

High-frequency Magnetic Properties of $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ Multilayer Film Served as Magnetic Core of Solenoid Inductor

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Abstract. In this study, we report the significant enhancement of high-frequency performance of solenoid inductors incorporated $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ magnetic multilayer film prepared by magnetron sputtering as magnetic core over their air-core counterparts. The integrated solenoid inductor with multilayered magnetic core revealed excellent high-frequency performance in a wide operation frequency range of 0-4 GHz, and acquired a peak inductance density of 72 nH/mm². Compared to their air-core solenoid inductors with equivalent geometry, there were more than 35-fold enhancement for inductance and 24-fold enhancement for peak quality factor of the 21-turn integrated solenoid inductor with multilayered magnetic core operating at 1.5 GHz. The results indicated that the multilayer magnetic core had promising prospect for applications in GHz frequency electromagnetic devices.

1. Introduction

With the development of electronic information industry, there was an increasing demand for the integration, miniaturization, and high frequency electromagnetic devices [1-3]. The compact inductors are indispensable passive component for radio frequency (RF) devices such as amplifiers, power transformers, and oscillators [4]. The miniaturization of inductors necessitated a decrease in physical size and increase in operating frequency. However, the miniaturization of inductors devices were progressed slowly because of the value of inductance sharp decreased with reducing the size of the inductors, which hampered the development of the entire electronic information industry. It was well known that, incorporated with a magnetic core could significantly improve the performance of inductors [5-8]. Especially for solenoid type inductors, the magnetic core can increase the magnetic induction intensity and reduce the magnetic flux leakage, thus increase the inductance and quality factor effectively. The present predicament was that the high-frequency performance of integrated inductors with magnetic core was poor because of the serious eddy current loss, high-frequency magnetic loss, and ferromagnetic resonance loss near the FMR frequency of the conventional magnetic core materials with very lower resonance frequencies (f_r) [9]. Therefore, the high-frequency soft magnetic materials were the key requirements for realizing large-scale integrated circuit technology [10]. The lower f_r of conventional magnetic materials limited the working frequency of the high frequency inductor components [11]. Our previous research results show that if the magnetic films possess in-plane uniaxial magnetic anisotropy (IPUMA), the f_r can be promoted to more than 1 GHz [12]. More importantly, the integrated inductors demand the magnetic films core maintain outstanding soft magnetic performance even if the film thickness exceeding 400 nm. However, the high-frequency magnetic performance of the magnetic granular films and monolayer films are



drastically degenerated due to the large grain size and strong inner stress when the film thickness rise to a few hundreds of nanometers. We discover that the laminated structure film can help to maintain the microstructure unchanged and promoted good high-frequency soft magnetic properties even though the total thickness exceeding 1 micrometer [13]. According to our previous research, the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ multilayer films, with $\text{Fe}_{80}\text{Ni}_{20}\text{-O}$ layer thickness of 5 nm and SiO_2 layer thickness of 3 nm, demonstrated good quality high-frequency performance with a low coercivity of 5.1 Oe, high ferromagnetic resonance of 2.5 GHz, and high permeability of 150 [12], which makes these films had promising prospect as magnetic core materials for solenoid inductors operating in GHz frequency range.

In this work, the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ multilayer magnetic core with a total thickness of about 400 nm were employed to fabricate the on-chip integrated solenoid inductors. Compared to their air-core solenoid inductors with equivalent geometry, the 21-turn integrated magnetic core solenoid inductor had more than 35-fold enhancement for inductance and 24-fold enhancement for peak quality factor when operating at 1.5 GHz. The optimal solenoid inductors performance with inductance density 72 nH/mm^2 and self-resonant frequency up to 4 GHz was obtained by incorporation our multilayer magnetic films core. The results revealed that the integration of the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ multilayer magnetic films could significantly improve the peak quality factor and inductance of the solenoid inductors.

2. Experiment

2.1. Prepared of the magnetic multilayer films

The $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ magnetic film with laminated structure were deposited by a multi-target magnetron sputtering equipment. Firstly, the vacuum chamber was exhausted to a base pressure superior to 4×10^{-4} Pa. Then the 20 sccm Ar gas was uninterruptedly injected to the chamber and the working pressure was kept at 0.4 Pa. Meanwhile, a small dose O_2 of about 0.2 sccm was injected into the chamber to regulate of in-plane uniaxial anisotropy and increase the resistivity. Another feature of the O_2 was to generate the SiO_2 insulating layer. During deposition process, the sputtering power was kept at 75 W and 100 W for $\text{Fe}_{80}\text{Ni}_{20}$ target and Si target, respectively. The substrate rotated at the speed of 24 rpm. The single-layer thicknesses for $\text{Fe}_{80}\text{Ni}_{20}\text{-O}$ (5 nm) and SiO_2 (3 nm) were precisely controlled by regulating the open/close time of the baffles by predetermined procedure. The total thickness of $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ multilayer film up to 400 nm was obtained by stacking the $\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2$ bilayer.

2.2. Fabrication of solenoid inductors

The solenoid inductors fabrication were started with forming a $0.5 \mu\text{m}$ thickness SiO_2 insulator layer on a 2-inch high resistivity silicon wafer by thermal oxide method to reduce substrate loss. Then an adhesion layer of Ti and seed layer of Cu were deposited successively by magnetron sputtering. AZ P4620 photoresist with thickness of about $6 \mu\text{m}$ was spin-coated, prebaked, exposure and developed to form trenches employed a chrome plate with patterns. The electroplating was utilized to deposit the bottom copper conductor wires in trenches with thickness of $3 \mu\text{m}$. After removing the seed layer and photoresist, polyimide (PI) with thickness of about $5 \mu\text{m}$ was spin-coated and cured in nitrogen atmosphere as interlayer insulator. The chemical mechanic polish (CMP) was used to realize a smooth surface to reduce the influence of roughness on the magnetic permeability. AZ 5214 reversal photoresist was used to form a pattern for magnetic core through photolithography technique. Then the multilayer magnetic core with total film thickness of about 400 nm was deposited by a multi-target magnetron sputtering equipment. A similar process of the PI and bottom copper conductor wires was applied to fabricate the top PI insulator layer and top copper wires. The top and bottom copper wires were connect via through-hole filled with copper.

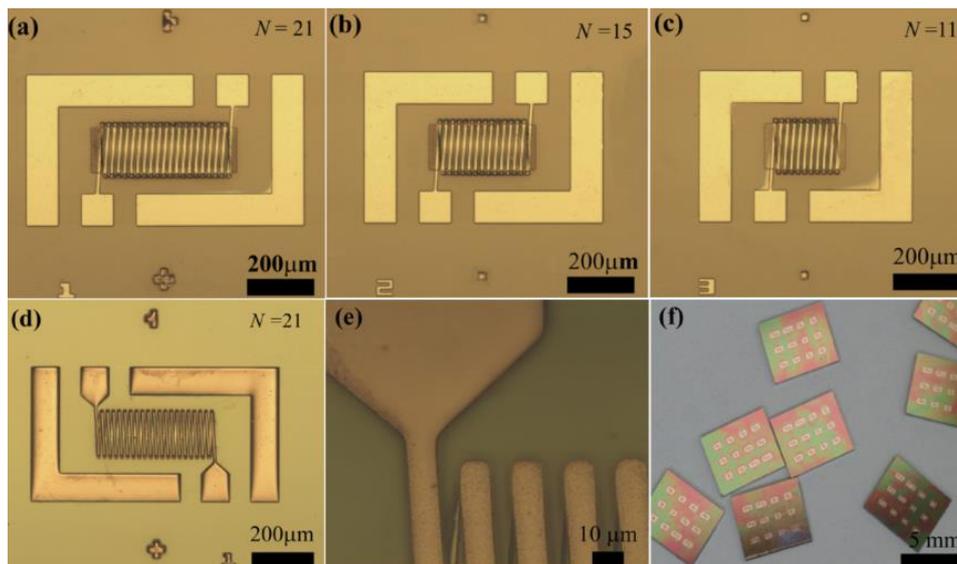


Figure 1. Optical photos of the solenoid-type inductors: (a), (b) and (c) are inductors with multilayer magnetic core; and (d) is the counterpart of (a) without magnetic core; (e) are the through-holes structure of inductors; (f) are the inductors fabricated on silicon wafers.

The optical photos captured by metallographic microscope of the solenoid inductors are presented in Figure 1. The solenoid inductors with different number of turns were fabricated. The air-core solenoid inductor counterparts with equivalent geometry were also fabricated for comparison.

2.3. Characterization and measurement

The structure and the phase of the multilayer film were analyzed by an X-ray diffraction (XRD, PANalytical B.V.). The film's surface topography was observed by scanning electron microscope (LEO-1530FE). The cross-sectional layered structure of the multilayer film was investigated by transmission electron microscopy (Tecnai F30). The hysteresis loop of the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ magnetic films were measured by a vibrating sample magnetometer (VSM, LakeShore 7404) at room temperature. The high frequency magnetic permeability spectrum was characterized ranging from 400 MHz to 5 GHz range by using a vector network analyzer (Agilent PNA E8363B) combined with micro-strip line fixture.

The measurement of both types inductors were performed in the frequency range from 300 kHz to 5 GHz by employing an Agilent N5230A vector network analyzer equipped with CASCADE M150 probe station and ACP40-GSG-150 microwave probe. Calibration structure solenoid inductors were also measured to eliminate the parasitic effects caused by the ground ring and the probe pads.

3. Results and discussion

Figure 2 exhibits the XRD pattern of the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ multilayer film deposited on black glass substrate. The patterns exhibit (110) preferred orientation of bcc phase FeNi alloy, and there are no diffraction peaks attributable to Fe and/or Ni oxide phase. The grain size of the multilayer estimated by Scherrer's equation was 5.3 ± 0.3 nm, which was close to the $\text{Fe}_{80}\text{Ni}_{20}\text{-O}$ single layer thickness. This indicated that the SiO_2 layer can observably interrupt the continuous growth of $\text{Fe}_{80}\text{Ni}_{20}\text{-O}$.

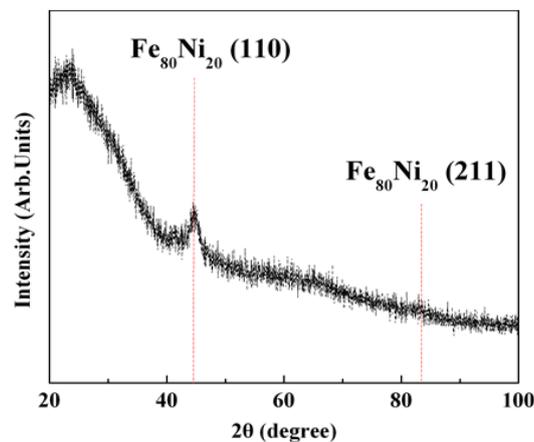


Figure 2. The XRD pattern of the multilayer film.

The SEM surface morphology of $[\text{Fe}_{80}\text{Ni}_{20}\text{-O}/\text{SiO}_2]_n$ multilayer film is shown in Figure 3(a). It is clear that the surface magnetic layer of the multilayer film is well-compacted and consisted of grains with smaller size. This was thanks to the introduced SiO_2 insulator layer interrupted the continuous growth of the $\text{Fe}_{80}\text{Ni}_{20}\text{-O}$ layer, leading to grain refinement. To verify the multilayer structure of the deposited multilayer film, cross-sectional TEM examination was performed and the result is shown in Figure 3(b). The layered structure and the interface between the nonmagnetic layers and magnetic layers can be seen clearly. Every magnetic layer was divided off by a tiny SiO_2 layer, resulting in grain refinement, which confirms the previous analysis of SEM and the grain size calculated by Scherrer's equation.

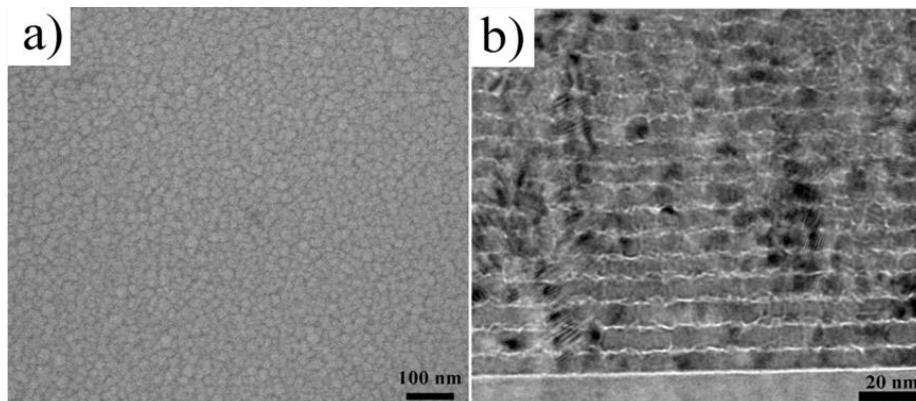


Figure 3. The surface morphological SEM image (a) and the cross-sectional image (b) of the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O}/\text{SiO}_2]_n$ multilayer film.

Figure 4(a) shows the easy and hard axis in-plane hysteresis loops of the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O}/\text{SiO}_2]_n$ multilayer film. Obviously, the static magnetic hysteresis shows a well-defined IPUMA and good soft magnetic properties. The oblique incidence can push the grain growth along normal direction of the substrate and induce IPUMA of the films. The coercivity of easy axis and hard axis were 5.1 Oe and 2.9 Oe, respectively, which were much lower than those of the $\text{Fe}_{80}\text{Ni}_{20}\text{-O}$ single layer thin film [14]. The low coercivity was ascribed to the grain refinement in $\text{Fe}_{80}\text{Ni}_{20}\text{-O}$ magnetic layer. Due to the introduction of the nonmagnetic SiO_2 layers, the saturation magnetization of the multilayer film decreased with certain degree, which was measured to be 0.85 T. But the resistivity of the magnetic core was up to $156.6 \mu\Omega \text{ cm}$, which has been greatly improved compared to that of $\text{Fe}_{80}\text{Ni}_{20}$ alloy film ($40 \mu\Omega \text{ cm}$) and $\text{Fe}_{80}\text{Ni}_{20}\text{-O}$ soft magnetic monolayer film ($90.7 \mu\Omega \text{ cm}$) [14].

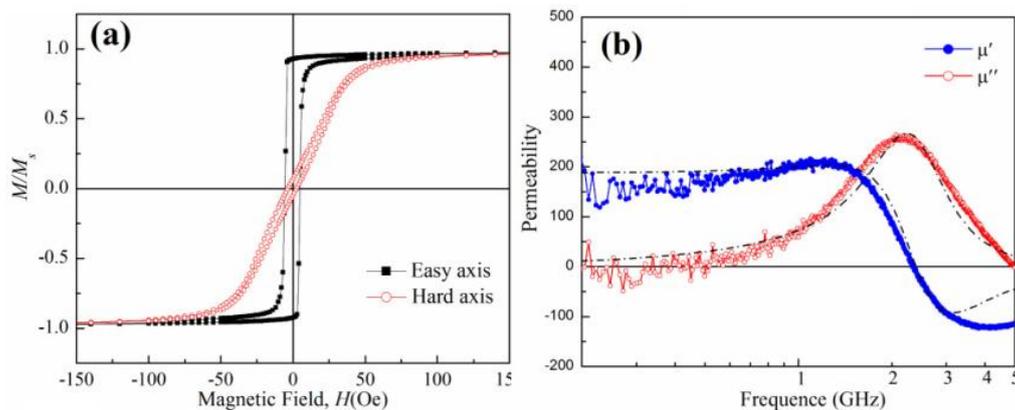


Figure 4. In-plane hysteresis loops (a) and the permeability spectra (b) of the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ multilayer film.

The real (μ') and imaginary (μ'') components of the high frequency permeability spectras of the $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ multilayer film are displayed in Figure 4(b). The $[\text{Fe}_{80}\text{Ni}_{20}\text{-O/SiO}_2]_n$ film shows excellent soft magnetic performance and obvious IPUMA. The ferromagnetic resonant frequency reached 2.5 GHz, and μ' can still be limited to a low level of about 150. Furthermore, the μ' and μ'' can be well fitted by the Landau-Lifshitz-Gilbert (LLG) equation (dash line in Figure 4b) which described the dynamic magnetization behavior of the films[10].

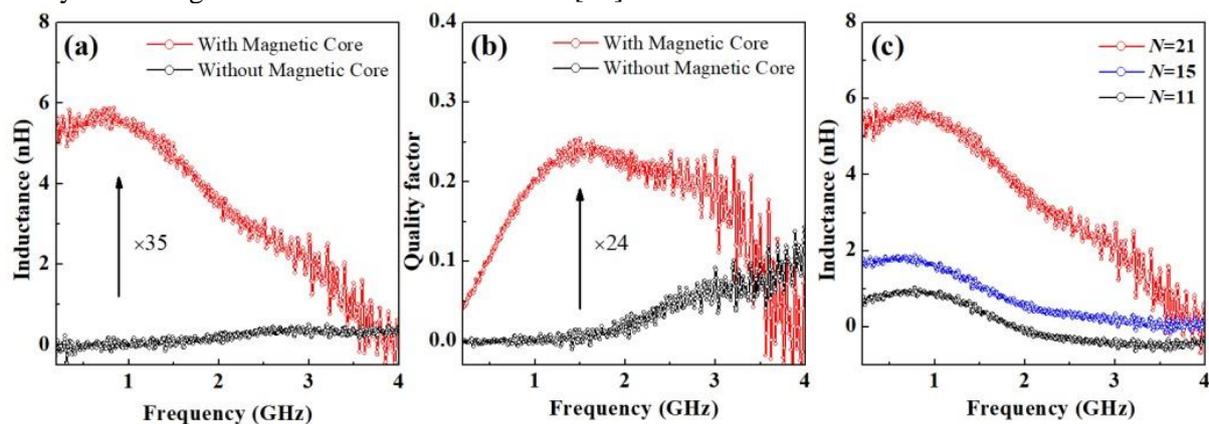


Figure 5. Inductance (a) and quality factor (b) of the solenoid inductors with multilayer magnetic core; (c) effect of turns number on inductance of the solenoid inductors with magnetic core.

The impact of the magnetic core on the inductance and quality factor of the solenoid inductors is displayed in Figure 5 (a) and (b). The inductance and quality factor of the magnetic core inductor dramatically increased compared to the air-core inductors with equivalent structure. The peak inductance was about 5 nH at 1.5 GHz for multilayer magnetic core inductor, which was about 35 fold enhancement compared to the air-core counterpart. Because of the two inductors had the identical geometry, the enhancement in inductance was a consequence of the integration multilayer films. Due to the ultra low profile of $0.17 \times 0.41 \text{ mm}^2$, the density of inductance reached to 72 nH/mm^2 , which was a considerable value among the reported inductance density recently [6].

The impact of magnetic multilayer films on quality factor is displayed in Figure 5(b). There was a more than 24-fold enhancement compared to their air-core counterpart. The quality factor of inductors was proportional to the inductance, and expressed as $Q = \omega L/R$, where ω is the angular frequency, L the inductance of inductor, R is the total resist of the inductor. The magnetic core can significantly increase the inductance, thus improved the quality factor of inductor. The self-resonant frequency (the quality factor equal to zero) of the magnetic core inductor reached up to 4 GHz, while self-resonant frequency of the air-core inductor is beyond 5 GHz. The low self-resonant frequency of the magnetic

core solenoid inductor was due to the effect of ferromagnetic resonance frequency of the multilayer film. Besides, we noticed that the quality factors of both two samples are extremely low. The low values may be caused by the bottom Cu oxidation during PI curing and dry-etching. So, further work need to be done to deal with the problem of Cu oxide and improve the quality factor of inductor.

Figure 5(c) presents the dependence of inductance on frequency of three different turns number. As the turns increased, the inductance increased from ~1 nH to 5 nH. For a solenoid inductor, the inductance is proportional to the relative permeability (μ') of the magnetic core and the number of turns, and can be expressed by traditional Soohoo's equation [15]:

$$L = \frac{\mu_0 \mu_r A_m N^2}{l_m} \quad (1)$$

where μ_r and μ_0 denote the relative permeability and vacuum of the magnetic film, A_m and l_m are the cross-sectional area and length of the closed magnetic core, N is the turns number. The A_m is the same for the three number of turns. Therefore, the rapid enhancement of inductance was attributed to the increase of turns. Additionally, Figure 5 (c) displayed that the inductance of the magnetic core inductor decreased with increasing the frequency. When operating at high frequency range, the eddy current loss in the magnetic core cannot be ignored. Therefore, the decrease of inductance was caused by the deterioration of the magnetic core performance near FMR [10].

4. Conclusion

In this study, we report the significant enhancement of quality factor and inductance operating at GHz frequencies for solenoid structure inductors incorporated $[\text{Fe}_{30}\text{Ni}_{20}\text{-O/SiO}_2]_n$ multilayer magnetic films. Compared to their air-core solenoid inductors with equivalent geometry, there were more than 35-fold enhancement for inductance and 24-fold enhancement for peak quality factor for the 21-turn integrated solenoid inductor with multilayered magnetic core operating at 1.5 GHz. The inductor shows an excellent high-frequency performance with wide operation frequency range of 0-4 GHz and high inductance density of 72 nH/mm². The results indicated that the magnetic core solenoid inductors had promising prospect for applications in GHz frequency electromagnetic devices.

5. Acknowledgment

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6. References

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