Cross-sectioning Technique for Bonded Silicon Substrates with Face-to-Face Interlaced Carbon Nanotubes in Microchannels

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Abstract—Cross-sectioning plays an important role in failure analysis. However, commonly used polishing method affects the bonded silicon microchannels and face-to-face interlaced carbon nanotubes (CNTs). Polishing damages the edge of the microchannels and the debris from polishing may be trapped in the microchannels. This paper proposes a novel cross-sectioning technique to realize precise cross-sectioning while maintaining the integrity of bonded silicon microchannels and face-to-face interlaced CNTs. Result shows intact cross-sectioning of the microchannels and CNTs inside.

Keywords—Microchannels, Carbon Nanotubes, Reliability, Failure Analysis.

I. INTRODUCTION

Active on-chip cooling for high power integrated circuits could effectively enhance CMOS chip performance [1,2]. Carbon nanotubes (CNTs) in microchannels could further improve the heat dissipation due to large surface area to volume ratio of the CNT [3]. Large heat dissipation capacity of cooling 5000 W cm⁻² power density hotspot down to 40 °C was achieved with CNTs microchannels [4]. To dissipate heat more effectively, higher pressure flow is preferred, but it is challenging to ensure good adhesion between the two bonded parts of microchannels when the pressure in channels is much higher than the atmosphere [5]. In mass production, small particles may contaminate the surface of the wafer, which leads to the unbounded region at the bonding interface. The smaller bonded area further limits the maximum pressure of flow in channels, which decreases heat dissipation capability. So it is meaningful to have a method, which effectively inspect detachment between bonded substrates at the bonding interface, and it will be better if the technique does not affect the CNTs in microchannels.

To inspect the bonding interface of microchannels, cross-section together with scanning electron microscopy (SEM) is a common method [6]. Mechanical cutting and polishing are frequently used to obtain cross-section for SEM inspection. However, for this application of cutting bonded microchannel samples with CNTs, there are some special considerations. Firstly, compared to normally packaged samples, it has microchannels, and CNTs in microchannels. These are not able to be able to withstand large mechanical force like milling or polishing. Secondly, compared to the single-layer silicon sample, the bonding interface could be considered as a preset defect, and could also be affected when there is a mismatch of shear force between the top and bottom substrates.

Polishing is a common cross-sectioning method, but there are three main challenges for this application. Firstly, the viscosity of epoxy for sample molding is usually high and could not penetrate small channels. Secondly, particles in lubricant and residue generated by polishing could be trapped in microchannels and affect the inspection. Thirdly, polishing is a strong mechanical process, and the interface between silicon and CNTs could be easily affected. As a result, cross-section polishing is not suitable for this application.

Diamond cutting is another method for obtaining cross-section. It is mainly used to cut single layer silicon samples because the crystallized substrate prefers to break along the crystalline phase. The advantage of this method is that it will not affect the interface between silicon and CNTs, so the sample does not need to be embedded in epoxy to protect the surface. However, there are also two other challenges to use this method to cut bonded substrates with microchannels and CNTs. Firstly, it is difficult to control the cutting position accurately, especially when the same position is required on two samples for comparison purpose. Secondly, depending on the method of silicon bonding, the interface may not be strong enough to overcome the shear force induced by diamond cutting.

To solve the problem, wafer saw is used. It is not commonly used for making cross-section, because it will result in a relatively rough edge compared with the previous two methods. However, when the depth of wafer saw does not penetrate through the bonded interface, the bonding will not be affected. Furthermore, the cutting depth and position could be precisely controlled, and silicon prefers to break according to the cutting line when the cutting depth is not through silicon. Taking these advantages, it has the potential to overcome the challenges of polishing and diamond cutting for this application.

II. EXPERIMENT

The purpose of this experiment is to inspect the cross-section of bonding defects while not affecting the silicon microchannels and CNTs inside the channel. As a result, a 0.5um gap beside the channel was designed and etched before the bonding process. The bonding process was chosen to be silicon dioxide to silicon dioxide hybrid bonding because the sealing performance of hybrid bonding depends on the cleanliness and the flatness of silicon dioxide surface. These could be controlled by microelectronic fabrication.

Meanwhile, CNTs were synthesized on both sides of face-to-face bonded silicon after dicing. It could be further broken into half to test the effect of the wafer saw assisted cross-sectioning to the interface between silicon and CNTs on both sides of face-to-face bonded silicon. At the same time, this experiment was also used to examine the effect of channel width on the synthesized height of CNTs inside the microchannels. Longer CNTs have a higher potential to assist complete heat exchange between the chip and the fluid.
As illustrated in Fig. 1 (Step 1 & 2), the fabrication starts from two 400µm thick (1 0 0)-4-inch silicon wafers. One wafer was patterned with the designed defect area and etched 0.5µm by reactive ion etching (RIE). Another wafer was patterned with silicon trenches and etched around 17µm by deep reactive ion etching (DRIE). Both wafers were cleaned and grown with 100nm silicon dioxide by wet oxidation. Then, the alignment patterns were made on the backside of each wafer. Subsequently, the 2nm Fe catalyst was evaporated on the front side of both wafers and patterned by a lift-off process.

The bonding process (Fig. 1 Step 3) starts from DI water rinse and N₂ gun dry. When there is no visible water droplets, two wafers were aligned and underwent wafer bonding by SUSS SB6. 400°C 2 hours bonding in 10⁻⁵ mbar vacuum with 2000N force was applied.

Wafer saw was conducted after the bonding process. Through-channel sawed was made on the sample in Fig. 1(a), which was then encapsulated and polished to achieve sample Fig. 1 (b). Corresponding SEM of the channels was shown in Fig. 2(a) and Fig. 2(b). Through-channel saw was also applied to dice bonded wafers with preset defects. However, the yield of chips that remained bonded after dicing was lower than 5%, so they were not used for comparison.

For samples of Fig. 1(c) and Fig. 1(d), aligned saw of about 200µm ± 50µm depth was made on top and bottom sides of bonded wafers. NBC-ZH 2050-SE 27HEEG DISCO dicing wheel was used, and the kerf width was 55.0µm ± 5.0µm. The dicing speed was 2mm/s with spindle 30000rpm. And the dicing position and depth were controlled with DISCO DAD321. Wafer saw depth could be checked with VK-X200 3D Laser Scanning Microscope. Polyethylene terephthalate (PET) base dicing tape ADWILLD-210 was used to protect the top side when cutting the bottom side and then released with a 10min 200W 365nm UV-A flood curing by ELC-4001. Both the boundaries of chips and the positions for cross-sectioning were cut at the same time. After the half depth wafer saw on both sides of bonded wafers, the sample could be manually broken along the expected positions. And the exposed microchannels could be inspected by SEM as shown in Fig. 2(c) and Fig. 2(d). The surface roughness of the wafer saw region and manual break region were quantitatively compared by the developed interfacial area ratio (Sdr) measured with 3D laser scanning microscope VK-X200.

For the sample in Fig. 1(d), after manually breaking the wafer into chips, CNTs were synthesized at 800°C for 5min in plasma-enhanced chemical vapor deposition (PECVD). Further cross-sectioning was also made by manual breaking along the wafer saw trench. Microchannels and CNTs inside were observed with SEM as shown in Fig. 3(a-d).

III. RESULTS

As is shown in Fig. 2(a), edges of microchannel were damaged, and silicon residues were trapped in the channel after the through-channel wafer saw. The grinding lines were also obvious because thick blade dicing wheel B1A801 was used for through-channel wafer saw. Similarly, as is shown in Fig. 2(b), the polishing process damaged the edge of the microchannel, and particles were trapped in the channel.

Compared with the cross-section result of through-channel wafer saw and polishing, the performance of wafer saw assisted manual breaking could achieve much higher sharpness of the channel edge shown in Figs. 2(c) and 2(d). As shown in Fig. 2(e), the Sdr of breaking regions (0.007) is much smaller than the Sdr of wafer saw regions (0.025).

The proposed novel method also makes it possible for the detection of 0.5µm preset defect gap shown in Figs. 2(d) and 2(d1). Undulative sidewall due to the Bosch process of DRIE could also be observable with high magnification zoom has shown in Fig. 2(c1).
Fig. 2. (a) SEM of microchannel cross section achieved by through-channel wafer saw; (b) SEM of microchannel cross section achieved by polishing; (c) SEM of no-defect microchannel cross section achieved by wafer saw assisted manual breaking; (c1) Zoom in of bonded interface; (d) SEM of with-defect microchannel cross section achieved by wafer saw assisted manual breaking; (d1) Zoom in of defect region; (e) Developed interfacial area ratio (Sdr) comparison of manual break regions and wafer saw regions.

Fig. 3. (a) SEM of CNTs in microchannel; (b) Zoom in SEM of the microchannel; (c) Zoom in SEM of the CNTs on top side; (d) Zoom in SEM of the CNTs on bottom side; (f) Plot of the CNTs height on top and bottom sides depended on the width of microchannels. Longer CNTs is preferred for more complete heat exchange.
According to Fig. 3, CNTs could retain their original structures in microchannels, and the interface between silicon and CNTs was not affected. As shown in Fig. 3(e), the height of CNTs increases from 4.2 to 4.45µm for the top side and from 4.5 to 4.85µm for the bottom side with the enlargement of channel width from 100µm to 400µm. The length growth of the CNTs saturated when the channel width was increased further. This indicates a relatively wider channel could result in longer synthesized CNTs to assist complete heat exchange.

IV. DISCUSSION

The key points of the wafer saw assisted cross-sectioning include the wafer saw depth and the manual breaking. Both of them are dedicated to preventing shear force mismatch among the two wafers.

There are three reasons why the wafer saw should not penetrate through the bonding interface. Firstly, according to Fig. 2(a), the wafer saw will damage the surface of microchannels. Secondly, according to Fig. 2(e), the cross-section cut by wafer saw has higher surface roughness compared to manual breaking. Thirdly, when there is a preset defect in some bonding region, the bonding force was weakened. If wafer saw penetrates through the bonding interface, the two wafers could be separated. It is because the weak bonding could not withstand shear force mismatch between the two wafers induced by the horizontal vibration of the dicing wheel.

After the wafer saw, the chips should be manually broken apart. Further cutting with a diamond stylus will also separate the bonded wafers due to mismatch in the induced shear force. When manually breaking the samples, the wafer was bent with four fingers holding on to both top and bottom sides of the wafer close to the target trench made by wafer saw, which defined the line of breaking. Over 90% yield could be achieved by wafer saw assisted manual breaking.

V. SUMMARY

In this paper, the method of the cross-section by trench assisted manual breaking is proposed. The preset 0.5µm defect could be observed with SEM. This method prevents the original situation of microchannels being damaged by the sample preparation processes. Even CNTs grown inside the channel could preserve their geometry.

Manual breaking to achieve the cross-section is easy for sample preparation. For the inspection of industrial mass productions that require consistent sample preparation, it may also be possible to make a mechanical fixture followed by four-point bending to replace the manual breaking step.