

Broadband Reduction of Switching Noise By Embedding High-Density Thin-Film Capacitor In a Laminated Package

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Abstract— Broadband noise reduction has been investigated by embedding a high-density thin-film decoupling capacitor as much as 1 μF in a laminate package. A complex programmable logic device (CPLD) was mounted on the laminate package instead of bare chip as a noise generating circuits. Then, the package was mounted on an evaluation board. Eight output buffer circuits of the CPLD were simultaneous switched. Switching noise between the power and ground pads on the package has been dramatically reduced by the existence of high-density thin-film decoupling capacitance inside the package.

I. INTRODUCTION

Simultaneous switching noise (SSN) is one of the most major sources of the power supply fluctuation and the electromagnetic radiation in the high-speed CMOS digital systems [1]-[2]. Surface mount device (SMD) type capacitors are normally closely placed to LSIs to reduce the switching noise. However, the impedance profile of the conventional discrete decoupling capacitor is narrow due to the equivalent series inductance (ESL) of the capacitor itself. So the decoupling capacitor is no longer effective in the higher frequencies over the self series resonant frequency. Furthermore, discrete SMD type capacitors cannot be attached closely enough to BGA type package on a board, because the backside of the board is almost occupied by many pads and breakout traces. Then, the overall impedance profile of power distribution network including discrete SMD capacitors placed around BGA package cannot be low by the additional inductance of extra traces[3].

In order to improve the impedance profile of the power distribution network, many papers have been published. The advantages of thin dielectric in a laminate package, or a printed circuit board were reported to increase in capacitance in a package, or board [4]-[10]. New materials with higher dielectric constant were also reported to increase the capacitance value [11]-[12]. Further, new package structures with decoupling capacitor inside package were proposed in recent workshops [13].

Fig.1 shows a CMOS output buffer circuit and the relationship between switching current flow $i(t)$ and power supply noise $v(t)$. When the on-package capacitor is not

existed in a package, the switching current $i(t)$ excites the power supply impedance $Z(\omega)$, so the frequency spectrum of power supply fluctuation $V(\omega)$ can be written in a following formula.

$$V(\omega) = Z(\omega)I(\omega)$$

where $I(\omega)$ is frequency spectrum of $i(t)$. By providing on-package capacitor with wideband decoupling property, most of high-frequency components of switching current can be bypassed.

In this paper, broadband reduction of switching noise has been investigated by embedding a new high-density thin-film decoupling capacitor in a laminate package. The capacitance density of it was as high as 1 μF in a 1 cm square. A CPLD device was mounted on a package substrate, and it was used as a noise source. The developed package was mounted on an evaluation board. Then, power-ground noises on the package were measured. Novel noise reduction has been observed for the packages with the thin-film decoupling capacitor compared to the one with SMD capacitor or without any capacitors.

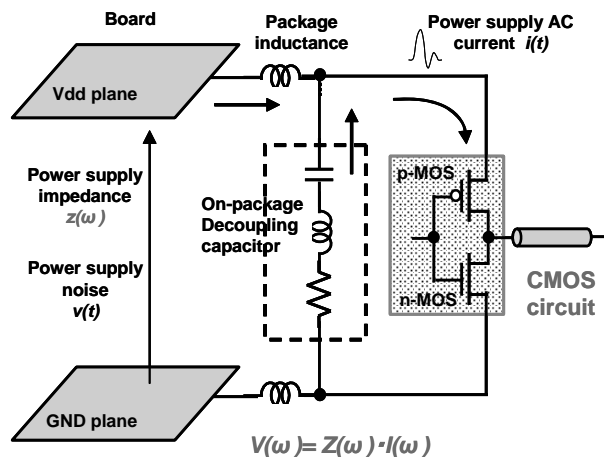


Fig.1 CMOS buffer circuit and the relationship between switching current flow and power supply noise

II. PACKAGE AND BOARD CONFIGURATION

A. Package configuration

A new thin-film decoupling capacitor was laminated inside the package substrate. Fig.2 shows external appearance of the package with a CPLD on it. The package size was 22 by 22 mm. Fig.3 shows a plane view of the package substrate and its cross-section.



Fig. 2 Top view of the package with a CPLD

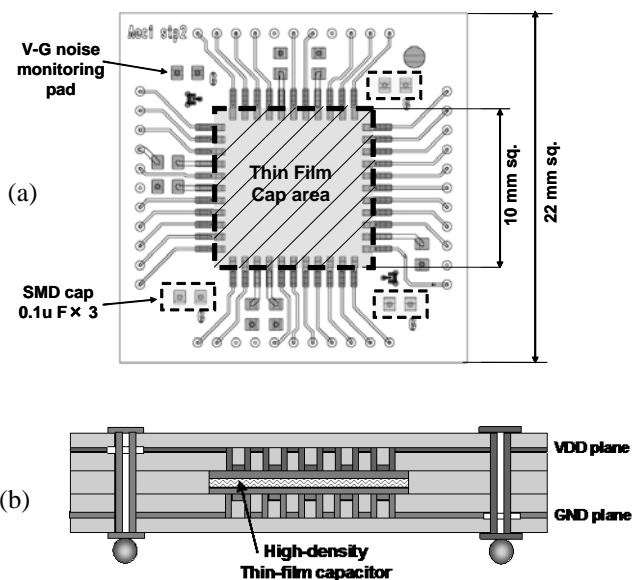


Fig.3 Plane view of package substrate with thin film decoupling capacitor (a), and cross-section (b)

The package substrate consisted of 6 conductive layers separated by glass-epoxy dielectric insulator. The size of the thin-film capacitor was 10 by 10 mm. The thin-film decoupling capacitor consisted of two electrodes, and dielectric layer of BaTiO₃, in which a part of Ba was substituted by Sr. Top electrode and bottom electrode were connected to the VDD plane and the ground plane in the package substrate, respectively. The capacitance value of the decoupling capacitor was as much as 1 μF in a 1 cm square size. A CPLD (Xilinx Cool-runner-II XC2C64A) with 44 pin count was used as a noise generating circuits. The body size of CPLD was 12 by 12 mm.

In order to compare the effectiveness of decoupling capacitor, three types of packages were prepared as shown in Table 1. First one was the package with no decoupling capacitors. Second one was with three SMD capacitors

(0.1uF) on the corners of the package as shown in Fig.3. Third one was the newly developed package with a high-density thin-film decoupling capacitor.

Table 1. Three types of packages

| | Decoupling structures |
|---|----------------------------|
| 1 | No Capacitors |
| 2 | SMD capacitors (0,1uF X 3) |
| 3 | Thin Film capacitor (1uF) |

B. Board configuration

Fig.4 shows an evaluation board on which the package with decoupling capacitor inside was mounted. The evaluation board consisted of 4 conductive layers and whose size was 150 by 200 mm. The logic circuits in the CPLD device were re-writable through the JTAG signal. Sixteen terminals were assigned as output buffer circuits. The maximum number of simultaneous switching output buffers was eight for the same power supply bank.

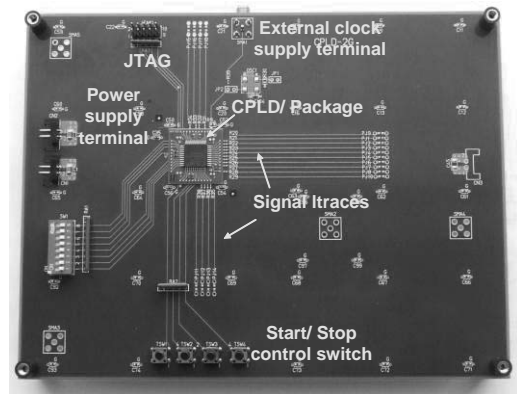


Fig.4 An evaluation board with a CPLD on the package

III. ANALYSIS AND MEASUREMENT RESULTS

A. S parameters of power supply plane in package

First, S parameters of the power supply plane of packages were analysed by using SIwave (Ansoft corp.) as shown in Fig 5.

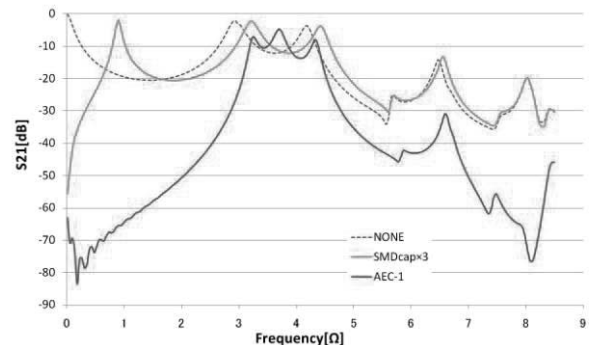


Fig. 5 Simulated S21of three types of package

Fig.6 shows measured S21 properties for the three types of packages. This S21 data were obtained by measuring the package substrates.

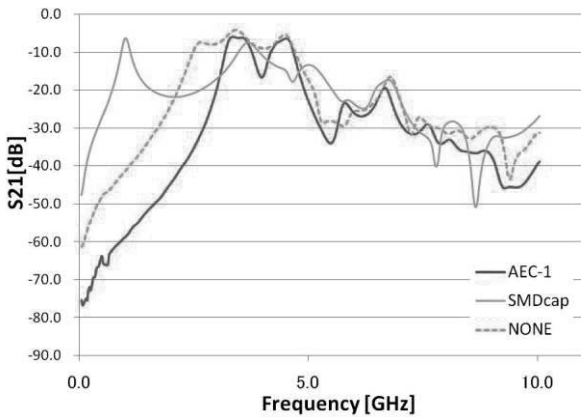


Fig.6 Measured S21 for the three types of packages.

B. Voltage fluctuation between power-ground plane

Next, the voltage fluctuations between power-ground planes were measured at the two points. One was measured on the monitoring pad on the package, another one was monitoring pad on the board (C50). The power-ground fluctuations were measured using an oscilloscope (Agilent Infiniium DSO 81204A) and high-impedance probes (InfiniMax). The voltage fluctuations were measured for three clock frequencies: 10MHz, 50MHz, and 100MHz.

Figs.7-9 shows output signals and power-ground bounces measured at monitoring pads on the package substrate for the clock frequency of 10 MHz. Fig.10 shows peak-to-peak noise amplitudes for the three clock frequencies. Through these experiments, the power-ground bounce was proved to be reduced to half compared to the package with SMD capacitors.

Fig.11 shows Fourier-transformed relative noise spectra $V(\omega)$ of time domain fluctuation waveforms $v(t)$ measured on the monitoring pad for the three cases. Fig.11(a) is measured at the frequency of 10 MHz, (b) is at 50 MHz, and (c) is at 100 MHz. Noise spectrum $V(\omega)$ for the case with thin-film capacitor has been greatly reduced in the wider frequency range compared to other two cases.

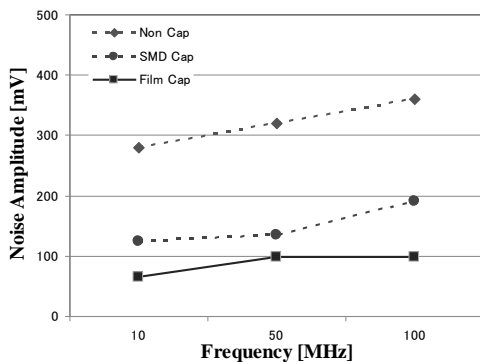


Fig.10 Peak-to-peak noise amplitudes for the three clock frequencies.

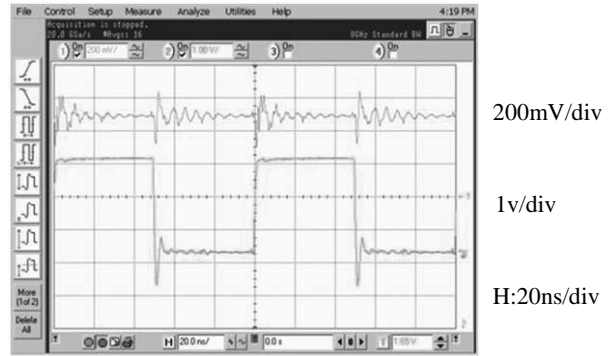


Fig. 7 Power-ground bounce (top) and output signal (bottom) and for the case without any on-package capacitors.



Fig. 8 Power-ground bounce (top) and output signal (bottom) and for the case with SMD capacitors.

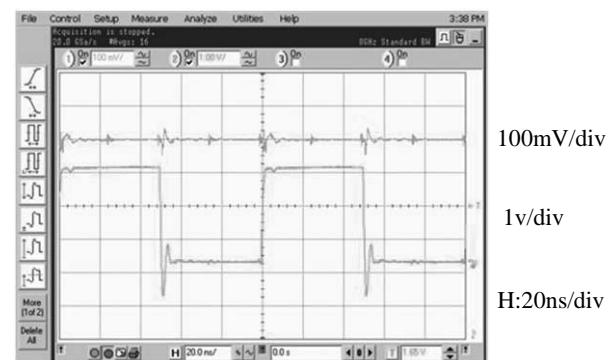
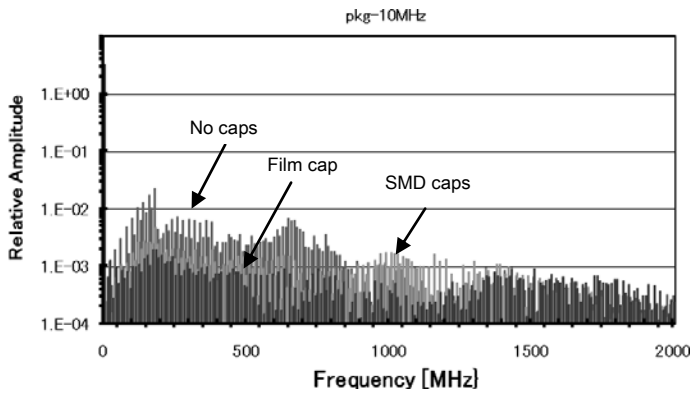
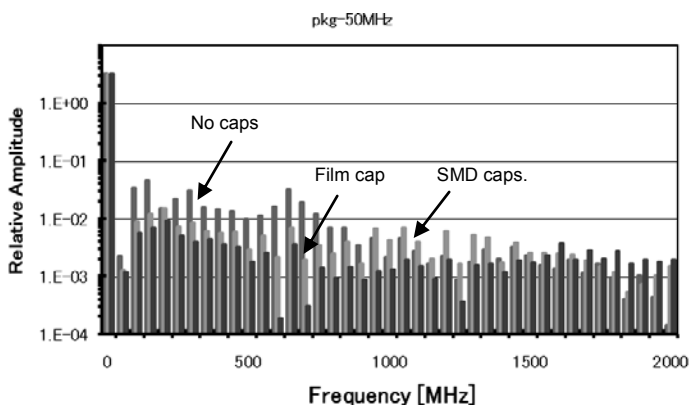


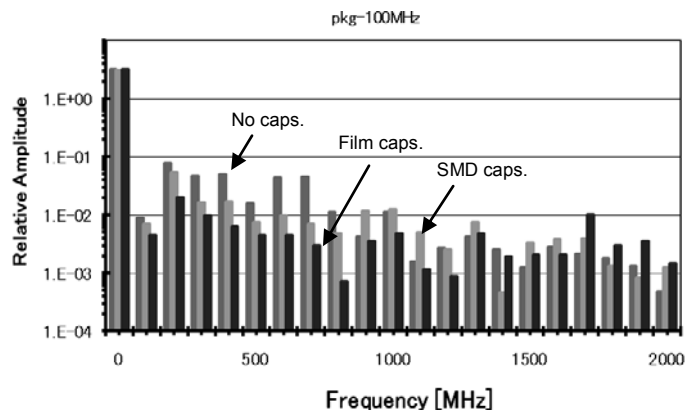
Fig. 9 Power-ground bounce (top) and output signal (bottom) and for the case with Thin-film capacitor.



(a) 10 MHz



(b) 50 MHz



(c) 100 MHz

Fig. 11 Comparison of noise spectra among three cases of capacitors at three clock frequencies.

IV. CONCLUSIONS

A package which embedded a high-density decoupling capacitor as high as $1 \mu\text{F}$ has been developed. A CPLD device was mounted on the package substrate instead of IC chip as a

noise generating circuits. Then, the voltage fluctuation between power pad and ground pad was measured for three different packages by varying clock frequency. It has been found that broadband reduction of switching noise has been observed by embedding high-density thin-film decoupling capacitor in a laminated package.

Acknowledgment

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