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SPS co-sintered monolithic transformers for power electronic

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Power integration is a key issue to reduce the volume and weight of electronic devices in power applications. But, transformers produced using classical planar assembly are limited in design. Spark Plasma Sintering (SPS) is a relatively new technology to produce multimaterial compact system with higher density and using lower sintering temperature. The purpose of this study is to manufacture of a cubic-centimeter size transformers for high frequency application using SPS. The prototype presented in this paper is composed of two spiral copper coils separated by an insulated layer and encapsulated in ferrite powder. The assembly is then co-sintered by SPS. The magnetic material used for the transformers is a nickel-zinc based ferrite, with copper substitution to allow sintering at low temperatures. The low conductivity of this mixed-ferrite ensures operation in the frequency range of 1 to 20 MHz of our final system. Computed tomography scanning has been used to optimize the design of the co-sintered structures. Effects of the composition of the ferrite and the sintering temperature on the transformation ratio are discussed. It is shown that a ferrite with very low conductivity is required to ensure galvanic insulation, as there is a direct contact between the copper spirals and the magnetic parts.

Index Terms—Power integrated circuits, Spinel ferrite, Transformers.

I. INTRODUCTION

POWER INTEGRATION is an important challenge to get more energy efficient embedded power systems. To achieve this goal, the research is focused on packaging of power semiconductors on one hand, and the design of the passive components on the other hand. Concerning magnetic components, many efforts have been consecrated to increase the switching frequency, which has for consequences an increase in magnetic losses. Hence, it is necessary to use low loss ferrite and to improve thermal management.

A possible approach is to develop more compact designs and assembly procedures based on NiZnCu ferrite [1]. In this work, the Spark Plasma Sintering (SPS) is proposed to produce monolithic transformers that have advantages regarding the commonly used classical planar transformers from the point of view of compactness and heat transfer.

SPS is a relatively new technology to produce multi-material compact systems with higher density, and using lower sintering temperature [2], [3]. Indeed, this process allows to sinter in an efficient way (heating rates over 100 K/min and overall duration of several tens of minutes) and to decrease the sintering temperature about 100 K due to the uniaxial pressure and diffusion enhancement.

The fabrication of co-sintered transformers by SPS offers some interesting features, such as avoiding the use of PCB (printed circuit board), which are needed in standard planar configurations. In addition, the magnetic circuit of the transformer obtained by SPS consists of a single block, which facilitates heat transfer from the coils to the core and eventually to a heat sink.

The interest of producing monolithic transformers has already been shown in literature. However, the high temperature of classical sintering (950 °C) forces the use of silver clay for the windings, since this material has a higher melting point than copper [4]-[9]. Due to the short duration and the lower sintering temperature of the SPS process, the use of copper becomes possible.

II. SAMPLE FABRICATION

The proposed transformer consists in two spiral copper coils, a dielectric layer, and a spinel ferrite magnetic circuit. An exploded view is shown in Fig. 1. The selected configuration is inspired from planar transformers; where the PCB is replaced by a thin dielectric that separates the two coils. Finally, the ferrite encapsulates the whole.

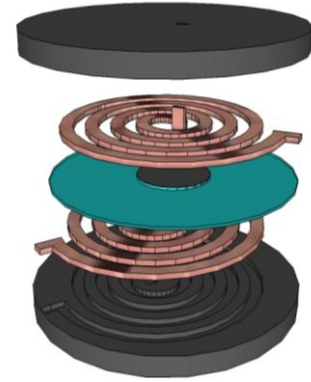


Figure 1: Exploded view of a monolithic transformer.

A. The copper spirals

The primary and secondary windings of the transformer are given by small copper spirals, fabricated by EDM (Electrical Discharge Machining) using a Robofil 300 from Charmilles Technologies. We selected a 0.45 mm thick slab to ensure that the windings resist to the high pressure during the sintering. The primary and secondary winding have slightly different shapes to enable the defined mounting, as represented in Fig. 2. In both cases, the number of turns is set to four. The width of a spiral arm and the distance between the arms are 0.5 mm. Then, the extremities must be drawn up manually to make them exceed the transformer. The largest parts are designed to have better access to contact after sintering.

B. The dielectric

The dielectric is necessary to ensure galvanic isolation between the two windings. For this application, it has to withstand a temperature of 800 °C and a pressure of 50 MPa during the sintering process. Our choice fell on mica washers. The outer and inner diameters and thickness are 16, 5 and 0.1 mm respectively. The assembly of the spirals and a washer is shown in Fig. 2.

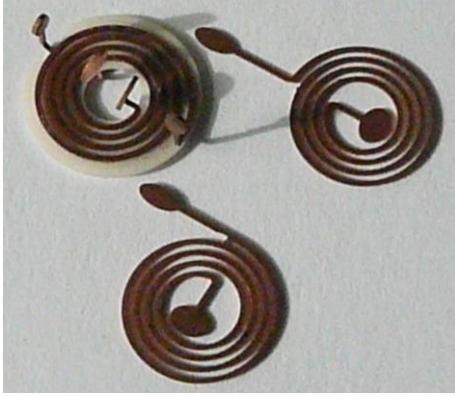


Figure 2: Copper spiral and mica washer.

C. The Magnetic Powder

In order to work at high frequency, we choose a high bandwidth magnetic material: the Ni-Zn-Cu ferrite. The powder of chemical formula $\text{Ni}_{0.27}\text{Zn}_{0.57}\text{Cu}_{0.16}\text{Fe}_2\text{O}_4$ was purchased from Marion Technologies.

The powder particles should have a large specific surface area to reduce the porosity of the sintered ferrite. To refine the powder, we use a planetary mill, Fritsch Pulverisette 7.

At this point, we decided to elaborate 2 different kind of powder by adding a V_2O_5 as a flux to one of them in order to improve the density of the sintered ferrite. Indeed, during the sintering stage, the vanadium oxide melts at around 680 °C and produces a liquid phase that enables faster diffusion of atoms between the particles [10], [11], [12].

In both cases, the grinding takes 3 hours with a rotational speed of 400 rpm. The grinding bowl contains 18 balls, which have a diameter of 7 mm and a mass of 1.4 g each, and a powder mass of 5.5 g.

D. The co-sintering

The SPS process allows sintering ferrite powder with metallic copper. To insure there is no inter-diffusion between the different phases during the sintering, a first test is performed. A copper foil is inserted in between two ferrite powder beds, in a graphite die and co-sintered at 850 °C, a temperature slightly higher than sintering temperature of the transformer, in order to keep a safety margin. The sintered sample was then cut diametrically, inspected by SEM, and chemically analyzed by EDS. The results, Fig. 3, show that the copper layer is welded to the ferrite. Moreover, oxygen and iron are absent in the metallic copper area.

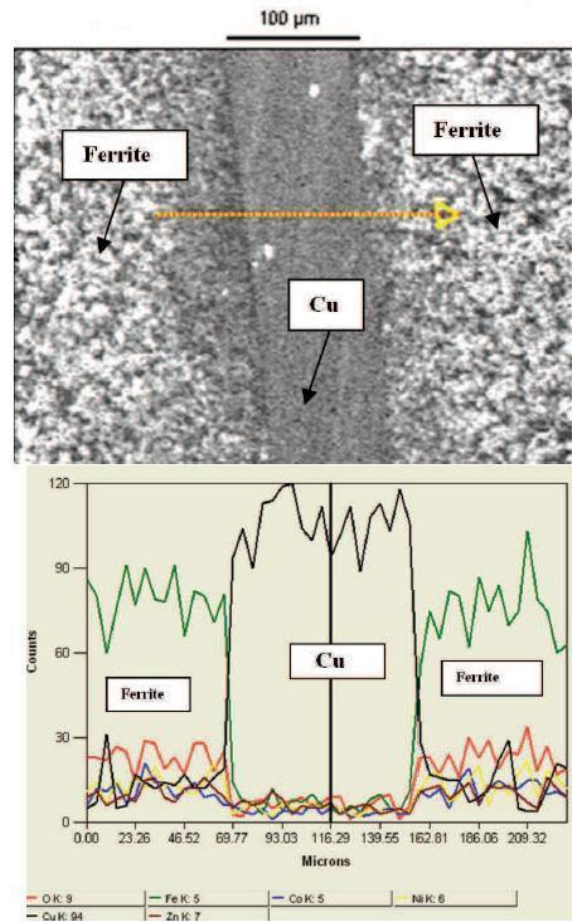


Figure 3: Copper and ferrite co-sintered.

According to the EDS analysis, the transition between metal and ferrite is sharp at least at the scale of the present analysis. Thus, it is assumed that under these conditions, there is no significant modification of materials properties due to inter-diffusion.

To produce the transformer, the different parts are prepared as shown in Fig. 4.

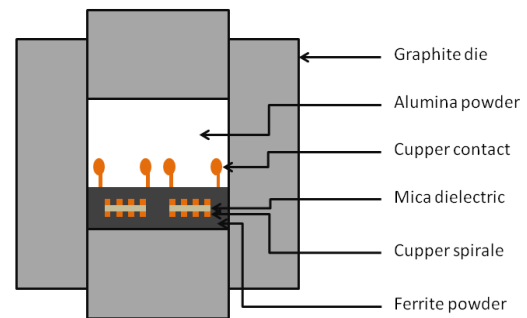


Figure 4: Preparation of a sample in cross-section.

The graphite die is used as the heat source when it is crossed by an electrical current. The alumina powder is necessary to prevent the pistons of deforming the extremities of the spirals. As a matter of fact, the alumina is inert during the process, and can be easily removed later.

The heat treatment consists in 3 steps. First, the temperature is increased from 20 °C to 800 °C in 5 min. Secondly, it is held constant at 800 °C for 10 min. Thirdly, the temperature is decreased to 20 °C in 5 min.

In Fig. 5, we show a picture of the transformer. The diameter is 20 mm, and the thickness is around 3.5 mm.

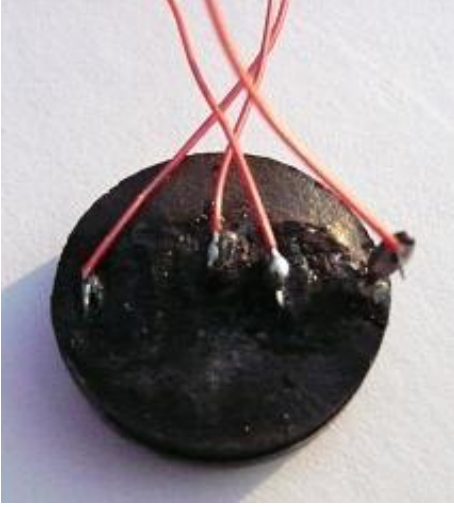


Figure 5: Co-sintered monolithic transformer.

III. EXPERIMENTS

A. Computed tomography scanning (CT scanning)

The first transformers had a crippling problem: the two windings were short-circuited. In order to determine the origin of this problem, we resort to the industrial computed tomography scanning. This non-destructive testing is very useful in this case because it enables a numerical selective view; we can choose to see only the spirals, or the magnetic material. This is possible because copper has a higher density than the other materials.

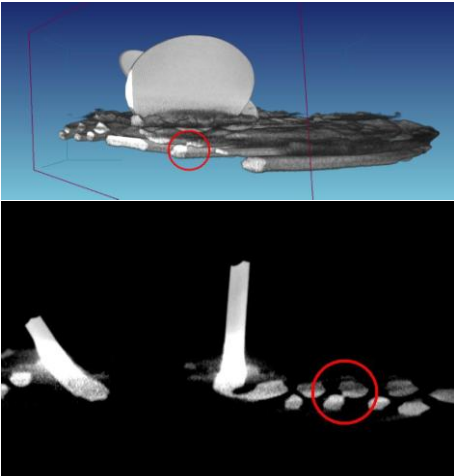


Figure 6: Views of spirals in a transformer. A short-circuit is visible.

The picture depicted in Fig. 6 reveals a short circuit. A part of the mica washer was damaged during the sintering stage.

Moreover, the washer, which was flat, seems to be out of shape. Although it decreases the magnetic coupling between the two windings, a simple solution is to increase the number of washers by overlaying. Four pieces are used to avoid any short-circuit, for an equivalent thickness of 0.4 mm, as represented in Fig. 7.

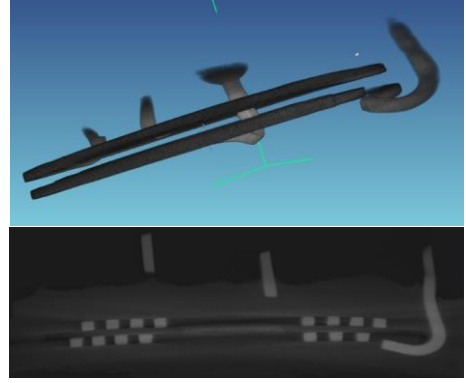


Figure 7: Transformers without short-circuit observed.

In this picture, the structure is greatly improved: both the insulation layer and the coil keep their original shape, and no electrical contact was detected by CT scanning.

B. Voltage ratio dependence on frequency

One of the essential characteristics of a power electronic transformer is the bandwidth. The gain of the transformer was measured by means of a spectrum analyzer (HP 4194 A) unloaded and a loaded by 50 Ω . The two aforementioned samples, with and without V_2O_5 , are examined. The results are presented in Fig. 8.

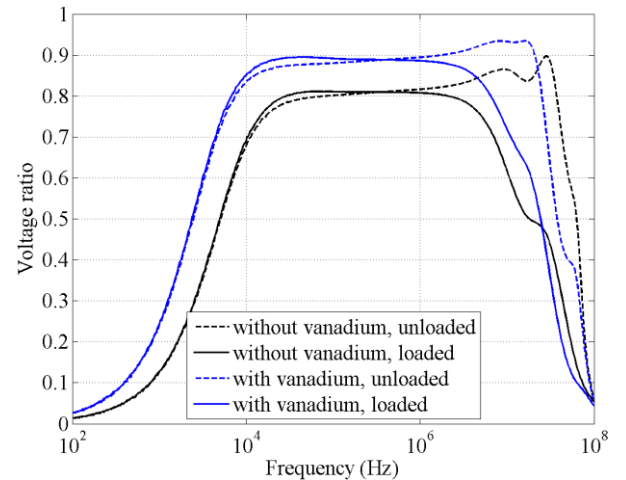


Figure 8: Gain of voltage ratio versus frequency.

Both transformers have a gain under one in the bandwidth, although the turn number ratio is one. Indeed, the measurements show that in practice the secondary voltage is lower than the primary, even within the bandwidth. This is in relation with an important leakage inductance, due to the transformer topology. When the transformers are unloaded, we also notice a resonance around the high cutoff frequency. It

can be explained by capacitive coupling between the two windings. This resonance is broken when the transformers are loaded due to an increase of the damping factor.

However, the addition of the vanadium oxide during the grinding stage, allows us to improve the voltage ratio. This is correlated with the density enhancement, presumably leading to an increase in permeability.

In addition, the bandwidth has been slightly enlarged for low frequencies. Nevertheless, for the targeted applications in this study, the interest is focused on high frequencies, where the bandwidth respects the ranges currently used in power electronics.

For more information, we have measured some characteristics of the transformer with vanadium oxide at 1 MHz. At this frequency, the ohmic resistance is 11.4 m Ω , the inductance of one coil is 1.94 μ H, the mutual inductance is 1.71 μ H, and the leakage inductance is 0.23 μ H.

C. SEM

In order to understand the effect of the vanadium oxide on the magnetic circuit permeability, we analyze the particle sizes with a scanning electron microscope. In general, larger particles lead to higher permeability. Therefore, we would expect that the particle size in the ferrite with vanadium oxide could be greater than in the pure ferrite sample. On the other hand, thinner particle usually lead to a higher cutoff frequency. However, both samples exhibit similar cutoff frequencies, around 15 MHz. This is explained by looking at pictures shown in Fig. 9.

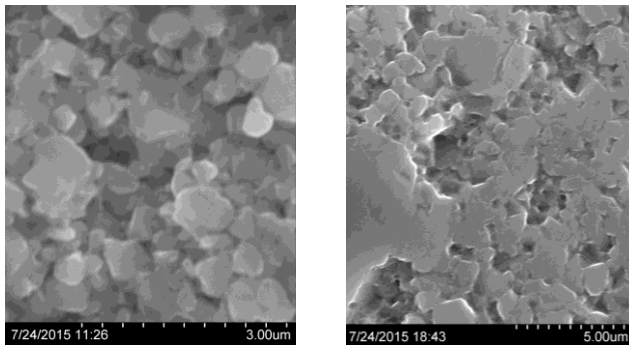


Figure 9: Ferrite without and with vanadium oxide.

In fact, the sample with vanadium oxide presents a more heterogeneous distribution of the particle sizes, but the porosity is reduced, which explains the increased permeability that led to the measured higher voltage ratio.

IV. CONCLUSION

In this work we have proven the feasibility of monolithic transformer for power electronics by the SPS process, which appears as a promising technique on power integration. The main advantage of this technique is the reduction of the sintering temperature, which allows us to co-sinter metallic copper with ferrite powder.

The first challenge that we encountered was related to the proper sizing of the transformer elements. In the first samples

the dielectric material was deformed by the heat and the uniaxial pressure. This issue was handled by increasing the dielectric cumulated thickness. Afterwards, one downside of having low sintering temperature appeared. The density of the initial ferrite was low, which entailed high leakage fluxes, reducing the voltage ratio of the final monolithic transformer. To face this drawback, vanadium oxide was added to the ferrite powder in order to improve the sintering, which deals to a decrease of the leakage inductance.

Current issues are related with the resistivity of the sintered spinel ferrite. In fact, the SPS process is carried on under Argon atmosphere and not Oxygen. Consequently, the sintered ferrite doesn't have the expected resistivity, which leads to a low electrical resistance between the primary and secondary windings. Further work is focused on this aspect and on the integration of the proposed transformer in a switched-mode power supply.

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