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ABSTRACT
Gelcasting is a well established process for ceramics manufacturing which recently has been proved to be successful for soft ferrites as well. This approach is particularly interesting for power electronics application in which the magnetic components (e.g. transformers and inductors) are three dimensionally integrated on the power module substrate. This paper proposes a gelcasting process adapted to make it more effective for 3D heterogeneous integration. The main novelties in this direction consist of low solid load (65wt%) and gelation without catalyst to improve casting and de-airing steps. The magnetic properties of gelcast samples are compared with commercial materials and correlated with the microstructure.

I. INTRODUCTION
Recent developments in wide bandgap (WBG) transistors have pictured a new perspective of very compact high switching frequency power converters. However, as the switching frequency increases, the requirements of minimising the parasitic elements in a switching cell become more critical. One of the promising packaging solution is to integrate the output inductor of a switching cell together with the switching devices on the same substrate. By such an integrated package, the high frequency switching noises will be contained at the source and will not affect the end user. In addition to that, the possibility to bond the inductor directly on the substrate ensures a better thermal conductivity enabling higher power density. The physical implementation of this concept presents many challenges, among them one of the most critical is the 3D integration of the magnetic component. On one hand, the inductor has to be compact and its shape should be designed according to the geometric constraints given by other components. On the other hand, its current rating and high frequency behaviour should be trimmed in a way to avoid saturation or high losses. In other words, low permeability and low losses at high frequencies are required to meet these constraints (Section II).

Nevertheless, both in literature and on the market, there are not many solutions in this direction. Distributed air gap materials, such as sendust, are available in many combinations of size and permeability. However, they are optimized to work in a relatively low frequency range (10-200 kHz) compared to WBG devices capability. In the last years, ferrite manufacturer started to develop low permeability NiZn ferrite cores with good behaviour in terms of losses in a broad range of frequencies (e.g. 1-10 MHz). Indeed, 4F1 (Ferroxcube) and material 67 (Fair-rite) are examples of these materials, but they are mainly available in toroidal shapes and in a small variety of dimensions. Slicing high permeability materials (e.g. MnZn ferrite) to obtain lower equivalent permeability may appear as a practical solution, in fact it has been proved that the core losses increase drastically when the material grains are damaged for cutting. Even amorphous materials can be processed to obtain low permeability. To this end, amorphous material strip are crushed into powder which is then cold pressed to form magnetic cores. Even though this methods ensures low hysteresis losses and higher
saturation, it cannot be applied straightforward to 3D integration because high hydrostatic pressure is required.

Gelcasting, on the contrary, enables near net shape manufacturing through pressure-less sintering process.\textsuperscript{12–18} Although this technique has been already applied to ferrite cores,\textsuperscript{16–18} it has not been optimised for integration purposes yet. In this paper, an innovative process has been developed to manufacture low cost and custom-made integrated magnetic structures (Section III). Gelcast NiCuZn toroids have been manufactured and characterised in the frequency range of interest for WBG devices application, comparing the performance with two different materials available on the market (KoolMu26 and 4F1) (Section IV). Finally correlation study between magnetic properties and microstructure is presented.

II. MAGNETIC MATERIALS PROPERTIES FOR 3D MAGNETIC INTEGRATION

The Standard Basic Power Cell\textsuperscript{1,19} (SBPC) has been proved to be the right approach to enable the new wide bandgap devices to switch at high frequency. The key feature is that each SBPC comes with all the passive components needed for its own independent operation, including the output inductor. In a 3D integrated version of SBPC, inductor and switches are bonded on the same substrate (see Fig. 1). The challenge is to provide a core that exploits in optimal way the available space. The core manufacturing technique must allow modifications in geometry and dimensions without extensive effort or mass production requirements.

Another aspect that is worth to be discussed is the magnetic permeability of the core material. Considering a SBPC application with WBG devices of 60 A rated current, switching in a range between 500 kHz and 1 MHz, 6-10 $\mu$H of inductance can be used for filtering the output current of the half-bridge. In this frequency range, NiZn ferrites are the most common options, therefore flux density higher than 200 mT would cause undue losses for the cell. Regarding volume constraints, taking into account a power density of 50 kW/dm$^3$ a volume of 40x40x10 mm can be dedicated to the inductor, the required relative permeability results to be in between 20 and 40. The ideal solution would then be using a closed core with a permeability that matches the application requirements.

Gelcasting as a forming technique which is based on the casting of a liquid slurry may offer both shape flexibility and permeability modulation.

III. GELCASTING: STEP BY STEP PROCEDURE

In this study, the process and chemical ratios have been tailored to meet the requirements described in Section II. Different ferrite powder ratios have been investigated in literature,\textsuperscript{16} and good results in terms of sample density were obtained with higher ratios (e.g. 80wt\%\textsuperscript{18}), however this choice limits the benefit of gelcasting in getting complex shapes. Here, the solid load is kept willingly low to reduce the viscosity and improve the casting. In addition to that, this solution enables the use of high speed electric mixers instead of ball millers, resulting in a faster and easier process. Another critical point consists in removing air bubbles from the slurry. In this paper, a double step de-airing is proposed, including de-airing the slurry in the moulds after casting. This step can be carried out just if the slurry is still liquid at this point, hence no catalyst has been used for gelation.

A. Monomer premix

The first step consists of dissolving in water the monomers for hydrogel creation. Methacrylamide (MAM) and N,N’,-methylenebisacrylamide (MBAM) are used respectively as chain monomer and cross-linker. In the literature, monomers ratio (MAM:MBAM) usually varies from 1:1 to 7:1. In this study, a ratio of 2:1 was chosen in order to get a stronger green body.

B. Ferrite and dispersant addition

A NiCuZn ferrite powder (LSF120, Powder and Processing Technology) is then added to the premix with a solid load of 65wt\%. In order to have an homogeneous slurry, a dispersing agent is needed, hence 2wt\% of DARVAN C is added per mass unit of ferrite. The slurry is then mixed using a high speed electric mixer.

C. De-airing and casting

A first de-airing (50 mbar for 30 minutes) is included in the process to remove air introduced by mixing. Prior to casting, a 5wt% aqueous solution of ammonium peroxydisulfate (APS) is added to the slurry as initiator. Silicone rubber has been chosen as a moulding material because thanks to its flexibility the de-moulding operation becomes less complicated. Once the slurry has been cast, another de-airing is carried out. At this stage, vibrating the mould while de-airing has proved to be extremely helpful.

D. Polymerization and de-moulding

Since no catalyst has been added, polymerization will be triggered through temperature increase to 80 $^\circ$C and hold for 30 minutes. Obviously the mould material must stand this temperature without dramatic expansions. Since the CTE (coefficient of thermal expansion) of silicone is not negligible, it is helpful to design the mould in separate parts to make the expansion harmless to the sample. Once the reaction has been completed, the moulds can be removed and the green bodies are ready to be fired.
E. Sintering in tube furnace

Due to the shrinkage caused by water and organics content, the temperature profile must be finely tuned to avoid failure by cracking. Many ramp rates, organic burnout temperatures and times have been tested. Finally, a good trade off between process duration and final outcome turned out to be respectively 2 °C/min as ramp rate and 200 °C for one hour for the binder burnout. So far, two sintering temperatures have been investigated, 1000 °C and 1100 °C for 3 hours.

IV. GELCASTING: RESULTS

Since the purpose of this project is to perform magnetic characterisation of gelcast cores, a toroidal shape has been chosen. As expected, due to water and organics elimination there is a significant shrinkage from green body to sintered sample, see Fig. 2. By observing 5 samples obtained with the procedure presented in Sec. III, the average linear shrinkage resulted to be 18% and 22% with sintering temperature of 1000 °C and 1100 °C, respectively.

In order to estimate the magnetic properties, two tests are considered: small signal analysis and fluxmetric measurements.

Small signal analysis has been carried out by winding well-distributed turns around the samples and evaluating by an impedance analyser (Keysight E4990A). Thanks to this measurement, real and imaginary permeability can be obtained (Fig. 3). It is interesting to note that with a sintering temperature of 1000 °C, the value of permeability is 42 which makes this core suitable for the application described in Section II. By sintering the samples at 1100 °C there is a significant increase in permeability which has been measured to be 200.

A sine wave generator (100 kHz - 1 MHz) and a power amplifier (NF HSA4101) have been used to perform fluxmetric measurements and calculating magnetic losses. In Fig. 3, losses of gelcast materials are compared to a commercial NiZn ferrite (4F1) and a sendust (KoolMu26). The higher the sintering temperature the lower the loss density. Indeed the samples sintered at 1100 °C show better performance than the solutions available on the market, especially above 500 kHz. If $T_{\text{sinter}} = 1000$ °C the loss density is higher, but due to the low permeability and shape flexibility, with this combination of parameters there is the possibility to design cores without gaps and cuts, hence removing additional losses in the windings for fringing fluxes and in the core for damaged grain structure.

Gelcast ferrite samples were mounted and polished down to a 0.025 μm colloidal silica finish. A Jeol 7800 SEM equipped with backscatter electron detector was used to produce SEM images (see Fig. 4). Image analysis was performed to quantify porosity using the particle counting feature and grain size using the linear intercept method. Due to the high porosity levels, 27%, the grain size in the
1000 °C sample could not be determined. On the other hand, the grain size and the porosity of the 1100 °C sample were estimated to be 5.62 ± 1.23 µm and 3.8%, respectively.

Bigger grains and reduced porosity at the grain boundaries contribute in reducing the interference with domain wall movement, hence they promote hysteresis losses reduction. This phenomenon explains why the sample sintered at 1100°C has improved loss density compared with the one sintered at 1000°C. Magnetic permeability can be influenced by grain size as well, however, it has been demonstrated that porosity affects permeability more than the dimension of grains.22–25 Indeed, the results shown in Fig. 3 together with the porosity measurements confirm this point.

V. CONCLUSIONS

In this paper, a novel gelcasting process, which has lower ferrite powder load in slurry and a gelling process without catalyst, has been introduced. This has been proved to be a successful manufacturing technique for 3D integration of inductors in power modules, both in terms of shape flexibility and magnetic properties. Combining SEM imaging and electrical measurement, it has been shown that grain size affects mainly losses, while the porosity may cause a significant reduction in permeability.

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