

A Fully Integrated Thin-Film Inductor and Its Application to a DC-DC Converter

Il-Yong Park, Sang Gi Kim, Jin Gun Koo, Tae Moon Roh, Dae Woo Lee, Yil Suk Yang, and Jongdae Kim

ABSTRACT— This paper presents a simple process to integrate thin-film inductors with a bottom NiFe magnetic core. NiFe thin films with a thickness of 2 to 3 μm were deposited by sputtering. A polyimide buffer layer and shadow mask were used to relax the stress of the NiFe films. The fabricated double spiral thin-film inductor showed an inductance of 0.49 μH and a Q factor of 4.8 at 8 MHz. The DC-DC converter with the monolithically integrated thin-film inductor showed comparable performances to those with sandwiched magnetic layers. We simplified the integration process by eliminating the planarization process for the top magnetic core. The efficiency of the DC-DC converter with the monolithic thin-film inductor was 72% when the input voltage and output voltage were 3.5 V and 6 V, respectively, at an operating frequency of 8 MHz.

I. Introduction

The demand for small and efficient power conversion systems has increased as the market for portable equipment has become widespread. The thin-film inductor is one of the promising devices for reducing the size of DC-DC converting systems. The total thickness of the DC-DC converter IC can be reduced to under a millimeter by using a thin-film inductor.

However, inductances with a micro-Henry and high quality factor over unity are needed to realize megahertz-switching DC-DC converters. Some papers [1]-[5] have reported on practical uses of discrete thin-film inductors for small DC-DC converters, but it has been difficult to integrate the thin-film

inductor with the DC-DC converter using a CMOS-compatible process.

This paper presents a simple, CMOS-compatible process to integrate thin-film inductors with DC-DC converters. We fabricated a boost-type DC-DC converter with a 0.8 μm CMOS-compatible high-voltage process and used an extended drain (ED) MOSFET as a switching device of the DC-DC converter. The thin-film inductor was composed of double rectangular electroplated copper coil upon an NiFe magnetic core. To simplify the process, we omitted the top magnetic core.

II. Experimental Results

Figure 1 shows the top view of the thin-film inductor, which has double, rectangular-type spiral coils on 2.5 μm thick NiFe magnetic films.

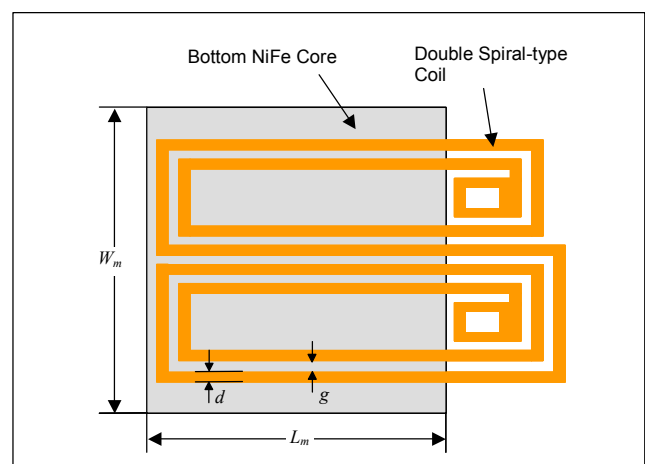


Fig. 1. Top view of the thin-film inductor.

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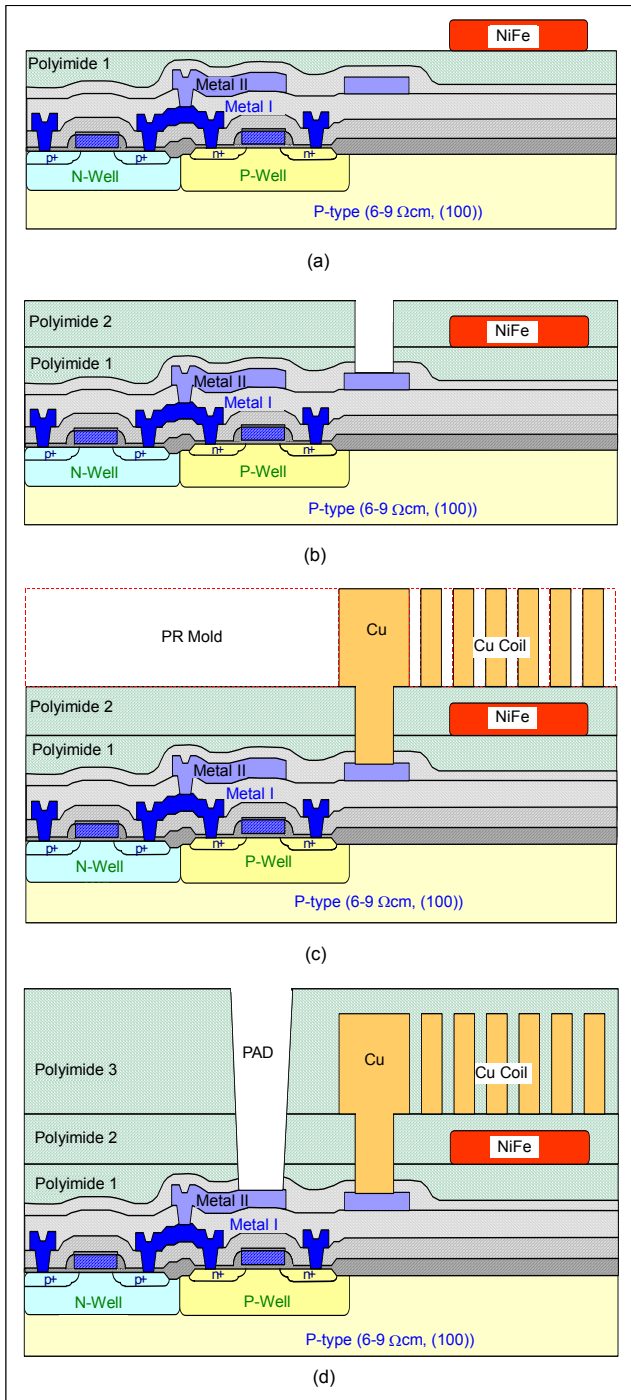


Fig. 2. Process sequences of integration between the thin-film inductor with the DC-DC converter IC:
 (a) deposition of polyimide and NiFe magnetic film,
 (b) via etching after the deposition of polyimide,
 (c) deposition of Ti-Cu seed layer, PR mold formation,
 and electroplating of copper, and (d) deposition of
 polyimide for passivation and etching for the pad.

The coils were made of 15 μm -thick electroplated copper and had 6 turns of coil. The width (d) of the coil was 92 μm and the spacing (g) 15 μm . The width (W_m) and the length (L_m)

of the magnetic thin-film were 3.5 mm and 2.45 mm, respectively.

Figure 2 illustrates the sequence of the integration process between the thin-film inductor and the DC-DC converter. We used 15 V high-voltage MOSFETs [6]-[9] for the switching transistor and substituted a synchronous rectifier for the conventional Schottky rectifier. Polyimide (PI2611, Dow Chemical) was coated for 30 seconds by a spin speed of 5000 rpm and was thermally cured in a vacuum oven for 40 minutes. Polyimide films were not only used to isolate the magnetic layer from the metal electrodes of the IC but also to relax the stress of the NiFe magnetic films during the sputtering process.

The 2.5 μm thick NiFe magnetic thin films for the bottom magnetic core were deposited on the polyimide films. We used a shadow mask to reduce the film stress during the deposition process. Additional polyimide films were coated and thermally cured to isolate the magnetic layer from the coil conductor lines. We made the interconnection between the electrodes of the DC-DC converter IC and the copper coil of the thin-film inductor through sequential processes of etching 6 μm thick polyimide, etching 8000 \AA PECVD oxide, deposition of a Ti-Cu seed layer, and electroplating copper coil. For etching the polyimide films, we used the Applied Materials RIE etcher (P-5000) with a pressure of 100 mTorr and a RF power of 500 watts. A PECVD oxide masking layer of 4000 \AA showed very

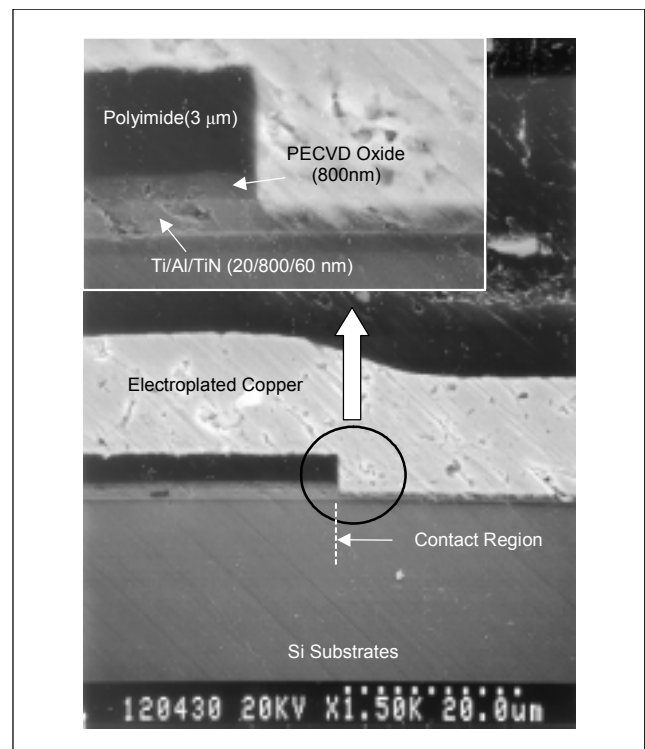


Fig. 3. A SEM photograph of a cross-sectional view at the Al-Cu contact region.

good masking characteristics because the etching process used only O₂ plasma without any other gases.

Figure 3 shows a SEM photograph of the cross-sectional view of the Al-Cu contact area. Ti/Al/TiN (50/800/60 nm) was used as a second metal for the DC-DC converter. The SEM photograph shows that the copper conductor was successfully connected from the metal electrodes of the DC-DC converter.

To determine the contact resistances between the Ti/Al/TiN second metal and the electroplated copper coil, we made a string pattern of 140 contacts with a contact area of 30 × 30 μm². An RF cleaning step was performed after the etching process of polyimide and PECVD oxide. The measured resistance was 4.62 to 4.84 Ω, while some samples not treated with RF cleaning showed 80 to 331 Ω. The specific contact resistance of the Al-Cu contact was 3.0 × 10⁻⁷ Ω·cm².

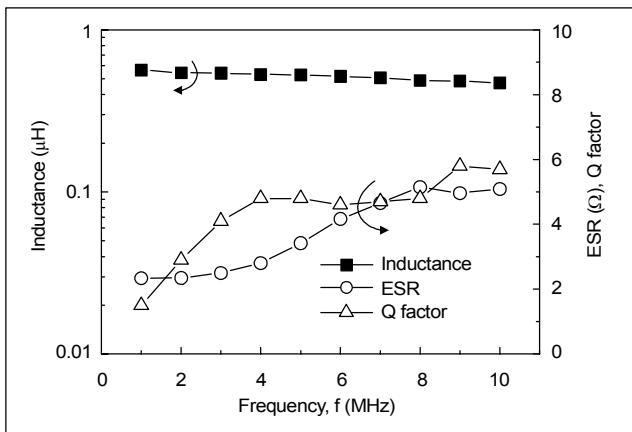


Fig. 4. Measured inductances, resistances, and Q factors as a function of frequency.

An impedance analyzer (HP 4194A) with a probe fixture 16095A measured the inductances, equivalent series resistances (ESR), and Q factors of the discrete thin-film inductor (Fig. 4). The measured inductances ranged between 0.5 and 0.6 μH in the frequency ranges of 1 to 10 MHz. The Q factors varied from 4.1 to 5.7 in the frequency ranges of 3 to 10 MHz, while the Q factors were less than 3 at frequencies under 2 MHz. These measured data are comparable to those of thin-film inductors with sandwiched magnetic layers [1]-[2].

Figure 5 shows a microphotograph of the DC-DC converter integrated with the monolithic thin-film inductor. The area of the thin-film inductor was 3.5 × 2.5 mm², while the area of the DC-DC converter was 4.8 × 4.8 mm². The DC-DC converter had a control circuit and gate driver. We tested the boost-type DC-DC converter and evaluated its performance. Figure 6 shows the switching waveforms of the fabricated DC-DC converter with the monolithic thin-film inductor at the conditions of V_i=5 V and R_L=100 Ω. The DC-DC

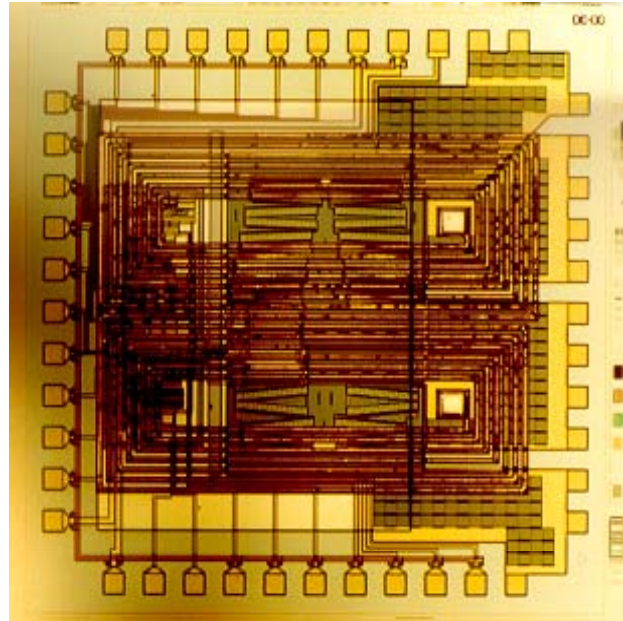


Fig. 5. Microphotograph of a DC-DC converter integrated with a monolithic thin-film inductor. The area of the thin-film inductor was 3.5 × 2.5 mm², while the area of the DC-DC converter was 4.8 × 4.8 mm².

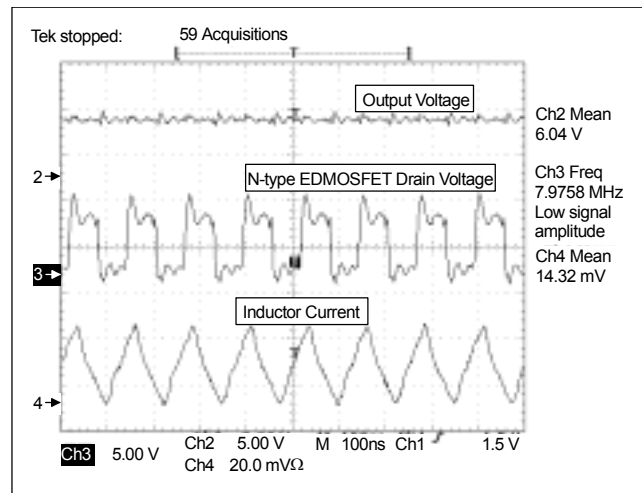


Fig. 6. Waveforms of FET switching voltage and thin-film inductor current when V_i=3.5 V, V_o=6.0 V, R_L=100 Ω, and the operating frequency was 8 MHz.

converter operated at 8 MHz and a regulated output voltage of 6 V. Its efficiency was 72% and its output power 360 mW.

III. Conclusion

In summary, a fully CMOS-compatible thin-film inductor with a bottom NiFe core was integrated with the DC-DC converter. By eliminating the ineffective top magnetic layer, we achieved a very simple process integration. The fabricated monolithic thin film inductor had an inductance of 0.49 μH and

a Q factor of 4.8 at 8 MHz. The fabricated DC-DC converter showed a V_{out} of 6.0 V and a power efficiency of 72% when V_{in} was 3.5 V and the operating frequency was 8 MHz.

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