Compliant interconnect technology for power modules in automotive applications

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ABSTRACT

This work presents a new bond-less and economic viable, technology for power dice interconnection in power modules for automotive applications. In the presented technology bond wires, the major cause of module failures, are replaced by compliant contacts embedded in a polymer core that are pressed, at a prescribed force, over the power dice to establish and maintain a stable low-resistance electrical contact. The absence of rigid bonds, or solder joints, over the silicon die eliminates the failures caused by the mechanical stress induced by the mismatch in thermal expansion coefficients of aluminum wires and silicon. The contacting structures are curved metal wires plated onto a silicon wafer that are bonded to a signal redistribution layer, extruded and embedded into a polymer. This technology can reduce the footprint of power modules. Control circuits can be built over the power dice, with the added value of reducing parasitic effects. Designed test vehicle are presented.

Keywords: compliant contacts, automotive, power electronics, contact resistance.

1 INTRODUCTION

Hybrid vehicles and, in general, energy-efficient vehicles make use of semiconductor power modules (usually called IPM, Integrated Power Modules) to drive the electric engine and to distribute energy to subsystems (lights, servo-systems, etc.)

In a typical high power module the power devices are assembled on a heatsink and, driver, sensor and protection circuits are mounted on separate PCBs assembled to the power devices. Higher integrated power modules are produced assembling power dice onto a DCB (Direct Copper Bond) substrate and interconnecting them by wire bonding technique [1]. The relative driver, sensor and protection circuits are surface mounted on a separate PCB assembled with the former.

Wire bonding technology, despite its enormous progresses in recent years, it still limits the possibility of three-dimensional packaging and puts major limits on creating low EMI and high frequency circuits. Moreover, wire bonding is the major cause of IPM failures, together with solder delamination [2]. The cause of failure is de-bond of aluminum wires due to thermo-mechanical stress evolution at the bond site caused by the different coefficient of thermal expansion of silicon and aluminum.

Thermal cycling during module operation can induce loss of contact failures on some of the wire. The loss produces the common "domino-effect" present in parallel systems: surviving wires are subject to higher currents accelerating their failure rate.

Two solutions are currently taken into consideration: stripe bonding and compliant contacts. Stripe bonding employs a sintering process to bond a metal strip to the silicon die and suffers (although to a lesser extent) of the same problems as wire bonding. Compliant contacts do not require any bond to guarantee the electrical contact that, in these technologies, is realized by applying a pressure between the die and a flexible contacting substrate, into which metallic "spring-like" structures are realized [2]. The applied force guarantees a stable electrical contact and the absence of any bond nullify the fatigue due to the thermal cycling. Compliant contacting technologies are an effective solution to improve reliability of power modules.

2 THE COMPLIANT CONTACT

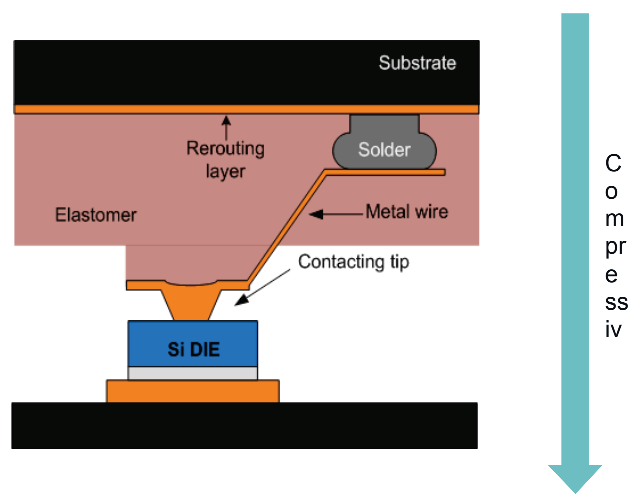

Figure 1: The compliant contact realized in this technology.

The compliant contact realized with the presented technology is, shown in figure 1. The technology steps are presented in [3]. It consists of a metal wire, embedded in an elastomer, ending with a shaped tip on one side and soldered to a substrate on the other. The tip provides the electrical contact with the silicon die and creates an electrical path to the substrate. The substrate can be single or multi-layer and is used to establish the necessary electric connectivity between dice.

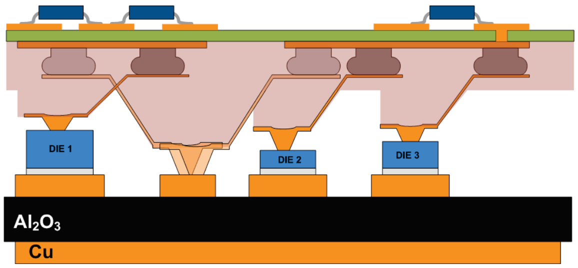

Figure 2: Application of the compliant contacting technology to a compact IPM.

To create a stable contact, a compressive force must be applied and kept during all the operating life of the module. The elastomer allows contacting dice with different heights as shown in figure 2, where contact dimensions are exaggerated with respect to dice dimensions to show the principle of the contacting technology. In actual application more than one wire is connected to a single device, as in wire bonding technology.

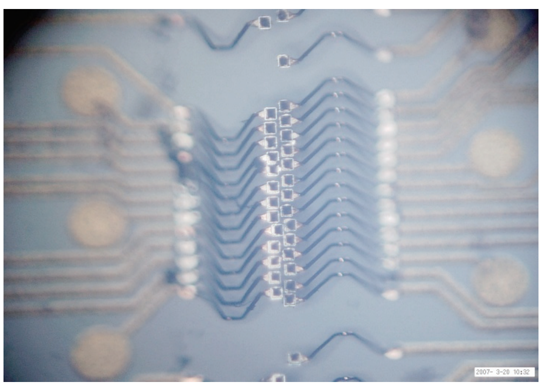
Figure 3: Test vehicle for the study of mechanical and electrical characteristics of the compliant contacts.

The advantage of this technology is that it is possible to retrofit existing designs re-using existing DCB. To reduce the volume of the module, the control circuitry can be integrated in the top substrate. Wire bonds in existing design are replaced as shown for silicon die 1, by connecting the device to the top substrate and back to the bottom. Newer design can use the top substrate only for connections, resulting in improved performances because of lower parasitics.

Two different test vehicles have been realized to evaluate the capabilities of the technology. The test vehicle in figure 3 has been designed to analyze the electrical and mechanical characteristics of the contact.

The wires have been embedded into PDMS (Polydimethylsiloxane) and soldered to a dual layer alumina PCB for electrical measurements.

The second test vehicle is a high density contacting structure consisting of a square array of 4500 contacts on 1 cm^2 area. The possibility to create a regular array of contacts over the entire die pad provides a homogenous thermal path (wire-bonds runs parallel and have only one or two contact points per wire over pad) for removing heat.

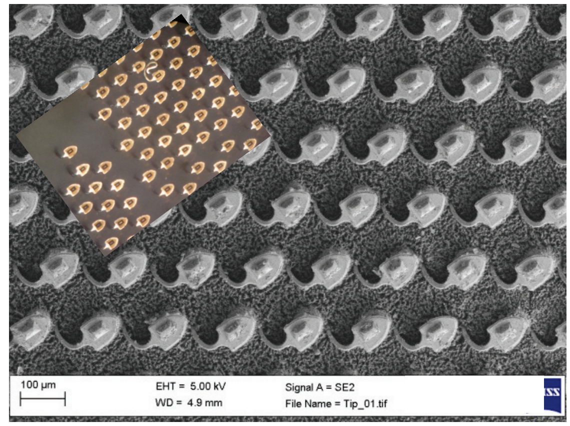

Figure 4: High density test vehicle: SEM and optical (inset) images.

The high-density vehicle (shown in figure 4) employs nano-particles loaded PDMS as embedding elastomer. The use of loaded materials improves thermal and mechanical characteristics of the base material and, in this application, is fundamental for the force/displacement optimization necessary to guarantee the stable electrical contact.

2.1 Contact design

Successful design of a compliant contact must consider the following factors:

- Contact force,
- Contact resistance,
- Contact stability,

The three parameters are related, as the force exerted on the contact influences both the electrical resistance and mechanical stability.

The total resistance of an electric contact is the sum of three terms:

$$R_{tot} = R_b + R_c + R_{ft} \tag{1}$$

where R_{tot} is the total resistance, R_b is the wire, R_c the constriction resistance and R_{ft} is the tunnelling resistance of the oxide film covering the pad surface. In a first order approximation, equation (1) can be expressed, according to the Holm's theory for a hertzian contact, as [4]:

$$R_{tot} = \rho_1 \frac{l}{S} + \frac{\rho_1+\rho_2}{4}\sqrt{\frac{\pi H}{F}} + \frac{\sigma_{film} H}{F} \tag{2}$$

In the above equation ρ_1 and ρ_2 are the bulk resistivity of the metals in contact, S is the wire section and l the wire length, H is the hardness of the softer material, σ_{film} is the resistivity of the film between the contacting surfaces and F is the force applied to the contact.

The values for materials used in contacting applications are reported in table 1.

Bulk resistivity [Ωm]	Copper	1.68e-8
	Nickel	6.80e-8
	Aluminum	4.00e-8
Film resistivity [Ωm]	Alumina	1.00e-12
Hardness	Aluminum	1.30e10

Table 1: resistivity values for materials used in the compliant contacts.

The contact resistance of a compliant contact can be computed applying (2) with the values in the table 1. The contact resistance of copper and nickel contacts over aluminum, at different force values, is shown in figure 5.

Wire resistance (R_b) is neglected, as is not force dependent.

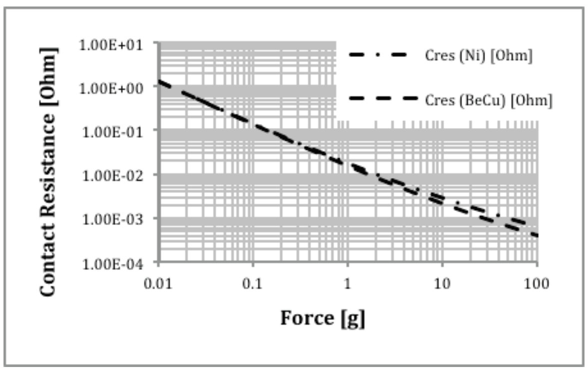

Figure 5: contact resistance at different force levels.

The contact force is relative to a single contact only. The total force that must be applied to the assembly should be multiplied times the number of contacts. This parameter becomes critical when dice with multiple heights must be contacted. In such complex application (multiple heights), finite elements simulations must be used to compute the force and evaluate stress imposed on the different contacting points.

Metal	L<0.04" (0.1cm)	L>0.04" (0.1cm)
Aluminum	22000	15200
Gold/Copper	30000	20500
Silver	15000	10500
Other metals	9000	6300

Table 2: values of the constant "k" in MIL-38510.

Wire cross-section should be designed to withstand the maximum currents in the device.

MIL-M-38510 (section 3.5.5.3) rules that the maximum steady (DC) current in a single wire should be computed with the following formula:

$$I = kd^{3/2} \tag{3}$$

Where "k" is a constant that depends on wire material and length and "d" is wire diameter in inches. Values for the "k" constant for materials used in wire-bonding and different lengths (L), are tabulated in table 2 (from MIL-M-38510). Equation (3) determines the wire diameter and, together with equation (1) (and Ohm's law), allows for correct contact electrical design.

3 CONTACT SHAPE AND MECHANICS

The value of contact force is critical for the design and FEM simulations of the actual geometry are required, together with extensive characterization of the materials employed.

Figure 6: SEM image of the compliant contact.

This technology uses pyramid-shaped contacting tips, realized by anisotropic etching of silicon, on top of a column of polymeric material as shown in figure 6.

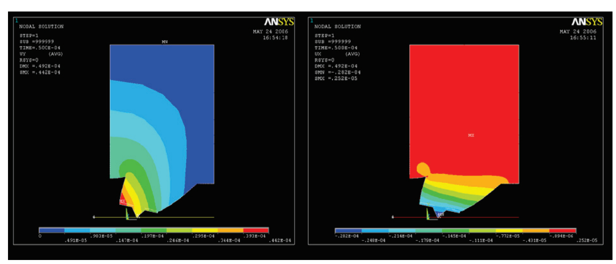

Figure 7: FEM simulation of the compliant contact: vertical displacement (left) and scrubbing (right).

Finite elements simulations of the contact are shown in figure 7. The vertical displacement (figure 7, left) occurs when the interconnection substrate is pressed against the silicon die or the other substrate. The normal component of the reaction provides the stable contact; the tangential one produces a displacement that performs the scrub action (figure 7, right), useful to remove the oxide in the contacted area.

The scrub movement is generated by the mismatch between the center of mass of the tip and the application point of the reaction, and can be controlled with masses distribution. All contacting tips are designed to present a lower inertia in the wanted direction of scrubbing.

The contact resistance determined in equation (2) sets the necessary vertical reaction force. The displacement necessary to obtain such value depends on the embedding polymer.

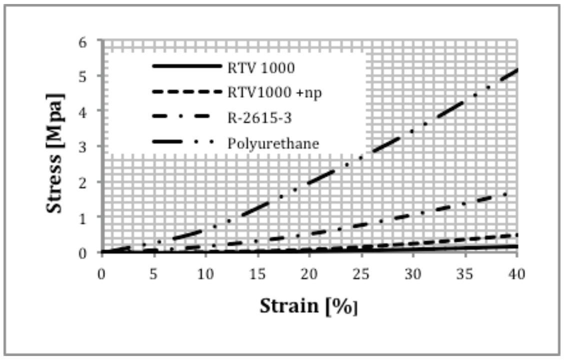

Figure 8: Stress-strain plots for the evaluated polymers.

Silicone based materials have been evaluated for use in this technology. Figure 8 shows the stress/strain plot for two types of silicone: RTV-1000, RTV 1000 loaded with nanoparticles, and R-2615-3. Polyurethane has been tested as material for high-force contacts. The polymers used in this technology are hyper-elastic materials and are described by the Ogden's theory [4].

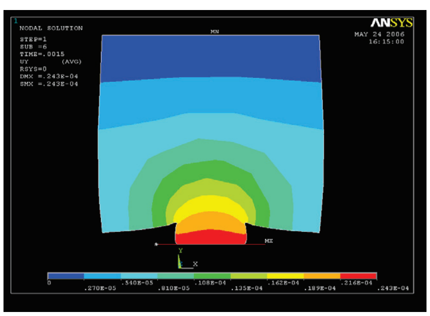

Figure 9: Vertical Displacement contour with a 150 mg vertical load.

Hyperplastic materials have a non-linear stress/strain characteristic that can be exploited to obtain higher reaction normal forces at lower displacements compared to metals. This is useful to obtain high forces with shorter wires and shorter assemblies, thus reducing the total volume of the IPM.

FEM simulators can extract the parameters that model such class of materials from measurements. Tensile, compressive and biaxial tests have been performed on materials to perform realistic simulations [3]. Furthermore, multibody FEM simulations have been performed using the contacts method to simulate the tip's vertical compressive effect. The result, shown in figure 9, confirms the experimental tests [6], [7].

4 CONCLUSIONS

A new compliant contacting technology for power devices is presented. Preliminary tests are proving that such technology seems able to overcome the main limitation of wire bonding technology (i.e. 3D packaging, low EMI and high frequency). Preliminary tests showed the possibility to reach up to $720 A/cm^2$, in conformance to the MIL rules. Using polymer as compliant material offers the possibility to nano-fill it with nanoparticles allowing to tune the correct force in order to warrant a stable and low electrical contact with a reduced length respect a normal metal spring. The value of 74 mΩ has been measured as contact resistance for the test vehicles.

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