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Ultrasonic transducer tuning using wafer bonding method

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This study demonstrates the wafer bonding method for performance tuning of piezoelectric Micromachined Ultrasonic Transducer (pMUT) from on-the-shelf piezoelectric disc (PZT). Polydimethylsiloxane (PDMS) and Epoxy were studied as adhesive materials. A thick bonding layer was deposited using the spin coating technique. Wafer bonding was carried out at room temperature to simulate in-situ pMUT repairing scenario. Bonding integrity is analyzed using Field Emission Scanning Electron Microscope (FESEM) images, while electrical characterization of pMUT is carried out using impedance analysis. Fabricated pMUTs have been calibrated using the pulse-echo technique in a freshwater tank. This study found that PDMS at the minimum thickness of 28 μm is preferably compatible for in-situ wafer bonding of pMUT compared to the Epoxy. PDMS has significantly reduced device impedance at 62.4 % reduction compared to 58.9 % reduction for Epoxy. Both pMUTs were able to transmit and receive short acoustic ping with the calibrated speed of sound of 1333.3 m/s. PDMS has successfully contributed to a broader operating frequency between 30 – 150 kHz for transmission and 75 – 140 kHz for the reception.

[**Keywords**: Piezoelectric, Piezoelectric micromachined ultrasonic transducer, Sonar, Ultrasonic, Underwater, Wafer bonding]

Introduction

Typically, a piezoelectric Micromachined Ultrasonic Transducer (pMUT) consists of an active element of piezoelectric material attached to the top and bottom electrodes[1]. The active part is then supported by an elastic membrane forming an elastic structure for vibrations and energy conversion[2]. Various designs and studies have been carried out regarding pMUT design, development, and characterization, primarily for air-loaded applications[3]. The performance of pMUT is tunable by manipulating the thickness and width of the vibrating structures[4-6]. This study introduced a surface modification method to achieve quick, in-situ repair and performance tuning of pMUT for underwater applications.

In a nominal fabrication ecosystem, the layer thickness is achieved by controlling the deposition parameters[7]. In this study, the thickness of the adhesive layer is manipulated. Two adhesives are studied, namely PDMS and Epoxy. First, a simple planar monomorph consisting of a single active piezoelectric layer on the passive silicon substrate is examined, as illustrated in Figure 1(a). Then, an active layer was employed by the PZT (Lead Zirconate Titanite) layer sandwiched between Cu top and bottom electrodes. At the same time, a single side polished silicon wafer was used as a substrate. Finally, these two layers are adhered to using either Polydimethysiloxane (PDMS) or Epoxy.

The total device thickness is 700 μm to ensure usable underwater frequency between 20 – 200 kHz. First, a single element pMUT device is packaged in a cylindrical PVC case with a conditioning and matching circuit placed below the device. At the same time, the acoustic matching layer is deposited using liquid rubber. Next, the remaining gap inside the transducer is filled with Epoxy. Finally, a permanent coaxial at 2 m of length with a BNC connector is attached to the transducer. The studied prototype is shown in Figure 1(b).

Fabrication and Methodology

A. Adhesive wafer bonding

A thick adhesive layer of PDMS and Epoxy is deposited on silicon substrate using the spin coating technique. Two parameters have been manipulated, namely spin time and rpm. SCK-300P spin coater is utilized for layer deposition. Before the spin coating deposition, both PDMS and Epoxy were prepared. PDMS was prepared by mixing PDMS with hardener at the ratio of 10:1. Thus, 12 minutes of cure time is imposed before deposition takes place. In the Epoxy solution, resin and hardener were mixed with the ratio of 3:1 with the same 12 minutes curing time. The spin

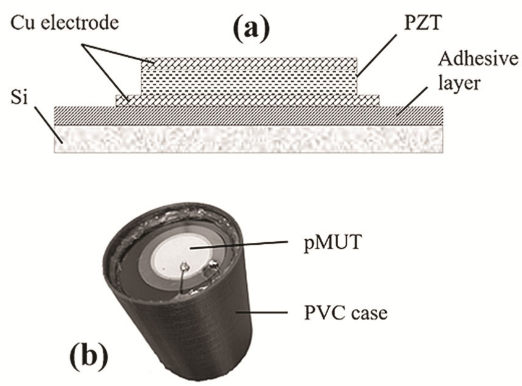

Fig. 1 — Piezoelectric micromachined ultrasonic transducer, pMUT: a) Schematic, and b) Prototype transducer

coating process was carried out at room temperature of 26 °C. Ambient humidity was not controlled and monitored.

Substrate preparation was carried out outside the cleanroom at the room temperature of 26 °C, to simulate an in-situ repair scenario. Circular <100> Si wafer is cut and diced using a conventional diamond cutter. All substrates are placed inside plastic Petri dishes and labelled after manually wiping with a 20 % isopropyl alcohol swab. As described in the solution prep procedure, a total of 12 minutes lapse for mixing, stirring, and vacuuming. In detail, the mixing of PDMS and Epoxy was both carried out between 60 – 80 seconds intervals. Then, both solutions were stirred (manually) for the next 40 – 60 seconds before being placed in a vacuum chamber. Finally, all solutions went through the vacuuming process for 10 minutes to remove air bubbles. Vacuuming was carried out at room temperature of 26 °C.

Both PDMS and Epoxy are dropped on a silicon wafer at 3 points, as illustrated in Figure 2(a). The separation distance between the three beads is not measured. Spin coating is carried out at two stages, starting with 500 rpm for 10 seconds followed by 1000 rpm for the next 50 seconds. After spinning, a coated silicon wafer is placed inside a petri dish, and a piezoelectric disc is carefully placed on top of the silicon wafer to initiate the bond. To avoid the formation of air bubbles or trapped air, the PZT disc was placed starting from the side of the substrate, and the bonding is developed without any external forces, as depicted in Figure 2(b). Bonded wafers were then placed inside the incubator at the temperature of 30 °C for 24 hours for the drying process. Similar procedures are repeated, and a total of 3 samples were fabricated for each type of adhesive material.

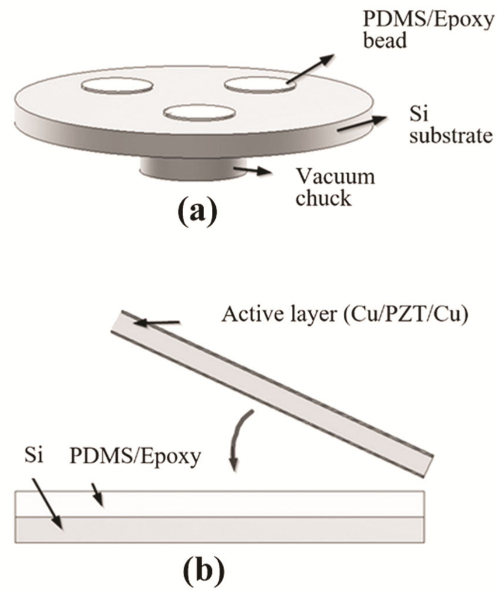

Fig. 2 — Wafer bonding process: a) Adhesive beads before the spin-coating process, and b) Wafer bonding using the gravitational pull

After the drying process, the wire bonding process is carried out to connect the pMUT device with conditioning and matching circuits. A single cove wire is utilized for all samples at the same length of 10 cm, soldered to the Cu top and bottom electrodes using a tin solder at a temperature between 200 – 220 °C. A single contact point for all prototypes is placed at the side of the sample.

B. Impedance analysis

Impedance analyses have been carried out using the Wayne Kerr LCR meter (4300 series). Before the testing, the LCR meter was warmed up for 20 minutes, followed by short-circuit and open-circuit calibration procedures. Then, all pMUTs were tested against series and parallel equivalent circuit tests for the impedance value (Z). Two drive voltages were chosen at 0.5 V, and 5.0 V. Frequency range for this study is between 5 – 100 kHz, with a 5 kHz increment. For the control experiment, a sample of PZT disc at the same thickness with Cu top and bottom electrodes is measured using the same setup.

C. Pulse-echo underwater calibration

Fabricated transducers have undergone underwater calibration using the pulse-echo method. Three reference transceivers (Benthowave Inst. Inc.) were employed to determine all fabricated transducers transmit and receiving sensitivity. Freshwater sourced from water tap is filled in an untreated echoic fibreglass tank. The Device Under Test (DUT) is placed in front of the reference transceiver. The separation distance is at 8 cm. Both are submerged at a depth of 20 cm, as depicted in Figure 3. The setup was located in the middle of the tank to minimize the ringing effect[8]. Ringing occurs when repeated acoustic reflection happens at the tank's wall and floor. Acoustic background noise is suppressed by lifting the tank approximately 40 cm above the concrete base, using an iron base. Water temperature is monitored throughout the calibration procedures.

For receiving response characterization, trigger pulse or sonar ping is sent from the arbitrary function generator at the drive voltage of 10 V peak to peak to the reference projector. The unamplified signal from the DUT is measured and captured using an oscilloscope. A trigger pulse is sent to the DUT during transmitting response characterization. The echo received by the reference hydrophone is captured using an oscilloscope. Speed of sound calibration was carried out before pulse-echo procedures were performed.

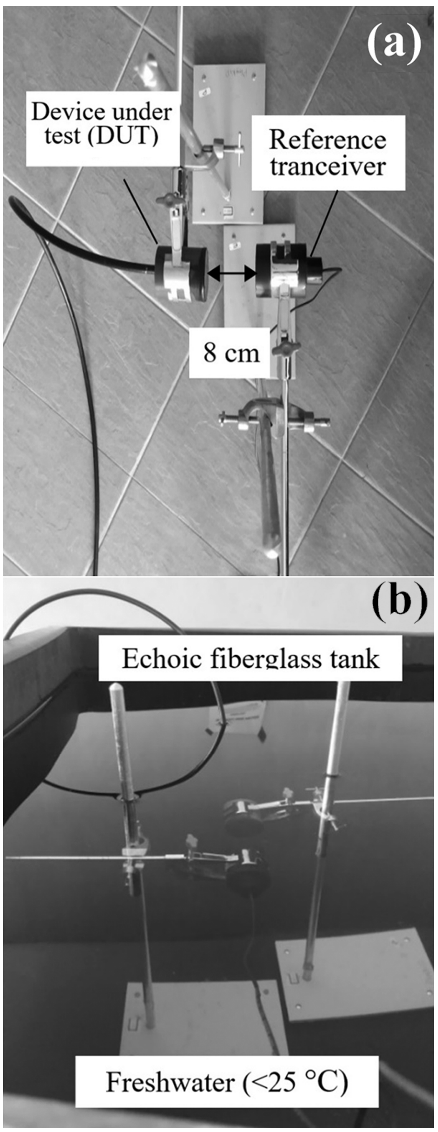

Fig. 3 — Underwater calibration setup: a) Pulse-Echo method, and b) Speed of sound calibration

Result and Discussion

A. Post fabrication analysis

Wafer bonding using gravitational pull is successfully implemented and demonstrated at room temperature outside the cleanroom using PDMS and Epoxy as adhesive. Field Emission Scanning Electron Microscope (FESEM) cross-sectional analysis revealed that Epoxy's bonding quality is poor where a non-uniform adhesive layer with air bubbles is present, as denoted in Figure 4(a). The thickness of the epoxy film is between 17 – 21 µm. Most of the bonded area occurs at the edge of the Cu bottom electrode resulting in good bonding strength.

A uniform adhesion layer is formed when PDMS is used, as in Figure 4(b). At the uniform thickness of 28 µm, no air bubbles are present, resulting in unbreakable bonding between the active piezo layer and the silicon substrate. Furthermore, a clear boundary can

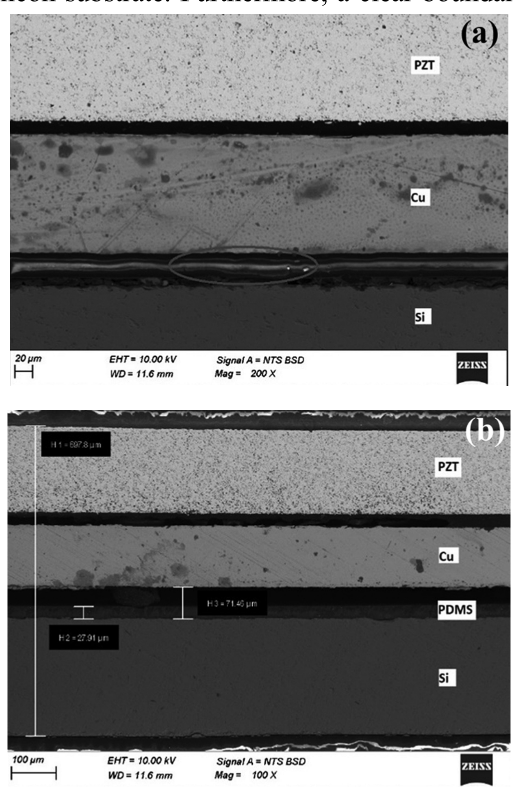

Fig. 4 — Cross-sectional of pMUT using different adhesive material: a) Epoxy, and b) PDMS

be seen between PDMS and carbon passivation layer underneath Cu bottom electrode, indicating no chemical reaction and material interactions at the border. As a result, all pMUTs are successfully fabricated with a total thickness between 690 – 702 µm.

Further analysis was carried out to investigate and compare material interaction at the bonding boundary using Energy Dispersive X-ray analysis (EDX). As indicated in Figure 5(a), there were interactions between the epoxy adhesive and carbon passivation layer under the Cu electrode. Exotherm occurrences while epoxy resin cured during and after the spin-coating deposition process cause this interaction. Generated heat has expanded the adhesion layer film resulting in overflow towards the edge of the pMUT, leaving a significant amount of air cavity. No interaction occurs at the PDMS boundary, leaving a smooth and uniform film as in Figure 5(b).

B. Electrical characterization

Impedance analysis found both pMUTs fabricated using the wafer bonding technique have lower impedance than a control PZT disc (without substrate) across 5 – 100 kHz of tested frequency, as depicted in Figure 6(a). Comparatively, PDMS has contributed to the lower impedance of the device than epoxy-bonded pMUT, denoted with a higher percentage difference as in Figure 6(b). At the average reduction of 62.4 % across 5 – 100 kHz of test frequency, PDMS-bonded pMUT carries the value of impedance reduction rate at -0.072 % for every Hz of frequency increment. For epoxy-bonded pMUT, the average difference is slightly lower at 58.9 % across the same frequency range, with impedance reduction rate at -0.144 % for every Hz of frequency increment. Both pMUTs with PDMS and Epoxy were tested using parallel curve fitting have approximately similar impedance values across the frequency range

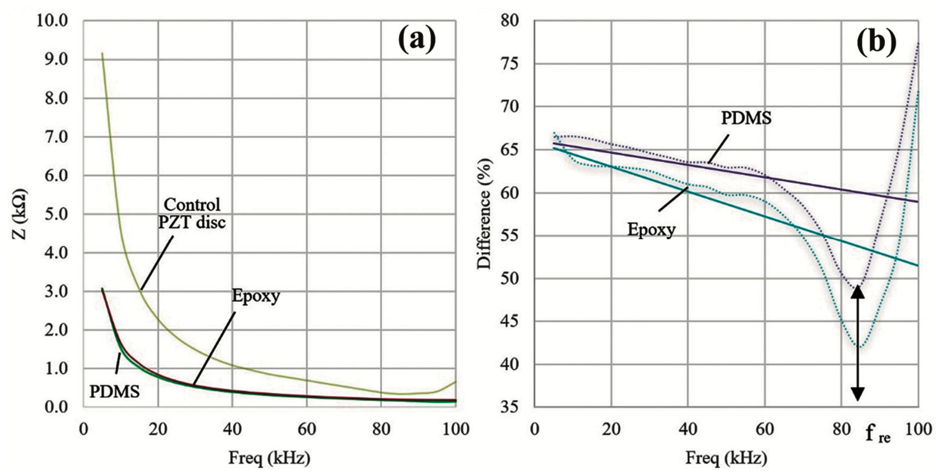

Fig. 5 — EDX analysis on pMUT using different adhesive materials: a) Epoxy, and b) PDMS

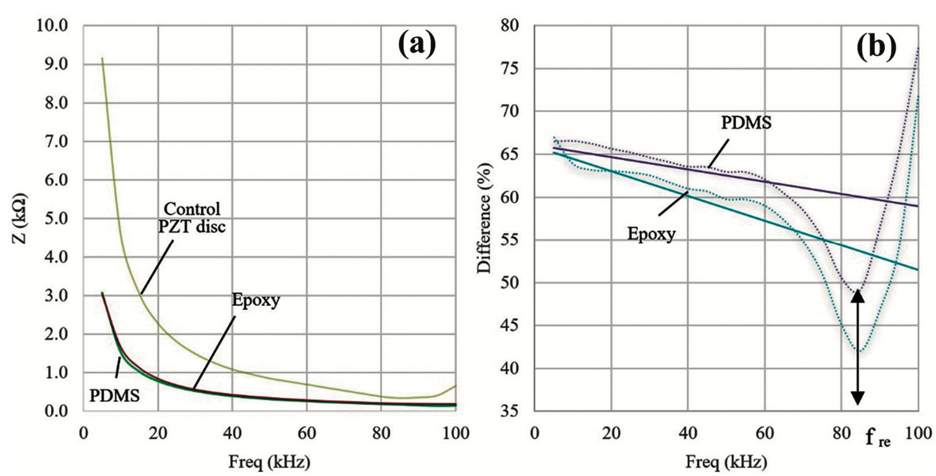

Fig. 6 — Impedance v/s frequency results for electrical characterization: a) Series circuit, and b) Parallel circuit

of 5 – 100 kHz and will not be further investigated in this study.

It is worth noting that electrical characterization has been carried out with air-load. Therefore, from the exact Figure 6(b), airborne electrical resonant occur at approximately 85 kHz for both fabricated pMUTs. Acoustic resonant for both devices will be further investigated and discussed in the underwater calibration section. Adding a solid backing Si substrate has drastically changed the pMUT behaviour electrically.

Both fabricated pMUTs are expected to produce higher Sound Pressure Levels (SPL) at the identical drive voltage compared to the pMUT without solid or rigid substrates. In receiving mode, pMUT with lower impedance is expected to be more sensitive by producing a higher current with the same input vibration as the one with higher impedance. Furthermore, the wafer bonding technique demonstrated in this study has simplified the development process of the pMUT by bonding two wafers at room temperature.

C. Underwater calibration

Speed of sound measurement has been carried out before pulse-echo measurement to ensure the experimental ecosystem's stability. A 60 ± 10 µs delay was measured between a trigger pulse and the echo. At a separation distance of 0.080 ± 0.001 m between projector and hydrophone, the measured speed of sound within this setup is 1333.3 m/s. These procedures were carried out reciprocally using DUT (PDMS), DUT (Epoxy), and reference transceiver. Captured signal is shown in Figure 7.

Based on the transmitting response character in Figure 8, both DUTs can be differentiated based on sensitivity and bandwidth. Peak performance for DUT using Epoxy as adhesive occurs at 120 kHz of the frequency with the maximum amplitude of 53 mV, while peak performance for DUT using PDMS as adhesive occurs at 100 kHz of the operating frequency with the maximum amplitude of 92 mV.

Both comparisons are made using the generated trigger pulse via reference hydrophone A. At peak amplitude, PDMS has contributed to 74.3 % more sensitive when transmitting sound. Interestingly, on the other hand, Epoxy has successfully flattened the response over the broader frequency range.

Receiving response for both DUTs is shown in Figure 9. For a DUT using Epoxy as adhesive, any signal below 80 kHz of frequency cannot be detected, while for DUT using PDMS as adhesive, the readings started 10 kHz early at 70 kHz of frequency. Similarly, maximum receiving response for both DUTs occurs between 90 – 100 kHz of operating frequencies. Following the same trend of transmitting a response, DUT using PDMS adhesion is 50 % more sensitive in receiving mode compared to the DUT using epoxy adhesion layer.

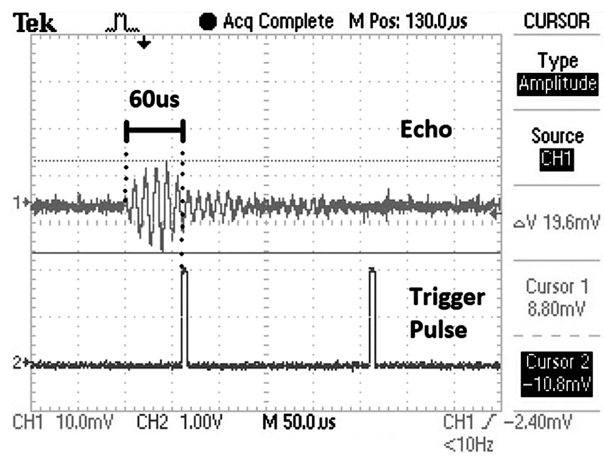

Fig. 7 — Speed of sound calibration before pulse-echo measurement

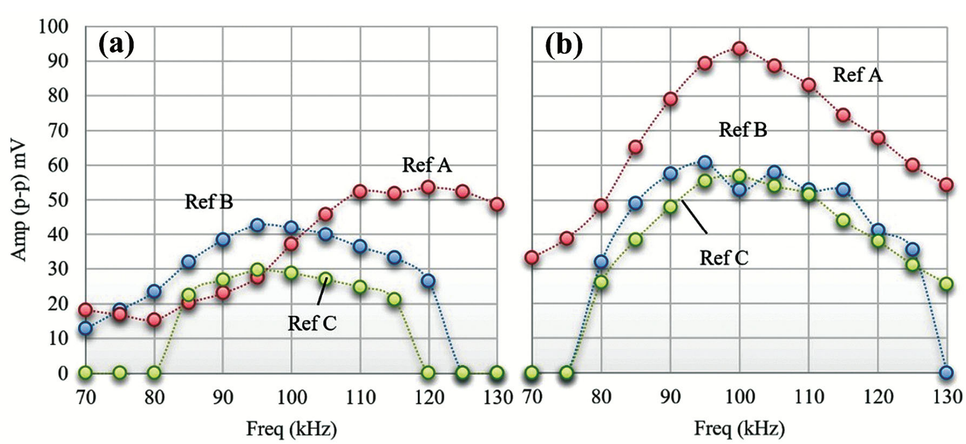

Fig. 8 — Transmitting response: a) DUT using Epoxy, and b) DUT using PDMS

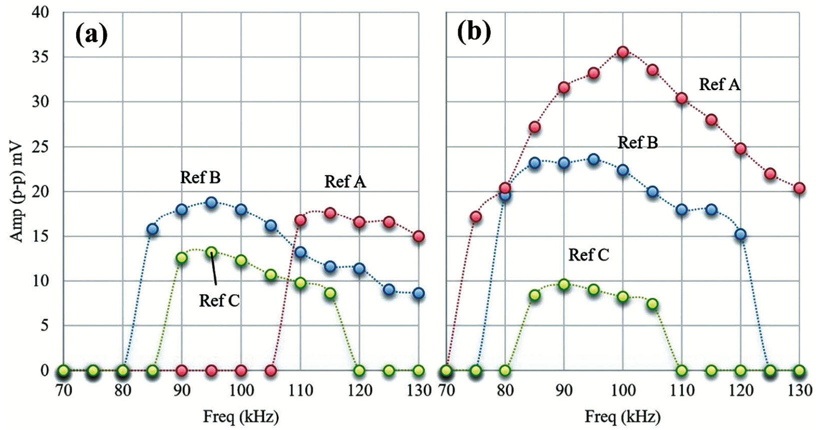

Fig. 9 — Receiving response: a) DUT using Epoxy, and b) DUT using PDMS

Table 1 — pMUT performance based on adhesive materials

Parameter	Epoxy	PDMS
Adhesion thickness	21 µm	17 µm
Transmit response	53 mV @ 120 kHz	92 mV @ 100 kHz
Receive response	18 mV @ 95 kHz	35 mV @ 100 kHz
Air-loaded resonant	85 kHz	85 kHz

Conclusion

In conclusion, pMUT have successfully fabricated using a simplified wafer bonding technique at room temperature. Both PDMS and Epoxy at the thickness between 17 – 21 µm can be used as adhesive to bond the active piezoelectric layer and Si substrate. Furthermore, recommended bonding procedures were successfully discussed and presented, resulting in pMUT thickness between 690 – 702 µm.

Structural analysis revealed an exotherm issue when Epoxy is utilized, resulting in an uneven layer with air bubbles present. Both adhesive materials are proven to ensure the acceptable electrical and acoustic performance of pMUT at the performance simplifies in Table 1; however, PDMS is significantly better than Epoxy as far as transmitting and receiving sensitivities are concerned.

Future studies will include more industrial-grade epoxy resin, marine-grade liquid rubber, and silicone-based adhesives, all of which are readily available on marine vessels for quick in-situ repairs. The oil-based backing layer will also be considered in the future. Comprehensive electrical analysis procedures that include equivalent circuits, resistivity, and conductivity curve-fittings are ongoing and presented in other reports.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: JWH & MIHY; Parameter analysis: JWH; Fabrication: JWH; Formal analysis writing, original draft preparation: JWH; and Review and editing: MIHY.

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