

3.3.2 Power Supply Noise Coupling into the Substrate

The voltage noise on the VSS supply couples into the substrate through the biasing contacts and through the capacitance of metal wires and reversed biased PN junctions.

The coupling through substrate contacts is illustrated by the resistor R_A in Figure 3.39.

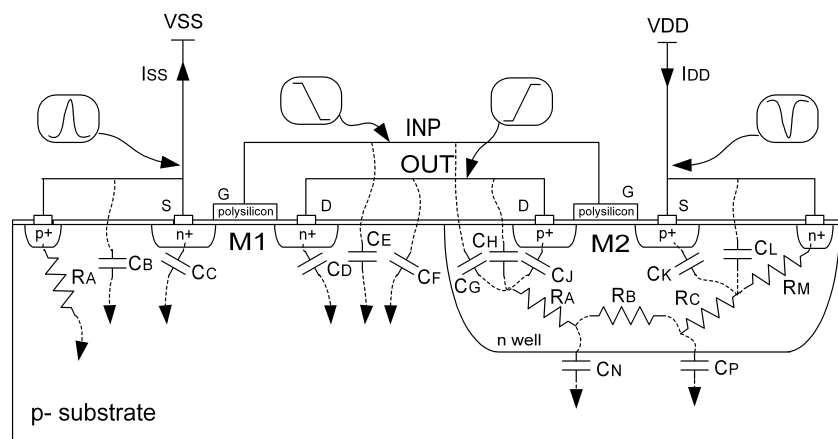


Figure 3.39 Illustration of the power supply noise injection into substrate and n-wells.

Typical designs implement a large number of substrate biasing contacts. Therefore, the majority of substrate noise injected from the VSS supply occurs through these biasing contacts.

The VSS noise coupling through wires capacitance is illustrated by the capacitor C_B in the figure. Because of the high-pass filtering effect, only high frequency spectral components generate substrate noise this way. The highest coupling capacitance per unit area forms between the lowest routing metal layer and the substrate. The capacitance gradually decreases for higher routing layers. Therefore, the power lines on the lower metal layers generate more noise than the power lines on the higher metal layers. However, in some designs, wide and dense power grid lines on higher metal layers can have large coupling capacitance with the substrate.

The noise on the VSS supply couples into the substrate also through the capacitance of the reversed biased PN junctions. The junctions participating in this mechanism are the source of NMOS transistors connected to the VSS supply, as illustrated by C_C in the figure. Because the coupling path includes a series capacitance, only high frequency spectral components generate substrate noise through this path. This mechanism becomes dominant in the digital cores of CMOS mixed-signal integrated circuits, due to the large number of logic gates and large dI/dt current transients.

The voltage noise on the VDD supply couples in similar ways into the n-well. The coupling through biasing contacts is illustrated by R_M in the figure, the coupling through wire capacitance by C_L , and the coupling through reversed biased diffusion junctions by C_K .

Active signals couple into substrate and n-wells through the capacitance of metal wires and reversed biased junctions. C_D to C_J illustrate this mechanism. Not shown in the figure for simplicity, the VDD noise may couple into the substrate through wire capacitance, and similarly the VSS noise may couple into the n-well through wire capacitance.

Coupling occurs also between the substrate and the n-well through the interface junction capacitance. For large n-wells, this coupling may be distributed across the interface surface, as illustrated by C_N and C_P in the figure.

3.3.3 Power Supply Noise Coupling into the Package and PCB

The supply transient currents generate noise also on the power distribution circuit nodes of the package and PCB. The mechanism is based on the $V = RI + L dI/dt$ equation, similarly to the supply noise generated on the chip VDD and VSS supplies. The noise magnitude depends on the transient current and the inductance and resistance through which it flows. The noise on the package is lower than the noise on the chip, and the noise on the PCB is lower than the noise on the package. This mechanism is illustrated in Figure 3.38 by waveforms W_3 to W_6 .

The evaluation of the package and PCB noise becomes important in integrated circuits using multiple voltage supplies. In these cases, the noise generated on one supply may couple in the other supplies through the parasitic capacitance and inductance, and through the shared impedance. These mechanisms will be analyzed in Chapter 4.

3.3.4 Power Distribution Resonance

In a power distribution circuit, the *DC* current flows in a loop from the voltage supply to the circuit on the chip, and back to the voltage supply. The *AC* transient current splits and flows through different loops, depending on the placement and types of decoupling capacitors and on the frequency spectrum. Because these loops contain resistors, capacitors, and inductors, resonance may occur in the frequency response of the power distribution circuit.

Figure 3.40 shows a simplified example of the power distribution in an integrated circuit.

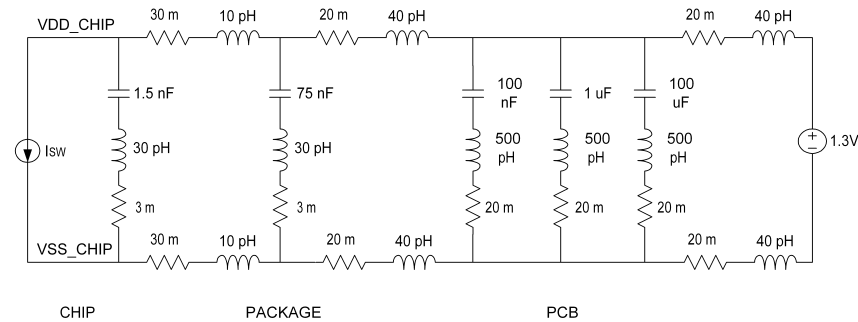


Figure 3.40 Simplified example of the power distribution in an integrated circuit.

The horizontally drawn resistors and inductors represent the parasitic resistance and inductance of the power distribution interconnects on the chip, package, and PCB.

The vertically drawn RLC branches represent the equivalent models of the decoupling capacitors on the chip, package, and PCB.

The parasitic inductance and resistance of the decoupling capacitors are the ESL and ESR parameters from the manufacturer specifications.

By using a sinusoidal current source instead of I_{SW} , we can simulate the variation of the power distribution impedance with frequency. The result is shown in Figure 3.41.

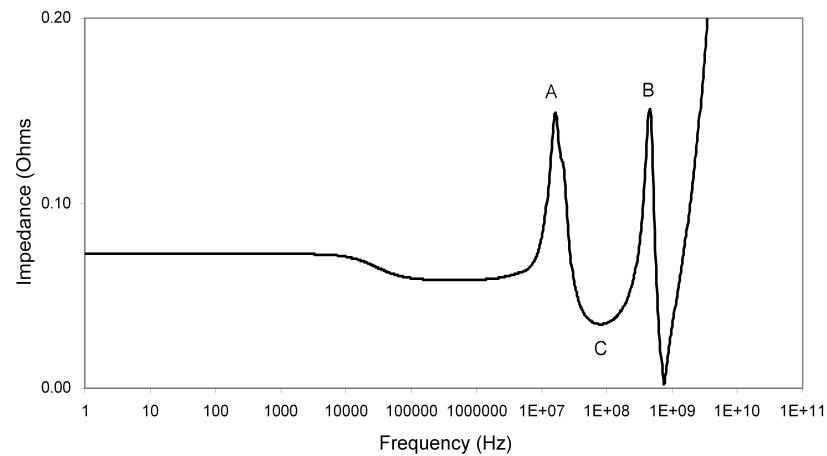


Figure 3.41 Simulated variation of the power distribution impedance versus frequency.

It can be noticed in this graph that the power distribution impedance has two resonant frequencies, one at about 15 MHz and the other one at about 400 MHz, as marked by labels *A* and *B* in the figure. The power distribution impedance increases at these resonant frequencies. At about 100 MHz, the impedance has a local minimum value, as marked by label *C* in the figure. Therefore, the supply current spectral components of 400 MHz will see higher impedance than the spectral components of 100 MHz.

Suppose, for example, that the circuit on chip drives a square pulse current having a magnitude of 1 A, a frequency of 100 MHz, and rise and fall times of 500ps. These settings correspond to the low impedance point *C* in the frequency response. Because of the power distribution impedance, this current will generate voltage noise on the *VDD* and *VSS* supplies.

Figure 3.42 shows the simulated transient noise generated on the *VDD* supply. This waveform has a damped ringing of about 2.5 ns period, marked by (a), and a part of a low frequency ringing, marked by the dotted line (b). Since half-period of the low frequency ringing takes 30 ns, we can estimate the full period to be about 60ns. These two ringing waveforms are caused by the two resonant frequencies of the power distribution impedance.

Suppose now that the current pulse has a frequency of 400 MHz, instead of 100 MHz before. This new frequency corresponds to one of the peak resonance of the power distribution circuit.

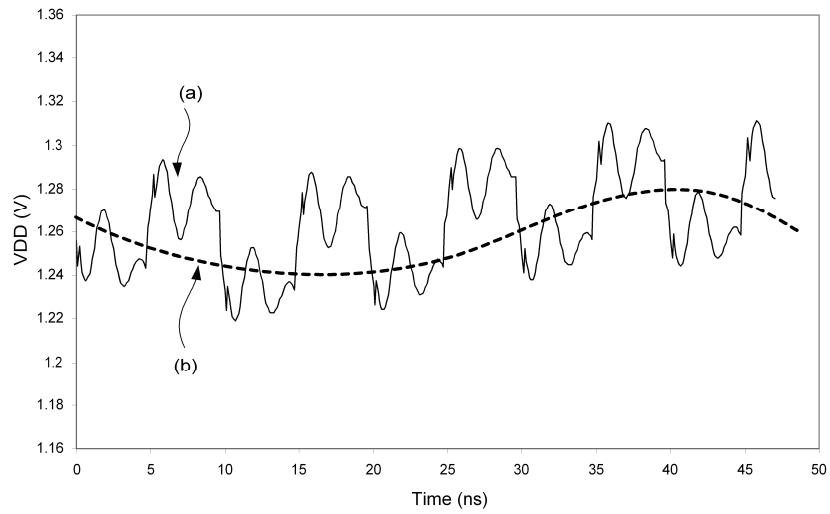


Figure 3.42 Simulated transient noise generated on the *VDD* supply by a square pulse current having a magnitude of 1 A, a frequency of 100 MHz, and rise and fall times of 500ps.

Figure 3.43 shows the simulated transient noise generated on the *VDD* supply, plotted using the same vertical scale as the previous example.

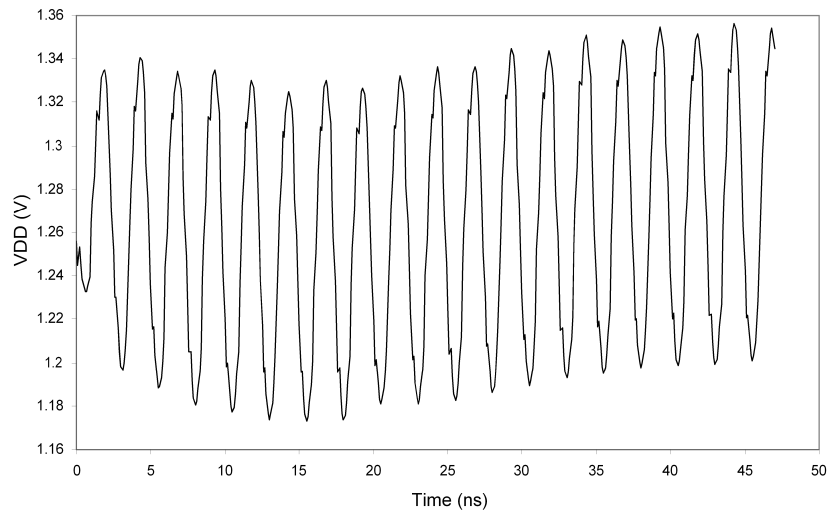


Figure 3.43 Simulated transient noise generated on the *VDD* supply by a square pulse current having a magnitude of 1 A, a frequency of 400 MHz, and rise and fall times of 500ps.

Notice that the magnitude has increased from 70 mV, in the previous 100 MHz case, to 150 mV.

Since the 400 MHz spectral component of the supply current sees higher power distribution impedance, the generated noise has larger magnitude. Therefore, the generated supply noise increases significantly if the circuit on the chip operates at the resonance frequencies of the power distribution.

The resonance frequencies and the corresponding peak impedances can be adjusted by the choice of the decoupling capacitors. For example, let's increase the decoupling capacitance on the chip and package in the previous power distribution circuit by four times. The variation of the power distribution impedance with frequency, simulated on the new power distribution model, is shown in Figure 3.44.

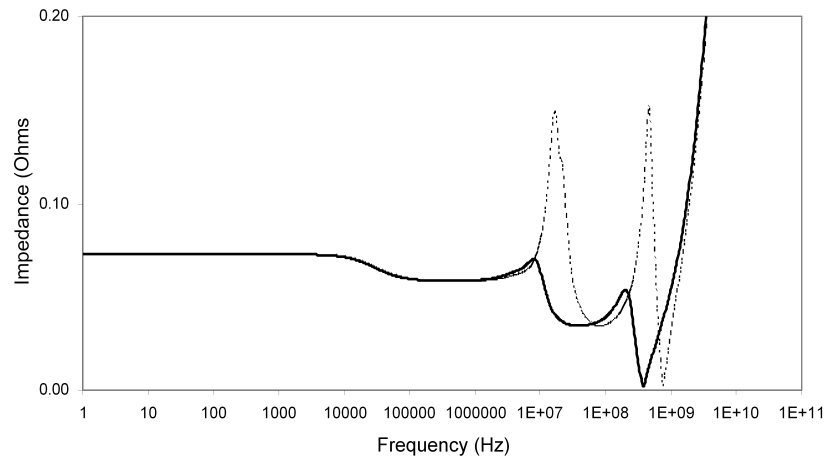


Figure 3.44 Simulated variation of the power distribution impedance with frequency, before increasing the value of the decoupling capacitors (dotted line) and, after (solid line).

The dotted line represents the previous impedance, and the solid line represents the impedance after increasing the capacitance. It can be noticed that the resonance occurs at lower frequencies and the power distribution impedance at these resonant frequencies has been reduced significantly.

The same circuit that in the previous example was operating at 400 MHz sees much lower impedance with the new decoupling capacitance. Figure 3.45 shows the simulated transient noise generated on the *VDD* supply, in this case plotted using the same vertical scale as the previous examples.

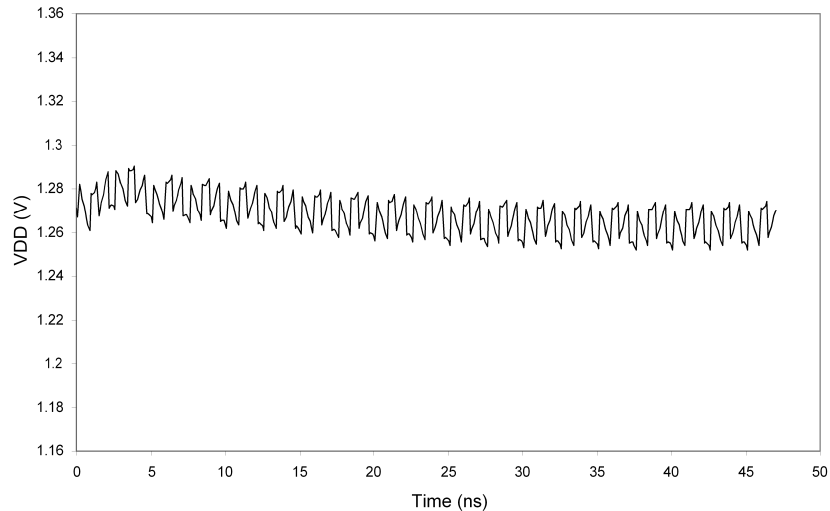


Figure 3.45 Simulated transient noise generated on the V_{DD} supply by a square pulse current having a magnitude of 1 A, a frequency of 400 MHz, and rise and fall times of 500ps, after increasing the value of the decoupling capacitance.

Notice that the noise magnitude has decreased from 150 mV to 20 mV. This is a significant reduction achieved only with an increase in the value of the decoupling capacitors on the chip and the package.

As a comment here, the increase of the decoupling capacitance on the package reduced the resonance peak at 15 MHz, and the increase of the decoupling capacitance on chip reduced the resonance peak at 400 MHz. Since in this example the circuit operates at 400 MHz, similar noise reduction could have been obtained by increasing only the decoupling capacitance on the chip and not on the package. However, the decoupling capacitance on the package has been increased also because, in practice, it is recommended to reduce all the peak resonant frequencies.

To reduce the power supply generated noise, the decoupling capacitors should be selected based on both the parasitic elements of the power distribution and the functional specifications of the powered circuits.

SUMMARY

- Transient supply currents generate power supply noise due to the inductance and resistance of the power distribution circuits.
- The noise is generated on the chip, package, and PCB.
- The AC shunting through decoupling capacitors creates transient current loops closing on the chip, package, and PCB.
- Due to the RLC structures, the power distribution loops experience resonant frequencies.
- Significant noise can be generated by supply currents having spectral components close to the resonant frequencies of the power distribution.
- The choice of decoupling capacitors needs to be based on both the parasitic elements of the power distribution and the functional specifications of the powered circuits.