

Measured electrical performance of V-groove inductors for microprocessor power delivery

S. Prabhakaran
C. R. Sullivan
K. Venkatachalam

From *IEEE Transactions on Magnetics*, vol. 39, no. 5, pp. 3190–3192.

©2003 IEEE. Personal use of this material is permitted. However, permission to reprint or republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

Measured Electrical Performance of V-Groove Inductors for Microprocessor Power Delivery

Satish Prabhakaran, *Student Member, IEEE*, Charles R. Sullivan, *Member, IEEE*, and Kapil Venkatachalam

Abstract—Thin-film V-groove inductors for microprocessor power delivery are discussed. A 10-MHz, 3.3-V to 1.1-V, 7-A dc–dc converter with V-groove inductors has been predicted to have an efficiency of 88% and power density of 60 W of output power per cm^2 of substrate area. The first prototype inductors with composite granular Co–ZrO₂ thin-films were fabricated with dimensions smaller than those required for a 7-A converter in order to fabricate them on standard 25-mm silicon wafers. For these prototype devices, we predicted that a 10-MHz, 3.3-V to 1.1-V, 2.1-A dc–dc converter would have 60% efficiency. Measurements on the prototypes indicate that a 2.1-A converter would have 55% efficiency with a power density of 28 W/cm². Measured losses were 23% higher than predicted. We have demonstrated that V-groove inductors can be fabricated with performance close to predicted results.

Index Terms—Cobalt, dc–dc power conversion, high current, low voltage, power inductors, thin-film devices, zirconium oxide.

I. INTRODUCTION

LOW VOLTAGES, high currents, and fast load transients are emerging challenges in power delivery for microprocessors. DC–DC converters for these applications need to have fast response, high efficiency, and small size. The inductor in the dc–dc converter plays a central role in determining the performance in each of these aspects [1]. We are developing new high-performance microfabricated power inductors in the 1–50-nH range to be applied in 3.3-V to 1.1-V, 7-A dc–dc power converters operating between 1 and 50 MHz. Though inductance of such small values may be easy to achieve, these inductors are also designed for low loss even at very high currents. The high flux density and low loss of thin-film magnetic materials enable significant advantages relative to ferrites [2]. Many prototype microfabricated thin-film power inductors have been reported in [2]–[17]. However, most are typically limited by low efficiency (often 60% or lower) and low power density (often under 1 W of output power per cm^2 of substrate area). We expect our devices to be capable of achieving high efficiencies at higher power densities.

II. FABRICATION

The “V-groove” design and fabrication process are intended specifically to maximize power density and efficiency in high-current low-voltage applications [1], [18]. The inductor design

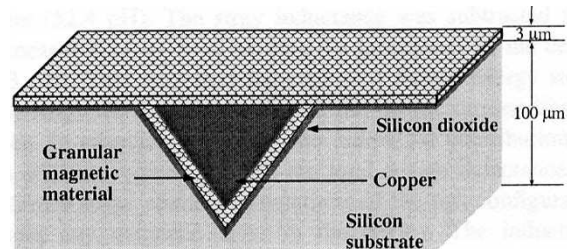


Fig. 1. Schematic of V-groove inductor (not to scale).

is in the form of a triangular wire surrounded by magnetic material, embedded in a silicon substrate as shown in Fig. 1. The fabrication process for these devices can be summarized as follows; more details are provided in [19]. A V-trench is formed by anisotropic etching of a silicon substrate. Composite magnetic material consisting of Co–ZrO₂ is deposited in the trench to form the core. Copper is filled in the groove to form the conductor and an overlayer of magnetic material completes the core of the inductor. The magnetic material is wrapped around a single wire thus forming a one-turn inductor.

III. MAGNETIC MATERIALS

Microfabricated magnetic components are often made with thin layers of magnetic material to reduce eddy-current losses. This is effective at controlling loss resulting from flux travelling in the plane of the film, but flux components out of the plane can still induce eddy currents that result in substantial losses [18]. Granular composite magnetic materials can be used instead of multilayer thin films to effectively control eddy-current loss due to magnetic flux in and out of the plane of the magnetic film. The work in [20]–[23], for example, has proven that high performance is possible in vacuum-deposited materials with nanoscale particles of Co or Fe.

We have deposited Co–ZrO₂ films using a target containing 85% Co and 15% Zr that was reactively sputtered at 250 W RF power in argon at a background pressure of 20×10^{-3} torr. The base pressure achieved before sputtering was 4×10^{-6} torr. Normally, we would introduce oxygen for reactive sputtering [24]. The sample that we report was deposited without additional oxygen, using only the residual oxygen in the deposition system. Deposition was performed in the presence of a transverse dc field of 400 Oe. The best Co–ZrO₂ film that we have deposited has a relative permeability of 40, a coercivity of 2 Oe, and a resistivity of $600 \mu\Omega\text{-cm}$. We choose to operate at a peak flux density equal to the point at which a sharp increase in coercivity is observed. Though the saturation flux density is higher than this point, we choose to operate at a lower flux density,

Manuscript received January 8, 2003. This work was supported in part by Intel Corporation and the National Science Foundation under grant ECS-9875204.

The authors are with the Thayer School of Engineering, Dartmouth College, Hanover, NH 03755 USA (e-mail: satish.prabhakaran@dartmouth.edu; chrs@dartmouth.edu)

Digital Object Identifier 10.1109/TMAG.2003.816053

0.4 T for this sample, to achieve high efficiency while still being able to achieve the large power densities reported in this paper.

IV. INDUCTOR DESIGN

The V-groove inductor design process involves calculating the dimensions of the inductor using measured properties of the magnetic core *viz.*, coercivity, permeability, peak flux density, and resistivity of the magnetic material. The thickness of the core is first fixed. The perimeter of the V-trench is the magnetic path length and can be calculated from peak flux density and permeability for a given output current. The width of the inductor can then be calculated from the geometry of the V-trench. At 10 MHz, the choice of ripple current in the 3.3-V to 1.1-V converter establishes the inductance requirement. The inductance requirement is used along with the other geometrical parameters to calculate the length of the inductor. The losses in the conductor, magnetic material and MOSFETs in the converter can then be calculated using the process detailed in [24]. An efficiency and power density for the design are then determined. The efficiencies and power densities discussed here include the loss and area of the MOSFETs as well as the inductor.

The above routine was used to calculate the inductor design for a 10-MHz, 3.3-V to 1.1-V, 7-A converter. The magnetic properties of the best thin-film sample have been discussed in Section III. For copper, we achieved a resistivity of $2.2 \mu\Omega\text{-cm}$ in our fabrication process (discussed in Section V). These properties are the best we have currently achieved in our fabrication process. Using these properties in our design routine, we calculate the dimensions of the inductor to be 22 mm long, $567 \mu\text{m}$ wide and $400 \mu\text{m}$ deep with a $10\text{-}\mu\text{m}$ -thick core for the 7-A converter. We predict the efficiency of the complete converter circuit to be 88% with a power density of 60 W/cm^2 , which are attractive properties for power inductors for microprocessor power delivery.

Our first prototype V-groove inductors are 3.8 mm long and $140 \mu\text{m}$ wide, with a $3\text{-}\mu\text{m}$ -thick Co-ZrO₂ core. The dimensions of the prototype inductors make them suitable only for a rated dc current of 2.1 A. Therefore, we investigated the performance of a 10-MHz, 3.3-V to 1.1-V, 2.1-A converter. The magnetic material on the die containing our prototypes was deposited during another deposition and the magnetic properties are different from the best thin-film sample we described in Section III. The following are details specific to the prototypes. The relative permeability of the magnetic material in and on the die was measured to be 31 using a vibrating sample magnetometer (VSM). The inductance measurement on the prototype yielded a relative permeability of 27.2—the value that we used in the design routine. The coercivity was found to be 6.6 Oe. We choose to operate at a peak flux density of 0.4 T. The resistivity of copper is $2.2 \mu\Omega\text{-cm}$. Using these properties, we predicted a converter efficiency of 60% at 28 W/cm^2 .

V. ELECTRICAL PERFORMANCE OF V-GROOVE INDUCTORS

Small-signal measurements were performed at 10 MHz on a prototype inductor having dimensions stated in Section IV, using an impedance analyzer (Agilent 4294A) and a custom designed

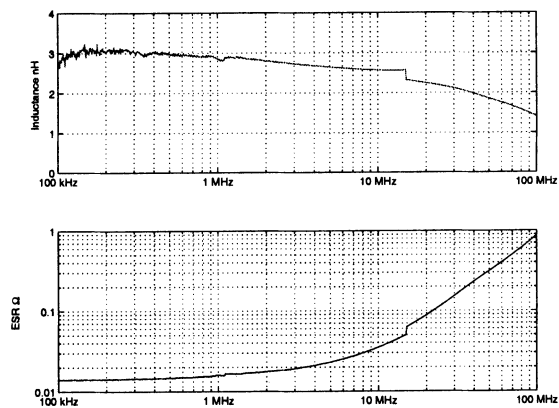


Fig. 2. Measured inductance and resistance of microfabricated V-groove inductors. The glitch at 15 MHz is a result of $50\text{-}\Omega$ terminations that come into effect at this frequency in the measuring equipment used. Measurement error is at least as large as the 11% glitch.

ultralow stray inductance test fixture [25] onto which the inductor was soldered. Fig. 2 shows the measured performance of the inductor. The measured result of 2.58 nH at 10 MHz on the plot includes the stray inductance of the test fixture (52.4 pH). The stray inductance was subtracted from the measured result to determine the inductance of the device (2.53 nH). This corrected inductance is due to energy stored in the magnetic layer in the device and the air surrounding the device. In order to determine the individual contributions of each of these regions toward the total device inductance, we performed finite-element simulations of the test configuration without any magnetic layer in the device. The inductance was found to be 1.51 nH; this represents the air inductance surrounding the device. The difference between the total device inductance and the air inductance is the contribution of the magnetic layer to the device inductance (1.02 nH). We chose to use a simulation rather than a measurement as the reference point for this calculation because it was easier to accurately duplicate the geometry in a simulation.

The advantages of using of a magnetic core are that it allows fabrication of devices with higher power density and higher efficiency than air-core devices for a given inductance requirement and that devices with a core can be spaced closer to the ground plane than air-core devices for a given inductance requirement thereby reducing electromagnetic interference. Reference [18] compares calculated performance of air-core and V-groove designs in more detail.

We also simulated the prototype inductor with a $3\text{-}\mu\text{m}$ -thick magnetic layer at 10 MHz. Using the relative permeability (31), the simulation suggested that our prototype inductors would have inductance of 2.83 nH, excluding the stray inductance of the test fixture. The measured device inductance of 2.53 nH is close to the simulated result thus confirming that the device works as expected.

We performed dc resistance measurements using a four-point measurement on the prototypes. The measured dc resistance of the conductor was found to be $13.96 \text{ m}\Omega$ indicating that we achieved a copper resistivity of $2.2 \mu\Omega\text{-cm}$.

We measured the effective series resistance (ESR, which is the real part of the impedance) to be $29.89 \text{ m}\Omega$ at 10 MHz after

subtract the test fixture from the measured result at 10 MHz. The efficiency of a 10-MHz, 3.3-V to 1.1-V, 2.1-A converter using the prototype inductor with the measured values of dc resistance and ESR is projected to be 55% at 28 W/cm². We project this number using the same MOSFET losses as those used for our prediction in Section IV. The predicted efficiency of 60% at 28 W/cm² in Section IV for the previously mentioned converter was calculated for an inductor with the same width (140 μm), thickness of core (3 μm) and permeability (27.2). We do not include the air inductance surrounding the device. To be realistic, the efficiency of a 10-MHz, 3.3-V to 1.1-V, 2.1-A converter including the air inductance along with the measured inductance due to the core is expected to be 74% at 67 W/cm².

VI. CONCLUSION

Thin-film V-groove inductors have been fabricated and tested. Measurements on our prototype inductors indicate that a 10-MHz, 3.3-V to 1.1-V, 2.1-A converter would be 55% efficient—only 5% less efficient than the predicted efficiency of 60% at 28 W/cm². Our best thin-film sample that was deposited independent of the inductor fabrication process (Section III) suggests that better performance in the magnetic material is possible. A minor discrepancy in efficiencies between expected and measured results of the prototypes exists. The fact that the discrepancy is not drastic encourages us to proceed towards realizing a 10-MHz, 3.3-V to 1.1-V, 7-A converter with inductors that are 22 mm long, 567 μm wide, and 400 μm deep with a 10-μm-thick core. We predict a converter efficiency of 88% (650-mW loss in inductor and 370-mW loss in MOSFETs) with a power density of 60 W/cm² for this case. All these designs include only the inductance due to the magnetic material for a fair comparison. The high efficiency combined with the superior power density of thin-film V-groove inductors makes them attractive for power delivery to microprocessors.

REFERENCES

- [1] G. J. Mehas, K. D. Coonley, and C. R. Sullivan, "Converter and inductor design for fast-response microprocessor power delivery," in *Proc. 31st IEEE Annu. Power Electronics Specialists Conf.*, June 2000, pp. 1621–1626.
- [2] C. R. Sullivan and S. R. Sanders, "Design of microfabricated transformers and inductors for high-frequency power conversion," *IEEE Trans. Power Electron.*, vol. 11, pp. 228–238, Mar. 1996.
- [3] K. H. Kim, J. Kim, H. J. Kim, S. H. Han, and H. J. Kim, "A megahertz switching DC/DC converter using FeBN thin film inductor," *IEEE Trans. Magnetics*, vol. 38, pp. 3162–3164, Sept. 2002.
- [4] J. M. Boggetto, Y. Lembeye, J. P. Ferrieux, and J. P. Keradec, "Microfabricated power inductors on silicon," in *Proc. 33rd Annu. Power Electronics Specialists Conf.*, 2002.
- [5] M. Brunet, T. O'Donnell, J. O'Brien, P. McCloskey, and C. O'Mathuna, "Design study and fabrication techniques for high power density microtransformers," in *Proc. 16th Ann. IEEE Applied Power Electronics Conf. and Expo.*, 2001, pp. 1189–1195.
- [6] M. G. Allen, J. Y. Park, J.-W. Park, and Y.-H. Joung, "Fabrication of high current and low profile micromachined inductor with laminated Ni/Fe core," *IEEE Trans. Magn.*, vol. 25, pp. 106–111, Jan. 2002.
- [7] S. Ajram and G. Salmer, "Ultrahigh frequency DC-to-DC converters using GaAs power switches," *IEEE Trans. Power Electron.*, vol. 16, pp. 594–602, Sept. 2001.
- [8] M. Edo, M. Gekinozu, Z. Hayashi, Y. Katayama, K. Kuroki, K. Matsuzaki, H. Nakazawa, S. Sugahara, and E. Yonezawa, "Micro DC–DC converter that integrates planar inductor on power IC," *IEEE Trans. Magn.*, vol. 36, pp. 3518–3521, Sept. 2000.
- [9] L. Daniel, C. R. Sullivan, and S. R. Sanders, "Design of microfabricated inductors," *IEEE Trans. Power Electron.*, vol. 14, pp. 709–723, July 1999.
- [10] V. Korenivski and R. B. van Dover, "Design of high frequency inductors based on magnetic films," *IEEE Trans. Magn.*, vol. 34, pp. 1375–1377, July 1998.
- [11] M. Xy, T. M. Liakopoulos, C. H. Ahn, S. H. Han, and H. J. Kim, "A microfabricated transformer for high-frequency power or signal conversion," *IEEE Trans. Magn.*, vol. 34, pp. 1369–1371, July 1998.
- [12] J. Y. Park and M. G. Allen, "Low temperature fabrication and characterization of integrated packaging-compatible, ferrite-core magnetic devices," in *Proc. IEEE Applied Power Electronics Conf.*, vol. 1, 1997, pp. 361–367.
- [13] Y. Sasaki, S. Morita, T. Hatanai, A. Makino, T. Sato, and K. Yamawata, "High frequency soft magnetic properties of nanocrystalline Fe-(Co)-Hf-O films with high electrical resistivity and their application to micro DC–DC converter," *NanoStruct. Mater.*, vol. 8, no. 8, pp. 1025–1032, 1997.
- [14] M. Mino, K. Tsukamoto, K. Yanagisawa, A. Tago, and T. Yachi, "A compact buck-converter using a thin-film inductor," in *Proc. Applied Power Electronics Conf.*, Mar. 1996, pp. 422–426.
- [15] C. R. Sullivan and S. R. Sanders, "Measured performance of a high-power-density microfabricated transformer in a DC–DC converter," in *Proc. 27th Annu. Power Electronics Specialists Conf.*, vol. 1, June 1996, pp. 287–294.
- [16] K. Yamaguchi, E. Sugawara, O. Nakajima, and H. Matsuki, "Load characteristics of a spiral coil type thin film microtransformer," *IEEE Trans. Magn.*, vol. 29, pp. 3207–3209, Nov. 1993.
- [17] K. Yamasawa, K. Maruyama, I. Hirohama, and P. Biringer, "High-frequency operation of a planar-type microtransformer and its application to multilayered switching regulators," *IEEE Trans. Magn.*, vol. 26, pp. 1204–1209, May 1990.
- [18] G. J. Mehas, K. D. Coonley, and C. R. Sullivan, "Design of microfabricated inductors for microprocessor power delivery," in *Proc. IEEE Applied Power Electronics Conf.*, Mar. 1999, pp. 1181–1187.
- [19] S. Prabhakaran, C. R. Sullivan, and C. G. Levey, "Fabrication of thin-film V-groove inductors using composite magnetic materials," in *Proc. IMAPS Advanced Technology Workshop Integrated Power Passives*, June 2002.
- [20] S. Ohnuma, H. J. Lee, N. Kobayashi, H. Fujimori, and T. Masumoto, "Co-Zr-O nano-granular thin films with improved high frequency soft magnetic properties," *IEEE Trans. Magn.*, vol. 37, pp. 2251–2254, July 2001.
- [21] Y. Hayakawa, A. Makino, H. Fujimori, and A. Inoue, "High resistive nanocrystalline Fe-M-O (M=Hf, Zr, rare-earth metals) soft magnetic films for high-frequency applications (invited)," *J. Appl. Phys.*, vol. 81, no. 8, pp. 3747–3763, 1997.
- [22] S. Ohnuma, H. Fujimori, S. Mitani, and T. Masumoto, "High-frequency magnetic properties in metal-nonmetal granular films," *J. Appl. Phys.*, vol. 79, no. 8, pp. 5130–5135, 1996.
- [23] Y. Hayakawa and A. Makino, "Soft magnetic properties of Fe-M-O (M=Hf, Zr, Y, Ce) films with high electrical resistivity," *NanoStruct. Mater.*, vol. 6, pp. 989–992, 1995.
- [24] K. Venkatachalam, "Optimization of microfabricated buck converters," M.S. thesis, Thayer School Eng., Dartmouth College, Hanover, NH, 2002.
- [25] S. Prabhakaran and C. R. Sullivan, "Impedance-analyzer measurements of high frequency power passives: Techniques for high power and low impedance," in *Proc. IEEE Industry Applications Soci. Annu. Meeting*, Oct. 2002, pp. 1360–1367.