Study on high temperature resistant die bonding formed by Al/Ni nano-particles composite paste

Yasunori Tanaka, Tatsumasa Wakata, Norihiro Murakawa, Tomonori Iizuka, and Kohei Tatsumi
Graduate school of information, production and systems, Waseda University
2-7 Hibikino, Wakamatsuku
Kitakyushu-shi, Fukuoka
Ph: 81-93-692-5192; Fax: 81-93-692-5192
Email: spg27yx11@akane.waseda.jp

Abstract

In power modules using SiC devices, high temperature operation is expected. Therefore, a bonding technology having high temperature resistance of 250℃ or more is required. In recent years, research on low temperature sintering bonding by Ag nanoparticles, Cu nanoparticles and sub-micron particles has been conducted as a new bonding technology corresponding to SiC power devices. Nanoparticles are sintered at a temperature much lower than the sintering temperature in ordinary powder metallurgy. We focus on Ni having high melting point and excellent corrosion resistance as a new bonding material and are conducting research on high temperature resistant interconnection technology using Ni nanoparticles. We have found that bonding is possible at a bonding temperature of 400℃ or less and enable to interconnect SiC devices for high temperature operation. However, there are still following problems to be improved, as follows, especially for a large chip size : Voids formed in the bonding layer and cracks generaled stress caused by a difference in thermal expansion coefficient(CTE). In this paper, we propose a bonding material of composite paste in which Ni nanoparticles and Al particles are mixed. From the results of the research, it was found that the occurrence of cracks and gas void was suppressed by mixing Al particles. Also the thermal stress analysis by FEM, the addition of Al particles shows to reduce the thermal stress during thermal cycle test (TCT).

Key words

SiC Power Devices, Al/Ni nano-particles composite paste, High temperature resistant, Die bonding
Stress relaxation structure.

I. Introduction

In recent years, wide bandgap semiconductors such as SiC and GaN have attracted attention as next generation power semiconductors. By using these semiconductors for a power module, it can be made compact, lightweight, high performance and high efficiency, and operation at higher temperature than Si power module becomes possible [1]-[3].

In current power modules using Si - IGBTs, the high operation temperature is 150℃, while high temperature operation at 200℃ or higher is expected, but currently interconnection technology used in the Si power module is difficult to use in the temperature range expected as the high temperature operating of the SiC power module[4], [5].

Bonding techniques such as high temperature lead-free solder [6], TLP (Transient Liquid Phase) bonding [7], and sintered bonding of metal nanoparticles, are being studied. Among them, sintering bonding by metal nanoparticles is a promising bonding technology.

In recent years, investigations on metallic materials such as silver and copper are advanced in low-temperature sintering of metal nanoparticles [8]-[11]. However, Ag is expensive, and copper itself is subject to oxidation. Therefore, at our laboratories, focusing on Ni as a new bonding material, we are studying low temperature sintering joining by Ni nanoparticles. The melting point of Ni(1453℃) is higher than silver and copper, and the electrical resistance of Ni(6.99×10-8Ωcm) is lower than that of Sn - Pb eutectic solder (15×10-8Ωcm) or lead – free solder(Sn-Ag-Cu : 11×10-8Ωcm). We have clarified that bonding can be carried out at 400 °C or less and the bond shows heat resistance at 250℃ or higher. It is also possible to achieve direct bonding to Al [12]-[16]. However, it was found that large gas voids and cracks occurred in the bonding layer after sintering as indicated by arrows in Fig.2.

In addition, in bonding by metal nanoparticles, it is hard to release the stress caused by the difference in CTE, resulting in decrease the bonding strength remarkably for larger chips. Researches are being made to improve the bonding property by increasing the packing ratio of the bonding layer by adding particles having different particle diameters. Studies have also been conducted on suppression of the growth of microporous structure inside the bonding layer at high temperature by addition of compound particles such as SiC or W [17]-[19].

In this study, the stress relaxation structure was investigated by mixing micron-size Al particles with Ni nanoparticles. Since direct bonding of Ni nanoparticles to Al is found to be possible and Al shows low yield strength, the stress relaxation effect in Ni nanoparticle layer after sintering can be expected. In addition, we verified the reduction effect of voids in the bonding layer by mixing micron-size Al particles. We also attempted to verify the stress relaxation effect by thermal stress analysis of FEM.

II. Experimental procedure

A. Preparation of bonding

A paste composed of Ni nanoparticles with a particle diameter of 100 nm or less, Al micron-size particles with an average particle diameter of 10μm, solvent, and a binder was used as a bonding material. The proportion of Ni nanoparticles and Al micron-size particles in the paste was 1: 1 by weight ratio (0.24 : 0.76 by volume ratio). For comparison, a paste of Ni nanoparticles alone was also used as a bonding material. For bonding evaluation, a TO-247 Cu lead frame with Ni plating on its surface and Si chips of 2.7 mm × 2.7 mm, 5.0 mm × 5.0 mm, and 7.0 mm × 7.0 mm were used. Al layer having a thickness of 1μm is formed on the bonding surface of the chip by a vapor deposition method. Using a metal mask made of a stainless steel plate having a thickness of 0.1 mm, the paste was applied to the TO-247 lead frame, and the chip was bonded onto the lead frame (Fig.1). Bonding conditions were as follows atmospheric, heating rate 5℃/min, holding temperature 350℃ holding time 60 minutes, pressurization 0.5 MPa.

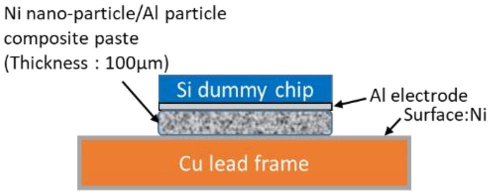


Fig.1 Schematics of bonding sample structure

B. Bonding strength measurement

The bonding strength was evaluated by shear tester (universal type bond tester 4000 Plus manufactured by Nordson Advantage Technology). The height of the shear tool tip from the test sample was set at 100μm and the moving speed of the tool was set at 100μm / sec. The fracture surface of the sample after the bonding strength test was observed with a scanning electron microscope (SEM, Hitachi High-Technologies: SU 3500).

III. Results and discussion

A. Cross section and surface observation after bonding

Fig.2 shows a cross-sectional image of an optical microscope of a bonded sample using Ni nanoparticles. Large cracks and gas voids were observed in joining with the Ni nanoparticle paste. On the other hand, as shown in Fig.3 large cracks and gas voids were not observed from the cross-sectional image of the joining by the Ni nanoparticle / Al particle composite paste.

As shown in Fig.4, it is considered that the Al particles form the nearly closest packed structure in the bonding layer having the vacant spaces there-between. The occurrence of cracks and gas voids are suppressed by the existence of passage of the solvent vaporized.

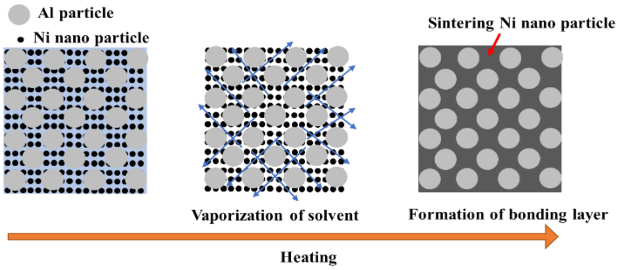


Fig.4 Image of bonding process by Ni nanoparticle/Al particle composite paste.

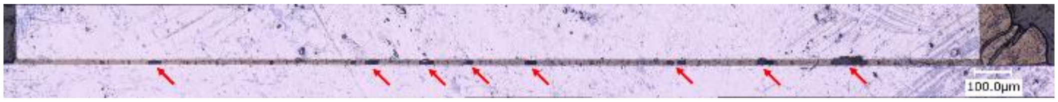


Fig.2 Cross section of the sample bonded by Ni nanoparticles paste

Fig.3 Cross section of the sample bonded by Ni nanoparticle/Al particle composite paste

B. Evaluation of bondability

1) Comparison of bonding strength by chip size

Fig.5 shows a comparison of shear strength by chip size. In case of using Ni nanoparticles, as the chip size increases, the bonding strength decreases. On the other hand, in case of using Ni nanoparticle / Al particle composite paste, the bonding strength increases with increasing the chip size.

As the chip size increases, the influence of thermal stress due to the difference in CTE increases. From these results, it was considered that the bonding strength was decreased for large chip bonding with Ni nanoparticle paste because the thermal stress could not be released. On the other hand, the bonding strength using the Ni nanoparticle paste was observed. From this result, it is considered that the Al particles in the bonding layer act as a stress release part.

Fig.6 and Fig.7 show graphs of the stress-strain curve during shear tests for 5.0mm x 5.0mm chips bonded with Ni nanoparticles and Ni nanoparticles/Al particles, respectively. The Y-axis and the X axis exhibit the bonding strength and the displacement of the tool in the shear stress direction, respectively. The curve is divided into three deformation areas. It appears the first region is corresponding to the elastic deformation and the second region is corresponding to the plastic deformation. The displacement amount of the bond in which the Al particles are mixed is larger than that formed by the Ni nanoparticles, markedly. It is considered that the Al particles extend and are plastically deformed when shearing stress is applied to the Al particles, resulting in increasing the displacement amount.

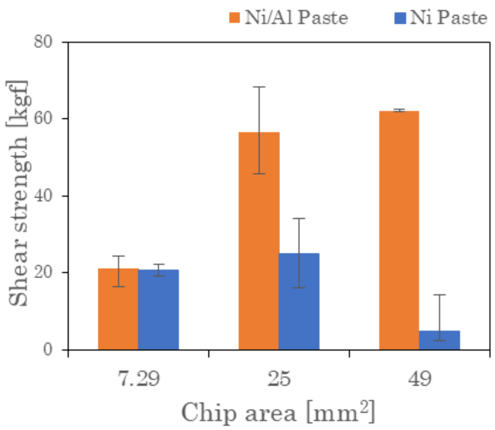


Fig.5 Comparison of shear strength of samples bonded using Ni nanoparticles and Ni/Al nanoparticles in different chip sizes

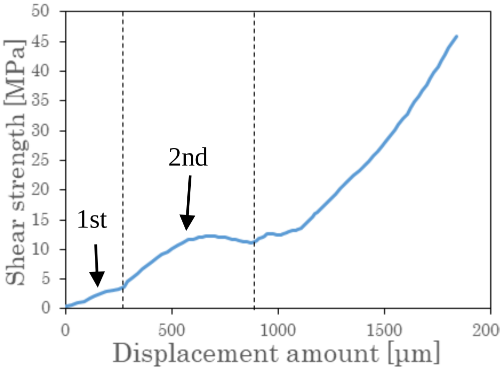


Fig.6 Relationship between tool displacement amount and shear strength of sintered Ni nanoparticles/Al particles

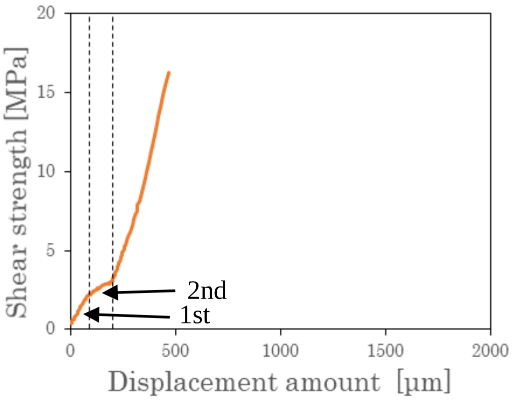


Fig.7 Relationship between tool displacement amount and shear strength of sintered Ni nanoparticles sample

2) Fracture surface observation after shear test

Fig8 shows optical microscope images of the both fractured surfaces after the shear tests. The breaking occurred in the vicinity of the interface between bonding layer and the lead frame. From this result, it is considered that the Al surface of the chip has better bondability than the Ni surface of the lead frame.

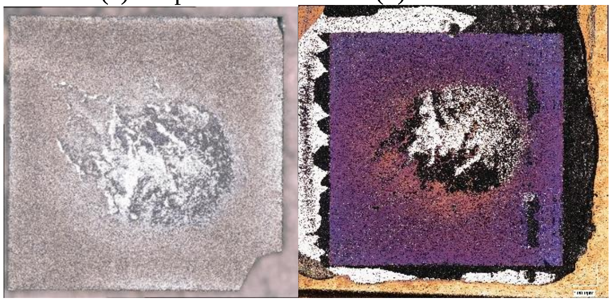

(a) Chip (b) Lead frame

Fig.8 Observation of a fracture mode of sample bonded Ni nanoparticle/Al particle composite paste after Shear test (Chip size : 5.0mm x 5.0mm)

The SEM image of the fracture surface and element mapping analysis results are shown in fig.9. In almost cases, no spherical shape of Al particles were seen on the fracture surface after the shear test, and it seemed that the Al particles were extended in a plate shape. In addition, from the elemental analysis mapping, elements of Ni were detected between the deformed Al particles.

C. Study on thermal stress analysis using FEM

In this study, thermal stress analysis was attempted by Marc Mentat. Fig.10 shows a mesh model diagram used for thermal stress analysis for the bond set of SiC chip and Cu substrate during thermal cycle test (TCT). The condition of FEM analysis was following : chip size : 7.0 mm × 7.0 mm. substrate size : 10.0 m × 10.0 mm. Al : Ni = 0.74 : 0.26 (vol) upper limit of the temperature cycle : 250℃. lower limit : -45℃.

The fig.11 shows the stress distribution for each sample at the high temperature in the 5th cycle. From the analysis results, the highest stress is generated at the outer edge of the bonding interface of the bond formed by Ni nanoparticles. On the other hand, at the joining of Ni nanoparticles / Al particles, the stress generated at the outer end portion of the joining interface was reduced smaller, and the generated stress is dispersed as a whole.

Fig.12 shows the comparison of the stress history at the outer edge of the joint interface for Ni nanoparticle and Ni nanoparticle/Al particle.

From this result, it was confirmed that the generated stress was smaller for bonding by the Ni nanoparticle / Al particle than the joining by the Ni nanoparticle. Especially, the maximum stress value for Ni nanoparticle/Al particle is about half as small as that for Ni nanoparticle.

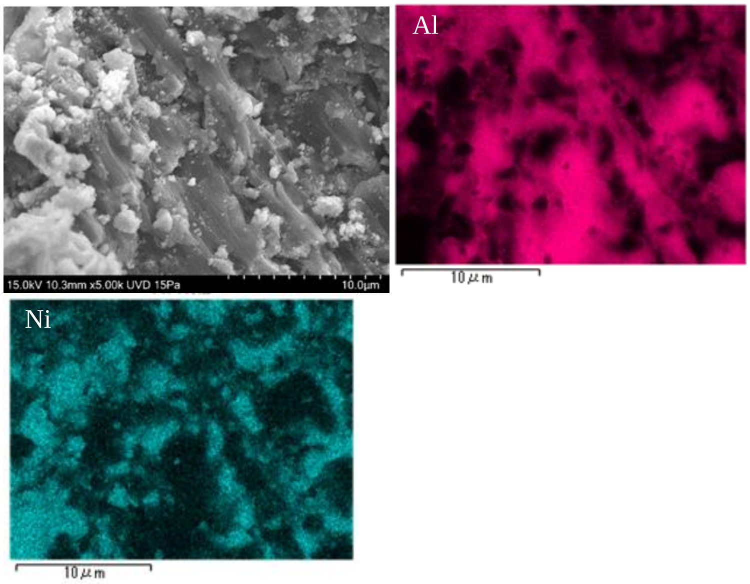


Fig.9 SEM image and element mapping analysis results of a fracture surface at the sintered Ni nanoparticle/Al particles after shear test

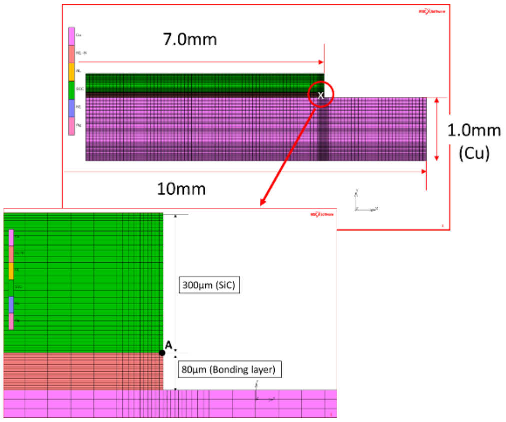
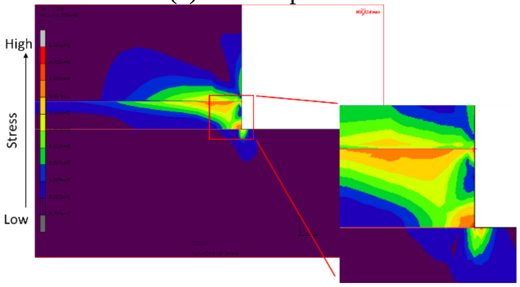


Fig.10 Analysis model diagram

(a) Ni nanoparticle



(b) Ni nanoparticle/Al particle

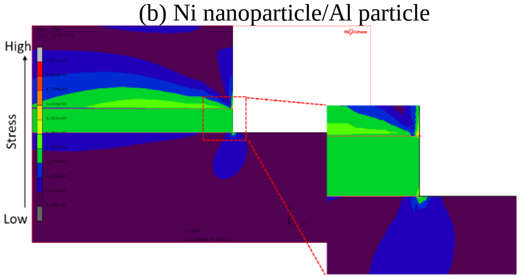


Fig.11 Stress distribution of Ni nanoparticle bonding layer type at the 5th cycle

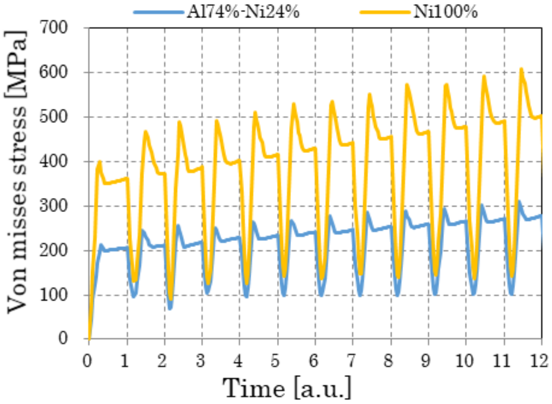


Fig.12 Comparison of equivalent stress history at A point of Fig.11.

IV. Conclusion

The properties of Die bonding Ni nanoparticle / Al particle composite paste was investigated and the following results were obtained.

(1). It was found that mixing of micron-size Al particles suppressed the occurrence of large cracks and gas voids in the bonding layer formed with Ni nanoparticles.

(2). Since the bonding strength using the Ni nanoparticle / Al particle mixed paste was not lower than that of the Ni nanoparticle bonding. Bonding with Ni nanoparticles / Al particles has made good bonding.

(3). From the surface found to be observation after shear tests Al particles were extended and plastically deformed.

(4). Thermal stress analysis was performed by FEM. The results suggest that the maximum stress was reduced by mixing Al particles in the bonding layer.

Bonding using micron-size Al particles can be expected as a solution to the problem of void generation in metal nanoparticles and thermal stress problem due to the difference in CTE in large chip size.

Acknowledgment

This work was supported by the Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), and "Nextgeneration power electronics/ Research and development of packaging technology for high temperature resistant SiC module of automobile of next-generation SiC power electronics" (funding agency: NEDO) We acknowledge greatly to Tsukuba Power Electronics Constellations (TPEC) for their generous supply of SiC devices.

References

[1] A. Itoh, T. kimoto, H. Matsunami, "High performance of high-voltage 4H-SiC Schottky barrier diodes", IEEE Electron Device Letters, vol. 16, no. 6, pp. 280-282, Jun 1995.

[2] S-H. Ryu, S. krishnaswami, M. O'Loughlin, J. Richmond, A. Agarwal, J. Palmour, A. R. Hefner, "10-kV, 123-mΩ・cm2 4H-SiC Power DMOSFETs", IEEE Electron Device Letters, vol. 25, no. 8, Aug 2004.

[3] P. G. Neudeck, R. S. Okojie, L. Y. Chen, "High-Temperature Electronics-A Role for Wide Bandgap Semiconductors?", Proc. IEEE, Vol. 90, no. 6, pp.1065-1076, Jun 2002.

[4] V. R. Manikam, C. Kuan Yew, "Die Attach Materials for High Temperature Applications: A Review", IEEE Trans. CPMT., vol. 1, no. 4, pp. 457–478, Apr 2011.

[5] L. Coppola, D. Huff, F. Wang, R. Burgos, and D. Boroyevich, "Survey on high temperature packaging materials for SiC-based power electronics", Proc. PESC, Orlando, FL, pp.2234-2240, 2007.

[6] G. Zeng, S. McDonald, K. Nogita, "Development of high-temperature solders : Review" , Microelectronics Reliability, vol. 52, no.7, pp. 1306-1322, Jul 2012.

[7] Habib A. Mustain, William D. Brown, Simon S. Ang , "Transient Liguid Phase Die Attach for High Temperature Silicon Carbide Power Devices" , IEEE Trans. Compon. Packag. Technol., vol. 33, no. 3, pp. 563–570, Sep 2010.

[8] Y. Akada, H. Tatsumi, T. Yamaguchi, A. Hirose, T. Morita, and E.Ide, "Interfacial Bonding Mechanism Using Silver Metallo- Organic Nanoparticles to Bulk Metals and Observation of Sintering Behavior", Materials Transactions, vol. 49, no. 7, pp.1537-1545, 2008.

[9] J. G. Bai, J. Yin, Z. Zhang, G-q. Lu, J. D. vanWyk, "High-Temperature Operation of SiC Power Devices by Low-Temperature Sintered Silver Die-Attachment", IEEE Trans. Advanced Packaging, vol. 30, no.3, Aug 2007.

[10] Y. Kobayashi, T. Shirochi, Yasuda, T. Morita, "Metal-metal bonding process using metallic copper nanoparticles prepared in aqueous solution", International Journal of Adhesion and Adhesives, vol. 33, pp. 50-55, Mar 2012.

[11] T. Ishizaki, T. Satoh, A. Kuno, A. Tane, M.Yanase, F. Osawa, Y. Yamada, "Thermal characterizations of Cu nanoparticle joints for power semiconductor devices", Microelectronics Reliability, vol. 53, no. 9-11, pp.1543-1547, Sep-Nov 2013.

[12] N. Kato, S. Hashimoto, T. Iizuka, and K. Tatsumi "High-temperature-resistant interconnections formed by using nickel micro-palting and Ni nano-particles for power devices," Trans. Of the japan institute of electronics packaging, Vol.6 No.1, p.87-92 2013.

[13] Y. Tanaka, S. Hashimoto, T. Iizuka, K. Tatsumi, N. Matsubara, S. Ishikawa, and M. Tanaka , "High-temperature-resistant interconnection using nickel nanoparticles", International Microelectronics Assembly and Packaging (IMAPS), Octorber, 14-15, 2014, pp561-565.

[14] Y. Tanaka, K. Ota, H. Miyano, Y. Shigenaga, T. IiZuka, and K. Tatsumi, "High Temperature Resistant Packaging for SiC Power Devices Using Interconnections Formed by Ni Micro-Electro-Plating and Ni Nano-particles " 65th ECTC 2015, pp1371-1376, 2015.

[15] T. IIZUKA, Y. TANAKA, K. KAMEI, M. INAGAKI, N. MURAKAWA, K. TATSUMI, "High-Temperature-Resistant Interconnection by Using Nickel Nano-particles for Power Devices Packaging", 2016 International Symposium on Semiconductor Manufacturing (ISSM), December, 12-13, 2016.

[16] K, Tatsumi. METAL JOING STRUCTURE USING METAL NANOPARTICLES AND METAL JOING METHOD AND METAL JOING MATERIAL. U.S.9,960,140 B2. May 1, 2018.

[17] K. Suganuma, S, Sakamoto, N. Kagami, D. Wakuda, K. S. Kim and M. Nogi, "Low-temperature low-pressure die attach with hybrid silver particle paste" Elsevier Microelectronics Reliability, Vol.52 pp375-380, (2012).

[18] H. Zhang, S. Nagao nad K. Suganuma, "Addiction of SiC Particles to Ag Die-Attach Paste to Improve High-Temperature Stability; Grain Growth Kinetics of Sintered Porous Ag", Journal of ELECTRONIC MATERIALS, Vol.44, No.10, 2015

[19] K. Sugiura, T. Iwashige, J. Kawai, K. Tsuruta, C. Chen, S. Nagao, H. Zhang, T. Sugahara and K. Suganuma "Prominent Interface Structure and Bonding Material of Power Module for High Temperature Operation", The 29th International Symposium on Power Semiconductor Devices and ICs (ISPSD2017), The Institute of Electrtical Engineers of Japan, Sapporo, pp491-494 (2017)