High-Frequency Characterization of Self-Aligned Z-axis Interconnects on Silicon substrates

***Sungwook Moon*[1], *William Chappell*[2], *Tim Brummer*[3], *S. Kummar Khanna*[4]**

[1] Purdue University, School of Electrical and Computer Engineering
465 Northwestern Avenue P.O. Box 363, West Lafayette, IN 47907-2035, USA, moon8@purdue.edu

[2] Purdue University, School of Electrical and Computer Engineering
chappell@purdue.edu

[3,4] Nexaura Systems, LLC, 112 West Carmel Drive, Carmel, IN 46032, USA
tmbruemmer@nexaura.com

Abstract

A novel anisotropic conductive adhesive (ACA) is investigated for high-frequency applications. In the presence of a DC magnetic field, columns for interconnecting between a chip and substrate are created by the self-alignment of ferromagnetic particles into conductive columns within an epoxy. To demonstrate its performance, coplanar waveguides with 80 μm x 100 μm transitions are fabricated on silicon substrates and then they are assembled with a high-accuracy flip-chip bonding process. As a result, loss difference from a sample with solder-bumps is less than 0.5 dB per transition in the entire range up to 30 GHz.

1. Introduction

Self-alignment in an epoxy is the process by which randomly distributed particles are aligned by an externally-induced magnetic force. To promote this process, these conductive particles contain ferromagnetic metal. Under the presence of a magnetic field, a particle by itself generates an induced magnetic field and interacts with other neighboring particles [1]. On a microscopic scale, the particles interact like small bar magnets, aligning themselves end-to-end in groups. On a macroscopic scale, these groups of particles also move to align themselves into longer columns. Finally, by a torque motion or magnetic attraction, the microscopic combined particles create a vertical column with a relatively uniform distribution between other neighboring columns. Anisotropic conduction by self-alignment is useful for highly-integrated circuitry. In order to apply this property in RF packaging technology, both sufficient horizontal spacing for isolation and reliable vertical connections are crucial. Thus, our aim is to investigate how the conductive particles' properties affect spacing and electrical interconnectivity with the ultimate goal of optimizing their properties for highly-efficient packaging.

To date, packaging technologies have been diversified for vertical integration and wafer-level packaging because a cost-effective solution for massive integration is necessary for production [2, 3]. In order to utilize the advanced packaging methods, appropriate bonding materials for interconnects between homogenous or heterogeneous materials need to be effectively chosen based on various factors such as product performance, cost impact, and environmental friendliness. For example, for temperature-sensitive applications with small pads, anisotropic conductive films (ACF) have been widely used because of their low curing temperature and reasonable reliability. However, ACFs have been found to be sensitive to bonding conditions such as pressure and heating temperature during the flip-chip bonding process [4]. Also, the ACF has a relatively large parasitic capacitance due to its monolayer conductive layer. This parasitic capacitance in the transition region causes degradation of RF performance [5].

In this paper, a novel anisotropic conductive adhesive (ACA) is introduced. The adhesive consists of micron-sized nickel particles suspended in an epoxy resin. Under a strong uniform magnetic field, the created columns are interconnected vertically between a top and bottom silicon substrate and isolated horizontally because of the relatively uniform spacing between neighboring columns. This epoxy introduces several advantages over current approaches: it is a lead-free, patterning-free, low-temperature, and environmentally-friendly assembly process. In addition, the Z-axis ACA has a low parasitic capacitance because of multilayer-particles structure in the gap, allowing its use in higher-frequency applications than ACF.

2. Material properties

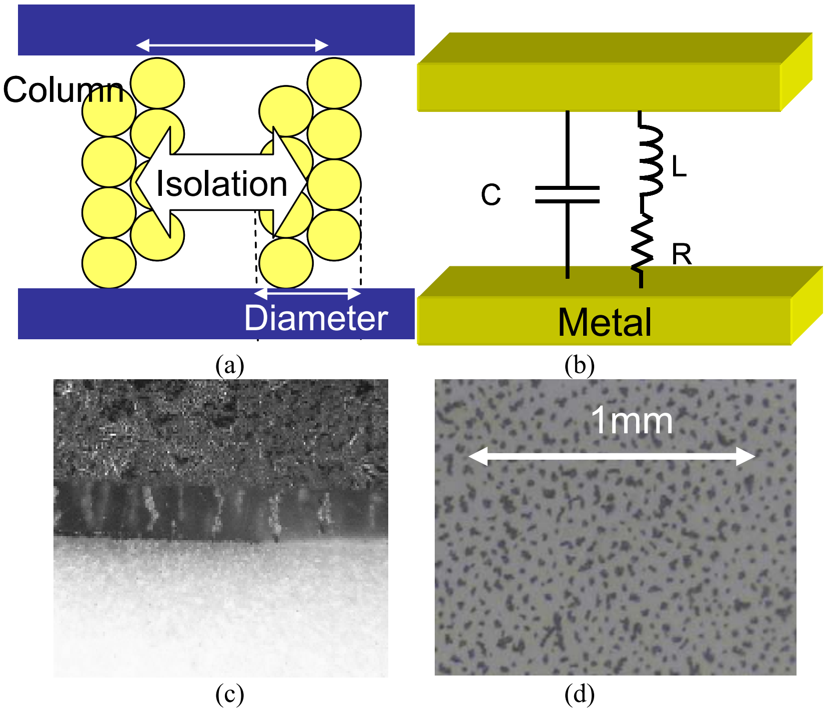


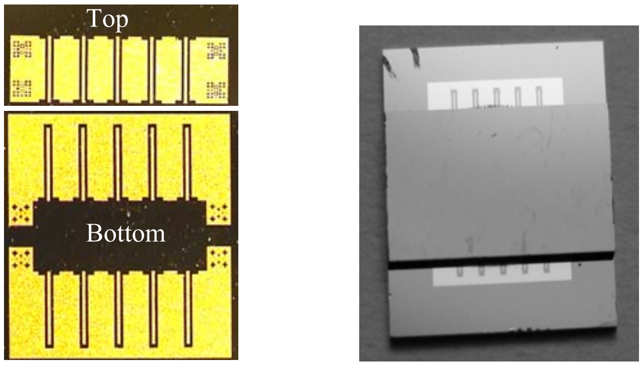
Fig. 1. (a) Schematic of Z-axis anisotropic conductive adhesive (ACA), (b) an equivalent circuit model of created columns, (c) side view and (d) top view of cured ACA. In (c), the conductive columns show up as lighter-colored lines. In (c), the conductive columns are the darker-colored dots.

The types of an anisotropic conductive epoxy are classified by application style; one is film type (ACF), which contains an epoxy with conductive particles in thin-layer film and it is applied to a flat surface in chip-on-glass technology [6], the other uses a syringe application (ACA) for direct distributing of the adhesive in the gap between a chip and a substrate. An epoxy generally consists of resin and fillers. In this study, we use ferromagnetic particles for vertical self-alignment in the presence of a magnetic field. The epoxy is hardened by crosslinking of the resin in a thermal curing process. Epoxy adhesives are considered as desirable for thermal-sensitive applications because the curing temperature can be controlled by adjusting the composition of chemical components in the epoxy matrix, without sacrificing any other main properties such as the operating temperature range, the thermal expansion coefficient (CTE) and the glass transition temperature.

In the ACA studied, the core of the conductive particles is made of a nickel particle whose surface is coated with gold (with a weight ratio 8%). This Au coating on the surface prevents oxidization on the nickel core layer and promotes electrical connection between particles in the column. This Z-axis ACA has a curing temperature of 160 °C, a relative permeability (ε_r) of 2.96, and a loss tangent of 0.03 and was developed by Nexaura Inc. To ascertain the variation of RF performance with respect to changes of particle properties, two types of particles in Z-axis ACAs are compared in terms of RF characteristics. The “F” formulation has spherically shaped particles with 6.6 micrometer (μm) average diameter, which combine to form columns with a 10 μm average diameter. The “A”-formation has elliptical particles with a nickel-plated graphite core and 25 μm average diameter, which creates a column with the same average diameter. This is partially accounted for by the movement of particles in a Z-axis epoxy; smaller spherical particles tend to move around more and group with other magnetized particles in an external magnetic force. It is desirable to have a horizontally isolated spacing with high density distribution of columns. From top-view images of samples with created columns, the average distance between columns is investigated and the spacing of F and A type Z-axis ACA is 32 μm and 55 μm, respectively.

3. Fabrication and measurement

A silicon substrate with high resistivity (ρ=10,000 cm·Ω) is useful for validating high-frequency characteristics of Z-axis ACA because it has low loss tangent (tanσ=0.005) and high permittivity (εr=11.9). Substrate fabrication

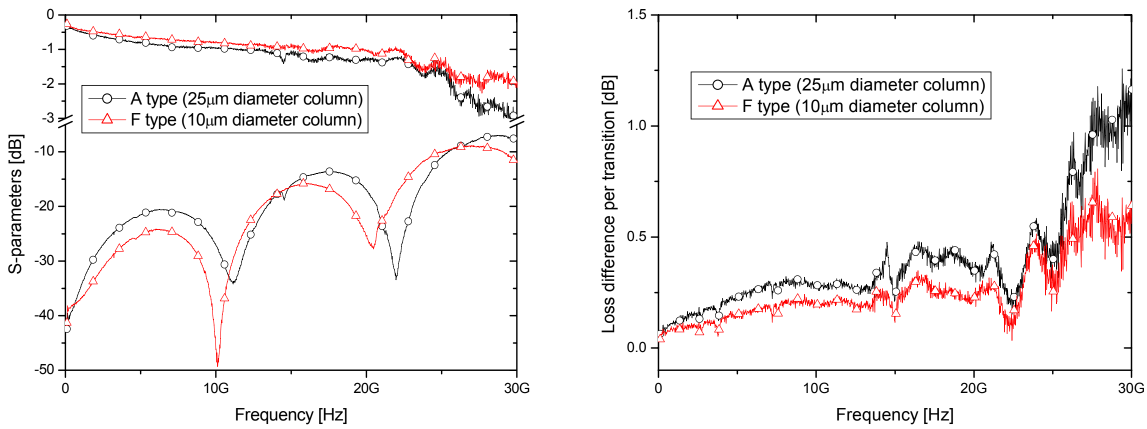


(a) (b)

Fig. 2. (a) Top views of fabricated substrates and (b) an assembled silicon sample.

processes for this experiment are as follows; (1) deposition of titanium (Ti) and gold (Au), (2) patterning work (lithography), (3) wet etching, and (4) dicing the wafer. The width of the fabricated coplanar waveguide (CPW) is 80 µm and the width of the gap between the signal and ground lines is 90 µm. The transmission line's characteristic impedance is 53 Ω. Using a flip-chip bonding apparatus (FINEPLACER® Pico RS system, +/- 5µm accuracy), an assembly process aligns and uses the ACA to bond the two silicon substrates is carried out. The transition region is 80 µm x 100 µm and the gap between the two silicon substrates is approximately 50 µm. Assembled samples are cured in a magnetic oven for 15 minutes in presence of a 2,500 gauss (0.25 Tesla) magnetic field. In an assembled silicon sample the signal travels through a 2 mm-long straight CPW line, traverses a 50 µm upward vertical transition in the ACA, again travels down a 2 mm-long straight CPW, crosses another 50 µm downward vertical transition through the ACA, and finally travels down one more 2mm-long straight CPW.

Using an Agilent 8722 network analyzer, assembled samples are measured from 0.1 to 30 GHz after SOLT (Short-Open-Load-Thru) calibration using the Cascade Widepitch Impedance Standard Substrate (ISS). As shown in Fig. 3, the return loss of both F and A type Z-axis ACA is more than 15 dB, and the loss difference per transition from a sample with solder bumpers is less than 0.54 dB (F-type) and 1.04 dB (A-type) in the entire range.



(a) (b)

Fig.3. Measurement result of assembled silicon samples with A-type and F-type Z-axis ACA (a) S-parameters (b) loss difference from a sample with solder bumps

From a repeatability test using 5 samples in each type of ACA, it is shown that the loss difference between the worst sample and the best sample is 0.37 dB (F-type) and 1.21 dB (A-type). Thus, the RF characteristics between samples in the F type epoxy with smaller particles are more repeatable. Upon inspection of columns' distribution, the number of columns in F-type epoxy is 7.8 average columns in the 80µm x 100 µm transition region while 2.6 average columns in A-type epoxy over the same area. Therefore, the number of columns per unit area has a strong influence on the RF performance for pads smaller than 100 μm x 100 μm

4. Conclusion

In this study, we analyzed the RF characteristics of a novel Z-axis ACA. It was demonstrated that the RF performance of Z-axis ACAs are similar to that of a silicon sample with solder bumps. Therefore, given Z-axis ACA's unique advantages it is expected to become a promising alternative to the conventional soldering technology. Especially, the epoxy (F-type) with 10 μm average column diameter is suitable for applications with down to 100 μm x 100 μm pad dimension. In addition, it was shown that the distribution of the conductive columns is related to the RF reliability of the assembled samples. Finally, the Z-axis ACA is expected to be successfully performed in high-frequency applications by virtue of its small parasitic capacitance.

5. Acknowledgments

The authors would like to acknowledge the support of the 21st century fund of the state of Indiana.

6. References

1. Seppo K. Pienimaa, Jani Miettinen, and Eero Ristolainen, "Stacked modular package, *IEEE Trans., Adv. Pakag.,* vol. 27, no. 3, Aug. 2004.

2. Hasan Sharifi, Tae-young Choi, and Saeed Mohammadi, "Self-aligned wafer-level integration technology with hign-density interconnects and embedded passives," *IEEE Trans., Adv. Pakag.,* vol. 30, no. 1, Feb. 2007.

3. 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.

4. 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.

5. Itsuo Watanabe, Tohru Fujinawa, Motohiro Arifuku, Masaki Fuji, 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.