High Dielectric Constant Thin Film Embedded Capacitor for Suppression of Simultaneous Switching Noise and Radiated Emission

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Abstract— **In this paper, we thoroughly investigated and experimentally demonstrated the great advantages of thin film embedded capacitors of high dielectric constant in reducing the power/ground impedance and suppressing the SSN and the radiated emission up to a frequency of 1 GHz. About 10 dB or more suppression of the radiated emission was acquired for a wide frequency range, including high-numbered harmonics of the clock frequency, by using the thin film embedded capacitor of high dielectric constant.**

Keywords-component; embedded capacitor, high dielectric constant, power/ground impedance, SSN, radiated emission

I. INTRODUCTION

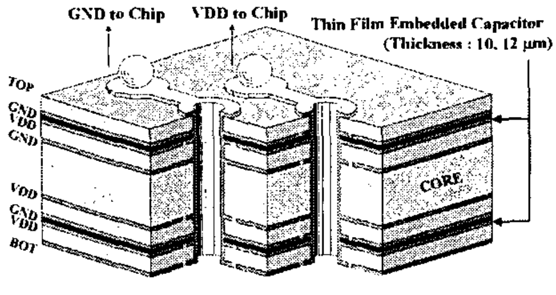
The voltage fluctuations of the power/ground networks on IC's, packages, and PCBs have become the major source of the radiated emission. Therefore, the distribution of stable power supply voltages and the suppression of simultaneous switching noise (SSN) and the radiated emission become important design issues in modern high-speed and high-current digital ICs, packages, and PCBs. In particular, these design challenges become even more serious as CMOS device technologies advance rapidly, as operating clock frequencies are steadily increased into the GHz range, and as total power needed at IC is increased. [1][3]

Generally, discrete decoupling capacitors have been adopted to stabilize the voltage fluctuations of the power/ground networks and to suppress the resulted SSN and radiated emission. However, the discrete decoupling capacitor is not effective above a few hundred MHz due to its unavoidable large serial inductive parasitic component including the inherent inductance of the discrete component itself, the power/ground traces, the power/ground vias, and the mount pad. Also, combined suppression techniques including shielding, cabling, and filtering at the package level and the PCB level are not enough for the complete suppression of radiated emission especially at GHz range. Consequently, a thin film embedded capacitor inside a multilayer package or PCB is strongly recommended as a promising method of overcoming the limitations of discrete decoupling capacitors. The thin film embedded capacitor can provide the capacitance of low equivalent series inductance (ESL) because it can eliminate the ESL of the power/ground network that is caused by the mounting pad and the power/ground traces for discrete capacitors. [2][4]

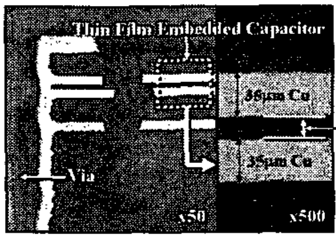
In this paper, we thoroughly investigated and experimentally demonstrated the great advantages of thin film embedded capacitors of high dielectric constant in reducing the power/ground impedance and suppressing the SSN and the radiated emission up to a frequency of 1 GHz as well as low frequency below few tens MHz. The power/ground impedance, SSN, and the resulted radiated emission were observed as functions of the film thickness, and the dielectric constant. Especially, the accurate power/ground impedance was obtained by using two-port self-impedance measurement technique with G-S microprobe. [5] It is found that the thinner embedded capacitors we use, the more suppression of SSN and the resulted radiated emission we can acquire in the GHz frequency range. That is, the major source of the inductive impedance in this frequency range is the inductive current path, but it is not related to the dielectric constant of the film. We have also demonstrated that the thin film embedded capacitor of high dielectric constant has a role of efficient decoupling at the low frequency range as well as the high frequency range. Consequently, the embedded capacitor of high dielectric constant was proven to be an essential and useful component for the high performance digital systems and packages.

II. TEST PCB WITH THIN FILM EMBEDDED CAPACITOR

A cross-sectional structure and layer stacking of the eight-layer test PCB with the thin film embedded capacitor are depicted in Fig. 1-(a). Two pairs of the thin film embedded capacitors are inserted near each mount side to reduce the inductance introduced by via which connects the thin film embedded capacitor to surface mounted device or measurement pad. A scanning electron microscope (SEM) microphotograph of the fabricated test PCB is shown in Fig. 1-(b). Test PCBs with thin film embedded capacitors of slightly different thicknesses (12 μm and 10 μm) and different dielectric constants (4.6 and 25) were used to investigate the influences of the dielectric constant on the power/ground impedance, the SSN, and the radiated emission.



(a)



	Thickness	Dielectric Constant
Material "A"	12μm	4.6
Material "B"	10μm	25

(b)

Figure 1. (a) The cross-sectional structure and layer stacking of the eight-layer PCB with thin film embedded capacitor used in the experiment and analysis in this paper (b)SEM microphotograph of the cross-section of the fabricated eight-layer PCB with the thin film embedded film capacitor (left: 50x magnification; upper-right: 500x magnification). The thicknesses of the embedded capacitors are 12 μm (Material "A") and 10μm (Material "B"), respectively. The dielectric constants of the thin film embedded capacitors are 4.6 ("A") and 25 ("B"), respectively.

To investigate the effect of the dielectric thickness, we also have fabricated test PCBs with different dielectric thicknesses (12μm, 25μm, 50μm with same dielectric constant; 4.6). The power/ground impedance was measured using Two Cascade FPC-series G-S probes with Agilent 8753ES Vector Network Analyzer. The size of the test PCBs was 5cm by 5cm.

In addition, ALETRA devices were used to generate significant SSN and the resulted radiated emission. The devices were programmed as octal-output buffers which drive 3-pF load capacitors with 50MHz operating frequency. The radiated emissions from test PCBs with ALTERA devices were examined inside an anechoic chamber using a log-periodic and biconical antenna.

III. Power/Ground Impedance

The measured impedance curves are shown in Fig. 2. Without any decoupling capacitor, the measured curve (Dotted line) shows a large resonance peak around 100MHz where most harmonics of 50MHz clock signal reside. This resonance peak was introduced by parallel resonance between the dc power supply inductance and the power/ground plane capacitance. In this experiment, a tantal capacitor with 500mΩ ESR was attached near dc connection point to screen out the large inductance of the dc power supply. With sixteen 100-nF discrete decoupling capacitors (MLCC), the resonance peak was shifted upwards of around 500MHz and impedance below the resonance frequency was decreased (Dashed line in Fig. 2).

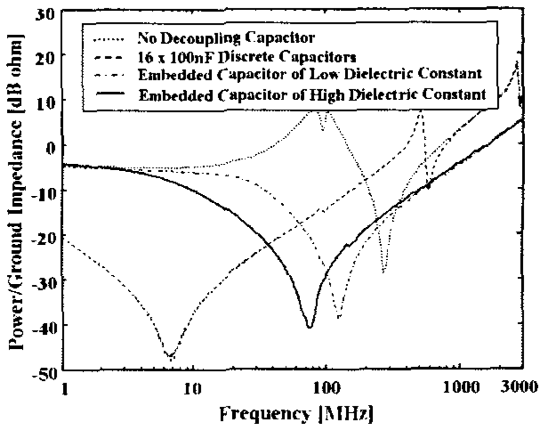
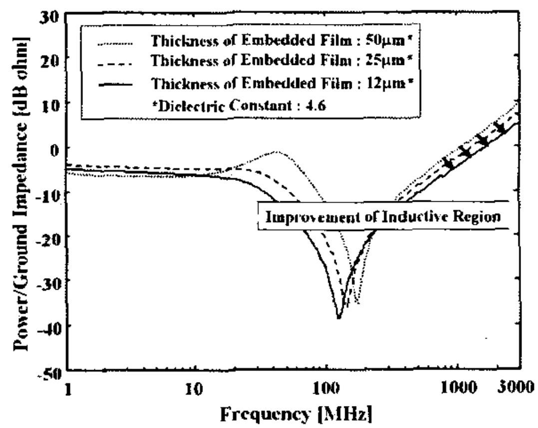
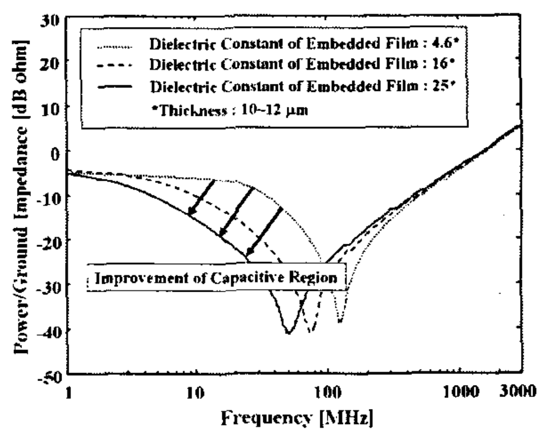


Figure 2. The measured power/ground impedance curves. The curves are obtained without any decoupling capacitor (dotted line); with only discrete capacitors (dashed line); with the thin film embedded capacitor of low dielectric constant (dash-dot line) and with the thin film embedded capacitor of high dielectric constant (solid line) inside the PCB.



(a)



(b)

Figure 3. The measured power/ground impedance curves (a) with respect to dielectric thickness (Dotted: 50μm, Dashed: 25μm, Sold: 12μm) and (b) with respect to dielectric constant (Dotted: 4.6, Dashed: 16, Solid: 25)

However, there was no improvement of the power/ground impedance at the high frequencies over 500MHz. Over GHz, two impedance curves without and with discrete decoupling capacitor are almost same. That is, the discrete decoupling capacitor is not effective above a few hundreds MHz range as mentioned previously.

On the contrary, we successfully demonstrated a significant reduction of the power/ground impedance at frequencies up to 3 GHz by using the thin film embedded capacitor as shown in Fig. 2. Because the impedance of the capacitor above self-resonance is dominated by its inductive nature and the ESL of the thin film embedded capacitor is proportional to its thickness, very low impedance over GHz range was able to be achieved by using the embedded capacitor with very small thickness around 10μm. The thinner embedded capacitor we use, the lower impedance in the high frequency range we can obtain as shown in Fig. 3-(a).

It is also clearly found that there is no significant resonance over 100MHz where the self-resonance of the thin film embedded capacitor occurs. Moreover, $TM_{02/20}$ mode cavity resonance which is found around at 3GHz with the discrete decoupling capacitor was disappeared by using the thin film embedded capacitor. According to the cavity model, the magnitude of the power/ground impedance near resonance is related to the quality factor (Q-factor) of the cavity structure. The conductive loss and the dielectric loss cause the quality factors to be very low in the test PCB with the thin film embedded capacitor, which results in low resonance peaks. [4]

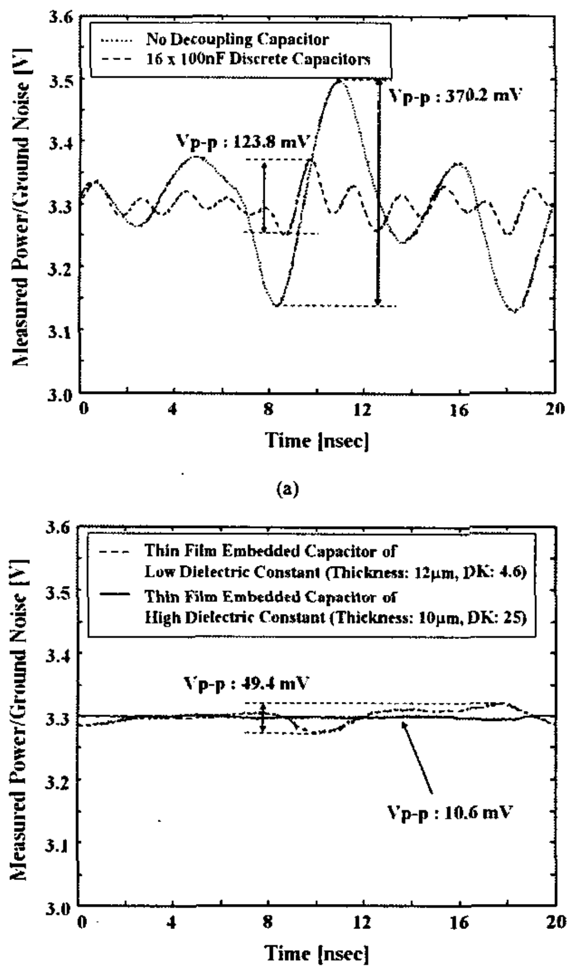
However, with the thin film embedded capacitor of low dielectric constant, the impedance (dash-dot line in Fig. 2) at frequencies below 100MHz where capacitive behavior dominates the curve is not enough low to suppress the SSN and the radiated emission sufficiently. With the thin film embedded capacitor of high dielectric constant, it is found that the measured curve (solid line in Fig. 2) exhibits sufficient low impedance at the low frequency range as well as the high frequency range. Function of the dielectric constant with the power/ground impedance can be easily found in Fig. 3-(b). As a result, with the thin film embedded capacitor with high dielectric constant, low impedance at the low frequency region can be insured as well as high frequency range over GHz.

IV. SSN AND RADIATED EMISSION

The power/ground impedance is reflected onto the SSN and the radiated emission as shown in Fig. 4 and 5, respectively. Output driver with 50MHz clock frequency was used to generate the SSN and the radiated emission.

In Fig. 3-(a), with sixteen 100-nF discrete decoupling capacitors, the reduction of the SSN was observed from 370.2mV to 123.8mV. However, with the discrete capacitors, high frequency components distinctly appeared on the measured power/ground noise. This high frequency component was introduced by the parallel resonance peak between ESL of the discrete capacitors and the capacitance of the power/ground plane as shown in Fig. 2. (Dashed curve) Same analysis can be applied to the radiated emission. As shown in Fig. 5-(a) and 5-(b), the radiated emission around few hundreds MHz was suppressed with the discrete capacitors. But, high numbered harmonics of clock frequency around 500MHz were amplified.

The further reduction of the SSN and the radiated emission were obtained by using the thin film embedded capacitor of low dielectric constant. In this case, the SSN was reduced to 49.4mV. But, there are still low frequency components on the measured power/ground noise. The measured radiated emission also exhibited the same result as shown in Fig. 5-(c).



(b)

Figure 4. Measured (a) SSN noise with (dotted line) and without (dashed line) the discrete decoupling capacitor and (b) SSN noise with the thin film embedded capacitor of low dielectric constant (dashed line) and high dielectric constant (solid line), respectively

Finally, the sufficient reduction of the SSN was observed by using the thin film embedded capacitor of high dielectric constant. In case of high dielectric constant, the SSN was limited to 10.6 mV, compared to 370.2 mV of the bare test PCB without decoupling capacitor. As can be noticed clearly, about 10-dB or more suppression of the radiated emission (Fig. 5-(d)) was acquired for a wide frequency range, including high-numbered harmonics of the clock frequency, by using the thin film embedded capacitor of high dielectric constant. Also, low frequency components remained in the case of low dielectric *constant as shown in Fig. 5-(c) was suppressed over 5dB.* These results emphasize that the thin film embedded capacitor of high dielectric constant can suppress the radiated emission for a wide frequency range.

V. CONCLUSION

The thin film embedded capacitor of high dielectric constant is an essential and useful component for future high performance digital systems and packages. In this paper, we have experimentally demonstrated the usefulness of the thin film embedded capacitor of high dielectric constant. Firstly, it is found that the thinner the embedded capacitors we use, the more suppression of the SSN and the resulted radiated emission we can acquire in the GHz frequency range. We have also demonstrated that the thin film embedded capacitor of high dielectric constant has a role of efficient decoupling at the low frequency range as well as the high frequency range. We would like to emphasize that the thin film embedded capacitor of high dielectric constant can suppress the radiated emission for a *wide frequency range.*

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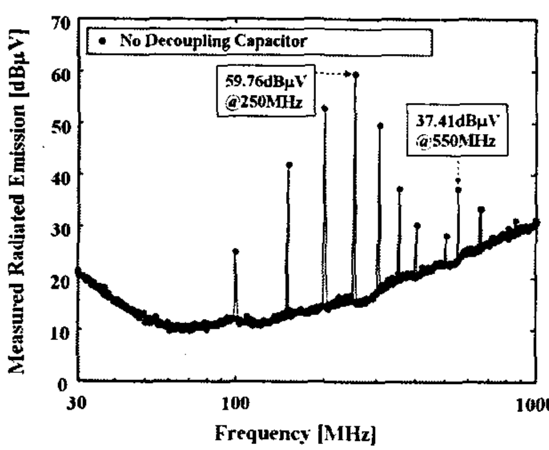

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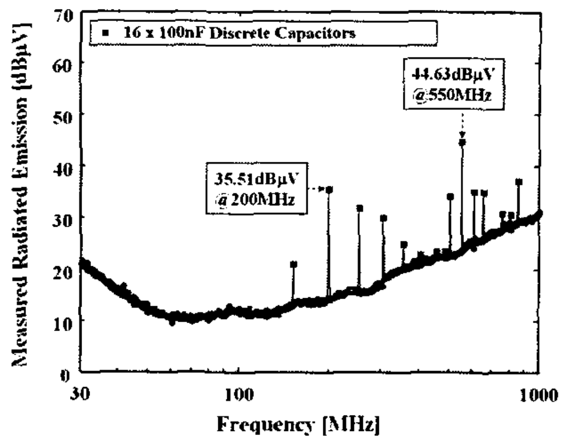

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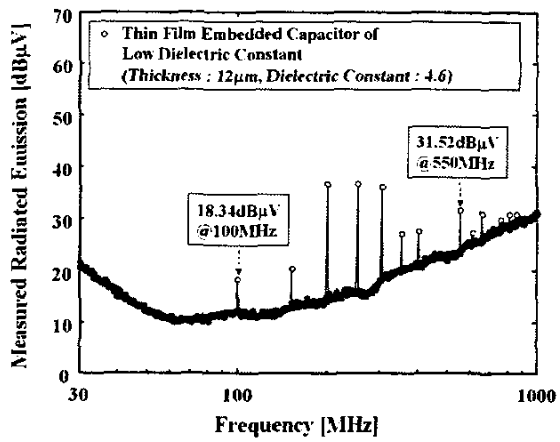

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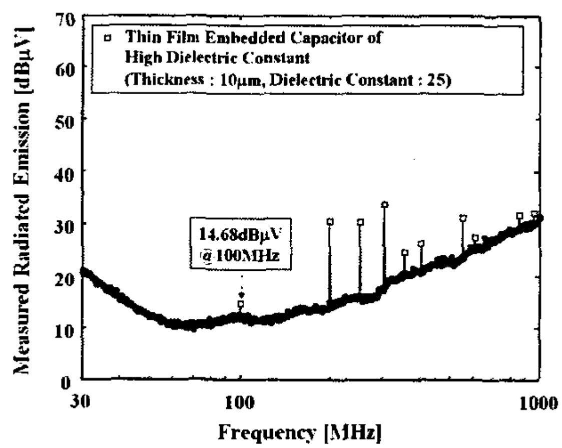

(d)

Figure 5. Measured spectrums of the radiated emission from the fabricated devices under test (a) without any decoupling capacitor, (b)with only the discrete decoupling capacitors (sixteen 100-nF MLCCs), (c)with the thin film embedded capacitor of low dielectric constant, and (d)with the thin film embedded capacitor of high dielectric constant.