Optical Characterization and Defect Inspection for 3D Stacked IC Technology

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Abstract

Advanced packaging technologies are rapidly evolving and 3D architectures requires new inspection and metrology techniques. Existing techniques need to be improved but new techniques must be developed to address new challenges induced by the last fabrication processes.

In this paper, we will present fast and nondestructive optical sensors based on low coherence infrared and white light interferometry and spectrometry techniques. These different sensors mounted on the same tool allow to characterize specifically with an excellent sensitivity, the different process steps described above. Concerning the defect inspections, techniques based on infrared microscopy and images techniques processing, it will be detailed and results will be presented to illustrate the possibilities of this new inspection technic.

Key words: Optical Coherence Tomography, NIR Microscopy, Chromatic Confocal, 3D integration, TSV.

Introduction and Background

All roadmaps predict a large spread of 3D heterogeneous integration technologies for the fabrication of miniaturized systems in the coming years. 3D integration which is one of the most significant innovations in semiconductor technology these last year generates new challenges in terms of metrology and defects inspection for TSV formation, wafer/die bonding, thinning and interconnection processes as well as for 3D architectures. The development of non-destructive optical metrology techniques is therefore critical in order to provide information on the dispersion of the related key parameters TSV depth, carrier and glue thickness, Remaining Silicon Thickness (RST) – the thickness of the silicon on top of the TSV after thinning – and the copper nails dimension, i.e. the height of the TSV extrusion after the TSV reveal process (Fig. 1).

In this paper, we present results obtained with several optical metrology techniques combined with several microscopy techniques to control the different process steps mentioned above.

Hardware description and optical metrology techniques

Fig.2 shows an internal view of the patented optical system developed and used for the experiments. It includes a top optical head with microscope objectives designed to allow thickness, airgap and etch depths measurements by Near Infra-Red (NIR) optical coherence tomography (OCT), wafer shape profiling by visible confocal chromatic microscopy, pillar co-planarity by white light full field OCT, and defects/alignment inspection by transmission optical microscopy in the NIR range. A bottom NIR OCT head can also be inserted for double side measurements. Mapping can be performed with a fast motorized XY translation of the open 300mm wafer chuck.

Figure 1: Simplified process flow with key process steps and associated parameters.
Time domain OCT:

The OCT system is based on the principle of low coherence interferometry which is presented in a simplified way in Figure 3. The light source is a super luminescent diode (SLD) with a center wavelength: \( \lambda = 1.31\,\mu m \) and a typical spectral bandwidth of 100 nm or more. A fiber optics coupler splits the light into the two interferometer arms. The sensor works as a comparator of optical group delays. The group delay along the optical axis of the probe interferometer arm containing an object, for example a multilayer on a substrate or an assembly of several wafers, is compared with the group delay of the reference arm containing a movable delay line. The latter consists of a reference mirror that is linearly displaced on a translation stage. The length of the scan defines the measurement range which is between a few \( \mu m \) up to 5 mm (optical distance), this distance can be adjusted by the equipment supplier. The optical group delay is defined as the product of group refractive index \( n_g \) and physical distance \( d \), with the group refractive index at a given wavelength \( \lambda \) being defined as:

\[
n_g(\lambda) = n(\lambda) - \frac{\delta n}{\delta \lambda}.
\]

The signals reflected by the reference mirror and by a (partially) reflecting interface in the object to be measured are combined on the detector where a low coherence interference signal is generated when the optical group delays in the two interferometer arms match each other to within the round-trip coherence length of typically 25 \( \mu m \). Each interferogram consists of a sinusoidal fringe pattern modulated by a slowly varying envelope. The fringe period equals half of the center wavelength. Assumining a Gaussian source spectrum, the full width at half maximum of the envelope is given by the round-trip coherence length.

The maximum of the fringe envelope corresponds to a group delay difference of zero between the two interferometer arms. By detecting this position of group delay difference zero and measuring the corresponding position of the delay line mirror one can determine the position on the optical axis of a (partially) reflecting surface in the object to be measured. Thanks to the limited temporal coherence of the source, i.e. limited width of the envelope, multiple surfaces of the object can be detected during a single scan of the delay line. The position of the reference mirror is measured by an internal metrology system (laser interferometer).

The minimum measurable thickness is defined by the wavelength bandwidth of the NIR source:

Minimum thickness = \( 0.44 \times \frac{\lambda^2}{\Delta \lambda} \).

With: \( \lambda \): source wavelength: 1.31 \( \mu m \) and \( \Delta \lambda \): source bandwidth: 100 nm.

Typically, using this technique, Silicon thickness from 8 \( \mu m \) up to 1500 \( \mu m \) could be measured with an excellent repeatability of 0.1 \( \mu m \) (3\( \sigma \)).

By adding an internal reference optical device, the IR interferometer can also be used as a distance measurement metrology solution. An air gap can be measured between a reference signal and the surface of the sample. This mode can be used for total thickness measurement (dual mode), bow, warp and surface flatness characterization.

Multi-Wavelength Spectrometry:

As mentioned in the previous section, the minimum measured thickness is limited to 8 \( \mu m \) for silicon. Taking in account the value of the refractive index of silicon which is 3.68 for this wavelength (1.31 \( \mu m \)), the minimum optical thickness (n.d) could be estimated to 30 \( \mu m \). To reach silicon thickness measurement capability down to 1 \( \mu m \), the SLD source is replaced by a halogen lamp. The beam is reflected at the front surface and back surface of the layer itself. Interferences are then
directly produced by the thin layer and the signal is analyzed by a spectrometer (fig.4). The Fourier Transform of the signal will give directly the layer thickness.

**Figure 4: White Light Chromatic Confocal.**

For Surface profiling metrology, the white light chromatic confocal can be used. Confocal detection consists in looking at the image of a hole reflected by a surface of interest through a similar hole. When the surface is in focus, the flux going through the detection hole is maximal, and decreases rapidly when the surface is going out of focus. A usual way for measuring a distance is then to vary the distance to the sample and then to locate the position for which the maximum power is returned.

However a smart approach was developed in the nineties in order to gain in rapidity and precision which consists in substituting the spatial scan by a spectral scan. As shown in figure 5, a custom lens is used, with very large axial chromatic aberration. Thus every wavelength of the large spectrum source is imaged in a different plane. The one focused on the surface is more coupled with the detector than the others. Looking at the returned spectrum allows knowing the distance at which the surface is lying as there is a unique correspondence between wavelength and distance.

**Figure 5: Chromatic confocal technology.**

The maximal depth of the measurement is settled by the optical design of the lens through the length of the axial chromatic aberration. Several models were designed to achieve different ranges of distances. Axial resolution is settled by spectral resolution and the choice of the holes diameter combined with the focal length of the objectives. No moving parts are needed and acquisition frequency can be several KHz.

**White Light Full-Field OCT:**

In this approach, the optical view of the sample is converted to an elevation map using interferogram processing techniques. The height of each pixel is determined independently from one to each other with a nanometer accuracy in a single scan.

**Figure 6: Michelson type full field interferometer.**

Figure 6 shows the principle of a Michelson interferometer. Light is emitted by a selectable light source (So). A beam splitter (Sp) divides the light beam in two half beams marked as 1 and 2. This device is integrated inside the interferometric objective. One of the two beams is reflected by a reference mirror (M), the other is reflected at the sample surface (P) or at internal interface in the case of transparent layers. The cube (Sp) combines the two beams and sends the resulting image, through the tube lens (L) to the camera (C).

The intensity I(d) which is measured for each pixel of the CCD camera, varies in function of the difference of length (d) between the two beams ways 1 et 2. This result in an image showing interference fringes following the equal-height lines on the sample.
Process steps characterization

The different optical metrology techniques described above are used to characterize different steps of the 3D process integration flow from the TSV etching to the TSV reveal and dye stacking (Fig. 1).

Through Silicon Via (TSV) etching

By using the NIR-OCT, a patented method consists in using an IR beam spot size larger than the TSV diameter. Two groups of waves are coming back from the top and bottom of the measured TSV and gives directly the depth of the TSV without aspect ratio limitation. The combination of this technique with white light microscopy in the same optical path, allows the user to position the spot very precisely and to get top CD dimensions at the same time (Fig. 7).

Figure 7: TSV depth measurement principle.

Figure 8 shows the “M” shape uniformity of 5µm diameter TSV depth across a 300mm wafer diameter (aspect ratio: 10).

Back-side processing and wafer thinning

The combination of NIR OCT, chromatic confocal and IR microscopy is a perfect choice for temporary bonding and wafer thinning process control. Wafer bow and warp, individual thickness and Total Thickness Variation (TTV) of each layer and bonding interface inspection are performed at the same time. Figure 9 shows results on a Si wafer temporary bonded with glue on glass wafer after thinning down to 628 µm.

Figure 9: a) Si thickness map (TTV: 1.74 µm, standard deviation 0.34µm) b) Glue/glass thickness map (TTV: 5.7 µm, standard deviation 1.52µm) c) Bow: 127.2µm, Warp: 226.7µm.

Figure 10 shows back side roughness after grinding and NIR inspection of temporary bonded wafers (defects detection and notch to notch alignment).

Figure 10: Back side roughness characterization and NIR inspection.

At the grinding process step, it is extremely important to control the Remaining Silicon Thickness (RST) below the TSV to adjust wafer thinning process parameters. The combination of NIR microscopy, NIR OCT and IR multi-wavelength spectroscopic techniques allows positioning the measurement spot on a defined TSV through the silicon bulk. Figure 11 shows the RST uniformity across a 300 mm wafer diameter just before the TSV reveal process. The results obtained depend directly from both TSV formation and wafer thinning process uniformities.
TSV reveal

After the last step of the wafer thinning process, the TSVs are revealed at the back side of the wafers. Chromatic confocal and/or full field white light OCT can perform pillar height and co-planarity measurements. Figure 12 shows the revealed pillar co-planarity within a die and Figure 13 the pillar height uniformity across the whole wafer surface.

Die stacking

The combination of multi wavelengths OCT and NIR microscopy has been used to control a die to wafer stacking process. Figure 14 shows results obtained on a test vehicle using micro-inserts for interconnection. A Kelvin bump pattern which includes a matrix of 16 micro-inserts has been used for electrical resistance measurement.

The figure 15 shows the mapping of interconnect resistance measurement between dies and the wafer. An edge effect is clearly observed, with much higher values on the edge.

The minimum resistance values obtained which are closed to 30 mΩ are located in the wafer center. This could be explained by non-homogeneity of pressure during the stacking process and confirmed by gap measurements between substrate and die using infrared microscopy combined with infrared interferometry. The results show that gaps for stacks
on periphery are 5µm higher than in the wafer center (fig.16).

Figure 16: Relative gap measured by infrared microscopy combined with infrared interferometry and chromatic confocal technology.

Thanks to this on line measurement method, pathways of improvement yield were identified and pressure stacking homogeneity issue has been improved.

**Conclusion**

Thanks to the combination of microscopy from white light to infra-red, with IR OCT, chromatic confocal, multi-wavelength spectroscopy and white light full-field OCT techniques. The multi sensor approach is able to monitor all specific process steps related to 3D IC applications.

**References**


