Sensor packaging

Body-Implantable RFID Tags Based on Ormocer Printed Circuit Board Technology

Gianmario Scotti[1], Sue-Yuan Fan[1], Chun-Hsiang Liao[2], and Yi Chiu[1*]

[1] Department of Electrical and Computer Engineering, National Chiao Tung University, Hsin Chu 30010, Taiwan
[2] Institute of Biomedical Engineering, National Chiao Tung University, Hsin Chu 30010, Taiwan
[*] Member, IEEE

Manuscript received May 4, 2020; revised June 10, 2020; accepted June 28, 2020. Date of publication July 14, 2020; date of current version July 31, 2020.

Abstract—This letter demonstrates, for the first time, a biocompatible radio frequency identification (RFID) tag fabricated on an Ormocer substrate and encapsulated in it. Ormocomp belongs to a group of hybrid organic-inorganic photostructurable materials called Ormocers. It is biocompatible, chemically inert, and electrically insulating—ideal for body-implantable applications. In this letter, we have developed an Ormocomp-based printed circuit board and packaging method and implemented a biocompatible RFID tag.

Index Terms—Sensor packaging, biocompatible, implantable radio frequency identification (RFID) tag, Ormocer, packaging, printed circuit board (PCB).

I. INTRODUCTION

Since the first implantable pacemaker in 1958, numerous implantable devices have been developed to address various physiological, biochemical, or physical needs for medication, caring, and monitoring [1]–[3]. Due to the diverse functions and specifications of these implantable devices, different materials, structures, and electronics have to be applied and designed. Nevertheless, one common challenge in developing implantable devices is the biocompatibility of materials that are exposed to body tissues [2]. Therefore, implanted devices are either encased with biocompatible materials or covered with biocompatible coatings. Modern implanted devices with sophisticated electronic functions need printed circuit boards (PCBs) for system integration. However, traditional lamination-based PCB technology is not biocompatible.

Hence, the first goal of this letter is to develop a biocompatible PCB technology from an Ormocer, specifically Ormocomp. Ormocers are a class of biocompatible copolymers synthesized from siloxane and organic monomers. The properties of Ormocers can be tuned with the addition of other copolymers and photoinitiators [4]. The cytotoxicity of Ormocers has been extensively tested and they have been used in dentistry since 1988 [5]–[8].

In this letter, Ormocomp was chosen as it is readily available and extensively used in the fabrication of various microdevices such as microfluidic devices [9]–[11] and cell growth scaffolds [6], [7]. The optical transparency of Ormocomp allows for the fabrication of optical waveguides and sensors [12]–[15]. In [10], a free-standing electrophoresis–electrospray device was fabricated in Ormocomp, demonstrating the feasibility of the material as a substrate for microfabrication. In a preliminary study [16], a PCB technology based on cured Ormocomp substrates was suggested. On such a PCB, conductors and integrated circuits (ICs) of various types (including microelectromechanical system (MEMS) sensors) can be integrated into one, easy to encapsulate, unit. The conductors serve to interconnect the ICs and to implement antennas and inductive as well as capacitive elements. This allows for the creation of highly integrated body implants with only Ormocomp facing the body tissues. Such device integration technology using a singular biocompatible substrate and encapsulation is not yet available in current technologies.

As a proof of concept, in this letter, we describe the fabrication process of an Ormocomp-based electronic product code (EPC) ultra high frequency (UHF) Gen2 radio frequency identification (RFID) tag containing a control IC and a loop antenna. The RFID functionality is demonstrated by inserting the tag under a piece of swine tissue and successfully detecting with an RFID reader. The detection range and received signal strength indication (RSSI) were measured and compared with a commercial tag.

II. ORMOCOMP RFID TAG FABRICATION

The fabrication of the Ormocomp-based RFID tag (as well as any other Ormocomp PCB based body-implantable device) can be broken down into the following five main steps:

1) preparation of a thin Ormocomp substrate or “wafer;”
2) lamination of copper or aluminum metallization on one or both sides of this substrate;
3) patterning the metallization using traditional photolithography techniques;
4) bonding of electronic components on the Ormocomp PCB;
5) finally, encapsulation of the device in Ormocomp so it is entirely biocompatible and can be safely body-implanted.

The Ormocomp substrates were prepared by casting between two glass plates. The glass plates were first immersed in a 5% solution of dimethyldichlorosilane in toluene to reduce the adhesion of cured Ormocomp. A more detailed description of the subsequent process flow of the lamination-based Ormocomp PCB process is illustrated in Fig. 1.

a) Liquid Ormocomp is sandwiched between two glass plates with 250 μm spacers to control the thickness of the substrate.
b) The liquid Ormocomp is cured for 5 min. using an LED UV lamp at a wavelength of about 400 nm.
c) The cured substrate is removed from the glass plates.
d) A small amount of Ormocomp is applied to a 25 μm thick copper foil or a 15 μm thick aluminum foil.

Corresponding author: Gianmario Scotti (gianmario.scotti@gmail.com).
Associate Editor: S. S. Li.
Digital Object Identifier 10.1109/LSENS.2020.3009126

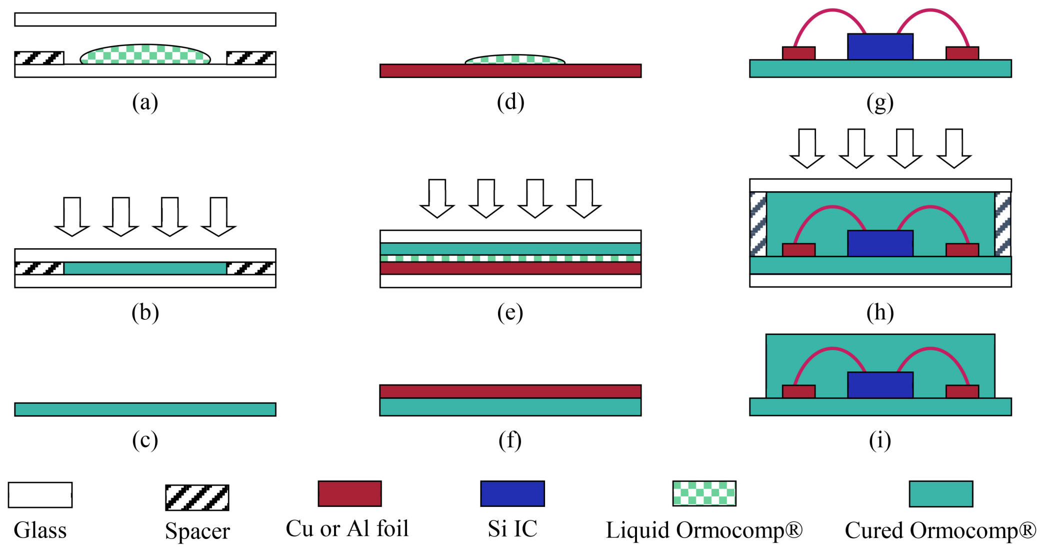

Fig. 1. Illustration of fabrication steps of an Ormocomp PCB-based body-implantable device.

e) The Cu or Al foil is pressed against the Ormocomp substrate prepared in (c) between glass plates to bond the foil with the substrate by UV-curing the Ormocomp applied in (d) for 1 min.
f) The metal-cladded substrate is detached from the glass plates.
g) Conductor traces are patterned by traditional photolithography, and electronic components (e.g., an RFID control IC, Alien Higgs 3 [17], in this study) are attached and wire-bonded.
h) To encapsulate the Ormocomp PCB, liquid Ormocomp is poured on the component side of the PCB and UV-cured between glass plates for 3 min.
i) Finally, the encapsulated Ormocomp PCB is diced for individual body-implantable devices. It is noted that the encapsulation can also be conducted at device level by dicing the PCB in (g) first.

III. EXPERIMENTAL RESULTS

Fig. 2(a) shows a clear Ormocomp substrate prepared by following steps (a) through (c) in Fig. 1. The roughness of cured Ormocomp substrates was measured by a white light interferometer, as shown in Fig. 2(b). The height histogram of a typical measurement is shown in Fig. 2(c). The root mean square surface roughness Rq at various locations was about 30–60 nm. Fig. 2(d) shows multiple Cu loop antenna patterns for RFID tags on the substrate. Fig. 2(e) shows a micrograph of an RFID controller IC, which was wire-bonded to the loop antenna and covered with Ormocomp. Fig. 2(f) shows a similar tag based on Al metallization, indicating the versatility of the developed PCB technology. It is noted that metallization can also be achieved by using deposited metallic films [11]. However, lamination of metal foils was adopted in this study to demonstrate low cost manufacturing for future large scale commercialization.

Fig. 3(a) and (b) shows diced and encapsulated tags with Cu and Al metallization, respectively. These are EPC global Gen 2 RFID tags and measure 10 × 12 mm. To test the functionality of the Ormocomp RFID tag, the tag was placed under a 5-mm-thick piece of raw pork (muscle and fat) to emulate human body tissues [see Fig. 3(c)]. We used a Sparkfun Simultaneous RFID Reader shield [18] on top of a Sparkfun RedBoard [19] (Arduino UNO compatible) to implement an RFID reader/transmitter operating in the UHF 860–960 MHz range. The board was programmed using the SparkFun Simultaneous RFID Tag Reader Arduino Library and the Example_Constant_Read program.

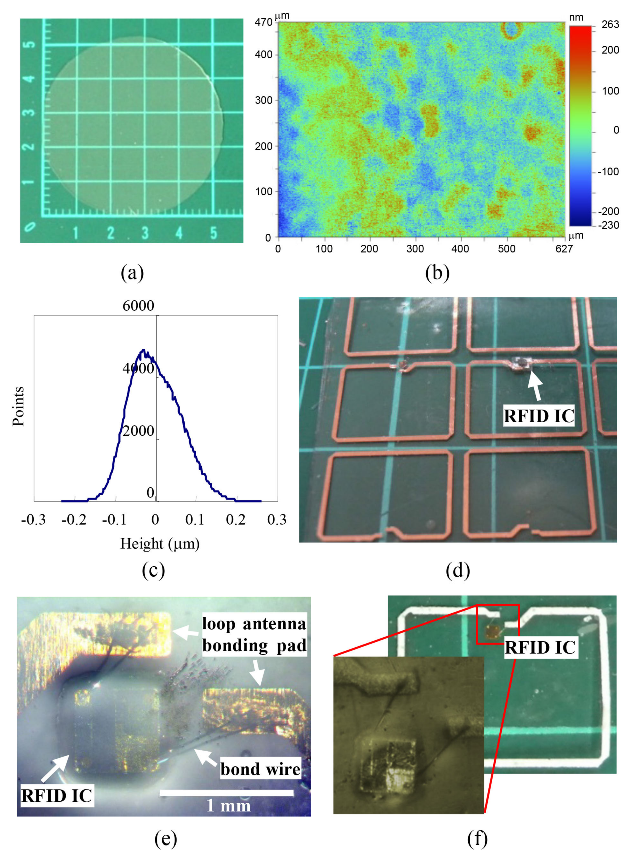

Fig. 2. Fabricated Ormocomp devices. (a) Substrate. (b) Surface roughness measurement. (c) Height histogram. (d) Patterned Ormocomp PCB with Cu loop antenna and bonded RFID controller IC before dicing. (e) Optical micrograph of an RFID IC bonded to the Cu loop antenna. (f) Ormocomp RFID tag based on Al metallization.

Fig. 3(d) is the messages obtained by the reader with or without the tag under the tissue. It clearly shows successful reading of the tag ID when the tag was present.

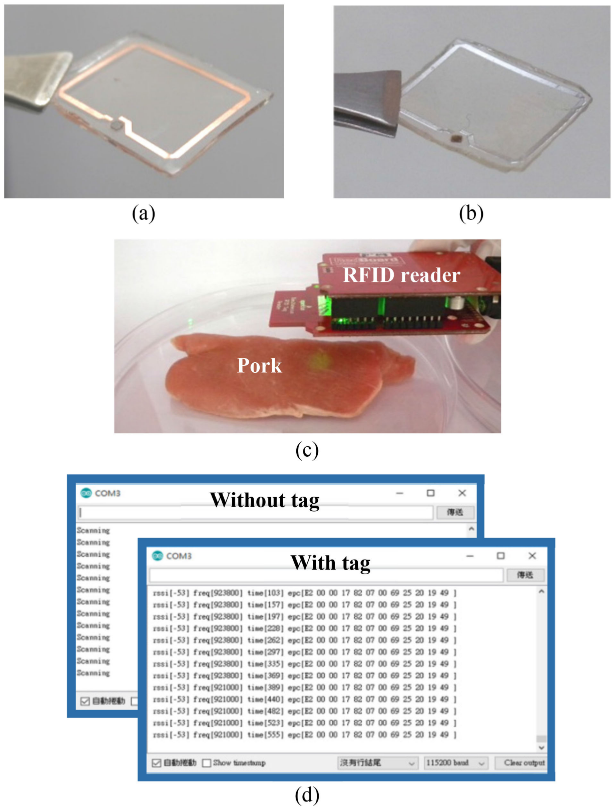

Fig. 3. (a) Photograph of an Ormocomp-based RFID tag with Cu metallization. (b) RFID tag with Al metallization. (c) Interrogation experiment set-up. (d) Screenshot of RFID tag readings with and without the tag under the tissue.

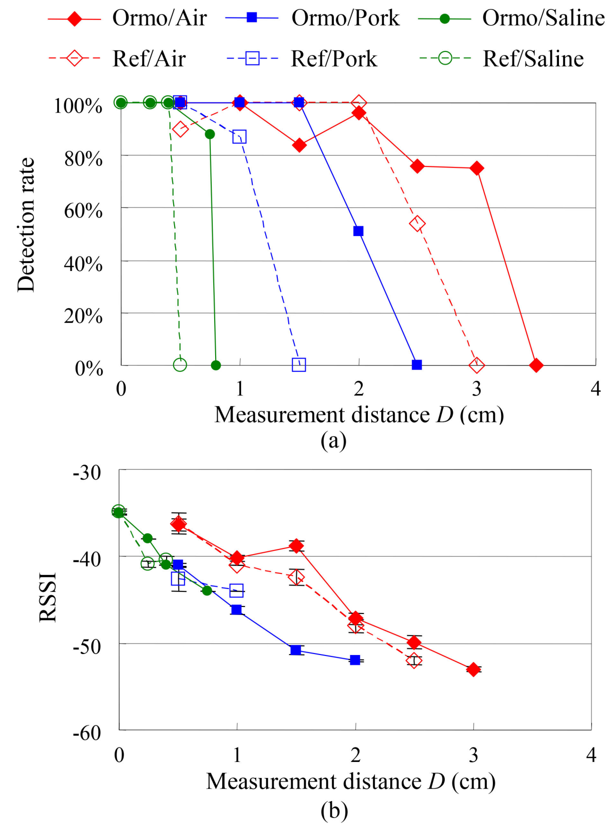

Fig. 4. (a) Successful detection rate and (b) average RSSI of the fabricated Ormocomp tag ("Ormo") and a commercial tag ("Ref") in different media.

The performance of the fabricated Ormocomp tag was compared with that of a reference commercial AZ 9613 tag with the same loop antenna and RFID IC. The tags were placed in different media (in air, under pork, or submerged in isotonic 0.9% saline), and the RSSI and rate of successful detection were measured with 5 dBm measurement power at various distance D, as shown in Fig. 4. For measurement in air, D is the distance between the reader and the tag; under pork, D is the pork thickness; in saline, D is the submersion depth of the tag while the reader was kept 5 mm above the liquid. The detection range for the Ormocomp tag decreases from air (~3 cm) to pork (~2 cm) to saline (~0.7 cm) due to increased conductivity of the media [20]. The test in saline, which is a good model for human blood, also demonstrates the waterproofness of the Ormocomp encapsulation. Fig. 4 shows that the Ormocomp tag performed slightly better than the reference tag. We speculate there are two possible reasons: 1) The Cu loop in the fabricated tag has better conductivity than the Al loop in the commercial tag, and 2) the connection of IC to the loop by wire-bonding in the fabricated tag is more robust than the attachment by conductive adhesive in the commercial tag.

IV. DISCUSSION

The cytotoxicity of Ormocers has been extensively tested and they have long been used in dentistry as restoration materials [5]–[8]. While most biocompatibility tests involving Ormocomp were in vitro, preliminary in vivo tests of Ormocore, another variant in the Ormocer family, have shown good biocompatibility [21], [22]. While in vivo cytotoxicity studies of Ormocomp-based devices, such as the RFID tag presented in this letter, are needed for future implantable applications, their positive outcome could be expected.

In addition to new biocompatible implants, we aim to develop a PCB-like technology based on lamination, printing, and etching. Minimum line width of 30 μm has been demonstrated in multilayer circuits on flame retardant 4 (FR4) substrates with Ormocer as dielectric spacing layers in [23]. With the good surface roughness of cured Ormocomp substrates reported in this article, multilayer circuits and systems in the proposed Ormocomp PCBs are promising.

However, a number of challenges remain to be overcome in the future development of this technology.

1) Currently, the substrates and encapsulation are fabricated by cast molding. The demolding process often causes cracking or delamination.
2) The adhesion of Ormocomp substrates with deposited metal films is good while the adhesion with metal foils needs to be improved for low cost and high-yield manufacturing.

The use of wire bonding was necessitated in this study by the fact that manual soldering of the miniature RFID IC was challenging and would require a specialized soldering station. A wire bonder was, however, readily available. It is noted that our preliminary experiments with soldering on Ormocomp PCBs showed that low-temperature solder, based on tin and bismuth, yielded the best results. An advantage of tin–bismuth solder alloys is that they are less toxic than either lead or silver [24] (the latter being used in contemporary lead-free solders). Low-temperature solder paste can be printed and allows for high volume production with more robust interconnection. This process will be developed and optimized in our future work.

V. CONCLUSION

This preliminary work shows the feasibility to fabricate an Ormocomp-based PCB that can be processed and used similarly to ordinary PCBs. A proof-of-concept body-implantable RFID tag with only a biocompatible material facing the tissues is demonstrated. More complex devices integrating various sensing, actuation, control, and RF data communication and power transfer ICs should be possible. Such devices made of a singular biocompatible substrate and encapsulation are not yet available in current technologies. Hopefully, this letter will open the door for an entirely new class of highly biocompatible body-implantable devices.

ACKNOWLEDGMENT

This work was supported in part by the Ministry of Science and Technology, Taiwan, R.O.C., under Grant MOST 106-2221-E-009-091-MY2, Grant MOST 108-2221-E-009-109, and Grant MOST 109-2639-E-009-001, in part by the National Center for High-Performance Computing, in part by the Chip Implementation Center, in part by the National Chiao Tung University Nano Facility Center, in part by the National Nano Device Laboratory, Taiwan, R.O.C., for various simulation, fabrication, and characterization tools, and in part by the Academy of Finland Mobility under Grant 316153.

REFERENCES

[1] R. Sobot, "Implantable technology: History, controversies, and social implications [Commentary]," *IEEE Technol. Soc. Mag.*, vol. 37, no. 4, pp. 35–45, Dec. 2018.

[2] Y. H. Joung, "Development of implantable medical devices: from an engineering perspective," *Int. Neurourol. J.*, vol. 17, no. 3, pp. 98–106, 2013.

[3] K. Bazaka and M. V. Jacob, "Implantable devices: Issues and challenges," *Electronics*, vol. 2, no. 1, pp. 1–34, 2013.

[4] K. H. Haas and H. Wolter, "Synthesis, properties and applications of inorganic–organic copolymers (ORMOCERs)," *Current Opinion Solid State Mater. Sci.*, vol. 4, no. 6, pp. 571–580, 1999.

[5] A. Doraiswamy *et al.*, "Two photon induced polymerization of organic–inorganic hybrid biomaterials for microstructured medical devices," *Acta Biomater.*, vol. 2, no. 3, pp. 267–275, 2006.

[6] E. D. Han, B. H. Kim, and Y. H. Seo, "Anti-cell adhesion characteristics of nanotextured surface for implantable biomedical device," *Int. J. Precis. Eng. Manuf.*, vol. 18, 239–244, 2017.

[7] S. Schlie *et al.*, "Three-dimensional cell growth on structures fabricated from ORMOCER by two-photon polymerization technique," *J. Biomater. Appl.*, vol. 22, no. 3, pp. 275–287, 2007.

[8] E. Käpylä *et al.*, "Ormocomp-modified glass increases collagen binding and promotes the adherence and maturation of human embryonic stem cell-derived retinal pigment epithelial cells," *Langmuir*, vol. 30, no. 48, pp. 14555–14565, 2014.

[9] S. Aura, T. Sikanen, T. Kotiaho, and S. Franssila, "Novel hybrid material for microfluidic devices," *Sens. Actuator B: Chem.*, vol. 132, no. 2, pp. 397–403, 2008.

[10] T. Sikanen, S. Aura, S. Franssila, T. Kotiaho, and R. Kostiainen, "Microchip capillary electrophoresis–electrospray ionization–mass spectrometry of intact proteins using uncoated Ormocomp microchips," *Anal. Chim. Acta*, vol. 711, pp. 69–76, 2012.

[11] A. Bonabi, S. Tähkä, E. Ollikainen, V. Jokinen, and T. Sikanen, "Metallization of organically modified ceramics for microfluidic electrochemical assays," *Micromachines*, vol. 10, 2019, Art. no. 605.

[12] S. Uhlig *et al.*, "Polymer optical interconnects—A scalable large-area panel processing approach, *IEEE Trans. Adv. Pack.*, vol. 29, no. 1, pp. 158–170, Feb. 2006.

[13] T. Grossmann *et al.*, "Direct laser writing for active and passive high-Q polymer microdisks on silicon," *Opt. Express*, vol. 19, no. 12, pp. 11451–11456, 2011.

[14] M. Foerthner *et al.*, "Hybrid polymers processed by substrate conformal imprint lithography for the fabrication of planar Bragg gratings," *Appl. Phys. A*, vol. 122, 2016, Art. no. 240.

[15] D. Jucius *et al.*, "UV-NIL replication of microlens arrays on flexible fluoropolymer substrates," *Microsyst. Technol.*, vol. 24, no. 2, pp. 1115–1125, 2018.

[16] G. Scotti, S.-Y. Fan, and Y. Chiu, "Ormocomp-based printed circuit board technology for body-implantable applications," in *Proc. 45th Int. Conf. Micro Nano Eng.*, Rhodes, Greece, 2019.

[17] [Online]. Available: https://www.alientechnology.com/products/ic/higgs-3/. Accessed: Jun. 7, 2020.

[18] [Online]. Available: https://www.sparkfun.com/products/14066. Accessed: Jun. 7, 2020.

[19] [Online]. Available: https://www.sparkfun.com/products/13975. Accessed: Jun. 7, 2020.

[20] Y. Huang, S. Kellnberger, G. Sergiadis, and V. Ntziachristos, "Blood vessel imaging using radiofrequency-induced second harmonic acoustic response," *Sci. Rep.*, vol. 8, no. 1, 2018, Art. no. 15522.

[21] M. Malinauskas *et al.*, "In vitro and in vivo biocompatibility study on laser 3D microstructurable polymers," *Appl. Phys. A*, vol. 108, pp. 751–759, 2012.

[22] I. A. Paun *et al.*, "3D superparamagnetic scaffolds for bone mineralization under static magnetic field stimulation," *Materials*, vol. 12, no. 17, 2019, Art. no. 2834.

[23] C. Johansson *et al.*, "Microwave circuits in multilayer inorganic-organic polymer thin film technology on laminate substrates," *IEEE Trans. Adv. Pack.*, vol. 26, no. 1, pp. 81–89, Feb. 2003.

[24] A. Ku, A. A. Shapiro, A. Kua, O. Ogunseitan, J. D. Saphores, and J. M. Schoenung, "Lead-free solders: Issues of toxicity, availability and impacts of extraction," in *Proc. Electron. Compon. Technol. Conf. 53rd Annu. Symp.*, 2003, pp. 47–53.