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From *Transactions of the Magnetics Society of Japan*, vol. 3, no. 4,  
pp. 126–8.

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

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## 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  $\text{Al}_2\text{O}_3$ . 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  $\text{MgF}_2$  sources [21]. We are presently using reactively sputtered Co-ZrO<sub>2</sub> 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].

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

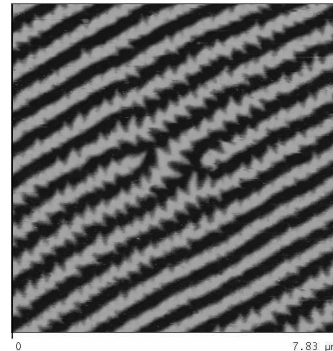


Fig. 1. MFM image of stripe domains in Co-ZrO<sub>2</sub>

## 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 toroidal designs, because, like a conventional toroidal 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 toroidal 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<sub>2</sub> is deposited in the trench to form the core. Copper is filled in

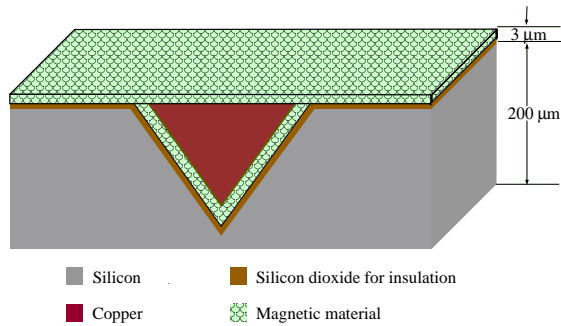


Fig. 2. Schematic of V-groove inductor (not to scale)

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.

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