Inkjet Filling of TSVs with Silver Nanoparticle Ink

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Abstract

Through silicon vias (TSVs) have been used in 3D packaging of microelectronic devices and MEMS devices, where they provide electrical interconnections through the stacked wafers and devices. Currently, chemical vapor deposition (CVD) or electroless deposition are used to partially or fulfill the vias. However, these methods are time consuming. Thus, the potential of inkjet printing to linearly fill the TSVs with silver nanoparticle ink, as an additive digital fabrication technique, will be reviewed. This technique could make the via metallization process much faster, agile, and cost-efficient.

In this study, vias with the outer diameter of 80µm and depth of around 115µm fabricated with dry-reactive ion etching (DRIE) are filled with a silver nano-particle ink NPS-J from Harima Chemicals using Dimatix inkjet printer (DMP-2800) with 10pl cartridge. Substrate temperature was found to be potentially more affective to print more droplets rather than increasing waiting time. Moreover, printing on the 60 ºC substrate with no delay was optimum considering the uniformity, thickness and quality of the coverage.

Introduction

Designing the short vertical interconnections with low resistivity has always been demanding in MEMS (Micro Electro-Mechanical Systems) manufacturing and 3D packaging. Since micro electeromechanical devices and electronic devices in general are going to be increasingly miniaturized, vias with smaller pitch and diameter (higher density) are more demanded. For this purpose, through silicon vias (TSVs) are being used which could be created by deep reactive ion etching (DRIE) and masking, or laser drilling that is more flexible and agile. Vertical vias are short and fast for data transfer (e.g. between memory or acceleration sensor and processor) and also need less power and produce less heat compared with longer wire bondings [1] [2]. However, wire bonding (10 USD for 100,000 wire bonds) could be a cheaper method compared with plating process [3].

In a conventional method, these vias are filled with masking and low pressure chemical vapor deposition (LPCVD) which is a subtractive method with waste water. After the filling, the back side of the wafer with the blind vias is polished until reaching to the end of via hole, to make the connectivity from the top side to the down side of the wafer. Fischer et al. investigated filling of TSVs by bonded conductive gold wires surrounded by polymer in [4]. The same authors also worked on filling the TSVs using the nickel wires and placing them into the TSVs by magnetic self-assembly [5]. This method could be a replacement for the metallization processes and wafer thinning [5].

Inkjet printing offers another and better alternative to plate the vias with conductive inks based on metallic nanoparticles. Metal nanoparticles are small enough to pass through the nozzles of inkjet head, have a lower sintering temperature, and also have shown promising electrical performance particularly using a proper sintering method like photonic sintering [6]. In this non-contact printing method, the material is printed exactly over the vias at relatively high speed and with minimum waste material which makes it more convenient and cost efficient compared with the subtractive method. This method, as a digital fabrication and additive method, has lately seen a considerable increase in electronic applications. Using inkjet printing offers the ability to apply a controlled amount of functional (i.e. conductive, dielectric, and semi-conductive) material with very high precision on many different substrates ranging from ceramics to low-cost plastics and even paper [7]. The direct deposition of materials in inkjet printing has the potential to make the fabrication process more favorable (e.g. in embedded packaging of electronic devices) [8]. Generally, the focus of printed electronics research has been more on organic devices rather than in the fabrication steps of semiconductor technologies. Very thin patterns produced by inkjet printing for instance could be used in organic electronics [9].

Plating the vias with conductive inks based on silver and gold nanoparticles has already been demonstrated. Andreas Rathjen et al. [10] concluded that partial filling could be more favorable compared with complete filling. They also studied the homogeneity of the fillings using the silver ink made of particles with mean diameter of 300nm. In another study by Gerard Cummins et al. [11], copper nanoparticle ink was used to fill the vias and the effect of substrate temperature and evaporation rate on the uniformity and crack formation was studied. They concluded that crack-like void forming during the printing on substrate with 30 ºC could be associated with the evaporation rate of the solvent. Gold nanoparticle ink was also used successfully to fill the vias with diameter of 50-100µm without any void [12]. The reported resistance of the TSVs was also 50mΩ which is less than 10% of the bulk resistivity.

This paper investigates the inkjet printing method to understand the influence of printing parameters on filling ratio and quality of fillings in TSVs.

Experiments

Silicon wafers with a thickness of 675µm including the vias with outer diameter of 80µm and depth of around 115µm (Figure 1) created by DRIE method, was used without any pre-treatment. For the printing silver nanoparticle ink (NPS-J) from Harima Chemicals was printed by Dimatix inkjet printer (DMP-2800) with 10pl cartridges (Figure 2). Table 1 shows the specifications of the ink reported by the manufacturer [13]. At the beginning, the ink was warmed 60min in room temperature, then sonicated 15min and finally filtered (0.45µm) before loading the cartridge to avoid nozzle clogging as far as possible.

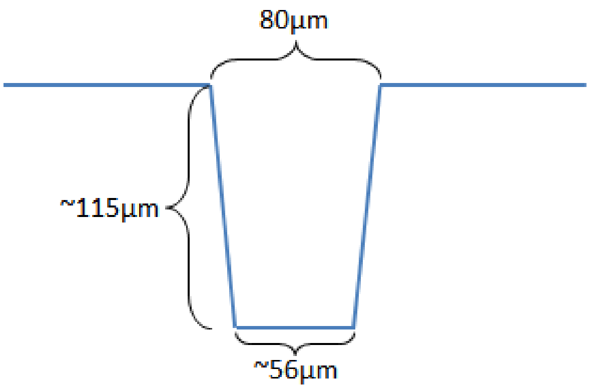

Figure 1 Dimensions of TSV cavities

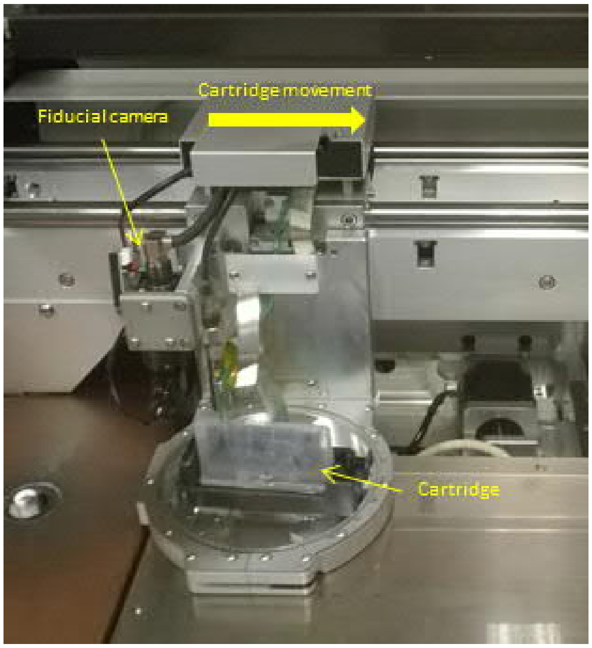

Figure 2 Printing setup of Dimatix inkjet printer

Table 1 Specifications of the NPS—J silver nanoparticle ink

Characteristics of ink before annealing	Particle size	12 nm
	Metal contents	65 %
	Solvent diluent	Tetradecane
	Viscosity	9 mPa.s
	Specific gravity	1.8~2.2
	Sintering conditions	220ºC (60min)
Characteristics after sintering	Specific resistance	3 µΩ·cm
	Thickness	4µm
	Thickness shrinkage	83%

First, estimate number of the droplets needed to fill the vias was calculated (~42 drops) without considering shrinkage of the ink by evaporation. It can be calculated by knowing drop volume (10pl for Dimatix) and TSV volume. Afterwards GIMP 2 was used to make a pattern with 13 pixels which is equal to 13 droplets (Figure 3). The smaller circle shows the estimated diameter of the droplets in the air (26.73µm). For the printing, center of the via hole and center of the pattern were both selected as the reference point and the maximum resolution (5080dpi) was used. Therefore, every pixel in the pattern was equal to 5µm. Since the diameter of the injected droplets is 26.73µm in the air, there should theoretically be at least 2 pixels or 10µm safety margin beside the pattern (Figure 3). However, in practice to avoid the collision of droplets to the wall and wasting the material, it is better to also consider the repeatability of the Dimatix printer which is ±25µm and take at least 5 pixels as safety margin around the pattern.

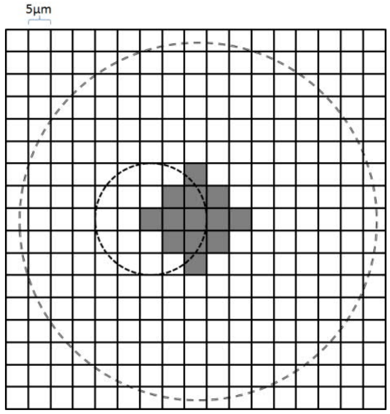

Figure 3 Designed pattern with resolution of 5080 dpi

In the next step suitable cartridge setting and waveform was chosen to have good jettability. Droplets should not be misdirected or have long tails during the printing, to avoid jetting outside of the vias and short circuits. Printing was started once the jetting was stable and desired. Table 2 represents the cartridge settings and overall waveform frequency that was used for the printing.

Table 2 Cartridge settings and overall waveform controls used for the printing

Cartridge Settings	
Cartridge temperature (in C)	Room temperature
Meniscus Vacuum (inches H_2O)	4.0
Jets to Use	1
Cartridge Print Height (mm)	0.800
Overall Waveform Controls	
Width (µs)	11.904
Maximum Jetting Frequency (kHz)	9.0

Three different substrate temperatures (40, 50 and 60 ºC) were chosen and printing the pattern was done with no delay and also after a 30 seconds delay between the layers. Since 1 minute delay between the layers is not suitable for the high volume and industrial production, 30 seconds was the only delay time used for this study. To fill more than one via in a row, the first and last vias in a row were selected for the alignment and then the pitch value was adjusted to 125µm (distance between the vias). The aim was to understand the effect of substrate temperature and delay time on the filling ratio of the vias.

In cases 5 and 6, since the temperature was high, purging 0.1s was done to make the nozzles active before printing a new layer. It is more necessary for case 6 because standing idle on top of the substrate with 60 ºC for 30 seconds could easily make the nozzles dry.

In all cases the fillings were observed by the fiducial camera of the printer just after the printing. Then all the samples were sintered in 220 ºC for 60 min; Sintering is done to remove the solvent and polymer shell from the particles enabling merging of the nanoparticles in order to make the vias conductive [14]. After sintering, the vias were also characterized by optical microscope from top view.

Zeiss Ultra 55 scanning electron microscope (SEM) and optical microscope were used to study the cross-section of the filled vias. All the samples were mounted in liquid epoxy under the vacuum, for sample preparation process. Samples were grinded with SiC paper (Grit 800, 150rpm, 10N) until reaching the filled TSVs structure. Afterwards, polishing was done with 3µm diamond suspension (150rpm, 10N 130sec) and for final polishing silica colloid (0.04 microns) was used (150rpm, 19N, 130sec).

Results

Table 3 reports the maximum amount of layers to fill the vias before overflooding. As the results show, number of droplets could be increased by increasing delay time or temperature.

Table 3 Printing parameters used for the filling

Case	Substrate temperature (ºC)	Delay (Sec)	Droplets/Layers
1	40	0	52/4
2	40	30	65/5
3	50	0	78/6
4	50	30	78/6
5	60	0	78/6
6	60	30	91/7

Except case 4 which printing 7 layers was not successful, evaporation of the solvent during the 30 seconds delay between the layers increased the number of layers by one (13 droplets). The higher temperature could also increase the evaporation rate and number of printed layers by one or two layers (case 1 & 3). Case 6 was the only exception because printing 7 layers caused too much overflooding and created connective path between the vias.

Figure 4, shows the optical micrographs of filled vias after the sintering. There was some partial overlooding in case 3 (c), case 4 (d) and case 6 (f). Overflooding in (c) was decreased in (d) with 30 seconds delay. Besides, it did not happen in (e) by increasing the temperature to 60 ºC. In case 6 (f), although the amount of overflooding is not that much to connect the vias, but it shows that 91 droplets is not the optimum number of droplets for the via filling.

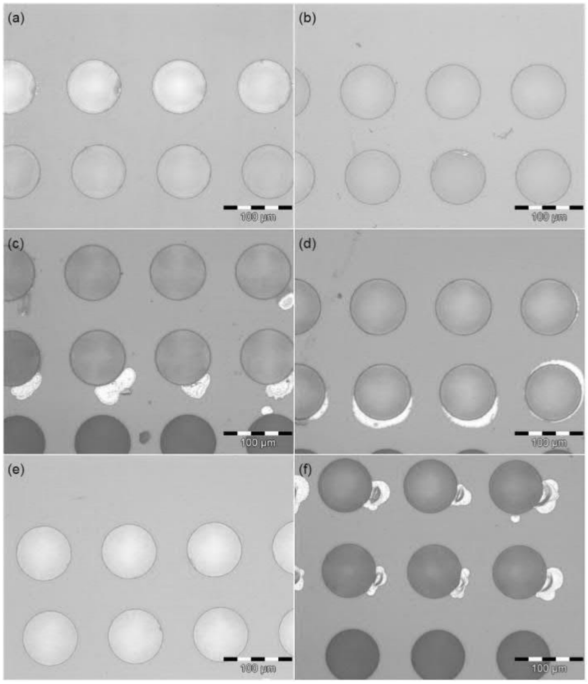

Figure 4 Optical micrographs of filled vias after sintering from top view

Figure 5 and Table 4, respectively, show the optical micrograph of the via cross sections (after the sintering) and the estimated wall thickness in the middle and top of the vias. SEM micrographs of the cross-sections (Figure 6) also show the quality of the coverage on the walls with no specific void or crack. In cases 1 and 2, because of the low substrate temperature, the ink was concentrated mostly at the bottom of the via and made the wall coverage less uniform. As presented also in Table 4, the thickness at top of the via in case 1 was less than 1µm and ~2µm in case 2. The thickness in the middle of the via was also ~3µm and ~5µm respectively. In addition, results show that the wall coverage in cases 3, 4, and 5 with same amount of droplets was not much different (~6-6.5µm and ~3-4µm) and also more uniform than other cases. This can also be confirmed by Figure 5 (c, d and e). In case 3, 4 and 5 (78 droplets), since 30 seconds delay and increasing the temperature by 10 ºC did not have much effect on wall coverage, and was not enough to add one more layer, it can be understood that 6 layers could be the optimum amount of layers. Among the cases 3 (c), 4 (d) and 5 (e) though case 5 (e) seems to be more convenient because no overflooding during the printing was observed (Figure 4 (e)).

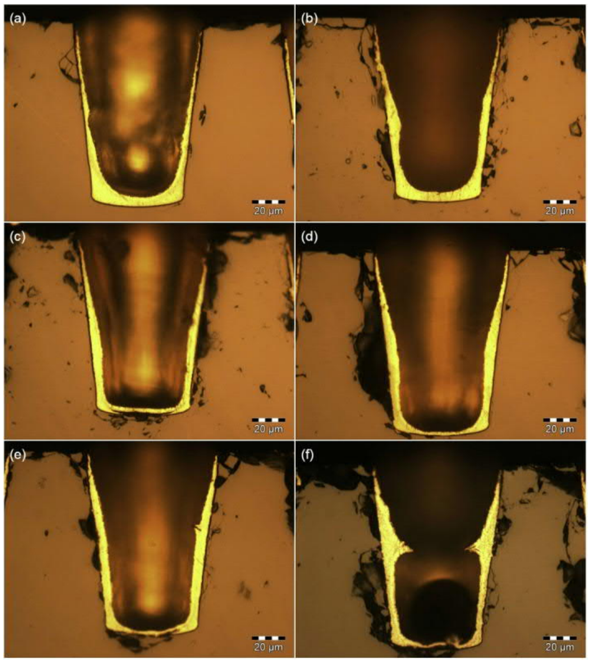

Figure 5 Optical micrographs of cross-sections of filled and sintered vias

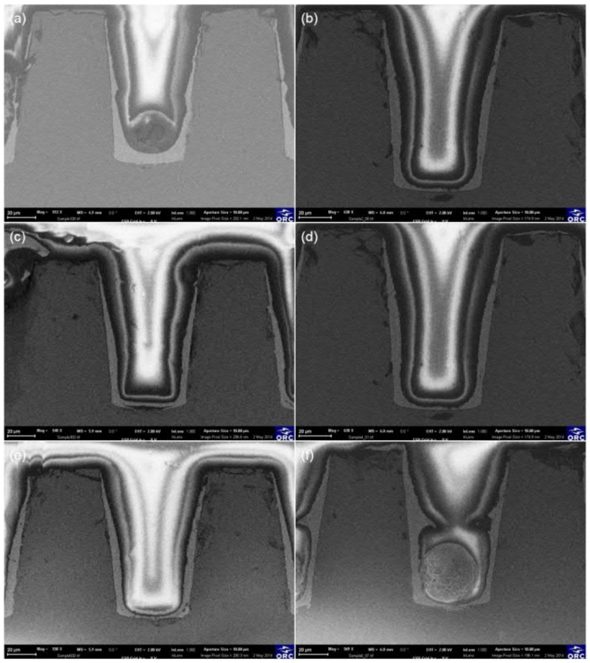

Figure 6 SEM micrographs of cross-sections of filled and sintered vias

Regarding the case 6 it was concluded from Figure 4 (f) showing overflooding, that 91 droplets was too much for the via with this size. It can also be confirmed by cross-section pictures. Also, shifting the ink towards top of the via, shown in Figure 5 (f) and Figure 6 (f), could also be attributed to the high amount of droplets that resulted a kind of capping even in the middle of the via cavity. This phenomenon made the coverage of the ink nonuniform.

Table 4 Wall coverage of the ink in µm (middle and top)

Case	Wall thickness (middle)	Wall thickness (top)
1	~3 µm	~1 µm
2	~5 µm	~2 µm
3	~6 µm	~3 µm
4	~6.5 µm	~3 µm
5	~6.5 µm	~4 µm
6	~5 µm	~6 µm

Conclusions

This paper studies the filling of TSVs with silver nanoparticle ink (Mean dia. 12nm) and 13px pattern. The aim of the study was to understand the effect of delay time and substrate temperature on filling ratio and also the quality and uniformity of the wall coverage.

It was concluded that the delay between the layers and substrate temperature both affect the number of the droplets that could be printed into the TSVs but temperature could be more effective to print more layers or droplets. Among all the trials, printing on 60 ºC with no delay was more optimal because no overflooding was observed, the thickness was the maximum and the coverage of the ink on top and middle of the vias was also uniform. Furthermore, quality of the print was acceptable in all the cases without any specific voids or cracks which is needed for the conductivity of the vias.

In future investigations, filling the vias with smaller diameters could be studied using the printing technologies with much smaller droplets.

Acknowledgments

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