MEMS based Electrochemical Process for Fabrication of Laminated Micro-Inductors on Silicon

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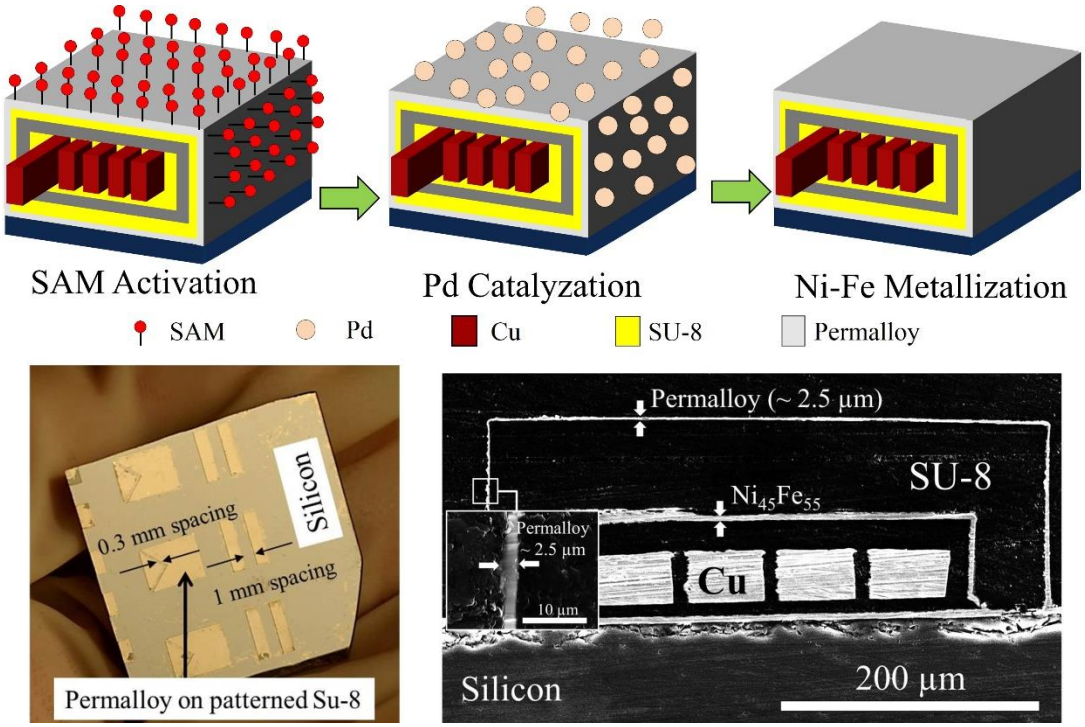

Highlight: Activation and seedless site-selective metallization of SU-8 for top core lamination.

Abstract:

Soft metallic magnetic alloys (such as Co, Ni and Fe based alloys) have been extensively used as core material in integrated inductors and transformers for DC-DC conversion. Compared to ferrite materials, these materials have excellent soft magnetic properties such as high saturation flux density, low coercivity and high permeability. High electronic conductivity, however, makes these alloys susceptible to eddy current losses. As a result, core material thickness is often limited by the skin depth depending on operational frequency (10 MHz-100 MHz), thus reducing the inductance density. Laminated magnetic films where the active layers are separated by a dielectric film can increase the overall core thickness without compromising on its power handling capability. In this work, a CMOS compatible electrochemical-resist-electrochemical based core lamination deposition technique is described whereby a laminated top magnetic core is microfabricated with a self-assembled process. The process is site-selective and has excellent step coverage which is ideal for MEMS based metallization.

I. Introduction

Over the last two decades there has been significant research in the field of power magnetic devices [1-3]. These devices are an integral part of a power supply circuitry of portable or hand-held devices. The introduction of such point-of load switched mode power supplies has increased battery life by replacing conventional linear regulators. Moreover, developments in new efficient topologies have reduced systemic losses further in power converter circuitry often introduced in micro-processors and micro-controllers as step-down power conversion rails. However, the efficiency of magnetic passive devices (such as micro-inductors and transformers) can be the limiting factor for the overall efficiency of the power supply circuitry. Moreover, the key challenge is to miniaturize these devices without decreasing their efficiencies.

The major problem in realizing micro-machined inductors is the loss contribution from the copper windings and magnetic core. The authors have previously reported an increased cross-sectional area copper process [4] to address winding losses. However, loss contribution from the magnetic core still remains a major roadblock. Excellent soft magnetic properties (low coercivity, high permeability and high saturation flux density) make Ni-Fe-Co based alloys the most widely used soft magnetic material and preferred over ferrites. Moreover, these materials can be deposited in CMOS compatible processes, ideal for integrated magnetics. However, high electrical conductivity makes these films prone to eddy current losses at high frequencies, reducing the device efficiency. In order to eliminate the influence of core eddy current losses, the thickness of the core is restricted according to the skin depth for a designed frequency of operation. This in turn limits the flux confined in the core and restricts inductance density. Higher inductance density without increasing eddy current losses is achievable by inclusion of non-magnetic dielectric layers. Such laminations could potentially reduce the number of winding turns and the overall footprint area. Previous reports to achieve this include laterally and vertically laminated structures [5-6], dielectric separated by magnetic films electrodeposited on a seed layer [7], sequential sputtering of dielectric and magnetic films [8] and sequential plating of magnetic material and copper followed by selective copper etching [9-11]. Surface catalyzation with the co-deposition of electrophoretic resist and Pd ions has also been reported [14]. Although these processes have shown improvements in the device operation, the complexity, cost and process inefficiencies remain a challenge.

In this work a novel self-assembled chemistry is exploited to deposit magnetic metal alloy (Ni-Fe) on SU-8 to increase the inductance density without increasing eddy current losses. This method involves selective activation of an SU-8 layer dielectric with a self-assembled monolayer (SAM) followed by palladium catalyzation. The deposition process is based on the fact that there is a preferable bond formed between the SU-8 surface and the SAM which does not occur between the SAM and the surrounding silicon. With this approach a laminated structure was fabricated with in which the top core lamination was ~ 2.5 µm in thickness. The fabricated devices were tested before and after lamination. A complete power inductor with laminated core was realized with a CMOS compatible integrated process. Moreover, such a process has the following advantages over previously reported methods: the process is

- Site specific and seed-less (deposits only on SU-8), eliminating the need for etching of seed layers [7-8].
- CMOS compatible obviating the need for the laminated core to be co-packaged [11].
- Cost/time effective. A dilute and simple Pd solution is required rather than Pd laden electrophoretic resist [12].

- Capable of accessing recessed and high-aspect ratio structures which is not possible with physical vapour deposited (PVD) processing.
- Structurally integrated and no new material is introduced in the process [6-8].

Figure 1 depicts analytically, the influence of a modelled racetrack inductor design on the frequency response with the number of laminations for a micro-inductor (3 mm^2 footprint area). As the number of laminations increase, the frequency response of the inductors become more stable. Micro-inductors and transformers with inductances > 300 MHz range (Ultra high frequencies) could potentially find applications in hand-held devices such as cellular phones and as inductive components in matching resonant circuits. The next section describes the specification for the magnetic core, followed by the chemical process. The results of validation experiments on test structures will also be discussed.

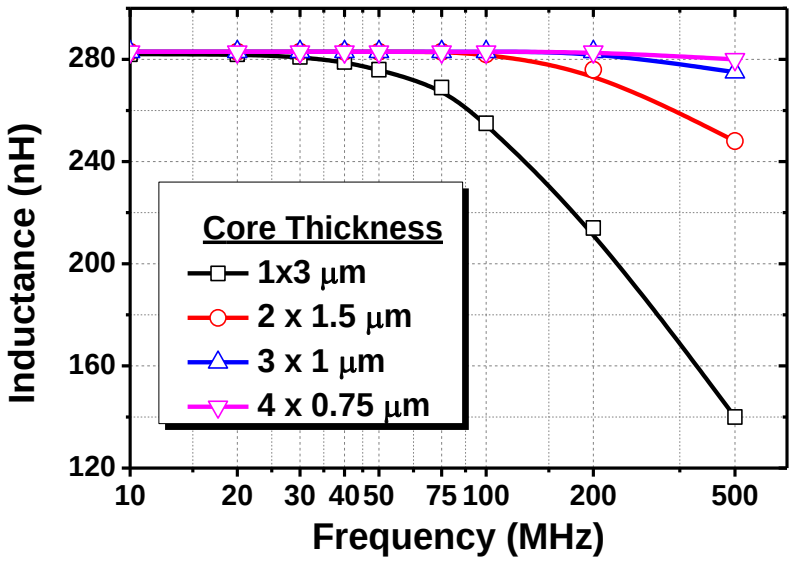

Figure 1. Frequency response of laminated micro-inductors (core resistivity: 45 µOhm-cm; core relative permeability: 280; dielectric thickness: 10 nm; core length: 3 mm; core width: 1 mm; winding gap: 15 µm and thickness: 30 µm with 4 turns).

II. Magnetic Core Specification

The total core losses can been divided into eddy current (P_e), hysteresis (P_h) and anomalous losses (P_a):

$$P_T = P_e + P_h + P_a = K_e f^2 B^n + K_h f B^n + K_{ex} f^{1.5} B^{1.5} \quad (1)$$

where, K_e, K_h and K_{ex} are the material dependent constants, 'f' is the frequency of operation while 'B' is the saturation flux density.

As indicated in the equation, eddy current losses ($P_e=K_e f^2 B^n$) become severe at high frequencies. The current carrying Cu winding generates flux which is confined within the magnetic film. However, the change in the flux in the magnetic film generates an induced current which in turn opposes the confined flux. As a result of the flux is contained in the core and the inductance is significantly reduced. It is apparent that for high frequency power converter circuitry, core eddy current losses from magnetic passives are a significant roadblock. This can be bypassed by laminating the core magnetic film. Magnetic laminations are effective when the dimension of each magnetic layer is thinner or the same as the skin depth for a specified magnetic material and operation frequency [13]. This is expressed in the skin depth equation:

$$t_{skin\ depth} = \sqrt{\rho / \pi \mu_0 \mu_r f} \tag{2}$$

where, ρ and μ_r are resistivity and relative permeability of the core material.

The core inductance of the micro-inductor is directly proportional to the thickness of the core and at low frequencies can be expressed as:

$$L_{Core} = \frac{\mu_r \mu_o N^2 l_{Core} t_{Core}}{l_{Magnetic\ Path}} \tag{3}$$

The thickness of the core is determined by the skin depth of the material at a specified operating frequency (e.g. 2.25 µm at 100 MHz for permalloy). Substituting equation (3) in (2), gives the frequency dependent inductance value as:

$$L_{Core} = \frac{N^2 l_{Core}}{l_{Magnetic\ Path}} \sqrt{\frac{\rho \mu_r \mu_0}{\pi f}} \tag{4}$$

It is apparent that at high frequency operation, the inductance being inversely proportional to the square root of frequency is restrictive. However, as the inductance decreases with frequencies, losses (like R_{ac}) will increase. At high frequencies the core inductance is frequency dependent and may be expressed by one-dimensional analysis of the electromagnetic diffusion in a laminated core with ac sinusoidal excitation [14]:

$$L_{Mag}\ (f) = L_{Core} \left(\frac{t}{2b}\right) \left(\frac{Sinh(2b/t) + Sinh(2b/t)}{Cos(2b/t) + Cos(2b/t)}\right) \tag{5}$$

The net inductance can be expressed as the sum of the air-core inductor and magnetizing inductance as:

$$L_{Net} = L_{Air} + L_{Core} \left(\frac{t}{2b}\right) \left(\frac{Sinh(2b/t) + Sinh(2b/t)}{Cos(2b/t) + Cos(2b/t)}\right) \tag{6}$$

Where, '*2b*' and '*t*' are the single lamination thickness (thickness of single magnetic film and the dielectric) and only the magnetic film thickness respectively. As the number of laminations increase, the net magnetic film thickness and the resulting magnetizing inductance and net inductance also increase.

Electrodeposited magnetic films are widely used for low cost, high deposition rate and nanometre to millimetre range deposit thickness. Table-I lists some electrodeposited soft magnetic materials reported to date for integrated magnetics applications. Ni-Fe remains one of the most widely used magnetic materials for its excellent magnetic and electrical properties. In this work the inner core is fabricated with electroplated Ni-Fe (45/55) with a reported [15] resistivity ~ 45 µOhm-cm, coercivity < 40 A/m and relative permeability ~1000. The outer top core is electrolessly deposited permalloy NiFe (81/19) film.

TABLE-I

Magnetic Material	B_{Sat} (T)	H_c (A/m)	P (μΩ-cm)
NiFe (80/20) [16-17]	1	32	20
NiFe (80/20) electroless [18]	1	29.4	24
NiFe (45/55) [19]	1.5	39.8	45
NiFe (37/63) electroless [18]	1.75	97	63
CoNiFe electroless [20]	2.15	97	29
CoP [21]	0.9-1.2	<39.8	116-136
NiFeCo (with DETA) [22]	1.9	143.2	90
CoNiFe (with DETA) [23]	1.7	477.5	130

The focus of the work is to demonstrate a simple site-selective electrochemical process and integrate the process with existing CMOS compatible micro-fabrication processes. This two-step lamination process does not require additional lithography or an electrophoretic deposition step unlike previously reported work [12].

III. Lamination Technique

In this section the electrochemical process is described, where the passivation polymer (SU-8) is activated with a SAM and subsequently catalysed in an acidified $PdCl_2$ solution. The process eliminates electrophoretic resist processing and nickel seed layer deposition and etch steps.

(a) Site-Selective Deposition on SU-8

Conventional metal electrodeposition requires a thin conductive seed layer which is often PVD deposited. This is a line-of-sight process and cannot deposit the seed in recessed regions of a device. Moreover, metal patterning then requires a wet chemical etching step. This can result in considerable device structure undercuts [4]. A more sustainable alternative would be low energy site-selective deposition of magnetic films without any conductive seed layer and capable of metal deposition in recessed regions.

4 inch silicon wafers <100> were cleaned and spin coated with SU-8 to a thickness of 65 μm. The coated SU-8 was exposed on a UV mask aligner (Cannon PLA 501FA) and treated in an oxygen plasma for 600 seconds (250 W and 30 cm^3/min flow rate). The oxygen plasma treatment activates the SU-8 surface for subsequent chemical processing. This is followed by 1800 seconds of immersion in (3-Aminopropyl)-triethoxysilane (APTES) solution. The solution is prepared with 46.5 ml Ethanol, 2.5 ml di-ionized water and 1 ml of (3-Aminopropyl)-triethoxysilane. This process allows a monolayer to be formed on the SU-8 selectively binding the silane group to the activated SU-8 surface in a covalent bond [13]. The excess APTES layers are removed by ultra-sonication. The SU-8 surface after O_2 plasma treatment was found to be more susceptible to activation than the surrounding Si surface. This can be attributed to increased oxide or hydroxide coverage at the surface of the SU-8 after oxygen plasma treatment. Immersion in a solution of palladium ions leads to the formation of palladium nuclei which can be reduced and activate successive electroless chemical deposition. The Pd layer is found to be chemically resistant to most solvents (e.g. acetone and IPA).

An in-house plating bath with dimethylamine-borane (DMAB) reducing agent was prepared to deposit the permalloy films. The authors have previously reported details for the electroless Ni-Fe-B alloy deposition process [18, 24]. Figure 2 depicts the three step process sequence. Anisotropic films deposited in the presence of an external magnetic field have been demonstrated. The bath formulation is given in table-II. It is important to maintain the bath temperature at 75 ºC and pH at 6.5 during deposition with magnetic stirring at 200 rpm.

Table-II

Bath Contents	Concentration (mol/dm^3)
Ammonium Citrate Dibasic	0.027
Lactic Acid	0.22
$NiSO_4 \cdot 6H_2O$	0.060
$FeSO_4 \cdot 7H_2O$	0.058
Dimethylamine borane complex	0.034
Ammonium Hydroxide solution	Added to maintain 6.5 pH

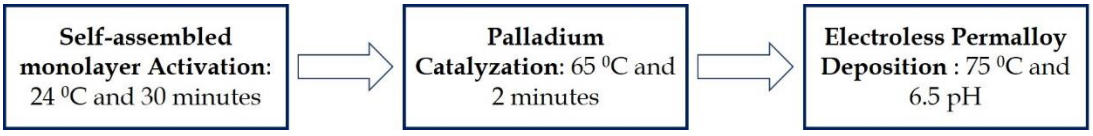

Figure 2. Sequence for the site-selective Permalloy film deposition on SU-8 without seed layer.

(a) Process Integration

Fabrication of thin film magnetic devices involves a thick passivation layer for top core patterning and protection. Figure 3 depicts a cross-sectional schematic of the process developed to activate the final SU-8 passivation layer. It is important to note that the exposed copper windings (as shown in figure 3 (a)) were concealed with thick temporary resist (such as THB-151N) as this resist cannot be activated with APTES and protects the windings from subsequent steps. The devices were plasma treated and immersed in the SAM solution as described earlier (figure 3 (b)). This was followed by ultra-sonic cleaning in acetone, IPA and DI. The devices were then catalysed in $PdCl_2$ solution (figure 3(c)) followed by electroless deposition of permalloy (~ 2 µm) (as shown in figure 3 (d)). The magnetic film thickness and uniformity of the process was confirmed with SEM analysis.

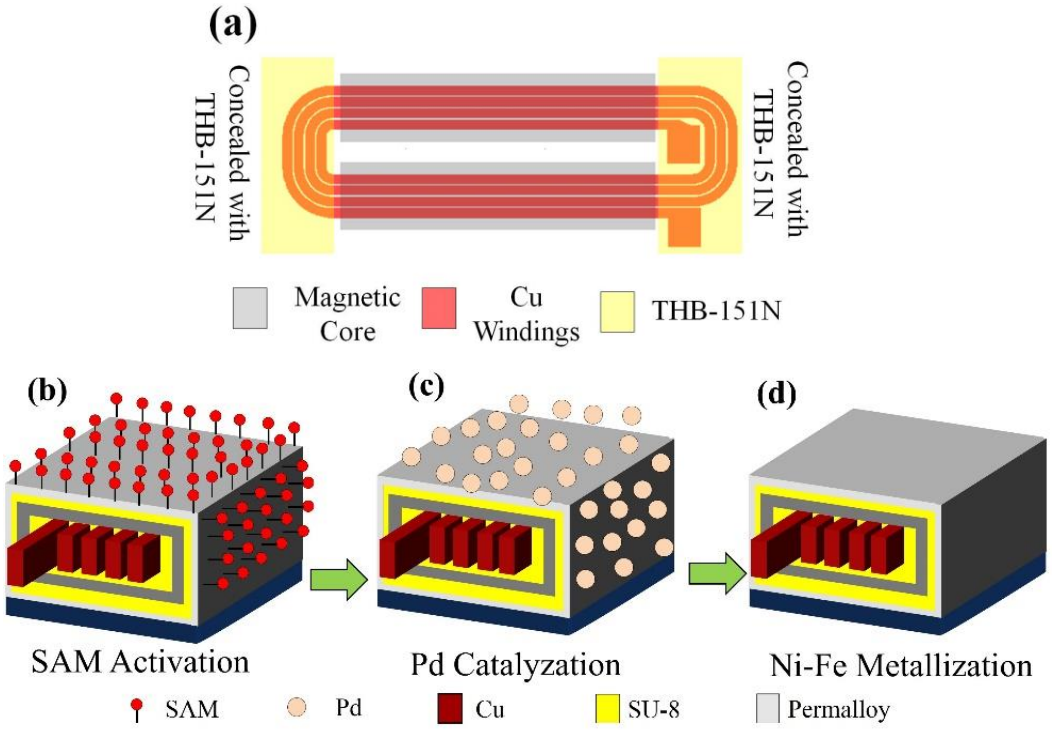

Figure 3. Electrochemical lamination process: (a) Top view of a racetrack inductor with concealed Cu coils with THB-151N. (b) SU-8 passivation layer activated with SAM. (c) Pd catalyzation and (d) Electroless permalloy deposition.

IV. Results and Discussions

Figure.4 (a) is an optical image of the site selective permalloy deposits on a patterned substrate. As observed from the image, the metal deposit is uniform all across the sample. Selective deposition with feature separations of 0.3 mm has been successfully achieved, which is ideally the core separation in integrated micro-inductors/transformers. Electron dispersive X-ray (EDX) analysis established the material composition to be Ni: 79 ± 2% and Fe: 20 ± 2%. Small trace of Pd can also be observed on the EDX spectra (figure 4 (b)). Figure 5 (a) is a scanning electron microscopic (SEM) image of the Ni-Fe alloy cross-section on a planar SU-8 surface. The uniformity of deposition on the planar surfaces is confirmed in the inset depicting the top surface of the film. The cross-section image of a 65 µm thick patterned SU-8 (figure 5 (b)) acquired by mechanically polishing the cross section confirms the uniformity of deposition on patterned structures with the inset depicting the SU-8 side-wall completely covered with permalloy.

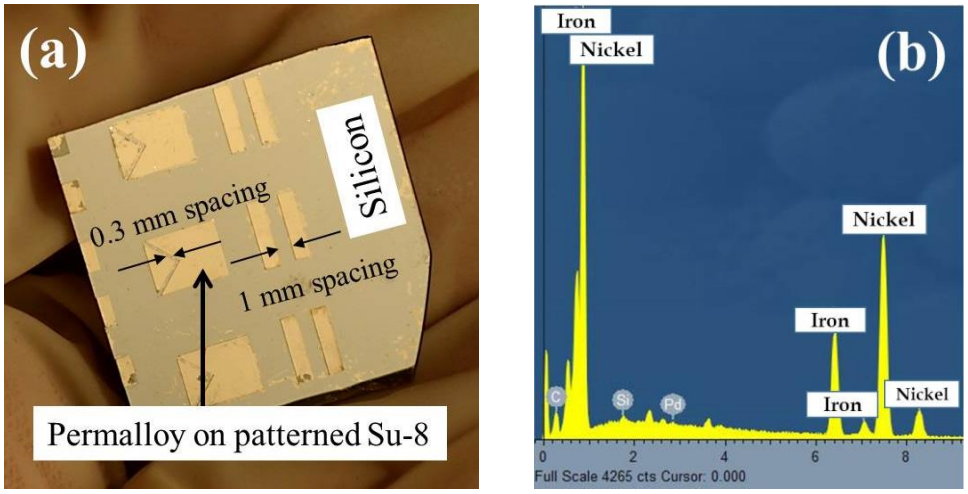

Figure 4. (a) Selective permalloy deposited on 65 µm thick SU-8 and (b) EDX spectra of the deposited permalloy film on 65 µm thick patterned SU-8.

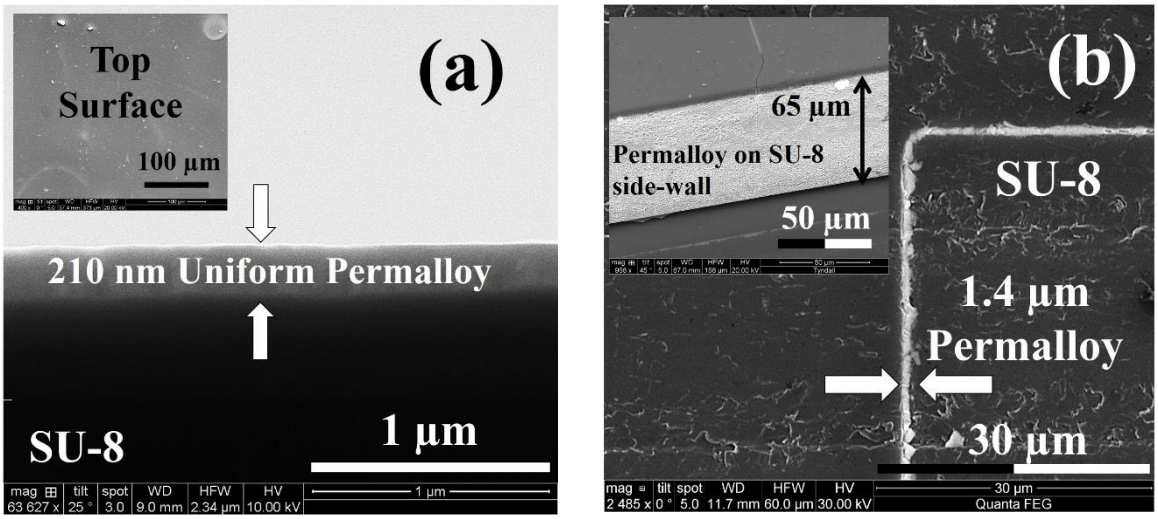

Figure 5. (a) Uniform Permalloy deposited on SU-8 without PVD deposited seed layer. (a) On planar SU-8 resist with inset depicting the top surface. (b) Cross-section of 65 µm thick patterned SU-8 with ~ 1.4 µm thick permalloy deposit and the inset depicting 45º tilted image of uniformly deposited permalloy around 65 µm thick side-wall.

The established process was then integrated with a CMOS compatible micro-inductor fabrication process. Figure 6 (a) depicts the top core fabricated with seed-less permalloy deposition on 50 µm thick SU-8. Permalloy thickness of ~ 2.5 µm was deposited on activated SU-8 patterns corresponding to the material skin depth for ~ 20 MHz operation (considering resistivity and relative permeability of 25 µOhm-cm and 500 respectively for electroless permalloy). The uniformity of the deposits is well maintained at the resist side-walls. Moreover, the conformal solution based electrochemical nature of the process eliminates poor step coverage in which is challenging for PVD deposited seed layer [25] in deep or recessed structures. This is further demonstrated in the undercut regions beneath the SU-8 (figure 6 (b)), where thick uniform permalloy is deposited without a metal seed layer. Although such undercut regions are not desirable for lamination, the deposition in such recessed regions demonstrates the ability to metallise recessed structures applicable to the wider MEMS fabrication community. SU-8 is a widely used passivation layer [26-27] in micro and nanofabricated devices being relatively immune to atmospheric and temperature/humidity changes. Figure 6 (c) shows a cross-section for a fabricated micro-inductor with an outer protective SU-8 layer. The thickness of deposited permalloy is uniform all across the surface of 70 µm thick SU-8.

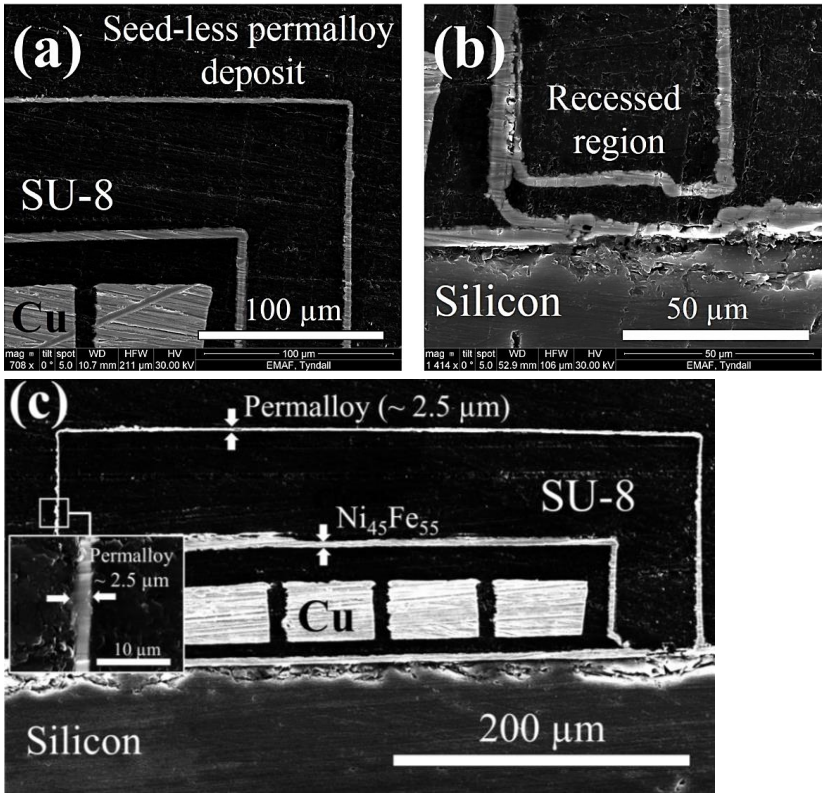

Figure 6. SEM micrograph of the device cross-section with integrated process. (a) Uniform ~ 2.5 µm thick permalloy outer-layer deposit on SU-8 including (b) recessed regions underneath SU-8 (not possible with PVD dependent processes) (c) complete device cross-section with process integrated to laminate top core.

The authors have previously reported the magnetic, structural and electrical characterization of the permalloy electrolessly deposited by the aforementioned process [18]. Anisotropic films have been deposited in the presence of external magnetic field. Moreover, the static hysteresis loop and permeability spectra suggested excellent soft magnetic properties. Figure 7 depicts the permeability spectrum of 3 layer laminated permalloy film with SU-8. As observed from the figure, the operation frequency could be increased to > 100 MHz for UHF applications. This approach could be further adapted to achieve laminated solenoid or toroidal micro-inductors with co-packaged laminated cores.

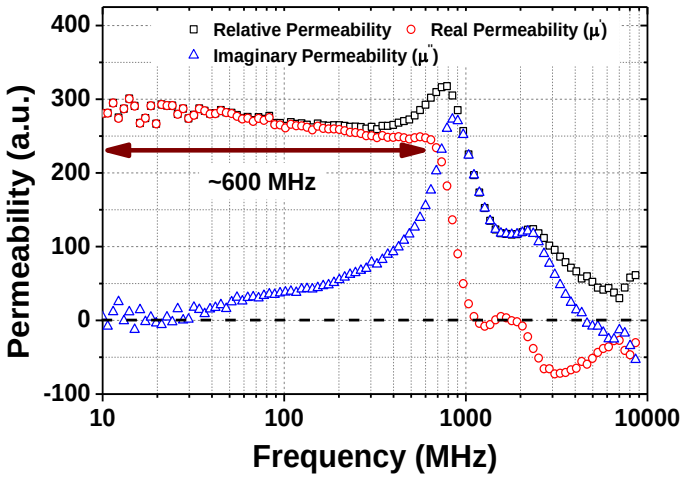

Figure 7. Permeability vs frequency of laminated film: three layers of permalloy (~ 0.5 µm) separated by SU-8 (~ 1 µm) at null bias.

V. Conclusion

An electrochemical process has been reported to deposit magnetic thin films on polymers such as SU-8. This process has been exploited to deposit permalloy site-selectively on an SU-8 passivation layer to form a laminated core structure. This process eliminates the need for electrophoretic resist patterning and subsequent Ni seed deposition. SU-8 patterns of ~ 65 µm thick were activated and electrolessly deposited with permalloy. Patterned bilayer structures with ~ 2.5 µm thick uniform permalloy were fabricated on the SU-8 insulator and integrated with CMOS compatible micro-magnetic devices (micro-inductors and micro-transformers) to form the top magnetic core. It is a site-selective process for metallization of polymer layers on silicon. Furthermore, it is an ideal metal deposition process in recessed regions which would find applications in MEMS devices.

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References

[1] C. O′Mathúna, N. Wang, S. Kulkarni and S. Roy, “Review of integrated magnetics for power supply on chip (PwrSoC),” IEEE T. Power Electr., vol. 27, Iss. 11, 4799-4816.

[2] C. R. Sullivan, D. V. Harburg, J. Qiu, C. G. Levey and D. Yao, “Integrating magnetics for on-chip power: a perspective,” IEEE T. Power Electr., vol. 28, no. 9, 2013, pp.4342-4353.

[3] J. Kim, M. Kim, J. K. Kim, F. Herrault and M. G. Allen, “Anisotropic nanolaminated CoNiFe cores integrated into microinductors for high frequency dc-dc power conversion,” J. Phys. D Appl. Phys., vol. 48, no. 46, 2015, pp. 1-6.

[4] R. Anthony, N. Wang, S. Kulkarni and C. O′Mathúna, “Advanced in planar coil processing for improved micro-inductor performance,” IEEE T. Magn., Vol. 50, Iss. 11, 2014, pp.1-4.

[5] M. Xu, T. M. Liakopoulos and C. H. Ahn, “A microfabricated transformer for high-frequency power or signal conversion,” IEEE Trans. Magn., vol. 34, no. 4, 1998, pp.1369-1371.

[6] D. P. Arnold, I. Zana, F. Cros and M. G. Allen, “Vertically laminated magnetic cores by electroplating Ni-Fe into micromachined Si,” IEEE Trans. Magn., vol. 40, no. 4, 2004, pp.3060-3062.

[7] J. Y. Park, S. H. Han and M. G. Allen, "Batch-fabricated microinductors with electroplated magnetically anisotropic and laminated alloy cores," IEEE Trans. Magn., vol. 35, no. 5, 1999, pp.4291-4300.

[8] C. R. Sullivan and S. R. Sander, "Micro-fabrication process for high-frequency power-conversion transformers," Proc. 26th Annu. Power Electronics Specialist Conf., June 1995, pp. 658-665.

[9] J. W. Park, F. Cros and M. G. Allen, "A sacrificial layer approach to highly laminated magnetic cores," 15th IEEE Int. Conf. Micro Electro Mechanical Syst., 2002, pp.380-383.

[10] J. Kim, M. Kim, F. Herrault, J. Park and M. G. Allen, "Highly laminated soft magnetic electroplated CoNiFe thick films," IEEE Mag. Lett., vol. 4, 2013, 5000204.

[11] M. Kim, J. Kim, F. Herrault, R. Schafer and M. G. Allen, "A MEMS lamination technology based on sequential multilayer electrodeposition," J. Micromech. Microeng., vol.23, 2013, 095011, pp.1-9.

[12] M. Brunet, T. O. Donnell, A. M. Connell, P. McCloskey and S. C. O′Mathúna, "Electrochemical process for the lamination of magnetic cores in thin-film magnetic components," IEEE J. Microelectromech. S., vol. 15, no. 1, 2006, pp. 94-100.

[13] V. Sunkara, D. K. Park, H. Hwang, R. Chantiwas, S. A. Soper and Y. K. Cho, "Simple room temperature bonding of thermoplastics and poly(dimethylsiloxane)," Lab Chip, vol. 11, 2011, pp. 962-965.

[14] T. O' Donnell, N. Wang, S. Kulkarni, R. Meere, F. M. F. Rhen, S. Roy and S. C. O′Mathúna, "Electrodeposited anisotropic NiFe 45/55 thin films for high-frequency micro-inductor applications," J. Magn. Magn. Mater., vol. 322, pp.1690-1693, 2010.

[15] J. Lammeraner and M. Stafl, Eddy Currents, Iliffe books Ltd., London, pp.30-37, 1966.

[16] N. Wang, T. O' Donnell, S. Roy, M. Brunet, P. McCloskey and S. C. O′Mathúna, "High-frequency micro-machined power inductors," J. Magn. Magn. Mater., vol. 290-291, 2005.

[17] J. W. Park, F. Cros and M. G. Allen, "Planar spiral inductors with multilayer micrometer-scale laminated cores for compact-packaging power converter applications," IEEE T. Magn., vol. 40, no. 4, pp 2020-2022, 2003.

[18] R. Anthony, B. J. Shanahan, F. Waldron, C. O′Mathúna and J. F. Rohan, "Anisotropic Ni-Fe-B Films with Varying Alloy Composition for High Frequency Magnetics on Silicon Applications," Appl. Surf. Sci., Vol. 357, 2015.

[19] R. Meere, T. O' Donnell, N. Wang, S. Kulkarni and C. O′Math'una, "Size and performance trade-off in micro-inductors for high frequency dc-dc conversion," IEEE T. Magn., vol. 45, no. 10, pp 4243-4237, 2009.

[20] J. F. Rohan, B. M. Ahern, K. Reynolds, S. Crowley, D. A. Healy, F. M. F. Rhen and S. Roy, "Electroless thin film CoNiFe-B alloys for integrated magnetics on Si," Electrochim. Acta, vol. 54, pp. 1851-1856, 2009.

[21] P. McCloskey, B. Jamieson, T. O' Donnell, D. Gardner, M. A. Morris and S. Roy, "High frequency nanostructured magnetic materials for integrated inductors," J. Magn. Magn. Mater., vol. 320, pp. 2509-2512, 2008.

[22] T. Osaka, "Electrodeposition of highly functional thin films for magnetic recording devices of the next century," Electrochim. Acta, vol. 45, pp. 3311-3321, 2000.

[23] T. Yokoshima, M. Kaseda, M. Yamada, T. Nakanishi, T. Momma and T. Osaka, "Increasing the resistivity of electrodeposited high Bs CoNiFe thin film," IEEE T. Magn., vol. 35, pp.2499-2501, 1999.

[24] R. Anthony, C. O′Mathúna and J. F. Rohan, "Permalloy Thin Films on Palladium Activated Self-Assembled Monolayer for Magnetics on Silicon Applications," Elsevier Proc. Phys., 2015.

[25] T. Karabacak and T. M. Lu, "Enhanced step coverage by oblique angle physical vapour deposition", J. Appl. Phys., vol. 97, pp.124504-1-5, 2005.

[26] A. Olziersky, P. Barquinha, A. Vila, L. Pereira, G. Goncalves, E. Fortunato, R. Martins and J. R. Morante, "Insight on the SU-8 resist as passivation layer for transparent Ga2O3–In2O3–ZnO thin-film transistors," J. Appl. Phys., vol. 108, 064505 , 2010.

[27] X. Yu, M. Ki, F. Herrault, C. H. Ji, J. Kim and M. G. Allen, "Silicon-embedding approaches to 3D toroidal inductor fabrication", J. Microelectromech, vol.22, no. 3, 2013, pp.580-588.