: the closer the substrate contact is to active device, the smaller is the value of the resistive path, which makes the noise coupling easier to be sunk to the ground.

Figure 16 shows the TSV to planer/FinFET devices noise coupling with a substrate contact either 10 μ m or 50 μ m away from the active devices. As expected, Figure 16 indicated a 4-6 dB noise reduction by placing the substrate contact closer to the active device.

Figure 15. Substrate contact location to active devices

Figure 16. TCAD simulation: impact of substrate contact location on noise coupling.

D. Keep Out Zone (KOZ)

To define the TSV keep-out-zone, the relative change of saturation current induced by TSV coupled noise and TSV stress for both FinFET and planar device are given as a function of distance in Figure 17 and Figure 18, respectively. As we can see, the stress induced current change decreases rapidly with increasing distance; when the active device is 20 μ m away from TSV, the stress induced current change is close to zero for both planar and FinFET devices.

With respect to the stress induced current change [6], the coupling induced current change decreases with distance much slower, which means the noise coupling can have significant influence on the KOZ. In order to extract the KOZ accurately, coupling induced current variations must be considered together with the stress induced current change. When an active device is located at 10 μ m away from TSV, the current change induced by TSV stress is only 0.2% for FinFET device and 0.6% for Planar device. But these values increase to 2.23% and 3.55% when the impact from TSV noise coupling is added up at 10 GHz (2.03% for FinFET device and 2.95% for planar device).

Figure 17. Coupling and stress induced saturation current variation for planar device.

Figure 18. Coupling and stress induced saturation current variation for FinFET device.

We have also noticed that the coupling induced current variation for active devices increases when the high speed signals travel through TSVs. This may imply a bigger TSV KOZ for high frequency and high speed applications.

Since the coupling induced current change decreases slowly with distance, minimizing the KOZ requires noise mitigation techniques such as substrate contact and guarding. As shown in Table 3, placing the substrate contact closer to the active devices led to a reduction of the coupling induced current variation to 1.05 % (at 1 GHz) for planar devices and 0.2% (at 1 GHz) for the FinFet case. Depending on the level of allowed current variation, this may have a big impact on the KOZ extraction: if the maximum allowed total current variation for planar devices is 2% at 1 GHz, the KOZ is 28 μm ; with the grounded closed substrate contact [7], the KOZ is as small as 8 μm

Table 3. Coupling and stress induced saturation current variation with 10 μm distance between active device and TSV

	Current change in Planar (%)	Current change in FinFET (%)
Stress induced	0.6	0.2
Coupling induced @10GHz	2.95	2.03
Coupling induced @1GHz	2.08	0.36
Coupling induced @ 1GHz + closer substrate contact	1.05	0.2
Coupling @ 10GHz + stress induced	3.55	2.23
Coupling @ 1GHz + stress induced	2.68	0.56
Coupling @ 1GHz + stress induced + closer substrate contact	1.65	0.4

Conclusions

The impact of TSV noise coupling on nearby active devices including both FinFET and planar transistors has been investigated up to 40 GHz based on S-parameter measurements. The key coupling mechanisms were identified for both types of active devices. Two mechanisms exist: noise amplification through the bulk transconductance (gmb) as well as capacitive coupling. For planar nMOSFETs, noise amplification through the bulk transconductance (gmb) mechanism dominates for the ON state, leading to large noise coupling. For FinFETs, the dominant coupling mechanism was capacitive even in the ON state. This demonstrates that FinFETs have better noise coupling immunity over planar nMOSFETs, which makes FinFETs a strong candidate for the future system integration with TSVs.

In addition, calibrated TCAD models were developed to perform a complete analysis of the coupling mechanisms between TSVs and active devices. Both the impact of the TSV architectures and the substrate contact location on the noise coupling have been simulated. Finally, both coupling and stress induced saturation current variations as a function of TSV to active devices distance were investigated. We have shown that it is important to use noise mitigation techniques to reduce the electromagnetic coupling effects in order to minimize the KOZ.

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