Electrically Yielding Collective Hybrid Bonding for 3D Stacking of ICs

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Abstract
The production of non-monolithic 3D-systems by stacking and interconnecting components through substrate vias (TSVs) is intrinsically limited to the stacking of thin dies, typically ranging from 100µm down to 15µm. Since dies or wafers of such thickness are no longer rigid, it is an important requirement that the bond guarantees mechanical stability and rigidity to the thin stacked die or wafer. The route followed here combines the fixation of a thin wafer or die by means of a dielectric adhesive with the formation of a metallic interconnect. This process is called Hybrid Bonding. The introduction of a tacky polymer as an intermediate glue layer in the direct bonding scheme offers the possibility for die-to-wafer throughput optimization: the opportunity lies in the separation of die pick-and-place and bonding operations. This process is called Collective Hybrid Bonding. Two polymers have been selected (so called polymer A and polymer B) according to their reflowing and bonding properties, and a die pick and place procedure has been defined and optimized for each of them, allowing a fast and reliable operation. Moreover, electrical measurements of daisy chains showed a comparable and reproducible yield of 80% working chains up to 1000 TSVs.

Introduction
The restriction in thin die stacking not only stems from the desire to shrink system height, but is also imposed by the limited capabilities of TSV processing. Depending on the type of TSV technology employed, the final wafer or die thickness typically ranges from 100µm down to 15µm. Since dies or wafers of such thickness are no longer rigid, it is an important requirement that the bond guarantees mechanical stability and rigidity to the thin stacked die or wafer. Pure dielectric bonding guarantees such stability simply by the fact that the thin die or wafer is bonded over its entire surface. This method, however, limits the options for electrical interconnection to a via-last approach enhancing the risk of system yield loss during via processing. A very recent approach combines fixation of a thin wafer or die by means of a dielectric adhesive with the formation of a metallic interconnect. This is typically the route followed by IMEC and is so called 3D-Stacked IC (3D-SIC) [1,2]. An illustration of this 3D concept is shown in Fig.1. In this approach, standard single damascene techniques are combined with extreme wafer thinning and direct Cu-Cu thermo-compression bonding.

In this integration scheme, a die-to-wafer stacking approach is preferred: indeed, as compared to wafer-to-wafer bonding, it may be of more interest for the fabrication of heterogeneously integrated systems as it does not impose the requirement of equal die size. The method is also compatible with the selection of Known Good Die prior to stacking and, therefore, is of interest in cases where one of the components in the stacked system is a product with limited yield.

The cost of die-to-die or die-to-wafer stacking for most bonding methods is limited by the throughput of the process, especially when heat needs to be applied to achieve the bond, which is a lengthy process. The introduction of a tacky polymer as an intermediate glue layer in the direct bonding scheme now offers the possibility for die-to-wafer throughput optimization. This process is called Hybrid Bonding. The opportunity lies in the separation of die pick-and-place and bonding operations. First, the TSV-dies are aligned and placed onto a landing wafer on which the polymer glue layer has been previously processed and patterned (by standard photolithography step). This patterned and tacky dielectric weakly bonds the stacked dies and fixes them during further handling. This operation is performed ideally at low temperature with the pick-and-place process repeated until the full wafer is populated. In a second stage, the fully populated wafer is moved to a wafer-level bonding tool where pressure and heat are applied to all stacked dies at once. Thus, the dielectric layer reflows and the metallic interconnect bonding is performed for all stacked dies simultaneously. This process is called Collective Hybrid Bonding and is illustrated in Fig.2.

Figure 1. Illustration of the 3D-SIC concept: dies are separated by a thin dielectric glue layer, and interconnected through Si Cu vias (TSVs).

Figure 2. Illustration of the die pick and place and the collective hybrid bonding process.
The choice of the intermediate glue layer depends not only on its bonding properties that have to be compatible with the Cu-Cu direct bonding process, but also depends on its capability of reflowing and deforming upon application of pressure during the collective bonding process to allow good electrical interconnections between the different top dies and the landing wafer. Two polymers have been selected (so called as polymer A and polymer B) according to these criteria, and a die pick and place procedure has been defined and optimized for each of them.

Die pick and place and hybrid collective bonding

Different landing wafers were processed by standard photolithography with respectively polymer A and polymer B as glue material. Patterning of the polymer glue layer is required as the collective bonding relies on the reflow and the deformation of the material upon application of temperature and pressure. The patterning of the polymer glue layer results in a uniform distribution of tiny dots across the wafer surface as shown in Fig.3, except in locations where TSVs will make an electrical contact after bonding. The lithography process has been optimized for both polymers to result in a layer thickness slightly higher than the initial TSV height (typically 0.7µm). The idea of the pick and place procedure is to connect at low temperature the top die to the landing polymer glue layer only, in a fast and reliable operation, leading to a high throughput process. The experimental pick and place operation has been performed at die level (after dicing of the landing wafer) on a flip-chip bonder type FC150. Different die attach conditions in pressure, time and temperature have been evaluated.

Figure 3: optical picture of a landing wafer after dielectric patterning showing a uniform distribution of polymer structures (dots).

Figures 4 and 5 show the test conditions as used to determined reliable pick and place conditions both for polymer A and polymer B. Each condition has been tested on 5 samples. The success criteria is defined as ‘all 5 samples stay in place’. The experiments clearly show the existence of 2 regions: the first region systematically leads to failure (at least 1 die fell off), and the second determines a safe set of conditions for which a reliable die attach is obtained.

Figure 4: Die pick and place experimental conditions as function of top die temperature and contact time as used for polymer A.

Figure 5: Die pick and place experimental conditions as function of force and contact time as used for polymer B. Note that both top and bottom dies stay at room temperature.

As shown in Fig.4 for polymer A, a reliable die attach occurs for top die temperatures above 80°C while the landing die including the polymer layer stays at room temperature. It is an important parameter to keep the bottom die at low temperature to prevent polymer curing during the pick and place operation that would lead to failure. The best conditions have been established for a top die temperature of 100°C, a bottom die at room temperature, a touch down (or contact) time of 5 sec and 10kg force. Lowering the force or further decreasing the touch down time lead to systematic failure (all dies fell off). Concerning polymer B (Fig.5), both top and bottom dies stayed at room temperature. The variables here are touch down time and contact force. As previously mentioned, the definition of a successful die attach region allows to determine reliable and repeatable bond conditions. As compared to polymer A, a much lower force has to be applied for much shorter times. The best conditions have been established for a room temperature process, 1kg force and 3sec contact time. With this respect, polymer B is a better candidate than polymer A. A significant reduction in bonding force and contact time makes polymer B an attractive material for die pick and place.

The next step in 3D stacking is the collective hybrid bonding operation. After populating a landing wafer (including the patterned polymer layer, A or B) with TSV dies and using the best known method as described previously, the landing wafer is transferred in a wafer bonder type EVG520. The final bonding process is performed in 2 steps: in the first step at relatively low temperature, the polymer refloows and
deforms upon application of a force, putting into contact the Cu TSVs of the top die and the Cu landing pads. In the second step, the temperature is further increased to realize the Cu-Cu direct bonding, and at in the same time the electrical connections between top and bottom Cu layers. A picture of a landing wafer after collective hybrid bonding is shown in Fig.6.

Figure 6. Picture of a landing wafer after pick and place of 10 TSV dies and collective hybrid bonding.

Electrical measurements of daisy chains showed a comparable and reproducible yield of 80% working chains up to 1000 TSVs, both for polymer A and polymer B, as shown in Fig.7.

Figure 7. Electrical yield obtained on 10000TSV daisy chains after collective hybrid bonding with respectively polymer A and polymer B.

Conclusion

The 3D stacking approach proposed here relies on the introduction of a tacky polymer as an intermediate glue layer in the direct bonding scheme. It offers the possibility for die-to-wafer throughput optimization. The opportunity lies in the separation of die pick-and-place and bonding operations. Two polymers have been selected according to their reflowing and bonding properties, and a die pick and place procedure has been defined and optimized for each of them. The best known method allows a die pick and place at room temperature, with an indicative throughput of a few seconds per die placement (excluding alignment). After collective hybrid bonding of TSV dies to a landing wafer, electrical measurements of daisy chains showed a comparable and reproducible yield of 80% working chains up to 1000 TSVs.

References
