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HIGH-SPEED METAL-FILLING OF THROUGH-SILICON VIAS (TSVs) BY PARALLELIZED MAGNETIC ASSEMBLY OF MICRO-WIRES

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ABSTRACT

This work reports a parallelized magnetic assembly method for scalable and cost-effective through-silicon via (TSV) fabrication. Our fabrication approach achieves high throughput by utilizing multiple magnets below the substrate to assemble TSV structures on many dies in parallel. Experimental results show simultaneous filling of four arrays of TSVs on a single substrate, with 100 via-holes each, in less than 20 seconds. We demonstrate that increasing the degree of parallelization by employing more assembly magnets below the substrate has no negative effect on the TSV filling speed or yield, thus enabling scaled-up TSV fabrication on full wafer-level. This method shows potential for industrial application with an estimated throughput of more than 70 wafers per hour in one single fabrication module. Such a TSV fabrication process could offer shorter processing times as well as higher obtainable aspect ratios compared to conventional TSV filling methods.

INTRODUCTION

TSVs have become one of the key enabling technologies for 3D-integration of integrated circuits and micro electromechanical systems (MEMS). Especially 3D-integrated System in Package (3D-SiP) solutions that are based on vertical stacking of different chips are one of the driving forces behind the More-than-Moore paradigm. As compared to side-by-side integration, such as System-on-Chip and 2D-System-in-Package solutions, 3D-SiP offers more compact designs with lower volume and weight, and therefore decreased costs. 3D-SiP solutions also benefit from shorter signal paths, which improves the system performance and lowers the power consumption [1, 2, 3]. System integration by chip stacking relies on TSVs to vertically interconnect different chips in the stack. Therefore, there is a demand for fast and cost-effective fabrication methods for realizing high performance TSVs.

Currently, the most common TSV fabrication methods utilize metal filling processes such as electrodeposition of copper [4, 5, 6] as well as chemical vapor deposition (CVD) of tungsten [2] or polysilicon [2, 7]. Electrodeposition and CVD processes are well established in the semiconductor industry and are widely available. However, these kinds of processes typically suffer from long processing times and are limited in the achievable aspect ratios of the TSVs [8, 9]. Especially electrodeposition of copper has proven to be challenging for implementing void-free filling of high-aspect ratio TSVs [5, 10, 11]. This limitation on the aspect ratio and consequently on the depth of conventional TSVs usually necessitates thinning of the substrate, which causes a considerable increase in fabrication cost and requires very challenging thin substrate-handling.

Fischer et al. [12, 13] have proposed an alternative method of TSV fabrication by magnetic assembly of pre-fabricated nickel wires. By utilizing pre-fabricated solid nickel wires, this method offers inherently void-free TSV conductors. Furthermore, the magnetic assembly method enables fabrication of TSVs with very high-aspect ratios of more than 24 and lengths of over 450 μm . However, the magnetic assembly approach demonstrated in [12, 13] is based on a sequential process resulting in limited overall throughput. Only a small number of TSVs could be assembled simultaneously and the assembled area of TSV structures typically was in the order of less than 1 cm^2 . A larger number of TSV structures or wafer-level assembly

would have to be performed in a sequential die-by-die fashion, thus resulting in long processing times and low throughput.

The work presented here introduces the concept of parallelization for magnetic assembly of TSVs, thus proposing a TSV fabrication approach suitable for high-speed, full wafer-scale TSV manufacturing with the potential to be scaled-up to industrial high-volume fabrication.

Figure 1: Magnetic assembly method. a) Ferromagnetic micro-wires align themselves to the magnetic field lines of a magnet placed below the substrate. b) Moving a magnet along the backside of the substrate drags the micro-wires into the via-holes. As a final step, the gap between the micro-wires and the via-hole side walls is filled with a polymer insulation liner.

ASSEMBLY METHOD

The proposed method of high-speed metal TSV filling is based on magnetic assembly of ferromagnetic nickel wires previously reported in [12]. The concept of magnetic assembly utilizes the ferromagnetic property of nickel in order to align and manipulate a large number of nickel wires simultaneously. Since magnetism acts as a non-contact force over large distances, the nickel wires can be manipulated by a magnet on the backside of the substrate. Figure 1a) shows how ferromagnetic nickel wires align themselves along the magnetic field lines when exposed to a magnetic field from a permanent magnet placed below the substrate. By moving the magnet along the backside of the substrate, the nickel wires can be steered along the front side and dragged into the via-holes, as is schematically depicted in Figure 1b). This method of magnetic assembly of nickel wires has been successfully demonstrated 100% assembly yield. Since the TSV conductors consist of pre-fabricated solid metal wires, there is no increased process complexity with increasing aspect ratio or via length.

TSV Fabrication

The TSV fabrication process can roughly be divided into three separate parts; the via-hole formation, followed by the nickel wire fabrication and assembly, and finally the filling of the insulator layer. Here, the via-holes were created by deep reactive ion etching (DRIE) of the silicon substrate. DRIE is a very well established etching technology and is well suited to etch thick substrates with very high aspect

Figure 2: a) The assembly setup, including the robotic arm, wafer holder, and a wafer with via-holes. b) Illustration of the 3D-printed magnet carrier with four assembly magnets that are held in place by counter magnets on the backside.

ratios. In order to avoid any potential electrical short-cuts to the substrate, the via-hole side walls are oxidized, as can be seen in Figure 1b).

For the fabrication of the nickel wires, a wire cutting process has been developed. A very long piece of nickel wire was fixed on top of a plain substrate and embedded with a thick layer of polymer. A Disco DAD 320 wafer dicing saw was used to cut the long nickel wire into well-defined short rods. The polymer can subsequently be dissolved and the retrieved nickel micro-wires can be assembled into the via-holes, as shown in Figure 1. A significant improvement of the assembly speed was achieved by removing the burrs at both ends of the nickel wires in a quick wet etching step.

The final step of the TSV fabrication consists of filling the gap between the nickel wire and the via-hole side wall with an insulation layer. The polymer Benzocyclobutene (BCB) was used as insulating material. To ensure a void-free insulation layer, the BCB was cured in vacuum. In addition to electrical insulation, the polymer layer also provides mechanical stability to the TSV and holds the nickel wire in place.

Parallelized Magnetic Assembly

In this paper we introduce the concept of parallelization to the magnetic TSV assembly approach. Instead of just assembling TSV structures on one single die at a time, this approach is capable of simultaneously assembling many dies over the entire wafer. Parallelization is achieved by employing multiple magnets below the substrate in parallel. As shown in Figure 2, all the magnets are fixed to the same robotic setup and thus they all describe exactly the same movement pattern for the TSV assembly. The placement of the magnets can be designed to exactly match the position of the TSV structures on the wafer. Thus, each magnet is perfectly placed to assemble the TSV structures on one or multiple dies. This approach exhibits no limitation on the substrate size or the positioning of the TSV structures on the wafer. As shown in [13], the magnetic assembly is also insensitive to different TSV structure designs, making it possible to assemble many different TSV structures with different numbers of vias and even varying via densities side-by-side.

Furthermore, the parallelization approach can very easily be scaled-up to full wafer-level fabrication. By utilizing hundreds or thousands of magnets in a one-magnet-per-die configuration, this assembly method is capable of assembling an entire wafer in one single assembly step. This results in a high-speed wafer-level assembly process for TSVs with a very high throughput.

EXPERIMENTAL RESULTS

Multiple magnetic assembly experiments were performed in order to verify the assembly speed and filling yield of the proposed TSV fabrication approach. Furthermore, great emphasis was placed on studying the influence of parallelization of magnets on the performance of the magnetic assembly process.

The robotic setup shown in Figure 2 was modified to accommodate different numbers and configurations of magnets. A custom 3D-printed magnet holder was designed, fabricated, and mounted on the end of the robotic arm. Figure 2b) shows the recesses in the magnet holder for precise placement of the assembly magnets. On the backside of the holder, counter magnets were utilized in order to hold the assembly magnets in place during the assembly process.

The magnetic assembly experiments were performed on silicon substrates with a thickness of 350 μm . TSV test structures were fabricated prior to the assembly experiments. As depicted in Figure 3, the TSV test structures consisted of multiple arrays of 100 via-holes each. The via-hole diameter was 55 μm and they had a depth of 350 μm , reaching all the way through the substrate. The bottom end of the via-holes was closed by a 2 μm -thick layer of silicon oxide, in order to prevent the wires from falling through the via-holes. The arrays were placed in a grid formation with a pitch of 35 mm in the x-direction and 26 mm in the y-direction.

Figure 3: The experimental TSV structures consisted of four arrays with 100 via-holes each. Four magnets were simultaneously moved across the arrays below the substrate as indicated by the arrows.

Assembly processes with two different configurations of magnets were studied with 2 and 4 magnets fixed to the magnet holder, respectively. The robotic movement patterns were reprogrammed to match the exact placement of the TSV arrays on the substrate. Figure 3 indicates the position of all 4 magnets relative to the TSV arrays, as well as the movement pattern across the arrays. For the assembly experiments approximately 3000 ferromagnetic micro-wires were dispensed on top of the substrate above each assembly magnet. By executing the robotic movement pattern, according to Figure 3, the micro-wires were simultaneously assembled into the via-holes of all the TSV arrays. Figure

4 shows a microscope image of a completely filled TSV array. The high reflectivity of metal wires results in a high contrast between filled and empty (not present in Figure 4) via-holes, allowing for a very easy inspection of the filling yield of the TSV arrays.

Figure 4: Microscope image of a TSV array with ferromagnetic metal wires assembled into each via-hole. 55 μm -wide via-holes and 45 μm -diameter metal wires were used in the experiments. The high contrast between the metal wires and the silicon substrate allows for easy inspection of the filling yield.

The results of the magnetic assembly experiments performed with 2 and 4 parallel magnets, respectively, are shown in Figure 5. In all cases, the arrays were completely filled, proving a consistent filling yield of 100%. In the 2-magnet configuration, 100% filling was reached after 10 s for array 1 and after 20 s for array 2. It is important to note, that the filling yield of array 1 does not decrease after reaching 100%, even under continuous assembly movement by the magnet along with the excess wires on top of the substrate. This indicates that no wires are being disassembled by prolonged assembly motion and thereby demonstrates the robustness of the assembly process.

The configuration with 4 parallel magnets showed very similar results. Again, all TSV test arrays were filled with 100% yield. The assembly speed was also very similar, with the arrays reaching 100% filling yield within 12 to 16 s, which lies within the same range as the 2-magnet configuration. The similarity between the 2-magnet and the 4-magnet configuration demonstrates the repeatability and consistency of the assembly speed and filling yield. More importantly, however, it indicates that increasing the degree of parallelization of the magnetic assembly, by utilizing a larger number of magnets on the backside of the substrate, does not affect the assembly speed or yield. This enables further increase in degree of parallelization up to full wafer-scale fabrication without any loss of speed or reliability.

DISCUSSION

For a TSV fabrication method targeted at industrial applications, it is not sufficient to have a fast fabrication process, but it also has to be capable of processing very high numbers of wafers. This is in order to successfully meet the high-volume demand of the semiconductor industry. At the same time, short process times are also important to keep the fabrication costs low. In certain cases, long process times and therefore low throughput can be compensated by utilizing batch processing, in which multiple wafers can

Figure 5: Parallelized TSV filling experiment with a) 2 magnets and b) 4 magnets. In all cases, 100% yield was achieved in less than 20 s. This demonstrates that increasing the degree of parallelization does not affect the yield or the speed of the assembly process.

be loaded into the same fabrication module and processed simultaneously.

Conventional TSV filling methods, such as electrodeposition and CVD, typically suffer from long processing times and thus limited throughput. By using electrodeposition of copper, very shallow TSVs with a depth of just 70 μm can typically be filled in about 35 min [8], while deeper TSVs of 390 μm depth may take as much as 12 h to fill [9]. Substrates with shallow TSVs have to be thinned after the filling, which drastically increases fabrication costs and further reduces the throughput. For the deeper TSVs, even a batch process with 100 wafers will only result in a throughput of less than 10 wafers per hour.

In comparison, the proposed magnetic assembly method is capable of filling an entire wafer within 20 s, while still offering the capability to fabricate high aspect ratio TSVs. Our experiments suggest that the filling speed of the magnetic assembly technology is independent of the aspect ratio and therefore offers a consistent high-speed metal filling method for almost any via depth and aspect ratio, unlike the heavily restricted conventional filling methods. In order to calculate the expected throughput of the presented TSV filling approach, the complete processing time including the overhead was estimated, revealing a total cycle time of 50 s which results in a potential throughput of 72 wafers per hour. A detailed list of all process steps is presented in Table 1.

Table 1: Estimated processing times of a magnetic micro-wire assembly module, showing a throughput of 72 wafers per hour (wph), as compared to typical throughputs of less than 10 wph of conventional manufacturing equipment, e.g. based on electrodeposition.

Sequence	Target [s]
Prepare – open chamber	5
Load wafer (get-put)	5
Micro-wire dispensing	10
Magnetic assembly	20
Excess wire collection	5
Unload wafer (get-put)	5
Total cycle time	50
<hr/>	
Summary	
Process time	20
Overhead	30
Time in chamber	50
<hr/>	
Throughput per module	72 wph

CONCLUSION

We proposed a parallelized magnetic assembly method as a fast and cost-effective TSV metal filling process. The robotic setup of the magnetic assembly has been modified to accommodate a custom-made magnet holder for the parallelized assembly. Experiments conducted with different configurations of magnets showed very short process times of less than 20 s and reliable filling yield of 100%. The experiments also demonstrate that increasing the degree of parallelization, by adding additional magnets in parallel, does not negatively affect the assembly speed or yield. Therefore, the parallel magnetic assembly approach shows potential suitability for full wafer-scale processing. By utilizing a one-magnet-per-die approach, an entire wafer could be assembled in one single assembly step, taking less than 20 s.

Furthermore, the throughput of the parallelized magnetic assembly process was examined. By estimating the processing overhead, consisting of wafer handling and micro-wire dispensing, a total cycle time of 50 s per wafer was calculated, thus resulting in a projected throughput per module of 72 wafers per hour.

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