The Development of New Amorphous Cores for High Frequency Power Applications

WHITE PAPER

INTRODUCTION

Increased electrification is driving the development of more efficient energy solutions for all market segments. Designers of semiconductor technology have developed new methods for switching such as soft switching or zero current switching, which have contributed to increased bandwidth and the introduction of devices using GaN and SiC materials. Increased bandwidth helps to reduce the size of magnetic components as the magnetizing inductance increases, yet core materials can struggle to dissipate less power as the frequency increases. Typically, materials with high flux density and low coercivity exhibit excess core losses as the frequency approaches 1 MHz.

This paper introduces new core material research published at APEC 2019 and PCIM 2019 by Bourns in collaboration with Tyndall Research Institute. The purpose of developing new magnetic materials is to achieve minimal core losses at high switching frequencies. The paper provides an overview of core material terminology and describes the results obtained from new material produced by Bourns with a discussion on the application of these results and future work planned.

ADVANCED MAGNETIC MATERIALS TERMINOLOGY

Magnetic materials differ from non-magnetic materials by the way they react when a magnetic field is applied. If a magnetic field is generated, the atoms in magnetic materials will experience a torque proportional to the flux density in the field by a vector quantity called the magnetic moment. A strip of magnetic material can be described furthermore by groups of magnetic moments, known as domains, where every domain has a different direction. Once a field is applied, the domains will align along the direction where the least amount of energy is lost (called the easy axis as shown in Figure 1). All magnetic materials have these qualities although some have higher anisotropic energies, which is the energy required to rotate the magnetic domains to a saturated state where the applied field has no effect, than others and a few materials enable better performance at different switching frequencies compared to others.

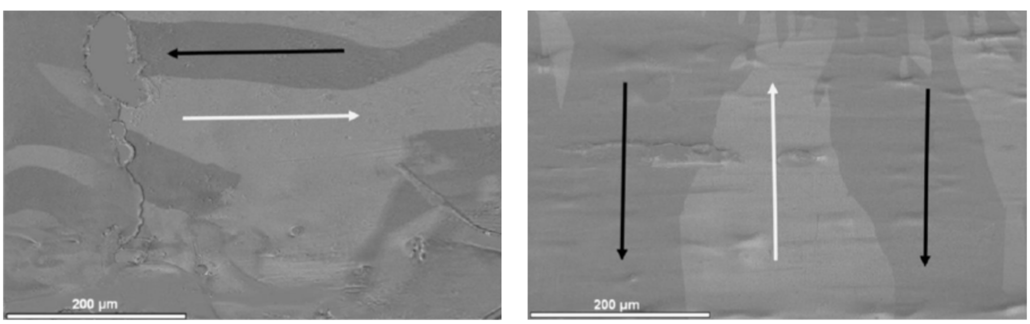

Figure 1: Electron Microscope Image of Amorphous Material With Domain Wall Movement (Left) and Domain Rotation (Right)

Figure 2 shows the saturation flux densities of various commercially available materials on the market. Nickel–iron alloy (NiFe) cores are commonly used in power inductor applications as they offer good coercivity compared to ferrites and have higher flux densities as well.

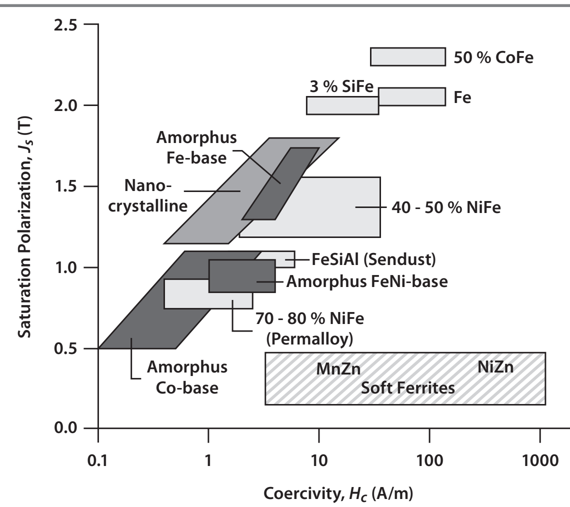

Figure 2: Overview of Different Materials Categorized by Coercivity and Saturation Flux Density

ADVANCED MAGNETIC MATERIALS TERMINOLOGY (CONTINUED)

The chart in Figure 2 shows that amorphous materials have a good mixture of coercivity and saturation flux density. The composition of amorphous materials consists of trace elements such as Cobalt and Iron together with mixtures of Silicon and other elements such as Niobium. One of the objectives of this research was to prepare and test amorphous material which did not depend on traditional elements and resulted in reducing the material cost by 30 %.

The experimental material used in this research was based on Cobalt and Iron and other elements. In order to prepare the material, the elements were carefully weighed and arc-melted at temperatures of 4000 °C in an arc furnace producing 1 g ingots. The ingots were subsequently put into an induction heater and the molten liquid ejected onto a spinning disk and cooled at a very severe rate (1 million degrees per second) producing 20 µm thick, 1 mm wide ribbons into a quartz vial. Figure 3 illustrates the steps taken in the first stage of making the material.

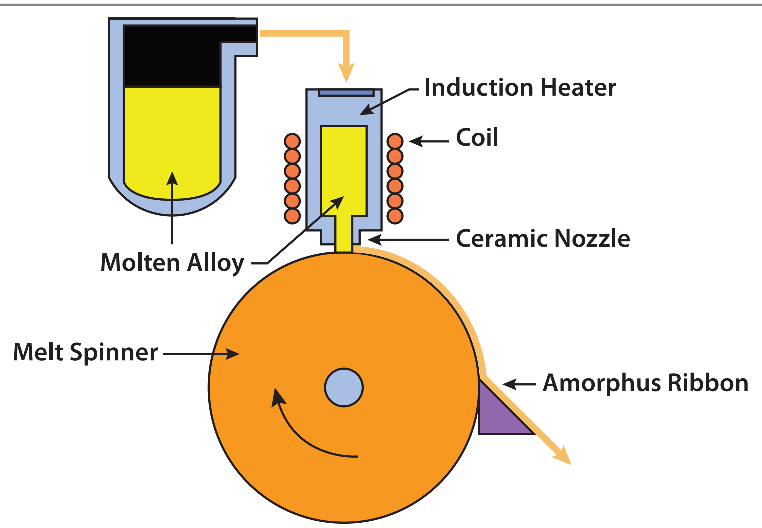

Figure 3: Illustrates the First Stage of Production as Quenched Samples of Amorphous Material

ADVANCED MAGNETIC MATERIALS TERMINOLOGY (CONTINUED)

The ribbons, once gathered in the quartz vial, are known as "quenched". The B-H loop of this material was gathered using a B-H loop tracer and is shown in Figure 4 (black line). The curve is known as the magnetization curve. The magnetic domains are aligned in the longitudinal direction and the magnetization is known as domain wall movement. The core losses of amorphous material with domain wall movement magnetization are high and are dominated by anomalous losses. This is corrected by applying magnetic annealing (up to 5T magnetic field) in a transverse direction to the easy axis at different temperatures starting from 500 °C. The effect of magnetic annealing is to change the magnetization process from domain wall movement to domain wall rotation. Domain wall rotation reduces anomalous core losses significantly. The B-H loop of magnetically annealed samples can be seen in the green curve in Figure 4. There is an obvious difference in the slope of the B-H curve with magnetization requiring a larger field (H) and, hence, higher anisotropic energy.

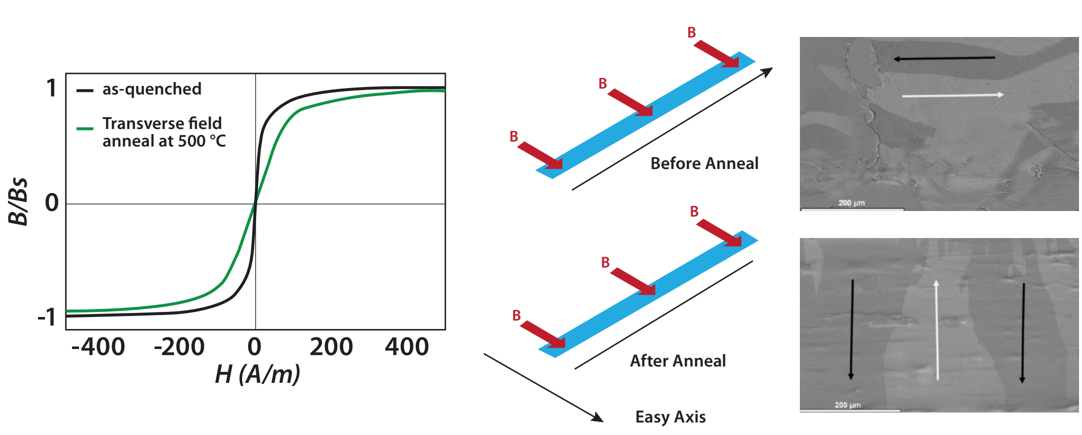

Figure 4: B-H Curve of Bourns Amorphous Material Before and After Annealing

CALCULATION AND MEASUREMENT OF CORE LOSSES

Core losses can be divided into three categories as follows:

A. Hysteresis losses P_h: This is a function of the B-H curve of the material and is proportional to the product of the AC Magnetic Field, the Flux Density and the frequency as shown in Equation 1:

$$P_h = 4fB^2 \frac{H}{B_{sat}} \text{ : Equation 1}$$

B. Eddy Currents P_e: Eddy currents induced in the core material are affected by the resistivity of the material. The resistivity in turn is affected by the skin depth at the switching frequency.

$$P_e = \frac{\omega^2 \phi^2 \sigma b \delta}{8l} \left(\frac{\sinh\frac{a}{\delta} - \sin\frac{a}{\delta}}{\cosh\frac{a}{\delta} + \cos\frac{a}{\delta}} \right) \text{ : Equation 2}$$

Where ω represents angular speed (radians per second or 2πf); δ represents skin depth; σ is the electrical conductivity; a and b refer to the sheet thickness and width; and l is the overall length. Eddy current losses are, therefore, proportional to the square of the switching frequency. P_e can be reduced by keeping *a* as close to the skin depth as possible.

C. Anomalous loss: The anomalous loss is about 70 % of the losses in amorphous cores. It is caused by variations in the demagnetization curve due to fluctuations in the domain wall rotation. Anomalous loss is calculated by measuring the core loss of the material, then calculating hysteresis and eddy current losses using Equations 1 and 2 and then subtracting them from the measured core loss.

Figure 5: Photograph of the Test Fixture Used to Measure Core Loss

CORE LOSS MEASUREMENTS

To measure core losses, the research team used a 5 cm solenoid (5 mm radius) with 150 turns of copper wire connected to an LCR meter. The 150 turns completely filled the solenoid so as to ensure a uniform magnetic field inside the solenoid. The impedance of the solenoid was measured with and without the material sample. The core loss is the difference in impedance multiplied by the square of the current injected by the LCR meter as shown in Equation 3.

$$P_{loss} = R_e\{Z_c - Z_a\}I^2 \text{ : Equation 3}$$

The flux density in Tesla with the solenoid is calculated using Equation 4.

$$B = \frac{Im\{Z_c - Z_a\}I}{2\pi f S} \text{ : Equation 4}$$

Where f and S are the measurement frequency and cross-sectional area of the sample magnetic material inside the solenoid.

The resultant core loss measurements were then recorded and plotted on Figure 6 and shown in comparison with commercial grade NiFe material at a frequency of 1 MHz. As the graph shows, there was a vast improvement in the power losses with the tested Bourns material. It was at least 30 % lower than the NiFe material. Furthermore, the permeability was measured from the B-H curve as 770 compared with typical values of 100 or less with NiFe cores. Assuming an NiFe core with an initial permeability of 77, the ratio of extra turns required to reach the same inductance value compared with the Bourns amorphous material would be 3.16. The amorphous material had a strong advantage over NiFe when it came to form factor reduction as fewer turns would be needed, and it would be more efficient as thicker wire with lower copper losses could be introduced.

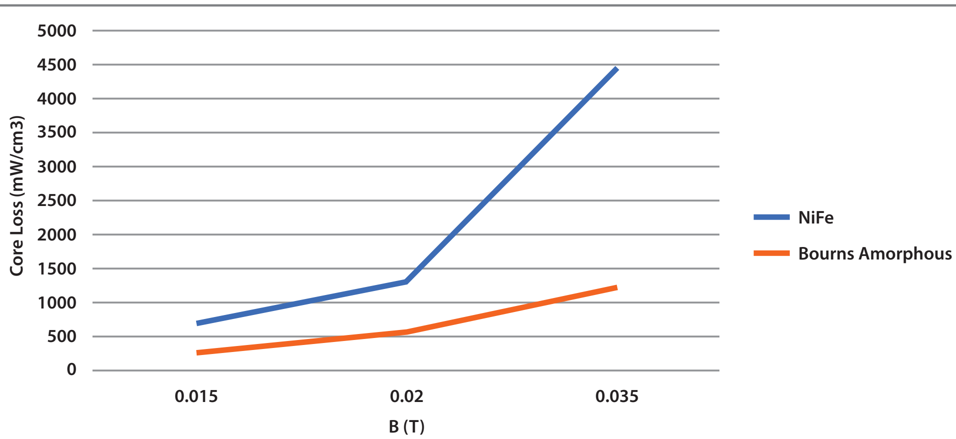

Figure 6: Core Loss Density Measurements of Bourns Material and NiFe Material

CORE LOSS MEASUREMENTS (CONTINUED)

The temperature stability of this material is also very strong and comparable to NiFe cores, giving a strong advantage in EMI filtering applications where inductance drift with temperature can affect the insertion loss of common mode filters. However, the 10-fold increase in permeability allows this material to be used where inductance values typically requested are higher than what NiFe can typically provide without increasing significantly in form factor.

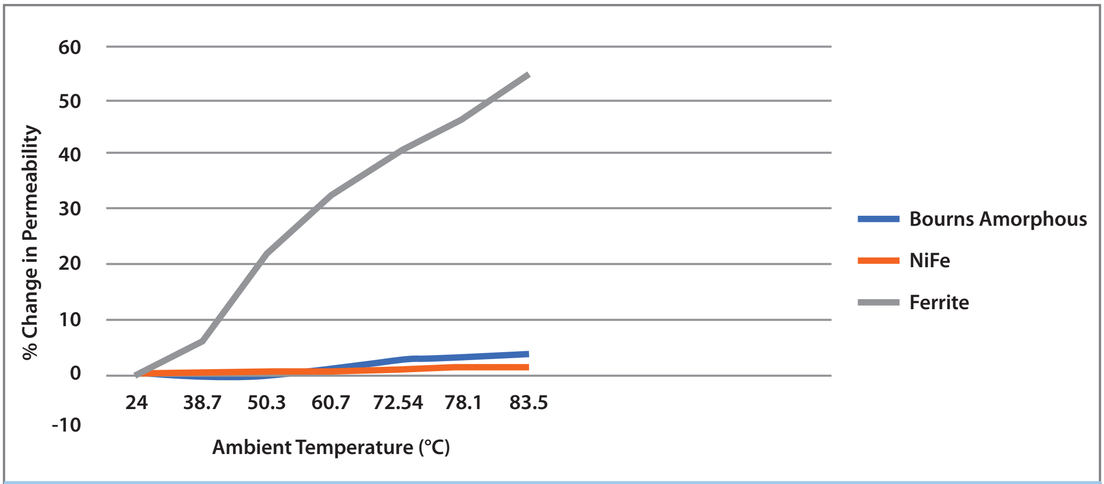

Figure 7: Change In Permeability (%) Over Operating Temperature of Bourns Material Compared with Ni Fe and Ferrite

Figure 7 illustrates the similarity in temperature drift between NiFe and the Bourns amorphous material. It also shows the stability of a commercial off-the-shelf ferrite material. The only way to reduce the ferrite material's temperature instability would be to introduce a gap into the core. The Bourns material's permeability was calculated by creating a toroidal magnetic component and recording the magnetizing inductance in a temperature chamber at different temperatures. Figure 8 shows a photograph of the prototype magnetic device (push-pull transformer) on a test board.

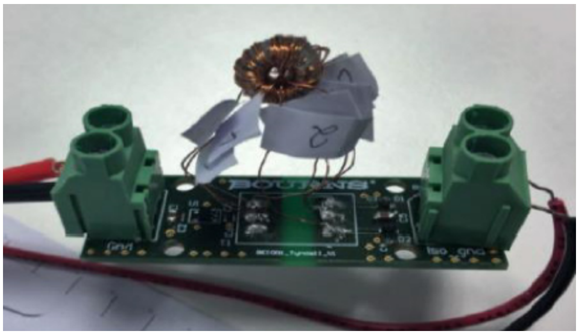

Figure 8: Photograph of Prototype Transformer Made with Bourns Amorphous Core

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SUMMARY

The work here to create an amorphous core material using less exotic trace elements for high switching frequencies has produced some interesting initial results. At 1 MHz, the core losses were much lower than other materials with similar coercivity such as NiFe. More research is still needed to evaluate the amorphous material for alternative high frequency cores in high power converters or filters requiring low coercivity, good temperature stability and high permeability.

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