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Micro-LED and PPG Sensor Integration Using Flexible Fan-Out Wafer-Level Packaging for Trans-Nail Pulse-Wave/SpO_2 Monitoring

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Abstract

Our research activity has been focusing on advanced flexible hybrid electronics (FHE) where chiplets embedded in flexible substrates are heterogeneously integrated based on Fan-Out Wafer-Level Packaging (FOWLP). This paper deals with an integrated photoplethysmographic (PPG) sensor system for trans-nail monitoring of pulse wave and percutaneous oxygen saturation (SpO_2). In this study, a PPG sensor module consisting of red /near-IR micro-LEDs and a PPG sensor IC chip are fabricated in polydimethylsiloxane (PDMS). The micro-LEDs are successfully operated by LED drivers in the PPG sensor IC *via* fan-out redistribution layers (RDLs). In addition, we address a serious die shift issue in FOWLP by using an anchoring layer.

1. Introduction

Since single crystalline Si with a thickness less than 50 µm is known to be a flexible material, typical FHE process combines printable wiring technologies with ultra-thin dies fabricated by grinding and polishing to make them bendable to follow curved profiles. On the other hand, Si devices are sensitive to mechanical stress, and thus, their characteristics degradation would be induced by the stress [1]. Therefore, ultra-thin die assembly on flexible substrates is challenging due to the limited processes without thermal compression bonding. We have employed small embedded chiplets ranging in thickness from 50 to 200 µm in advanced FHE based on die-first FOWLP [2]. The biggest advantage of the FOWLP widely used in mobile applications is that no bonding processes are required. High bendability is given by our unique embedment structure as shown in Fig. 1.

We have previously proposed an integrated photoplethysmographic (PPG) sensor system for trans-nail pulse-wave monitoring and verified that the PPG sensor can be monitored in both the reflection and transmission modes with an external LED chip and a thick IC chip having photodiodes and an LED driver [3]. Fig. 2 shows the conceptual schematic of the trans-nail PPG sensor module as an advanced FHE. 3D-printed nail chips are molded by OpenNail®. The tailor-made nail chips are designed to fit their own nail curves with various curvature radius with a 3D scanner. In this study, we demonstrate the PPG sensor module integration with micro-LEDs and a small capacitor as a passive die. In addition, we describe the effectiveness of an anchoring layer to drastically reduce die shift with the tiny dies toward future FOWLP.

2. Fabrication

Fig. 3 shows the process flow of this FHE fabrication. First, embedment of 200-µm-thick PPG sensor IC chip (2.5 mm by 2.5 mm) having the photodiode and LED driver circuits in a biomedical grade PDMS were performed with two carrier Si wafers on which thermo-release tapes were laminated. These dies were gently placed on the 1st carrier wafer having one lower-temperature releasable tape in a face-down configuration, and then, a 1-µm-thck anchoring layer of Parylene-C was deposited on the dies to fix them. After that, the PDMS monomers were poured on the die-on-wafer structure, followed by vacuum defoaming and the subsequent wafer-level compression molding/curing with the 2nd carrier having the other higher-temperature releasable tape. After debonding of the 1st carrier at 130°C, the dies were embedded in the PDMS on the 2nd carrier. These dies and PDMS were planarized without any mechanical processes. Prior to the following metallization processes, a stress buffer layer (SBL) was coated on the dies/PDMS. By using standard photolithography with metal sputtering/wet etching, 500-nm-thick Au wirings were formed on the SBL at the wafer-level. Finally, the FHE module were debonded from the 2nd carrier.

3. Results and Discussion

Die shift issues are resulted from thermomechanical and fluidic effects. The former includes temporary bonding strength (die placement load, adhesion, die size etc.), CTE mismatch between mold and wafers, and curing temperature, whereas the latter involves mold viscosity/thickness, die thickness/pitch, compression speed and so forth. Such a die-shift failure is occurred when compression molding including the vacuum defoaming step. Large die shift over 10 µm or more gives alignment error and restricts the fine-pitch (<100 µm) interconnect formation for the advanced FHE with embedded tiny dies. In fact, the red micro-LED (270 µm by 270 µm) and near-IR micro-LED (340 µm by 340 µm) are shifted over 800 µm along the IC chip sidewall. We employ a vapor-deposited parylene thin film as an anchoring layer to lower the die shift. As shown in Fig. 4, surprisingly, the die shift is significantly reduced even with the tiny red and near-IR micro-LEDs in addition to the capacitor by using the anchoring layer. It is found that the die shift is reduced to less than 1/20 by using the anchoring layer that enables the tiny dies to tightly keep their position on the tape.

A PPG sensor module is integrated by embedding the

PPG sensor IC chip, red/near-IR micro-LEDs, and a capacitor die in PDMS for trans-nail pulse-wave and SpO_2 monitoring. The trans-nail PPG sensor module is so flexible that the module perfectly fits the nail curve, and fan-out RDLs are formed as designed on the PDMS through the SBL at the wafer-level as shown in Fig. 5. As seen from Fig. 6, red light emission is confirmed from the red micro-LED driven by the LED driver fabricated in the PPG sensor IC *via* the fan-out RDLs. The red and the other near-IR micro-LEDs are well operated without property degradation. These results including significant die-shift reduction suggest that fine-pitch/high-density fan-out RDL formation can be implemented by the flexible FOWLP methodology with an anchoring layer technique to give high-performance FHE systems.

4. Conclusions

Drastic die-shift reduction with an anchoring layer of Parylene-C is achieved even when 270-µm-square tiny dies are temporarily bonded on a thermo-release tape. Two red/near-IR micro-LEDs and a capacitor die are embedded in PDMS and integrated with a PPG sensor IC chip having LED drivers and photodiodes. The resulting fan-out RDLs formed on the PDMS can drive the embedded micro-LEDs by the LED drivers through the capacitor. This die-first FOWLP technology can realize high-density fan-out RDL formation on biocompatible flexible substrates and highly integrated FHE fabrication without thermal compression bonding with solder microbumps.

References

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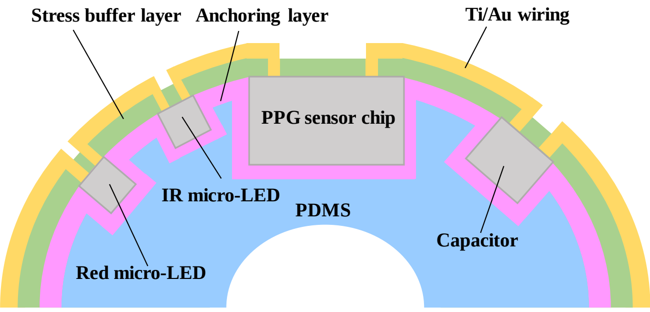

Fig. 1 Cross-section of FHE-based PPG sensor module.

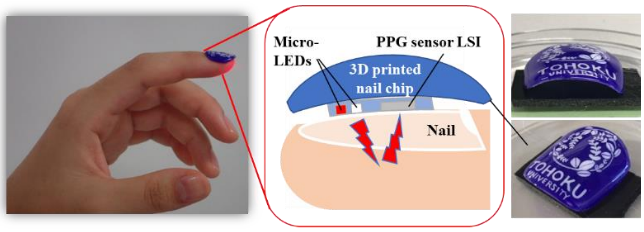

Fig. 2 The conceptual schematic of integrated PPG sensor system for trans-nail pulse-wave and SpO_2 monitoring.

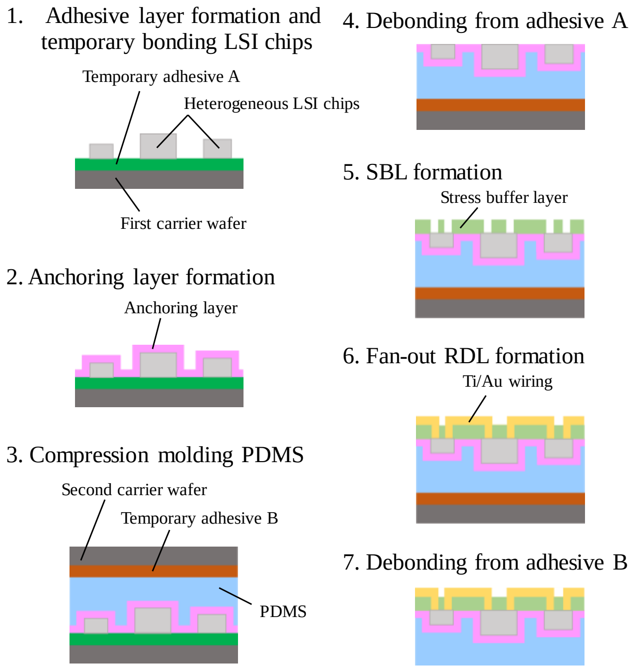

Fig. 3 A process flow of FHE-based PPG sensor module fabrication using die-first FOWLP.

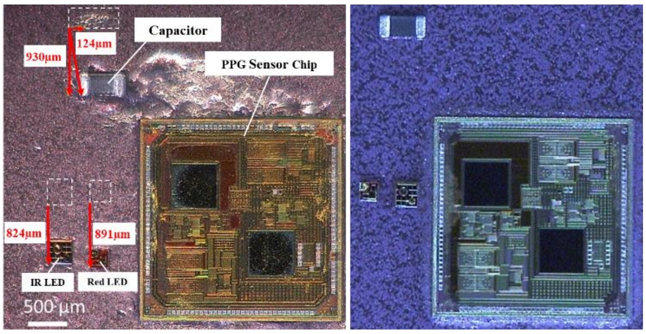

Fig. 4. Die-shift comparison without an anchoring layer (a) and with the anchoring layer (b).

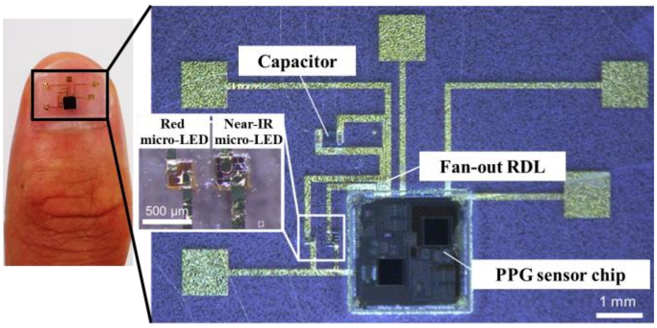

Fig. 5. Photos of PPG sensor module with two micro-LEDs.

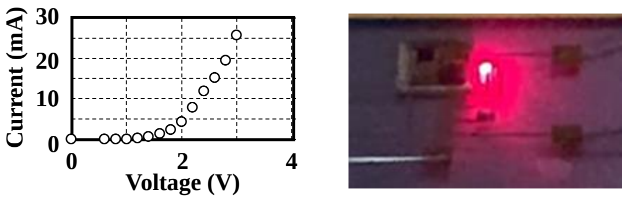

Fig. 6. I-V characteristics of the red µLED after die embedment and RDL formation and the light emission from the red micro-LED through fan-out RDL integrated on PDMS.