2023 IEEE 73rd Electronic Components and Technology Conference (ECTC)

CMOS-Compatible Fine Pitch Al-Al Bonding

Hemanth Kumar Cheemalamarri
Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore.
hemanthkc@ime.a-star.edu.sg

Binni Varghese
Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore.
vargheseb@ime.a-star.edu.sg

Sharma Jaibir
Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore.
shramaj@ime.a-star.edu.sg

Li Hongyu
Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore.
lihy@ime.a-star.edu.sg

Chandra Rao S S
Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore.
bhesettisscr@ime.a-star.edu.sg

Navab Singh
Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore.
navab@ime.a-star.edu.sg

Vempati Srinivasa Rao
Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore.
vempati@ime.a-star.edu.sg

King-Jien Chui
Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore.
chuikj@ime.a-star.edu.sg

***Abstract* — The metal-metal bonding has become more promising for fine-line hermitic sealing and electronic packaging applications. Even though aluminum has CMOS compatibility and extensive utilization in MEMS, its fine pitch bonding and bonding at low thermal budgets is still challenging. In this paper, we have demonstrated a fine pitch (~6 µm) direct Aluminum – Aluminum bonding process achievable at a low temperature ≤ 350 °C, which is compatible with CMOS Back-End-Of-Line (BEOL) processes. Successful bonding was achieved by using optimally ultra-thin titanium as a surface passivation layer. The passivation layer not only helps in protecting the surface from oxide formation, but also helps in the modification of surface microstructure and morphology. Systematic investigation of surface oxidation and grain structure using EDS and XRD, as well as AFM analysis of surface roughness revealed that the optimal passivation layer thickness to be ~2-4 nm. With optimized passivation layer thickness, wafer level blanket bonding has been achieved at a temperature and pressure of ≤300 °C and < 1MPa, respectively. Reliable interface bonding quality in fine-pitch structures (with ~16% metal pattern density) has been achieved at ≤350 °C bonding temperature and ≥1 MPa bonding pressure. These investigations suggest that passivation materials can help reduce the bonding temperature further to achieve advanced interconnect bonding and MEMS sealing at low thermal budgets.**

Keywords—Fine pitch, thermocompression bonding, low thermal budget, passivation.

I. INTRODUCTION

Microelectromechanical systems (MEMS) are typically transducer devices that interface between the physical world and electronic processing systems [1]. MEMS devices are extremely important for sensing optical, physical, and chemical signals, and play a key role in advanced electronic automation [2,3]. However, for precision and accuracy, these devices must be encapsulated in either a hermetically sealed environment (such as for infrared image sensors, accelerometers, gyroscopes, and resonators), or have a direct physical interface with the ambient (such as for flow sensors, pressure sensors and microphones) [4-5]. To improve performance, advanced packaging strategies helps integrate MEMS devices to complementary metal oxide semiconductor (CMOS) circuitry, in a single package by 2.5D or 3D architectures [6,7]. The hermiticity of MEMS devices and their integration with CMOS integrated circuits (ICs) continues to be challenging.

Thermo-compression wafer-to-wafer bonding technology plays a vital role in the wafer-level fabrication of hermetically sealed cavities, which are crucial for the reliable functioning of most MEMS systems [8-10]. Direct metal diffusion bond interconnections are attractive for achieving fine line sealing and improved electrical interconnections [10]. Copper, gold, and aluminum are promising for the formation of fine metal interconnections as well as fine metal seal rings. Compared to copper and gold, which are established materials for these applications, aluminum has several benefits owing to its relatively high electromigration resistance (with the addition of minor amounts of copper [11]), high electrical and thermal conductivities, and low cost. These properties combined with CMOS compatibility make aluminum a promising candidate in the integration of CMOS to MEMS, where the MEMS actuator is bonded to the electrical IC.

All the BEOL metal layers in CMOS devices, thus far, have used either aluminum or copper. Aluminum was commonly used in CMOS-BEOL interconnections until 1997 [12]. Scaling of devices necessitated denser interconnects with lower electrical resistivity. One of the bottlenecks that initially precluded the usage of copper was electromigration. Having resolved it with the addition of 2% silicon in copper, aluminum was replaced with Cu in 1998 by IBM at FEOL [13]. That said, foundries still use aluminum as the final layer in CMOS chips for external contacts. On the other hand, Au is generally avoided in semiconductor CMOS technology because it acts as the hubs for deep level traps and recombination centers. Moreover, Au diffuses effectively from the deposited thin film to the

2377-5726/23/$31.00 ©2023 IEEE
DOI 10.1109/ECTC51909.2023.00294

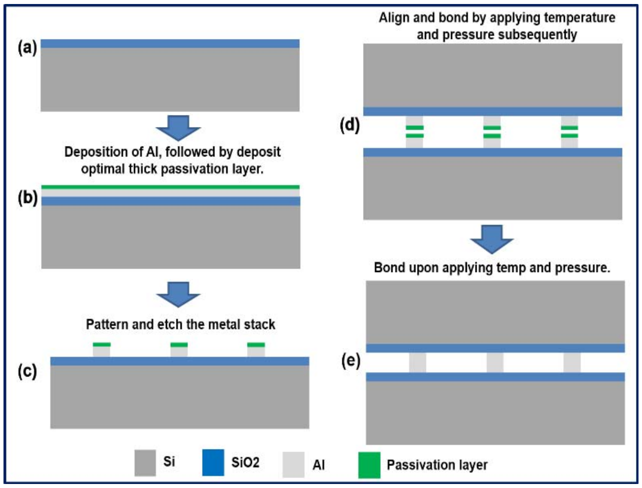

Figure 1. Process flow for the fine pitch aluminum-aluminum bonding.

underlying Si substrate, even at moderate temperatures. Aluminum/dielectric hybrid bond interconnects or direct bonding of aluminum could help reduce integration complexity and process costs in the fabrication of redistribution layers (RDL) for interconnecting MEMS to ICs.

However, the formation of a surface native oxide layer with high chemical stability on aluminum surfaces is tough to eliminate by chemical treatment. This thin oxide layer turns into a strong diffusion barrier at the bonding interface between aluminum substrates [14]. Due to this, not much research has been carried out on microelectronics package interconnections using aluminum, and its applications have been limited to MEMS sealing applications. However, due to its low cost and the comparable thermal and electrical characteristics to copper and gold, aluminum can be envisaged as an interconnect material for a variety of applications beyond MEMS sealing, provided bonding is achieved at a relatively low temperature and pressure. In the case of aluminum, surface oxidation hinders the realization of direct Al-Al thermo-compression bonding at low-thermal budgets [14-15].

Direct metal-metal thermo-compression bonding, especially with Al, has received limited attention so far because of the inherent high temperature and high-pressure requirements. Al-Al bonding necessitates a temperature greater than 450 °C and high contact force (around few 10s to 100s of MPa) to overcome the thin, chemically stable surface oxide (Al_2O_3) barrier.

Akin to Cu, several explorations have been carried out to reduce the temperature and pressure requirements. Chen H. et al. [16] proposed a bonding mechanism that utilized argon-ion pretreatment. Before bonding, pure aluminum specimens were etched by high energy (1 keV) argon ion beams up to 120s in an ion cleaning chamber. Then the bonding was then carried out in vacuum at 350 °C for 3 hours at a pressure of 10 MPa, by using an ion-activated vacuum diffusion bonding furnace. M. Wietstruck [17] and S. Schulze et al. [18] achieved Al-Al bonding using EVG ComBond® High-Vacuum automated bonding System, at 300 °C for 1 hour with a bonding force of 60 kN. Prior to bonding, surface roughness was reduced to 1.1 nm, with pre-surface treatment conducted in the same equipment. Shiro Satoh et al. [19] proposed a passivation method using tin as the passivation layer for Al. Bonding was carried out at 360 to 390 °C with a bonding pressure of 43 to 65 MPa.

The bonding pressures and temperatures reported so far in the literature have been high or highly sophisticated equipment (eg. High vacuum automated bonding systems [18]) are detrimental to the performance of both CMOS and MEMS devices. Thus, it is imperative to reduce both the temperature and pressure and this publication makes a significant contribution towards this end.

In this study, we focus on wafer-level Al-Al bonding at low pressures and with low thermal budget. The importance of surface morphology and microstructure in achieving good quality bonding under the desired conditions is discussed. Subsequently, fine-pitch bonding is demonstrated after wafer-level blanket bonding is optimized.

II. FABRICATION PROTOCOL

In this experiment, 200 mm, single-side polished p-type Si wafers with ~1 µm grown thermal oxide were used. The wafers were subjected to standard cleaning protocols prior to the deposition of metal layers. Aluminum metal layer (1 µm thickness) was deposited followed by a thin titanium (Ti) film passivation layer without vacuum break using sputter physical vapor deposition (PVD) deposition technique. High vacuum was maintained during deposition as well as in the chamber interlocks while transferring the wafers among the metal target chambers. After deposition, the surface was inspected using atomic force microscopy (AFM), x-ray diffraction (XRD), x-ray photoelectron spectroscopy (XPS), and for optimizing the passivation thickness. Ssurface roughness and surface oxidation were the key parameters considered while optimizing the passivation thickness. Then, blanket aluminum wafers with optimized passivation film thickness were subjected to bonding. Key bonding conditions, namely temperature and pressure, were optimized based on bonding quality inspection by confocal scanning acoustic microscopy (C-SAM).

For fine pitch interconnect integration, the thin films were patterned using a positive photoresist and exposed in an i-line stepper with UV-C wavelength. The exposed patterns were dry-etched using chlorine chemistry with a PR mask layer. These wafers were aligned and bonded under optimized thermo-compression bonding conditions. The bonding process flow is shown in Figure 1. Post bonding reliability analysis was carried out using dicing and interface inspection by X-SEM, to study the interface contact formation. These investigation results are explained in detail in the following results and discussion section.

III. RESULTS AND DISCUSSION

At low temperatures, grain boundary diffusion dominates all the other transport mechanisms in polycrystalline metal thin films [20-21]. The passivation layer protects the Al surface from oxidation. In the case of Al-Al thermo-compression bonding, the passivation layer should also allow the diffusion of Al atoms. The key to lowering bonding temperature and pressure lies in the selection of the right passivation layer with the right

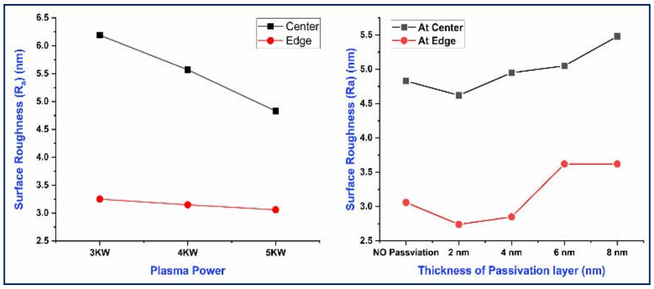

Figure 2. The resulted average surface roughness (5μm x 5μm area). (a). On the Al surface with varying the plasma power. (b). By varying the passivation layer thickness.

thickness, for which good diffusion of Al across the passivation layer is the fundamental consideration.

In this work, we propose a method of protecting the Al surface with a thin layer of titanium as a passivation layer, to prevent the formation of aluminum oxide. Even though titanium gets oxidized rapidly, it was selected due to its high CMOS compatibility, comparable conductivity to Al, and low activation energy of Al towards Ti/TiO$_x$ [22]. Passivation layer thicknesses of 2, 4, 6, and 8 nm were deposited on the surface of Al and the surface morphology and microstructural changes were studied. Optimization has been carried out to maximize Al diffusion across the bonding interface.

A. Optimization of passivation layer thickness

The passivation layer may result in variations in the surface morphology and microstructural properties. Optimizing its thickness is essential for stopping Al oxidation and allowing Al diffusion and interfacial Al-Al contact formation. If the thickness of the passivation layer is high, passivation layer-to-passivation layer bonding may occur instead of Al-Al bonding, which may degrade the interconnect performance. This suggests that the passivation film thickness should be minimal.

1. Effect of passivation layer on surface roughness

Metal-to-metal thermocompression bonding requires atomic-level interdiffusion across the bonding interface. Maximizing the interfacial contact area improves interdiffusion. Surfaces with low roughness are important for increasing contact area while bonding.

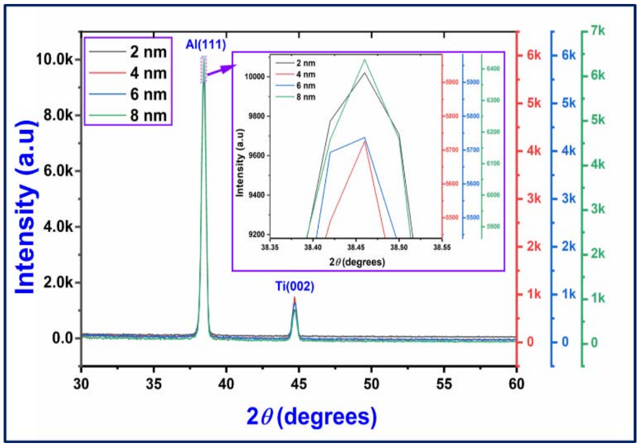

Figure 3. The grazing angle XRD inspection of Al surface with varying passivation layer thickness.

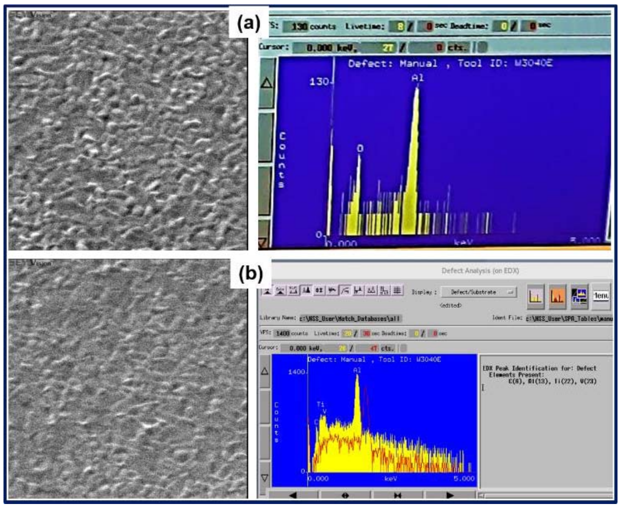

Figure 4. The energy dispersive spectroscopy areal scan on, (a). the surface of Al without passivation layer. (b). On the surface of the thin Ti passivated Al surface.

Prior to the deposition of a passivation layer on Al, we optimized plasma power during the deposition of Al to achieve low surface roughness. Al was deposited at room temperature using various plasma power values. AFM study was conducted on the Al surface with various thicknesses of passivation layers. Figure 2(a) suggests that higher deposition powers helped lower the surface roughness of Al with reduced non-uniformity from the center to the edge of the wafer. Next surface roughness obtained upon the deposition of a passivation layer on the optimized Al surface is shown in Figure 2(b). Passivation thicknesses of 2 nm and 4 nm on the Al surface resulted in ~12% reduced surface roughness compared to the non-passivated surface of Al. This suggests that the passivation layer helps in reducing challenges associated with higher surface roughness.

2. Effect of passivation layer on crystal grain orientation

The thin-film grain structure and grain texture play a significant role in the atomic interdiffusion of metal thin films. Towards this end, Al surfaces with ultrathin passivation layers were inspected using grazing angle x-ray diffraction spectroscopy (GI-XRD) and the results are shown in Figure 3. A high-intensity sharp peak was observed at 2θ = ~38.4°, which is attributed to highly textured Al-(111) plane (as per (JCPDS)-(ICDD) data [23]). It has been suggested that high-density (111)-oriented surface planes help in higher diffusion across the bonding interface [24]. In the peak intensities of passivated Al films shown in Figure 3, the 2nm passivated film shows dominant intensity of (111) planes followed by 8nm, 6nm and 4nm passivated films. Since low surface passivation layer thickness and low surface roughness are important for this application, the 2 nm passivation film is optimum.

3. Effect of passivation layer on surface oxide

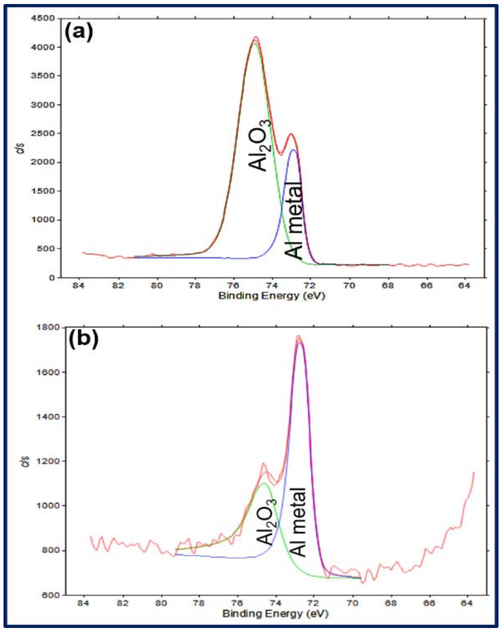

Figure 5. XPS spectra of Al2p core level analysis of Al surface with, (a). no passivation layer. (b). 2nm Ti passivation.

As mentioned in section I, Al is prone to surface oxide formation immediately upon exposure to the oxygen ambient. The surface oxide acts as a strong diffusion barrier for the interdiffusion of Al atoms across the bonding interface. The effect of the passivation layer in protecting Al against surface oxide formation was studied using SEM-EDS. Figure 4(a) shows the areal scan for an un-passivated Al film, while the corresponding EDS map shows the intensity peaks for Al and O elements. On the other hand, Figure 4(b) shows the EDS map for a thin (~4 nm) Ti passivation film deposited over Al, indicating the presence of Al, Ti and small traces of C, and the absence of O element. The result suggests that the surface oxidation of aluminum has been controlled by passivation with ultrathin Ti.

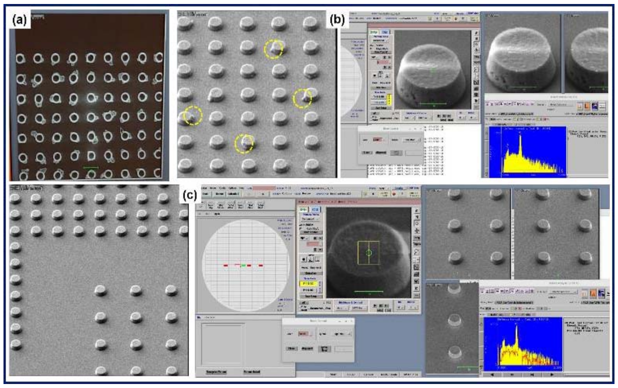

Figure 6. The DR-SEM inspection of Al patterns with passivation layer, (a). The surface after PR strip off. (b). pits on the edges (circled in yellow label) with EDS on respective pattern. (c). The clear pattern with respective surface EDS scan.

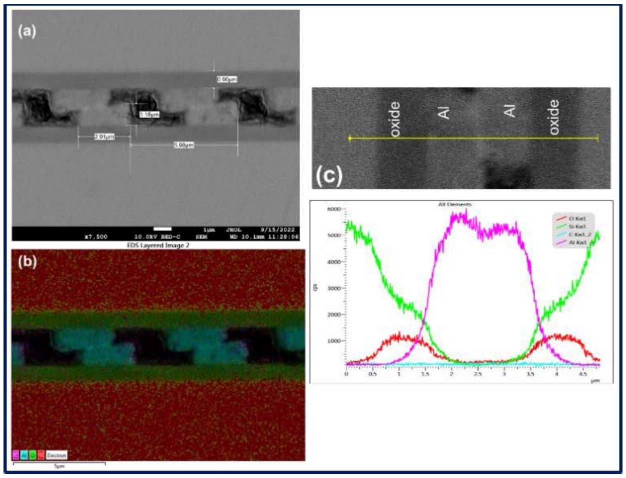

Figure 7. (a) The X-SEM image of the fine pitch bonded interface. (b). The EDS elemental areal map of the bonded wafers. (c). The EDS line scan across the bonded interface.

In addition, the surface investigation using x-ray photoelectron spectroscopy (XPS) on the minimum (2nm) passivated and un-passivated samples. The Al2p of narrow scans of the both the samples are mentioned in the Figure 5. The Al2p narrow scan provide information about Al and Al_2O_3 with Al metal peak centered at the binding energy of 72.8 eV and Al_2O_3 peak at 74.9 eV. Figure 5(a), show the dominated aluminum oxide peak as compared with the Al. On the other hand, The XPS narrow scan spectra of 2nm Ti passivated sample is shown in the Figure 5(b). The Al peak with higher intensity counts than the aluminum oxide. It evident that, the formation of oxide on blanket/unprotected surface is dominant without surface protection or preclean. However, the smaller passivation layer thickness of even ~2nm will help protecting the surface form oxide formation.

B. Fine-pitch bonding with process flow challenges

Wafers with optimized Al film and Ti passivation layer, were patterned using a standard lithography process. Following this, the film was dry-etched using chlorine chemistry and inspected in defect review scanning electron microscopy (DR-SEM) after in-situ photoresist strip. Some of the surfaces were found to exhibit surface corrosion with chlorine, as shown in Figure 6(a). These wafers were subjected to a solvent clean (NE14) after prolonged storage resulting in pits at the wafer edges. In addition, the surface of these wafers lost the passivation layer, which might be due to the reaction between chlorine residues and the Ti layers as shown in Figure 6(b). On the other hand, the wafers processed with solvent NE14 clean immediately after the photoresist strip resulted in a clean surface without loss of passivation layer. Figure 5(c) shows that with 30 sec Ar plasma treatment following NE14 clean, an oxide-free surface can be obtained as shown in the EDS results.

After obtaining the desired patterns with the oxide-free surface, thermocompression bonding was performed. The process parameters were optimized by checking the interface reliability upon dicing the wafers. We observed a high-reliability bonding interface for patterned wafers bonded at ~350 °C with a pressure of 1 MPa onwards. The need for higher bonding temperature and pressure could be due to the reduced surface contact area as compared with the blanket-bonded wafers.

Patterned wafers with a fine pitch of 6 μm and pattern size of 3 μm were bonded and a X-SEM image as shown in Figure 7(a). The EDS areal map across the bonding interface clearly shows continuity in the Al-Al bonded interface as shown in Figure 7(b). Moreover, continuous growth of Al across the bonding interface was verified by using a line scan across the bonded interface. Figure 7(c) shows continuous Al elemental distribution due to Al growth under the optimized bonding conditions.

IV. CONCLUSION

Fine pitch Al-Al bonding with ultra-thin surface passivation layer has been demonstrated. Passivation layers of ~2nm-~4nm thickness were optimized by systematically minimizing surface roughness and surface oxidation. The optimization studies helped in achieving blanket wafer bonding at a low temperature of ≤300 °C and at a pressure of <1 MPa. In the case of patterned wafers, we observed that good interface bonding quality could be achieved at ≤350 °C at ≥1 MPa, at a fine pitch with ~16% metal pattern density. The ultrathin passivation layer helps in achieving bonding at CMOS-compatible thermal budgets. We suspect that the increased bonding temperature and pressure needed for fine-pitch bonding might be due to lower contact area compared to blanket wafers and needs to be investigated further. Nevertheless, the method of passivation of Al with a suitably optimized material supports Al-Al bonding at reduced bonding temperature and pressure. The proposed method not only supports hermetic sealing for MEMS applications but can also be an approach for Al/dielectric hybrid bonding for future advanced packaging applications like 3D ICs and high-bandwidth memory (HBM) technologies without additional RDL layers.

ACKNOWLEDGMENT

All the authors are thankful to the Institute of Microelectronics (IME) – Agency for Science and Technology research (A*STAR), Singapore, for their support.

REFERENCES

[1] K. J. Gabriel, "Microelectromechanical systems," in Proceedings of the IEEE, vol. 86, no. 8, pp. 1534-1535, Aug. 1998, doi: 10.1109/5.704257.

[2] Bogue, R., "Towards the trillion sensors market", Sensor Review, Vol. 34 No. 2, pp. 137-142, 2014 doi:10.1108/SR-12-2013-755

[3] G. Hancke, B. Silva, and G. Hancke, Jr., "The Role of Advanced Sensing in Smart Cities," Sensors, vol. 13, no. 1, pp. 393–425, Dec. 2012, doi: 10.3390/s130100393.

[4] C. B. O'Neal, A. P. Malshe, S. B. Singh, W. D. Brown and W. P. Eaton, "Challenges in the packaging of MEMS," Proceedings International Symposium on Advanced Packaging Materials. Processes, Properties and Interfaces (IEEE Cat. No.99TH8405), Braselton, GA, USA, 1999, pp. 41-47, doi: 10.1109/ISAPM.1999.757284.

[5] Esashi, Masayoshi. "Wafer level packaging of MEMS." Journal of Micromechanics and Microengineering, vol. 18, no. 7, pp. 073001, 2008, doi: 10.1088/0960-1317/18/7/073001.

[6] M. Lapisa, G. Stemme and F. Niklaus, "Wafer-Level Heterogeneous Integration for MOEMS, MEMS, and NEMS," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 17, no. 3, pp. 629-644, May-June 2011, doi: 10.1109/JSTQE.2010.2093570.

[7] F. Niklaus et al., "Wafer-level heterogeneous 3D integration for MEMS and NEMS," 2012 3rd IEEE International Workshop on Low Temperature Bonding for 3D Integration, Tokyo, Japan, 2012, pp. 247-252, doi: 10.1109/LTB-3D.2012.6238096.

[8] Cheemalamarri, H. K., Bonam, S., Vanjari, S. R. K., & Singh, S. G., "Effect of ultrathin palladium layer in achieving a low temperature and pressure wafer level aluminum to aluminum bonding," Surface Topography: Metrology and Properties, vol. 8, no. 4, pp. 045008, 2020, doi: 10.1088/2051-672X/abbb81

[9] Cheemalamarri, H. K., Bonam, S., Vanjari, S. R. K., & Singh, S. G., "Ti/Si interface enabling complementary metal oxide semiconductor compatible, high reliable bonding for inter-die micro-fluidic cooling for future advanced 3D integrated circuit integration," Journal of Micromechanics and Microengineering, vol. 30, no. 10, pp. 105005, 2020, doi: 10.1088/1361-6439/ab9f00

[10] C. H. Tsau, S. M. Spearing and M. A. Schmidt, "Fabrication of wafer-level thermocompression bonds," in Journal of Microelectromechanical Systems, vol. 11, no. 6, pp. 641-647, Dec. 2002, doi: 10.1109/JMEMS.2002.805214.

[11] Braunovic, M., Myshkin, N.K., & Konchits, V.V., "Electrical Contacts: Fundamentals, Applications and Technology (1st ed.)," CRC Press, 2007. doi:10.1201/9780849391088.

[12] J. D. Meindl, "Low power microelectronics: retrospect and prospect," in Proceedings of the IEEE, vol. 83, no. 4, pp. 619-635, April 1995, doi: 10.1109/5.371970.

[13] Semiconductor Industry Association. (2009). International technology roadmap for semiconductors. http://www. itrs. net.

[14] Nicolet, M. A., "Diffusion barriers in thin films," Thin Solid Films, vol. 52, no. 3, pp. 415-443, 1978, doi: 10.1016/0040-6090(78)90184-0

[15] Dragoi, V., Mittendorfer, G., Burggraf, J., & Wimplinger, M, "Metal thermocompression wafer bonding for 3D integration and MEMS applications," ECS Transactions, vol. 33, no. 4, pp. 27, 2010, doi: 10.1149/1.3483491

[16] Chen, H., Cao, J., Tian, X., Li, R., & Feng, J., "Low-temperature diffusion bonding of pure aluminum," Applied Physics A, vol. 113, no. 1, pp. 101-104, 2013, doi: 10.1007/s00339-013-7860-7.

[17] M. Wietstruck et al., "Al-Al Direct Bonding with Sub-μm Alignment Accuracy for Millimeter Wave SiGe BiCMOS Wafer Level Packaging and Heterogeneous Integration," 2019 IEEE 69th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, USA, 2019, pp. 942-947, doi: 10.1109/ECTC.2019.00147.

[18] S. Schulze et al., "Optimization of a BEOL Aluminum Deposition Process Enabling Wafer Level Al-Al Thermo-Compression Bonding," 2019 IEEE 69th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, USA, 2019, pp. 218-224, doi: 10.1109/ECTC.2019.00040.

[19] SATOH, S., FUKUSHI, H., ESASHI, M. and TANAKA, S., "Low-Temperature Al-Al Thermocompression Bonding with Sn Oxidation Protect Layer for Wafer-Level Hermetic Sealing," Electron Comm Jpn, vol. 100, no. 8, pp. 43-50, 2017, doi: 10.1002/ecj.11975

[20] Kaur, I., Mishin, Y., & Gust, W., "Fundamentals of grain and interphase boundary diffusion," John Wiley, 1995.

[21] Shewmon, P.G., "Thin films-interdiffusion and reactions", J. M. Poate, K. N. Tu, and J. W. Mayer, Eds., Wiley-Interscience, New York, 1978, 578 pp.. J. Polym. Sci. B Polym. Lett. Ed., vol.17, pp. 39-39, 1979, doi: 10.1002/pol.1979.130170107

[22] Mishin, Yu, and Chr Herzig. "Diffusion in the Ti–Al system," Acta materialia, vol. 48, no. 3, pp. 589-623, 2000, doi: 10.1016/S1359-6454(99)00400-0

[23] Yang, C.Z., D.C. Xie, G.Z. Chen, and F.M. Zhong., "Phase diffraction analysis," Metallurgical Industry Press, Beijing, 1988.

[24] Shimatsu, Takehito, and M. Uomoto., "Atomic diffusion bonding of wafers with thin nanocrystalline metal films," Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena, vol. 28, no. 4, pp. 706-714, 2010. doi: 10.1116/1.3437515.