

Spin-on-Glass (SOG) Based Insulator of Stack Coupled Microcoils for MEMS Sensors and Actuators Application

(Penebat Gelelung Mikro Gandingan Tertimbun Berasaskan Spin-atas-Kaca (SOG) untuk Aplikasi Pengesan dan Penggerak MEMS)

JUMRIL YUNAS*, BURHANUDDIN YEOP MAJLIS, AZRUL AZLAN HAMZAH & BADARIAH BAIS

ABSTRACT

A comprehensive study on the spin-on-glass (SOG) based thin film insulating layer is presented. The SOG layer has been fabricated using simple MEMS technology which can play an important role as insulating layer of stack coupled microcoils. The fabrication process utilizes a simple, cost effective process technique as well as CMOS compatible resulting to a reproducible and good controlled process. It was observed that the spin speed and material preparation prior to the process affect to the thickness and surface quality of the layer. Through the annealing process at temperature 425°C in N₂ atmospheric for 1 h, a 750 nm thin SOG layer with the surface roughness or the uniformity of about 1.5% can be achieved. Furthermore, the basic characteristics of the spiral coils, including the coupling characteristics and its parasitic capacitance were discussed in wide range of operating frequency. The results from this investigation showed a good prospect for the development of fully integrated planar magnetic field coupler and generator for sensing and actuating purposes.

Keywords: Insulating layer; MEMS fabrication; sensor and actuator; spin-on-glass; stack coupled microcoils

ABSTRAK

Satu kajian menyeluruh mengenai lapisan penebat filem nipis berasaskan spin-atas-kaca (SOG) dibentangkan. Lapisan SOG telah difabrikasi menggunakan teknologi mudah MEMS yang memainkan peranan penting sebagai lapisan penebat gelelung mikro gandingan tertimbun. Proses fabrikasi tersebut menggunakan teknik mudah, kos efektif serta serasi dengan CMOS dan menghasilkan proses pengulangan dan kawalan yang baik. Dapat diperhatikan bahawa kelajuan putaran dan penyediaan bahan sebelum proses memberi kesan kepada ketebalan dan kualiti permukaan lapisan. Melalui proses penyepuhlindapan pada suhu 425°C dalam atmosfera N₂ selama 1 jam, lapisan SOG nipis setebal 750 nm dengan kekasaran permukaan atau keseragaman yang dicapai adalah sekitar 1.5%. Seterusnya, ciri-ciri asas gelelung lingkaran, termasuk ciri-ciri gandingan dan kapasitan parasitik juga turut dibincangkan dalam berbagai julat frekuensi operasi. Hasil kajian ini menunjukkan prospek yang baik bagi pembangunan pengganding medan magnet dan penjana planar bersepadu untuk tujuan pengesanan dan pergerakan.

Kata kunci: Fabrikasi MEMS; gelelung mikro gandingan tertimbun; lapisan penebat; pengesan dan penggerak; spin-atas-kaca

INTRODUCTION

Recently, thin film insulator based on spin-on-glass (SOG) material plays an important roles in many micro devices, such as passivation layer of microelectronics devices to protect the active structures from environment (Gaeta & Wu 1989), sacrificial layer in MEMS structure (Hamzah et al. 2007) and also low-k dielectric layer of small gap capacitor (Aw 2004). Spin-on-glass is also used as insulator and planarization layer for multilevel CMOS structure because of its simple technology and excellent dielectric property of the Si-oxide interfacial layer. SOG is in general Si-O network polymers in organic solvent and prepared through the hydrolysis condensation reaction that implied the sol-gel technology. Its dielectric constant ϵ , lies in range 3-5 which is better than that of vapor deposited or oxidation

based silicon oxide which is among the best insulators and has the one of the highest field strength of all dielectric materials (Qin et al. 1998; Schmidt et al. 2007).

Various types of magnetic devices such as magnetic sensors, microactuators, transformers and filters that are driven by magnetic induction principle have been reported in some literatures (Lee et al. 2009; Shen et al. 2008; Tapia et al. 2011). Most of them utilized the planar spiral coil, solenoid coil or toroid coil with an additional thick permanent magnetic material for the coupling, which unfortunately affect the volume density of the device. On the other hand, several techniques utilizing MEMS technique to fabricate the coil structures have been reported and several of those include also stack planar, solenoid, toroidal type, 3-D on chip suspended structure and out of

plane coil structure (Brunet et al. 2001; Gel 2002; Yoon et al. 1999; Yunas et al. 2009). First planar coupled coil integrated with active device was reported by Mino et al. (1995), while planar coreless coil and stack structure were then developed to create new high efficiency and high density coil structures using thin film technology (Arshak & Almkhtar 1999).

Although high quality factor and high coupling factor could be achieved, the reported structures were complex and fabricated using expensive technique, which still becomes the fundamental problem in realizing integrated micro-magnetic devices. Furthermore, implementing the coupled inductor coils that operate at high frequency remains problematic when fabricating the device in silicon based integrated circuit. The parasitic influences of the material become dominant and cause an increase of the skin, proximity and eddy current effects. Therefore the use of stacked coil structures with as thin as possible insulating layer should overcome the problems mentioned above.

In this paper we report an experimental study on the fabrication of thin insulator layer by means of spin coating method of thin SOG based oxide. In this work, two separated metal layers of planar coupled coil that is formed in stacked structure on silicon substrate are isolated from short-circuit. The stack coil structures consist of two separated interwinding coil levels, forming a vertically stack structure with a relatively low distance between them. Therefore, high resistivity of the oxide layer is required for isolation purpose which also has the function to prevent the substrate effect on the device. Other function of the SOG is as mask in etching process and buffer layer for suspended MEMS structure.

THEORETICAL ANALYSIS

Stacked microcoil is a planar spiral type metal conductor line that is structured stacked each other and separated by a thin insulating layer. The structure forms a double layer of planar interwinding coil which is able to generate and couple magnetic flux through its parallel metal trace in both vertical and lateral direction (Figure 1). On each layer, two separated coils with the width of $50\ \mu\text{m}$ and the spacing of $50\ \mu\text{m}$ are wound side by side. Each coil has square spiral configuration consisting of 3 winding numbers with an inner coil area of $500 \times 500\ \mu\text{m}^2$. This structure represents a planar interwinding coupled micro-coil structure.

Theoretically, the structure of each inductor coil can be modeled as pi-lumped element model that includes the capacitance of SOG insulating layer (C_{ox}), parasitic component of the substrate (C_{si} and R_{si}), as shown in Figure 2. The series inductance and resistance of the coil in the model are represented by the series L_s and R_s , respectively. The capacitances between the conductor traces and fringes are represented as coupling capacitance that can be measured between the output pads of the devices and modeled as C_s .

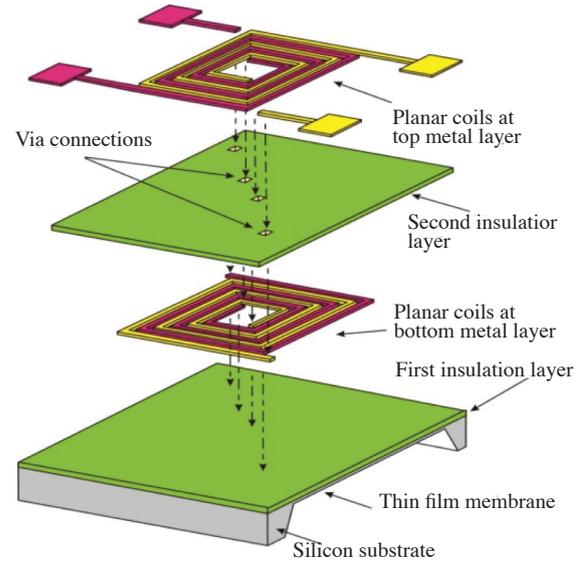


FIGURE 1. Schematic configuration of coupled coil structure

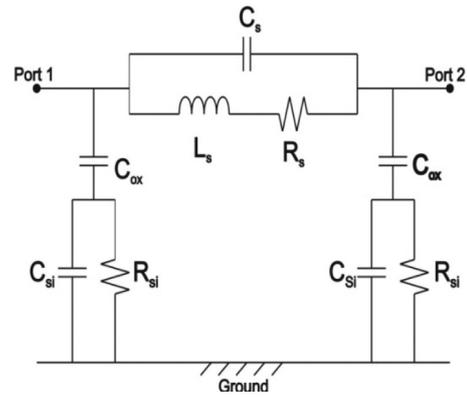


FIGURE 2. Simplified Pi-lumped element circuit model of a spiral coil

In the pi-model, parasitic elements of oxide (C_{ox}) and substrate (C_{si} and R_{si}) are modeled as a separated element that is useful for the analysis of coil characteristics in frequency independent model. These parasitic elements can be further simplified to R_p and C_p in order to enable an analysis of highly frequency dependent model, where:

$$R_p = \frac{1 + \omega^2 R_{si} (C_{si} + C_{ox})^2}{\omega^2 R_{si} C_{ox}^2}, \quad (1)$$

$$C_p = \frac{C_{ox} \{1 + \omega^2 R_{si} C_{si} (C_{si} + C_{ox})\}}{1 + \omega^2 R_{si} (C_{si} + C_{ox})^2}, \quad (2)$$

thus, the parasitic elements of the planar coil can be considered as components which are strongly frequency dependent. The C_p and R_p value can be therefore predicted as the reason of large shifting of the resonance frequency of the coil.

FABRICATION OF THE SOG LAYER

In this works, spin coating method of glass material is the preferred method to form an isolation layer between two coil layers, which is due to the simple process and the possibility to produce planar thick oxide layer. The Spin-on-Glass (SOG) material has been widely used as dielectric layer, insulator and planarization scheme in multilevel metallization schemes in the fabrication of IC's.

Producing the oxide layer is done by dripping some of the SOG liquid (from *Honeywell T14-314*) on the center of the wafer and spinning the wafer with some specified rpm value (typically 1000 to 5000 rpm). Centrifugal forces will distribute the liquid evenly on the wafer and a thin layer (typically around 0.8 to 1.5 μm) is formed. To the process, the layer thickness depends on the rotation speed of the spin coater and baking procedure. The higher the speed the thinner oxide layer can be achieved.

Furthermore, baking process using direct-contact hot plate is one important step in this process, which is aimed to remove the water contain in the material. Care must be taken during baking process, because fast temperature change in direct contact with hot plate systems often causes film cracking and the layer becomes crystallized due to the high temperature stresses (Figure 3). Therefore the maximum baking temperature should be controlled up to 250°C and the temperature should be slowly increased in a gradually ramping, profile as shown in Figure 4.

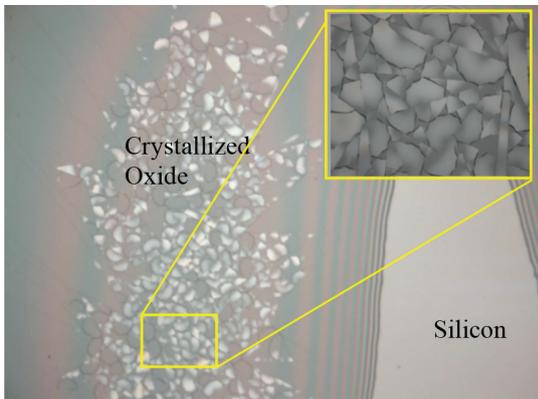


FIGURE 3. Microphotograph of crack building due to the thermal stress

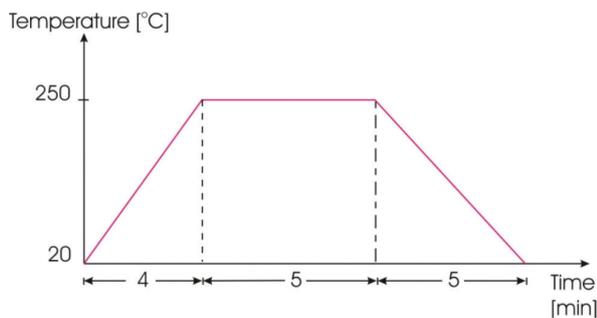


FIGURE 4. Temperature ramping profile in baking procedure of SOG layer

RESULTS AND DISCUSSION

The SOG thickness depends strongly on age of the liquid, spin speed and sample preparation before coating. The spin and baking procedure affect directly to the performance of the surface quality and mechanical characteristic of the layer. Therefore, it is very important to follow the procedure carefully. Keeping the SOG liquid in room temperature more than 1 h before coating will affect the glass concentration due to the quick evaporation of the water content. This condition sometime allows us to achieve thick oxide layer. However smooth and uniform surface is difficult to obtain.

In this work we are able to control the SOG film properties using direct contact baking on hot plate systems followed by thermal annealing process in N_2 atmospheric chamber without generating cracks and crystal particles in SOG films. The oxide thickness and quality of the surface is analyzed using optical microscopes and optical surface profiler. The typical surface view of spin-coated oxide shows a color variation ranging from orange to dark green. These color variation indicates a difference in layer thickness due to non-uniform material distribution during spinning (Figure 5). Furthermore, incomplete baking or uniform baking also results in poor uniformity, hence affecting the different etch rate in the following etch process steps.

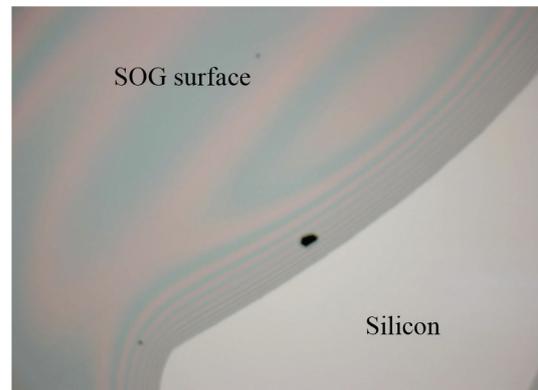


FIGURE 5. Color variation of deposited SOG layer

The results in Figure 6 shows the measured surface profile of SOG layer. The plotted profile indicates a rapid decreasing of the layer thickness as spinning speed increases from 1500 to 4000 rpm. For spinning speed of 1500 rpm we get a 1095 nm thick oxide, however 5% surface roughness is obtained. Lower oxide thickness is achieved by spinning the SOG at 4000 rpm. It resulted in a minimum thickness of 830 nm with a 2.8% surface roughness.

For better oxide quality, we put the deposited SOG after normal baking process in the annealing chamber to further reduce the water contain and at the same time to decrease the permittivity constant of the layer. After hard

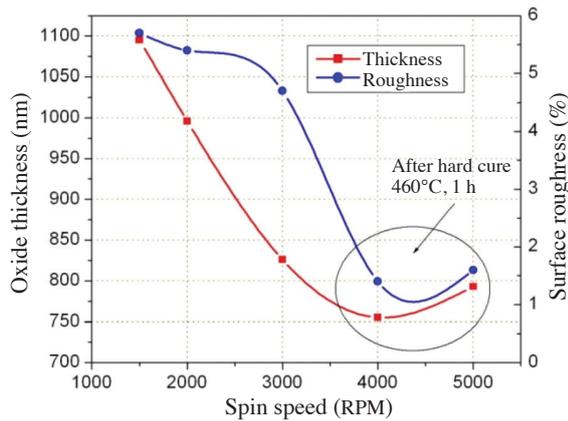


FIGURE 6. Characteristics of SOG by spin speed variation

curing the layer at temperature 425°C in N_2 atmospheric for 1 h, the oxide thickness shrinks up to 18–20% resulting to a thickness of 760 nm and surface roughness improves 1.5%. The uniformity of the oxide surface below 2% is a preferable condition for further coating step of the next layer.

To investigate the effect of the SOG layer to the coil performance, several coils having various SOG layer thicknesses are analyzed in wide range of operating frequency. In general, the variation of the layer thickness doesn't affect to significant changing of the series inductance or resistance value. The thick insulating layer affects not only the parasitic capacitances but also the parasitic resistance. Hence it reduces the operating frequency of the device.

It is shown in Figure 7 that low C_p is obtained when thick oxide layer is used. The reason for the reduced parasitic capacitance is that the EM field generated by the spiral coil cannot penetrate in the conductive substrate layer. Hence it blocks the eddy current induction to the coils. This means that the distance between coil and substrate should be designed to be as far as possible.

Figure 8 shows that as metal-to-metal distance (insulating layer thickness between the metals) decreases

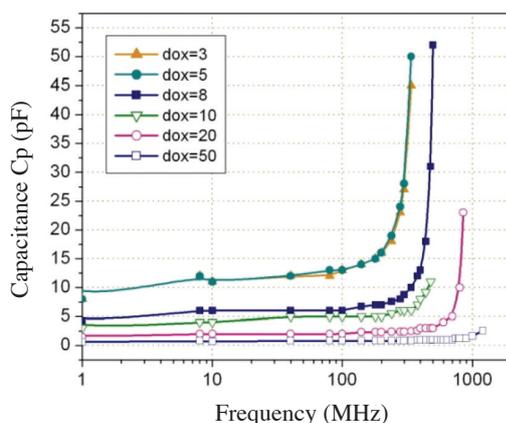


FIGURE 7. Parasitic capacitance vs. frequency for various oxide thickness

the coupling will slightly improves, since the resonance frequency are suppressed due to the increase of the metal-metal capacitances. For large distance, no significant increase of coupling is obtained which is due to high leakage.

It is therefore considered to fabricate as closest as possible metal layer of the coils to keep high vertical coupling. On the other side it is shown that the total insulating layer thickness affects a small influence of the magnetic coupling. Reducing the insulator thickness will improve the coupling, which is in opposite to the quality factor. There are therefore compromises in technological consideration required to find appropriate transformer design.

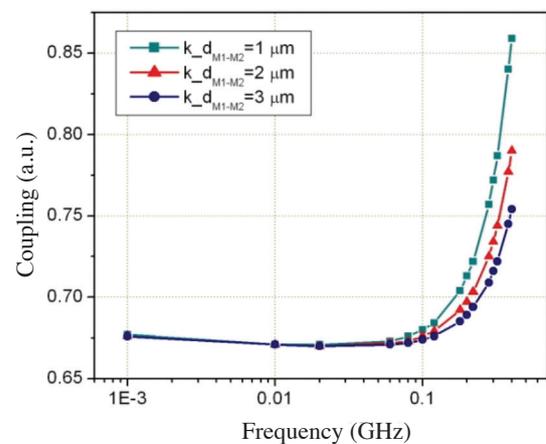


FIGURE 8. Coupling characteristics as a function of oxide thickness between metal and substrate, $N = 3$, $w = 100$ micrometers, $s = 50$ micrometers

CONCLUSION

The thin film insulating layer made of SOG material has been studied and fabricated using MEMS process technique. The structure of the layer can affect the performance of the stack planar fabricated microcoil used for microsensor or microactuator devices applications. A simple technique in fabricating the layer has been optimized in order to enable a reproducible process. An annealing process at temperature 425°C in N_2 atmospheric for 1 h could reduce the SOG thickness 18–20% resulting to a thickness of 760 nm and improved surface roughness of 1.5%. The study on the characteristics of the insulator layer showed that a thin oxide layer between the metal layers is preferred in order to keep high magnetic coupling between the coils. Moreover, a sufficiently thick oxide layer between the coil and substrate is important to prevent eddy current effect of the substrate to the device. It is also concluded that fabricating as closest as possible metal layer of the coils is required to keep high vertical and high density of planar magnetic coupling device.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Science Technology and Innovation under the project Nr. 03-01-02-SF0841 (Development of Integrated Electromagnetic Micro-pump Based on Embedded Planar Micro-coil for Ultra Low Fluid Injection of Bio-Samples).

REFERENCES

- Arshak, K.I. & Almukhtar, B. 1999. Development of high frequency coreless transformer using thick film polymer technology. *Microelectronics Journal* 30(2): 119-125.
- Aw, K.C. 2004. Reliability of MSQ spin-on glass as low-k interlayer dielectric in VLSI device. *Proc. of IEEE International Conference on Semiconductor Electronics (ICSE)*, 7-9 Dec.
- Brunet, M., O'Donnell, T., O'Brien, T., Mckloskey, J. & O'Mathuna, C. 2001. Design study and fabrication techniques for high power density microtransformers. *Proc. of Applied Power Electronics Conference and Exposition. 2001. APEC2001. Sixteenth Annual IEE*. 2: 1189-1195.
- Gaeta, I.S. & Wu, K.J. 1989. Improved EPROM moisture performance using spin-on-glass (SOG) for passivation planarization. *Reliability Physics Symposium, 27th Annual Proceedings.*, International, Santa Clara, US: 122 – 126.
- Gel, M. 2002. Fabrication method for out of plane, micro-coil by surface micromachining. *Sensor and Actuators A*: 97-98.
- Hamzah, A.A., Majlis, B.Y. & Ahmad, I. 2007. HF etching of sacrificial spin-on glass in straight and junctioned microchannels for MEMS microstructure release. *J. Electrochem. Soc.* 154(8): D376-D382.
- Lee, C.Y., Chen, Z.H., Chang, H.T., Wen, C.Y. & Cheng, C.H. 2009. Design and fabrication of novel micro electromagnetic actuator. *Microsyst. Technol.* 13(11-12): 1171-1177.
- Mino, M., Yachi, T., Yanagisawa, K., Tago, A. & Tsukamoto, K. 1995. Switching converter using thin film microtransformer with monolithically integrated rectifier diodes. In *Power Electronics Specialist Conference, PESC '95 Record, 26th Annual IEEE (Volume 2)*.
- Qin, S., Zhou, Y., Chan, C. & Chu, P.K. 1998. Fabrication of low dielectric constant materials for ULSI multilevel interconnection by plasma ion implantation. *IEEE Electron Device Letter* 19(11): 420-422.
- Schmidt, V., Senz, S. & Goesele, U. 2007. Influence of the Si/SiO₂ interface on the charge carrier density of Si nanowires. *Appl. Phys. A* 86(2): 187-191.
- Shen, M., Yamahata, C. & Gijs, M.A.M. 2008. A high-performance compact electromagnetic actuator or a PMMA ball-valve micropump. *J. Micromech. Microeng.* 18: 025031.
- Tapia, J.A., Agustin, L. Pedro, H.M., García-Ramírez, J., Martínez-Castillo, J., Figueras, E., Flores, A. & Manjarrez, E. 2011. Sensing magnetic flux density of artificial neurons with a MEMS device. *Biomed. Microdevices* 13: 303–313.
- Yoon, J.B., Ahn, C.H. & Kim, C.K. 1999. High performance three dimensional on-chip inductors fabricated by novel micromachining technology for RF MMIC. *IEEE MTT-S International Microwave Symposium Digest* 4: 1523-1526.
- Yunas, J., Hamzah, A.A. & Majlis, B.Y. 2009. Fabrication and characterization of surface micromachined stacked transformer on glass substrate. *Microelectronics Engineering* 86: 2020-2025.

Jumril Yunas*, Burhanuddin Yeop Majlis & Azrul Azlan Hamzah
Institute of Microengineering and Nanoelectronics
Universiti Kebangsaan Malaysia
43600 Bangi, Selangor
Malaysia

Badariah Bais
Faculty of Engineering and Built Environment
Universiti Kebangsaan Malaysia
43600 Bangi, Selangor
Malaysia

*Corresponding author; email: jumrilyunas@ukm.my

Received: 7 January 2013

Accepted: 22 July 2013