# Comparative Study of Die-Attach Materials for LED Die Bonding


Liangxing Hu,[1#] Shuyu Bao,[2] Yue Wang,[2] Simon Chun Kiat Goh,[3] Yu Dian Lim,[1] Peng Zhao,[1] Michael Joo Zhong Lim,[1] Weiyang Miao,[1] Van Quy Dinh,[1] Sai Choo Tan,[4] Kai Hwa Chew,[4] and Chuan Seng Tan[1,2,5#]

[1]School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798

[2]Low Energy Electronic Systems (LEES), Singapore-MIT Alliance for Research and Technology (SMART), Singapore 138602

[3]POET Technologies, 21 Changi North Way, Singapore 498774

[4]Quantum Chemical Technologies (S) Pte Ltd, 47 Pandan Road, Singapore 609288

[5]Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore 117685

[#]Email: lhu001@e.ntu.edu.sg, tancs@ntu.edu.sg



## Abstract

In this work, the bonding conditions of different die-attach materials are optimized for LED die to substrate bonding. The die-attach materials are characterized for their mechanical bonding strength, hermeticity, and surface morphology. Among the investigated materials, it is found that SAC solder has the largest bonding strength of ~60 MPa. The hermeticity is at least 10× below the rejection limit of MIL-STD-883E standard ($5\times10^{-8}$ atm-cc/s) for all die-attach materials. The results show that high-quality bonding is achieved. Moreover, LEDs are fabricated and bonded onto substrate with die-attach materials. The electrical, electroluminescent, and photoluminescent properties of the un-bonded and bonded LEDs are investigated. The results reveal that non-conductive electrical adhesive has the least negative impact on the electrical property of LEDs, Ag paste has the largest positive effect on electroluminescent and photoluminescent properties. In addition, this comparative study can be used as guidelines to further optimize the process parameters, to characterize the material properties of die-attach materials (e.g. porosity, optical reflectance, volume resistivity, and thermal conductivity, etc.), and to study the effect of temperature on reliability luminous efficacy, and optical property of the packaged LEDs.


## Introduction

Adhesive materials, including Sn-Ag-Cu (SAC)-based solder, silver (Ag) paste, and non-conductive electrical adhesives, are widely used as part of semiconductor packaging. Such materials are typically used for microelectronics and active component die attach such as light emitting diode (LED) die bonding, etc. [1]. Die-attach materials are a key role in the performance and reliability of electronic devices [2-6]. Increasingly, numerous effort has been invested on the development and the selection of suitable die-attach materials for specific applications. The main selection criteria are material properties (thermal, optical, mechanical, and electrical, etc.), performance (light output and thermal dissipation of LEDs), reliability (fatigue resistance and creep), packaging process (yield and throughput), compatibility with the desired application, and cost (price performance), etc.

In the case of LED die bonding, die-attach materials interface directly with the LED die. As illustrated in Fig. 1, their thermal, optical, mechanical, and electrical performances have a considerable effect on LED lumen maintenance, light extraction, and light output over time. Therefore, it is essential to evaluate different die-attach materials for LED die bonding.

In this study, properties of different die-attach materials will be analyzed. The material characterizations serve as a comprehensive fundamental for subsequent bonding and packaging of LED dies, where the corresponding performance of the bonded LEDs with different die-attach materials would be compared.

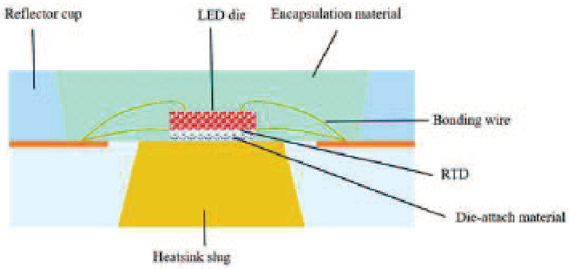


Fig. 1. Cross-section schematics of a typical packaged LED emitter with die-attach material.

## Approach

The overall workflow for this comparative study of die-attach materials for LED die bonding is proposed, as shown in Fig. 2. The detailed steps are: 1) die-die bonding with different die-attach materials; 2) material properties characterization of different die-attach materials; 3) LED die fabrication; 4) LED die bonding with different die-attach materials; 5) resistance temperature detector (RTD) fabrication; 6) packaging of RTD-integrated LED die.

## Results and Discussion

### 1. Die-die bonding with different die-attach materials

The experimental bonding steps designed for die-attach materials are: 1) 6" silicon (Si) substrates are deposited with a 200 nm thick insulation layer of silicon dioxide ($SiO_2$) by plasma enhanced chemical vapor deposition (PECVD) (step 1 in Fig. 3), the substrates are subsequently deposited with a 10/100 nm thick layer of titanium/copper (Ti/Cu) by electron-beam evaporation, respectively (step 2 in Fig. 3); 2) after wafer singulation to form the desired bottom and top dies (step 3 in Fig. 3), die-attach materials are dispensed onto the top-side surface of the bottom die where their position and thickness are limited by a cut-sized thermal tape affixed on the die substrate (step 4 in Fig. 3); 3) the top die is flip-chip bonded onto the top side of the bottom die with the dispensed die-attach materials, as shown in Fig. 4(a); 4) subsequently, the bonding process is initiated by applying a force at an elevated temperature (step 5 in Fig. 3); 5) finally, the bonded dies are annealed for a set period of time (step 6 in Fig. 3) [7-18].

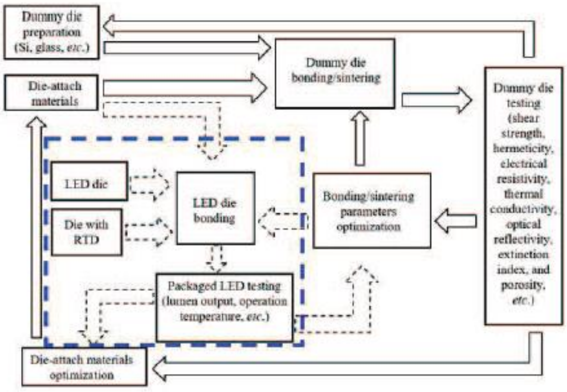


Fig. 2. The overall approach for comparative study of die-attach materials and their application for LED die packaging.

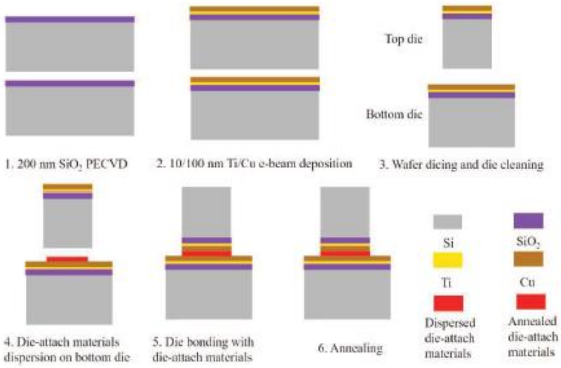


Fig. 3. The detailed steps for die-die bonding with die-attach materials.

## 1.1 Shear strength of bonded dies with different die-attach materials

The bonded dies with different die-attach materials (Ag paste, SAC solder, and non-conductive adhesive), as shown in Figs. 4(b), 4(c), and 4(d), are mechanically sheared to obtain the mechanical bonding strength [19]. The corresponding shear strength and the sheared dies are shown in Fig. 5. The largest average shear strength obtained so far is ~60 MPa by using SAC solder, and the smallest average shear strength obtained is ~8 MPa by using Ag paste. The bonding experiment will be further extended to other die-attach materials under investigation, albeit with optimized bonding parameters to obtain the highest shear strength for the respective materials.

## 1.2 Hermeticity of bonded dies with different die-attach materials

Fine leak test was performed on the bonded dies with different die-attach materials. The corresponding results are presented in Table 1. All bonded dies show a very low leakage rate below $5\times10^{-9}$ atm-cc/s, which is at least 10× below the rejection limit of MIL-STD-883E standard ($5\times10^{-8}$ atm-cc/s) [20]. This indicates a high-quality bonding hermeticity of the bonded dies.

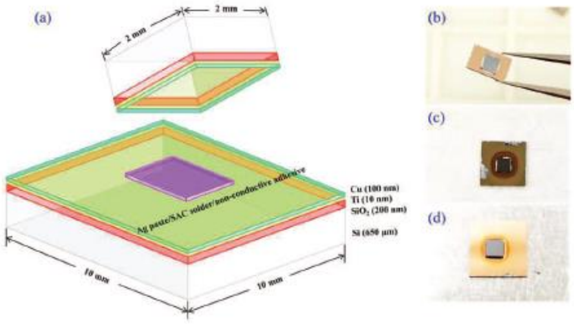


Fig. 4. (a) Schematics of die-die bonding with different die-attach materials, (b) A bonded die with Ag paste, (c) A bonded die with SAC solder, and (d) A bonded die with non-conductive adhesive, respectively.

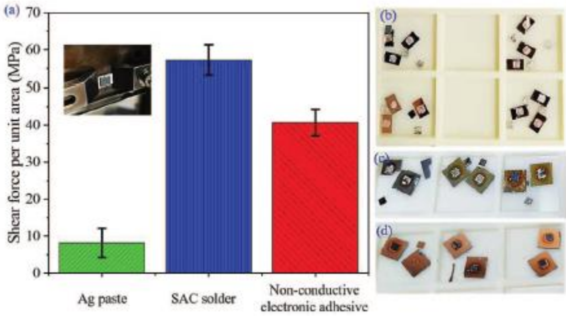


Fig. 5. (a) Shear strength of the bonded dies with different die-attach materials, (b) The sheared dies with Ag paste, (c) The sheared dies with SAC solder, and (d) The sheared dies with non-conductive adhesive, respectively.

Table 1. He leakage rate for the bonded dies with different die-attach materials.

| Die-attach materials | He leakage rate (atm-cc/s) |
|---|---|
| Ag paste | $4.3 \times 10^{-9}$ |
| SAC solder | $8.2 \times 10^{-10}$ |
| Non-conductive adhesive | $1.9 \times 10^{-9}$ |

## 1.3 Surface morphology of the sheared die-attach materials

The FESEM images of the sheared Ag paste, SAC solder, and non-conductive electrical adhesive are shown in Figs. 6(a), 6(b), and 6(c), respectively. From the FESEM images, one can obtain that Ag paste is made from flakes.

## 2. LED die bonding with different die-attach materials

The LEDs used for bonding in this work were reported in the literature [21]. After the bonding parameters for the die-attach materials had been optimized, the bonding process of the LED dies were evaluated [15]. The un-bonded and bonded LED dies are shown in Fig. 7. As shown in Figs. 7(b), 7(c) and 7(d), the LED dies were well-bonded onto the substrate with Ag paste, SAC solder, and non-conductive electrical adhesive, respectively. The corresponding side-view images of the bonded LED dies are shown in Fig. 8. Thereafter, the LED performance was studied in the following experiments.

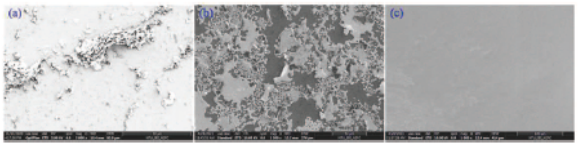


Fig. 6. (a), (b), and (c) FESEM images of the sheared Ag paste, SAC solder, and non-conductive adhesive, respectively.

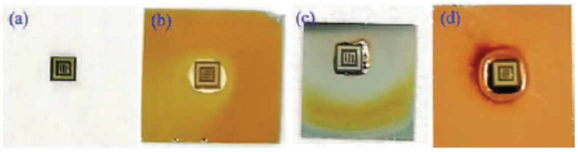


Fig. 7. (a) Image of an un-bonded LED die, (b) Image of a bonded LED die with Ag paste, (c) Image of a bonded LED die with SAC solder, and (d) Image of a bonded LED die with non-conductive adhesive, respectively.


Fig. 8. (a), (b) and (c) Side-view images of the bonded LED dies with Ag paste, SAC solder, and non-conductive adhesive, respectively.

### 2.1 Electrical property of LED

The I-V characteristics of both un-bonded and bonded LED dies were investigated at voltage swept from -3 to +3 V. The results are plotted, as shown in Fig. 9. From the results, the switching voltage of the LED is ~+1.5 V. Among the bonded LED dies, the non-conductive electrical adhesive bonded LED die has the least-decreased current compared to the un-bonded LED die, which demonstrates that the non-conductive electrical adhesive has the least negative effect on the LED's I-V output.

### 2.2 Electroluminescent property of LED

The electroluminescence (EL) spectra for un-bonded and bonded LED dies were extracted at wavelength ranging from 300 to 1100 nm. The results are plotted, as shown in Fig. 10. From the figure, the peak of the EL spectra of the bonded LED dies was much larger than that of the un-bonded LED die, and the bonded LED die with Ag paste had the largest peak. The results reveal that the Ag paste has the largest positive effect on the LED's EL performance.

### 2.3 Photoluminescent property of LED

The photoluminescence (PL) spectra for un-bonded and bonded LED dies were extracted at wavelength ranging from 300 to 1100 nm. The results are plotted, as shown in Fig. 11. From the results, the peak of the bonded LED die with Ag paste was much larger than that of the un-bonded LED die. It demonstrates that the Ag paste does have a positive effect on the LED's PL performance. While the peaks of the bonded LED dies with SAC solder and non-conductive electrical adhesive were smaller than that of the un-bonded LED die, which demonstrates that the SAC solder and non-conductive electrical adhesive have a negative effect on the LED's PL performance.

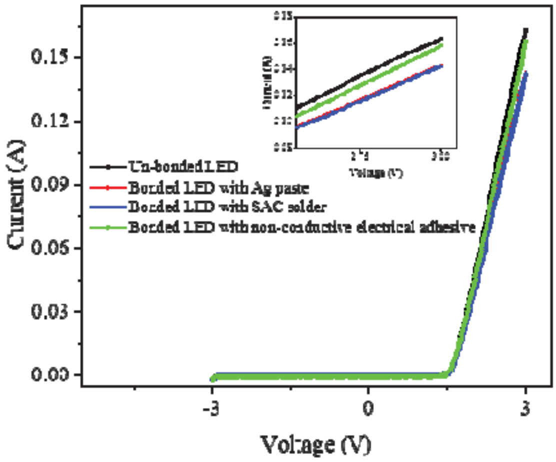


Fig. 9. I-V curves of the un-bonded LED, bonded LED with Ag paste, bonded LED with SAC solder, and bonded LED with non-conductive adhesive, respectively. The inset shows the I-V output at voltage from +2.5 to +3 V.

## Summary and Perspectives

In summary, we have conducted comparative studies, including bonding process optimization, die shear test, and fine leak test for different die-attach materials. It was found that SAC solder has the largest bonding strength of ~60 MPa among the investigated die-attach materials, and the hermeticity is at least 10× below the rejection limit of MIL-STD-883E standard ($5\times10^{-8}$ atm-cc/s) for all die-attach materials. The results indicated that high-quality bonding was achieved. We fabricated LED dies and bonded them onto substrate with different die-attach materials, characterized the bonded LED dies to obtain their I-V, EL and PL. The results showed that non-conductive electrical adhesive has the least negative effect on I-V output of LEDs, Ag paste has the largest positive effect on EL and PL spectra. The obtained experimental outcomes can be used as guidelines to further optimize the process parameters, to characterize the material properties of die-attach materials (e.g. porosity, optical reflectance, volume resistivity, and thermal conductivity, etc.). For future work, the bonding and packaging of RTD integrated LED dies with different die-attach materials will be performed, and the effect of temperature on reliability, luminous efficacy, and optical spectra (e.g. PL and EL spectra) of the packaged LED dies will be characterized.

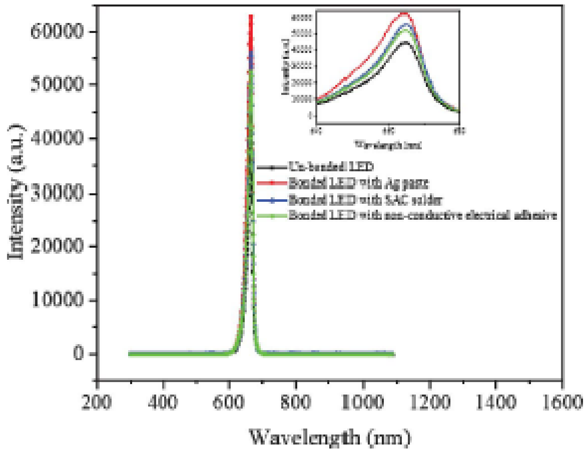


Fig. 10. EL spectra of the un-bonded LED, bonded LED with Ag paste, bonded LED with SAC solder, and bonded LED with non-conductive adhesive, respectively. The inset shows the EL spectra at wavelength from 640 to 680 nm.

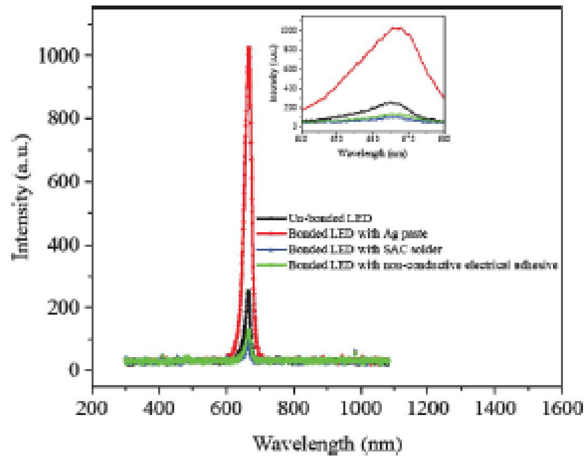


Fig. 11. PL spectra of the un-bonded LED, bonded LED with Ag paste, bonded LED with SAC solder, and bonded LED with non-conductive adhesive, respectively. The inset shows the PL spectra at wavelength from 640 to 680 nm.


**Acknowledgments**

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**References**


1. Lu, D., and Wong, C., Materials for Advanced Packaging, Springer (Boston, 2009), pp. 733-766.
2. Chang, S., and Tsou, C., "A Novel Silicon-Based LED Packaging Module with an Integrated Temperature Sensor," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 4, No. 5 (2014), pp. 769-776.
3. Shih, Y., Kim, G., You, J. P., and Shi, F. G., "Optical Interaction Between LED Backside Reflectors and Die Attach Adhesives," *IEEE Photonics Technology Letters*, Vol. 28, No. 13 (2014), pp. 1446-1449.
4. Schneider, M., Leyrer, B., Herbold, C., and Maikowske, S., "High Power Density LED Modules with Silver Sintering Die Attach on Aluminum Nitride Substrates," *IEEE 64th Electronic Components and Technology Conference (ECTC)*, Orlando, FL, 2014, pp. 203-208.
5. Manikam, V. R., and Cheong, K. Y., "Die Attach Materials for High Temperature Applications: A Review," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 1, No. 4 (2011), pp. 457-478.
6. Kim, G. W., Shih, Y. C., You, J. P., Shi, F. G., "Optical Role of Die Attach Adhesive for White LED Emitters: Light Output Enhancement Without Chip-Level Reflector," *Journal of Solid State Lighting*, Vol. 2, No. 1 (2015), pp. 1-8.
7. Chua, S. L., Hu, L., Tao, J., and Tan, C. S., "Process Development and Reliability Study on Ar/$N_2$ Plasma Activated Cu-Cu Wafer-Level Bonding," *The Conference on Wafer Bonding for MEMS, 3D- and Wafer Level Integration – WaferBond'19*, Halle/Saale, Germany, 2019, pp. 15-16.
8. Hu, L., Goh, S. C. K., and Tan C. S., "Ar/$N_2$ Plasma Induced Metastable $Cu_xN_y$ for Cu-Cu Direct Bonding," *ECS Transactions*, Vol. 98, No. 4 (2020), pp. 203-210.
9. Hu, L., Goh, S. C. K., Tao, J., Lim, Y. D., Zhao, P., Lim, M. J. Z., and Tan, C. S., "In-Depth Parametric Study of Ar or $N_2$ Plasma Activated Cu Surfaces for Cu-Cu Direct Bonding," *IEEE 71st Electronic Components and Technology Conference (ECTC)*, San Diego, CA, 2021, pp. 420-425.
10. Hu, L., Wang, N., Tao, K., Miao, J., and Kim, Y. J., "Circular Steering of Gold-Nickel-Platinum Micro-Vehicle Using Singular Off-Center Nanoengine," *International Journal of Intellient Robotics and Applications*, Vol. 5, No. 1 (2021), pp. 79-88.
11. Hu, L., Goh, S. C. K., and Tan C. S., "Ar/$N_2$ Plasma Induced Metastable $Cu_xN_y$ for Cu-Cu Direct Bonding," *ECS Meeting Abstracts*, Vol. MA2020-02, No. 22 (2020), pp. 1646.
12. Hu, L., Goh, S. C. K., Tao, J., Lim, Y. D., Zhao, P., Lim, M. J. Z., Salim, T., Velayutham, U. M., and Tan, C. S., "Time-Dependent Evolution Study of Ar/$N_2$ Plasma-Activated Cu Surface for Enabling Two-Step Cu-Cu Direct Bonding in a Non-Vacuum Environment," *ECS Journal of Solid State Science and Technology*, Vol. 10, No. 12 (2021), pp. 124001.
13. Hu, L., Goh, S. C. K., Wu, S., and Tan, C. S., "Sputtered Copper Nitride-Copper Nitride Direct Bonding," *2021 IEEE 7th International Workshop on Low Temperature*

*Bonding for 3D Integration (LTB-3D 2021)*, Nara, Japan, 2021, pp. 23.

14. Hu, L., Goh, S. C. K., Lim, Y. D., Zhao, P., Lim, M. J. Z., and Tan, C. S., "Multi-Die to Wafer Bonding Through Plasma-Activated Cu-Cu Direct Bonding in Ambient Conditions," *2021 IEEE International 3D Systems Integration Conference (3DIC)*, Raleigh, NC, 2021, pp. 1-5.
15. Hu, L., Tao, J., Bao, S., Goh, S. C. K., Lim, Y. D., Zhao, P., Lim, M. J. Z., Tan, S. C., Chew, K. H., and Tan, C. S., "Systematic Investigation and Characterization of Ag Paste for LED Die Attach," *2021 IEEE 23rd Electronics Packaging Technology Conference (EPTC)*, Singapore, Singapore, 2021, pp. 140-143.
16. Hu, L., Lim, Y. D., Zhao, P., Lim, M. J. Z., and Tan, C. S., "Plasma-Activated Cu-Cu Direct Bonding in Ambient for Die-Die and Die-Wafer Bonding," *2022 6th IEEE Electron Devices Technology & Manufacturing Conference (EDTM)*, Oita, Japan, 2022, pp. 276-278.
17. Hu, L., Lim, Y. D., Zhao, P., Lim, M. J. Z., and Tan, C. S., "Two-Step Ar/$N_2$ Plasma-Activated Al Surface for Al-Al Direct Bonding," *2022 IEEE 72nd Electronic Components and Technology Conference (ECTC)*, San Diego, CA, 2022, pp. 324-329.
18. Wang, N., Bora, M., Hao, S., Tao, K., Wu, J., Hu, L., Liao, J., Lin, S., Triantafyllou, M. S., and Li, X., "Hyaluronic Acid Methacrylate Hydrogel-Modified Electrochemical Device for Adsorptive Removal of Lead(II)," *Biosensors*, Vol. 12, No. 9 (2022), pp. 714.
19. Die Shear Strength, Method 2019.5, MIL-STD-883E (1996).
20. Seal, Method 1014.9, MIL-STD-883E (1995).
21. Wang, Y., Wang, B., Sasangka, W. A., Bao, S., Zhang, Y., Demir, H. V., Michel, J., Lee, K. E. K., Yoon, S. F., Fitzgerald, E. A., Tan, C. S., and Lee, K. H., "High-Performance AlGaInP Light Eemitting Diodes Integrated on Silicon Through a Superior Quality Germanium-on-Insulator," *Photonics Research*, Vol. 6, No. 4 (2018), pp. 290-295.