

Silver-Copper Hybrid Nanocomposite Thermal Interface Materials for Power Electronic Device Packaging

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Abstract

Thermal interface materials (TIMs) play a crucial role in the thermal management of power electronic devices. In this study, a new class of TIMs, the silver-copper micro-nano hybrid composite pastes (AgCuMNH), was presented utilizing the sizes and shapes the materials natural properties of copper microparticles (CuMPs), silver nanoflakes (AgNFs), and silver nanoparticles (AgNPs), to form the low temperature sintering Ag-Cu hybrid nanocomposites, which demonstrated superior thermal conductivity up to 330.0 W/(m·K) under the process conditions of 220 °C of temperature and 0.7 MPa of pressure. It was found that the solvent choices would play a significant role in the paste formulation since the polarity of solvent highly affect the disperse and distribution of the silver nanoparticles and nanoflakes in the pastes, which dictated the degree of sintering in the hybrid nanocomposites and hence showed large differences in material thermal and electrical conductivities. To further validate the AgCuMNH as high performance TIMs for power electronic device packaging, they were used as the die-attach pastes for a model LED chip packaging structure. The thermal resistance of AgCuMNH as the die-attach TIMs was 0.56 K/W. Compared with the best commercially available low-temperature sintered silver paste from Kyocera (CT2700R7S), whose thermal resistance in the same device was measured to be 1.00 K/W in the parallel tests, there were more than 40% improvement in performance as the TIMs for packaged devices.

1. Introduction

The third-generation semiconductors, such as SiC and GaN, which have presented great advantages in higher power density and energy conversion efficiency, are core components of new-type power devices. They have demonstrated enormous potential applications in fields such as renewable energy vehicles, 5G communications, and aerospace^[1–3]. The operating temperature of wide-bandgap semiconductor devices like SiC can reach up to 250–300°C, which far exceeds the 180 limit of Si devices and thus places higher requirements on packaging materials^[1, 4, 5]. Traditional Sn-Pb alloy solders have been widely used at the thermal interface materials (TIMs) in electronic device packaging, owing to their relatively low melting point and excellent wettability^[6]. However, due to the harm of Pb to human health and the environment, as well as the tendency of Sn-Pb solders to undergo creep and fatigue failure under high-temperature conditions^[7], Sn-Ag-Cu (SAC) alloys have become the mainstream lead-free alternative to replace Sn-Pb solders, such as SAC305 (Sn-3.0Ag-0.5Cu)^[8]. Although these solders are environmentally friendly, they still pose challenges in high-temperature applications. Studies have shown that the mechanical properties of lead-free solders are highly dependent on the testing temperature. At temperatures ranging from 125 °C to 200 °C or even higher, the stress-strain behavior and creep properties of lead-free solders undergo significant changes^[9]. High-temperature aging can lead to microstructural evolution and degradation of mechanical properties of the solders, thereby affecting their long-term reliability^[10]. Gold-based alloys such as Au-Sn solders, which possess relatively higher melting points and excellent electrical conductivity, have found applications in certain high-temperature scenarios. However, their exorbitant cost limits the large-scale commercial application^[11].

Silver nanoparticles (AgNPs), due to their unique size effect, endow packaging pastes with advantages in low-temperature sintering and high-temperature service. The microstructure formed after the sintering of AgNPs often presents a highly dense silver crystal network^[12], whose melting point is close to or equal to that of bulk silver (961.78 °C). This enables the sintered silver TIMs to work stably in environments far above the melting point of traditional solders (e.g., the melting point of lead is 327 °C), effectively overcoming the limitations of traditional solders in applications under extreme high-temperature conditions^[1, 13]. In the field of power electronic device packaging, the compounding of AgNPs with other metals to prepare hybrid composites and multi-scale packaging TIMs is a current research focus. This approach aims to address the challenges of high ion mobility and high cost faced by pure silver TIM pastes, while integrating the advantages of different materials to meet the increasingly stringent packaging requirements of electronic devices^[13–15]. In this study, we present to the field with a carefully designed copper-silver and micro-nano hybrid composite system, which would take the advantages of not only the material compositions but also the size-effects of microstructure, enable the best performance and cost for TIMs of high power electronic device packaging.

In the hybrid pastes, the voids between micron-sized copper particles can be filled with smaller nano-sized silver flake-shaped particles, which enables more efficient packing density, significantly reduces the internal porosity of the material, increases the volume fraction of the filler, and thereby improves mechanical strength, electrical conductivity, and thermal conductivity^[16, 17]. AgNPs with size less than 10 nm in the hybrids would act as a "bridging" material by sintering, connecting micron-sized particles to more integrated hybrid nanocomposite TIMs^[18]. Due to their inherent low-temperature sintering property, AgNPs first undergo sintering at a low process temperature and form dense connections between the larger particles. This process promotes the faster formation of sintering neck structures between larger particles, which present the key structures for enhancing the performance of the hybrid nanocomposite TIMs. During the sintering process, applying pressure has a similar effect to promote connections and neck structures between the microparticles in the hybrid nanocomposite TIMs^[19].

Based on the aforementioned proposal, this study used copper microparticles (CuMPs) with size of 2–4 μm as the framework and introduced silver nanoflakes (AgNFs) and AgNPs (sized less than 10 nm) as interstitial fillers to construct a micro-nano hybrid composite structure. The study analyzed the effects of four solvents (Terpineol, Dibasic Ester (DBE), Glycol, and 1,2-Propanediol) in the paste formulation on the thermal and electrical conductivity of silver-copper micro-nano hybrid composites (AgCuMNHs) and rationalized the dispersion mechanism of AgNFs and AgNPs in AgCuMNH from the perspective of solvent polarity. Meanwhile, the study also investigated the sintering temperature and pressure on the microstructure formation of the AgCuMNH TIMs. The experimental results showed that the chosen solvent to compromise dispersity of both AgNFs and AgNPs enable them to disperse more evenly in the AgCuMNH, therefore resulting in the TIMs with better thermal and electrical conductivity. It was also demonstrated that under the conditions of processing temperature at 220 °C and pressure of 0.7 MPa, the sintered hybrid TIMs form a continuous sintering neck network structure, and the thermal conductivity can reach 330.0W/(m·K) after process optimization, which is the highest of the hybrid TIMs

ever reported. Finally, the AgCuMNH and a commercially available silver paste from Kyocera, which is regarded as the best performance benchmark nano-silver TIMs in the field, were respectively tested using for LED chip packaging, and thermal transient testing was conducted with the packaged devices. Comparative results showed that the hybrid paste designed in this study has better thermal conductivity, with its thermal resistance being only 56% of that of the benchmark paste. This design of multi-component and multi-scale hybrid composite paste exhibits great application potential in the field of high-power electronic device packaging.

2. Results and Discussion

2.1. The effect of AgCuMNH solvents

The AgCuMNH consists of 55wt% CuMPs with an average size of 3 μm (Fig. 1a), 25wt% AgNFs with flake sizes of 0.3–0.5 μm and thickness ≤ 50 nm (Fig. 1b), 10wt% AgNPs with particle sizes of 8–10 nm (Fig. 1c), and 10wt% organic solvent. Each component weighed in proportion was placed in a mortar, ground thoroughly for 30 minutes, and thus AgCuMNH was prepared. In order to ensure that the organic solvent in the AgCuMNH can be completely volatilized after sintering, four low-boiling point solvents were chosen in the experiments: Terpineol, Glycol, 1,2-propanediol, and DBE. To investigate the electrical and thermal conductivity of the AgCuMNH, the sintering process of the composite silver paste was carried out as follows: first, a sample of about 2g of the AgCuMNH was weighed and uniformly filled into the mold. The temperature of the hot press was set to the target temperature for 10 min of preheating treatment, and then the hot press sintering process was carried out for 20 min under the preset pressure conditions. Subsequently, an electrical transport property testing system (ECT ET9007) and a laser flash analyzer (LFA467) were used to test the electrical conductivity and thermal conductivity of the sintered samples, respectively.

The AgCuMNH system was so designed having the CuMPs to form the base frame of the material and the AgNFs to fill the voids between the CuMPs together with the smaller sized AgNPs which enable the low temperature sintering. After the sintering process, the AgNFs and AgNPs would fuse together to form interconnects of a sintered neck structure between CuMPs. The process is depicted schematically in Fig. 1d.

The thermal conductivity and electrical conductivity of four groups of sintered (220 $^{\circ}\text{C}$, 0.7 MPa) samples with different solvents were tested, as shown in Table 1. From the test results, it is concluded that the sintered sample prepared with 1,2-propanediol as solvent has the highest thermal conductivity of 247.4 W/(m·K). While the sintered sample prepared with Terpineol as a solvent had the lowest thermal conductivity of 105.1 W/(m·K). In our early work^[20], we found that the thermal conductivity and electrical conductivity of those AgCuMNH are highly related to the porosity of the sintered samples caused by the material compositions. However, in this study by testing the porosity of four groups of sintered samples (Table 1), it was found that there was no dramatic difference in porosity among the four sets of samples, in range of 26.06% to 29.67%, but the thermal and electrical conductivities of the samples exhibited very

large differences, ranging from 105.1 W/Km to 247.4 W/Km and from 14 MS/m to 27 MS/m, respectively. Therefore, we believe that there must be some other factors that dictated the thermal and electrical conductivities of the sintered samples, so we investigated further by examining microstructures of the sintered samples.

Table 1

Parameters of sintered samples prepared by different solvents

Solvent	Terpineol	DBE	Glycol	1,2- Propanediol
Electrical conductivity (MS/m)	14	21	20	27
Thermal conductivity(W/(K·m))	105.1	185.2	153.1	247.4
Porosity	26.06%	27.94%	29.67%	26.67%

Figure 2a-d showed that microstructures in the samples prepared with different solvents had significant differences in their metrology, showing different degrees of materials sintering. The sample prepared with 1,2-Propanediol showed the most complete sintering (Fig. 2d) as the AgNFs were fully fused together caused by the low temperature melting of the 8–10 nm AgNPs, while the samples prepared with other three solvents still had significant amount of AgNFs remained in the samples. We would relate the higher thermal and electrical conductivities of the materials to the higher degree of sintering of AgNFs between the CuMPs since they provide more efficient conducting paths in between the CuMPs. To further understand what causes those large differences between samples, we examined the Energy Dispersive Spectroscopy (EDS) mapping of Ag and Cu with those four groups of samples (Fig. 2e to 2l) and found that the silver distribution in the sample prepared with Terpineol was not as uniform as the others. It is noteworthy that, due to the extremely small size of AgNPs, under the magnification of an SEM equipped with EDS, the detected silver element would mainly originate from AgNFs, while the EDS signals of AgNPs would be invisible. We would reasonably relate the lower thermal and electrical conductivities of this sample to the inefficient distribution of AgNFs in the material matrix, as they could not evenly fill the voids in between the CuMPs throughout the sample. Therefore, we believe that the solvent chosen could highly affect the nano-sized materials distribution in the sample which cause the effectiveness of AgNFs filling and sintering in the AgCuMNH.

It is a widely accepted fact that the dispersibility of nanoparticles in the pastes would highly dictate the homogeneity of distribution of the nanoparticles in the applied samples. Therefore, we suspect the polarity of solvents used to prepare the samples play a significant role in the dispersibilities of both AgNPs and AgNFs in the pastes. The Molecular Polarity Indices (MPI) of the four solvents calculated using Multiwfn^[21, 22] are shown in Table 2. It can be observed that Terpineol exhibits the lowest Molar Polarizability Index (MPI) of 6.85 kcal/mol, indicating the weakest polarity, while both 1,2-Propanediol and Glycol possess relatively high MPI values, with significantly stronger polarity. This is mainly attributed to the fact that both compounds contain two hydroxyl groups (-OH) in their molecular structures, resulting in similar polarity at the molecular level^[23]. However, in the liquid state, the additional methyl group (-CH₃) in the 1,2-Propanediol molecule imposes steric hindrance on the

formation of intermolecular hydrogen bonds, which leads to a relatively lower polarity solvent than Glycol, evidently showing a lower dielectric constant of 1,2-Propanediol compared with Glycol (Table 2). [24]

Table 2

The MPI and dielectric constants of different solvents

Solvent	Terpineol	DBE	Glycol	1,2- Propanediol
MPI(kcal/mol)	6.85	9.84	13.99	13.69
Dielectric constant	2.6	8.5	37	32

During the preparation of AgNFs, polyvinylpyrrolidone (PVP) was used as a capping agent coated on the surface to prevent agglomeration.^[25] PVP possesses hydrophilicity as well as strong hydrogen bond donor and acceptor capabilities and thus exhibits excellent dispersibility in 1,2-Propanediol and Glycol. In contrast, The PVP coated AgNFs rather have poor dispersibility in low polarity solvent such as terpineol, resulting on the uneven distribution in the samples (Fig. 2e). The poor dispersibility of AgNFs directly impairs the thermal and electrical conductivity of the slurry. On the other hand, even though 1,2-propanediol and Glycol both possess high polarity, however, the thermal conductivity of AgCuMNH samples made from the two solvents exhibits significant differences. As shown in Fig. 2d, the sample prepared with 1,2-propanediol achieves the most complete sintering; in contrast, it was observed from the SEM pictures in Fig. 2c that there are still obviously unsintered AgNFs in the sample prepared with Glycol.

The size effect of AgNPs is recognized as the key factor enabling sintering of AgCuMNH at low temperatures under 250 °C, which is far below the melting point of silver metal at 961 °C. In the AgNPs synthesis, a mixture of oleylamine and dodecylamine were used as surfactants to regulate the size of AgNPs^[25]. The long carbon chains in oleylamine and dodecylamine endow the surface of AgNPs with significant hydrophobicity. That would lead to less compatibility in Glycol which has stronger polarity than 1,2-propanediol. Consequently, the AgNPs may distribute more evenly in between the AgNFs in 1,2-propanediol with relatively weaker polarity. Therefore, during the sintering process, the size-dependent melting of AgNPs, as well as their fusion into the interfaces between AgNFs and CuMPs, could more effectively promote the sintering of the AgCuMNH samples prepared with 1,2-propanediol, which showed a higher degree of material fusion (Fig. 2d) than that with Glycol (Fig. 2c).

The degree of particle dispersion in a solvent is closely related to the compatibility of the organic substances on the particle surface with the solvent. Although it is theoretically inferred that there might be solvent systems with better performance, among the four solvents investigated in this study, 1,2-Propanediol exhibits the most prominent performance in terms of both dispersion effect and sintering property.

2.2. The Impact Of Sintering Processes

The sintering processes (including pressure and temperature) have significant effects on the properties of the sintered samples. It is found that both electric and thermal conductivities exhibit an optimal point regarding the process pressure and temperature. In terms of pressure effects, experiments with four sets of gradients set at 0.3, 0.5, 0.7, and 0.9 MPa (preheating at 220 °C for 10 min and sintering for 20 min) showed that applying pressure during AgNPs sintering would promote densification of the AgCuMNH leading to higher electric and thermal conductivities. When the pressure was increased from 0.3 to 0.7 MPa, it can be seen from Fig. 3 that the particles contacted more closely under pressure, which increased the contact area between the particles and formed more fusion channels, and at the same time, assisted by the pressure, the air voids left by volatilization of the organic solvent were squeezed, the porosity was reduced, and the electrical conductivity increased from 2.5×10^7 S/m to 2.9×10^7 S/m, and thermal conductivity increased from 189.7 W/(m·K) to 252.5 W/(m·K). However, after the pressure exceeded 0.7 MPa, the degree of densification was saturated, the pressure effect is limited and even adverse.

In terms of temperature effects, experiments in the range of 180 °C to 240 °C (preheating for 10 min and sintering for 20 min at 0.7 MPa pressure) show that at lower temperatures (180 °C) sintering is insufficient, and the fusion of AgNPs into AgNFs is limited. As shown in Fig. 3e, the AgNFs remain incompletely sintered with retained lamellar morphologies, and the material exhibits electrical and thermal conductivities of only 2.4×10^7 S/m and 208.9 W/(m·K), respectively. As the sintering temperature increases, the densification rate accelerates. Grain boundary diffusion and volume diffusion dominate the densification process, the volatilization of the surface coating agent becomes more complete, and the degree of densification of the sintered body increases accordingly. When the temperature reaches 220 °C, more sintering neck structures were formed, as shown in Fig. 3g. At this point, the electrical and thermal conductivities reach their maximum values of 3.1×10^7 S/m and 253.6 W/(m·K), respectively, and the density is also the highest. With continued increase in temperature up to 240 °C, we found a small decrease in performance, we could reasonably attribute the adverse effect to the surface oxidation of CuMPs in the AgCuMNH. Comprehensively, the temperature of 220 °C and pressure of 0.7 MPa were shown to be the optimal combination of process parameters, resulting in the sintered AgCuMNH with the best electrical and thermal properties. Subsequently, through the optimization of the formulation of AgCuMNH and the sintering process, the thermal conductivity of the material was increased to 330.0 W/(m·K).

To further investigate the adhesion strength of AgCuMNH, Cu-AgCuMNH-Cu sheet interconnection samples were prepared. The copper substrates used had dimensions of 100 mm × 12 mm × 1.5 mm and were used without any treatment. The prepared AgCuMNH was coated onto the bonding areas of the copper substrates, with an interconnection area of 12 mm × 25 mm. The interconnection samples were placed in a hot press at 220 °C, first preheated for 10 minutes, then sintered under a pressure of 0.7 MPa for 20 minutes at the same temperature, and finally held at the temperature for another 10 minutes. After the process, the interconnection samples were taken out and cooled naturally. Subsequently, the shear strength of four groups of samples was tested using a universal testing machine (LD22.203), and the average shear strength measured was 9.513 MPa. Preliminary verification indicates that under the low-

temperature and low-pressure sintering process conditions of this study, this AgCuMNH can meet the minimum requirement of 6.25 MPa specified in the industry standards (MIL-STD-883K METHOD 2019.9) for TIMs used in chip packaging.

2.3. Applications in LED chip packaging

To evaluate the performance of AgCuMNHs as the TIMs in real devices, we applied the AgCuMNH as the die attach adhesive or binder in a typical power LED test device, in comparison with a commercially available low-temperature sintered silver adhesive (Kyocera CT2700R7S), which is considered the-state-of-art benchmark material in current chip packaging. This Kyocera CT2700R7S paste with all silver in composition is claimed to have the processed thermal conductivity of about 200 W/(m·K) according to vander's specifications^[26]. The two pastes were applied as die attach TIMs for LED chips (Jingneng Optoelectronics (Jiangxi) Co., Ltd. LPTBG56D. Maximum optical power: 760 mW) in parallel processes, and the packaging processes were completed through die bonding, wire bonding, and sealing processes following the industrial protocols. The device structure is schematically shown in Fig. 4(a).

A Die Bonder machine (ASM AD860) was used to attach LED chips with gold substrates to silver bases by applying the TIM pastes in between to form a structure of Au-TIMs-Ag with the interconnection area of 4.13mm². A non-pressured sintering process was carried out at 260°C for 30 min (with an elevating temperature rate at 10 °C/min) in a process oven. After thermal annealing, the devices were cooled down to room temperature, and a weld strength tester (DAGE-SERIES-4000PXY) was used to analyze the bonding strength of the sintered TIMs. The shear strength of the sintered joints was measured at the shear rate of 350 µm/s and shear height of 20 µm.

To obtain the thermal characteristic parameters of the device under test (DUT), thermal transient testing was conducted using a T3ster (Thermal Transient Tester) under the advanced static mode. It enables real-time acquisition of the junction temperature variation process of the DUT over time in comply with the JEDEC thermal testing standards. The specific testing procedure is as follows: First, a heating current of 1000 mA was applied to the DUT. After the device reached a thermal steady state, the heating current was rapidly turned off while a test current of 1 mA was maintained. Under the continuous action of the 1 mA test current, the curve of the DUT's junction temperature changing with time was recorded in real time until the device reached a thermal steady state again (Fig. 4(b)). After the test, the acquired transient curve was processed using the data analysis software T3sterMaster to convert it into a differential structure function (Fig. 4(c)).

In the differential structure function, the inflection points between peaks and valleys correspond to the boundaries between two different structures, which facilitate the identification of each internal layer structure of the device. Additionally, the peak-to-peak correspondence indicates the layer-to-layer structure in the sample. The four characteristic peaks of this differential structure function correspond to different structures of the device in sequence: the first peak corresponds to the junction, the second to the chip, the third to the substrate, and the fourth to the cold-plate. Among them, the interval from the second peak to the third peak represents the thermal resistance from the chip to the substrate, which is

contributed by the thermal resistance of the die-attach layer. As observed in Fig. 4(c), within the interval from the second peak to the third peak, there is an obvious deviation between the two curves of the two types of devices. This phenomenon directly indicates a difference in the thermal resistance of their die-attach layers. Through calculation, the thermal resistance of the die-attach layer prepared with our AgCuMNH is 0.474 K/W, while that prepared with the Kyocera CT2700R7S is 1.265 K/W. The averaged values of four devices with each kind of TIMs tested in these experiments are listed in Table 3 for more generalized comparison. At the end of the differential structure functions of the two groups, their values tend to a vertical asymptote, which indicates that the heat transfer has reached the air layer at this point. Therefore, we can conclude that the difference in total thermal resistance between the two groups of DUTs mainly stems from the significant difference in the thermal resistance of the die-attach layer or the TIMs.

Table 3
Parameters of the die attach fabricated with different TIMs

Samples	AgCuMNH	CT2700R7S
Die attach Thermal Resistance (K/W)	0.56 ± 0.06	1.00 ± 0.26
shear strength (MPa)	18.0 ± 1.7	27.6 ± 1.4

Although the shear strength of the die attachment with the AgCuMNH is somewhat lower than that of the devices fabricated using Kyocera CT2700R7S as the TIMs, the average value of 18.0 MPa still meets the industry standard (MIL-STD-883K METHOD 2019.9 DIE SHEAR STRENGTH) of the minimum of 6.25 MPa; However, the an average reduction of 44% in thermal resistance presents huge advantage of the AgCuMNH at the die-attach TIMs for chip packaging, not mentioning the silver content reduction from almost 100% to less than 40%, which presents another huge advantage in device fabrication cost. Therefore, these AgCuMNH as a new class of TIMs for next generation power chip device packaging deserve significantly more attention by the industry for new product developments.

3. Conclusion

In this presented work, we have demonstrated a new concept in designing a new class of die-attach thermal interface materials (TIMs) for the high-power chip packaging technology to meet the application challenges that the next generation power electronic devices are facing. The design of the new hybrid nanocomposite thermal interface materials utilizes the characteristic properties of silver nanoparticles, nanoflakes as well as copper microparticles, including their dimensions, shapes as well as their thermal and electrical properties, to compromise with each other and form the silver-copper micro-nano hybrid structured materials achieving the optimized TIM performance superior to any single components themselves. In the AgCuMNH, the CuMPs are selected to form a flame structure of the materials, while the AgNFs are designed to fill into the spaces between the CuMPs and the ultra-fine AgNPs (< 10 nm in size) spread between all interfaces, which enable the hybrid materials to sinter at the low process temperature by thermal annealing. It is found that to achieve such designed effect, the organic solvent

selection in the paste formulation plays a significant role, as the solvents with proper polarity to help all metal particles evenly dispersed in the mixture achieve optimized material performance as the samples show best sintering by forming more connection necks between the metal particles. It is also demonstrated that the process conditions can also affect the performance of the AgCuMNH TIMs, while with the optimal process conditions (220 °C, 0.7MPa, 20mins) the highest thermal conductivity of AgCuMNH TIMs is obtained as 330.0 W/(m·K) with a bonding strength satisfactory by the industrial standards. By applying the AgCuMNH in the model device packaging as the die-attach adhesive TIMs and analyzing the device thermal characteristic parameters by the thermal transient testing, it is demonstrated that the AgCuMNH present only about 56% in thermal resistance compared to the best performance all silver low temperature sintering paste (KYOCERA CT2700R7S), that is almost doubled in efficiency, while the AgCuMNH only cost less than 40% of the all silver pastes since more than 60% of precious metal is replaced with much less expensive metal copper in materials. In conclusion, these new AgCuMNH are found to be very promising as the thermal interface materials for the high-power electronic device packaging, which may bring in a big leap in the new technology development.

Declarations

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Figures

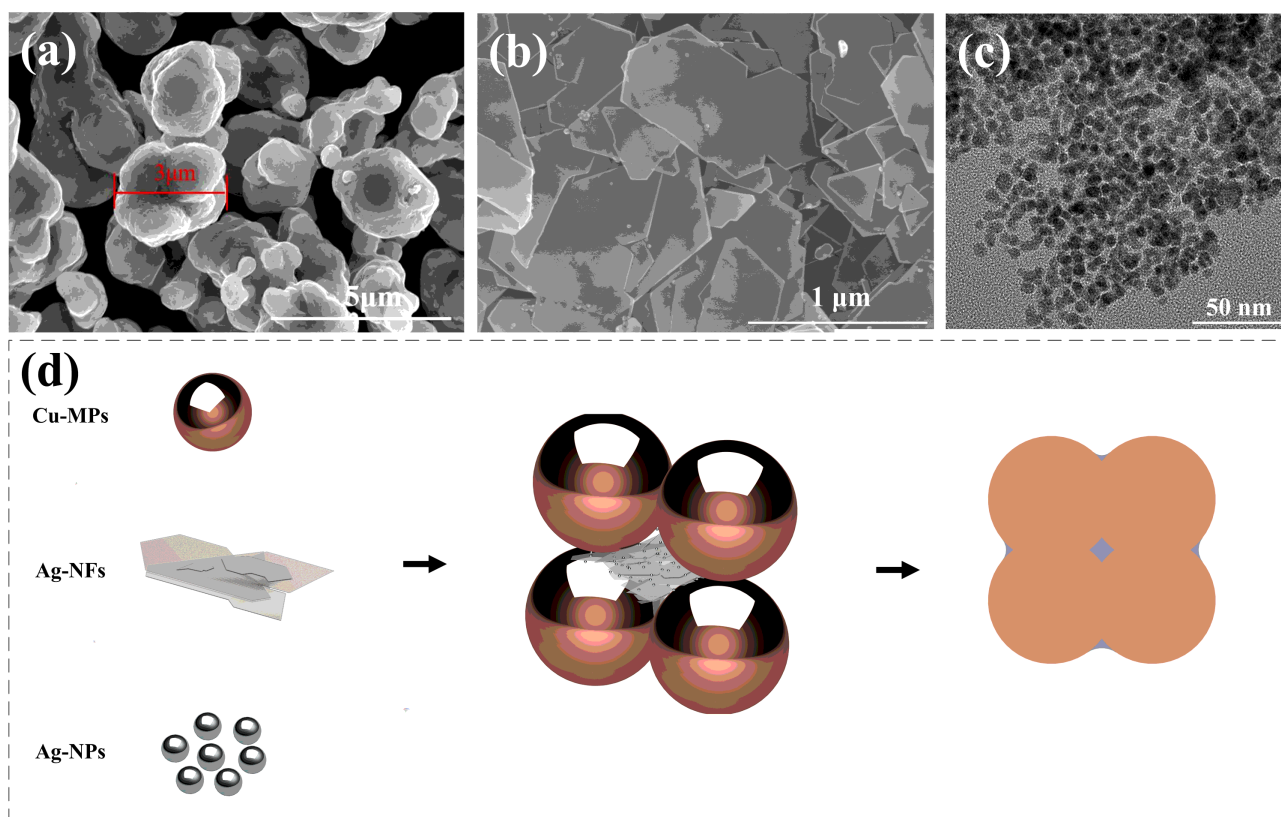


Figure 1

Microstructures of AgCuMNH components: a-b) SEM images of CuMPs and AgNFs, c) TEM image of AgNPs. d) Schematic of the filling between AgNFs, AgNPs and CuMPs.

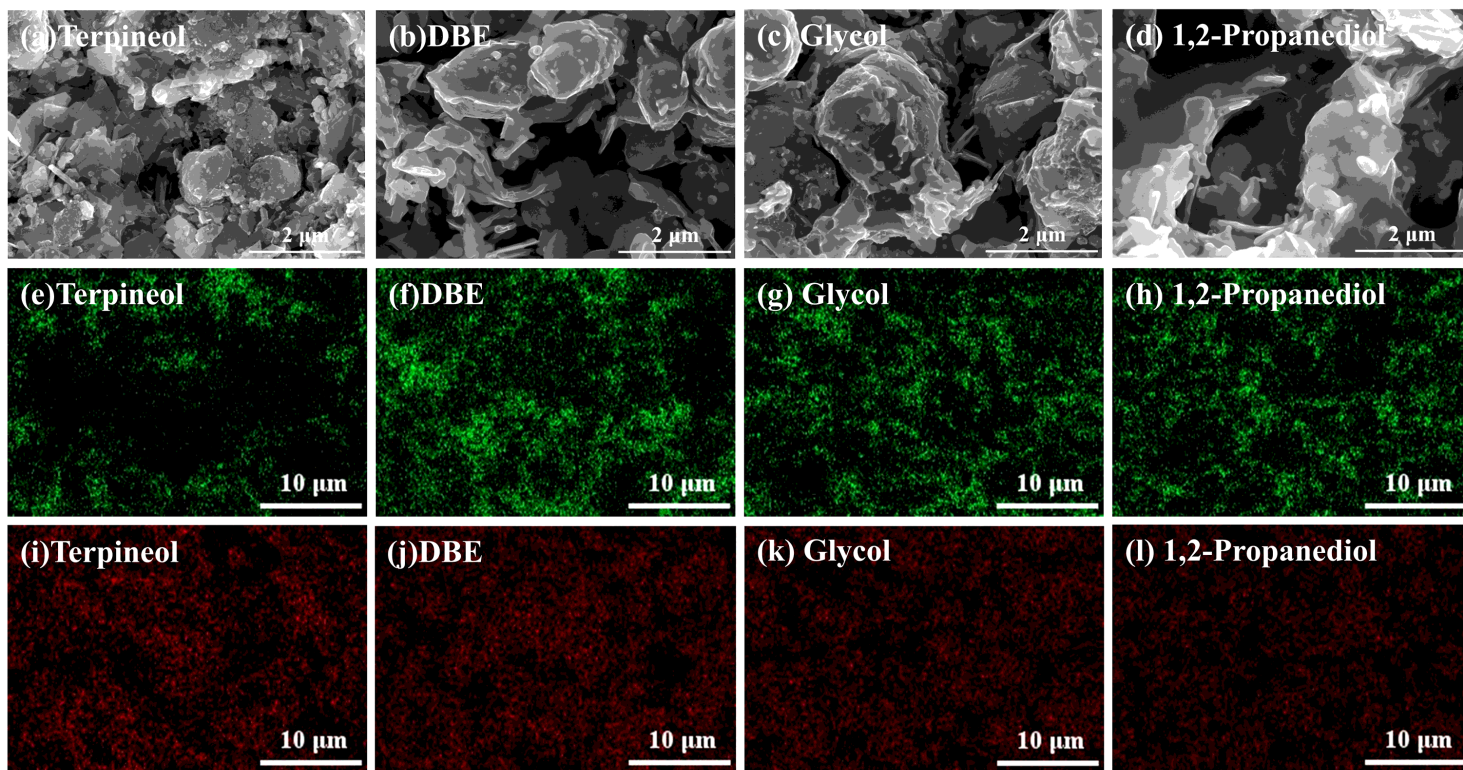


Figure 2

SEM of sintered samples prepared by different solvents a-d), EDS of silver e-h) and copper i-l) element distribution of samples of samples prepared by different solvents.

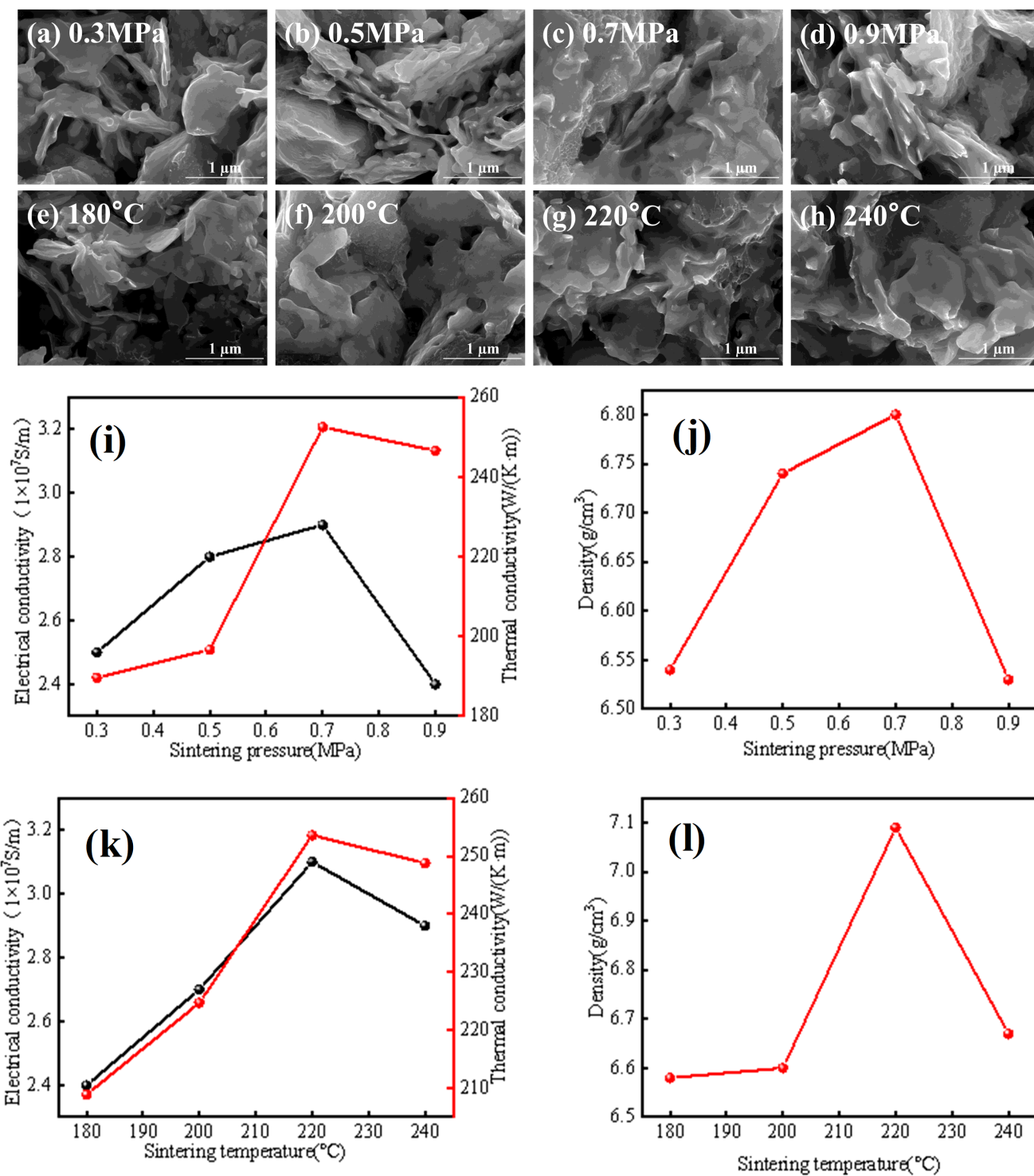


Figure 3

SEM of AgCuMNH after sintering at 220 $^{\circ}\text{C}$, 0.3, 0.5, 0.7, and 0.9 MPa: a-d) after sintering at 0.7 MPa, 180, 200, 220, and 240 $^{\circ}\text{C}$: e-h) Effect of sintering pressure i) and temperature j) on the density, thermal conductivity, and electrical conductivity properties.

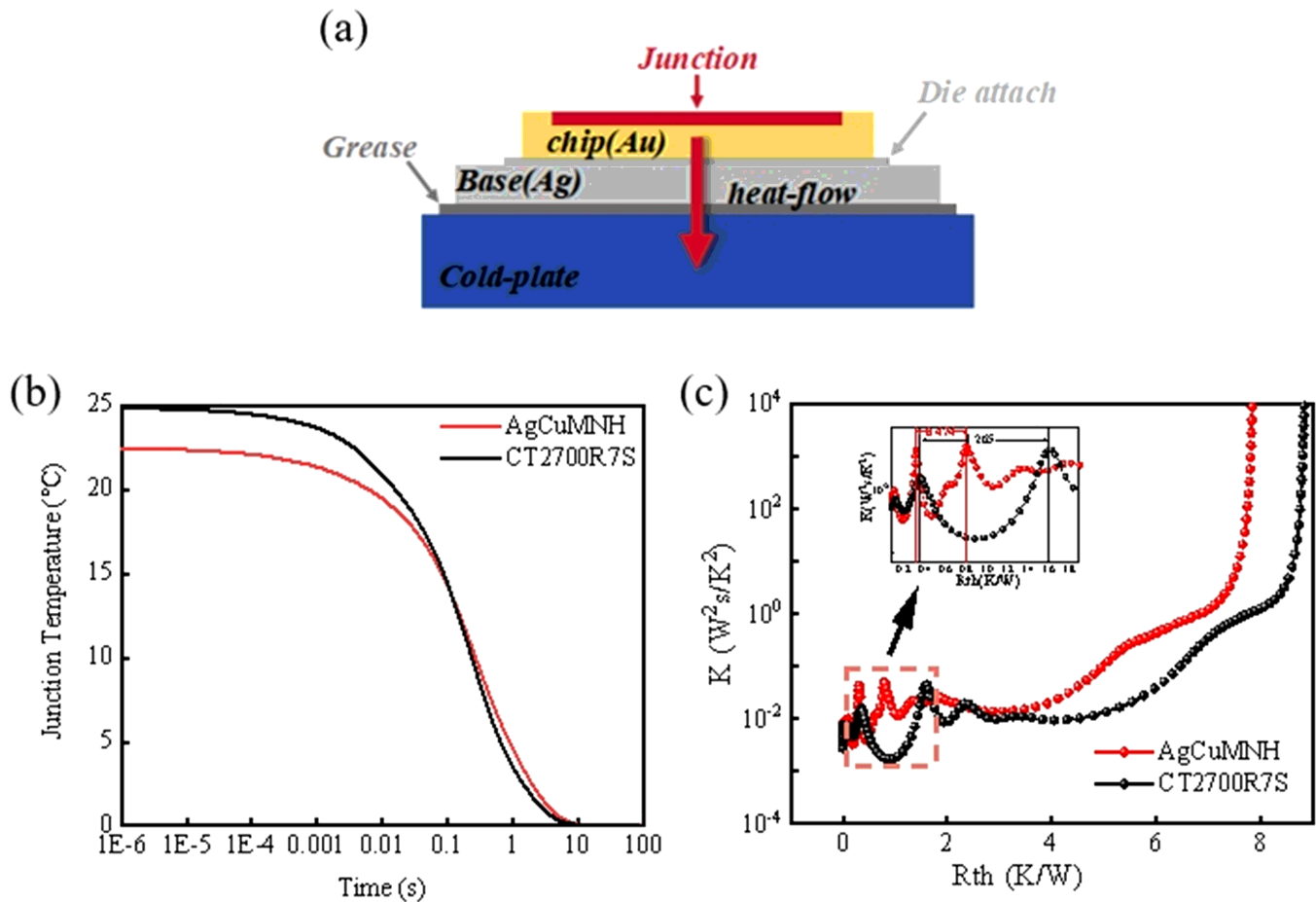


Figure 4

a) Schematic diagram of LED chip structure and heat conduction path; b) Junction temperature of devices fabricated from AgCuMNH and Kyocera CT2700R7S; c) Differential structure function of devices fabricated from AgCuMNH and Kyocera CT2700R7S