Bonding and TSV in 3D IC Integration: Physical Analysis with a Plasma FIB

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INTRODUCTION

3D integration schemes, which stack integrated circuits and other microelectronic or MEMS devices and interconnect them using through silicon vias (TSV), are likely to be the next revolution in electronic fabrication. They can be used to continue the increases in speed and density of microelectronic systems described by Moore’s Law (More Moore), but they may offer even greater benefits when used to connect devices of different technologies (More than Moore), packing more performance and functionality into smaller volumes.

In either case, the ability to physically characterize the TSVs and mechanical bonds used to connect devices of different technologies is essential for developing robust manufacturing processes and fabricating reliable products. Focused ion beam (FIB) systems have long provided physical analysis in the manufacture of integrated circuits, but conventional FIB cannot remove material fast enough to analyze these relatively large structures used in 3D integration. The launch of a new plasma-based FIB system now provides the speed and precision needed to develop and deploy these exciting new technologies.

3D INTEGRATION

While the performance and productivity of microelectronics have increased continuously over more than four decades due to the enormous advances in lithography and device technology, it has now become questionable if advances in these areas alone will be able to...

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overcome the predicted performance and cost problems of future IC fabrication. The ITRS roadmap predicts 3D integration as a key technology to overcome this so-called ‘wiring crisis’ and the solution will most likely be based on TSV technology.

The most promising 3D integration schemes currently under consideration involve the vertical stacking of integrated circuits and other devices. These schemes vary in their details but all must solve two central problems: how to bond the integrated layers together and how to create electrical connections among them. Bonding and TSV technologies each have their own unique set of considerations which often center around how the structure will hold up during subsequent processing, such as the addition of another layer:

- Will the stresses induced by additional thermal processing cause debonding or shifting of the existing bonds?
- Will the stress and strain cause cracks or delamination in the TSVs?
- What are the best materials and processes to use to minimize these negative effects?

**PLASMA FOCUSED ION BEAM**

FIB systems, which use an ion beam to cut and image cross sections through subsurface structures with nanoscale precision and imaging resolution, have long been a mainstay of physical analysis for integrated circuits. Although the structures used in 3D integration can be expected to decrease in size as the technologies evolve, they are much larger than the dimensions of the transistors and interconnects used in current integrated circuits, and the cutting speed of FIBs designed for ICs is generally inadequate for TSVs and bonding structures. A typical 10 µm × 10 µm IC cross-section requires the removal of 1000 µm³ of material and takes a few minutes. A 100 µm × 100 µm TSV cross-section requires the removal of 1,000,000 µm³ of material and would take most of a day with conventional FIB.

The Vion PFIB system (FEI Company, Hillsboro, Oregon, USA) uses an inductively coupled plasma source [1-3] (Figure 1) to provide material removal rates 20× faster than conventional FIBs that use liquid metal ion sources (LMIS). A LMIS is essentially a point source 50 nm in diameter with a low angular intensity. The Vion system’s plasma source is larger, 15 µm, but has a much higher angular intensity. Because of its small virtual size, the LMIS is easy to focus into a small spot at low beam currents, but at beam currents above 10 nA spherical aberration effects severely degrade performance. The plasma source can deliver currents in excess of a µA (>20× greater than a typical LMIS based system) while still maintaining a well focused beam. Since material removal rates are primarily a function of beam current, the PFIB has an advantage of 20× or more over conventional FIB at high currents, while still preserving excellent milling precision and imaging resolution at low beam currents.

The xenon ion beam emitted by the plasma source has high sputtering yield, high brightness and low energy spread. In addition, by introducing various gases, the PFIB can selectively etch specific materials or deposit patterned conductors and insulators (similar to conventional FIB systems). The plasma source also offers the potential to use different ion species to enhance performance in specific applications.

**CURTAINING**

The difference in FIB milling rates of the various materials present in a device (Cu, Si, Sn, dielectrics, polyimides and mold compounds) can cause ‘curtaining’ when milling cross-sections. This milling artifact can make detailed...
analysis of the structures difficult or even impossible.

Figure 2 shows typical curtaining effects on the silicon substrate as well as the TSV itself, caused by milling through the overlying rough poly crystalline metal film. These curtaining effects can be effectively suppressed by rocking the sample during the FIB milling process. Milling in a sequence of alternating incidence angles creates a clean cross section free of curtaining artifacts without the need for time-consuming low current polish steps.

**EXAMPLES OF APPLICATIONS OF PLASMA FOCUSED ION BEAM**

**Through Silicon Vias**

TSVs are themselves subject to a number of effects that can result in defects and failures. For example, the large differences in thermal expansion between copper via fill and the surrounding silicon substrate can cause cracking within the copper and delamination from the via sidewall during thermal processing. ’Key-holing’ results from incomplete filling of vias (Figure 3).

**Solid Liquid Interdiffusion Bonding**

One of the most difficult issues to address is the behavior of bonds between chips during subsequent processes (Figure 4). For example, it is critical that a bond between the first chips in the stack not be disturbed by the subsequent bonding of an additional chip. Solid-liquid-interdiffusion (SLID) [4] is a unique direct metal bonding technology that avoids remelting of existing bonds during the formation of new bonds by using high melting intermetallic phases. During bond formation, solid metal diffuses into the liquid phase of a lower melting metal resulting in high melting point final phase that remains solid during subsequent bond forming processes.

**Anisotropic Conductive Adhesives**

Anisotropic conductive adhesives (ACA) can be used [5] to bond wafers together physically and electrically using an organic bonding compound (benzocyclobutene, BCB) filled with 4-µm sized metal covered polymer spheres (MPS). The BCB assures mechanical strength whereas the MPS provide the required electrical conductivity at interconnection points. The concentration of MPS must be high enough to ensure good electrical contact between opposed pads and at the same time low enough to guarantee electrical insulation where pads are not present.

To study the bonding in detail, samples were cleaved, then milled with the plasma-FIB to reveal the bonding region and finally inspected with plasma-FIB imaging. The plasma-FIB milling speed makes it possible to prepare the sample (~200 × 50 × 600 µm³ material removed) within 30 minutes. The metal layer covering the polymer spheres could be observed at the bonding interface with sufficient resolution to estimate both the local MPS density and their compression state between the bond pad metal layers. In Figure 5 the bonding process is illustrated in the top

**Figure 3:**

(a, b) Differing thermal expansion between copper via fill and silicon substrate caused delamination shown in this via before (a) and after (b) annealing.

(c) Key-holing occurred when this via was not filled completely with tungsten.

**Figure 4:**

The void between these pads is the result of an incomplete SLID bonding process. The various intermetallic phases are clearly visible above, below and to the right of the void.
images and the bottom plasma-FIB images show details of the bonding interface and compressed spheres.

3D Test Chip
The 3D integrated reliability test chip shown in Figure 6 is a 3-level-stack with a modular layout designed to permit evaluation of assembly processes between two initial layers and, subsequently, the effects of adding a third layer [6]. The PFIB can mill a cross section through the entire three layer stack showing critical details of both upper and lower bonding regions and the complete TSV through the middle layer.

CONCLUSIONS
By combining high-speed milling and deposition with precise control and high quality imaging, the plasma focused ion beam provides critically needed physical analysis for TSV and bonding processes that are essential to current 3D integration schemes. At high beam currents, cross-sections with dimensions of hundreds of micrometers can be completed in less than an hour, fast enough to provide effective feedback on process performance. At low beam currents, the same system delivers high resolution imaging for accurate structural analysis.

The PFIB provides an effective, practical tool for a variety of 3D integration applications, including failure analysis of bumps, wire bonds, TSVs, and stacked die; site specific removal of package and other materials to enable failure analysis and fault isolation on buried die; circuit and package modifications to test design changes without repeating the fabrication process or creating new masks; process monitoring and development at the package level; and defect analysis of packaged parts and MEMS devices.

REFERENCES

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Figure 6:
The high milling speed of PFIB permits cross-sections through the full three layer stack of the test chip, revealing both upper and lower bonding regions and the entire TSV.