MASKLESS MANUFACTURING OF THROUGH GLASS VIAS (TGVS) AND THEIR TEST STRUCTURES

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ABSTRACT

Through glass vias (TGVs) are a key component in glass-based interposers and microelectromechanical-system lid wafers. Magnetic-field-assisted self-assembly has been demonstrated earlier in fabrication of through silicon vias. Here we present an entirely maskless TGV fabrication process utilizing magnetic assembly. Femtosecond laser is used for ablative direct patterning of surface metal layers and for exposing the TGV conductors after wafer thinning. The proposed TGV structure is shown to be electrically functional by measuring the TGV resistance values.

INTRODUCTION

Electronic systems are unceasingly miniaturized to improve performance and allow new applications in areas such as mobile and wearable electronics or the Internet of Things. Integrated digital circuits have in the past followed Moore's law but complete electronic systems, including sensors and actuators often realized using microelectromechanical-system (MEMS) technology [1], have not always kept pace [2]. Miniaturization of complete heterogeneous systems can be achieved by 2.5D packaging where chips are placed on a common interposer that has a high interconnect density [3]. Chips can even be placed on top of each other, as is done in 3D packaging. Both of these solutions require through substrate vias, that is, electrical connections through the substrate material. Silicon is dimensionally stable material allowing dense wiring and it has been proposed for interposer use in 2.5D packaging. Interconnections through silicon are called through silicon vias (TSVs) [3]. Glass has received attention as a possible alternative to silicon owning to its lower costs, partly originating from the possibility to process on large glass-panels instead of wafers [4]. The somewhat tunable coefficient of thermal expansion (CTE) of glass allows CTE tailoring in consideration of other materials in the package [5]. Glass has several electrical property advantages over silicon; these include lower dielectric losses in microwave and radio frequency regimes [6] while high resistivity of glass removes the need for additional insulation layers. The low thermal conductivity of glass can hamper the removal of the dissipated heat but it also provides thermal isolation between chips if needed [7].

Glass is also commonly used as a MEMS lid material in wafer level packaging (WLP) where MEMS devices are sealed already at the wafer level before die separation. WLP reduces package size and cost while increasing yield and reliability [8]. Sealed devices can use through glass vias (TGVs) for electrical contacts through the glass lids [8]. Glass interposers have also been proposed to include optical communications alongside the electrical ones [10] and femtosecond lasers allow fabrication of 3D microstructures such as waveguides and microfluidic channels inside glass [9]. This opens a possibility of very high speed communications and a wide range of functionalities to be tightly integrated in a single package.

Deep reactive ion etching (DRIE) Bosch process is the standard method used in TSV hole formation. For glass, such a standard via formation process does not yet exist but several methods have been proposed, for example wet etching in the case of photo-structurable glass ceramics [11], laser drilling, electric discharge machining [12], and reactive ion etching which however suffers from low mask-selectivity [13] and speed [11]. The glass hole formation methods seem to lack the capability to produce strictly vertical hole sidewalls and some can cause damage to the surrounding glass material.

The via holes in glass have to be filled with conductive material in order to form the electrical connections. Electroplating of copper is often used for this purpose. Electroplating needs a conductive seed layer that can be either sputtered or electrolessly plated onto the via-hole sidewalls. Plating can also be done as a bottom-up process starting from the bottom of an open via [14]. Electroplating starting from sidewalls is a challenging process which risks creating voids in the plated metal. This can be alleviated by electroplating a thick liner on the via sidewalls instead of filling the via completely. Plating only the liner also reduces plating time and problems arising from CTE mismatch between TGV metal and the glass substrate. However, open via-holes create complications in photoresist spin-coating in the following lithography steps. Other metal filling methods such as metal paste filling [15] and fully-additive digital inkjet printing [16] have been proposed.

There exist several commercial TGV products based on glass reflowing around preformed conductive TGV cores. The conductive parts used are doped silicon, tungsten, or iron-nickel alloys; the selection being presumably limited by the incompatibility of the high-temperature reflow process with materials having a large CTE. Tungsten TGVs are reported to have a minimum core diameter of 100 µm and a placements accuracy of ±50 µm which limits TGV density [11]. Glass reflowing around DRIE-patterned silicon mold allows very precise definition of the vias but doped silicon has three orders of magnitude [11] higher resistivity in comparison to tungsten. The silicon mold material in TGVs can be etched away after glass reflowing and be replaced with electroplated copper [17]. The molding process requires several chemical-mechanical polishing (CMP) steps and the properties of the reflown glass such as optical transmittance and high frequency RF-characteristics suffer [18].

Here we propose the use of magnetic-field-assisted self-assembly for fabricating TGVs. In magnetic assembly, a magnetic field pulls metal rods, which contain ferromagnetic material, into prefabricated holes in a substrate. Magnetic assembly has been demonstrated earlier for creating TSVs made of different metals, namely nickel [19], gold-coated nickel for RF-applications [20], and Invar iron-nickel alloy for wide temperature-range applications [21]. The assembly method has been projected to be capable for high assembly throughput [22]. Magnetic assembly is an intrinsically void-free and semi-additive method. It is complemented in the present work by digital direct-patterning using femtosecond laser (Spirit 1040-4-SHG, Spectra-Physics) ablation. Together, these methods enable an entirely maskless process. Ultra-short pulse length of femtosecond lasers permit material removal with very limited thermal damage to the surrounding material [9].

FABRICATION

TGVs were fabricated in a 300 µm thick alkaline-free glass wafer (Eagle XG, Plan Optik AG) with preprocessed blind (non-through) via holes. The holes were 120 µm deep and 70 µm wide at the openings. The TGV fabrication presented in Figure 1 started with magnetic-field-assisted self-assembly of nickel rods which act as conductors in the finalized TGVs. The nickel rods were cut with a dicing saw from commercially available 44 µm diameter nickel wire (California Fine Wire Co.) using the process described by Fischer et al. [23] as an outline. Burr defects created at the ends of the nickel rods by the dicing were removed in a wet etching step. The nickel rods were spread on the wafer surface and pulled into the holes by the magnetic field of a permanent magnet placed underneath the wafer (Figure **1**: Process flowFigure 1a).

The nickel rods were fixated in the holes by filling the gap between the hole sidewall and the rod with spin-on glass (400F, Filmtronics). The spin-on glass (SOG) was soft cured at 250 ºC and the wafer surface was mechanically lapped thus removing protruding rod ends and the SOG remaining on the wafer surface. Figure 2 shows a SEM image of a TGV cross-section after SOG soft-cure and surface planarization. The SOG was further hard-cured at 425 ºC for 1 hour in a N_2 atmosphere. The SOG filling and curing sequence was repeated to ensure complete SOG fill of all vias and to compensate for SOG shrinkage during the hard cure (Figure 1b).

A TiW/Au metal layer (150 nm/1 µm) was sputter-deposited after an argon sputter-cleaning done in the same tool. A 5 µm thick gold layer was electroplated (RENA EPM 202F) on top of the sputtered TiW/Au layer, by using a cyanide-free gold plating solution (MICROFAB HUE AU R, Enthone) and a current density of 1.5 mA/cm^2. The resulting metal layer was patterned by ablative direct-writing using femtosecond laser (Figure 1c).

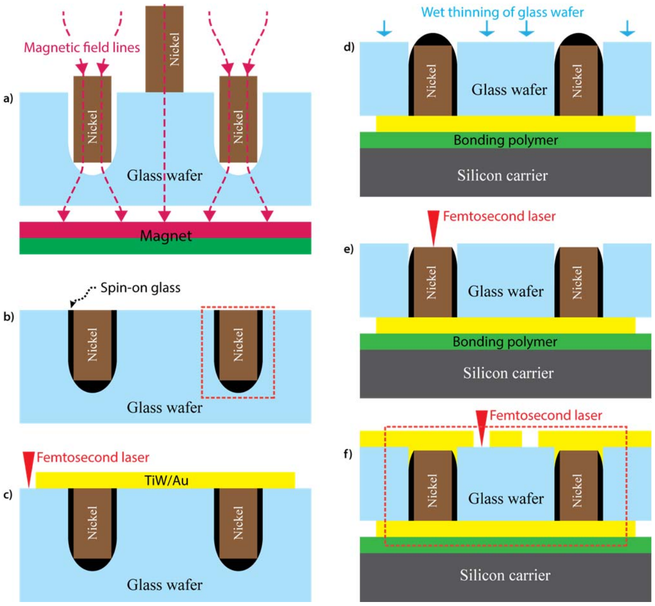

Figure 1: Process flow: a) magnetic assembly of Ni-rods into prefabricated via holes, b) fixing Ni-rods in place with SOG and planarizing the surface (boxed area shown in Figure 2), c) deposition and electroplating of TiW/Au layer followed by laser direct-patterning, d) wafer thinning with HF wet etch, e) uncovering of Ni surfaces by mechanical planarization and laser direct patterning, and f) TiW/Au layer formation followed by laser direct-patterning (boxed area shown in Figure 6).

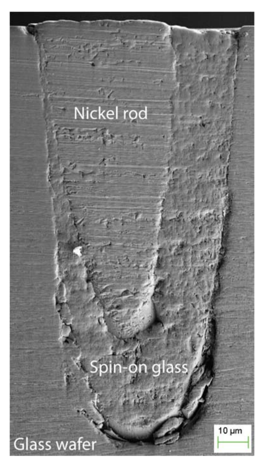

Figure 2: Cross-section SEM image showing a Ni-rod secured in the hole by soft-cured SOG layer as indicated in Figure 1b.

A top-view of the patterned metal layer together with the ends of the nickel rods can be seen in Figure 3. In order to uncover the nickel rods from the opposite side, the glass wafer had to be thinned down to a thickness of 120 µm, for which a carrier wafer was needed. Therefore, a polymer layer with a thermal release function was used to temporarily bond the glass wafer to a silicon carrier wafer. The glass wafer thinning was done by etching in a 50 vol% hydrofluoric acid (HF) solution, achieving an etch rate of ~25 µm/min (Figure 1d).

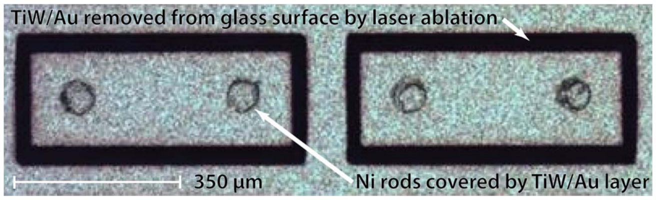

Figure 3: Optical microscope image showing a top view of the laser patterned metal surface before bonding to the Si carrier as indicated in Figure 1c.

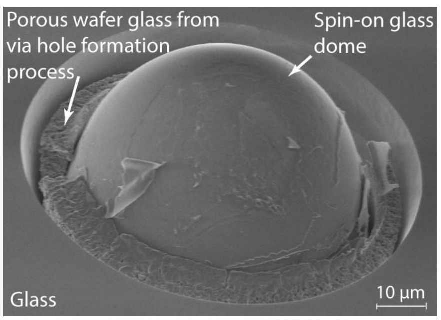

Figure 4: SEM image showing the end of a TGV after wet wafer thinning showing a protruding SOG dome and the porous glass surrounding the TGV as indicated in Figure 1d.

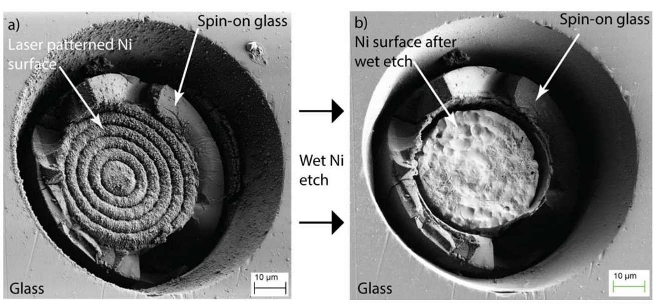

Figure 5: a) Revealed Ni surface after SOG removal by mechanical planarization and laser ablation as indicated in Figure 1e. b) Ni surface after wet Ni-etch removing possible surface contaminations.

The SOG material has a lower etch rate in the HF-solution than the glass substrate and SOG is therefore not significantly removed during the HF etching. Thus, a protruding SOG dome covering the nickel rod is formed as can be seen in Figure 4. The HF-etching revealed a thin layer of porous glass around the TGVs. Since the HF etch rate was higher in these porous glass regions, a valley between the wafer surface and the SOG layer surrounding the nickel rod is created. The porous glass layer is believed to originate from the hole formation process. The protruding SOG dome was removed by first using mechanical planarization. The planarization was complemented by a laser assisted removal of the remaining SOG from the top ends of the nickel rods. The revealed nickel rod in Figure 5a shows a ring pattern on its surface created by the circular movement of the laser focal point on top of the rod. Figure 5b shows a nickel surface cleaned by wet etching (5 min at 49 ºC in 16:1:1:2 H_3PO_4:$C_2H_4O_2$: HNO_3:H_2O), designed to remove any residues from the nickel surface (Figure 1e).

A 150 nm thick TiW adhesion layer and a gold layer with a nominal thickness of 3 µm were sputter-deposited after an argon sputter-cleaning done in the same tool. The deposited metal layer was again patterned with the femtosecond laser (Figure 1f).

RESULTS AND DISCUSSION

Figure **6** presents a SEM image of a cross section of a TGV pair in glass. The materials used are clearly visible and realization of the TGV fabrication process is confirmed. Digital direct-patterning by laser ablation successfully created approximately 3 µm wide isolation lines on the wafer surface as indicated in Figure 6. The SOG-layer securing the nickel rods inside the TGV holes is void-free and shows no delamination even after high temperature cure at 425 ºC. The porous glass surrounding the bottoms of the TGV holes had a faster HF-etching rate than the other materials which led to trenches surrounding the TGVs. Wet wafer thinning can in principle be replaced by CMP or the wet thinning could be followed by a CMP process to further planarize the surface.

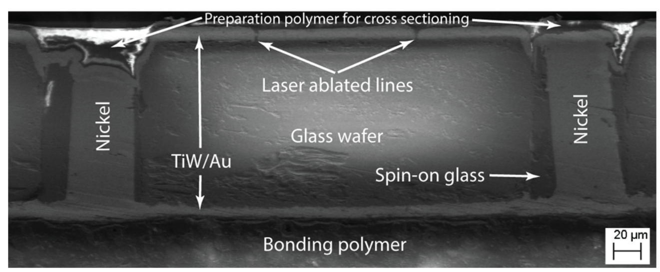

Figure 6: SEM image of a cross section of a TGV pair as indicated in Figure 1f.

Pairs of TGVs connected in series as shown in Figure **6** were used to demonstrate the electrical functionality of the fabricated TGVs. Four-terminal resistance measurements of 47 TGV pairs showed a median value of 161 mΩ for two TGVs connected in series. This resistance value includes the resistance from the surface metal layers and the contact resistances between the TGVs and the surface metal layers on both sides of the glass wafer. The contact resistance between the nickel rods and the TiW/Au layer is likely the source for the increased resistance in comparison to the resistance of about 11 mΩ that is expected to originate purely from the nickel rods themselves. Resistances of over 100 mΩ and also with a significant contribution from contact resistances have been reported for electroplated copper TGVs [18]. However, lower contributions from contact resistances have been reported [23] for magnetically assembled nickel TSVs with a TiW/Au surface metal layer, indicating a possibility for further resistance decrease.

CONCLUSIONS

A novel method for fabricating TGVs is presented and demonstrated to produce functional TGV structures. Fabrication is done entirely with maskless fabrication methods allowing rapid prototyping and product development.

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