Thin-Film Inductor Designs and Materials for High-Current Low-Voltage Power

Charles R. Sullivan, Satish Prabhakaran, Parul Dhagat, Yuqin Sun
Thayer School of Engineering, Dartmouth College, Hanover, NH 03755-8000, USA
Email: chrs@dartmouth.edu, satish.prabhakaran@dartmouth.edu, parul.dhagat@dartmouth.edu, yuqin.sun@dartmouth.edu

I. INTRODUCTION

Low voltages, high currents and fast load transients are emerging challenges in power delivery for high-performance digital electronics such as microprocessors. Power converters for these applications need to have fast response, high efficiency and small size. The inductor in the power converter plays a central role in determining the performance each of these aspects. Thin-film inductors offer possible advantages [1]–[16]. However, these applications require higher efficiency, higher power density, and higher current than is offered by most thin-film inductors.

In order to meet these requirements, we are studying both magnetic materials and inductor designs. As a typical example, we are fabricating inductors for a 3.3 V to 1.1 V, 7 A DC-DC power converter operating between 1 MHz and 50 MHz.

II. 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 magnetic 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 [17]. Granular composite magnetic materials can be used instead of multilayer thin films to effectively control eddy-current loss due to flux in and out of the plane of the film. These materials consist of nanoscale particles of Co or other magnetic metals in a ceramic matrix such as Al_2O_3. Conventionally they are deposited using reactive sputtering of an alloy target (e.g., [18], [19], [20]). When a Co-Al target is sputtered in the presence of a small amount of oxygen, the Al ideally combines with O, leaving Co to form a separate phase. We have also experimented with depositing similar materials by evaporation, using Co and MgF_2 sources [21]. We are presently using reactively sputtered Co-ZrO_2 films [22]. A Halbach array [23] is used to provide a highly uniform magnetic field in the substrate region.

In several different granular materials, we have observed the formation of stripe domains (Fig. 1), which result in dramatically different magnetic properties [24]. The stripe-domain hysteresis loop includes a lossy open loop in the central region, but at moderate fields it has lower permeability regions associated with domain rotation. In some applications, the lossy central region cannot be avoided, and stripe domains are considered detrimental. However, in dc-dc converter, inductors typically operate with unidirectional current, and thus unidirectional flux. Thus, it may be possible to make use of the low-permeability region for power-converter applications. Although the available flux swing is reduced with stripe domains, the low permeability allows high H values without saturation, similar to a high H_k value. Whether the disadvantages of stripe domains outweigh the advantages probably depends on the application. The engineering of deposition parameters to control stripe domain formation is discussed in [24].

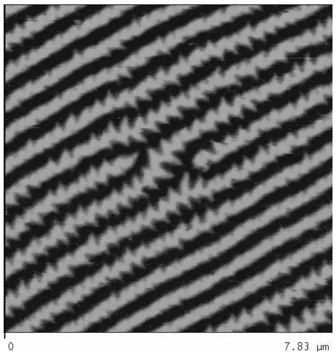

Fig. 1. MFM image of stripe domains in Co-ZrO_2

III. DESIGN

An inductor or transformer with a closed magnetic core consists of two interlinked loops: one is conductor and one is magnetic material. In most cases the conductor loop comprises multiple turns, although for low-voltage, high-current applications, the impedance is low enough that a single turn is optimal. In any case, interlinking the two requires at least three deposition steps. In [25] these two approaches were compared, using a theoretical analysis of power density and efficiency. The designs in the class using two depositions of magnetic material are termed pot-core designs, because, like a conventional pot-core transformer, they have magnetic material surrounding a coil. The designs in the class using two depositions of conductor are termed torroidal designs, because, like a conventional torroidal transformer, they have a coil surrounding a core. In [25], it was shown that using two magnetic layers (the "pot-core" design) results in higher power density for a given efficiency. In addition, it is difficult to achieve high efficiency in torroidal designs using anisotropic magnetic materials, because the direction of flux is different in different regions.

In multi-turn designs, a critical parameter is the aspect ratio in the conductor patterning, because, for a given resolution, it determines the thickness and thus the resistance of the winding. Much progress has been made in developing high-aspect ratio winding processes [3]. However, for low-voltage high-current applications, with a single turn, conductor aspect ratio is much less important. Instead, the overall space available within the core for the conductor, and the ac resistance of the conductor become the important factors.

The "V-groove" design and fabrication process [17], [26], [27], [28] is intended specifically to maximize power density and efficiency in high-current low-voltage applications. The inductor design is in the form of a triangular wire surrounded by magnetic material, embedded in a silicon substrate as shown in Fig. 2. The fabrication process for these devices can be summarized as follows; more details are provided in [28]. A V-trench is formed by anisotropic etching of a silicon substrate. Composite magnetic material consisting of Co-ZrO_2 is deposited in the trench to form the core. Copper is filled in

This work was supported in part by Intel Corporation and by the United States National Science Foundation under grant ECS-9875204

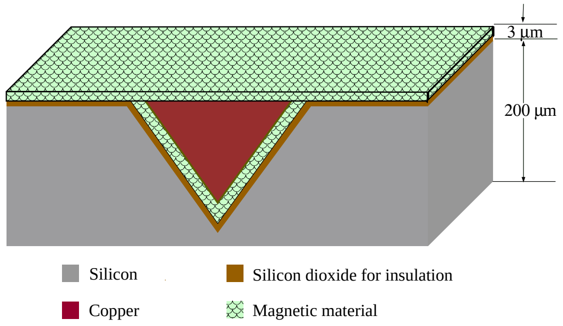

Fig. 2. Schematic of V-groove inductor (not to scale)

the groove to form the conductor and an overlayer of core material completes the core of the inductor. The magnetic material is wrapped around a single wire thus forming a one-turn inductor.

To achieve high performance, it is important to perform design calculations that specifically address the application of interest. These calculations are discussed in [17], [26], [29]. Depending upon the specific assumptions about the magnetic material and the geometrical constraints, we predict performance of 50 to 200 W of power converter output per square centimeter of inductor substrate area with inductor efficiency of 85 to 90% or better, based on an 8 MHz converter switching frequency. Recently analysis has addressed optimization of the complete power converter, including area and losses in the power FETs [29]. This work indicates that, for FETs implemented in an advanced low-voltage CMOS process, higher switching frequencies, in the 20 to 50 MHz region, may be advantageous to allow even higher power densities.

Our first prototype V-groove inductors [30] were used to test the fabrication process, but were smaller than the designs required for high-performance in the ultimate application. The characteristics measured using the techniques described in [31] were close to our predictions, although the scaled-down devices are not capable of high efficiency or power density.

IV. CONCLUSION

Granular magnetic materials offer performance advantages for thin-film magnetic components. For low-voltage, high-current applications, the V-groove design offers high performance combined with a simple fabrication process.

REFERENCES

[1] Hee Jun Kim, Hi Jung Kim, Jong Ryoul Kim, Ki Hyeon Kim, and Suk Hee Han, “A MHz switching dc/dc converter using FeBN thin film inductor”, in *International Magnetics Conference (INTERMAG) 2002*, 2002.

[2] J.M. Boggetto, Y. Lembeye, and J.P. Keradec J.P. Ferrieux, “Micro fabricated power inductors on silicon”, in *33rd Annual Power Electronics Specialists Conf.*, 2002.

[3] Brunet M, O’Donnell T, O’Brien J, McCloskey P, and O’Mathuna C, “Design study and fabrication techniques for high power density microtransformers”, in *16th Annual IEEE Applied Power Electronics Conference and Exposition*, 2001.

[4] M. Edo, M. Gekinozu, Z. Hayashi, Y. Katayama, K. Kuroki, H. Matsuzaki, K.and Nakazawa, S. Sugahara, and E. Yonezawa, “Micro - dc-dc converter that integrates planar inductor on power IC”, *IEEE Transactions on Magnetics*, vol. 36, no. 5, pp. 3518–3521, 2000.

[5] Allen M.G., Jae Yeong Park, Jin-Woo Park, and Yeun-Ho Joung;, “Fabrication of high current and low profile micromachined inductor with laminated ni/fe core”, *IEEE Transactions on Magnetics*, vol. 25, no. 1, pp. 106–111, 2002.

[6] Ajram S. and G. Salmer, “Ultrahigh frequency dc-to-dc converters using gaas power switches”, *IEEE Trans. on Power Electronics*, vol. 16, no. 5, pp. 594–602, 2001.

[7] Kiyohito Yamasawa, Kenji Maruyama, Isao Hirohama, and Paul Biringer, “High-frequency operation of a planar-type microtransformer and its application to multilayered switching regulators”, *IEEE Transactions on Magnetics*, vol. 26, no. 3, pp. 1204–1209, May 1990.

[8] K. Yamaguchi, E. Sugawara, O. Nakajima, and H. Matsuki, “Load characteristics of a spiral coil type thin film microtransformer”, *IEEE Transactions on Magnetics*, vol. 29, no. 6, pp. 3207–3209, 1993.

[9] Kazuyuki Yamaguchi, Shigehiro Ohnuma, Takao Imagawa, Jirou Toriu, Hidetoshi Matsuki, and Koichi Murakami, “Characteristics of a thin film microtransformer with circular spiral coils”, *IEEE Transactions on Magnetics*, vol. 29, no. 5, pp. 2232–2237, 1993.

[10] M. Mino, K. Tsukamoto, K. Yanagisawa, A. Tago, and T. Yachi, “A compact buck-converter using a thin-film inductor”, in *Proceedings of Applied Power Electronics Conference, APEC’96*, Mar. 1996, pp. 422–426.

[11] Charles R. Sullivan and Seth R. Sanders, “Measured performance of a high-power-density microfabricated transformer in a dc-dc converter”, in *27th Annual Power Electronics Specialists Conf.*, June 1996, vol. 1, pp. 287–294.

[12] T. Sato, Y. Miura, S. Matsumura, K. Yamasawa, S. Morita, Y. Saski, T. Hatana, and A. Makino, “New applications of nanocrystalline Fe(Co-Fe)-Hf-O magnetic fils to micromagnetic devices”, *J. of Applied Physics*, vol. 83, no. 11, pp. 6658–6660, 1998.

[13] Luca Daniel, Charles R. Sullivan, and Seth R. Sanders, “Design of microfabricated inductors”, in *27th Annual Power Electronics Specialists Conf.*, June 1996, vol. 2, pp. 1447–1455.

[14] V. Korenivski and R. B. van Dover, “Design of high frequency inductors based on magnetic films”, *IEEE Transactions on Magnetics*, vol. 34, no. 4, pp. 1375–1377, 1998.

[15] Y. Sasaki, S.Morita, T. Hatanai, A. Makino, T. Sato, and K. Yamasawa, “High frequency soft magnetic properties of nanocrystallien Fe-(Co)-Hf-O films with high electrical resistivity and their application to micro DC-DC converter”, *NanoStructured Materials*, vol. 8, no. 8, pp. 1025–1032, 1997.

[16] Ming Xy, Tirfon M. Liakopoulos, Chong H. Ahn, Suk Hee Han, and Hi Jung Kim, “A microfabricated transformer for high-frequency power or signal conversion”, *IEEE Transactions on Magnetics*, vol. 34, no. 4, pp. 1369–1371, 1998.

[17] Gustavo J. Mehas, Kip D. Coonley, and Charles R. Sullivan, “Design of microfabricated inductors for microprocessor power delivery”, in *IEEE Applied Power Electronics Conference*, Mar. 1999.

[18] S. Ohnuma, H. Fujimori, S. Mitani, and T. Masumoto, “High-frequency magnetic properties in metal-nonmetal granular films”, *Journal of Applied Physics*, vol. 79, no. 8, pp. 5130–5135, 1996.

[19] Y. Hayakawa and A. Makino, “Soft magnetic properties of Fe-M-O (M=Hf, Zr, Y, Ce) films with high electrical resistivity”, *NanoStructured Materials*, vol. 6, pp. 989–992, 1995.

[20] 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.

[21] K.D. Coonley, G.J. Mehas, C.R. Sullivan, and U.J. Gibson, “Evaporatively deposited Co-MgF$_2$ granular materials for thin-film inductors”, *IEEE Transactions on Magnetics*, vol. 36, no. 5, Sept. 2000.

[22] 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 Transactions on Magnetics*, vol. 37, no. 4, pp. 2251–4, July 2001.

[23] Halbach Klaus, “Design of permanent multipole magnets with oriented rare earth cobalt material”, *Nuclear Instruments and Methods*, vol. 169, no. 1, 1980.

[24] Pei Zou, W. Yu, and J.A. Bain, “Influence of stress and texture on soft magnetic properties of thin films”, *IEEE Transactions on Magnetics*, vol. 38, no. 5, pp. 3501–20, Sept. 2002.

[25] C.R. Sullivan and S.R. Sanders, “Design of microfabricated transformers and inductors for high frequency power conversion”, *IEEE Transactions on Power Electronics*, vol. 11, no. 2, Mar. 1996.

[26] Gustavo J. Mehas, Kip D. Coonley, and Charles R. Sullivan, “Converter and inductor design for fast-response microprocessor power delivery”, in *31st IEEE Annual Power Electronics Specialists Conference.*, June 2000.

[27] S. Prabhakaran, D.E. Kreider, Yu Lin, and C.R. Sullivan, “Fabrication of thin-film V-groove inductors using composite magnetic materials”, in *IEEE International Workshop on Integrated Power Packaging*, July 2000, pp. 102–5.

[28] Satish Prabhakaran, Charles R. Sullivan, and Christopher G. Levey, “Fabrication of thin-film v-groove inductors using composite magnetic materials”, in *Advanced Technology Workshop on Integrated Power Passives*, June 2002.

[29] Kapil Venkatachalam, “Optimization of microfabricated buck converters”, Master’s thesis, Thayer School of Engineering, Dartmouth College, May 2002.

[30] S. Prabhakaran, C.R. Sullivan, and K. Venkatachalam, “Measured electrical performance of V-groove inductors for microprocessor power delivery”, in *Intermag*, Mar. 2003, abstract EA-06.

[31] Satish Prabhakaran and Charles R. Sullivan, “Impedance-analyzer measurements of high frequency power passives: Techniques for high power and low impedance”, in *IEEE Industry Applications Society Annual Meeting*, Oct. 2002.