<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper presented at *18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)*.

Citation for the original published paper:

Liljeholm, J., Ebefors, T., Rohrmann, H., Shah, U., Oberhammer, J. (2015)
Multilayer ferromagnetic composites enabling on-chip magnetic-core inductors beyond 1 GHZ.
In: (pp. 811-814). IEEE
<http://dx.doi.org/10.1109/TRANSDUCERS.2015.7181047>

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-172290>

MULTILAYER FERROMAGNETIC COMPOSITES ENABLING ON-CHIP MAGNETIC-CORE INDUCTORS BEYOND 1 GHz

J. Liljeholm¹, T. Ebefors¹, H. Rohrmann², U. Shah³ and J. Oberhammer³

¹Silex Microsystems, Stockholm, Sweden

²Evatec Advanced Technologies AG, Balzers, Liechtenstein

³Royal Institute of Technology, KTH, Stockholm, Sweden

ABSTRACT

This paper report of fabricated unpatterned ferromagnetic NiFe/AlN multilayer composites and an established process flow for magnetic core material suitable for integration with Silex 3D RF TSV technology. The fabricated single-loop test inductors achieved an inductance enhancement of 4.8 and a quality factor enhancement of 4.5 at 400 MHz. Simulations show that magnetic material in connection with 3D TSV inductors result in an inductance enhancement up to a factor of 5 at GHz frequencies for the same inductor area, or the same inductance can be achieved at 9 times smaller area and cost.

KEYWORDS

NiFe/AlN multilayer composite, magnetic materials, RF microstrip, micro machined inductors, MEMS foundry.

INTRODUCTION

The ongoing trend towards higher miniaturization and integration is an ever increasing challenge in the design of complex RF systems. Similarly, the advancement of these RF ICs technologies is raising the costs for each successive processing node and in conjunction with the packaging trends where higher levels of integration and packaging density are required, even more complex processing is needed, illustrated in Figure 1 a). The currently available on-chip integrated inductors, used as passives in RF ICs or system-on-package interposers are employed as air-core inductors with a maximum inductance density of 200 nH/mm² [1]. Previous presented work on RF TSVs enabling 3D integration using Silex Met-Via® TSV as a key element for 3D inductors, showed high Q-factor (>30) and self-resonance frequency (> 6 GHz) for inductors in the range of 1-15 nH [2], Figure 1 b). To enhance the performance of 3D inductors it is desirable to increase both the inductance density and the quality factor, however inductors with higher quality factors tend to have lower inductance density. By integrating magnetic material with the on-chip inductors, Figure 1 c), the inductance and the quality factor can be increased as well as reduce the capacitance and the resistance, which result in smaller and more cost effective devices [1].

Evaluation of magnetic materials, such as thin film NiFe, at lower frequencies (DC to 10 MHz) has shown that the relative permeability can be as high as 3000 for thin films, and with an optimized deposition process even a permeability of 8500 has been presented [3].

Figure 1. a) EPAMO example of RF system with inductor IPD. b) fabricated 3D inductor without magnetic and c) concept drawing of 3D inductor with magnetic core.

While extending the frequency above 100 MHz several limitations are encountered due to the magnetic resonance of the magnetic material. Limitations such as the magnetic NiFe layers are metallic and thus conductive which results in induced currents counteracting the magnetic field, increasing losses and reducing the effective inductance. To suppress the flow of RF eddy currents and decrease the losses in these films, only very thin NiFe layers can be used. Unfortunately, it is counteractive since for 3D inductors larger magnetic volumes and thus thicker layers are desired. By adding insulation layers in-between thin layers of NiFe film the induced currents in the NiFe film can be suppressed and at the same time increase the ferromagnetic resonance [4], [5]. Other ways to increase the otherwise low ferromagnetic resonance in the magnetic materials is to introduce shape-induced magnetic anisotropy by patterning the magnetic material [6].

Besides that the magnetic material needs to have high permeability and good linearity, exhibit minimal hysteretic loss, high saturation magnetization and high resistivity, the material needs to be compatible with MEMS processing, such as Cu TSVs for integrated resistors and high-k MIM capacitors. Additional requirements are therefore high-temperature stability (post processing above 300°C), a good deposition and etching technique, and compatibility with Si-technology [1]. Magnetic materials of interest are therefore NiFe/Cr, IrMn/CoFe, NiFe/AlN, CoZrTa and similar amorphous alloys.

The novelty as presented by Shah et. al [7] was to increase the thickness of the ferromagnetic material without increasing its conductivity, by using an unpatterned ferromagnetic NiFe/AlN sandwich structure as magnetic core material. This article is a continuation and will further focus on the fabrication and integration challenges with magnetic material, when aimed at integration with thin wafer used for Silex 3D RF TSV inductors, illustrated in Figure 1 c), to further improve the inductor performance.

CONCEPT AND DESIGN

The ferromagnetic material chosen for this evaluation was nickel-iron (Ni-Fe) because of its common use in semiconductor fabrication, in particular for magnetic sensors and hard disk read-write heads, known for easy manufacturability with high yield and low cost of ownership. Between the individual NiFe layers, thin aluminum nitride (AlN) insulation layers are inserted to suppress leakage and induced currents flowing in the ferromagnetic core layer which results in an increase in the ferromagnetic resonance frequency. In addition, the AlN layers act as stress compensation for the sputtered NiFe layers, much more efficiently than SiO₂ insulating films.

Transmission lines for RF parameter extraction was designed and fabricated with 10 μm width and 500 μm length and for inductor evaluation a single-loop microstrip was implemented by a 2.3 mm long and 5 μm wide microstrip line, which is short-circuited at one end to its ground layer, shown in Figure 2. The extracted RF material properties (μ' , ϵ and self resonance frequency) are presented in detail elsewhere in [7].

Figure 2. a) Cad file of the unit cell used for evaluation and measurement and b) photograph of part of the wafer showing the fabricated microstrip test structures. c) SEM image of the single loop inductors.

FABRICATION

The fabrication was performed with a three mask-set process using 200 mm diameter Si-wafers and the final cross-section is presented in Figure 4. To minimize and reduce the risks of losses, the silicon substrate used was 305 μm thick high resistivity MCZ silicon wafers (3-10 k $\Omega\cdot\text{cm}$) from Okmetic Oyj. If regular CZ Si-wafers had been used with low resistivity ($\leq 100 \Omega\cdot\text{cm}$), the magnetic fields would penetrate deeply into the substrate causing losses and reducing both the inductance and Q-factor [8], and be a lossy medium for RF signals [9]. The purpose to use thin Si-wafers is to be able integrate the magnetic process flow with Silex established Cu-metalized TSV process flow [2], which requires 305 μm wafers. The wafers were thermally oxidized with 1 μm SiO₂, and 0.5 μm of TiW was deposit, acting as a barrier and adhesion layer. The ground layer is required to be as smooth as possible and consisted of 2 μm

sputtered Cu, by PVD process in Unaxis Balzers LLS EVO. Automatic wafer handling of 305 μm thin wafers can be challenging and adding thick (1-5 μm) magnetic materials will implement stress causing large wafer bow and thus the wafer more brittle, makes it even more complex to fabricate. To compensate for the applied stress and lower the wafer bow, compressive/tensile material was deposit on the backside and to mimic the full metalized 3D TSV inductor process, the material used on the backside was either SiO₂ or TiW/Cu, see Table 1.

The magnetic film deposition was optimized by an iteration process, where the first deposition (Run1) was to optimize the SiO₂ deposition and during Run2, Run3 and Run4 the magnetic multilayer stack process parameters was altered. The stress applied by the magnetic deposition process was measured on monitor wafers, and by optimize and altering the chopped DC deposition of the magnetic layer composition, the stress was greatly reduced. The wafer bow after the magnetic film deposition on the 305 μm thick wafers is also presented in Table 1. The TiW/Cu film clearly reduces the wafer bow compared to the wafers with only SiO₂ on the back side. This is most desirable since a TiW/Cu film will be present on the back side of the wafer when processing the full metalized 3D TSV inductors.

The magnetic film was designed as a laminated stack to achieve lowest coercivities, reduced eddy currents and well defined tunable magnetic anisotropy. 20 sub layers of 100 nm NiFe were laminated with insulating intermediate layers, in Run2, by 8 nm reactively sputtered AlN, in Run4 by 10 nm RF-sputtered SiO₂, and in Run3 periodically by thicker SiO₂ intermediates for improved high frequency response.

To reduce the capacitive coupling seen for the NiFe sublayers of Run2 every fourth intermediate was built by a stack of (4 nm AlN/50 nm SiO₂/4 nm AlN). The RF sputter deposition of the 500 nm SiO₂ bottom layer was optimized for low micro roughness to minimize the coercivity of the laminated stack. The deposition of the intermediates was adjusted for their intended multi-task; electrical isolation to reduce eddy currents, smooth interfaces and suppression of the growth of large magnetic crystallites for low coercivity and linear ordered microstructure to support alignment and magnitude of the magnetic anisotropy. As a good compromise for these interactions a layer thickness of 8 to 10 nm was chosen for the interfaces and 100 nm for the NiFe sublayers.

The resulting 2 μm magnet layer thickness is a balance of available magnetic moment, RF performance and manufacturability, since one long life target in the Oerlikon LLS lasts for 350 8" wafers of 2 μm NiFe. The top of the layer stack was encapsulated by a 500 nm SiO₂ film.

This elaborated multi-layer deposition with linear ordered micro-structure and well defined interfaces could be achieved in an economic way by an Oerlikon LLS sputter system. The substrates, mounted on a rotating cylinder, move in front of the linear sputter cathodes providing an oblique incidence of the sputter material for an uniform linear order in the films. This effect can be supported by a

collimator of parallel blades, for the magnetic layers as well as for the nonmagnetic intermediates, to engineer the value of the magnetic anisotropy. The tool gives also the freedom to optimize the magnetic alignment by a linear field in the film plane. The layer systems discussed in this report were deposited with a linear collimator of aspect ratio 1:1 and a linear aligning field of ~ 25 Oe for the NiFe films and no extra collimation for the seeds and the intermediates [10]. Figure 3 shows a SEM image of the cross section, where the NiFe/AlN multilayer stack is visible.

Table 1: Magnetic film deposition at Oerlikon

Magnetic dep.	Thickness [Å]	Stress Monitor [MPa]	Stress comp. material	Wafer bow [μm]
Run1 (SiO ₂)	5154	89	TiW/Cu	-170
Run2	32067	260	SiO ₂	-500
			TiW/Cu	-450
			TiW/Cu	-450
Run3	30790	23	SiO ₂	-230
			TiW/Cu	-160
			TiW/Cu	-160
Run4	30290	-96	SiO ₂	-40
			SiO ₂	-40
			TiW/Cu	-130
			TiW/Cu	-130

The vertical interconnects were created by etching the magnetic/dielectric layers in a Veeco Nexus IBE dry ion beam etching tool. A sloping profile of the etched magnetic stack is required to achieve complete step coverage when encapsulating the magnetic multilayer stack with an insulating layer (SiO₂), prohibiting short-circuiting between the magnetic multi layers when depositing the top metal. The ion beam etch angle was 50 degrees with an etch rate of 70 nm/min and stopped on the 0.5 μm SiO₂ using optical emission detector, see Figure 3.

Figure 3. a) SEM image of the cross-section of the magnetic NiFe/AlN multilayer composite structure after via etch with tilted 50° ion beam. b) Optical emission data obtained during ion beam etching at Veeco.

A high temperature (300°C) PECVD 0.3 μm SiO₂ deposition was used for depositing an insulation layer after etching, which might have affected the magnetic performance of the NiFe layer, causing the final test structures to have higher permeability and ferromagnetic resonance. A second lithographic layer was used to etch the 0.3 μm SiO₂ and the 0.5 μm SiO₂, creating an opening to the Cu ground layer. Additional process steps were performed to ensure low contact resistance between the ground and top metal Cu layers. For interconnection, plated Cu was used since it has shown a quality factor about 20 times higher than previously used aluminum-based inductors [1]. The top Cu layer was plated with total thickness of 6 μm.

Figure 4. SEM and schematic cross-section images showing the vertical connection and the complete multi layer stack.

EXPERIMENTAL RESULTS

The fabricated single-loop test inductor, Figure 2, is shallow and showed low Q-factor due to poor area to loop-length ratio. Still, an inductance enhancing factor of 4.8 and a quality factor enhancement factor of 4.5 measured at 400 MHz of the magnetic stack as compared to a reference loop using a SiO₂ dielectric layer, Figure 5.

Figure 5. Inductor measurements on the single-loop test inductor with and without the ferromagnetic NiFe/AlN multilayer composite a) extracted inductance and b) extracted quality factor.

Also, the contact resistance for the vertical connection was measured by a four-probe measurement using the test structures shown in Figure 2 a) and SEM cross-section in Figure 4, and the obtained Cu to Cu contact resistance was 4.1 mΩ.

Figure 6. Simulation results when implementing a magnetic core in Silex 3D TSVs to match the 7.5 nH Murata inductor LQW18AN7N5D00.

Further, simulations show that magnetic materials in connection with Silex 3D RF TSV inductors could result in an inductance enhancement up to a factor of 5 at GHz

frequencies for the same inductor area, or the same inductance can be achieved at 9 times smaller area and cost. Figure 6 show simulation results when implementing a magnetic core in Silex 3D TSVs inductors, matching to a Murata SMD inductor [11].

CONCLUSION

This paper has focused on the processing and manufacturability aspects when integrating advanced NiFe/AlN laminates into on-chip inductors designs. By process optimization, stress compensation and low temperature insulation layers, a complete compatible process flow to integrate the multilayer NiFe/AlN composite material as core material was established, suitable for integration with Silex 3D RF TSV technology.

OUTLOOK FOR FUTURE

To further improve the performance of the 3D inductors and increase the ferromagnetic resonance, shaped-induced pattern, creating anisotropy in the magnetic material could be preformed. Also, high temperature deposition process (SiO₂) should be avoided to reduce the risk of affecting the magnetic performance. Recent research has shown that lowering the power used during magnetic deposition would result in smoother and stronger uniaxial magnetic anisotropy [12]. For full scale high volume manufacturing implementation in MEMS foundry environment further cost of ownership calculation and process optimization needs to be obtained. Thick film magnetic inductor core material with fabrication costs lower than 0.1 cent/mm² is in progress.

ACKNOWLEDGEMENTS

For the work on ferromagnetic, the authors acknowledge the process development by Vincent Ip and Katarina Rook of Veeco Instruments, as well as Lucas Held and David Jansson at Silex for design support.

Financial supports by VINNOVA under "mag-MEMS" Forska och Vax grant agreement no. 2012-00515. Umer Shah at KTH-MST is greatly acknowledged for the simulation, modeling and RF measurement work.

For the work on RF TSV and IPD Inductors, part of Silex developments has been accomplished under support by the European Union [ENIAC JU grant no. 270692-2], National Swedish funding is provided in part by VINNOVA, the Swedish Governmental Agency for Innovation Systems and National Finnish and Dutch funding from TEKES respectively. The views expressed in this paper are not intended as an endorsement by the funding agencies or the EPAMO consortium.

REFERENCES

- [1] D. S. Gardner, G. Schrom, F. Paillet, B. Jamieson, T. Karnik, and S. Borkar, "Review of on-chip inductor structures with magnetic films," *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4760–4766, Oct. 2009
- [2] T. Ebefors, J. Fredlund, D. Perttu, R. van Dijk, L. Cifola, M. Kaunisto, P. Rantakari, T. Vaha-Heikkila, "The development and evaluation of RF TSV for 3D IPD applications," *3D Systems Integration Conference (3DIC)*, IEEE International, pp.1-8, 2-4 Oct. 2013
- [3] M. Glickman, T. Niblock, J. Harrison, I. B. Goldberg, P. Tseng, and J. W. Judy, "High permeability permalloy for MEMS," in *Proc. Hilton Head, 2010*, [CD ROM].
- [4] Y. Zhuang, M. Vroubel, B. Rejaei, E. Boellaard, and J. N. Burghartz, "Investigation of microstrips with NiFe magnetic thin film (I): Experiment," *Trans. Magn. Soc. Jpn.*, vol. 2, no. 5, pp. 367–370, 2002
- [5] M. Vroubel, Y. Zhuang, B. Rejaei, and J. N. Burghartz, "Investigation of microstrips with NiFe magnetic thin film (II): Modeling," *Trans. Magn. Soc. Jpn.*, vol. 2, no. 5, pp. 371–376, 2002
- [6] P. K. Amiri, "Magnetic Materials and Devices for Integrated Radio-Frequency Electronics" Ph.D. dissertation, Delft University of Technology, Delft, The Netherlands, Oct. 2008
- [7] U. Shah, J. Liljeholm, T. Ebefors, and J. Oberhammer, "Permeability Enhancement by Multilayer Ferromagnetic Composites for Magnetic-Core On-Chip Inductors," *Microwave and Wireless Components Letters*, IEEE, vol.24, no.10, pp.677-679, Oct. 2014
- [8] X. Mi and S. Ueda, "Integrated Passives for High-Frequency Applications" in *Advanced Microwave Microwave Circuits and Systems*, pp. 249-285, 2010
- [9] B. Chen, V. N. Sekhar, C. Jin, Y. Y. Lim, J. S. Toh, S. Fernando and J. Sharma, "Low-Loss Broadband Package Platform With Surface Passivation and TSV for Wafer-Level Packaging of RF-MEMS Devices", *IEEE Trans. On Components, Packaging and Manufacturing Technology*, 2013
- [10] H. Rohrmann, "Manufacturing Magnetic Materials for Nano Devices" *Chip Visionary industrial solutions*, pp 26-27, 2012, available at: www.issuu.com/oerlikonsystems/docs/chip2012_web1
- [11] T. Ebefors and J. Oberhammer, "Through-Silicon Vias and 3D inductors for RF Applications", *Microwave Journal*, vol. 57, pp. 80-84, Feb. 2014
- [12] K. Koh, D.S. Gardner, C. Yeng, K.P. O'Brien, N. Tayebi and L. Lin "High Frequency Microwave On-Chip Inductors Using Increased Ferromagnetic Resonance Frequency of Magnetic Films" *Micro Electro Mechanical Systems (MEMS)*, 2015 28th IEEE International Conference, pp.208-211, 18-22 Jan. 2015

CONTACT

*J. Liljeholm, tel: +46(0)70 166 01 23; info@silex.se