ULTRA-SMALL VIA-TECHNOLOGY OF THINFILM POLYMERS USING ADVANCED SCANNING LASER ABLATION

Michael Töpper
Fraunhofer Research Institution for Reliability and Microintegration IZM | Germany

Martin Wilke, Klaus-Dieter Lang
Fraunhofer Research Institution for Reliability and Microintegration IZM | Germany

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In this paper a new process technology will be discussed which uses a laser scanning ablation process. Laser ablation of polymers is in principle not a new technology. Low speed and high cost was the major barrier for further developments twenty years ago. But the combination of a scanning technology together with a quartz mask has opened this technology to overcome the limitation of the current photo-polymer process. The new technology is described in details and the results of structuring BCB down to less than 4μm via diameter in a 4μm thick film has been demonstrated. The via-side wall can be controlled by the fluence of the laser pulse.

This is different for the photo-polymers which are a permanent part of the future systems. Therefore it has a strong influence on the reliability but also on the performance of the system. Properties like high thermal stability, excellent mechanical properties, low water up-take, low dielectric constant and low loss have to be achieved together by the chemical synthesis of the polymer and are therefore limiting the optical resolution. Depending on the application the importance of the polymer properties may be different. Highly important are also the following properties:

- Cu-Compatibility
- Low temperature cure
- High Breakdown V
- Low cost by alternative processes

Mainly photo-polymers are used for electronic packaging and MEMS applications today. Mask aligners and steppers with UV light are used. For most of the thinfilm polymers like PI (Polyimide), PBO (Polybenzoxazole) and BCB (Benzocyclobutene) limits of the via sizes are in a range of 20-30μm in production. The lithography tools have a much higher resolution but the photo-sensitivity of the thinfilm polymers are limited which is not more compatible for the roadmap of 4μm lines and space of the metallization in the near future. Vias must have similar sizes as the metal lines to achieve a dense routing.
LASER ABLATION TECHNOLOGY

Pulsed-laser ablation is a process when material is removed by a short high-intensity laser pulse. This ablation takes place far from equilibrium. Therefore the excitation energy can be suppressed beyond the volume that is ablated during the ablation.

In general a single- or multiphoton excitation is essential for the process. This energy can be transformed instantaneously into heat which will raise the temperature of the material and vaporization will follow (or thermal induces stress if the energy was too low).

Each material has a threshold for the laser ablation. If the fluence is below this threshold the energy of the laser will be absorbed and transferred into heat. The threshold value for laser ablation is in the range of 10-100 mJ/cm² for polymers. The bonding energies of C-C and C-H are between 3.6 eV and 4.3 eV. If the fluence of the laser is higher as this threshold the laser ablation process starts immediately. The chemical bonds will break and gaseous products will be formed. The enormous change in volume changing from the solid state to the gaseous state leads to an explosive-like ablation process.

PROCESS DESCRIPTION OF LASER ABLATION TECHNOLOGY COMPARED TO PHOTO-POLYMERS

The process for structuring photo-sensitive polymers consists of multiple steps. First the polymer (in the pre-cursor state) has to be coated on the substrate mainly using spin-coating technique for WLP applications. Emphasis has to be taken into account that these polymers are temperature-sensitive. The shelf-life of some of the materials is limited to one week at room temperature. Therefore a sophisticated material support has to be established from the polymer supplier to the pump of the spin-coater module at the wafer production site. After the coating most of the solvent has to be removed from the coated polymer layer by heating the wafer on hotplates. This process has a high influence on the whole process and has to be optimized for each polymer type. If the temperature (or time) of the process is too high (or too long) the photo-sensitive components will be damaged which will heavily limit the resolution of the via. If the temperature (or time) is too low (or too short) the vias in the polymer will not be formed well. It may even lead to a dissolving effect in the later developing step. After the baking process the photo-polymers are exposed to UV light using either mask aligner or steppers. Some of the photo-polymers then need a post-exposure bake to improve the UV-induced chemical reaction in the polymer. Then the polymers have to be developed i.e. the polymers have to be washed out of the vias. There is a difference in the process for positive- or negative-acting polymers which is shown in Figure 1:

![Figure 1](image-url)

The developing step is also very sensitive to the duration of the process. The developing solvent may swell the polymer and may lead to a strong film loss (i.e. reduction of film thickness) or even a complete delamination. The next step is then the polymerization process (i.e. called cure) which
gives the mechanical properties for the later application. Some of the polymers will shrink to close to 50% of the film thickness which also has an influence on the via shape. For some of the polymers a descum process is necessary to remove any residues in the via to ensure a low electrical contact resistivity for the next metallization layer. In summary the photo-process is a quite complex process which has multiple time- and temperature-sensitive process steps. This is totally different for the laser ablation process of non-photo-sensitive polymers. All these sensitive process steps are not necessary. The thin film polymer is coated on the wafer similar to the photopolymer step but the cure will be done as the next step. Final process is the laser ablation process described in details in the next chapter. The process can be also used for photo-sensitive polymers if the cure is done directly after the coating.

LASER SCANNING ABLATION PROCESS USING A MASK

The wavelength of the system used for this investigation is 248nm which is excellent to pattern a wide variety of dielectrics. The excimer is a powerful, pulsed, ultraviolet laser that is well-proven in microlithography. The laser ablation process can be simply described by as the removal of the polymer without damaging the surrounding areas. No cracks or any other heat affected zone should limit the high density applications. 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 without destroying the metal underneath for example 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. Each pulse lasts a few nanoseconds and removes a thin layer of the polymer. It is assumed that the process is relatively cold. 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. Main requirement for the mask is the transmission of the glass material to the wavelength of the laser. Therefore quartz has to be used. For the light blocking metal Al is most suitable due to a very high threshold level which makes the mask stable for a long production cycle time. The UV laser beam path of the equipment of SUSS MicroTec is shown in Figure 2:

![Figure 2: Eximer UV Laser Beam Path](image)
area depends on the laser power and the ablation threshold of the target material. In this work a laser ablation system from SUSS MicroTec (ELP 300) has been used. The laser was a Coherent LXPpro 305 with a power of 40 W. The laser characteristics are summarized below:

- Wave length: 248 nm (KrF)
- Shoot repetition rate: 50 Hz
- Puls length: ~ 30 ns
- Beam spot size: 6,5 x 6,5 mm²
- Fluence range: 70 - 650 mJ/cm²

Therefore the throughput is very high (i.e., multiple vias per second) and at higher pitches, the number of vias per second actually increases. 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 pulse intensity and the specific materials to be ablated. So only the stepping of the mask is the limiting factor for the process besides the nature of the polymer and the thickness of the layer (Figure 3).

The maximum scan speed is therefore 50 / s x 6.5 mm = 325 mm / s.

Because ablation directly breaks the interatomic bonds with minimal thermal effects, it results in excellent surface quality, no micro-cracking and no recast (melted) debris. The only postlaser process is a cleaning step.

The smallest feature (x-y axes) that can be ablated with the laser depends on the laser wavelength, the optical resolution of the projection lens and the photomask. The precision depth control in z-axis is controlled mainly by the number of pulses. The high pulse-to-pulse energy stability of the latest excimer lasers means that every pulse will remove an identical depth of material. So depth control is easily provided simply by programming a fixed number of pulses at each stepper site location. In addition, excimer laser ablation even allows control of sidewall angle, by adjusting the laser intensity (fluence) and other means. A higher fluence produces a via or trench with steeper sidewalls, whereas a lower fluence results in a shallower side wall which has been proven using BCB (Figure 4):
Dry-etch BCB has been used for this investigation with a thickness of around 8μm on 200mm wafers using a test mask with via sizes between 20μm and 30μm. With a low fluence the sidewall is in a range between 67° to 71° influenced by the via dimension on the mask. The angel can be as high as 83° if the fluence is increased to 650mJ/cm². This is different to the photo-sensitive polymers.

LASER ABLATION PROCESS OF BCB
The main requirement for a successful ablation process is the absorption of the polymer to be ablated to the UV light of the laser system. This has been already tested for BCB in the past.

For the evaluation of the laser ablation process BCB has been coated on 200mm oxidized Si-wafers. The BCB was the so-called dry-etch BCB (Cyclotene 3000 series, trade-mark from The Dow chemical Company). The BCB-process was done according previous published results using an adhesion promoter before BCB coating. The BCB was fully cured at 250°C for 90min.

Each pulse removes a certain amount of material. The etch rate of the process is the amount of material removed by each pulse. The ablation rate is higher for larger fluence which is also shown in Figure 5:

CLEANING PROCESS OF LASER ABLATED BCB
One of the few disadvantages of laser ablation processes is the fact that some of the ablated material will condense as a kind of dust on the layer. Therefore a cleaning process is essential to avoid any interference with the subsequent process steps. No changes to this for the laser scanning process introduced here.

One approach has been evaluated which is also common in laser ablation technology: The usage of a protection layer (Figure 6):

In this case a very thin layer of an addition thinfilm polymer is deposited on the BCB or other polymer after the cure. It acts as a sacrificial layer. Any residues which will fall as a debris on the polymer not being ablated will be removed after the process using a simple stripping process. The advantage of the process is that very mild stripping solvents can be used for this process. An example is given in Figure 7:

The etch rate is less than 50nm for low fluence of 100mJ/cm² and can reach over 250nm per pulse for the high.

The debris is well visible on the BCB on the left hand side of Figure 7. No residues are in the opening which are here small lines. The stripping
process is then removing the protection layer together with all debris (right hand side in Figure 7). The main advantage is the usage of very mild stripper which will not affect the surface chemistry of the polymer layer. Even water-soluble protection layers are under investigation by the authors. The disadvantage is the additional process step which implies a coating process of polymeric layer after the cure of the polymer being ablated. This might require an additional coater module in production. Therefore a trade-off has to be made between the process line and the impact on the surface chemistry by the stripping solvents which may vary for different polymer.

TEST LAYOUT FOR LASER ABLATION PROCESS EVALUATION

The prime property to judge the quality of a new via formation process is the electrical contact resistance between the metallic layers. Therefore a test mask has been designed to give feedback from electrical point of view. A classical two-layer metallization has been designed which gives information about single via resistance using 4-Point Kelvin structures. The metal layers are structured using full-field mask aligner technology. 200mm wafer size was chosen for this evaluation. The equipment is fully compatible to 300mm wafer technology but 200mm was chosen to save cost.

There was no issue to adjust the alignment marks generated by the mask aligner to the mask of the laser ablation tool. The optical resolution of the tools is correlated to a precise alignment system for an accurate layer-to-layer registration. This is done by an automated alignment system – global and site-on-site with autopattern recognition. Front side alignment precision is much below ±1μm.

Details of the test structure are shown in Figure 8:

The via sizes have been varied on the laser mask between 2μm and 30μm to see the limits of the process. A via with a mask dimension of 10μm in 4μm thick BCB is shown in Figure 9:

The opening is around 9.3μm at the top and 7.9μm on the bottom. The result for the 7μm mask dimension is shown in Figure 10:

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For this mask the via size is less than 6μm on the top. A via with 4μm opening on the top and less than 3μm on the bottom can be achieved with the 5μm mask. Such small vias have never been published for BCB using mask aligner or stepper technology.

The threshold of different sputtered metals has been compared. Values of 1000mJ/cm² threshold for sputtered Cu and Al have been published. To verify this data for this new process and expand them to plated metal the following three metallization schemes for the first metal layer have been tested in this evaluation: 1μm AlSi, 1μm sputtered Cu (200nm TiW underneath) and 1μm plated Cu on 300μm Cu with a 200nm TiW layer as an adhesion layer. All test were done on 200mm Si wafer with an 100nm Oxide layer.

A comparison of these metals for metal 1 in the laser ablation process is shown in Figure 12:

The FIB (focus ion beam) cuts show the clean interface between the metal 1 and metal 2. No metal was damaged by the laser process. This indicates the large difference in the threshold between polymers like the BCB and the metal like Al or Cu. No difference haven been found between sputtered Cu and plated Cu. All sample had an protection layer for the removal of the debris. No descum-like process was used after the removal of the protection layer. Standard back-sputtering of Ar was used before the sputtering of metal 2 (AlSi).
SUMMARY AND CONCLUSION: COMPARISON OF LASER ABLATION VS. PHOTO-LITHOGRAPHY

Lithography in general is a multi-step process involving developers and other wet chemicals making it increasingly unattractive. All the risks and cost associated with these chemicals, and their safe handling and disposal can be eliminated using the laser ablation process. Like every other industry, advanced packaging and interposer manufacturing is under pressure to use greener manufacturing that is less polluting and more energy efficient.

It is important to distinguish excimer ablation from laser direct imaging called LDI. Excimer laser ablation is a direct one-step subtractive process which do not need any developing agents for structuring. Only a cleaning step is required after the structuring process. LDI needs photo-sensitive material and more linked to classical photo-lithography if the process flows are compared except that a focused laser beam directly writes a pattern on a resist instead using a mask. With this new process the resolution of the BCB has been improved by a factor of around 10x (Figure 13).

This technology is currently under evaluation for other polymers like PI and PBO. First results are similar to BCB.

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