NEW EXCIMER LASER-BASED DUAL DAMASCENE PROCESSES FOR HIGH I/O APPLICATIONS WITH ULTRA-FINE LINE ROUTING

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In the future, FOWLP will be used more and more for multi-chip packages. The function of the chip-to-chip routing, which is normally done on Printed Circuit Boards (PCB), is now done by the redistribution layer. This results in increasing demand for RDL and sets new challenges on the layers stacking. The new approach of laser enabled dual damascene process for wafer-level packaging could be used to overcome these challenges.

The laser structuring of the dielectric layer for interconnect formation between metal layers is the dominating process in PCB processing. The structuring is done with UV or IR lasers, where ultra-short picoseconds pulses are used. The laser process is proven to be a cost efficient process with the benefit to realize a feature size of the via which is less determined by the choice of the used material. Figure 1 shows a UV laser drilled via to connect an embedded die in a printed circuit board with a diameter of 30 µm.

In contrast to PCB technology, the structuring of dielectric layers for wafer-level packaging is mainly done by a photolithographic process. The feature size is dominated by the photolithographic properties of the used polymer material.

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In this paper a novel excimer laser dual damascene process is presented to generate a fine line multi-metal layer routing. A laser stepper technology together with a quartz mask allows a high throughput in combination of ultra-fine RDL and via openings below 5 µm. The depth of ablation into the polymer is controlled by the number of laser pulses and fluence. The patterning of RDL and Via is done in one excimer laser ablation step, with an aspect ratio of 1:1. A landing pad is not needed in the lines to allow via full contact because of the sub-micro meter overlay accuracy of the laser ablation system, which allows to realize a fine routing layer density. The vias and lines are metallized by a galvanic process. Test structures have been designed and fabricated by using low cure temperature PI, BCB, and ABF as dielectric material to demonstrate the material flexibility.

**INTRODUCTION**

Advanced packaging has become the key point for reaching the goal of continuous miniaturization, higher performance, low cost and decreasing of time-to-market of electronic devices. The wafer-level packaging is today the dominating method in high-end mobile smartphone systems and it is still trending to increase. The next big packaging trend will be Fan-Out Wafer-Level Packaging (FOWLP) with reconfigured wafers based on placed known good dies which are embedded in molding compound. This opens a lot of opportunities for innovative packaging and is also a key for heterogeneous packaging like the integration of memory and ASIC chips aside of passives in one package. The major application today is only a single chip package, where the molding is used as expanded area for higher pitch breakout of one chip. The demands regarding the feature size is similar to the classical Fan-In package and still relatively moderate and could be achieved with one copper redistribution layer.
The laser ablation of thin film polymers is in principle not a new technology for wafer-level packaging. The laser ablation of polymers was first reported by Srinivasan et al. [1] in 1982. Low speed and high cost was the major barrier for further developments twenty years ago. But the combination of excimer laser systems with scanning/stepper technology platforms with quartz masks has improved this technology to overcome the limited throughput. The excimer laser structuring is able to realize smaller vias with smaller feature sizes compared to current photo-polymer processes where a via is limited to an aspect ratio below 1.5. In this work a laser ablation system from SUSS MicroTec (ELP300) has been used which is equipped with a laser source from Coherent (LPXpro 305) where vias are generated with an aspect ratio close to 5 (Figure 2). The laser has a power of 40 W and the characteristics are summarized below:

- Wave length: 248 nm (KrF)
- Shoot repetition rate: 50 Hz
- Puls length: ~ 30 ns
- Beam spot size: 6.5×6.5 mm²
- Fluence range: 70-650 mJ/cm²

The used tool is configured for a reticle size of 6.5 by 6.5 mm and the moving speed of the stage is 50 mm/s.

LASER SCANNING ABLATION PROCESS USING A MASK

The laser ablation process can be simply described by the removal of the polymer without damaging the surrounding areas. No cracks or any other heat-affected zone should limit the high-density applications [2]. When a high-energy UV-Laser pulse is focused onto a material so that the intensity (which is measured as the fluence) is above a material-dependent threshold value, then the high-energy ultraviolet photons directly excite electrons and break interatomic bonds. This threshold is quite important because it can be used to structure polymers on top of inorganic materials like metal without destroying the metal underneath because the threshold of metals is mostly very different to the threshold of dielectric materials. Along with the subsequent shock wave, this causes material to be ejected at high velocity in the form of a fine powder or gaseous organic byproducts. Each pulse lasts a few nanoseconds and removes a thin layer of the polymer. Unlike most other laser types, the excimer produces a large area beam that is usually rectangular in cross-section. This has the advantage to be highly compatible with the use of photomasks. For the light blocking metal Al is most suitable due to a very high threshold level.
which makes the Al mask stable for a long production cycle time. The schematic of the excimer laser stepper is shown in Figure 3.

The aluminum is patterned as the inverse of the pattern to be structured on the actual polymer layer. The openings in the metal on the mask define the pattern that will be laser ablated. The photomask output is then reduced through a reduction lens (for example 2.5 x) onto the target - the targeted area depends on the laser power and the ablation threshold of the target material. Regarding the reduction of the optical system there are less demands of the feature resolution of the mask which leads to lower mask costs. Hence, the throughput is very high compared to a PCB drilling system because multiple vias are generated simultaneously during exposing of one reticle. (i.e., multiple vias per second) and throughput is independent from the number of vias. The reason is that the amount of material removed with each laser pulse, i.e., the depth of any hole or trench, is dependent only on the fluence (energy), number of pulses and the specific materials to be ablated. The etch rate in relation to the energy is shown in Figure 4. The reticle size and the fluence are defined by the available laser systems.

The etch rate is less than 50 nm for low fluence of 100 mJ/cm² and can reach around 300 nm per pulse for a fluence of 650 mJ/cm² (this is the maximum of the used laser system) and can reach up to 1000 nm per pulse for some materials with a fluence of 1,200 mJ/cm², which is the maximum fluence, if a 300 W laser source is used. The investigations show that the ablation rate between different polymers is nearly similar. Figure 5 shows the etching profile of a line into a low cure polyimide layer at a fluence of 400 mJ/cm² with different number of pulses from 1 to 30.
The ablation rate is nearly constant for different geometry sizes and is not affected by the depth of the structure which could be seen in Figure 6.

The throughput for such a system is now defined by the fluence power of the laser system, the number of pulses per second and the reticle size. From view of the tool design the important factors are the reticle size and the stepping speed of the mask. The nature of the polymer is less important and only the thickness of the polymer layer is important.

**EXCIMER LASER DUAL DAMASCENE PROCESS**

The principle of the excimer laser ablation process is the direct removal of polymer materials from the desired pattern on a fully cured film. Patterning after curing provides complete pattern integrity of the structure profile as compared to structures made using photolithography process. For example, the via formed by a lithography process will need to be subjected to a curing process after exposure which in turn reflow/shrink the resist. Therefore, the initial via profile will be in turn lost. In the dual damascene process using excimer laser, the Via and RDL patterning is done in one step and would be either via first and trench (RDL) last or trench first and via last. The last option is the most preferred one for advanced packaging as it allows better control of the via profile and its bottom critical dimension. The dual damascene is already well defined and vetted in the Front-End-of-Line (FEOL) using lithography and dry etching. The process flow for an excimer laser enabled dual damascene process is shown in Figure 7 (trench first and via last process).

First step is the polymer coating on the wafer and curing. The curing of the polymer is done before the patterning process. The thin film polymer could incur shrinkage during cure up to 40 percent, which limits the feature sizes patterned by the photolithography. In the next step the traces are ablated into the polymer layer with the excimer laser. The ablation depth is set by the number of pulses. After trace ablation the mask is changed, and the vias are drilled by the laser. The tool allows high sub-micron alignment accuracy between the two mask layers. It is therefore not necessary to provide a larger capture pad size. After formation of the via and RDL, a seed layer is sputtered which consists of 100 nm titanium adhesion layer and 400 nm copper layer.
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The structure is then filled by electro plated copper. The copper overburden is removed by a chemical and mechanical polishing step (CMP). Instead of a regular semi-additive process the copper structure height is not defined by the plating process. Therefore the copper thickness is independent of the local feature densities, feature size differences and galvanic bath flow conditions over the wafer. The copper CMP process stops on the titanium adhesion layer. The laser is then used instead of a second CMP step to remove the remaining thin titanium metal layer by a single laser pulse process. The seed layer removal by excimer laser is proven to be much faster than the CMP process. Figure 8 shows an excimer laser dual damascene structure of a 5 µm line and a 5 µm via without any misalignment. We have also demonstrated a dense routing of a 5 µm lines structure with a space of only 2 µm. The titanium removal by laser shows no remaining metal parts even in small line spacing which will be very challenging to achieve for an SAP process. The seed layer removal has no effect on thicker copper trace lines. The successful isolation between dense lines was demonstrated by an inter-digital electrode structure where only a low leakage current below 10e-9 A was measured. The test results demonstrated an excellent isolation between dense lines using the excimer laser enabled dual damascene process described above.

A thicker metal layer is not affected by the laser because the energy threshold for metal ablation is much higher than for the polymer. This means that the via ablation can land on any underlying metal layers without harming it or features underneath. Figure 9 shows FIB cuts of laser drilled vias which stops on a sputtered AlSi layer.

Figure 8 Laser ablated line and via in a low temperature cured polyimide layer (via first dual damascene was used on this case)

Figure 9 Laser-ablated polymer via landing on AlSi (left) and plated Cu (right) (20 µm Via CD, 650 mJ/cm²), Met 2: 1 µm sputtered AlSi
and on a plated copper layer. AlSi is a typical metallization for contact pads from CMOS chips where the plated copper layer is used for multi-redistribution layers. For the second metallization only a sputtered AlSi layer was used. There is no undercut or recess at the via opening edge which indicates that the laser made no interaction with the metal layer. The polymer in the via is completely removed which is shown by the clean interface between the metal layers.

For the evaluation of the yield, a daisy-chain design was set up which contains two metal lines. The line width is 5 µm and the via diameter is also 5 µm. Each chain contains of 960 vias. The average resistance of a complete chain is in the range of 150 Ohms. Figure 10 shows a yield map of a 200 mm wafer where the daisy-chains where ablated in a low temperature cured (230°C) polyimide which is commonly used for RDL generation on temperature sensitive re-configured wafers. Each green mark is a functional chain and a red mark indicates an open circuit in the chain. Therefore an excellent yield over the whole wafer is demonstrated. The defected chains at the edge are related to the edge bead removal of the polymer.

The excimer laser based dual damascene process flow is currently under evaluation for other polymers which are used for fine line routing of organic interposers like the non-photo dry film Ajinomoto Build-up Film ABF. First results are comparable to polyimide results. Figure 11 shows a cross cut of an embedded line in ABF.

**CONCLUSION**

The application of the PCB like laser ablation technology on a stepper like platform allows the fabrication of ultra-fine structures with high throughput. Features sizes of 5 µm and below are demonstrated and show an excellent yield. There are many benefits from using excimer laser as compared to a regular lithographic structuring, such as the elimination of many process steps and consumables from the integration flow, the pattern integrity of the structuring (“What you see is what you get”), the ability to pattern ultra-fine vias and RDL, or the use of non-photo-definable materials that enable a wider option for CTE matching and are often cheaper. Therefore, the excimer laser enabled dual damascene process presents significant cost benefits compared to
the current process of record based lithography process flow. The excimer laser ablation enables users to reach the requirements for advanced packaging platforms where dense routing in combination with multi-layer build-ups are needed.

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