# Next Level of 1/1 μm Line and Space Copper Redistribution Layer Fabrication with Organic Dielectric Materials

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## Abstract
An electrical reliability of fine copper redistribution layer (RDL) with 1/1 μm line and space fabricated by using positive photosensitive polyimide (PSPI) has been demonstrated. The polyimide containing flexible molecular units in PSPI was introduced, in assumption to increase the entanglement of each polymer chain with a design concept of polymer backbone to enhance mechanical and thermal reliability. To conduct a series of tests, test vehicles with semi-additive copper RDL with 1/1 μm line and space were fabricated with Toray's PSPI for electrical reliability test. Through a series of electrical reliability tests utilizing our test vehicles, PSPI out-performed the phenol-based resin, which has been proven to have excellent mechanical and thermal stabilities when compared with other resins. 1/1 μm line and space electrodes after electrical reliability tests were also observed and cross-sectioned. The observation of electrodes clearly showed oxidation-reduction of the electrodes on anode and cathode, respectively. On the cathode, copper particles of several nm in diameter were formed on the PI film surrounding the copper wiring. On the anode, copper oxide layers of about 100 nm thickness were observed on the copper wiring surface, which turned out to be $Cu_2O$ when analyzed with Electron Energy-Loss Spectroscopy (EELS) measurement.

## Key words
Electrical reliability, fine copper wirings, low temperature curable, photosensitive polyimides, redistribution layers

## I. Introduction
As the package size of integrated circuits (ICs) and pin-pitches of the devices dramatically decrease, heterogeneous integration technologies for IC chips were developed to achieve higher performance. The interconnections between chips within heterogeneous packages are very narrow to reach higher density integrations and high-speed connections composed of non-conductive insulant materials such as photosensitive polyimides (PSPIs) and conductive fine patterned copper wiring metal as the redistribution layers (RDLs).

We have developed various type of low temperature curable positive-tone photosensitive dielectric PSPIs for several types of semiconductor devices and OLED displays [1]. The focal point of this report is to distinctively show our PSPI materials' excellent data acquired under a highly biased accelerated stress test (B-HAST) condition by using a test vehicle with fine copper RDLs with 1/1 μm line and space.

## II. Methods

### *A. Preparation of PSPI*
Low temperature curable positive-tone photosensitive polyimide, **LT-PI**, was prepared by the following procedures. Dried PI with flexible units (3.51 g) prepared by polycondensation according to previous reports [2], diazonaphthoquinone (DNQ, 0.62 g), and cross-linker (0.12 g) were mixed into 5.75 g of γ-butyrolactone (GBL). Then the solution was filtered through a 0.2 μm pore poly (tetrafluoro-ethylene) (PTFE) filter to remove the particles. On the other hand, **PS-Ph** was by a similar procedure as **LT-PI**, but with a few distinctive differences. Unlike **LT-PI**, for **PS-Ph**, mixtures of poly(hydroxystylene) based polymer (2.90 g), DNQ (0.97 g), cross-linker (0.54 g), and ethyl lactate (5.59 g) were used as well as diazonaphthoquinone (DNQ, 0.62 g), and cross-linker (0.12 g) mixture to be mixed

with 5.75 g of γ-butyrolactone (GBL). Then the solution was filtered through a 0.2 μm pore poly (tetrafluoro-ethylene) (PTFE) filter to remove the particles.

*B. Fabrication of test vehicles for reliability test*

Test vehicles were prepared by semi-additive RDL fabrication procedure divided into two steps, which are the fine line and space copper electrodes as first layer (Fig. 1) and the copper lead wires as second layer (Fig. 2). In the first step, photoresist was spin-coated on to a copper spattered Si wafer, then soft-baked. The film was exposed by an i-line stepper then developed by 2.38% tetrarmethylammonium hydroxide aqueous solution (TMAHaq.). After development, copper electroplating was carried out to fabricate fine line and space copper electrodes. For the last process of the first step, the substrates with fine copper comb electrodes were obtained after resist stripping and seed etching.

In the second step, copper lead wires were fabricated on to the substrate with fine copper comb electrodes by using organic dielectrics, **LT-PI** and **PS-Ph**, respectively. Coating and patterning were carried out by using each material; and copper seed layers were sputtered. Subsequently, a dry film resist was used to pattern the lead wires, but the lead wires for the second layer were formed by copper electroplating. Furthermore, the resist was stripped by using resist stripper, and the seed layer was etched to fabricate the second layer of the lead wiring. For the last process of the second step, **LT-PI** was coated to form a lead wire protection layer, then Ni/Au electroless plating pads were formed after the copper pads patterning. Specification of the test vehicle is shown in Fig. 3.

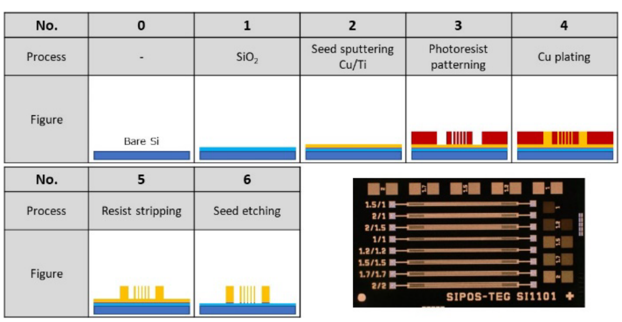


Fig. 1. The process of the first layer for 1/1 μm copper wiring patterns.

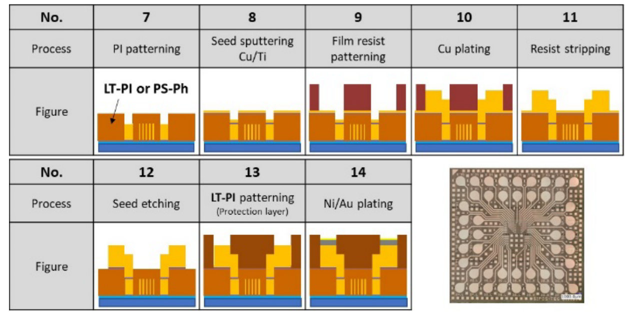


Fig. 2. The process of the second layer for the copper lead wires.

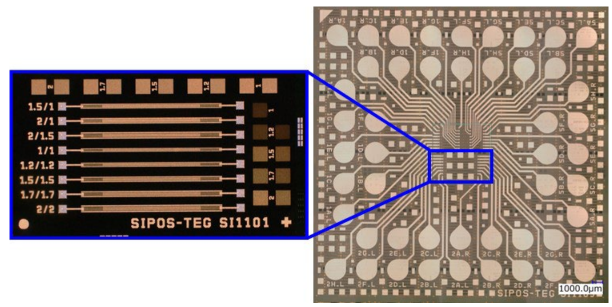


Fig. 3. Test vehicle with fine line and space copper electrodes.

*C. Copper migration test*

Copper migration test called B-HAST was carried out by using copper patterned substrate (1/1 μm line and space). During B-HAST, test substrate was stored in thermal and humidity chamber with 1.7 V or 3.3 V bias at a condition of 130 ºC, 85%RH for 200 hours. These test substrates were fabricated separately with **LT-PI** and **PS-Ph** to fabricate a test vehicle for each of the dielectric material.

## III. Results and discussions

*A. Design concept of* ***LT-PI***

Dielectric materials for copper RDLs of heterogeneous integration packages require good mechanical properties as well as low temperature curable in nature to fabricate reliable packages. In order to withstand various reliability tests, **LT-PI** must obtain excellent mechanical properties, especially, elongation (>40%), which we believe to be the key factor [3]. For this reason, we have introduced flexible molecular units in **LT-PI** with an assumption to increase the entanglement of each polymer chain. By implying flexible molecular units into **LT-PI** film, elongation became 70% when cured at 220 ºC for an hour. When comparing to the elongation of PS-Ph, which possesses an elongation of 30%, the difference is evident. Furthermore, the test vehicles with **LT-PI** have undergone accelerated stress tests [3] without any trace of physical degradations such as cracks nor copper RDL breakage, which reassured our assumption of elongation being an essential mechanical property to improve the reliability.

In addition to the findings during the accelerated stress tests [3] for **LT-PI**, a low-stress type of PSPI with more flexible units than **LT-PI** has been developed unintentionally. The finding of this low-stress PI was a bonus during our development. Although this material is at its early stage of development, knowing the importance of low-stress material needs for the insulating layer of the high-density packages with multiple layers of RDLs, this material may play a huge role for the dielectric materials in the future. All basic properties for this material are summarized in Table. 1 so that this material can be compared to our new LT-PI material.

Table. 1. General properties of LT-S series.

| Properties | | Measurement Method | LT-S series | | |
|---|---|---|---|---|---|
| | | | LT-PI | | Low stress type |
| Curing Condition | °C/min | Oven | 200/60 | 220/60 | 230/60 |
| Tensile strength | MPa | Tensile Test | 128 | 132 | 120 |
| Elongation | % | Tensile Test | 71 | 70 | 100 |
| Young's modulus | GPa | Tensile Test | 2.5 | 2.5 | 1.7 |
| CTE | ppm/°C | TMA | 59 | 57 | 68 |
| Residual stress | MPa | Bending Bow | 29 | 31 | 20 |
| 5% weight loss temp. | °C | TGA | 330 | 345 | 350 |
| $T_g$ | °C | TMA | 255 | 270 | 150, 280 |
| Volume resistance | Ωcm | LCR meter | $>1.0x10^{17}$ | $>1.0x10^{17}$ | $>1.0x10^{17}$ |
| Surface resistance | Ω/□ | LCR meter | $>1.0x10^{14}$ | $>1.0x10^{14}$ | $>1.0x10^{14}$ |
| Breakdown voltage | kV/mm | LCR meter | >400 | >400 | >400 |
| Photo sensitivity (7μm after Cure) | $mJ/cm^2$ | i-line stepper | 300 | 300 | 400 |
| Water Absorption | % | TGA | 1.1 | 1.1 | 0.8 |

*B. Results of B-HAST as an electro reliability test*

B-HAST is a method for evaluating insulation properties by applying certain voltages to a test vehicle under a constant condition of high temperature and high humidity environment condition of 130 ºC/85RH%/200 hours/1.7 V (Fig. 4). B-HAST was carried out by using test vehicle with 1/1 µm line and space electrodes of each fabricated with **LT-PI** and **PS-Ph**. As a result, **LT-PI** showed good insulation reliability even after 200 hours, while **PS-Ph** failed after 40 hours. This result indicates a test vehicle composed of **LT-PI** had higher reliability nature than of **PS-Ph** composed of phenol-based resin.

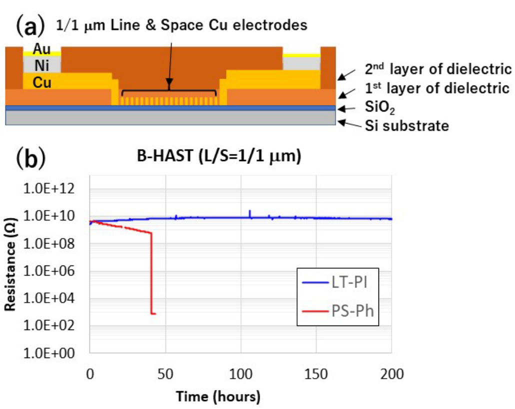


Fig. 4. (a) cross-section of the test vehicle. (b) resistivity of LT-PI and PS-Ph via 1/1 µm line and space copper electrodes at a condition of 130 ºC, 85RH%, and 1.7 V bias.

In addition, we have conducted a similar test at Research Center for Three-Dimensional Semiconductors and Fukuoka University (Fig. 5). B-HAST (130 ºC/85RH%/200 hours/1.7 V) was conducted on 1/1 µm line and space electrodes of test vehicles fabricated on $SiO_2$ and **LT-PI**. 5 Vehicles of $SiO_2$ and 6 vehicles of **LT-PI** were prepared for B-HAST (see Fig. 5 for vehicle IDs). As it is shown on Fig. 5, all vehicles passed by maintaining insulation reliability at 200 hours. When B-HAST extended to 400 hours, 1 out of 5 $SiO_2$ vehicles failed at 225 hours, while 6 out of 6 vehicles with **LT-PI** passed. These results indicate that the reliability of **LT-PI** is quite high because of its ability to keep a stable resistivity even after thermal humidity storage test. From this outcome, it is safe to say that an electrical reliability of **LT-PI** is comparable to that of $SiO_2$, which is as an inorganic insulator.

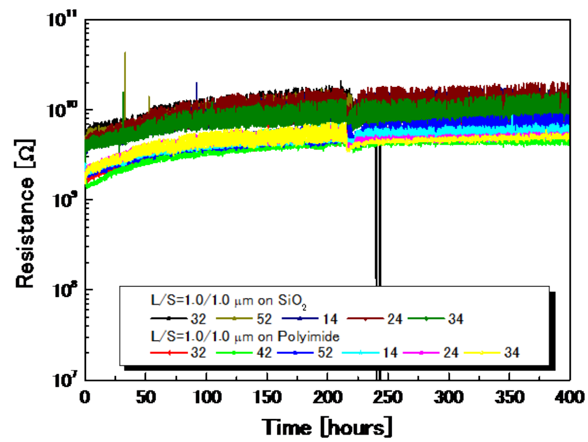


Fig. 5. Resistivity of **LT-PI** and $SiO_2$ with 1/1 µm line and space copper electrodes at a condition of 130 ºC, 85RH%, and 1.7 V bias.

Furthermore, B-HAST test under high voltage was also evaluated with 3.3V bias doubled from 1.7V one via 1/1 µm line and space copper electrodes at a condition of 130 ºC, 85RH%, which doubled the electric field strength (Fig. 6). As a result, a test vehicle applied with 3.3V bias shorted out in about 140 hours. The cause of this failure is under investigation; however, it can be assumed that along with the organic insulation layer, miniaturization of copper RDLs could have possibly reduce the insulation reliability of a test vehicle under such severe condition.

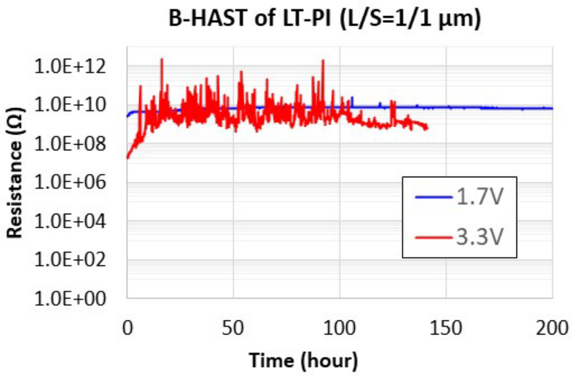


Fig. 6. Resistivity of **LT-PI** with 1/1 µm line and space copper electrodes at a condition of 130 ºC, 85RH%, and 1.7 V or 3.3V bias.

*C. Appearance and cross-sectional observation after B-HAST*

Fig. 7 shows a) an optical microscope (OM) and b) scanning electron microscope (SEM) images after 200 hours of B-HAST for 1/1 µm line and space electrodes of LT-PI. Oxidation-reduction of the electrodes were observed at anode and cathode, respectively, suggesting that B-HAST proceeded successfully. Furthermore, corrosion of copper wiring due to anodic oxidation was also observed from the SEM cross-sectional image.

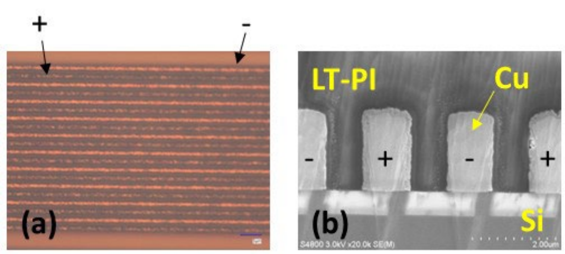


Fig. 7. (a) appearance OM image and (b) cross-sectional SEM image of 1/1 µm line and space electrodes.

A more detailed analysis was performed on the 1/1 µm copper wiring after the migration test. In Fig. 8, the cross-sectional images are (a) a secondary electron image and (b) a backscattered electron image for the anode and cathode, respectively. The backscattered electron image shows that the cathode is clearly surrounded by copper nanoparticles with diameters of several hundred nm over the distance of a hundred nm from the copper surface around the cathodes. On the other hand, copper oxides of approximately 100 nm thickness were observed on the anode surface.

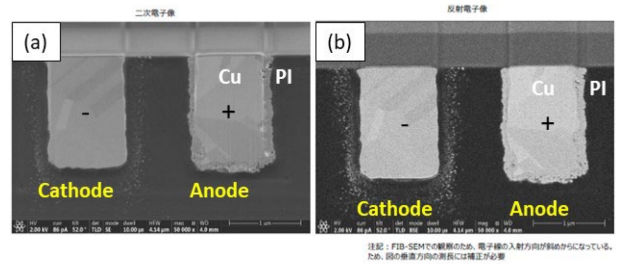


Fig. 8. cross-sectional images of (a) a secondary electron image and (b) a backscattered electron image for the anode and cathode.

Each copper and copper oxide could also be identified by Energy Dispersive X-ray Spectroscopy (EDX) in Fig. 9. As a result, it is assumed that the insulation reliability is maintained because copper particles generated at the cathode do not reach the anode. These new finding of redox reactions occurring at the anode and cathode when designing less than 1µm fine copper wiring patterns should be focused during migration tests.

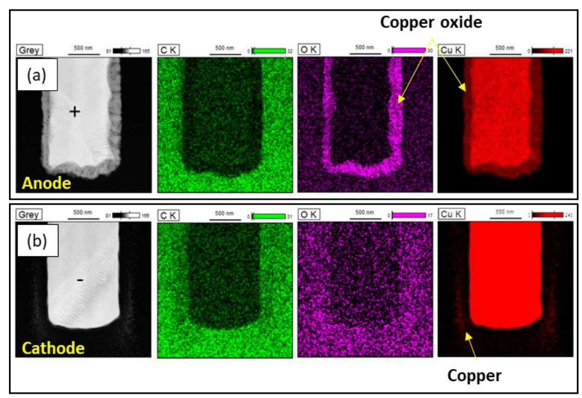


Fig. 9. EDX images of cross-sectional copper electrodes after 200 hours of B-HAST at a condition of 130 ºC, 85RH%, and 1.7 V bias; (a) anode and (b) cathode.

Furthermore, through studying the results of Electron Energy-Loss Spectroscopy (EELS) in Fig. 10. the copper oxide, which is marked with orange square, was observed on the anode is determined to be $Cu_2O$. The effect of $Cu_2O$ generated on the anode toward package reliability has not yet been clarified. Therefore, this phenomenal is one of subjects to be looked upon in the future works. Further study of this phenomenon will be analyzed and attempted to clarify the actual root cause of migration failures. As the featuring patterns for the next generations for devices shrink in sizes, it is important to study the mechanism of failure modes for the succession to develop new materials for the future.

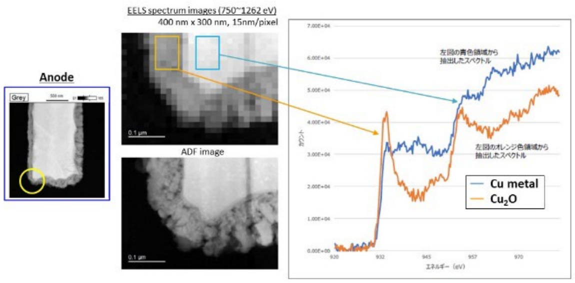


Fig. 10. EELS measurement of cross-sectional anode copper electrode after 200 hours of B-HAST at a condition of 130 ºC, 85RH%, and 1.7 V bias.

## IV. Conclusion

We have demonstrated the electrical reliability of polyimide-based low temperature curable dielectrics with flexible units through test vehicles with 1/1 µm line and space electrodes. The results show that PSPI has higher reliability nature than phenol-based resin. This PSPI material is expected to become the game changing material since the next generations of heterogeneous integrated semiconductor device packaging require smaller features and better reliability.

## Acknowledgment

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## References

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