

Vertical Interconnects Using Magnetically Aligned Anisotropic Conductive Adhesive for RF Packaging

Sungwook Moon

School of Electrical and Computer Engineering
Purdue University
465 Northwestern Ave
West Lafayette, Indiana, 47907
Phone: 765.494.9065, Fax: 765.494.6951
Email: moon8@purdue.edu

William J. Chappell

School of Electrical and Computer Engineering
Purdue University
465 Northwestern Ave
West Lafayette, Indiana, 47907
Phone: 765.494.6225, Fax: 765.494.6951
Email: chappell@purdue.edu

A novel anisotropic conductive adhesive (ACA) with ferromagnetic conductive particles is studied for vertical interconnects in high frequency applications. When the static magnetic field is induced, randomly dispersed conductive particles in an epoxy are aligned along the given magnetic field. To verify the RF characteristics of the ACA, coplanar waveguides (CPW) on silicon substrates were fabricated. Using a flip-chip bonding technology, fabricated silicon substrates with a $100\ \mu\text{m} \times 80\ \mu\text{m}$ transition region were assembled. The magnetically aligned Z-axis ACAs with two different diameter of conductive particles ($10\ \mu\text{m}$ and $25\ \mu\text{m}$) were used to characterize the created interconnects. As a result, it was observed that the density of created columns on a transition region dominates the performance of assembled samples at high frequencies and the performance of assembled samples using the smaller particle ($10\ \mu\text{m}$ diameter) is more repeatable in $100\ \mu\text{m} \times 80\ \mu\text{m}$ pad dimension. In comparison to the silicon sample with solder bumps, the difference in the insertion loss is less than 0.25 dB up to 20 GHz. Therefore, the magnetically aligned ACA is expected to become a promising alternative to high-frequency applications with less than $100\ \mu\text{m}$ pad dimension and narrow pitches.

Key words: RF packaging, anisotropic conductive adhesive, self-alignment, vertical interconnects.

1.0 Introduction

To date, a variety of bonding materials for interconnect have been widely used such as soldering, wire-bonding and etc. However, most of the high density interconnect processes using the conventional technologies are complicated and expensive. Therefore, an alternative process with limited number of processing steps is required. Specifically, an assembly method based on PbSn is one of the most familiar technologies thanks to superior mechanical/electrical reliability as well as less cost burden. However, recently many researchers have been searching for an alternative to this conventional method because recently taking into considerations for environmental friendliness as well as product performance and cost impact is required [1].

As an alternative to these conventional technologies, several anisotropic conductive films/adhesives (ACF/ACA) have been widely used for applications requiring high-density packaging based on a flip-chip bonding technique because its low curing temperature and reasonable reliability is attractive in an industrial field [2]-[4]. However, its assembly

process is sensitive to bonding conditions such as pressure and heating temperature during the flip-chip bonding process and it is required to optimize these conditions for successful assembly [5]. Still, the conventional ACA has relatively large capacitance because two interconnected pads are in parallel as far as around $10\ \mu\text{m}$ by a monolayer of conductive particles. Thus, the parasitic inductance and capacitance from the interconnects in the transitional region degrades RF performance at high frequencies [6].

In this paper, a novel anisotropic conductive adhesive (ACA) is introduced. When a magnetic field is induced, ferromagnetic particles move around in the epoxy and finally, they are aligned to create columns. Thus, as shown in Fig. 1, the created columns are interconnected vertically between a top and bottom substrate, and isolated horizontally keeping a relatively uniform spacing between other neighboring columns due to their magnetic polarity. Fig. 2 shows the creation process when a magnetic field is induced. It was observed that the self-alignment time to create fully grown columns is approximately 10 seconds.

The property of Z-axis conduction only in the Z-axis ACA is useful in high integrated circuitry with

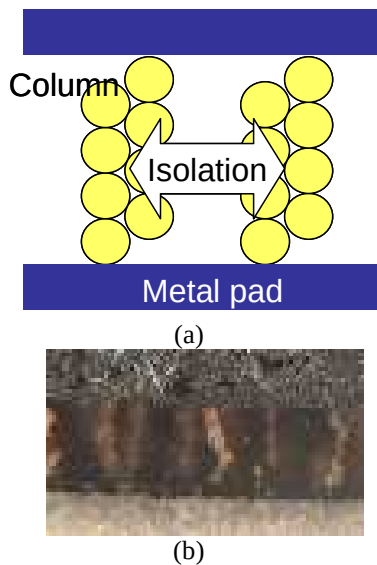


Fig. 1. (a) Schematic of Z-axis anisotropic conductive adhesive (ACA), (b) photograph showing created interconnects

extremely small pad (less than $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$) and narrow pitches because created columns in the Z-axis ACA allows only electrical interconnects in pads as long as the short connection between neighbor columns does not happen. Moreover, the diameter and spacing of created columns are expected to be related to particles' size and shape from the observation of the distribution of created columns. Thus, the Z-axis ACA can be flexibly applicable by changing the properties of conductive particles.

This epoxy includes several advantages; lead-free, patterning-free for an individual pad during an assembly process, low-temperature curing process and environmental-friendly property. These benefits of Z-axis ACA are expected to enhance the flexibility of application range in RF packaging field.

2.0 Z-axis ACA properties

An epoxy generally consists of resin and fillers. The resin is cross-linked between polymers by thermal curing process and this mechanism is considered as a desirable way for thermal-sensitive applications because the curing temperature is able to be controlled by the composition of chemical components in the epoxy matrix, not scarifying any other main properties such as operating temperature range, CTE and glass transition temperature. In this study, a ferromagnetic metal is used for vertical self-alignment in presence of magnetic field. The core of conductive particles is Ni and their surface is coated with Au (weight ratio 8%). This Au coating on the

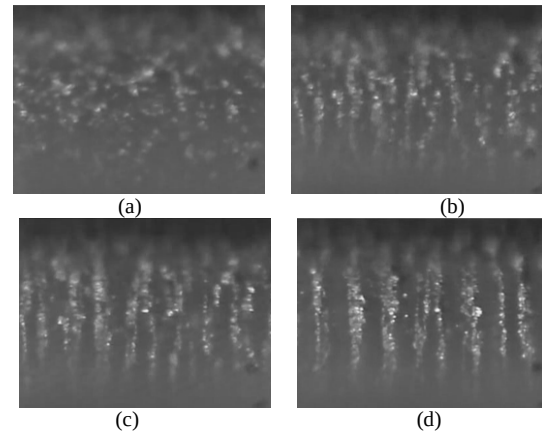


Fig. 2. Photographs showing the creation of columns in a Z-axis ACA (A formulation) when a magnetic field is induced at the elapsed time: (a) 0 second, (b) 2 seconds, (c) 5 seconds and (d) 10 seconds.

surface is to prevent from forming oxidization on Ni layer and promote electrical connection between particles in the column. The curing temperature of a Z-axis ACA is 160°C . Our main concerns are to characterize vertical interconnects created by the Z-axis ACA on a silicon-to-silicon substrate and analyze the influence of RF performance with a change of conductive particles' properties such as the diameter and the shape of conductive particles.

In this work, two types of conductive particles in a Z-axis ACA are compared in RF characteristics. The first type is an F formulation that has spherical shaped, nickel cores with an average diameter of $6.6\text{ }\mu\text{m}$, which creates columns with $10\text{ }\mu\text{m}$ average diameter. The second type is an A formation that has elliptical shaped, graphite cores with an average diameter of $23\text{ }\mu\text{m}$, which creates columns with $25\text{ }\mu\text{m}$ average diameter. The dimensions are determined from visual inspection using microscopic images of cured Z-axis ACA samples. From top-view images of samples with created columns, the density of columns is counted to have 977 columns/mm^2 and 193 columns/mm^2 for the F and A formulation respectively. Therefore, the F formulation Z-axis ACA with smaller conductive particles is expected to be more suitable for an application with denser and smaller pads because it creates relatively large number of columns to reduce the resistance of the transition region in the smaller pads.

3.0 Fabrication and measurement

A silicon substrate with high resistivity ($\rho=10,000\text{ cm}\cdot\Omega$) is useful for validating high-frequency characteristics of Z-axis ACA because it has low loss tangent and high permittivity ($\epsilon_r=11.9$,

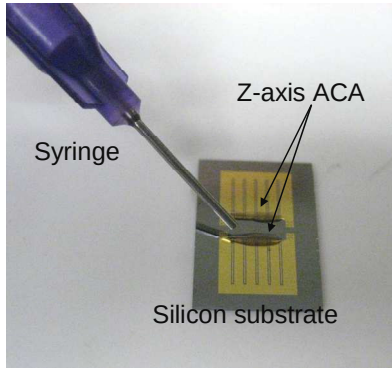


Fig. 3. Z-axis ACA dispensing for assembly using a syringe on a silicon substrate.

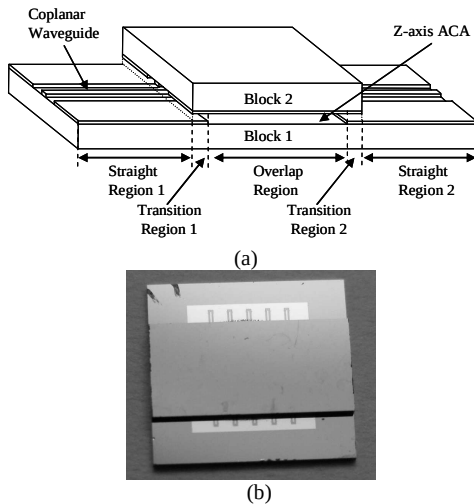
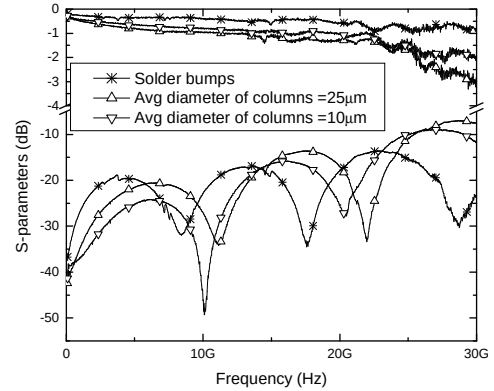


Fig. 4. (a) Schematic view of the designed CPW sample, (b) assembled silicon on silicon sample.

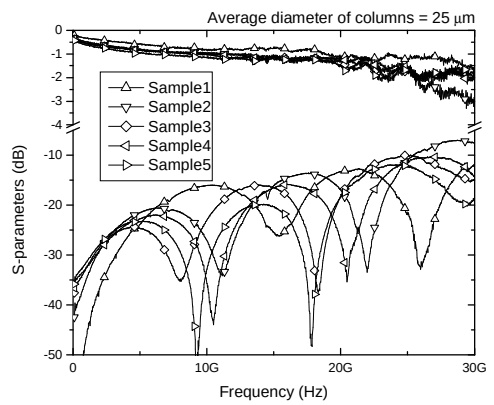
$\tan\sigma=0.005$). Substrate fabrication processes for this experiment are as follows;

- deposition of Ti and Au,
- patterning the features (lithography and development),
- wet etching
- dicing the wafer.

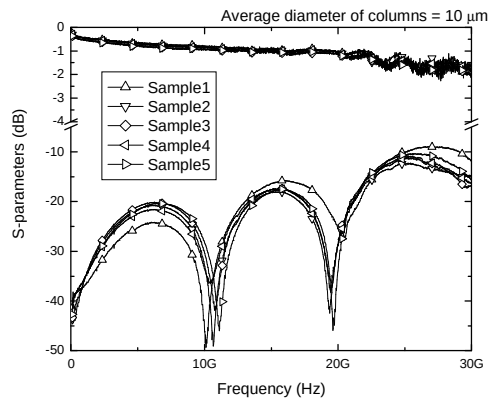
The width of the fabricated coplanar waveguide (CPW) is $80\text{ }\mu\text{m}$ and the width of the gap is $90\text{ }\mu\text{m}$. Using flip-chip bonding process (FINETECH GmbH & Co, $\pm 5\text{ }\mu\text{m}$ accuracy), an assembly process for the alignment between two silicon substrates is carried out. As shown in Fig. 3, a Z-axis ACA using a syringe is manually dispensed on the transition region of silicon substrate. This simplicity reduces the number of assembly steps. The transition region is $80\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ and the gap between two silicon substrates is approximately $50\text{ }\mu\text{m}$. Assembled samples are cured in a magnetic oven for 15 minutes in presence of 0.25 tesla magnetic field because the assembly processing time is not determined by the self-



(a)



(b)



(c)

Fig. 5. Measurement results of silicon samples assembled with both A and F formulation Z-axis anisotropic conductive adhesive (8% Au coated fillers): (a) comparison of the anisotropic conductive adhesive samples with solder bumps, (b) repeatability of A formulation interconnects, (c) repeatability of F formulation interconnects.

alignment time of created columns, but the curing time of epoxy resin. A signal flow in an assembled silicon sample is as follows; it goes through 2 mm-

long straight CPW, 100 μm upward vertical transition in overlap area, 1.8 mm-long straight CPW, 100 μm downward vertical transition, and 2 mm-long straight CPW. Using Agilent 8722 network analyzer, assembled samples are measured up to 30 GHz after Short-Open-Load-Thru (SOLT) calibration. The return loss of both F and A formulation Z-axis ACA is less than 15 dB in the entire range, insertion loss per transition is 0.54 dB (F formulation) and 1.04 dB (A formulation) at 30 GHz as shown in Fig. 4 (a).

From a repeatability test using 5 samples in Fig. 4 (b) and (C), it is shown that the variation of insertion loss is 0.37 dB (F formulation) and 1.21 dB (A formulation). Thus, the RF characteristics between samples in the F formulation epoxy with smaller particles are more repeatable. As a result of inspection of columns' distribution, the number of columns in F formulation epoxy is 7.8 average columns in the 80 μm x 100 μm transition region while 2.6 average columns in A-formulation epoxy assuming that the created columns is uniformly distributed. Therefore, in comparison between silicon samples assembled with F and A formulation, the number of columns is dominant to determine the RF performance such as insertion loss and repeatability in less than 100 μm x 100 μm pad dimension. In addition, the equivalent circuit of columns in the transitional area is modeled by RLC lumped components. It consists of a series resistor, a series inductor, and a parallel capacitor. A series resistor represents the contact resistance in an individual column and the number of columns in a pad, a series inductor is determined by the self-inductance and the mutual coupling of created columns, and a parallel capacitor is determined by an electric field created between two parallel pads.

Herein, the resistance is directly measured and it is approximately 0.45 Ω . Assuming that the resistance dominates the impedance at low frequencies, the insertion loss of a silicon sample at 100 MHz is calculated to be 0.26 dB, which agrees well with the measured insertion loss of 0.27 dB at the same frequency. The frequency dependence caused by the skin effect within the rods is not explicitly modeled, and as an approximation, this low frequency value is used throughout the frequency range. The capacitance is calculated in the transition area by HFSS[®] simulator and it is approximately 0.12 pF. To calculate the parasitic inductance of the Z-axis anisotropic conductive adhesive, we simplify the impedance in the transition area by removing the resistance in an HFSS[®] simulation model, by defining all metallic elements as perfect electric conductors. The inductance of the Z-axis interconnects is then calculated using de-embedding [7] in the HFSS[®] simulation,

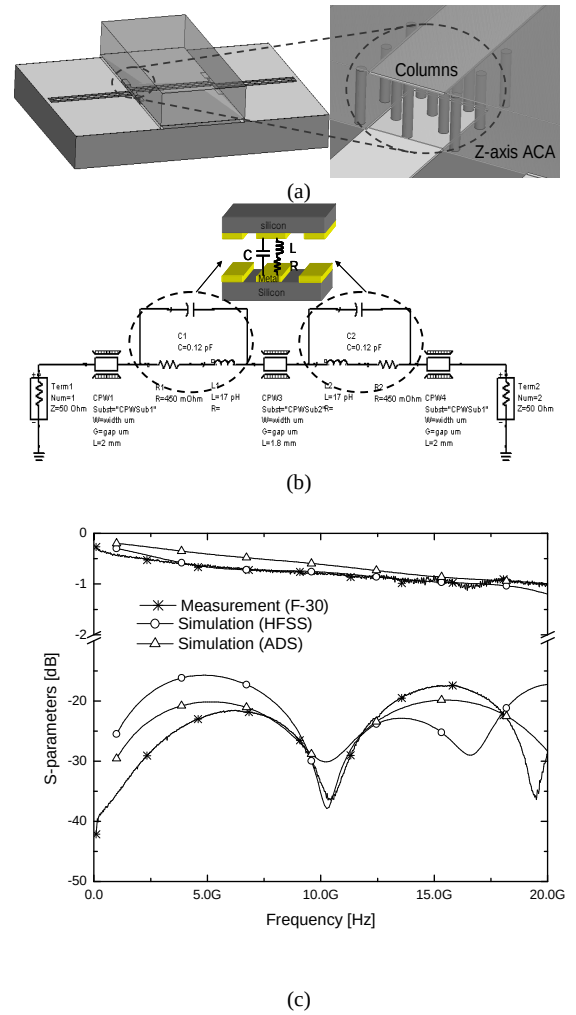


Fig. 6. Simulation result: (a) Modeling of an assembled structure using HFSS[®], (b) an equivalent circuit using ADS[®], and (c) S-parameters compared between simulation and measurement result (F formulation).

and it is approximately 17 pH for the 50 μm long interconnects. By a series inductance and a parallel capacitance, the calculated resonance frequency is approximately 110 GHz and it is high enough not to limit the packaging performance at our operating frequency range up to 30 GHz. As shown in Fig. 6 (c), the results using ADS[®] and HFSS[®] simulator agrees with the measurement up to 30 GHz. Therefore, Z-axis anisotropic conductive adhesive can be described with an equivalent circuit model containing lumped elements determined from the interconnect structure.

4.0 Conclusion

In this study, we analyzed the RF characteristics of a novel Z-axis ACA on silicon substrates. It was

demonstrated that the RF performance of Z-axis ACAs are similar to that of a silicon sample with solder bumpers. The silicon samples were assembled by manually dispensing a magnetically aligned Z-axis anisotropic conductive adhesive without any additional preparation for individual chip I/O pad bonding or any accurate dispensing technique to control the amount of this material. Despite the manual application, the silicon samples utilizing this process were demonstrated to work through 30 GHz. Consequently, the magnetically aligned anisotropic conductive adhesive can be considered for low-cost high-frequency interconnects instead of the conventional solder-bump technology.

Acknowledgments

The authors would like to acknowledge the State of Indiana's 21st Century Research and Development Fund for supporting this work and would also like to acknowledge the support of Tim Bruemmer and Dr. S. Kummur Khanna of Nexaura Systems for supporting us with Z-axis ACA.

References

- [1] V. Eveloy, S. Ganesan, Y. Fukuda, Ji Wu, and M.G. Pecht, "Are you ready for lead-free electronics?" *IEEE Trans. Compon. Packag. Technol.*, vol. 28, no. 4, pp. 884-894, Dec. 2005.
- [2] David D. Chang, Patricia A. Crawford, Joe A. Fulton, Richard McBride, Maureen B. Schmidt, Raymond E. Sinitski, and C. P. Wong, "An overview and evaluation of anisotropically conductive adhesive film for fine pitch electronic assembly," *IEEE Trans Comp., Hybrids, Manufact. Technol.*, vol. 16, pp. 828-835, Dec. 1993.
- [3] Lei L. Mercado, Jerry White, Vijay Sarihan, and Tien-Yu Tom Lee, "Failure mechanism study of anisotropic conductive film (ACF) packages," *IEEE Trans. Comp. Packag. Technol*, vol. 26, no. 3, pp. 509-516, Sept. 2003.
- [4] J. de Vries, "Failure mechanism of anisotropic conductive adhesive interconnections in flip chip ICs on flexible substrates," *IEEE Trans. Compon. Packag. Technol.*, vol. 27, no. 1, pp. 161-166, Mar. 2004.
- [5] Itsuo Watanabe, Tohru Fujinawa, Motohiro Arifuku, Masaki Fujii, Yasushi Gotoh,, "Recent advances of interconnection technologies anisotropic conductive films in flat panel display applications," *IEEE 9th Int'l Symposium on Advanced packaging Materials*, pp. 11-16, 2004.
- [6] Myung-Jin Yi, Woonghwan Ryu, Young-Doo Jeon, Junho Lee, Seungyoung Ahn, Joungho Kim, and Kyung-Wook Paik, "Microwave model of anisotropic conductive film flip-chip interconnections for high frequency applications," *IEEE Trans. Comp. Packag. Technol.* , vol. 22, no. 4, Dec. 1999.
- [7] Hanjin Cho and Dororthea E. Burk, "A three-step method for the de-embedding of high-frequent S-parameter measurements," *IEEE Trans. Electron Devices.*, vol. 38, no. 6, pp. 1371-1375, June 1991.