Microelectronic Engineering 156 (2016) 15–18

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Through-silicon-via (TSV) filling by electrodeposition with pulse-reverse current

Sanghyun Jin [a], Sungho Seo [b], Sangwo Park [a], Bongyoung Yoo [a,b,*]

[a] Department of Materials Engineering, Hanyang University, Ansan, South Korea
[b] Department of Bionanotechnology, Hanyang University, Ansan, South Korea

ARTICLE INFO

Article history:
Received 8 July 2015
Received in revised form 11 February 2016
Accepted 13 February 2016
Available online 15 February 2016

Keywords:
TSV
Cu
Electrodeposition
Pulse-reverse current

ABSTRACT

The through-Si-via (TSV) interconnection provides the ideal 3D interconnection in a next generation semiconductor device which has significantly innovated function, excellent performance and high efficiency. In this study, TSV fillings by electrodeposition of Cu with various current forms were carried out to improve the via filling rate. Especially, the influence of reverse current density and average current density on the TSV filling property was studied. ~7% of improvement in via filling rate compared with using direct current (DC) was achieved by applying the pulse-reverse current form, which was mainly caused by effective adsorption and redistribution of additives inside via.

1. Introduction

In the near future, 3D stacked semiconductor devices will be inevitably utilized due to the limitation of downscaling the device. Especially, TSV technology could interconnect whole stacked chips in most ideal way. Directly interconnected chips with shortest electric pathway by TSV could be rapidly and effectively operated [1–5].

TSV filing rate is critical issue in the industry because it directly relates with the cost of semiconductor process [6]. Therefore, tremendous endeavors have been put into for increasing the via filling rate and preventing the formation of defects such as void or seam which could cause serious reliability issues during the operation of semiconductor devices. The selection of optimum organic additives is one of key factors for successful bottom-up via filling by suppressing the Cu growth at top surface and via side wall, and accelerating at the via bottom [7–13]. The current is also critical parameter for achieving the fast via filling without forming defects. In the our previous research, significant improvement in via filling rate was achieved by applying the pulse current to the TSV filling process [14]. The controlled ion depleted layer by independently adjusted components of pulse current was important role in the increment of via filling rate.

In this study, pulse-reverse current form was adapted for achieving the Cu filling in the via with aspect ratio of 11, which could be corresponding to under 17 nm technology. The pulse-reverse current was consisted with the peak current density applied during the on time period and the reverse current density applied during the reverse time period [15]. The cupric ions in the electrolyte could be reduced by the cathodic peak current. In contrast, reduced Cu was dissolved into the electrolyte by the anodic reverse current. Influence of reverse current on the TSV filling was systematically investigated and researches for increasing the TSV filling rate was performed.

2. Experimental

The electrodeposition was performed in a 100 ml sized beaker. 1 M $CuSO_4$ and organic additives which were dissolved in the deionized (DI) water were used as electrolyte. The concentration of organic additives was fixed as suppressor (S-Additive B, Samsung Electronics Co.) to 10 mL/L and accelerator (S-Additive A, Samsung Electronics Co.) to 2 mL/L. The pH of electrolyte was adjusted to ~0.8 with H_2SO_4. Prepared electrolyte did not agitated and maintained room temperature during the electrodeposition. The via patterned Si (diameter: 5.5 μm, depth: 60 μm) wafer with CVD SiN diffusion barrier (200 nm)/sputter Ti adhesive layer (200 nm)/sputter Cu seed layer (500 nm), and Pt plate was used as working and counter electrode, respectively. The Ag/AgCl electrode was employed as reference electrode. The electrodeposition and cyclic voltammetry (CV) measurement was performed by using the potentiostat (Princeton Applied Research, model VersaSTAT4). Scan rate of CV measurement was 50 mV/s. Electrodeposited TSV samples were vertically molded in the epoxy resin to observe the cross-sectional image of filled Cu in the via. Vertical samples were polished by SiC paper (#400, #2000) and 1 μm diamond abrasive. Prepared

* Corresponding author at: Department of Materials Engineering, Hanyang University, Ansan, South Korea.
E-mail address: byyoo@hanyang.ac.kr (B. Yoo).

http://dx.doi.org/10.1016/j.mee.2016.02.020

samples were observed by optical microscope (OM, Hirox Co., model KH-7700).

3. Results and discussion

The influence of reverse current density (i_{rev}) on the TSV filling property was studied. The average current density (i_{avg}), peak current density (i_{peak}), on-time period (t_{on}) and the deposition time were fixed at 2 mA/cm^2, 450 mA/cm^2, 2 μs and 15 min, respectively. The reverse time period (t_{rev}) was properly varied along with reverse current density for maintaining the same average current density. The average current density of pulse-reverse current could be calculated by the following equation:

$$i_{avg} = \frac{i_{peak} \times t_{on} + i_{rev} \times t_{rev}}{t_{on} + t_{rev}} \quad (1)$$

Such high i_{peak} and short t_{on} were already optimized in our previous research for achieving the high pulse frequency with maintaining the proper i_{avg} [14]. Thin ion depleted layer could be obtained by applying the high pulse frequency and this brought the many advantages in the TSV filling such as low surface overpotential, high current efficiency and suppression of side wall growth.

The cross-sectional images of Cu filled TSVs (Fig. 1) are represented the filling characteristics with different reverse current densities ((a) −1 mA/cm^2, (b) −5 mA/cm^2, (c) −10 mA/cm^2, (d) −30 mA/cm^2 and (e) −50 mA/cm^2). The reverse time period was also adjusted for achieving the same average current density (Fig. 1 (a) 299 μs, (b) 128 μs, (c) 75 μs, (d) 28 μs and (e) 17 μs). The actual average current density of Fig. 1(e) was 2.6 mA/cm^2 due to the limited reverse time resolution of the potentiostat. The bottom-up filling rate at via bottom was gradually decreased, and the growth rate at via side wall was rapidly increased as the reverse current density increased. Especially, when the reverse current density was over −30 mA/cm^2, the bottom-up TSV filling was not occurred, but the side wall growth was significantly enhanced. A fast side wall growth induced the fast consumption of cupric ion inside via, as a consequence, the cupric ion could not supply enough into the deep via bottom, which caused the degradation of bottom-up filling. Such behavior should generate the void in the via as shown Fig. 1(e) (the reverse current density = −50 mA/cm^2).

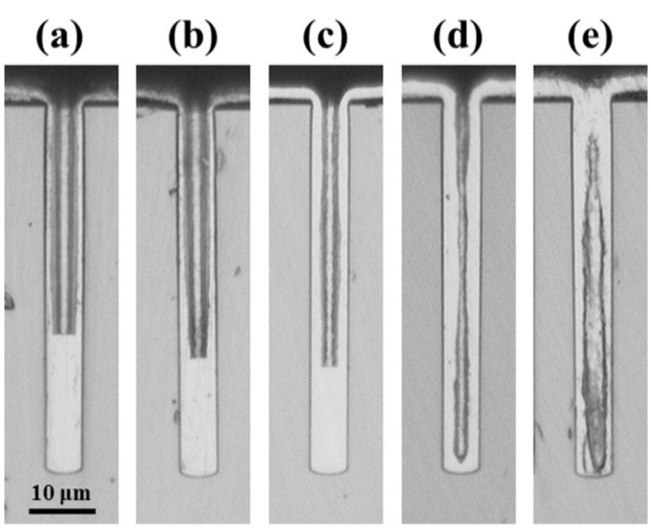

Fig. 1. Cross-sectional images of Cu electrodeposited TSV by pulse-reverse current with different reverse current densities; (a) −1 mA/cm^2, (b) −5 mA/cm^2, (c) −10 mA/cm^2, (d) −30 mA/cm^2 and (e) −50 mA/cm^2. The peak current density, average current density, on time and deposition time were fixed at 450 mA/cm^2, 2 mA/cm^2, 2 μs and 15 min, respectively.

Electrochemical analysis including the anodic charge analysis and the cyclic voltammetry was performed to understand the variation of via filling property by changing the reverse current density. Fig. 2(a) shows that the variation of the anodic charge density for one cycle of pulse-reverse period as the reverse current density was increased with fixed average current density. The anodic charge density ($= i_{rev} \times t_{rev}$) for one cycle of pulse-reverse period could be calculated by the following equation:

$$Anodic\ charge\ density = \frac{i_{rev} \times t_{on} \times \left(i_{avg} - i_{peak}\right)}{i_{rev} - i_{avg}}. \quad (2)$$

The actual experimental conditions were indicated by individual points on the calculated curve. According to this, the anodic charge density was rapidly increased by increased reverse current density due to fixed cathodic charge density (=450 mA/cm^2 × 2 μs) and average current density (=2 mA/cm^2). This means that the amount of dissolved Cu during the reverse time period increased as the reverse current density increased. Although cupric ion concentration could be increased by anodic dissolution of Cu, the anodic potential during the reverse period enhanced on the desorption of suppressor at the via side wall as well. More detail behavior of suppressor under anodic current was investigated by cyclic voltammetry (CV). The cyclic voltammogram showed almost linear characteristics, when there was not any additive in the electrolyte. Such linear characteristics explained that the forward and reverse scan were identical. On the other hand, when suppressor was added

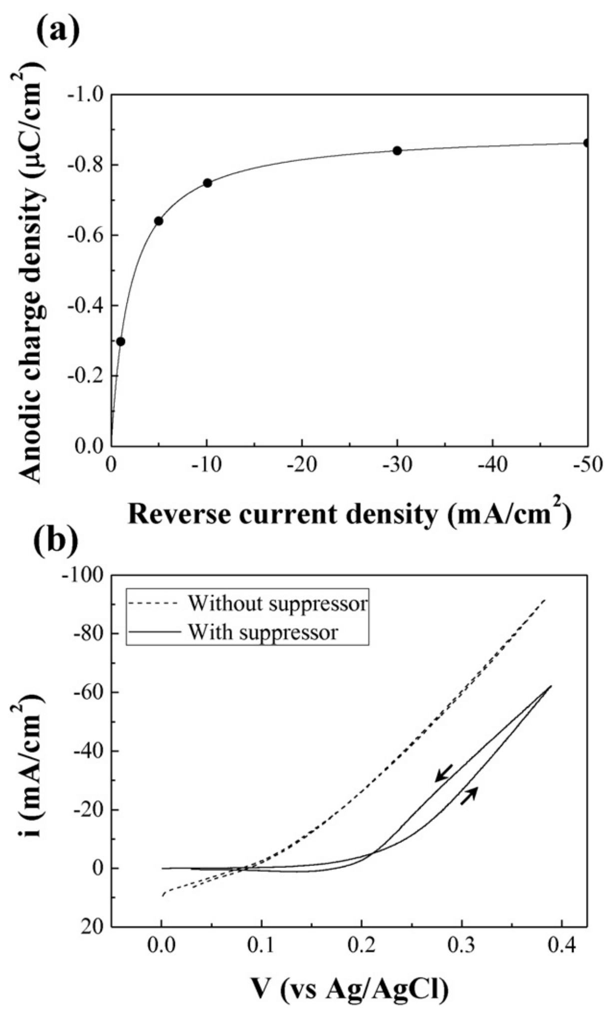

Fig. 2. (a) The variation of the anodic charge density for one cycle of pulse-reverse period as the reverse current density was increased with fixed average current density. (b) Anodic cyclic voltammetry from electrolytes with and without suppressor.