Evaluation of Silicon on Insulator (SOI) Bonded Wafers Using Automated Acoustic Micro Imaging

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ABSTRACT
There is increasing use of Silicon on Insulator (SOI) in the manufacture of integrated circuits due to advantages in speed and power (high speed/low power requirements) in the devices. In the process of manufacturing the SOI bonding defects can occur. Acoustic micro imaging has become an established laboratory method for defect detection in SOI bonds. Now, with the increase in demand there is a need to increase the rate at which the wafers can be inspected. Techniques have been incorporated for automated parts handling and computer image analysis to allow for inspection at a more rapid rate. Recent advancements in resolution, automated parts handling, and in image analysis software have been combined to significantly advance the application into the realm of practicality outside of the lab.

This paper will present a discussion of acoustic micro imaging as it applies to the analysis of SOI bonding and show how methods to avoid contamination of the wafers and automatic parts handling can be integrated into the inspection method to provide for rapid inspection rates of the wafers.

Key Words: SOI, Wafer bonding, Acoustic Micro Imaging

WAFER TO WAFER BONDING

Silicon-on-insulator (SOI) is a materials system that provides a thin device layer of silicon on a totally insulating substrate. Although SOI has been used over the years for specialty applications there is new attention being focused on SOI for advanced devices, SRAMs and DRAMs that require improved device isolation and latchup immunity, low power requirements and high-speed operation, and improved radiation immunity. [1][2]

One manufacturing technique to obtain the SOI structure is wafer–bonded SOI (BSOI). Basically, the initial step involves a contact bond between two wafers. At this point the wafers are held together by Van der Wals forces between hydrated surfaces [2]. Next, annealing at higher temperature strengthens the bond. Then thinning of one of the wafers is done to different degrees depending on the application of the device layer. High speed/low power devices will use a thinner layer where as high power, high voltage SOI circuits will use a thicker layer [3].

One of the most important problems that can occur in bonded wafer technology is voiding at the interface as it can result in the loss of the device layer in the unbonded region. [3] Acoustic Micro Imaging (AMI) has proven a successful method for the detection of voids at the bond interface in wafer to wafer bond samples.

ACOUSTIC MICRO IMAGING

Reflection mode acoustic microscopes operate in the pulse-echo mode, typically over a range from 5 to 300 MHz, to produce images of samples at specific depth levels. In general the higher the frequency the higher the resolution in the acoustic images. Lower frequencies, however, provide more transmission through materials. A focused ultrasonic transducer alternately sends pulses into and receives pulses from reflected signal and discontinuities within the sample. Since the echoes are separated in time based on the depths of the reflecting features in the sample, an electronic gate is used to select a specific depth or interface to view. A very high speed mechanical scanner is used to index the transducer across the sample and produce images in tens of seconds.

In reflection mode Acoustic Micro Imaging the fundamental information is contained in what is called the A-Scan. The A-Scan displays the echo depth information in the sample at each x,y coordinate. Echoes displayed in the A-Scan correspond to different interfaces in the device being examined. The distance between the echoes relates to their depth in the device. The amplitude and phase polarity information of the echoes is used to characterize the condition at the interface. The equation that describes the interaction between materials at an interface is as follows:

$$R = I \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Where R is the amplitude of the reflected pulse, I is the amplitude of the incident pulse, Z_1 is the intrinsic acoustic impedance of the material through which the pulse is traveling and Z_2 is that of the material which is encountered by the pulse.

The most common imaging method used to evaluate devices for delaminations and voids is the interface scan. This method involves gating the A-Scan signal for the appropriate echo from the interface to be investigated. The geometric focus of the acoustic beam is optimized for the interface as well. The acoustic image of the interface displays both the amplitude and phase (polarity) of the gated echoes via the AIPD (Acoustic Impedance Polarity Detector). In this mode an image is made of just the positive echoes or just the negative echoes or both combined within the same image. Different color maps are usually employed to differentiate the echo polarity information and the grey scale/color intensity used to display echo amplitude.

The acoustic impedance mismatch at an interface determines the contrast of features in the acoustic images. In the case of silicon to silicon bonding the bonded area returns little if any signal due to the impedance match at the interface of the identical materials. The void however reflects 100% of the ultrasound. This provides optimum contrast in the images for the detection of air-gap type defects in Si/Si bonded wafer samples. Figure 1 displays the acoustic image of a bonded wafer interface showing voids at the interface. A-scans are included comparing the signal from a bonded area to an area containing a void. The example shows a bonded wafer after annealing and before back thinning, however the analysis of the wafer/wafer bonds can be performed prior to and after annealing, and before thinning and, to some extent, after thinning of one of the wafers.

One of the major considerations in the acoustic analysis of the wafer bond interface is resolution/detectability of the minimum defect size. The minimum z-axis dimension for detectability of an air gap using ultrasound has been found experimentally to be on the order of 0.1 microns at 15 MHz and estimated to be much better at high frequency. With regard to spatial (x,y dimension) several factors affect the resolution in the acoustic image: The frequency of the transducer, focal length, fluid path, and signal strength. These factors are discussed in greater detail in a previous paper [4]. In short, high frequency combined with a low F# and short fluid path will give the best potential resolution in the image. At the same time a sufficient working distance must be maintained in order to obtain focus at the interface and scan the sample without mechanical interference. Silicon material allows for the transmission of ultrasound at high frequencies and the design of the transducers can accommodate the sample thickness without sacrificing resolution/detectability.

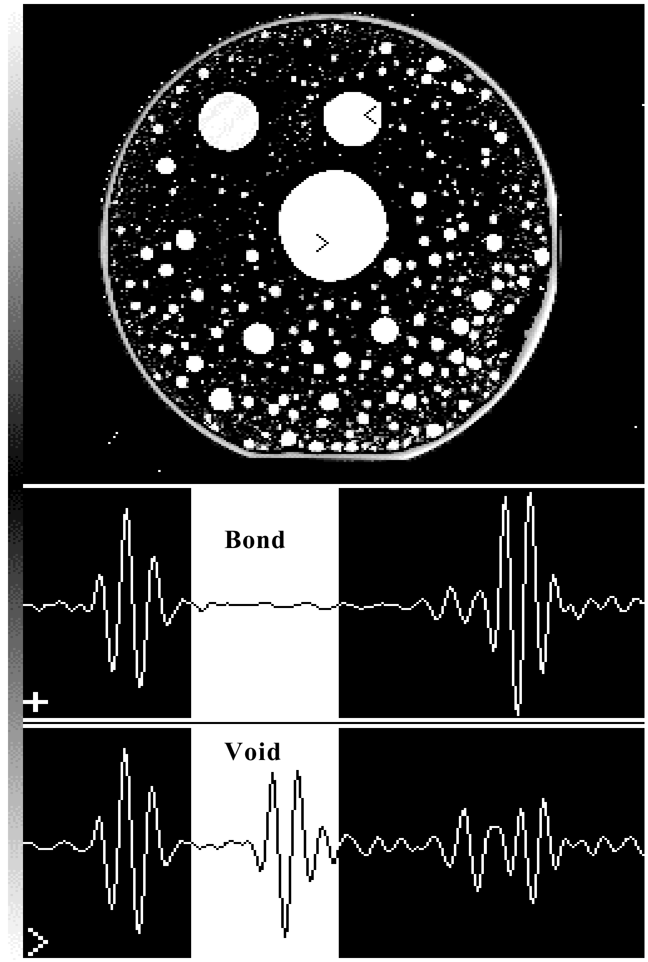

Figure 1 - The acoustic image shows the bond interface between two wafers. The voids appear white in contrast to the bonded areas shown in black. The A-scans below the image show the gate for the interface as the white window over the trace. The bonded area shows no reflection within the gate where as the void shows a high amplitude reflection.

Initial investigations into the quality of wafer/wafer bonds (circa 1990) used a frequency of 100 MHz. At this frequency resolution of features in test wafers was on the order of 23 microns. Since that time continuing developments in AMI have improved the resolution and therefore the minimum flaw detection capability. Experience with implanted flaws in test samples, and resolution targets have proven that at 230 MHz AMI has the capability of detecting flaws/features as small as 5 microns (spatial dimensions). Figures 2 and 3 show the results of scans of a Si/Si test target illustrating the present resolution/detection capabilities afforded using high frequency AMI.

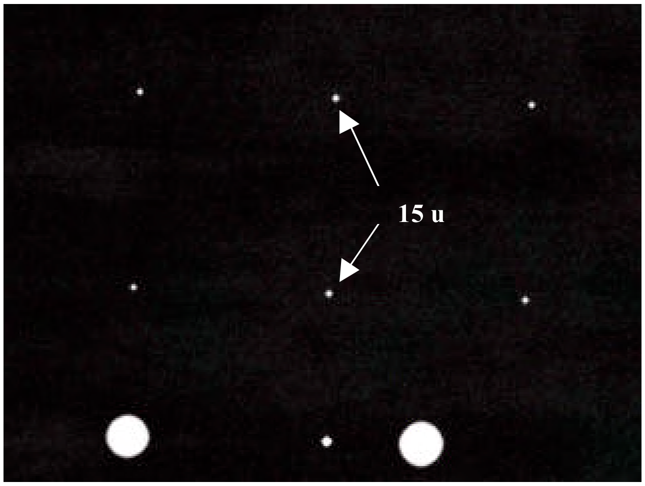

Figure 2 - Image of a silicon test wafer showing 15 micron “implanted” voids. The 15 miicron voids are the 6 small features in the image. The two sizes of larger voids at the bottom of the screen are on the order of 30 and 300 microns respectively.

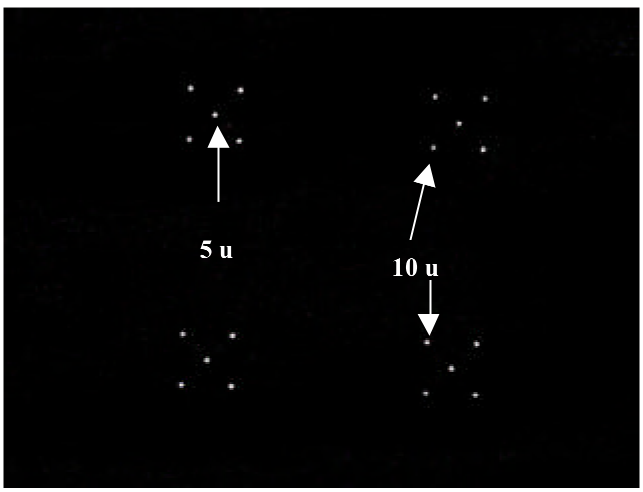

Figure 3 - Test wafer showing 5 and 10 micron voids. The 5 micron voids in the center of the pattern appear similar in size to the 10 micron voids. The 5 micron voids are beyond the theoretical resolution limit of the ultrasonic frequency, 230 MHz, however they are still readily detected at this frequency.

Parts Handling

In order to prevent contamination of the wafer samples, automated parts handling is incorporated into the inspection system. Earlier in the development of the application the wafers were individually introduced to the inspection area of the acoustic microscope using a tray that was loaded manually by operators using appropriate cleanliness precautions. This method was sufficient for low volume throughput for failure analysis or R&D type uses. Since that time wafers have been transported through the inspection area by means of stack loaded tray conveyors. This method is used in conjunction with an acoustic inspection system modified for in line use at production speeds. This method however was limited to inspection of wafers that fit within the dimensions of a JEDEC size tray (4 inch diameter wafers). Most recently robotic handling of the wafers to and from cassettes is used. The robotic handling of the wafers resembles the type of handling used in other systems involved in the processing of wafers into devices and is currently capable of accommodating up to 8-inch wafers.

Software Analysis

Objective, automated analysis of the information contained in the acoustic images is accomplished via digital image analysis software. The area for analysis is defined using a computer-generated window and the image within the window is converted to a binary format. The threshold for the intensity values in the image corresponding to voids is usually established from analysis of the histogram of intensities present within the windowed area. However in the case of Si/Si bonds there is no ambiguity for the threshold value between bond and void.

Accept/reject criteria that are appropriate for the application can be defined using image analysis software. The combination of automated parts handling and image analysis allows the AMI system to automatically scan and sort the wafers without operator intervention except to exchange the cassettes.

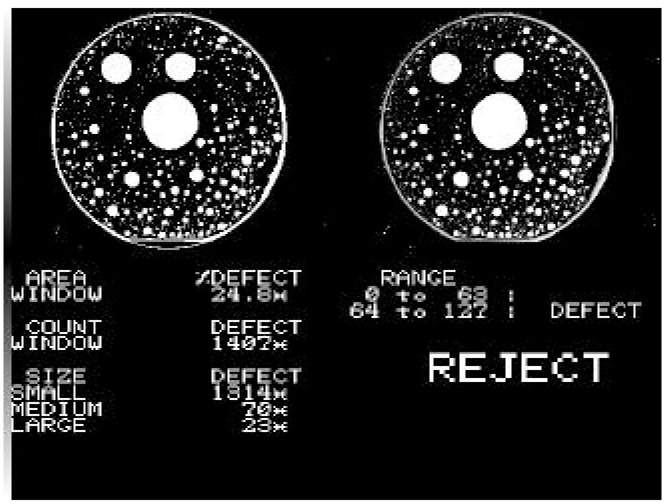

Figure 4 - The above image displays an example of image analysis of a wafer bond. The windowed, binary (thresholded) image (upper left) appears very similar to the original image of the wafer (upper right) due to the clear contrast difference between bond and voids. The statistics at the lower half of the screen give the values for the total area of voiding, total number of voids, and the number of voids in three size categories. Asterisks mark the values that are cause for rejection.

Related Applications

Evaluation of silicon wafer bonding using an epoxy adhesive layer has also been accomplished using AMI. The contrast between bonded areas and voids is not as great as in the bonds without an adhesive however it is sufficient to clearly discriminate voids from bonds. Figure 5 displays an image of an epoxy-bonded wafer. In the section of the wafer shown in the image the dark grey areas correspond to the epoxy bond. The white/light grey areas represent the stronger reflections from the gap. The device pattern is visible in the image of the interface as well. Silicon on glass/silicon sensor applications have similar considerations. In sensor applications the silicon layer has been thinned and it is necessary to adjust the imaging parameters to obtain the information at the bond interface. It is a matter of analyzing the reflection levels from the bonded areas compared to the reflections from the voids in order to establish the threshold value for the automatic analysis. In sensor wafers or devices the bond area is at the periphery of the devices. In a single device the bond area for analysis will appear as a frame around the central sensor cavity. Over the entire area of the wafer the bond pattern will appear as vertical and horizontal streets and alleys. The pattern of the bond is defined in the analysis software in order to eliminate extraneous information from the evaluation.

Crack detection in bonded or single wafers is also possible. In this application the cracks in the silicon are "shadowed" against the bond interface (as seen in the example of the epoxy bonded silicon wafer – Figure 5) or through to the back surface of a single wafer (Figure 6). The size of the shadow produced by the crack will be proportional to the depth of the crack. This normally renders the crack more detectable in the acoustic images and provides information in the images related to depth variations.

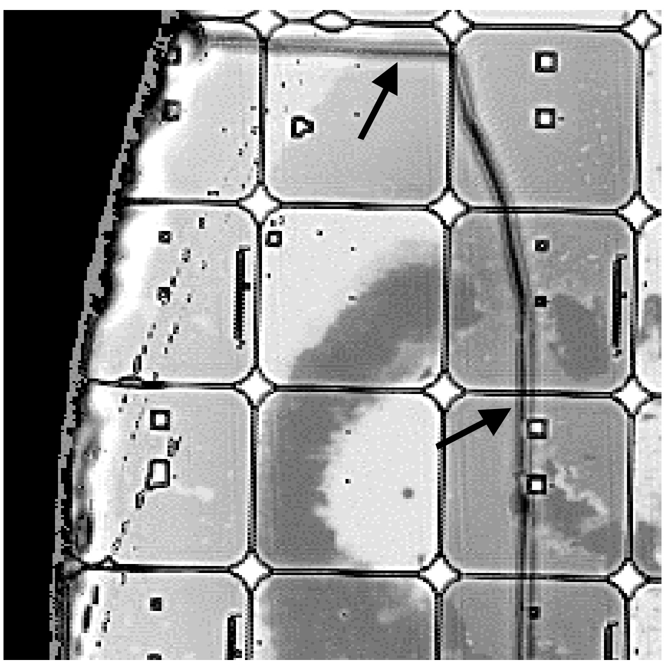

Figure 5 - Acoustic image of an epoxy bonded wafer. The bright areas indicate the disbonded areas. Dark grey areas indicate bonding. The pattern of the devices can be seen in the image. A crack is also present in this sample (arrows).

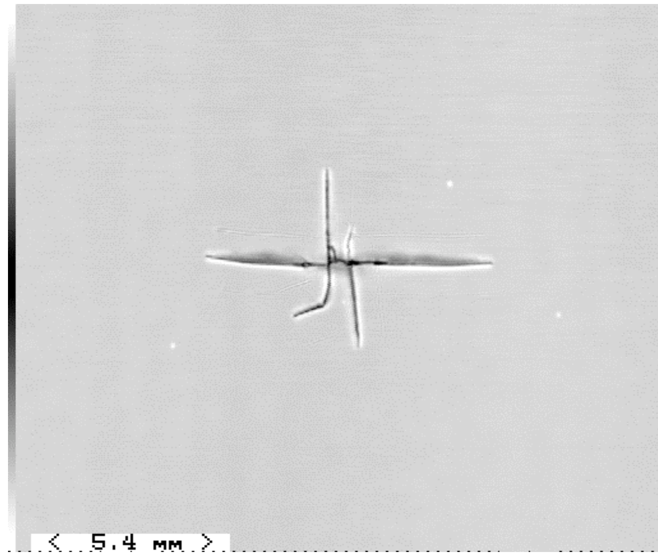

Figure 6 - The crack in a single wafer appears as an intersection of dark lines in the acoustic image. The thicker lines correspond to areas of the crack with a greater depth.

Conclusions

The evaluation of silicon to silicon bonded wafers has proved to be an excellent application for Acoustic Micro Imaging. The addition of automated parts handling and image analysis capabilities have moved the application from the R&D laboratory environment into the realm of production, quality control operation.

The continuing improvements in resolution in AMI not only benefit the silicon on insulator and related applications but impact packaging applications such as flip chip bonding, die attach/ laser diode attach, and Multi Chip Module/ hybrid bonds.

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