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Asundi, Anand Krishna; Ng, Chi Seng

2011

Ng, C. S., & Asundi, A. K. (2011). Rapid defect detections of bonded wafer using near infrared polariscope. Proceedings of SPIE - Instrumentation, Metrology, and Standards for Nanomanufacturing, Optics, and Semiconductors V, 81050P-.

<https://hdl.handle.net/10356/80598>

<https://doi.org/10.1117/12.894402>

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Rapid Defect Detections of bonded wafer using Near Infrared Polariscopes

Chi Seng Ng ^{a, b}, Anand K. Asundi^a

^aNanyang Technological University Singapore;

^bInfineon Technologies (M) Sdn. Bhd.

ABSTRACT

In modern field of microelectronics and MEMS, wafer bonding has emerged as an important processing step in wide range of manufacturing applications. During the manufacturing process, even in the modern clean room, small defects result from trapped particles and gas bubbles exist at bonded interface. Defects and trapped particles may exist on the top and bottom of the wafers, or at the interface of bonded wafer pair. These inclusions will generate high stress around debond region at the wafers bonded interface. In this paper, inspection at the bonded interface will be the interest of investigation.

Since silicon wafer is opaque to visible light, defect detection at the bonded interface of silicon wafer is not possible. Due to the fact that silicon wafer is transparent to wavelength greater than 1150nm, an Near Infrared Polariscopes which has showed some promises on residual stress measurement on silicon devices has been adapted and developed. This method is based on the well known photoelastic principles, where the stress variations are measured based on the changes of light propagation velocity in birefringence material. The results are compared and contrast with conventional Infrared Transmission Imaging tool (IRT) which is widely used to inspect the bonded silicon wafer.

In this research, the trapped particles that are not visible via conventional infrared transmission method are identified via the generated residual stress pattern. The magnitude of the residual stress fields associated with each defect is examined qualitatively and quantitatively. The stress field generated at the wafers bonded interface will looks like a 'butterfly' pattern. Wafer pairs Pyrex-Si and Si-Si bonded interface will be examined.

1. INTRODUCTION

The defect inspection at the interface is of great area to explore since there are already reliable methods using visible light to detect defects at the top and bottom surface of the wafers. Inspection at the interface of bonded wafer is not possible using visible light methods because silicon is opaque to visible light. Since silicon wafer is transparent to wavelength greater than 1150nm, near infrared NIR light source has been widely employed to detect defects that contribute to the reliability and robustness of silicon based devices. With modern clean room and technologies, particles and air bubbles still trapped on at the interface of bonded wafer pair, but the particle sizes are apparently much smaller. As a consequence, the particles and air bubbles are difficult to be visualized using conventional Infrared Transmission Tool (IRT). For most wafer fab and MEMS industry, the bonded interface of wafer pair will be inspected using IRT. The quality of the bonded interface will be judge based inspection results from IRT. The global trend of miniaturization has lead to adoption of thinner and larger wafer, Because of smaller defects, Newton's rings become less visible or do not generate at all. Further, the resolution of NIR camera is not as good as visible camera. This factor has actually has make IRT technique reaching its limit for defect detection at bonded interface if Si-wafers for modern manufacturing industry. Alternative solutions are needed to inspect the bond quality of the wafers.

Typical Infrared cameras have pixel size ranging from 25um-30um, any defects or particles trapped smaller than the camera pixel size become invisible. As a consequence, Grey field polariscopes has been developed to compensate the conventional IRT tool. Grey field polariscopes which is an evolution of plane polariscopes has been developed for full field photoelastic stress analysis. Grey field Photoelasticity was pioneer by Jon Lesniak at Stress Photonics to provide visible full field birefringence measurement in glass components [1, 2]. Instead of detecting the defects, Horn [4, 7] has presented the detection of stress field of defects and trapped particles using infrared photoelastic method. In this work,

similar approach is followed, the defects are indentified by its residual stress field generated around the defects. By using the Infrared Phase-shift Polariscopes developed, smaller defects and trapped particles can be easily distinguished by the shear stress field generated around the trapped particles. If there is a defect or trapped particle, there will be a stress field generated which looks like a ‘butterfly’ pattern if the specimen is analyzed using grey field polariscopes. In this research, wafers with glass and silicon bonded interface is chosen to take advantage of inspection of particles using visible light reflection microscopy. The regions with detected defects are compared and matched with the inspection results using photoelasticity technique. Next, bonded wafers with (100) plane are inspected.

2. INFRARED GREY FIELD POLARISCOPE

Polariscopes are optical instruments used to study the stress effect on the birefringent materials. In this section, the principles of grey field polariscopes [1, 2] will be discussed in detail. Both schematic and photograph of the proposed polariscopes are illustrated in Figure 1. The construction of grey field polariscopes includes two polarizers and a single quarter waveplate placed between the polarizers. Near infra-red light source with wavelength 1300nm is adopted. The light is projected through the first polarizer and quarter waveplate to achieve circularly polarization state. The circularly polarized light is then propagating through the birefringent material. The emerging elliptically polarized light is analyzed with a polarizer, or named analyzer.

The state of the birefringent specimen is then captured through the analyzer using near infrared camera and analyzed by a computer. The analyzer needs to be rotated in order to capture the specimen in different polarization state. For each rotation of analyzer, intensity changes are noted in each pixel in the image corresponding to the axes of polarization of the analyzer. The maximum intensity correlates to maximum stress amplitude. The phase angle between a reference of the polariscopes and the maximum and minimum intensity position represent the orientation of the shear stress.

Figure 1: Schematic and Photograph of IR Grey Field Polariscopes

The propagation of light through a polariscope can be described by Jones calculus [8]. The intensity view from the analyzer can be described as equation (1):

$$I = \frac{a^2}{2} [1 + \sin \Delta \sin 2(\alpha - \beta)] \quad (1)$$

The intensity, I is dependent on the angular position of the analyzer. As the rotating analyzer will align with the maximum intensity twice per full rotation, i.e. the brightness of a particular point will reach the maximum brightness twice per full rotation of the analyzer, the intensity will be modulated at 2α and with phase of 2β .

Equation (1) can be rewritten as below:

$$I = I_a + I_{c\alpha} \cos 2\alpha + I_{s\alpha} \sin 2\alpha \quad (2)$$

where

$$I_{c\alpha} = -\left(\frac{a^2}{2} \sin \Delta\right) \sin 2\beta, \quad (2a)$$

$$I_{s\alpha} = -\left(\frac{a^2}{2} \sin \Delta\right) \cos 2\beta \quad (2b)$$

and $I_a = \frac{a^2}{2}$, is the average intensity collected by the detector unit.

2.1. PHASE SHIFTING PHOTOELASTICITY

The phase shifting approach has been widely employed by many classical interferometric techniques. In most interferometers, phase differences can be added by altering the phase of the reference light beam with known phase values and measuring the local light intensity after each step. In photoelasticity, the change in phase can be obtained by the rotation of analyzer.

This technique offers rapid, accurate measurements resulting in full-field maps of isochromatic and isoclinic parameters. Patterson and Wang [9] have presented an algorithm that determines the fractional fringe order and principle stress directions from six equations.

In grey field polariscope as built in Figure 1, the emerging light from the analyzer at any point (x, y) take the general form as in equation (1). In phase shifting technique, at least four simultaneous equations are needed to solve for all the unknowns [8]. By rotating the analyzer, a set of equations of the form of equation 3 are generated to solve for Δ and β .

$$I_1 = I_a [1 - \sin \Delta \sin 2\beta] \quad (3a)$$

$$I_2 = I_a [1 + \sin \Delta \cos 2\beta] \quad (3b)$$

$$I_3 = I_a [1 + \sin \Delta \sin 2\beta] \quad (3c)$$

$$I_4 = I_a [1 - \sin \Delta \cos 2\beta] \quad (3d)$$

By mathematical manipulation of equation 3 the equation for Δ and β can be derived as follows:

$$\sin \Delta = \frac{1}{2I_a} \sqrt{[(I_3 - I_1)^2 + (I_4 - I_2)^2]^2} \quad (4)$$

$$\beta = \frac{1}{2} \tan^{-1} \left(\frac{I_1 - I_3}{I_4 - I_2} \right) \quad (5)$$

3. DEFECT INSPECTION OF BONDED WAFERS

In this section, trapped particle and defect inspection of several wafers using Infrared phase shift grey field polariscope will be discussed. The principle behind is that this polariscope measures the residual stress fields generated due to the defect or trapped particles attach at the interface between two bonded wafers. Stress generated under this situation can be termed as an elastic indentation problem [6]. There are literatures documented that even a small elastic indentation in brittle material such as silicon wafer leads to large stress that are easily measure using the photoelastic stress analysis method [15].

3.1. ANODIC BONDING WAFER

Pyrex wafer and Si-wafer is bonded to take advantage of inspection of particles using visible light reflection microscopy and infrared polariscope. The particles identified by reflection microscopy will be inspected using IR polariscope to confirm its existence and the generated stress field around the particles. Figure 2 shows the IRT image of the anodic bonded wafer. The field of view is about 18mm diameter. In this image, all kind of defects and contaminations at the top, bottom and bonded interface of the wafer are visible in the IRT image. This actually makes it difficult to differentiate between surface defects and defects at bonded interface. Defect inspection using IR polariscope is simpler, defects are trapped between the bonded wafer pair will generate a stress field around itself. This feature actually makes the defects differentiation more superior. In Figure 2, two Newton's rings are visible and highlighted in red dotted box. The two Newton's Rings are further inspected by using reflection microscopy to visualize the size and shape of the particles. The images of particles label region (a) and (b) in Figure 2 are shown in Figure 3, the images are captured by

the reflection microscopy. Consequently, the same location is being examined using IR polariscope by incorporating phase shifting technique. Figure 4 shows the four phase shifted images with equal shifting interval. Figure 5 shows the corresponding distributions of stress components and direction of principle stress. From the direction, k and phase retardation, Δ distributions, one can observe many more defects/trapped particles that are not visible in the IRT and phase shifted images. These small defects/trapped particles generate low stress to make the identification difficult using conventional IRT. By using our proposed technique, by observing the changes in principle stress direction and phase retardation distribution, the small trapped particles can be detected. The trapped particles are pointed by arrows in Figure 5. Shear stress magnitude calculation is not possible for the anodic bonded wafer, since the stress optic coefficient is not known. Only relative comparisons in stress components are possible in this study.

Figure 2: IRT image of Anodic Bonded wafer

Figure 3: Shape and size of the particle by reflection microscopy (a) Region a (b) Region b

Figure 4: Phase- shifted image using IR Polariscopes

Figure 5: Shear Stress components, I_{ca} , I_{sa} , principle stress direction, k & phase retardation, Δ

3.2. SI- SI BONDING

Quantitative values of the anodic bonded wafer cannot be calculated since the stress optics coefficient for glass-wafer interface is not known. For Si wafer, the stress optics coefficient can be obtained from equation 6:

$$C_{(100)} = (2.657 \sin^2 2\theta + 0.707 \cos^2 2\theta) \times 10^{-11} \text{ Pa}^{-1} \quad (6)$$

The value of C varies according to the viewing direction. Figure 6 shows the IRT image of (100) Si-Si bonded wafer, the arrays of lines are created using femtosecond laser with dimension varies from 100-200um. The patterned wafer is then bonded with another Silicon wafer using standard force, vacuum and temperature bonding parameters. The wafer is then annealed in the oven at 300°C for 3 hours. The 'butterfly' shear stress patterns initially were not visible at all, the shear stress patterns only appear after the annealing process. That means the bonding strength for the pattern wafer is weak, this may due to the surface irregularities. The plot of the principle directions shows that the stress direction oriented along 0 and 90 degree for this inspection. Further investigations are needed to confirm the orientation of the stress direction. Uniform shear stress patterns are observed at the beginning of each laser created slot.

Figure 6: IRT image of bonded patterned Si wafer

Figure 7: Phase shifted Images of bonded pattern Si wafer

Figure 8: Principle stress direction, k & Phase Retardation, Δ of patterned Si wafer

Large stress can be easily identified from IRT image. Small defects are not able to be distinguished without phase shift algorithm process. Figure 9 show another Si-Si bonded wafer this wafer pair is bonded directly without going through cleaning process. This wafer is claimed cleaned without contamination. Since the wafers are fresh from the seal wafer box, no large particles / Newton's Ring can be observed from the phase shifted image. But after the algorithm processed, there many small particles trapped at the bonded interface of the Si wafer pair. These trapped particles are easily identified in Figure 10.

Figure 9: Si-Si Bonded Si wafer

Figure 10: Principle stress direction, k & Phase Retardation, Δ of Si-Si wafer

Next another Si-Si wafer pair from same batch of wafer is wash with DI water before bonding process. The wafers are then spinned dry before bonding. The intention is to get rid of the small particles as seen in Figure 10. Figure 11 shows the Si-Si bonded wafer which is washed before bonding process. Examined under the IRT and IR polariscope, those small trapped particles associated with small magnitude of stress disappear. On the other hand, larger trapped particles are observed. These particles are believed to be water/vapors form at the interface of the bonded wafer. Repeated bonding process is performed and the same phenomenon is observed. Further verification will be carried out to verify the statement claimed. The shear stress pattern in Figure 12 also differs from those illustrations in this research.

Figure 11: IRT image of Si-Si bonded wafers

Figure 12: Principle stress direction, k & Phase Retardation, Δ of Si-Si wafer

Conclusion

IR grey field polariscope has proved its superiority over conventional IRT imaging system. Conventional IRT imaging system would not provide the information regarding the state of shear stress associated with the defects. Infrared Grey Field Polariscope offers the features to identify the defects via the stress field generated that are not visible via conventional IRT systems. Similar shear stress patterns in 'butterfly' form are observed regardless the size and shape of the defects. The Glass-Silicon bonded wafer confirms the butterfly pattern associated to trapped particle/defect. One Newton' ring may be attributed to several trapped particles/defects. From the findings, one butterfly pattern is associated to a trapped particles/defect.

ACKNOWLEDGEMENT

I would like to thank Dr. Tan Chuan Seng and Mr. Chong Gang Yih from School of EEE, Nanyang Technological University for the full support in silicon sample preparation. Their precious ideas and dedicated support on the bonded silicon sample are very much appreciated.

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