High frequency characteristics and magnetic properties of $FeCoB/SiO_2$ nanogranular films

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Soft magnetic films with high resistivity at high frequencies are required in areas like magnetic microinductors for communication devices and automotive industry. The hetero-amorphous structure composed of metal ferromagnetic – insulator films exhibits much higher resistivity in contrast to the conventional nanocrystalline structures because it holds magnetic softness without exchange interaction between the metal particles. Their high saturation magnetization and high resistivity are beneficial to obtain high power density and low loss in thin film inductors that can be used for R.F - Integrated Circuits. This paper reports some results concerning the high frequency behaviour of the electrical and magnetic properties for $[FeCoB/(SiO_2)]\cdot n$ thin films. The annealed $[FeCoB/(SiO_2)]\cdot 60$ thin films with the resistivity $\rho \cong 48.2$ mΩ·m, saturation magnetization $M_s \cong 149$ emu/g and coercive field $H_c \cong 7$ Oe were used for the frequency testings. This system exhibits a good electrical and magnetic response in the high frequency range.

(Received September 8, 2006; accepted September 13, 2006)

Keywords: High frequency, Electrical and magnetic properties, Thin films, Multilayers, Inductor

1. Introduction

With the rapid improvement and miniaturisation in electromagnetic devices, the soft magnetic thin films as core materials in these devices are required to have high initial permeability, low coercive force, high saturation magnetisation, high electrical resistivity, and low electrical and magnetic losses in the high frequency range [1,2]. Many current forthcoming applications of magnetic materials involve heterostructures or alloys containing magnetic and non-magnetic elements. The granular metal ferromagnetic – insulator films are composite materials consisting of magnetic nanograins embedded in an insulating matrix. The hetero-amorphous structure exhibits much higher resistivity in contrast to the conventional nanocrystalline structures because it holds magnetic softness without exchange interaction between the metal particles [1]. The high electrical resistivity of the multilayer ferromagnetic material/dielectric thin films can minimize the eddy current loss in the high frequency applications.

In these heterogeneous structures, the most important changes in the magnetic permeability were observed in the multilayers in comparison with the single layer magnetic film. Their high saturation magnetisation and high resistivity mainly determine the achievement of high power density and low losses in thin film inductors that can be used for R.F - Integrated Circuits [3].

This paper reports some results concerning the high frequency behaviour of electrical and magnetic properties for $[FeCoB/(SiO_2)]\cdot n$ thin films. The magnetic inductor with annealed $[FeCoB/(SiO_2)]\cdot 60$ thin film as core exhibits a good electrical and magnetic response in the frequency region (up to about 60 MHz).

2. Experimental details

The $[FeCoB/(SiO_2)]\cdot n$ films were prepared using a conventional R.F. diode sputtering system, by sequential deposition from two elemental targets, disc of FeCo alloy with chips of B on their surface and disc of SiO_2, mounted on two separate guns.

For evaluation of the frequency behavior of the electrical and magnetic properties for the $[FeCoB/SiO_2]\cdot n$ thin films, a planar magnetic inductor consisting of single turn conductor coil wrapped around a rectangular magnetic $[FeCoB/(SiO_2)]\cdot n$ thin film was employed. The planar coil of the magnetic inductor was realized on a silicon wafer (with native oxide on their surface) by using the multilevel metalization and photolithography techniques. The inductor was formed on the substrate by depositing/patterning the lower conductor (copper - Cu) layer, covering it again with SiO_2 layer, depositing the magnetic core having rectangular geometry, covering it with another layer of SiO_2, arranging for metal via contacts and finally depositing /platting the upper conductor layer (Cu). The use of Cu films, as conductor is appropriate for this magnetic inductor since high conductivity is important to achieve a high quality factor Q at high frequencies.

The magnetic characteristics (Ms and H_c) of the $[FeCoB/(SiO_2)]\cdot n$ thin films were measured using a vibrating sample magnetometer (VSM) in a maximum magnetic field of 1.8 kOe.

The frequency dependence of the electrical and magnetic properties for $[FeCoB/(SiO_2)]\cdot n$ films, in the range of 40 Hz–110 MHz, was determined with a Agilent 4294 A precision impedance analyzer. The electrical resistivity of the samples was measured using the DC four – point probe technique.

The as-deposited $[FeCoB/SiO_2]\cdot n$ thin films were annealed at temperature of 300^oC for 2 h, in vacuum of 2 x 10^{-3} Pa.

3. Results and Discussion

3.1. Testing of the magnetic material

A granular film [4] is advantageous in terms of the electrical resistivity ρ and the high anisotropy field H_k. The electrical resistance and the magnetic properties of the $[FeCoB/SiO_2]\cdot n$ thin films strongly depend on the composition and microstructure. These characteristics of the $[FeCoB/SiO_2]\cdot n$ multilayer thin films are very sensitive to the FeCoB and SiO_2 layers thickness and the microstructural changes caused by annealing. In figure 1 the dependence of the magnetic characteristics (saturation magnetization M_s and coercive field H_c) on the $FeCoB/SiO_2$ number layers (n) for as-deposited $[FeCoB/SiO_2]\cdot n$ multilayer thin films is shown.

As it can be seen the saturation magnetization, M_s, decreases with increasing the $FeCoB/SiO_2$ bilayers while the values of the corcive field H_c increase with increasing the FeCoB/ SiO_2 number layers up to 3 and decrease afterwards.

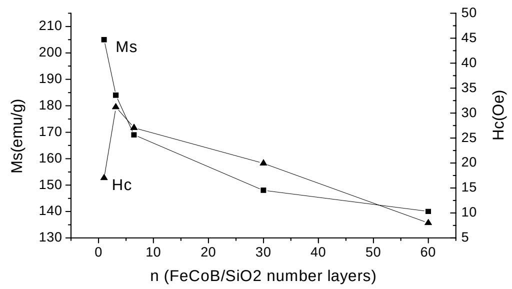

Fig.1. Dependence of the magnetization and coercive field on the $FeCoB/SiO_2$ number layers (n).

For frequency measurements the $[FeCoB/(SiO_2)]\cdot n$ magnetic thin films were employed as samples test. The $[FeCoB/(SiO_2)]\cdot 60$ thin films with the thickness of the FeCoB layers of 6 nm, exhibit good soft magnetic characteristics and high values for electrical resistivity after annealing at 300^oC such as M_s of 149 emu/g, H_c of 7 Oe and ρ of 48.2 mΩ·m, respectively [5].

3.2. Simulation

In order to accurately design and predict the behavior of the specific components of the microcoil, the some operations of numerical simulation using the MAPLE programme were achieved.

In figures 2 and 3 some simulation results are displayed, as follows: the skin depth δ in the Cu conductor line of the coil versus frequency (Fig. 2); the inductance L versus the number of the helices of the coil and the width of the conductor lines (Fig. 3).

A major difficulty in designing high frequency inductors is to account for influence of eddy current effects in the helices of the coil. The importance of the eddy current effect is determined by the ratio of skin depth δ to the conductor line thickness. The eddy curent effect in coil material is negligible only if the skin depth δ is much greater than conductor line thickness [6]. The skin depth δ is defined as: $\delta = \sqrt{\dfrac{\rho}{\pi\mu \cdot f}}$ where μ is the magnetic permeability of the conductor line (μ_{Cu}= $24.74\cdot10^{-12}$ H/m), f is frequency, and ρ is resistivity (ρ_{Cu} = $1.7 \cdot10^{-8}$ Ω·m). Figure 2 shows the relationship between the frequency (10 MHz and 100 MHz) and the skin depth δ in the Cu conductor lines of the planar coil. According to figure 2 the skin depth δ decreases with increasing the frequency, so that, for values above 100 MHz, the skin depth δ value decreases below 1 mm.

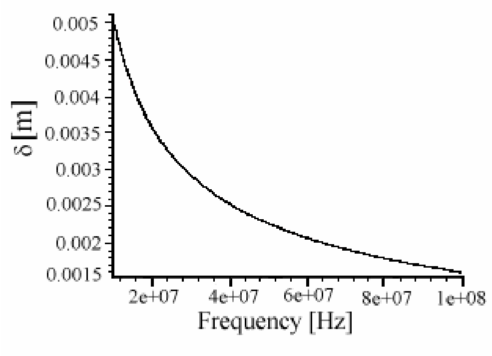

Fig. 2. Simulation of the skin depth δ in the conductor line of the coil versus frequency.

In Fig. 3 it can be observed that the inductance values L increase when the number of helices of the coil increases or the width of the conductor line decreases. So, for a simple microcoil having 5 helices with a width of the conductor line of 20 μm, a simulated inductance value L of about 70 nH is obtained.

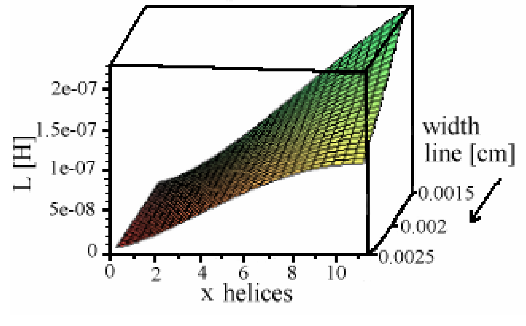

Fig. 3. Simulation of the inductance L versus helices number and width of the conductor line of the coil.

3.3. Testing of the magnetic inductor

In Fig. 4, the planar microinductor with [FeCoB/(SiO_2)]·60 thin film as magnetic core is shown. The dimensions of the planar magnetic inductor are as follows: the total inductor size is 270 μm x 230 μm; the coil has a single turn which consists of 5 helices; the cross sectional area of the magnetic core is 0.42 μm (thickness) x 180 μm and the conductor lines of the coil is 1 μm (thickness) x 20 μm.

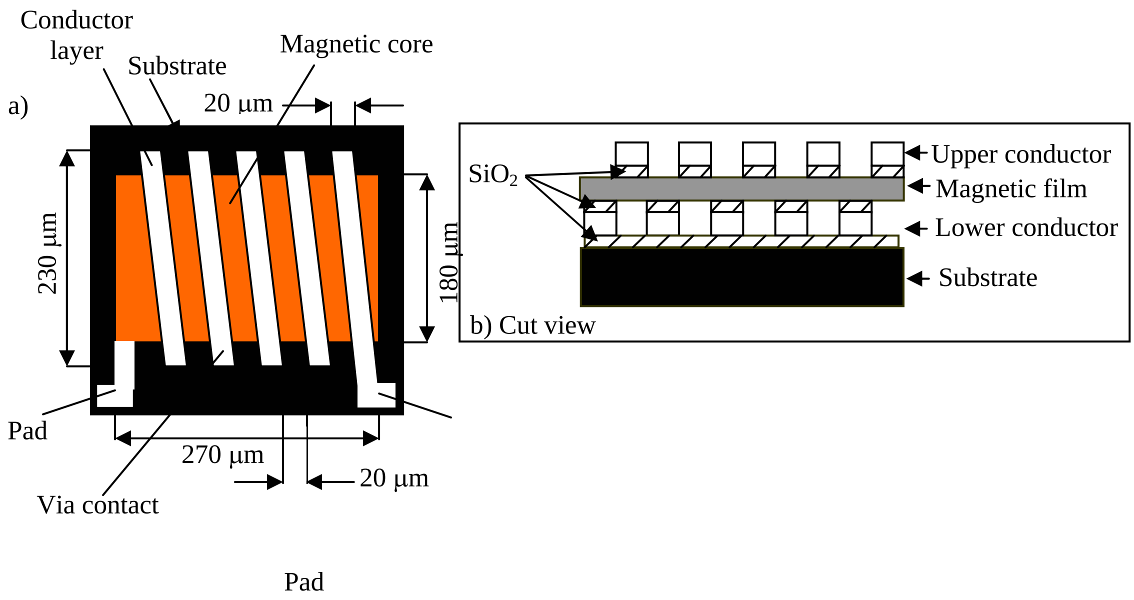

Fig. 4. Planar inductor with thin-film magnetic core: (a) schematic view; (b) cut view.

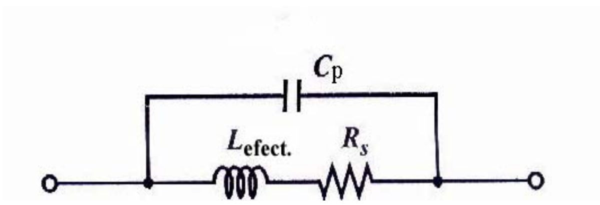

Fig. 5. Equivalent circuit of the inductor for electrical parameter evaluation.

The frequency dependence of electrical and magnetic characteristics of the microinductor with [FeCoB/(SiO_2)]·60 thin film as magnetic core was determined using a Agilent 4294 A impedance analyzer. In order to obtain the circuit parameters of the inductor, an equivalent circuit was assumed as shown in figure 5, where R_s is the electrical resistance including the skin effect, L_{eff} is effective inductance including intrinsic inductance and C_p is parasitic capacitance.

The measured DC resistance of the conductor lines for the coil of the magnetic inductor shown in figure 4 was about of 2.5 Ω.

The frequency dependence of the measured inductance L and electrical resistance R for a planar coil with [FeCoB/(SiO_2)]·60 thin film as magnetic core is shown in figure 6.

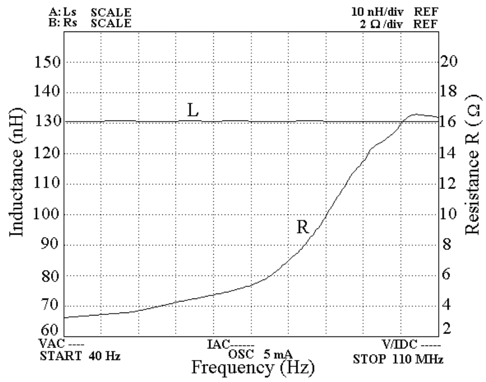

Fig. 6. The frequency dependence of the measured inductance L and the electrical resistance R of the planar coil with [FeCoB/(SiO_2)]·60 thin films as magnetic core.

For a magnetic inductor with a coil having 5 helices, the achieved inductance L was of about 130 nH, corresponding to a magnetic permeability of 7000 (at 1 MHz) for [FeCoB/(SiO_2)]·60 film used as core. As figure 6 shows the inductance L remains constant for frequency domain 40 Hz - 110 MHz. This fact reveals that the hysteresis loss are small in the ([FeCoB/(SiO_2)]·60 film, for the whole frequency domain.

Moreover, as figure 6 shows, there is a gradual increase of the electrical resistance of the coil with increasing the frequency up to 60 MHz, followed by an abruptly increase up to 100 MHz. The series resistance R of the microcoil includes the DC and frequency dependent component. The series resistance, R, can be expressed as:

$$R = \frac{\rho \cdot l}{w \cdot \delta \left(1 - e^{-\frac{t}{\delta}}\right)}$$

, where l is length of the conductor lines, w is width of the conductor lines, and t is thickness [6]. As can be observed from the figure 2 and the previously equation for R, when the skin depth δ decreases with frequency, the electrical resistance values R increase. In this case, on the frequency domain 60 MHz – 100 MHz, the losses by the eddy currents in the Cu conductor lines of the microcoil, govern the behaviour of the electrical resistance.

For frequencies more than 100 MHz, the electrical resistance values remain nearly constant up to 110 MHz, where is possible to exists a large ferromagnetic resonance peak.

The quality factor, Q, of the inductor is defined as the ratio of the reactive impedance to the equivalent series resistance and at low frequencies, Q is well described by $\omega L_s/R_s$. The dependence of the measured quality factor Q and the impedance Z on the frequency, for a planar coil with $[FeCoB/(SiO_2)]\cdot 60$ thin films as magnetic core is shown in figure 7. It can be seen that there is a continuous increase of the Q factor with the frequency up to about 60 MHz, followed by a little slower decrease up to about 100 MHz and then it remains approximately constant up to 110 MHz. The improvement of the Q factor in the low frequencies domain is due to the low conductor loss. It can also be observed from Fig. 7 that the impedance value slightly increases up to about 60 MHz, followed by an abruptly increase with the increase of the frequency up to 100 MHz, remaining approximately constant afterwards.

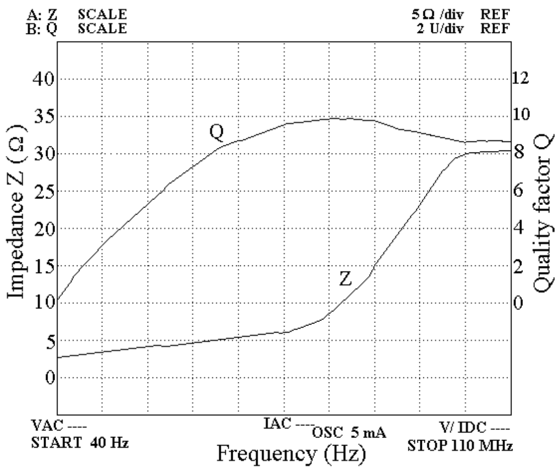

Fig.7. The frequency dependence of the measured impedance Z and the quality factor Q of the planar coil with $[FeCoB/(SiO_2)]\cdot 60$ thin film as magnetic core.

From the analysis of the presented data it can be concluded that the inductance values of the magnetic inductor with $[FeCoB/(SiO_2)]\cdot 60$ thin film as core remain near constant for the whole frequencies domain (40 Hz – 110 MHz). Thus, the $[FeCoB/(SiO_2)]\cdot 60$ thin films are a good candidate for magnetic core applications in the MHz range.

Further studies are needed in order to elucidate nature of the losses for frequencies more than 60 MHz. Thus, improvements will be made for the conductor lines of the microcoil as design and material performance (resistivity near to of the bulk material, structural stability), using the magnetic inductor with $[FeCoB/(SiO_2)]\cdot 60$ thin film as magnetic core for applications at frequencies more than 110 MHz.

4. Conclusions

The $[FeCoB/(SiO_2)]\cdot 60$ thin films after annealing at 300°C show good resistive and magnetic properties of the electrical resistivity $\rho \cong 48.2$ mΩ·m, saturation magnetization $Ms \cong 149$ emu/g and coercive field $Hc \cong 7$ Oe. Since $[FeCoB/(SiO_2)]\cdot 60$ thin films have favourable magnetic characteristics as well as electrical properties, it is potentially useful as magnetic core for inductive component in applications for magnetic microactuators, and micromagnetic devices as a DC/DC converter.

The magnetic inductor with the annealed $[FeCoB/(SiO_2)]\cdot 60$ thin film as core exhibits a good electrical and magnetic behaviour in the high frequency range (up to about 60 MHz).

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