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A LTCC low-loss inductive proximity sensor for harsh environments

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ABSTRACT

Proximity and position measurements with eddy current sensors are limited by the quality factor of the sensing coils. By enlarging the conductor path cross section, the quality factor can be increased. On ceramic multilayer substrates such cross sections, which are considerably larger in comparison to screen printed thick films, can be manufactured with an embossing and filling procedure, which is integrated into the conventional fabrication process. The conductor path layout is molded into the unfired ceramic substrate prior to filling the trenches completely with the conducting paste, thus generating a large cross section. This technique is applied for the sensing coil of an eddy current sensor. The higher quality factor leads to a doubled sensitivity in comparison to conventionally screen printed sensors. Due to the thermal and chemical durability of the ceramic substrate, the coils can be directly applied in a variety of harsh environment conditions, such as in situ engine monitoring.

1. Introduction

Eddy current proximity sensors are applied in many industrial environments because they are inherently insensitive against non-metallic dirt and opaque fluids. Thick film sensor coils based on ceramic substrates expand displacement measurements to harsh and high temperature environments. Their application as position sensors in magnetic active bearings is a proven solution [1]. Multilayer substrates such as low temperature co-fired ceramics (LTCC) are also used to manufacture position sensor coils [2,3].

The quality factor of the coils is commonly used as the sensing parameter. It is inversely proportional to the resistance of the coil. But conductor path resolution of thick film coils is limited to values between 80 μm and 200 μm as a consequence of the screen printing technology. The conductor thickness is limited to approximately 10 μm. This results in large resistances and therefore a limitation of the quality factor. If high quality factors are required, large dimensions for planar coils must be accepted due to high sheet resistivity [4,5].

A molding of the sensor coil layout into a ceramic multilayer substrate via embossing combined with a photolithographic process was used to overcome the dependency between conductor thickness and line resolution. High line resolutions are achieved using the Fodel® process [6], based on the photoimageable ink AG 6453, provided by DuPont [7]. However, the thickness of these conductors is still limited to approximately 7 μm. In [8] it was shown, that the use of embossed trenches and the subsequent filling with Fodel® ink leads to significantly enlarged conductor cross sections and thus to lower resistances and higher quality factors. In this contribution, the developed process is applied to design low-loss inductors, which can be applied as ceramic proximity sensors in harsh environments.

A commercially available tape with a chemical inertness comparable to that of borosilicate glass is the DuPont 951 GreenTape™ from DuPont de Nemours (further called DP 951) [9]. A wide range of functional pastes is available for this substrate. This simplifies embedded design solutions. The material is fully compatible to all hybrid technologies, which guaranties a reliable connection of the sensor coil with the signal processing.

Typically, the coil of an eddy current sensor is part of a resonant circuit operating at constant frequency. The impedance is used as a parameter for the proximity as shown in Fig. 1.

A conductive material entering the field generates losses due to the induced eddy currents, which further reduce the overall inductance of the sensor coil by their mutual inductance. Both parts reduce the quality factor $Q(x)$ of the coil, which is given by the relation:

$$Q(x) = \frac{\varpi L(x)}{R(x)} \tag{1}$$

The inductance $L(x)$ and the resistance $R(x)$ of the coil are a function of the target distance x. The excitation frequency of the sensor coil is designated with w. Although $L(x)$ experiences a larger change by varying target distance, the resistance is the defining parameter

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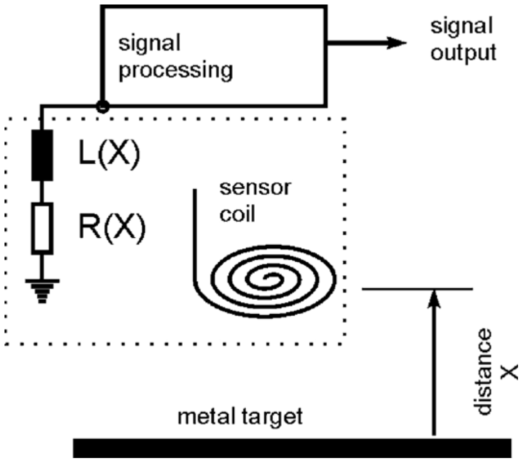

Fig. 1. Principle of proximity measurements with an eddy current sensor coil.

for the magnitude of the quality factor. A 50% resistance reduction results in doubling the quality factor.

2. Technological approach

Although the fabrication of enlarged cross sections is explained in [8], an overview of the procedure is given here with a more detailed presentation of the fabrication of embossing molds as well as the photolithographic thick film process.

LTCC form a compound of ceramic particles embedded in a glass matrix, which is realized by melting and solidifying glass particles in a sintering step. In the green, unfired state, the organic binder encloses mixed ceramic and glass particles. This soft and moldable mixture is cast into tapes, which can be processed by simple foil processing methods such as punching, and laser cutting, as well as screen printing and via filling. Embossing supplements the range of LTCC technologies, particularly in the scope of fine line processing. Fig. 2 shows the process flow for LTCC sheets including the embossing step.

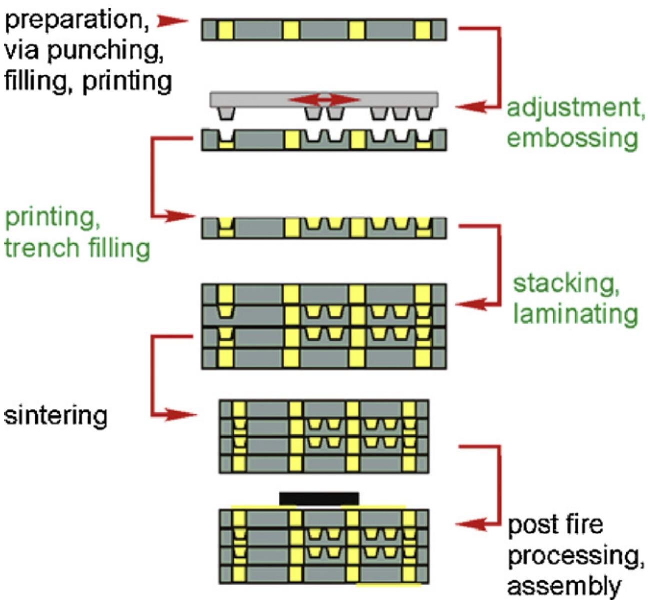

Fig. 2. LTCC-process flow including embossing steps (highlighted in green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

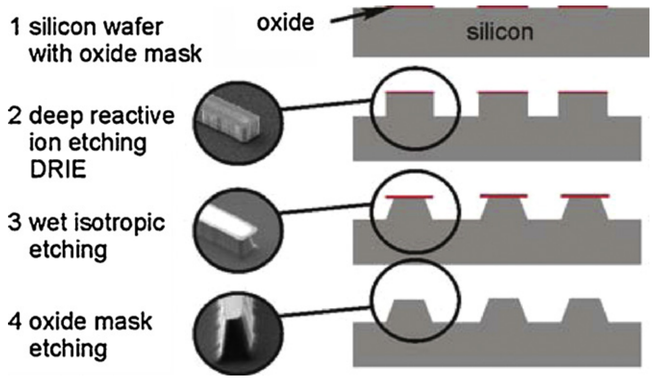

Fig. 3. Process schedule for the silicon mold manufacturing; SEM micrographs inside the highlighted circles show a 50 μm wide mold flank after each process step. (For interpretation of the references to color in text, the reader is referred to the web version of this article.)

After initial preparation the green tape is embossed with a structured mold, where the desired geometry is replicated as openings into the green tape. The embossed trenches are then filled with a thick film ink. The prepared single sheets are aligned, stacked and laminated under high pressure in an isostatic press. After sintering the three dimensional ceramic substrate is ready for postfire processing, separation and chip assembly.

Alongside to precision machined steel embossing tools, silicon has proven to be an able material for prototype manufacturing, since it offers acceptable mechanical strength and comparatively cheap and precise structuring technique. The fabrication process of the silicon tool is depicted schematically in Fig. 3.

The mold pattern is generated using a deep reactive ion etching (DRIE) process, the so called advanced silicon etching (ASE) [11]. Perpendicular side walls in silicon wafers are achieved by means of alternated plasma polymer deposition and etching cycles. A structured silicon oxide layer grown on the silicon substrate serves as the etch passivation layer. It is depicted as a red line in Fig. 3.

The silicon ridges feature side wall angles of approximately 90° (see step 2 in Fig. 3) as a consequence of the DRIE process. This geometry is inapplicable for embossing since it hampers the demolding significantly. The etched mold is treated in an isotropic etch bath with the composition $HNO_3:HF:CH_3COOH = 5:3:3$ for 20 s to generate an ejecting angle of approximately 85° (step 3 in Fig. 3). The very fast exothermic reaction causes a temperature gradient along the ridge, and therefore the etch rate is higher at the top of the structure. This technique was developed for in-house rapid prototyping of silicon molds. Since the exothermic reaction is very fast, the control of the side wall etching is a delicate process step. Finally, the oxide mask is removed with a buffered oxide etchant (step 4 in Fig. 3).

Embossing of fine lines in DP 951 is investigated in [10]. It is shown, that fine patterns with dimensions of 50 μm lines and spaces can be embossed accurately and that spatial tolerances are defined by the embossing mold. Further, optimum process parameters as there are a temperature of 60 °C; an embossing pressure of 100 MPa and a dwell time of 5 min are found. These results were taken as a basis for the current investigation.

The conventional Fodel® technique is equivalent to the photolithographic patterning on thin film substrates, i.e. for silicon. First, the Fodel® ink is applied on the whole substrate via screen or stencil printing. The ink is then exposed to UV-light through a structured mask, which transfers the desired pattern into the thick film by curing the exposed binder polymer. During development the excess material is dissolved and rinsed. The conventional Fodel® technique, which uses the photoimageable ink AG 6453 from DuPont, facilitates lines and spaces with highest resolution for