

Electroplated Aluminum Pillars for Ultrasonic Flip Chip Bonding

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Abstract

Flip chip bonding is a widely used method in 3D integration. In this study, the use of electroplated Aluminum as pillar structure for ultrasonic flip chip bonding is demonstrated for the first time. Al pillars were deposited from a chloroaluminate ionic liquid on a 6 inch silicon wafer. The influences of ultrasonic bonding parameters (bonding time, ultrasonic power and bonding force) were investigated at room temperature. Al pillar bonding was performed successfully in less than 1 s. High bonding forces are recommended as more pillars get mechanical contact to the substrate, thus, ultrasonic energy can be transferred to the interface causing bonding.

Key words

Aluminum pillars, electrodeposition, electroplating, flip chip bonding, ionic liquids, ultrasonic bonding

I. Introduction

The integration and combination of different functionalities in one system need compatible bonding processes. The fabrication of microsystems and microelectronics allows different materials, which could cause cross-contamination in equipment or failure of electronics through diffusion processes. Compatible materials in both fabrication lines are e.g. platinum, titanium, or aluminum. Thus, final metallization on contact pads are often made of Al or Al alloys. However, the assembly process using flip chip bonding uses mainly solder bumps or copper pillars with or without solder cap [1]–[4]. Thus, the Al pads have to be processed with a re-metallization layer stack of e.g. TiN, Ti and Cu. In the case of solder bumps, an under bump metallization (UBM) consisting of Cu, Ni, and Au is needed additionally [5]. Many process steps are needed to achieve the final metallization. Furthermore, different metal layers can cause reliability problems due to different coefficients of thermal expansion (CTE) and formation of intermetallic compounds, respectively [6].

The electroplating of Aluminum using ionic liquids (ILs) can be used to achieve bonding layers for different stages of integration. Therefore, achieving a homogeneous material system at the bonding interfaces is possible. Additionally, the

process steps to form the bonding layers can be reduced. In Fig. 1, a comparison between the layer stack differences is shown.

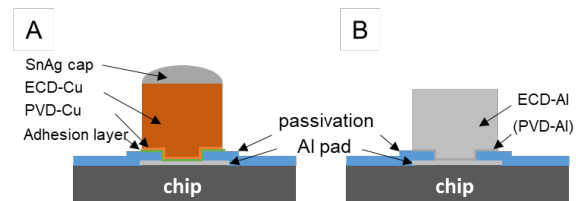


Figure 1: Schematic of different layer stack for pillar fabrication: A) Cu Pillar with solder cap, B) Al pillar

The electrochemical deposition (ECD) of Al has been discussed frequently in literature in the past 30 years. Usually, the research groups are working on the electrodeposition from different ILs, or other deep eutectic solvents as the deposition from water-based electrolytes is not possible due to the standard reduction potential of -1.67 V [7]–[11]. The integration of this electroplating process in microsystem and microelectronic application fields is only covered by the research group of Fraunhofer ENAS/ University of Technology Chemnitz and Tohoku University, as there is official cooperation [12]–[14].

In this research, the electroplating process of Al pillars on a

6 inch wafer level and the first steps for ultrasonic flip chip bonding with the electroplated Al pillars are reported.

II. Experimental methods

A. Pillar fabrication using electrodeposition

Due to the highly negative standard reduction potential of Al ($E = -1.67$ V), the 1-ethyl-3-methylimidazolium tetrachloroaluminate (EMImCl/AlCl₃) IL with ratio 1:1.5 was used. The IL was provided from IoLiTec GmbH. The IL has to be handled within a glovebox with a moisture free atmosphere to prevent hydrochloric gas formation. The electroplating process was carried out with a plating cell from Silicet AG on a 6 inch silicon wafer. A circular and perforated Al sheet (99.5 %) was used as anode. The Si wafer was coated with 1 μ m thick Al seed layer using sputtering. A negative photo resist (AZ125nxT, MicroChemicals GmbH) was used for photolithography serving as pattern plating mask. Prior to plating process, an oxide etching pulse is mandatory to achieve sufficient adhesion and continuous growing of the layer. That pulse was applied within the deposition cell. The deposition of Al on Al seed layer needs low current density of 5 mA/cm². A potentiostat (VersaStat3, Princeton Applied Research) was used to apply a low frequency pulsed current with a time ratio of 9:1. The deposition time was 98 min to reach 7 μ m, approximately.

After deposition, the resist was removed with TechniStrip P1331 (MicroChemicals GmbH).

B. Chip layout

The test design is divided into a peripheral structure and an array in the middle of the chip, as shown in Fig. 2. The peripheral ring forms a daisy chain with the substrate chip after bonding. It can be used for electrical connection tests. The middle part is used to enhance the mechanical stability of the bond. The influence can be investigated due to different fill percentage of the middle array at the bonding substrate. This is not shown in this work.

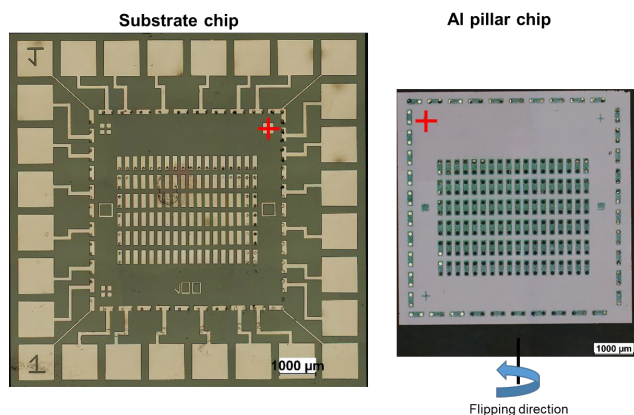


Figure 2: Light microscope pictures of substrate and pillar chip used for the evaluation of the bonding parameters. The red crosses indicate one aligned corners after flipping.

The pillar diameter was fixed over the wafer to 100 μ m, as a previous study has shown that different pillar diameters lead to inhomogeneous growth [15]. The pitch size was 260 μ m. The chip size was 5.8 x 5.8 mm² and the substrate was 10 x 10 mm².

C. Characterization methods

The pillar height was measured before and after bonding using tactile profilometry (Bruker Dektak XT). Light microscopy was used to investigate the imprint marks of the pillars after bonding. In some cases, scanning electron microscopy (SEM) was used for more detailed pictures. At this stage of research, the bonding strength was qualified manually directly after bonding. The chip and substrate were pulled apart manually.

Unfortunately, the electrical connection tests could not be performed for DOE samples due to over-etching of the connection pads between two pillars, shown in Fig. 5. The electrical contact for the planarized samples is characterized using a simple two-tip multimeter.

D. Ultrasonic Flip Chip Bonding

The flip chip bonding was performed in a Fineplacer FEMTO2 (Finetech GmbH, Germany). The machine is equipped with an ultrasonic module with a frequency of 42 kHz. An ultrasonic bonding tool in a pyramid stump shape was used for the experiments.

As no literature values are available for Al pillar chip bonding, some preliminary bonding tests were carried out to scan the parameter range for a design of experiments (DOE). As the pillars were used as-deposited, a small reproducibility study was performed for five samples with 60 N, 4 W and 0.5 s. Then, a DOE was made using Minitab® Statistical Software. The factors were ultrasonic power (2...10 W), bonding force (20...90 N) and ultrasonic time (0.2...1 s).

The influence of pillar thickness homogeneity was studied using a chemical mechanical planarization (CMP) step. The bonding force and ultrasonic power varied from 15 N to 90 N and 1.5 W to 4 W. The bonding time were fixed at 0.5 s based on prior knowledge of the DOE test.

All bonding experiments were carried out at room temperature of 22 °C $\pm$ 1 °C.

III. Results and Discussion

Previous internal studies known that the current density of 5 mA/cm² can reach a current efficiency higher than 90 %. The analysis and discussion of pillar thickness and uniformity are presented in previous work. [15]. In summary, the pillar thickness was 7.3 μ m $\pm$ 0.4 μ m and the variation in a die (VID) was 8 % - 17 %.

Three forces, 4 N, 15 N and 60 N, were applied without ultrasonic power within the preliminary test schedule. The imprint marks on the bonding substrate were investigated. The higher the applied force, the more imprint marks are

visible. However, the pillar thickness did not change on average. Applying ultrasonic power to the system, the ultrasonic softening effect takes place and leads to pillar compression, see Table 1.

Table 1: List of bonding parameters for the preliminary study. Pillar height h_{pillar} is the average of 80 pillar positions including transferred pillars as "0". $h_{\text{pillar, corrected}}$ shows pillar height excluding transferred pillars.

No.	Power [W]	Force [N]	Time [s]	h_{pillar} [μm]	$h_{\text{pillar, corrected}}$ [μm]
1	0.5	4	0.5	6.4 ± 0.6	-
2	4	15	0.5	5.7 ± 1.5	6.1 ± 1.1
3	4	60	0.5	5.7 ± 2.0	6.6 ± 1.1
4	4	60	0.5	5.1 ± 2.3	6.3 ± 1.0
5	4	60	0.5	6.2 ± 1.2	6.7 ± 0.8
6	4	60	0.5	4.9 ± 2.1	6.5 ± 1.0
7	4	60	0.5	6.3 ± 1.4	6.8 ± 0.6

For the lowest force of 4 N, it was not possible to apply the power of 4 W because the sample slipped away. The average pillar height values for 15 N and 60 N do not differ significantly. In Fig. 3, the differences become visible comparing the pillar damage and/or pillar transfer. The graph shows the measured pillar height around the chip. For 60 N, more pillars are transferred to the substrate than for 15 N. The bottom row of the pillars is less compressed than the top row. The top row of 15 N sample shows higher compression than the 60 N sample.

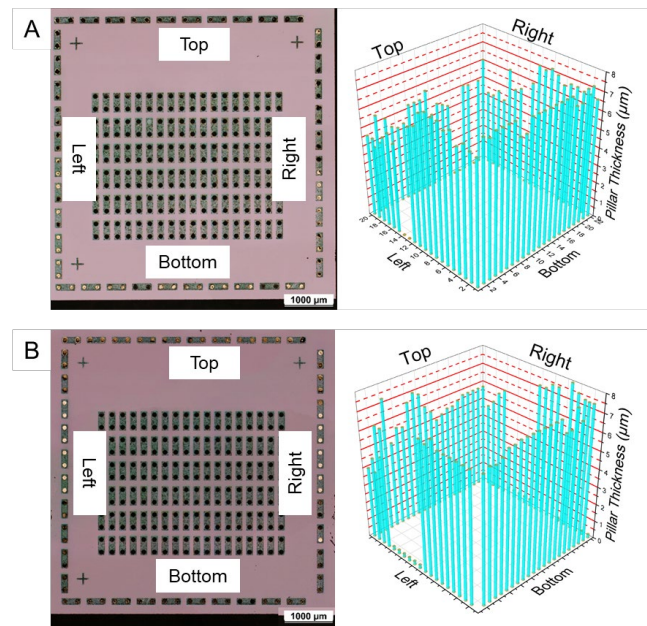


Figure 3: Light microscope pictures left and pillar height distribution at the peripheral ring measured with Dektak left. A) 15 N, 4 W, 0.5 s; B) 60 N, 4 W, 0.5 s

Thus, a reproducibility study was necessary to see if a parameter set behaves comparable or if the VID maybe influences the outcome. In Fig. 4, three of five reproducibility samples are shown. The left chip side shows the highest pillar transfer on each sample. Additionally, the bottom row is less compressed than the top row. It seems like there is a tilting in the combination of bonding tool and samples. However, comparing the overall corrected pillar height in Table 1, the compression of all samples is nearly the same. This preliminary study shows that the samples can be compared even though the VID is higher than usual for flip chip bonding.

Knowing some bonding conditions, the DOE was used to evaluate the most influencing parameters. Table 2 gives an overview of the DOE and a short result comment.

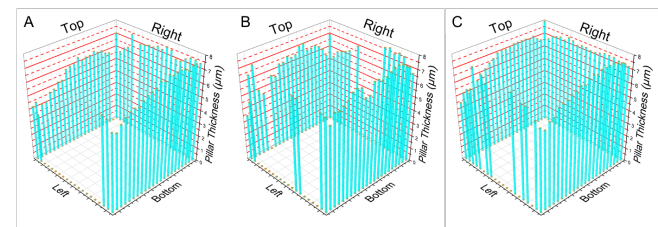


Figure 4: Pillar height distribution for reproducibility according to Table 1; A) No. 4, B) No. 6, C) No. 7

Table 2: Parameter set of Box-Behnken DOE and result comment

No.	Power [W]	Force [N]	Time [s]	comment
1	10	20	0.6	No bond, slipped
2	6	55	0.6	Bond
3	10	90	0.6	Partial bond
4	6	55	0.6	Partial bond
5	6	20	1	No bond, slipped
6	6	90	0.2	Bond
7	10	55	1	No bond
8	2	20	0.6	Partial bond
9	2	90	0.6	Bond
10	2	55	1	Partial bond
11	2	55	0.2	Partial bond
12	6	55	0.6	Partial bond
13	10	55	0.2	No bond
14	6	20	0.2	No bond, slipped
15	6	90	1	Partial bond

Fig. 5 shows SEM pictures of the chip and substrate of four samples with a bonding force of 55 N. The pillar height distribution on the peripheral ring is shown as overview. Fig. 5 A and B show the difference of longer bonding time at relatively low ultrasonic power of 2 W. The bonding time of 0.2 s shows less flattening of the pillar surface compared to 1 s. Furthermore, the imprint on the corresponding substrate pad is stronger for longer bonding time. However, this parameter set of 55 N and 2 W could not achieve good

bonding. Thus, Fig. 5 C and D show the impact of high ultrasonic power of 10 W and different bonding times. The pillars are smeared and flattened due to high ultrasonic power, even for 0.2 s. Pillar transfer occurs and the imprints on the substrate are more pronounced. Increasing the bonding time to 1 s (Figure 5 D), the pillars are literally damaged and also the bonding pad on the substrate side is influenced from the ultra-sonication. Concluding, the bonding time affects the ultrasonic softening at a given ultrasonic power. If the time is too short, no bonding can occur as the impact is too low. If the time is too long, it can cause in over-bonding or de-bonding. Hence, the bonding time should be selected in a range where bonding occurs but no over-bonding. This effect is more pronounced if the ultrasonic power is high.

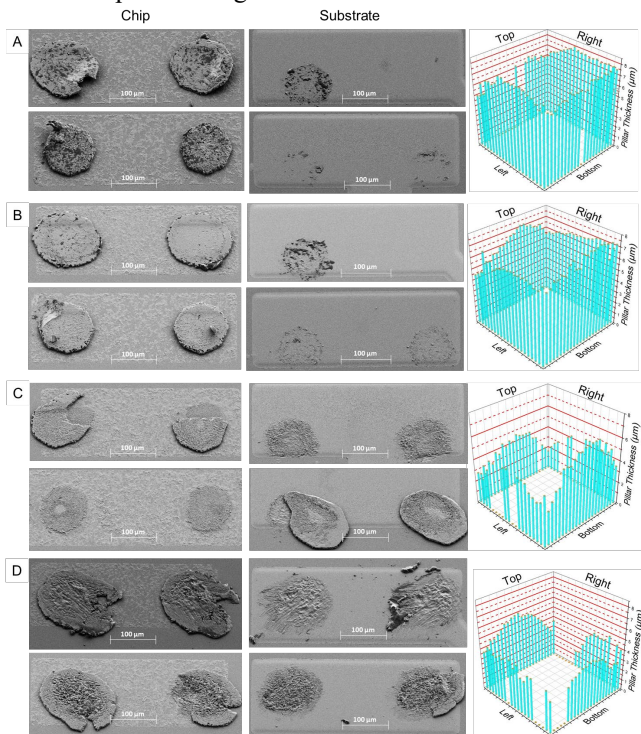


Figure 5: SEM pictures of pillar chip and corresponding substrate imprint at two different positions and graph of pillar height distribution for A) 55 N, 2 W, 0.2 s (No.11), B) 55 N, 2 W, 1 s (No.10), C) 55 N, 10 W, 0.2 s (No.13) and D) 55 N, 10 W, 1 s (No.7)

The influence of the bonding force is shown in Fig. 6 A and B. With a higher bonding force, it is possible to transfer or damage more pillars at low bonding time and ultrasonic power. A higher force can bring more pillars in contact to the substrate. Thus, the vibration of the ultrasound can be transferred to the substrate.

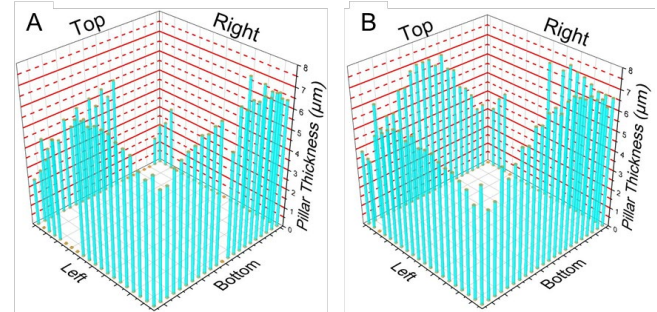


Figure 6: Graphs of pillar height after bonding with A) 90 N, 6 W, 0.2 s (No. 6) and B) 55 N, 6 W, 0.6 s (No. 12)

The Al ultrasonic flip chip bonding is mainly affected by the bonding force, which creates the mechanical contact of the pillars to the substrate. The Fineplacer FEMTO2 is limited to 100 N in the ultrasonic mode, thus, an increase in bonding force is limited for a specific layout. The influence of ultrasonic power is needed for a certain time to achieve a metallic bond. It is noticeable for all samples that the pillar compression at the corners is stronger than in the middle. There are two reasons for this behavior: Firstly, the corner pillars are taller due to electroplating. Secondly, the bonding tool applies the force mainly at the edges due to the pyramidal stump shape.

The first point is targeted by a post-treatment using CMP. A previous CMP test has broken the pillar structures, as the pillars were freestanding. Therefore, the CMP was carried out with the ECD resist or parylene C, as protection layer. The CMP with ECD resist failed. The removal of the resist is too fast and non-uniform. As the parylene is patterned using oxygen plasma and a sacrifice resist mask, only a relatively thin layer of 4 to 5 μm was deposited for this test. As a result, the Al pillars were plated for 4 μm. Three different CMP durations were tested, 3 min, 1 min and 1.5 min. The best result was achieved at 1.5 min. The thickness was reduced to 2.5 ± 0.1 μm. The electrical connection test could be performed due to a better etching process. Four contact forces (15 N, 30 N, 60 N and 90 N) were applied to test how the force affects the mechanical and electrical contact of the pillars to the substrate. No and low contact were observed for 15 N and 30 N, respectively.

The electrical contact was made with a higher force than 30 N for at least two pads away from the corners of the substrate pads. The middle pads have never been in contact.

The Fig. 7 show the pillar height distributions for 60 N (A and B) and 90 N (C and D) at 2 W (A and C) and 4 W (B and D). It is noticeable that higher ultrasonic power at 60 N shows less compression than the lower power. A higher force significantly impacts the compression at the same ultrasonic power. The pillars were partially electrically connected for all samples. The middle pillars were not in contact as before bonding with applied force. This observation can confirm the uneven pressure impact from the bonding tool at the chip corners. The VID in the as-deposited samples is not the

reason for stronger compression effect at the corners because the same behavior is recognized for planarized pillars. Furthermore, no pillar transfer is observed in comparison to the as-deposited samples. This may be attributed to the ultrasonic energy transfer through different pillar thicknesses [16]. Thus, the influence of pillar thickness on bonding process has to be investigated in the future.

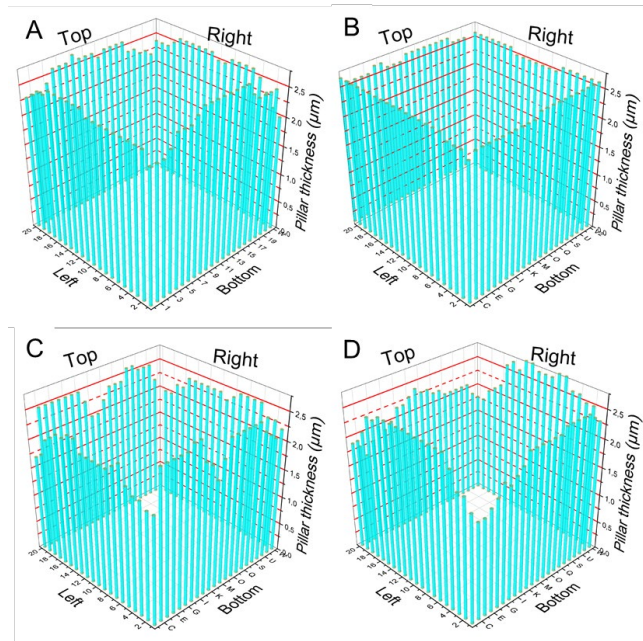


Figure 7: Graphs of pillar height distribution for the ultrasonic bonding with planarized pillars for 0.5 s. A) 60 N, 2W; B) 60 N, 4W; C) 90 N, 2W; D) 90 N, 4W

IV. Conclusion

Within this work, the ultrasonic flip chip bonding with electroplated Al pillars is reported for the first time. A sufficient high bonding force is necessary to achieve mechanical contact of many pillars to the substrate. In addition, the force is needed to hold chip and substrate in contact while applying ultrasonic energy. If the force is too low, the substrate will slip away.

The ultrasonic power determines the acoustic softening of the Al pillar. Low power needs a longer bonding time to achieve softening. However, ultrasonic energy is also necessary to scratch the natural Al oxide layer. If the energy input is too high, pillar damage is the consequence.

The bonding time is not as significant as force and power. For high ultrasonic power, a short time is recommended, otherwise over-bonding can occur. All three parameters need to be adjusted to each other, the bonding time gives a relatively wide operating range. For this layout, a bonding force between 55 N to 90 N combined with an ultrasonic power of 2 W to 6 W can achieve enough bonding strength to handle the bonded chips roughly.

The influence of the VID is discussed using as-deposited and

planarized samples. The VID in as-deposited samples is responsible for different pillar transfer positions but not for uneven compression from chip corners to middle parts. This behavior is also observed for planarized samples. The bonding tool applies the force mainly at the corners. Thus, a flat bonding tool will be tested in the future. But the chip size needs to be reduced as the vacuum holding is not sufficient for large chips. Furthermore, the influence of bonding temperature and pillar thickness needs to be investigated. A quantified analyzation of the bonding strength using shear test is mandatory for a comparison to Au stud bumping or Cu pillar bonding.

The Al flip chip bonding has a great potential in advanced packaging to build a monometallic metal interface, but there are still many open points that will be investigated in the near future.

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References

- [1] B. Wu, S. Zhang, F. Wang, and Z. Chen, "Micro Copper Pillar Interconnection Using Thermosonic Flip Chip Bonding," *Journal of Electronic Packaging, Transactions of the ASME*, vol. 140, no. 4, Dec. 2018, doi: 10.1115/1.4040794.
- [2] N. Islam, V. Pandey, M.-C. Hsieh, and K. Keontack, "Fine Pitch Cu Pillar Assembly Challenges for Advanced Flip Chip Package."
- [3] S.-M. Hong, C.-S. Kang, and J.-P. Jung, "Fluxless Sn-3.5 mass%Ag Solder Bump Flip Chip Bonding by Ultrasonic Wave," 2002.
- [4] A. Roshanghias, A. Rodrigues, S. Schwarz, and A. Steiger-Thirsfeld, "Thermosonic direct Cu pillar bonding for 3D die stacking," *SN Applied Sciences*, vol. 2, no. 6, Jun. 2020, doi: 10.1007/s42452-020-2887-9.
- [5] Madhav Datta, "Manufacturing processes for fabrication of flip-chip micro-bumps used in microelectronic packaging: An overview," *Journal of Micromanufacturing*, vol. 3, no. 1, 2020, doi: 10.1177/2516598419880124.
- [6] R. Rao, M. Seabock, T. Fang, and R. Carew, "Effect of Under Bump Metallization (UBM) Quality on Long Term Reliability," 8th international Conference on Electronic Packaging Technology, 2007.
- [7] S. Zein El Abedin, E. M. Moustafa, R. Hempelmann, H. Natter, and F. Endres, "Electrodeposition of nano- and macrocrystalline

- aluminium in three different air and water stable ionic liquids,” *ChemPhysChem*, vol. 7, no. 7, pp. 1535–1543, 2006, doi: 10.1002/cphc.200600095.
- [8] T. Jiang, M. J. Chollier Brym, G. Dubé, A. Lasia, and G. M. Brisard, “Electrodeposition of aluminium from ionic liquids: Part I-electrodeposition and surface morphology of aluminium from aluminium chloride (AlCl_3)-1-ethyl-3-methylimidazolium chloride ($[\text{EMIm}]\text{Cl}$) ionic liquids,” *Surface and Coatings Technology*, vol. 201, no. 1–2, pp. 1–9, 2006, doi: 10.1016/j.surfcoat.2005.10.046.
- [9] T. Jiang, M. J. Chollier Brym, G. Dubé, A. Lasia, and G. M. Brisard, “Electrodeposition of aluminium from ionic liquids: Part II - studies on the electrodeposition of aluminum from aluminum chloride (AlCl_3) - trimethylphenylammonium chloride (TMPAC) ionic liquids,” *Surface and Coatings Technology*, vol. 201, no. 1–2, pp. 10–18, 2006, doi: 10.1016/j.surfcoat.2005.12.024.
- [10] D. Pradhan and R. G. Reddy, “Dendrite-free aluminum electrodeposition from AlCl_3 -1-ethyl-3-methyl-imidazolium chloride ionic liquid electrolytes,” *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*, vol. 43, no. 3, pp. 519–531, 2012, doi: 10.1007/s11663-011-9623-1.
- [11] Y. Zhao and T. J. VanderNoot, “Electrodeposition of aluminium from nonaqueous organic electrolytic systems and room temperature molten salts,” *Electrochimica Acta*, vol. 42, no. 1, pp. 3–13, 1997, doi: 10.1016/0013-4686(96)00080-1.
- [12] M. S. al Farisi, S. Hertel, M. Wiemer, and T. Otto, “Aluminum patterned electroplating from AlCl_3 - $[\text{EMIm}]\text{Cl}$ ionic liquid towards microsystems application,” *Micromachines (Basel)*, vol. 9, no. 11, Nov. 2018, doi: 10.3390/mi9110589.
- [13] M. Salman Al Farisi, T. Tsukamoto, and S. Tanaka, “Fully CMOS-Compatible Wafer Bonding Based on Press Marking Using Thick Electroplated Aluminum; Fully CMOS-Compatible Wafer Bonding Based on Press Marking Using Thick Electroplated Aluminum,” 2021. doi: 10.1109/TRANSDUCERS50396.2021.9495544.
- [14] S. Hertel, M. Wiemer, and T. Otto, „Electrodeposition of Aluminum on different seed layer for printed circuit boards and microsystem technologies“ original: „Galvanische Aluminium-Abscheidung auf unterschiedlichen Startschichten für die Leiterplatten- und Mikrosystemtechnik,” in *Jahrbuch der Oberflächentechnik Band 74*, Eugen G. Leuze Verlag, 2018.
- [15] I. Cirulis *et al.*, “Optimal design configuration for aluminum pillar fabrication towards fine pitch ultrasonic bonding applications,” 2022, submitted for publication
- [16] Y. Arai, Y. Miyamoto, M. Nimura, and H. Tomokage, “Evaluation of ultrasonic vibration energy for copper-to-copper bonding by flip-chip bonding technology,” in *ICEP Proceedings*, 2014, pp. 658–661.