Ferromagnetic Inductors on Commercial Nanoporous Anodic Alumina

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***Abstract*— This paper studies the feasibility of integrated devices on nanoporous anodic alumina substrates filled with ferromagnetic nanowires. The presence of ferromagnetic material is responsible for an increase of the permeability at low frequency, and a tunability in frequency when an external DC magnetic field is applied. Tunability performance of the inductance and quality factor predicted by simulations are successfully validated by experiment. Below the FMR frequency, the measured quality factor is superior to that obtained for a similar device built on non magnetic Si wafer.**

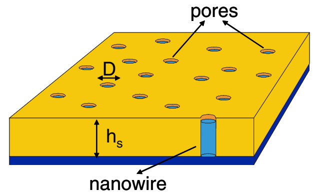

Fig. 1. Ferromagnetic nanowired substrate.

I. Introduction

Ferromagnetic nanowired substrates (Fig. 1) offer, due to their excellent material properties, the ability to build planar reciprocal and non-reciprocal devices for very high frequencies, as nowadays requested for wireless communication and automotive systems. The advantages of such substrates compared to classical ferrites are a fully planar integration of the ferromagnetic material, a higher saturation magnetization and a higher FerroMagnetic Resonance (FMR) frequency, resulting in a higher operation frequency obtained at remanence thanks to the very high aspect ratio of the nanowires. Besides operation at remanence, their properties are tunable by applying an external DC magnetic field [1].

Previous work has reported on the realization of integrated inductors over various bulk technologies (Silicon, quartz [2], anodic alumina [3]). In this paper, we study the feasibility of integrated devices on nanoporous anodic alumina substrates filled with ferromagnetic nanowires (hereafter denoted "nanowired alumina" or "nanowired Al_2O_3" substrate). Since the nanowires as ferromagnetic inclusions influence the permeability of the composite, we can expect a significant impact of the ferromagnetic content on the performance of inductors integrated on the nanowired substrate [4]. The paper is organized as follows. First, the fabrication process of passive integrated Coplanar Waveguide (CPW) transmission lines and inductors on the nanowired alumina template is described. Next, the properties of the nanowired alumina substrate are compared to those of a reference high resistivity silicon (Si) wafer using measurements of CPW lines lying on each substrate. As magnetic properties of the nanowired alumina substrate predicted by theory are validated by experiment, the resulting substrate modelling is used for predicting the performance of planar integrated inductors, at remanence and under DC magnetic field. An increase of the inductance value at low frequencies, proportional to the volumetric content in ferromagnetic nanowires, as well as a tunability with magnetic field of the quality factor are expected. Tunability predictions are successfully validated by experiment. Measurement also show that the quality factor of the inductor built on the nanowired alumina substrate is superior in low frequency range (below the FMR frequency) to that of the same geometry fabricated on high resistivity Si wafer.

II. Fabrication process

The nanowired substrate in Fig. 1 is based on self-supported nanoporous anodic alumina (Al_2O_3). A wide range of porosities, heights of membrane, pore sizes and pore space distributions are available. In this work an anodic alumina membrane from Whatman Ltd. (Anodisc 47, series 6809-5012) is filled with ferromagnetic Nickel (Ni) nanowires by electrodeposition, following the method reported in [1]. The thickness of the Al_2O_3 substrate is equal to 60 μm and its porosity is $p = 25\%$. The cylindrical pores have a diameter D=100 nm. Since the resulting wire diameter is smaller than skin depth at microwaves [5], the electromagnetic wave can propagate into the substrate. For comparison a reference bulk (non porous) Silicon (Si) substrate having a thickness of 750 μm and a thin oxide layer deposited on its top surface is also processed.

Fig. 2 shows illustrative parts of the mask used for the fabrication of planar integrated devices studied in this paper: CPW lines (top), meander inductors (bottom left), and spiral inductors (bottom right). For each family of device, different

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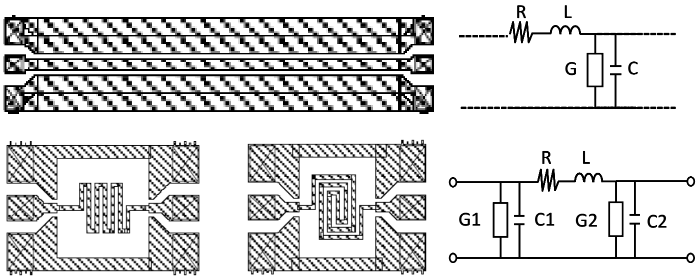

Fig. 2. Illustrative layout and corresponding equivalent circuit of planar integrated devices built on Al_2O_3 and Si substrates: CPW line (top), meander inductor (bottom left) and spiral (bottom right).

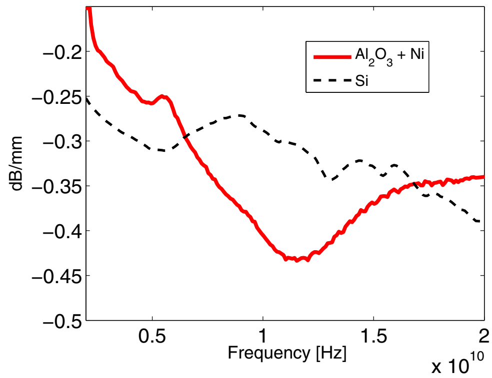

Fig. 3. De-embedded transmission factor T normalized per unit length, measured for the standard Si wafer (dashed) and Al_2O_3 substrate of porosity 25% (solid), filled with Ni nanowires over 40% of pore height. FMR absorption occurs around 11.5 GHz for nanowired Al_2O_3.

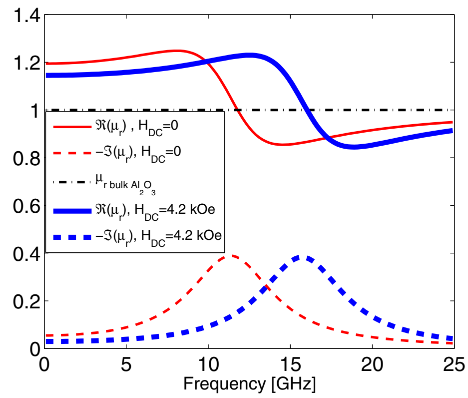

Fig. 4. Real (solid) and imaginary parts (dashed) of relative permeability μ_r of Al_2O_3 filled with ferromagnetic nanowires over 40% of substrate height, at remanence (H_{DC}=0, thin lines) and for a DC magnetic field applied parallel to the wire axis (H_{DC}=4.2 kOe, thick line). Dash-dotted line shows the permeability of bulk Al_2O_3 (without ferromagnetic nanowires, hence equal to air).

parameters (spacing between strip conductors, number of turns of meander or spiral, total length of device) are varied on the mask. Devices are fabricated by photolithography, on the alumina substrate filled with nanowires over 40% of the pore (and substrate) height, as well as on the bulk silicon wafer having a resistivity of 5 kΩ·cm. After photolithography, non protected parts of the photoresist are etched by using a chlorine plasma. The remaining photoresist is dissolved by boiling Acetone. Prior to the top aluminum deposition a 500 nm thick oxide layer is deposited between the alumina membrane and the metal, to obtain a smoother surface and to stop the plasma etching. Furthermore, it prevents the connection of several Ni nanowires via the top aluminum metallization, when high filling factors are required.

III. Electromagnetic properties of nanowired alumina substrate assessed by CPW measurements

On-wafer high-frequency measurements are performed from 40 MHz to 26 GHz using a Vector Network Analyzer Agilent Model PNAX-N5242A and coplanar ground-signal-ground (GSG) RF probes on a couple of CPW transmission lines having a central strip width of 38 μm, a slot width of 18 μm, and differing by a length ΔL= 500 μm. Prior to the CPW line characterisation, and to allow the extraction of the reference impedance of the TRL calibration method, on-wafer calibration using an impedance standard substrate (ISS) is performed. The propagation constant γ and the characteristic impedance Z_c of the CPW line are extracted after de-embedding the coplanar pads using the TRL technique. This allows us to determine first the de-embedded transmission coefficient of the line, that can be expressed as $T = e^{-\gamma \Delta L}$. Figure 3 compares the magnitude of this coefficient, normalized per unit length, for the two technologies considered in this paper: Si and Al_2O_3 filled with Ni nanowires. A significant absorption phenomenon is observed around the frequency of 11.5 GHz in the case of the nanowired Al_2O_3 substrate. This absorption can be correlated to the imaginary part of the relative permeability of the substrate at remanence, shown at Fig. 4 (thin dashed line, "H_{DC}=0"). This permeability is simulated using our models [6] taking into account the magnetic and geometrical parameters of the substrate, and a 40% filling height of the wires. From the complex propagation constant and characteristic impedance resulting from the de-embedding, the four parameters R, L, G, and C of the lineic equivalent circuit associated to the CPW transmission line (Fig. 2, top right) can be extracted. They are shown in Fig. 5 for each technology. For the nanowired alumina substrate (solid lines), the FMR resonance is clearly visible at 11.5 GHz on the series elements of the equivalent circuit, corresponding to the inductive or equivalently magnetic part of the device: the maximum in the lineic resistance R is correlated to the maximum of ferromagnetic loss in Fig. 4, while the inflection point visible around 11.5 GHz in the lineic inductance L is correlated to the inflection point in the real part of the relative permeability in Fig. 4. Such resonance phenomena are not present in the series lineic elements on the Si wafer, nor in the parallel capacitive elements G and C of both technologies, proving that the resonance can be clearly attributed to a magnetic effect induced by ferromagnetic nanowires.

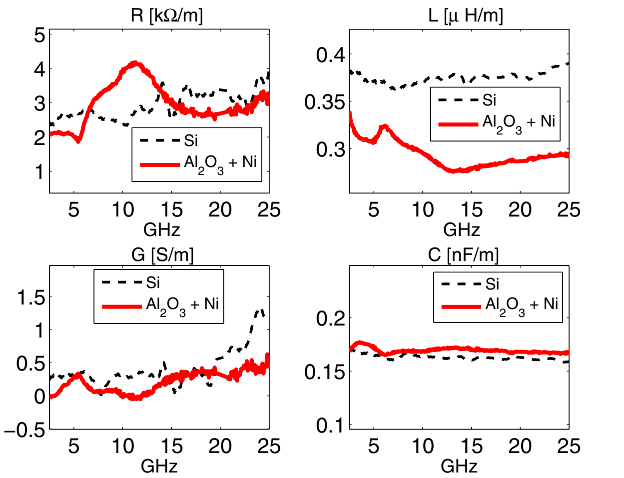

Fig. 5. Elements of the lineic equivalent circuit of Fig. 2 (top right), extracted from de-embedded measurements of CPW transmission line built on nanowired Al_2O_3 (solid) and Si (dashed), respectively. Small peaks observed at 6 GHz for the Al_2O_3 substrate are measurement artefacts.

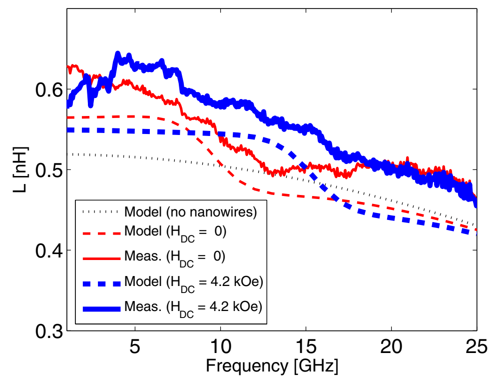

Fig. 6. Inductance L corresponding to meander inductor shown in Fig. 2. Dashed lines correspond to simulations, solid lines to measurements. Thin lines are obtained at remanence (H_{DC}=0), thick lines for applied DC magnetic field H_{DC}=4.2 kOe. Substrate is Al_2O_3 filled with nanowires, except for dotted curve where bulk permeability equal to unity is assumed. Small step visible between 3 and 8 GHz in the measured L value under DC magnetic field is due to spurious interaction between magnet and CPW measuring probes.

Moreover, away from the FMR frequency, the R and G lineic elements associated to losses have similar values for both technologies, meaning that dielectric losses in the nanowired alumina substrate are comparable to those of the bulk Si. The fact that the nanowires are metallic inside the membrane does not add additional losses, since their diameter D =100 nm is smaller than skin depth (of the order of 1 μm at microwaves) [5].

IV. Performance of Integrated Inductors on Nanowired Alumina Substrate

Simulations in Fig. 4 show that the presence of ferromagnetic nanowires inside the porous alumina induces an increase of the relative permeability of the resulting nanowired substrate by $\Delta\mu_r$=20%, up to the ferromagnetic resonance frequency (f_{FMR}), which is located for Ni nanowires grown in such template around 11.5 GHz. As the lineic inductance of transmission lines on such substrate closely follows the frequency dependence of the permeability, an increase of the inductance value associated to integrated inductors should occur in the presence of ferromagnetic nanowires. In order to validate this assumption, the frequency-dependent complex permeability modeled in Section III has been introduced as substrate parameter in the Comsol 3.5 finite-element solver. This sofware is used to simulate the S-parameters of the meander inductor shown in Fig. 2, with the following geometrical dimensions: width of the strip equal to 16 μm, spacing between strips equal to 10 μm, total length of the meander equal to 1500 μm. Fig. 6 shows the inductance L corresponding to the equivalent circuit in Fig. 2 (bottom), extracted from simulated S-parameters. Three kinds of simulations have been performed: substrate without nanowires (i. e. with relative permeability equal to unity, dotted line), nanowired Al_2O_3 substrate at remanence (thin dashed line "H_{DC}=0", i.e. complex permeability taken equal to thin lines in Fig. 4), and with an applied external DC magnetic field H_{DC}=4.2 kOe (thick dashed line), corresponding to the DC magnetic field value used for experiment. As for the CPW line measurements in Fig. 5, the inflection point in L associated to the f_{FMR} is clearly visible at 11.5 GHz at remanence (H_{DC}=0). Moreover, the inductance value L is enhanced by a factor 1.1 compared to the case where no nanowires are present in the substrate. This factor corresponds to the increase of effective permeability taking into account the surrounding air (μ_{eff}=(1+μ_r)/2, yielding $\Delta\mu_{eff}$=$\Delta\mu_r$/2=10%). Furthermore the inductor is tunable in frequency by applying an external DC magnetic field. Indeed, Fig. 4 shows that applying an external DC magnetic field perpendicular to the nanowired Al_2O_3 substrate, here H_{DC}=4.2 kOe, induces a shift of the ferromagnetic resonance frequency to a higher frequency, here f_{FMR}=16.5 GHz. As a consequence, the inflection point in L curve is also shifted to that frequency. Those predictions are successfully validated by measurements (solid lines) on the meander inductor of same geometry built on the nanowired Al_2O_3 substrate. For the measurements under DC magnetic field, the substrate is placed on a permanent self-biased magnet providing a uniform DC field of 4.2 kOe close to its surface before doing calibration and measurements.

The quality factor of an inductor can be approximated in the low frequency range as $Q = \omega L/R$. Values of Q-factors obtained from the R and L elements of the equivalent circuit (Fig. 2, bottom right), extracted from simulated and measured S-parameters, are compared in Fig. 7. Again simulations and measurements are in good agreement. When applying the DC magnetic field, the quality factor is increased, in the frequency range up to 13 GHz. Moreover, the Q-factor measured for the nanowired Al_2O_3 substrate is, below the FMR frequency (11.5 GHz for H_{DC}=0 and 16.5 GHz for H_{DC}=4.2 kOe), superior to the one measured for the same device built on the standard Si wafer (dotted line). This is well in accordance

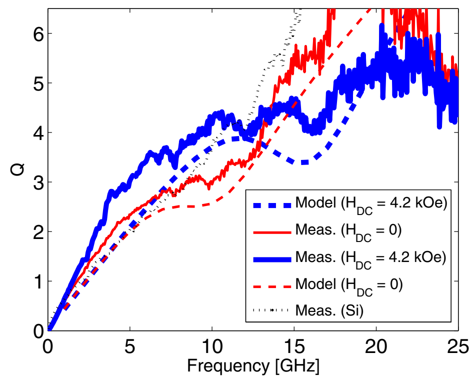

Fig. 7. Quality factor Q corresponding to meander inductor shown in Fig. 2. Dashed lines correspond to simulations, solid lines to measurements. Thin lines are obtained at remanence (H_{DC}=0), thick lines for applied DC magnetic field H_{DC}=4.2 kOe. Substrate is Al_2O_3 filled with nanowires, except for dotted curve which shows measured Q-factor of same device built on Si wafer.

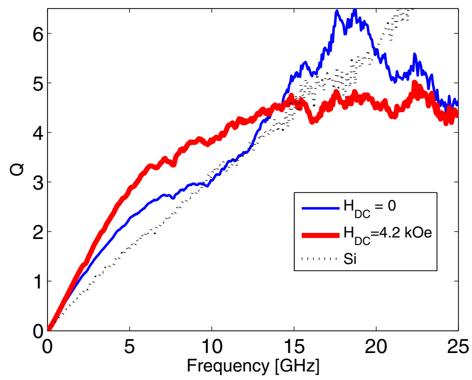

Fig. 9. Quality factor Q extracted from measurements of spiral inductor shown in Fig. 2. Thin lines are obtained at remanence (H_{DC}=0), thick lines for applied DC magnetic field H_{DC}=4.2 kOe. Substrate is Al_2O_3 filled with nanowires, except for dotted curve which shows measured Q-factor of same device built on Si wafer.

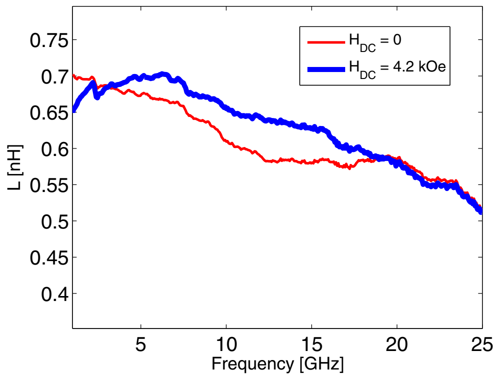

Fig. 8. Inductance L extracted from measurements of spiral inductor shown in Fig. 2. Thin lines are obtained at remanence (H_{DC}=0), thick lines for applied DC magnetic field H_{DC}=4.2 kOe. Substrate is Al_2O_3 filled with nanowires.

with the increase of the substrate permeability below the FMR frequency when nanowires are present (Fig. 4). The moderate increase of inductance and quality factor values is explained by the fact that the porosity of the membrane and the height of the nanowires are relatively low. Increasing those two parameters could compensate this problem, since our models [6] show that the relative permeability, hence the inductance, is proportional to the volume of ferromagnetic material.

It is worth noticing that a similar behavior is observed experimentally for the spiral inductor in Fig. 2 having same parameters as the meander. Figs. 8 and 9 show the measured spiral inductance and quality factor, respectively. Again, the quality factor extracted on the nanowired Al_2O_3 substrate is, up to the FMR frequency (11.5 GHz for H_{DC}=0 and 16.5 GHz for H_{DC}=4.2 kOe) superior to the one extracted on the standard Si substrate.

V. Conclusions

We have shown the possibility of using commercially available self-supported anodic alumina, filled with ferromagnetic nanowires, for designing microwave integrated inductors. CPW measurements show that this technology compete with high-resistivity Silicon in terms of dielectric losses. The tunability of the inductance and quality factor with respect to an external DC magnetic field has been predicted by simulation and demonstrated experimentally. Below the FMR frequency, measured quality factors are superior to that of an inductor of same geometry built on high-resistivity bulk Si. In the future these performances could be further enhanced by increasing the amount of ferromagnetic material in the membrane, e. g. increasing the porosity and height of nanowires.

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