Communication

Effect of Temperature on the Die Shear Strength of a Au-Sn SLID Bond

TORLEIF ANDRÉ TOLLEFSEN,
OLE MARTIN LØVVIK,
KNUT AASMUNDTVEIT,
and ANDREAS LARSSON

The effect of temperature on the die shear strength of a optimized Au-Sn solid–liquid interdiffusion SLID bond, a reliable high temperature die attach and interconnect technology, was investigated. The shear strength was greatly reduced with temperature from 140 MPa at room temperature to 20 MPa at 573 K (300 °C). This reduction was unexpected since the melting point of a Au-Sn SLID bond is 795 K (522 °C). Fractographic studies revealed a change in fracture mode with increasing temperatures. This work emphasizes the importance of performing bond strength quantification at the intended application temperature.

DOI: 10.1007/s11661-013-1725-8
© The Minerals, Metals & Materials Society and ASM International 2013

There is a rapid growth in the demand for reliable high temperature (HT) electronic devices. In applications like engine control, space exploration, drilling, and well intervention systems, the requirements for HT stability is becoming more stringent. Wide-bandgap semiconductors, in particular silicon carbide (SiC), are commonly considered as the semiconductor of choice for HT applications.[1,2] Reliable HT die attach and interconnect technologies, *i.e.*, the mechanical support and conductive path required to achieve connection from a circuit element to the rest of the circuit, are also emerging. Several alternatives exist, where Au-Sn solid–liquid interdiffusion (SLID) is an established technology.[3–7]

Methods to test and characterize the reliability of HT die attach and interconnect technologies typically consist of high temperature storage (HTS) and thermal cycling (TC) followed by bond strength quantification, electrical resistance measurements, cross-sectional analysis, and fractography.[3,6–11] Even though the HTS and TC are performed at the intended application temperatures, the characterization is mainly performed at room temperature (RT). This is believed to be tolerable as long as the investigated die attach and/or interconnect technology is stable in the temperature range between RT and application temperature, *i.e.*, it has no known phase transition it the temperature range.

In this work, the bond strength, or more precisely, the die shear strength, has been measured as a function of temperature from RT to 573 K (300 °C). Remarkably, the shear strength is greatly reduced with increasing temperature.

An optimized HT die attach and interconnect bond for a $Cu/Si_3N_4/Cu/Ni–P//Au/Au-Sn/Au//Ni/Ni_2Si/SiC$ package (representing a SiC transistor assembled onto a Si_3N_4 substrate utilizing Au-Sn SLID) was fabricated. The mechanical properties of the bond were optimized with respect to the SLID composition. It was found that the maximum strength (as measured at room temperature) was obtained with a considerable surplus of Au. Details about the processing conditions can be found in an earlier published work.[5]

The samples were die shear tested in a NordsonDage 4000Plus shear tester with a 200-kgf load cartridge. A test height of 110 μm above the substrate and a test speed of 10 μm/s were applied. Four sample groups, each containing six samples, were tested at RT, 373 K (100 °C), 473 K (200 °C), and 573 (300 °C). A custom-made sample holder was constructed to optimize the alignment of the sample to the tool, to minimize the sample movement, and to insure a uniform sample temperature during testing. The setup is shown in Figure 1. The actual temperature at the bonded interface during shearing was calibrated with a thermocouple.

Fractography was conducted on all tested samples. The fracture surfaces were investigated by optical microscopy (Neophot 32), scanning electron microscopy (SEM) (FEI Nova NanoSEM 650), and energy-dispersive X-ray spectroscopy (EDS).

The die shear strength of Au-Sn SLID bonds tested at RT, 373 K, 473 K, and 573 K (100 °C, 200 °C, 300 °C) is shown in Figure 2. Each point represents one single measurement value. There was a low spread in the results at each different temperature. Figure 3 shows the average die shear strength as a function of temperature. This figure emphasizes the substantial reduction in shear strength as a function of temperature. The drop from RT to 373 K (100 °C) was moderate, from an approximate average of 140 MPa to 130 MPa. This reduction was expected since increased thermal energy will reduce the chemical binding energy somewhat and lead to thermal softening.

From 373 K to 473 K (100 °C to 200 °C), the reduction in shear strength was significant, with the average dropping to 60 MPa. The trend continued at 573 K (300 °C), where the average was as low as 20 MPa, *i.e.*, less than 15 pct of the shear strength at RT. These severe reductions were unexpected. The optimized bond line of the Au-Sn SLID samples has previously been established to consist of a Au/ζ-phase ($Au_{0.85}Sn_{0.15}$)/Au layered structure at RT.[12] The ζ-phase has a melting point of T_{melt} = 795 K (522 °C),[13,14] *i.e.*, well above the

TORLEIF ANDRÉ TOLLEFSEN, Research Scientist, is with the SINTEF ICT Instrumentation, Oslo, Norway, and also with the Institute for Micro and Nanosystems Technology, Vestfold University College, Borre, Norway. Contact e-mail: torleif.tollefsen@sintef.no OLE MARTIN LØVVIK, Senior Scientist, is with the SINTEF Materials and Chemistry, Oslo, Norway, and also with the Department of Physics, University of Oslo, Oslo, Norway. KNUT AASMUNDTVEIT, Associate Professor, is with the Institute for Micro and Nanosystems Technology, Vestfold University College. ANDREAS LARSSON, Senior Scientist, is with the SINTEF ICT Instrumentation.

Manuscript submitted January 15, 2013.
Article published online April 17, 2013

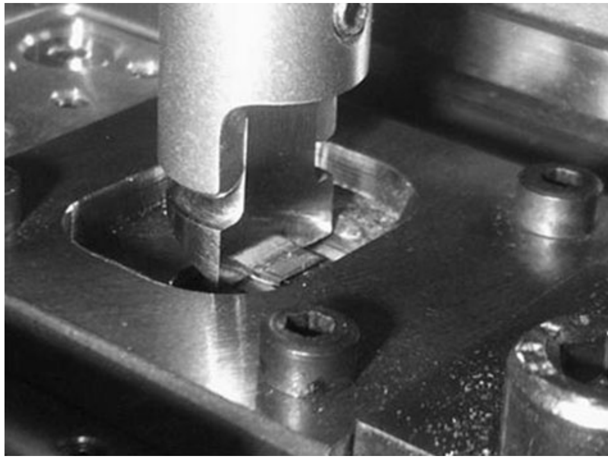

Fig. 1—Custom-made holder for temperature-dependent die shear testing.

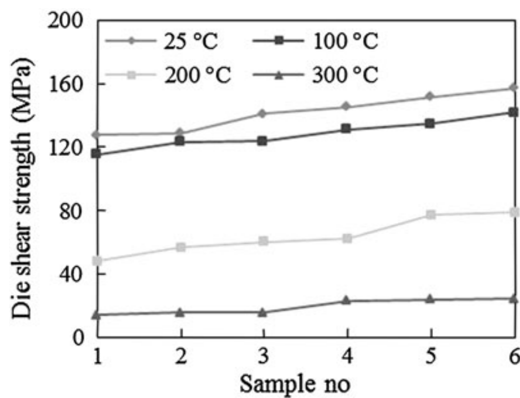

Fig. 2—The die shear strength of Au-Sn SLID samples tested at RT, 373 K, 473 K, and 573 K (100 °C, 200 °C, 300 °C). Each point represents one single measurement value.

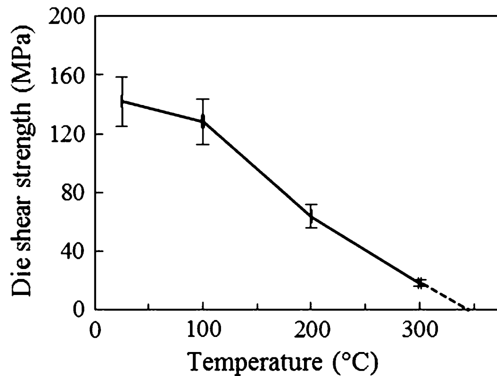

Fig. 3—The average die shear strength of Au-Sn SLID samples as a function of temperature [from RT to 573 K (300 °C)]. Each point is based on six measured samples. The dotted line represents an extrapolation of the line to indicate the effective melting point.

investigated temperatures. Therefore, the bond line was anticipated to be stable at the studied temperatures; *e.g.*, no phase transitions were expected to occur.

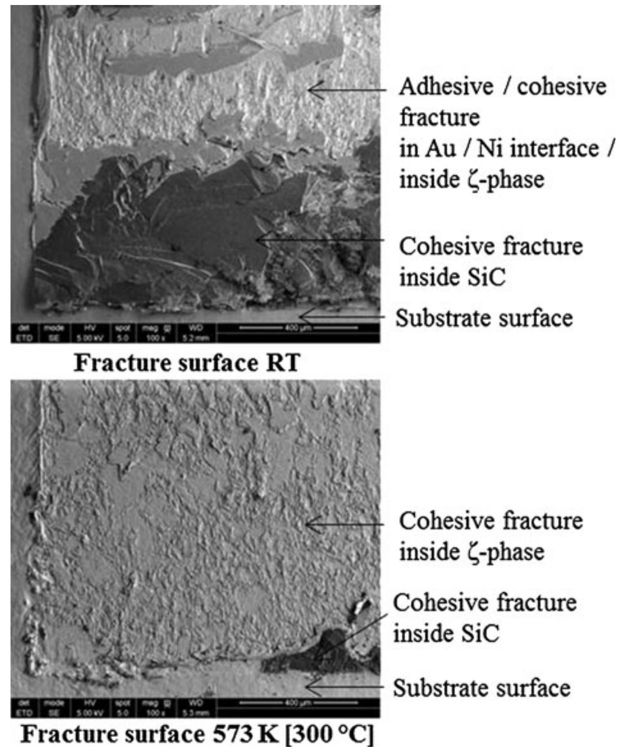

Fig. 4—SEM images of the fracture surface of Au-Sn SLID samples shear tested at room temperature (RT) and 573 K (300 °C).

In Figure 4, SEM images of the fracture surface of samples shear tested at RT and 573 K (300 °C) are shown. The fracture mode was changed from a combination of adhesive Au/Ni and cohesive ζ-phase/SiC fracture to a mainly cohesive ζ-phase fracture with increasing temperature. This demonstrates that the large reduction in shear strength originates from weakening of the Au-Sn SLID bond. It should be mentioned that the minimum die shear strength requirement in the MIL-STD-883 is 6 MPa, *i.e.*, the measured shear strength at 573 K (300 °C) was still above the requirement.

It is well known that the mechanical properties of metals are temperature dependent. The ideal shear strength of face-centered cubic (fcc) Ni was, *e.g.*, recently shown to decrease by approximately 30 pct from RT to 1873 K (1600 °C).[15] In general, mechanical strength starts decreasing around a temperature $T = 0.6\ T_{melt}$, decreasing to zero strength at the melting point. For the ζ-phase, this would imply that the decrease should start around $T = 473$ K (200 °C) and lose all strength at 795 K (522 °C). In reality, the strength had started decreasing already below 373 K (100 °C), and extrapolation of the straight line in Figure 3 indicates an effective melting point around 610 K (~340 °C).

Why is the effective melting point of the bond so much lower than that of the ζ-phase? One reason may be stresses induced by the CTE mismatch between Au and the ζ-phase, approximately 6 ppm/K.[16,17] Such interfacial stresses destabilize the system, possibly weakening the bond strength.

Another possible explanation can be that the ζ-phase is inhomogeneous. If there is a range of different Au:Sn ratios (between 11 and 16 at. pct Sn) in the bond, there will also be a range of melting points [between 551 K and 795 K (278 °C and 522 °C), increasing with increasing Au content].[13,14] The optimized Au-Sn SLID bond has a surplus of Au, and EDS measurements have established an average Sn content of approximately 12 at. pct.[4,5] Nevertheless, it is possible that local regions exhibit different compositions with Sn contents up to 16 pct, where the ζ-phase meets the eutectic phase at 551 K (278 °C) in the phase diagram. This is supported by the fractograph in Figure 4, where two different morphologies seem to be present at the fracture surface of the ζ-phase. The likely mechanism in this scenario is phase separation of the bond into Sn-poor ζ-phase with melting point 795 K (522 °C) and a small part of more Sn-rich ζ-phase with melting point approaching the eutectic temperature of 551 K (278 °C). The latter phase may exist as thin layers (X-ray amorphous) between the growing grains of the ζ-phase. Insight into this mechanism beyond the present speculations would require more thorough investigations beyond the scope of this work. However, it should be mentioned that this unexpected reduction in shear strength is most probably unavoidable. As already mentioned, a considerable surplus of Au was used in the studied Au-Sn SLID samples. The processing time was long enough to insure that the intermetallic diffusion was finished. Nevertheless, the result was a Au-Sn SLID bond with a non-uniform ζ-phase, reducing the effective melting point of the bond. A further increase in processing time or temperature would probably result a phase transition from the ζ-phase to the β-phase, which is mechanically weaker.[12]

Importantly, this study emphasizes the importance of characterizing HT electronic die attach and interconnect technologies at the intended application temperatures, since the properties of the applied materials can change dramatically for even "known" material phases. Furthermore, the authors suggest that the MIL-STD-883 should be updated to include a requirement regarding the test temperature: *"Die shear testing shall be conducted up to the intended application temperature."*

The die shear strength was measured as a function of temperature for a reliable HT Au-Sn SLID bond. The shear strength was reduced more than 85 pct from room temperature to 573 K (300 °C). This was an unexpected reduction since the Au-Sn SLID bond has a melting point of 795 K (522 °C). Partial melting/softening at the interface between the material grains in the inhomogeneous ζ-phase is suggested to be the cause of the observed behavior. This observation is important since it shows that a mechanically optimized Au-Sn bond is only stable up to approximately 610 K (~340 °C), 30 pct lower than previously believed.

This work was carried out within the HTPEP project. Funding from the Research Council of Norway (project no 193108/S60), Badger Explorer, SmartMotor, Fairchild, Emerson Roxar, and Norbitech is greatly acknowledged. The authors want to acknowledge Dr. Spyros Diplas for discussions and Dr. Maaike M. V. Taklo for her valuable review, helping shape this article.

REFERENCES

1. Z.J. Shen, B. Grummel, R. McClure, A. Gordon, and A. Hefner: *iMAPS HiTEC*, Albuquerque, NM, 2008.
2. N.G. Wright, A.B. Horsfall, and K. Vassilevski: *Mater. Today*, 2008, vol. 11 (1–2), pp. 16–21.
3. T.A. Tollefsen, A. Larsson, O.M. Løvvik, and K. Aasmundtveit: *Metall. Mater. Trans. B*, 2012, vol. 43B, pp. 397–405.
4. T.A. Tollefsen, A. Larsson, and K. Aasmundtveit: *iMAPS HiTEN*, UK, Oxford, 2011.
5. T.A. Tollefsen, M.M.V. Taklo, K. Aasmundtveit, and A. Larsson: *IEEE ESTC*, Amsterdam, 2012.
6. W.R. Johnson, C.Q. Wang, Y. Liu, and J.D. Scofield: *IEEE Trans. Electron. Packag. Manuf.*, 2007, vol. 30, pp. 182–93.
7. P. Zheng, P. Henson, R. W. Johnson, and L. Chen: *iMAPS HiTEC,* Albuquerque, 2010.
8. K. Fang, R. Zhang, T. Isaacs-Smith, R.W. Johnson, E. Andarawis, and A. Vert: *iMAPS HiTEN*, Oxford, UK, 2011, pp. 39–45.
9. S.A. Yang and A. Christou: *IEEE Trans. Device Mater. Reliab.*, 2007, vol. 7, pp. 188–96.
10. T.A. Tollefsen, M.M.V. Taklo, N. Lietaer, T. Bakke, P. Dalsjø, and J. Gakkestad: *International Wafer Level Packaging Conference (IWLPC)*, San Jose, 2012.
11. R. Kirschman: *High-Temperature Electronics*, IEEE Press, New York, NY, 1999.
12. T.A. Tollefsen, A. Larsson, M.M.V. Taklo, A. Neels, X. Maeder, K. Høydalsvik, D.W. Breiby, and K. Aasmundtveit: *Metall. Mater. Trans. B*, 2013, vol. 44B, pp. 406–13.
13. H. Okamoto: *J. Phase Equilib. Diffus.*, 2007, vol. 28(5), p. 490.
14. H.S. Liu, C.L. Liu, K. Ishida, and Z.P. Jin: *J. Electron. Mater.*, 2003, vol. 32, pp. 1290–96.
15. S.L. Shang, W.Y. Wang, Y. Wang, Y. Du, J.X. Zhang, A.D. Patel, and Z.K. Liu: *J. Phys. Condensed Matter,* 2012, vol. 24.
16. MatWeb: Material Property Data, www.matweb.com.
17. F.G. Yost, M.M. Karnowsky, W.D. Drotning, and J.H. Gieske: *Metall. Trans. A*, 1990, vol. 21A, pp. 1885–89.