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DOI
10.1109/ICEPT56209.2022.9872618

Publication date
2022

Document Version
Final published version

Published in
Proceedings of the 2022 23rd International Conference on Electronic Packaging Technology (ICEPT)

Citation (APA)
Chen, H., Zhang, J., Zhang, G., & Liu, P. (2022). Review of Laser Sintering of Nanosilver Pastes for Die Attachment: Technologies and Trends. In *Proceedings of the 2022 23rd International Conference on Electronic Packaging Technology (ICEPT)* (pp. 1-5). IEEE. https://doi.org/10.1109/ICEPT56209.2022.9872618

Review of Laser Sintering of Nanosilver Pastes for Die Attachment: Technologies and Trends

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2022 23rd International Conference on Electronic Packaging Technology (ICEPT) | 978-1-6654-9905-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICEPT56209.2022.9872618

***Abstract*—Nanosilver pastes have been regarded as the most promising die-attach materials for high-temperature and high-power applications due to their advantages such as excellent thermal conductivity, electrical conductivity, high temperature resistance, and good shear strength. However, the common hot pressing sintering process for nanosilver pastes has the limitations of long sintering time and complicated sintering processes. Thus, laser sintering has been proposed as a rapid sintering method that attracts increasing interest due to its advantages of high energy density, fast temperature rise, easy densification, etc. In this review, the recent advances in laser sintering processes were summarized, including pressure laser sintering, backside sintering, and hybrid bimodal laser sintering. The effects of various laser sintering process parameters on joint performance, such as laser power, sintering pressure, irradiation time, and defocusing amount, were further discussed. The rapid sintering mechanism of laser sintering silver nanoparticles(AgNPs) was revealed, while microscopic explanations need to be further explored. This review provided ideas and methods for subsequent researchers to develop rapid sintering methods for power electronic packaging.**

Keywords—Nanosilver, Laser sintering, Die Attachment

I. INTRODUCTION

A. *Nanosilver Pastes for Die Attachment*

With the rapid development of wide-bandgap power semiconductor devices, die-attach materials are required to apply in higher temperatures and harsher operating environments, bringing great challenges to their high temperature resistance and reliability. Commonly used materials for die attachment such as Sn-based solders and adhesives are no longer suitable because they cannot withstand harsh operating environments. Other alternative candidates like Zn-based and Au-based solders have many limitations such as poor high temperature and corrosion resistance, poor processability and high costs. Hence, in order to meet the high-temperature electronic requirements as well as the environmentally-friendly recommendations, new die-attach technologies have emerged. Among them, nanosilver sintering seems to be one of the most promising and attractive technologies[1].

Nanosilver pastes have not only high electrical and thermal conductivity ($4.1\cdot10^7$ S/m, 240 W/m·K, respectively), but also low process temperature and high operating temperature, as well as low elastic modulus. These advantages have provided microelectronic packaging with high thermomechanical performance and reliability, which can be adapted to more severe thermal and electrical constraints[2]. There is no doubt that nanosilver paste is one of the best candidates for die-attach material, but the complicated sintering process limits its large-scale industrial application. Most nanosilver pastes adopted the traditional hot pressing and pressureless sintering process[3]. The above process have some disadvantages such as complicated processes, long sintering time, and low production efficiency, leading to efforts to develop new sintering methods with simpler processes and shorter sintering times.

B. *The Development of Laser Sintering*

New rapid sintering methods are rapidly developing and emerging, including in-situ generation, spark plasma sintering, laser sintering, and current-assisted sintering[4,5]. Table 1 presents the advantages and disadvantages of traditional hot pressing sintering and several rapid sintering methods. Among others, laser sintering has attracted increasing attention due to its advantages of high energy density, fast temperature rise, easy densification, etc[6].

Laser sintering is a rapid sintering method that heats the target material to the sintering temperature to achieve densification by using the laser. What's more, it's easy to confuse laser sintering and laser-assisted sintering processes. The difference between laser sintering and laser-assisted sintering processes needs to be clarified, while the latter laser-assisted sintering is mainly combined with the hot plate sintering method for assisted sintering. At present, research on laser sintering were mainly focused on flexible printed circuits and conductive films[7,8]. For instance, Ji et al.[9] developed a selective laser sintering technique for the construction of microscopic electrodes and flexible circuits, and the results showed that the combination of laser-sintered microscale Ag flakes and nAg-MWNTs provided a high conductivity of 25012 S・cm^{-1} in a flexible matrix. Balliu et al.[10] fabricated the high-conductivity patterns based on nanosilver inks through a laser sintering process, exhibiting 26% higher conductivity compared to bulk silver. However, few reports were focused on applying laser sintering for power electronics packaging, especially laser sintering for die attachment.

Table 1 Comparison of different sintering processes

Sintering processes	Advantages	Disadvantages
Hot press Sintering	Low cost, low sintering temperature, high shear strength	Complex sintering process, long sintering time (20-60min), low production efficiency, sometimes require vacuum or atmosphere protection, difficult to automate
Pressureless Sintering	Simple equipment, automation, low cost	Long sintering time (more than 60min), low shear strength
In-situ generation	low process temperature (200 °C), low cost	Low Yield, difficult to control particle size distribution
Spark Plasma Sintering (SPS)	Simple operation, space saving, energy saving, heating evenly, high productivity	Require vacuum or atmosphere protection, high cost
Current-assisted sintering	Short sintering time, Relatively high shear strength	High cost, high current may damage chip and substrate
Microwave Sintering	Save energy, easy to control, safety, environmentally friendly	Complex equipment structure, small uniform microwave field, large temperature gradient, difficult to determine microwave sintering parameters
Laser Sintering	High energy density, rapid temperature rise, fast solidification, short sintering time, easy densification	Relatively low shear strength, high laser energy may damage the chip and substrate

Currently, laser sintering nanosilver for die attachment is usually classified into pressurized and non-pressurized processes. Pressureless laser sintering was performed for LED applications, while laser sintering with pressure was mainly applied in power die attachment. Generally, although laser sintering with pressure results in higher shear strength joints than the pressureless process, there is a risk of high-pressure damage to the chip and substrate. Not only the sintering pressure but other process parameters in laser sintering are also important, such as irradiation time and laser power. It is worth noting that increasing or decreasing a single process parameter is not conducive to obtaining laser-sintered silver joints with high shear strength and excellent reliability. Hence, it is essential to explore the influence of the key process parameters on the performance and their relationship during the laser sintering process, and seek the optimal solution.

By using laser sintering nanosilver pastes for die attachment, the chip and substrate were quickly connected, and the mechanical support and heat dissipation functions of the chip are realized. to achieve the mechanical support, heat dissipation and conduction functions of the chip. Due to the short process time of laser sintering nanosilver pastes, the sintering kinetic behavior of silver nanoparticles may be significantly different from the hot press sintering process, which will greatly affect the performance of sintered silver joints. However, the research on the sintering behavior and mechanism of the rapid sintering method are rarely investigated and reported, and has not been revealed yet.

In this review, recent advances in laser sintering of nanosilver pastes for die attachment are summarized and compared with the hot pressing sintering process. Then, the effects of key process parameters in laser sintering such as laser power, irradiation time and sintering pressure, on the properties of nanosilver joints were collected from different studies. The optimization solutions for key laser process parameters were proposed, while the rapid sintering mechanism needs to be further revealed. At last, the future challenges and prospects of laser sintering nanosilver pastes were discussed.

II. LASER SINTERING PROCESS

A. Laser Sintering without pressure-LED Application

With the increasing demand for high-power light-emitting diodes (LEDs) devices, thermal management problems in electronic packaging have been gradually exposed. In order to meet the heat dissipation requirements, various new die-attach technologies were widely investigated. In previous studies, hot-pressing sintering methods for nanosilver pastes were commonly used but with many limitations, and then the laser sintering process was proposed for electronic packaging. Initially, the laser sintering setup was relatively simple without pressure, and mainly applied in LED power device packaging.

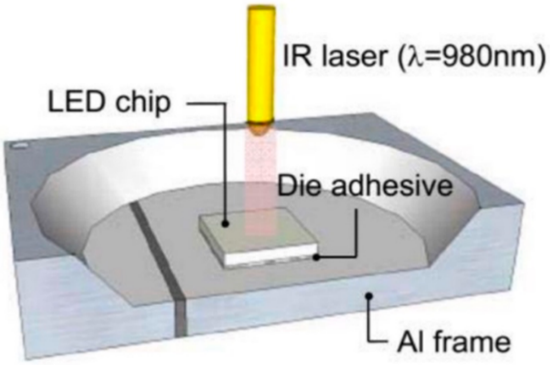

Fig.1 Schematic diagram of laser sintering[11].

Yu et al.[11] fabricated high power LEDs based on laser-sintered silver nanoparticles, which exhibited significantly improved in both power device performance and reliability. Conventional gallium nitride (GaN) LED chips (60 mil × 60 mils) and commercially available die adhesives such as epoxy and silicone, as well as silver nanoparticles with diameter sizes below 50 nm were prepared. An IR laser (30W, λ=980 nm) was utilized in this study. Fig.1 demonstrates the laser sintering process based on silver nanoparticles. The results showed that the nanosilver joints fabricated by laser sintering reached the shear strength of 12 MPa within 15 s, which was comparable to the properties of the joints obtained by hot pressing sintering in a convection oven (250 ℃, 3 h).

B. *Laser Sintering with pressure-Power Die Attach Application*

In the previous works, the laser beam was directly irradiated onto the coated or printed AgNP-layer without any load, whereas porosities in the obtained laser-sintered silver joints led to insufficient mechanical strength. Additionally, there may be a negative effect on the chip when the gas of the solvent and organic compounds volatilizes from the nanosilver pastes during the sintering process. If without pressure, it usually results in chip and substrate stripping. Hence, the pressureless laser sintering process becomes insufficient to satisfy the growing demands for electronic packaging of high-power devices due to its limited mechanical performance and reliability. In that case, it is necessary to develop a laser sintering process with pressure to increase the sintering driving force and further denser the microstructures.

Therefore, some pressure laser sintering setups for power device packaging were proposed from different studies, which mainly included the optical module, laser beam, loads, glass plate, ceramic plate, and X-Y stage, as shown in Fig.2.[12] From Fig.3, it was observed that the AgNP-layer by laser-assisted sintering became denser with the increase of sintering pressure and the large voids were released. It was calculated that the porosity decreased from nearly 17 % at 0.3 MPa sintering pressure to almost 3 % at 3 MPa sintering pressure, which indicated the shear strength of the Si-Ag-DBC joints were able to enhance by increasing the sintering pressure. Furthermore, the higher sintering pressure can not only increase the density of the AgNPs layer, but also drive the nanosilver pastes to be in closer contact with the chip surface. In conclusion, under the conditions of sintering pressure of 3 MPa, laser power of 70 W as well as an irradiation time of 5 mins, the average shear strength of the obtained joints reached 20.1 MPa.

As mentioned above, the increase in sintering pressure facilitates densification and enhances laser-sintered joint performance. It is mainly attributed to two reasons: on the one hand, the gases released by the decomposition of organic compounds in the nanosilver pastes will generate undesired stress, which is exactly offset by the externally applied pressure to obtain better interconnection quality. On the other hand, when other laser sintering process parameters remained the same, the applied pressure provided the sintering driving force, which was helpful to homogenize and densify the microstructure of the laser-sintered joints. Nevertheless, excessive laser sintering pressure may lead to damage to both the chip and substrate, which will significantly reduce the yield of power electronic devices. In such considerations, the sintering pressure parameters should be controlled within a certain range to better enhance the mechanical performances of the laser-sintered nanosilver joints. Hence, it is recommended that the applied sintering pressure should not exceed 5 MPa.

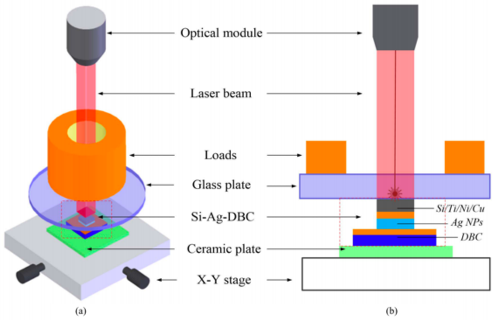

Fig.2 Schematic diagram of pressure laser sintering[12].

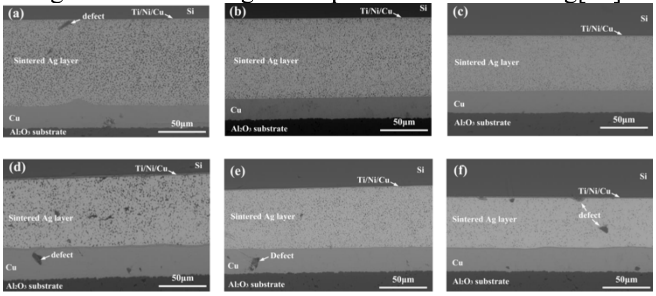

Fig.3 SEM images of cross-sections of the Si–Ag–DBC joints[12].
(a-c) Hotplate-based method, 300 °C, 30 min: (a)0.3 MPa, (b)1.5 MPa, (c)3 MPa. (d-f) Laser-based method, 70 W, 5 min: (d)0.3 MPa, (e)1.5 MPa, (f)3 MPa.

C. *Other key process parameters*

Besides sintering pressure in the laser sintering process, there are other key process parameters that also greatly affect the performance of the nanosilver joints like laser power, irradiation time and defocus amount, etc. The laser power was investigated first since it directly and positively affected the corresponding sintering temperature during the laser sintering process. The sintering temperature determined the nanoparticle size and crystallite size of the nanosilver layer, which should be limited in order to prevent thermal damage to temperature-sensitive components.

Some researchers innovatively proposed a backside sintering method to prevent the chip and substrate from being directly irradiated by the laser, and the results have shown that the shear strength of the obtained laser-sintered joints could reach 12-38MPa within 5-15s[13]. Furthermore, the effect of the laser power factor on the microstructure and properties of laser-sintered joints has been intensively discussed. As shown in Fig.4(a), there was a large gap between the sintered necks since the organic PVP in nanosilver pastes was not completely decomposed in low-power laser sintering, which results in low density and low shear strength of the laser-sintered nanosilver joints. While Fig.4(b) showed a significant difference, with the increasing laser power, the sintered neck coarsened and grew, and the porosity of the sintered joints decreased through diffusion, which enhanced the mechanical performances of the laser-sintered nanosilver joints. Obviously, increasing the laser power was beneficial for densification and obtaining nanosilver joints with higher shear strength. On the contrary, it is more likely to generate a eutectic structure and occur thermal shock on the chip when laser power is too high. There is a possible solution to avoid thermal shock damage to the electronic components is to set a gradient increase in the laser power. Based on the related results, it was suggested that the laser power parameters are preferably between 35W-130W.

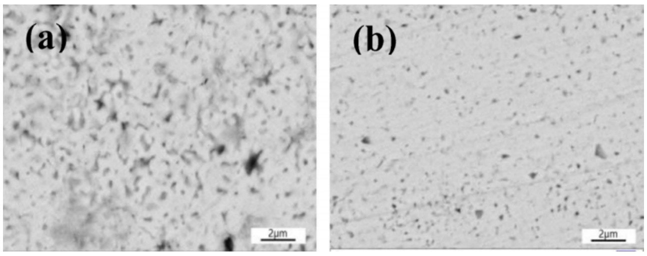

Fig.4 SEM images of laser-sintered joints(a)80 W, 5 s; (b)120 W, 5 s[13].

When laser sintering parameters are constant including the laser power, the amount of laser output energy will greatly depend on the irradiation time. This means that the irradiation time will directly affect the morphology and property of laser-sintered joints. Liu et al.[14] used pressurized laser sintering process to sinter nanosilver pastes prepared by mixed AgNPs (19 and 62 nm in diameter). During the laser sintering, a Yb-doped fiber laser was used. The sintering conditions were set as the laser power of 60 W, the pressure of 5 MPa, and the irradiation time of 5 s, 10 s, and 15 s, respectively. With increasing sintering time, the joints became more uniform and denser, and the sintered necks grew up. At the same time, the porosity of the joints decreased significantly, as shown in Fig.5. This is consistent with the results that the shear strength of laser-sintered joints increased positively with the irradiation time, and the laser-sintered nanosilver joints with minimum porosity were obtained after 15 s irradiation (Fig.6). The results showed that the highest shear strength of the obtained joints by laser sintering reached 32 MPa, when sintered at 60 W for 15 s under 5 MPa with 30 % (mass ratio) 62 nm AgNPs.

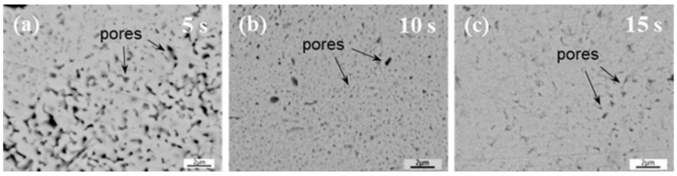

Fig.5 Cross-sections of 62 nm AgNPs samples sintered at 60 W for different times: (a)5 s, (b)10 s, (c)15 s[14].

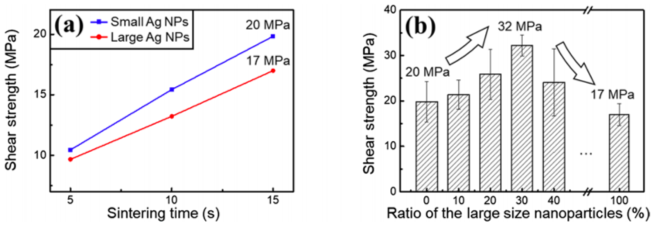

Fig.6 Shear strength of samples prepared by different pastes:(a) sintered by single Ag NPs for different times, (b) sintered by mixed pastes for 15 s at 60 W[14].

In general, the laser beam will precisely sinter the designated area so that there is no thermal shock damage to other temperature-sensitive electronic components[15]. Nevertheless, the power density at the laser focus is Gaussian distribution, which is not uniform and needs to be controlled within a reasonable range, so the change of the defocus amount is also critical. Some investigations have shown that with the increase of the defocuses amount, the power density distributed on the chip will decrease. If the power density is too low, it is likely to cause insufficient sintering of the nanosilver pastes, which will lead to increased porosity and decreased densification of the joints. However, it is also concluded that when the spot area exceeds the chip area, the heat-affected zone is enlarged and energy density decreases, leading to decreasing shear strength of the laser-sintered joints. In addition, the degree of absorption of laser radiation energy is related to the laser wavelength, which means that the metal nanoparticles absorb different wavelengths of laser light differently.

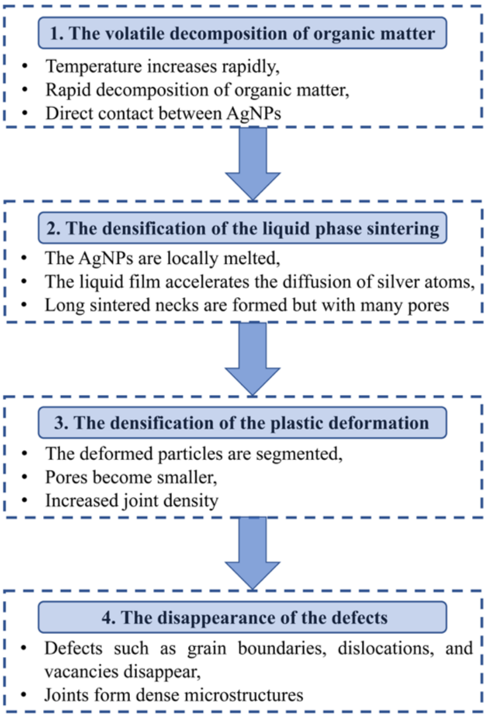

Fig.7 Schematic diagram of laser rapid sintering mechanism

III. RAPID SINTERING MECHANISM

As discussed above, due to the short process time of laser sintering, the sintering kinetic behavior of nanosilver might be significantly different from the hot-pressing sintering process. Therefore, sintering mechanisms based on slow diffusion mechanisms (grain boundary diffusion and lattice diffusion) are no longer suitable. Instead, rapid sintering mechanisms based on rapid diffusion mechanisms, such as surface diffusion, liquid phase diffusion, and plastic deformation, should be further explored. There is a convincing view that laser sintering is divided into four stages: the volatile decomposition of organic matter, the densification of the liquid phase sintering, the densification of the plastic deformation, and the disappearance of the defects, as shown in Fig.7[13]. After the nanosilver pastes absorb the laser energy, the temperature will rise rapidly, resulting in the rapid decomposition of organic matter, so that the silver nanoparticles can be directly contacted. During the liquid phase densification stage, the AgNPs are locally melted, which makes the arrangement of the AgNPs more compact. The diffusion of silver nanoparticles is accelerated through the liquid film, resulting in a long-sintered neck, while there are many pores between the sintered necks. As the laser power increases, plastic deformation becomes the dominant factor. The large pores in the sintered silver layer are filled with segmented deformed particles, resulting in smaller pores and denser microstructure. Finally, defects such as grain boundaries, dislocations, and vacancies gradually fade, allowing the joints to form dense microstructures. The existing hypothesis of the rapid sintering mechanism is immature since they only stay on observing the surface, so further research is needed to reveal it.

IV. CONCLUSION AND OUTLOOK

In summary, laser sintering for die attachment has the advantages of rapid processing (minutes or even seconds), sufficient shear strength, and local selective heating, compared with the traditional hot press sintering process. Laser sintering was proved to be sufficient for LED and power electronics packaging. However, the current laser rapid sintering technology still faces limitations such as uneven laser energy density and excessive local heating temperature, which leads to damage to the chip and substrate. With sufficient control of parameters of laser power, irradiation time, and assist pressure, laser sintering technology will explore more new opportunities for die attachment in high-temperature applications.

ACKNOWLEDGMENT

The authors thank the funding of the Key-Area Research and Development Program of Guangdong Province (Funder ID: 2020B010170002), Science and Technology Innovation Base of Shanghai Municipal Science and Technology Commission, Shanghai SiC Power Device Engineering and Technology Research Center, Fudan University (Funder ID: 19DZ2253400) and Fudan University-Heraeus cooperation project (Funder ID: 20549) for their financial support.

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