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Improved Microtransformer Design Utilizing Fe-Co Magnetic Core

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Abstract

This paper presents the design, fabrication, and characterization of on silicon integrated micro-transformers for high frequency power applications. This device has stable characteristic of L versus f up to frequencies higher as 50 MHz. The design is improved, so that the electrical resistance of coils is reduced and current capability is increased. The microtransformer shows an inductivity of about 50 nH, resistance of 350 mΩ and can be applied for current up to 1.5 A.

Keywords: Microinductor, Microtransformer, Thin-film Fabrication, MEMS, Magnetic,

1 Introduction

Increasing trend in electronics for higher power density and mobility causes the miniaturization of power supply and therefore the miniaturization of passive components like inductors or transformers. A permanent increase of a switching frequency of an electronic power circuit sets new requirements for inductive components regarding to size, inductance, and current capability. Recently, on the market are already available first commercial DC-DC converters with switching frequency of 20 MHz.

Based on increasing trends in power electronic to miniaturization and integration on one side and increasing of switching frequency on other side, inductors and transformers should provide smaller inductivity and smaller size. Decreasing of inductivity causes a decreasing of the inductor size and of the inductor profile height, therefore in thin-film fabricated micro microinductors and microtransformers are ideal components for fulfill this issue. Both, microinductors and microtransformers are in many research works fabricated and tested at higher switching frequencies up to 50 MHz [Feeney et al. (2015), Xing et al. (2013), Feeney et al. (2014), Wang et al. (2015)]. Based on these first results, the implementation of micro devices in power electronic applications should be possible.

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2 Design

First fabricated microtransformer device is presented before [Dinulovic et al. (2014)]. The design of new microtransformer device is improved. The aim was to reduce an electrical resistance and to increase a maximal current of device and efficiency. The microtransformer consists of a closed Co-Fe magnetic core and four coils. Two coils are on the primary and two coils are on the secondary transformer side.

The microtransformer device is fabricated using thin-film technology. As a magnetic material for the transformer core, Co-Fe alloy is chosen based on excellent magnetic properties. Co-Fe magnetic core has been deposited by Co-Fe electroplating. Coils are fabricated using Cu electroplating. Coils and magnetic core are embedded in polyimide.

The revised microtransformer was designed by using the CAD-Tool SolidWorks^{TM}. The new layout was simulated and optimized using Finite Element Method (FEM). The software tool Ansys Maxwell® was applied. To find an optimum between design and technology issues, the technological aspects of the thin-film fabrication also have to be taken into account during the simulations. The optimal design for the magnetic core as an oval core was shown in a previous presentation. The size of four coils was restricted by complete size (length of 2.5 mm) of a microtransformer device. As a complete size of a microtransformer an EIA standard size 1008 was chosen. Therefore, whole microtransformer device features a footprint of 2.5 mm x 2 mm.

The aim of simulation was to develop a design with as small as possible electrical resistance and at the same time the design should have maximal electrical inductance. As an optimal design, a system with electrical inductance of about 60 nH and resistance of about 300 m**Ω** was chosen. Based on fabrication parameters (i.e aspect ratio and flank angle, defined by the photolithography processes employed) and available device size, the new optimal coil design for four coils was defined. The coil consists of 5 turns. The cross-section of a coil turn is 60 µm (width) x 20 µm (height).

As a magnetic material for the transformer core, the alloy Co-Fe was chosen since previous investigations proved the material's suitability for magnetic MEMS applications. Fe-Co features saturation flux density B_s up to 2.3 T. The thickness of a magnetic core should be very thin to avoid core losses. The device was developed for DC-DC convertor application for switching frequency about 20 MHz. Beside of the reducing the electrical resistance, further aim was to achieve as high as possible inductance. Therefore, the made magnetic core have a thickness of 10 µm. In the future works we would work on applying the laminated core with couple of thinner magnetic layers.

3 Fabrication

The micro transformer is fabricated under cleanroom conditions using high aspect ratio microstructure technology (HARMST), combining UV depth lithography and electroplating [Ruffert et al (2011), Ruffert et al. (2008)]. A 4'' silicon oxide wafer with thickness of 500 µm is used as substrate material. At first a seed layer consisting of 50 nm chromium and 200 nm gold is applied on the substrate by sputter deposition. The coil's first level consists of electroplated copper and is integrated in a coating form made of AZ9260™. The loops are not arranged in-plane but perpendicular to the plane shown in Figure **1**.

The layer of the lower coil is 20 µm thick. After the electro-plating process of the Vias, the seed layer is removed by ion beam etching.

Polyimide photoresist is spun on the substrate as embedding and insulating layer. The dissolver is removed during a two-step soft bake with the first step is for 15 minutes at 70°C and subsequent 15 minutes at 100°C. After a cool down step to room temperature and a recovery, the polyimide is structured by a photolithographic process. During the following hard bake at 350°C for 1 hour, the resin in the resist film crosslinks. Meanwhile the polyimide's height reduces from 52 µm to 26 µm causing distortions above the copper structures. These are removed by Chemical Mechanical Polishing (CMP), which is essential to create an even surface that is again necessary for the upcoming process steps. An additional Advantage is the uncovering of the Vias. Concerning of the very low theoretical resistance of 0.05 Ω it is important to verify the conductivity of the Vias because of oxides or residues of the polyimide.

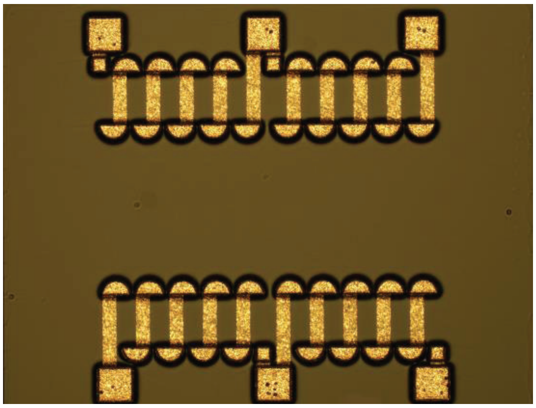

Figure 1. First layer of the copper coils and single step Vias.

Afterwards a seed layer stack consisting of 50 nm chrome and 200 nm NiFe is applied. Following a photolithographic mask is applied defining the ring core's structure. The 10 µm ring core consisting of Fe-Co is electroplated. After removing of the resist, the NiFe seed layer is removed as well by ion beam etching. The Fe-Co core is shown in Figure 2. Following a 50 nm chromium and 200 nm gold seed layer is deposited in order to apply the Vias by cooper electroplating. As the structure has been filled with copper and the seed layer has been removed, the Vias and the ring core are embedded in a second polyimide layer. Upon the exposed Vias the upper layer of coils is structured. The coils are closed by electroplated copper shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**

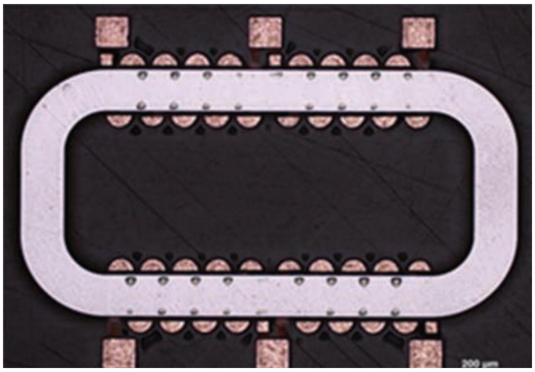

Figure 2. Electroplated Fe-Co core.

Figure 3. Deposited top layer of the copper

Simultaneously the contact pads are raised. In a third embedding step the completed micro transformer (shown in Figure 4 is insulated against external environmental influences. Finally, the completed wafer was separated into chips by dicing.

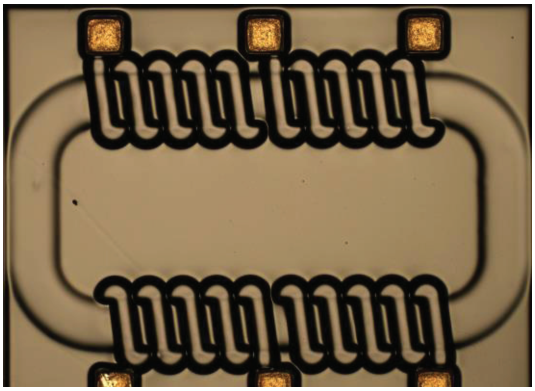

Figure 4. Complete insulated micro transformer.

4 Results

Diced microdevice chips were prepared for testing. Chips were mounted into open cavity QFN package and bonded. The bonding procedure is performed manually with an Ultra-Sonic-Bond process. The QFN housing 4 mm x 4 mm with 12 leads was used. For our tests only 6 leads were connected. Measurements were performed by applying Agilent Impedance Analyzer E4991A. The devices were measured with a signal oscillating level of 5 mA at 1 MHz. Figure 5 shows a characteristic of inductance versus frequency.

For this measurement all four coils were connected in series. The whole system shows an inductance of about 60 nH with very good performance up to frequencies higher than 100 MHz.

The measured electrical resistance of whole system (four coils in series) *Rdc* is about 350 mΩ. In the Figure 6 the characteristic of electrical resistance versus frequency is shown. At frequency of 100 MHz a microtransformer shows an electrical resistance of only 3 Ω.

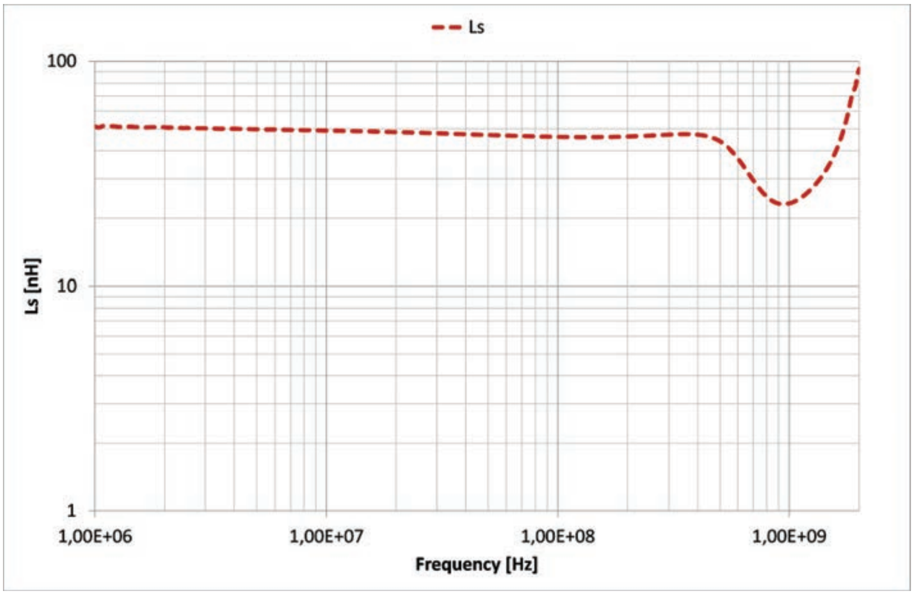

Figure 5. Characteristic *L* vs. *f* for four coils

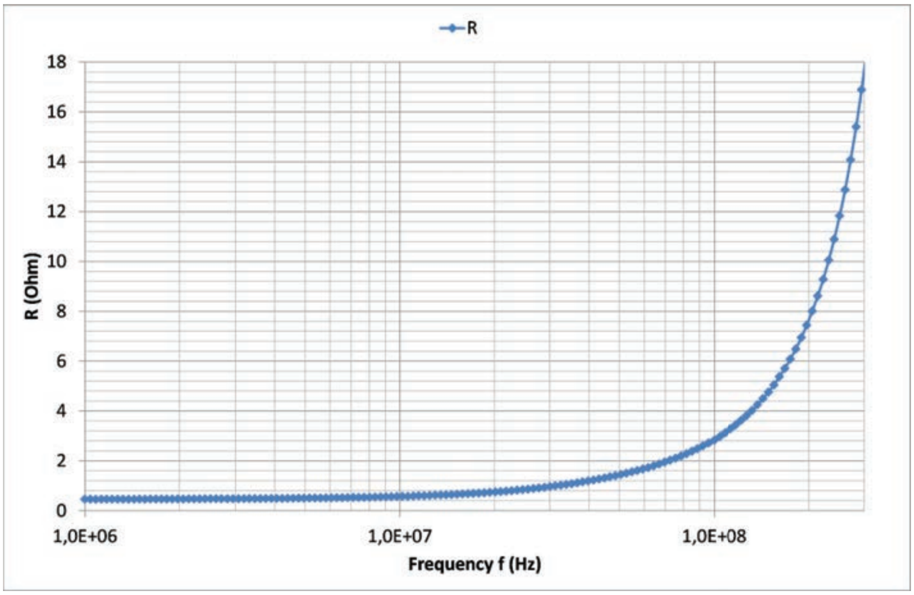

Figure 6. Characteristic *R* vs. *f* for four coils

Measurement of Q-factor is presented in the Figure 7. The Q-factor is increasing with increase of the frequency. The maximal value of 11 is achieved at frequency of 70 MHz.

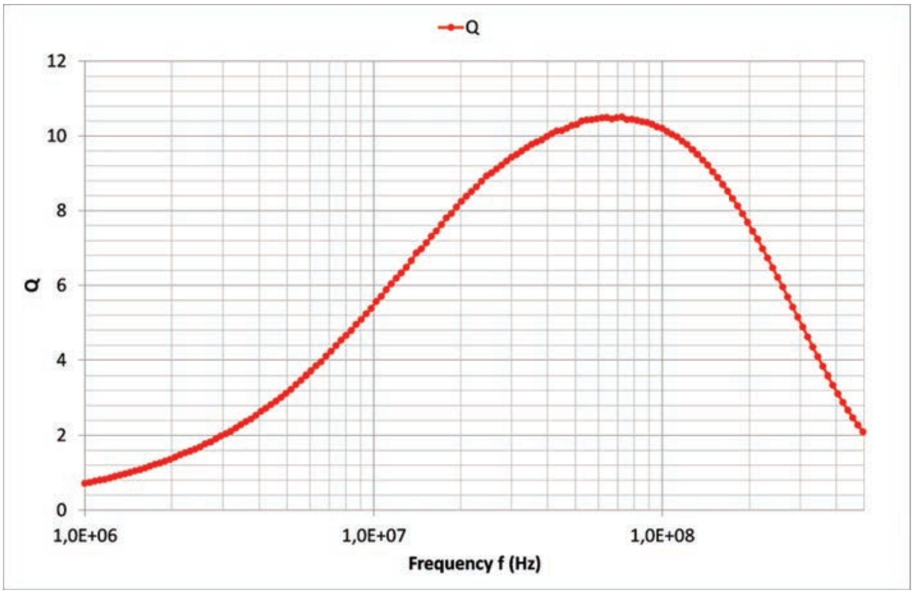

Figure 7. Q-factor of microtransformer

By further increase of the frequency, the Q-factor is decreasing. At frequencies over 100 MHz the decreasing is of Q-factor is fast.

DC-Bias characteristic of the transformer is shown in the Figure 8. DC-Bias measurement was performed using Wayne Kerr 3260B. DC-Bias measurements were carried out under same test condition (oscillating level 5 mA at 1 MHz). The maximal DC-Bias of 1500 mA was applied. For this measurement only 2 coils (i.e. primary side) were tested. The DC-Bias characteristic of two coils of microtransformer is very good and after 1500 mA the device don't achieve a saturation (30% decrease of inductance compared to initial inductance (ΔL/L= 30%)).

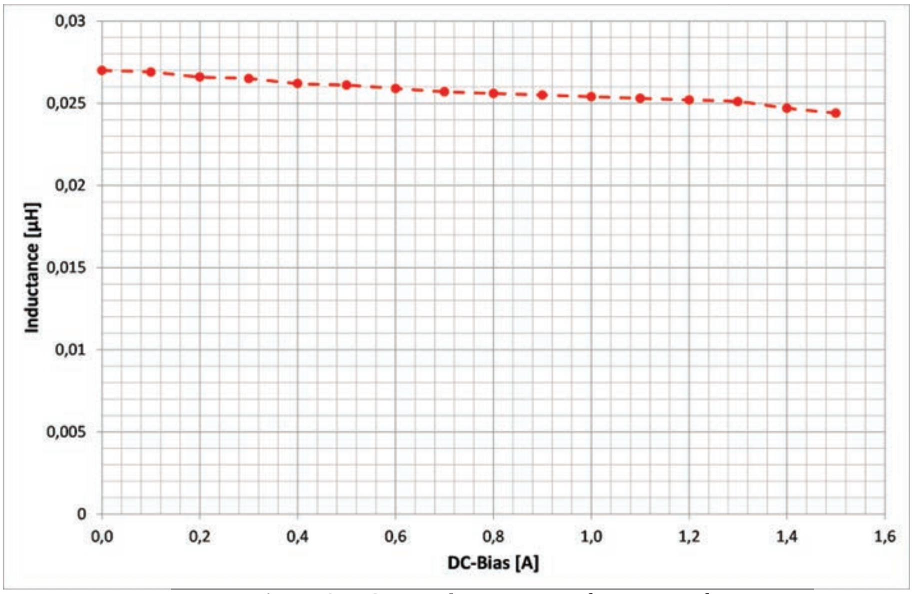

Figure 8. DC-Bias characteristic of microtransformer.

5 Conclusion

New design of microtransformer with the aim to improve the performance of the device was done. The design was changed in order to reduce an electrical resistance and to keep an inductivity as high as possible. The cross-section of coils was increased and the number of turns was reduced. On same time, the thickness of magnetic core was increased to 10 µm. Microtransformer device was fabricated using thin-film technology. The magnetic core is fabricated by using CoFe material by electroplating. New improved device shows very stable inductance characteristic up to frequencies higher than 100 MHz and device is suitable for applications at very high switching frequencies. The maximal inductance of device is about 50 nH (all four coils connected in series). The electrical resistance is decreased in the comparison to the first one device for a factor of 10. Whole device, all four coils in series show the resistance of only 350 mΩ The DC-Bias characteristic of mictrotransformer is improved and the saturation current is higher than 1500 mA. Very good electrical property of the microtransformer device allows a usage of this device for power application at very high switching frequencies. In the further work, the microtransformer device will be tested in DC-DC converter application at frequency of 20 MHz.

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