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Letters

A Lab-Scale Alternative Interconnection Solution of Semiconductor Dice Compatible with Power Modules 3-D Integration

Ludovic Ménager, Maher Soueidan, Bruno Allard, Vincent Bley, and Benoît Schlegel

Abstract—Increase in the power density of power modules requires an interconnection technology alternative to wire-bonding technology. Emerging interconnection technologies allow a 3-D packaging of power modules. A proposal of interconnection solution for the power semiconductor dice is presented here; it is based on copper microposts that are electroplated on top side of the die. The die with its microposts is then attached to a top direct-bonding copper (DBC) substrate using a copper/tin transient liquid phase technique. The assembly of the backside of the die to a bottom DBC substrate is processed concurrently using the same transient liquid phase technique. The benefits or limitations of the substrate on the assembly are not discussed in this letter. Manufacturing and electrical characterization of a power semiconductor die with the microposts interconnection is presented in detail.

Index Terms—3-D packaging, Electroplating, power density, semiconductor die, transient liquid phase bonding.

I. INTRODUCTION

THE MOST common die-level interconnect technology in power modules is wire bonding. Maturity, flexibility, and low cost are main factors that explain the use of the wire-bonding technology plus recent improvement with respect to tin-less solder regulation or high temperature capability. However, wire-bonding technology has electrical and thermomechanical limitations. A wire usually involves a parasitic inductance about 10 nH [1]. This parasitic inductance induces over voltages at the switch level and is globally a limiting factor regarding the maximum switching frequency. It slows down the turn ON/OFF of the switch that induces an increase in commutation losses. It also contributes to the dynamic current unbalancing in parallel-connected dice [1]. From a thermal point of view, the heat flux dissipation is limited to one direction. In fact, the main thermal path is the backside of the dice. Finally, wire bonds are

subject to thermomechanical stresses when temperature cycling is installed. This leads to a wire-bond fatigue and eventually a failure [2].

Alternative interconnection technologies have been developed to overcome the latter shortcomings in wire-bonding technology, and that allow a 3-D packaging of power modules in a compact-stacked layer structure [3]–[5]. The proposed technologies can be divided into four categories: solder interconnection, interconnection by springs, pressure contact, and interconnection by electroplated metallizations. The advanced interconnection technologies permit a decrease in the values of parasitic inductance and electrical resistance. They also offer opportunities to improve the thermal management by an access to the top side of the dice. However, the 3-D interconnection technologies have drawbacks. Literature reports, robustness, and reliability limits the solder interconnection technologies particularly under repetitive thermal cycling, and moreover under higher ambient temperature [6]. In the interconnection by springs, the heat-flux dissipation of the dice is realized mainly by the backside because the springs have a high thermal resistance [4]. The manufacturing process of the spring-interconnection technology is complex and limits its acceptance. Concerning the pressure contact, the main problems are the complicated mechanical structure and assembly programs. Moreover, some of the pressure contact technologies still include wire bonds for low-power connection [7]. In the interconnection by electroplated metallizations, the major drawbacks are the stress problems at the solder level as the mechanical rigidity of the assembly is augmented [7]. Finally, few alternative technologies to wire bonding have bridge the gap to industrial process and market acceptance [8]–[9]. Most of them remain laboratory-scale experience.

This letter details the experience of an alternative laboratory-scale interconnection technology called microposts interconnection. Our aim is to realize a 3-D assembly, compatible with low-cost and high-volume manufacturing solutions; the microposts are grown in one step on a whole silicon-dice wafer, and both the top and bottom of the die are bonded at the same time. Furthermore, by providing a thermal path on both sides of the power die (whereas cooling is done on one side only with the current technology), this 3-D structure is suited to high-power devices. The technology issues are described in Section II. Section III shows the electrical characterization of the microposts interconnection and the results are discussed in Section IV. Conclusions and perspectives are given in Section V.

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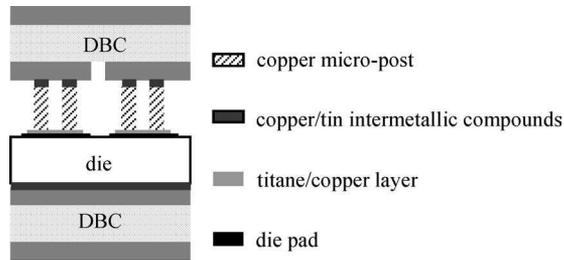


Fig. 1. Schematic of the proposed die interconnection using micro-posts.

TABLE I
BONDING MATERIAL FAMILIES WITH THEIR BONDING AND REMELTING TEMPERATURES [10]

Material	Bonding temperature (°C)	Remelting temperature (°C)
Nickel / tin	300	400
Silver / indium	175	880
Silver / tin	250	600
Copper / indium	180	307
Copper / tin	280	415
Gold / indium	200	495
Gold / tin	450	900

II. MICROPOSTS INTERCONNECTION OVERVIEW

The proposed interconnection is based on copper microposts that are electroplated on the topside of the die (see Fig. 1). The microposts have typically a square section in the range of $100\ \mu\text{m} \times 100\ \mu\text{m}$, up to $300\ \mu\text{m} \times 300\ \mu\text{m}$ (to keep a sufficient density) and a height in the range of $100\ \mu\text{m}$. The distance between two microposts is fixed to $300\ \mu\text{m}$ in the first step. Section dimension and postinterdistance are values to be optimized. Reducing section and increasing postdensity impact favorably the mechanical rigidity and the thermal performance so far but could degrade reliability perspectives. Copper presents a good tradeoff between sufficient electrical and thermal conductivities, cost, availability, and manufacturability. The microposts are realized by electroplating. Other plating methods like evaporation, sputtering, and electroless do not allow in achieving affordably thicknesses close to $100\ \mu\text{m}$ with large growth rate. Moreover, this plating method requires few equipments, and is thus low cost.

The die with its copper microposts is attached to the top direct-bonding copper (DBC) substrate by copper (Cu)/tin (Sn) transient liquid phase (TLP) bonding step (see Fig. 1). The TLP bonding step uses a low-melting temperature metal (tin, indium, . . .) to bond two high melting temperature metals (nickel, copper, silver, gold, . . .) together [10]. During the TLP bonding that necessitates quite a high temperature, pressure, and time-sensitive procedure, the diffusion of the low-melting temperature metal in the high-melting temperature metals induces a formation of intermetallic compounds. The presence of intermetallic compounds permits to have a joint with a remelting temperature more important than its bonding temperature. Table I lists some TLP bonding material families with their bonding and remelting temperatures. The DBC substrate was selected for compatibility with the copper microposts. Other combinations may be considered but have not been tested so far.

The main interests of the proposed microposts interconnection are the elimination of a solder layer between the die pads and the interconnection on the one hand. On the other hand, the Cu/Sn TLP bonding allows in achieving joints with a high remelting temperature above $300\ ^\circ\text{C}$, and so is a solution compatible so far with high temperature packaging [10]. The other advantages are the following. The small sizes of the microposts permit to create a matrix of contacts on a usual power die. It decreases the values of parasitic inductance and electrical resistance. From a thermal point of view, the microposts interconnection offers a thermal access on the topside of the die. The proportion of heat flux removal through this top connexion has not been yet measured but finite-element method simulations indicate a ratio of 20%–30% of the total heat flow (static operating conditions with COMSOL). It is then safe to consider a positive impact on the junction operating temperature of the die. The possibility to introduce a dielectric fluid and/or gel between the microposts will allow improving the heat flux dissipation from the topside of the die.

III. MANUFACTURING AND ELECTRICAL CHARACTERIZATION OF THE MICROPOSTS INTERCONNECTION

The different manufacturing steps to realize the microposts interconnection on a chip are presented in Fig. 2. Before the electroplating of the microposts, the die pads must be covered with a thin titanium (Ti)/copper (Cu) layer ($20/100\ \text{nm}$, respectively) if the pads are ready for wire bonding or bump. Properly prepared pads for copper electroplating would suppress this primary preparation of the die. Titanium is used as an adhesion layer and copper is employed as a conductive layer for the electroplating step. Before the deposition of the Ti/Cu layer, a photolithography step isolates the die pads (photoresist thickness close to $2\ \mu\text{m}$). This photoresist will permit to remove the Ti/Cu layer around the die pads by lift-off after the electroplating of the microposts, and so to avoid the short circuit between the die pads.

A second masking step is performed prior to the electrolytic growth of the microposts using a dry film photoresist (Riston PM275 dry film photoresist [11]) mainly seen in the electronics industry to realize printed circuit boards. The dry film photoresist is composed of a photoresist sandwiched between a polyethylene protective foil and a polyester support. It offers some benefits such as a simple process, a remarkable robustness to the acid bath, a decrease in the edge beads on the substrate, and a low cost. The dry film photoresist has a thickness of $75\ \mu\text{m}$ and a nominal resolution of $50\ \mu\text{m}$. The process to realize the pattern in one layer of the Riston PM275 is the following. The die is heated at $70\ ^\circ\text{C}$ for 1 min. This heating step allows improving the dry film photoresist adhesion on the die. The polyethylene foil is removed. The photoresist is deposited by lamination on the die ($100\ ^\circ\text{C}$ and $0.3\ \text{MPa}$ pressure). It is then exposed to an UV source with an intensity between 12 and $15\ \text{mW}/\text{cm}^2$, and a wave length of $385\ \text{nm}$, respectively. The exposure time is comprised between 5 and 7 s, respectively. After lamination and exposure, the polyester support is peeled away. Finally, the photoresist is developed with a spray system

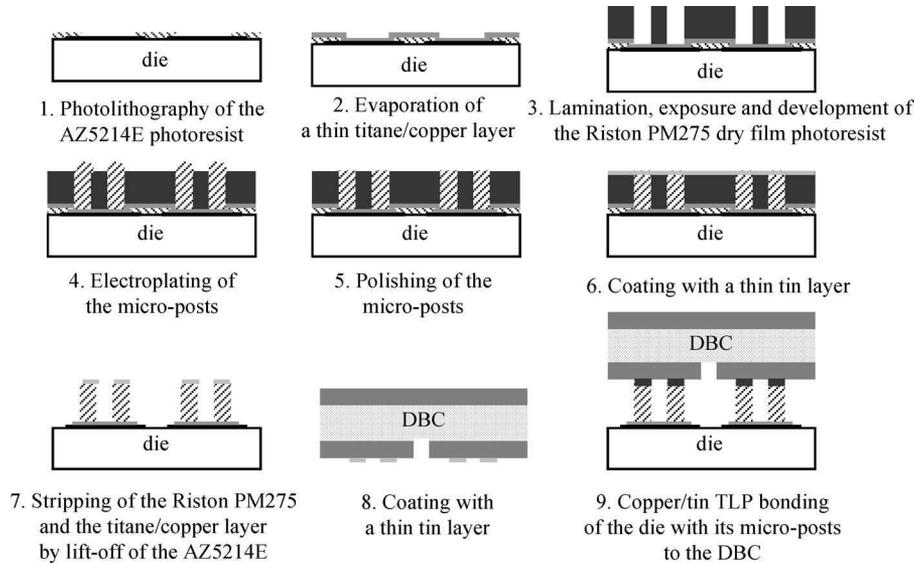


Fig. 2. Manufacturing process of the proposed interconnection.

in a sodium carbonate solution at 1% (5 g of sodium carbonate diluted in 500 mL of water) during 1 min and 30 s and with a processing temperature of 30 °C. The experimental electrolytic cell has horizontal electrodes. This configuration allows obtaining homogeneous microposts. The electrolytic bath is composed of pentahydrate copper sulphate (220 g/L), sulphuric acid (32 mL/L), hydrochloric acid (0.2 mL/L), and brightener and leveler additives (2 mL/L of Rubin T200-A, 8 mL/L of Rubin T200-G and 2 mL/L of Rubin T200-E). Electroplating of the microposts is performed at ambient temperature with a typical current density of 10 mA/cm². The experimental growth rate of the microposts is linear and close to 11 μm/h, for a current density of 10 mA/cm². The minimal deposit time has been set to 7 h. This deposit time achieves a microposts growth with a height larger than the thickness of the Riston PM275, and so allows then for a polishing and/or grinding step of the microposts in order to obtain a plane surface and ensure a good electrical and thermal contact between the microposts and the DBC substrate. A mechanical polishing is realized thanks to a cloth polishing disk and a diamond liquid with grains of 9 μm down to 1 μm in the laboratory-scale experiment. Thinner grains are available to improve further the state of surface. Fig. 3 shows the microposts for a deposit time of 8 h before and after the polishing step. The height of the microposts is, respectively, 96 and 62 μm before and after the polishing step. This step is essential to obtain a fixed final thickness of the die in case of multi-dice modules with dice of different initial thickness. A quite good tolerance is achievable with a grinding/polishing step (namely in the 100 nm range and better). This avoids the use of intercalars that multiply the interfaces if not increase the number of solder interfaces [12].

A diode die with its polished microposts is attached by Cu/Sn TLP bonding to the DBC substrate. A thin tin layer (thickness less than 1 μm) is deposited on the microposts and the DBC substrate. The tin thickness and bonding temperature are deduced from the Cu/Sn phase diagram in order to obtain a Cu-rich/Sn

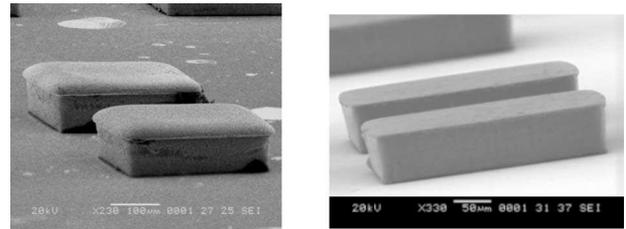


Fig. 3. SEM images of the microposts for a deposit time of 8 h before (a) and after (b) the grinding/polishing step.

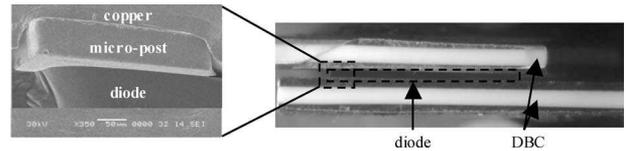


Fig. 4. Diode interconnected concurrently to top and bottom DBC.

joint. Fig. 4 presents a 3.5 kV-100 A diode with microposts on anode side and bonded concurrently to a top and bottom DBC through Cu/Sn TLP proposal. A tin thickness of 0,5 μm, a pressure of 10 MPa and a temperature of 300 °C during 7 min have been considered. A SEM image of the Cu/Sn joint between a microposts and a DBC is shown in Fig. 5. As a demonstration of a 3.5 kV-100 A diode integrity after interconnection process, the direct electrical characteristic is pictured in Fig. 6. This characteristic is identical to the manufacturer datasheet [13].

IV. DISCUSSION

The previous sections cover the details of a first experiment of a proposed interconnection technique to avoid wire bond and solder. So far only the feasibility of the technique has been demonstrated since many issues are under investigation: influence of micropost dimensions with regard to die pad dimension and positioning, parameters of electroplating growth

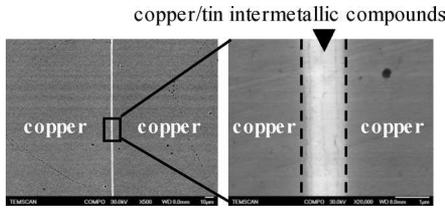


Fig. 5. SEM image of a Cu/Sn joint between a microposts and a DBC.

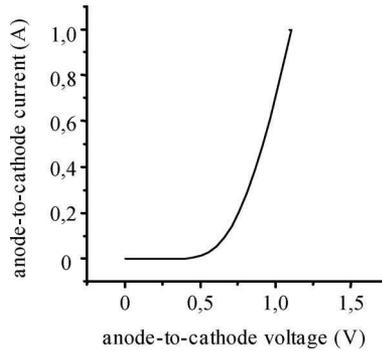


Fig. 6. Direct electrical characteristic of a 3.5 kV-100 A diode with the microposts interconnection.

TABLE II
COMPARISON OF ACTUAL PACKAGING TECHNOLOGIES WITH THE MICROPOSTS INTERCONNECTION

Interconnection technology	Parasitic inductance	Thermal management	Height compensation of dice with shims
Wire bonding	high	one-sided cooling	no
Solder interconnection	low	double-sided cooling	yes (flip chip on flex technology [3])
Interconnection by springs	low	one-sided cooling	no
Pressure contact	low	double-sided cooling	yes (3D press-pack technology [5])
Interconnection by electroplated metallizations	low	double-sided cooling	yes (embedded power technology [12]) no (power overlay technology [14])
Micro-posts interconnection	low	double-sided cooling	no

rate, tolerance of grinding/polishing step, optimal parameters of Cu/Sn TLP bonding, thermal performance measurement of assembly, intrinsic reliability analysis, interconnection parasitic components measurement and reliability of a multidice assembly. Probably the optimal parameters of TLP-bonding depend on the industrial setup. However, the copper intermetallic interface is under analysis to relate the shear force capability to the metallurgical composition. The dimensions of the microposts have a significant influence on the thermal performance of the assembly and the parasitic components. The latter components

make sense with respect to commutation what implies to realize a two-dice assembly (a diode and a MOSFET, for example). The accuracy of the grinding/polishing step is then of primary importance. So, a complete experiment plan is required and under development. Table II presents a comparison of actual packaging technologies to situate the micro-posts interconnection.

V. CONCLUSION

This letter has presented an alternative interconnection solution for power semiconductor dice that wishes to be compatible with 3-D integration of power modules. The different steps (electroplating and assembly by Cu/Sn TLP bonding) have been described. A first demonstrator on diode dice proves the feasibility of the proposal as the electrical characterization shows that the diode has kept its integrity and a satisfying electrical connection is obtained. Near future work focuses the production of a switching-cell (diode/MOSFET) for electrical transient characterizations and thermomechanical analysis. Moreover, electromagnetic and thermal simulations of the microposts interconnection will then be validated.

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