A Comparison of Various magnetic thin films for the application of microscale magnetic components

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Abstract. A novel method to manufacture and assemble a microinductor that is based on flip-chip bonding is described in this paper. The fabricated inductors have an inductance ranging from 0.3μH to 180μH. An optimum Q-factor of 14 was attained at 1MHz. Cobalt-Copper-iron cores maintained a constant inductance across a 1 kHz-1MHz bandwidth. The thin film laminate minimizes the eddy current loss and the hysteresis loss was negligible. Impedance increases linearly with frequency indicating that parasitic capacitance effects in this frequency range are negligible. The microinductor operated at an efficiency of 92% at 1MHz achieving a power density of 3.75 W/mm³.

1. Introduction
Magnetic components continue to be an essential element in power conversion and management circuits. The need for faster switching, reduced losses and smaller components have driven switching frequencies into the range of 0.5MHz-10MHz [1,2]. The limitation in going to higher switching frequencies lies in the loss of current magnetic components with frequency. Ferrites appeared to have reached their limits in terms of operating frequency for reasonable loss levels. With increasing frequency, the magnetic component becomes smaller, ac resistance losses increase and current handling capability is becoming more stringent. Hence, typical ferrite cores, whose useable flux density falls drastically at these higher frequencies, have to be replaced and a method of producing small windings developed. New core materials must have high resistivity, high saturation flux, permeability of 100-3000, low coercivity and be suitable for thin film deposition.

2. Inductor Design
The fabricated structure is displayed in Figure 1. The final component with 90 μm thick windings has dimensions 5mm x 2mm x 0.25mm.

The circuit equivalent of the inductor is a series resistance \( R_T \) and inductance \( L_T \) both in parallel with a capacitance \( C \). The first two parameters take into account the skin and proximity effects in the windings and eddy currents within the magnetic core. The parallel capacitance models the parasitic capacitance that emanates between turns, turns to insulation layer, and turns to core.
Figure 1 Fabricated micro-inductor of size 2mmx5mmx250μm (WxLxT). The nickel windings are clearly visible diagonally. The Ni(80)Fe(20) core of O-shape is assembled between the windings by flip-chip bonding.

The series inductance consists of the main inductance, L, and the leakage inductance of the windings. The latter can usually be neglected [5]. The expressions of the inductance L and the reluctance R of the inductor of Figure 1 are:

\[ L = \frac{\mu_0 \mu_r A_c N^2}{l_c}, \quad R = \frac{1}{\mu_0 \mu_r A_c} \]  

where \( A_c \) is the cross-sectional area of the magnetic core, \( l_c \) is the length of the closed magnetic path, \( N \) is the number of coil turns, \( \mu_0 \) and \( \mu_r \) are the permeability of free space and the relative permeability of the magnetic core, respectively. To avoid magnetically saturating the device, the maximum current that can be applied, \( I_{sat} \), is:

\[ I_{sat} = \frac{B_{sat} R A_c}{N} \]  

\[ d = \sqrt{\frac{1}{\mu_0 \mu_r f \pi \sigma}} \]  

\( B_{sat} \) is the flux density at which the magnetic core saturates. With the value of saturation current known, and for a fixed value of the current density (10A/mm² typically for PCB), the winding area can be determined to handle the saturation current. In order to minimize eddy current losses in the core and windings at high frequency, the skin depth, \( d \), has to be known. The equation for skin depth is (4). The increase in AC resistance, \( R_{ac} \), within the windings can be determined by:

\[ \frac{R_{ac}}{R_{dc}} = 1 + \frac{\Psi}{3} \Delta^4; \Psi = \frac{5 p^2 - 1}{15}; R_{dc} = \frac{\rho l}{A W} \]  

where \( p \) is the number of winding layers, and \( \Psi \) is the ratio of winding thickness to skin depth [6]. The resistance and inductance contribution from the core due to eddy currents can be determined by:

\[ L_{ac} = L_c \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \]  

\[ R_{ac} = a \times \frac{1}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \times \frac{2b}{2b} \]  

3. Fabrication of Thin Film Core

All core samples were fabricated on separate wafers to permit electrical and magnetic characterization prior to inclusion within the component. The electrodeposited core samples were fabricated by DC electrodeposition. The composition of the electrolyte is given in [12]. The Vitrovac and Metaglas foils were patterned with the photoresist AZ 9260 and wet etched to the desired dimensions. The etchant consists of HNO₃:HCl:H₂O, 2:2:1:3.

3.1. Fabrication of the Microinductor
A summarized fabrication process is given below:

**Step 1** Glass wafer prepared.

**Step 2** Ti/Ni seed layer deposition with electron beam evaporator. **Step 3** AZ 9260 deposited to obtain required conductor/core thickness. The resist is baked **Step 4** AZ 9260 patterned, forming the upper and lower winding layers, with UV light using an acetate mask. **Step 5** The windings are DC electroplated either Cu or Ni. **Step 6** AZ is re-deposited & patterned, and gold bumps are electroplated. The seed layer is etched and AZ insulation is deposited and patterned, Fig 2 displays the 3D plot and component image. **Step 7** Magnetic core is electroplated and etched free. The upper and lower windings are diced. **Step 8** The core is placed on the lower windings and the upper layer is flipped chip bonded. **Step 9** Ti etchant is used to release the glass substrate off the upper layer by etching the remainder of the upper seed layer.

3.2. Preliminary Testing of the Microinductor

A Hewlett Packard 4192A LF impedance analyzer was used to record the inductance, resistance, Q-factor, impedance and phase over a frequency range of 1 kHz-13 MHz. Components consisting of isotropic permalloy, CoFeCu, commercial films Vitrovac and Metaglas were fabricated and tested. The windings have a lower resistance, $R_{dc}$, at low frequency. However, when the operating frequency increases, the skin effect results in a greater resultant resistance. The inductance of the air core component was recorded. The leakage inductance is constant for each component as the only variable is core material. Leakage inductance is constant until the thickness of the winding equals that of the winding skin depth. The leakage inductance is negligible compared to the main inductance in fig 2 and 3.

As the frequency increases, the overall inductance value decreases due to the skin effect in the thin film core. The self resonating frequency of the inductor induced by the parasitic capacitance was not observed in the frequency range analyzed.

![Inductance vs. Frequency of the electrodeposited $Co_{83}Fe_{17}Cu_{10}$ and $Ni_{80}Fe_{20}$ alloy](image_url)

Figure 2 Inductance vs. Frequency of the electrodeposited $Co_{83}Fe_{17}Cu_{10}$ and $Ni_{80}Fe_{20}$ alloy
Figure 3 Inductance vs. Frequency of the commercial alloys

Even though the commercial alloys have a resistivity 6.5 times greater than the electrodeposited alloys, the thickness of the films and their high relative permeability makes them susceptible to skin depth effects. As a result the tail off in inductance and increase in eddy current resistance occur at a lower frequency. The inclusion of an air gap in the magnetic flux path, large enough to overcome fringing effects, reduces the effective relative permeability of the core and increases the bandwidth of the controllable inductance.

Using Equation 5 the theoretical DC saturation current of the thin film can be determined. This permits a theoretical assessment of the components performance. For example, the inductance of the 10μm thick NiFe core at 1MHz is 0.9μH with an \( I_{\text{sat}} \) of 106mA. The maximum voltage across the device is therefore

\[
V = \frac{LI}{T} = 95.5mV
\]

and the output power is

\[
\text{Power} = \frac{V^2}{2}\]

To calculate the core loss the peak flux density within the core is calculated [13]:

\[
B_{pk} = \frac{V}{KNA_f} = 0.14T
\]

\( K \) is a constant dependent on the waveform and in this instance a square wave is considered hence taking the value 4.

The core eddy current loss is added to the power dissipated by the windings according to the formula [13]:

\[
P_{\text{eddy}} = n \frac{(2\pi B_{pk})^2 2XYh^3}{24\rho_s} = 2.03\mu W
\]

where \( n \) is the number of laminate, in this case \( n = 1 \), X, Y and h are the dimensions of the core, and \( \rho_s \) is the core resistivity. In the same way the hysteresis losses can be calculated according to the formula [13]:
\[ P_{\text{sys}} = \frac{3}{2} XYh(4B_{r}H_{c}) = 4.96 \times 10^{-16} W \]  

(12)

The Joule losses in the windings are:

\[ (13) \]

The overall efficiency, \( \eta \), of the micro-inductor is therefore:

\[ \eta = \frac{P_{\text{out}}}{(P_{\text{out}} + P_{\text{core}} + P_{\text{Cu}})} = 92.27\% \]  

(14)

The power density is approximately 3.75 Watts/mm\(^3\).

4. Conclusion

Micromachined inductors with different magnetic cores and have been fabricated on glass using micromachined techniques borrowed from the LIGA process. The results shown in the Figs 2&3 demonstrate that equation (1) is only valid for uniform flux density. As a rule of thumb for laminated core, a laminate sheet should not have a thickness greater than the skin depth for a given frequency.

The performance of the commercial alloys is hindered by the thickness and the high relative permeability of the films. Electrodeposited alloys are better suited to the application due to the ability to vary film thickness, the relative permeability via magnetic field annealing and the resistivity through the addition of bath additives.

The micro-inductor presented in this article has proved that an efficient component can be manufactured via an inexpensive UV LIGA and DC electroplating process.

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