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Die separation and rupture strength for deep reactive ion etched silicon wafers

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Abstract

The work herein analyzes the bending stress required to separate and rupture die from notched silicon wafers. Trenches are formed on the wafers using either a dicing or Bosch deep reactive ion etching (DRIE) process. Weibull distribution parameters are reported for all variations of the fracture experiments. Additionally, the relative defect rate associated with DRIE-based die separation are compared with traditional saw methods for a variety of notch depths. Results indicate that the DRIE-based separation technique offers improved rupture strength over the traditional methods, but can also greatly reduce die strength if performed improperly. Dies completely separated by the DRIE process showed a mean failure stress of 1.16 GPa with a Weibull standard deviation of 682 MPa compared to 452 and 65 MPa mean and standard deviation stress for die completely separated by a traditional dicing saw.

1. Introduction

1.1. Background

Die separation and packaging are very important processes in the microfabrication industry. To achieve an undamaged, structurally stable device, care must be taken in the choice of separation technology. Separation methods include dicing saws, dice-by-thinning, chemical wet etching, stealth dicing, laser ablation, or a water jet approach [1]. Excessive forces, vibrations, and surface contact during some of these methods can cause undesirable side-wall chipping and microcracking [2], which often translates to inoperable devices or a weak device which fails prematurely. A parallel etching process, deep reactive ion etching (DRIE), offers an alternative technique for die separation with less mechanical force. A three-point bending rig can separate partially etched DRIE samples, or a wafer can be etched completely through its thickness.

Bulk processing improves the cost competitiveness of micro-scale devices by allowing dozens, if not hundreds, of devices to be fabricated on a single wafer. Additionally, these processes are generally scalable, letting fabrication facilities optimize throughput by performing batch processes on larger diameter wafers containing even more die. Improvements in die yield, die reliability, and reduced process time can lend tremendous savings to microfabrication based companies. Die yield is increased by reducing the amount of pre-maturely failed die right after the separation stage of processing. An increase in reliability is achieved by raising the failure strength of the die so that handling during packaging or operation is permissible. Very large diameter wafers containing many devices require long separation times when using serial dicing methods. Conversely, a clean cutting parallel separation method such as DRIE could address some of these reliability and production time issues.

1.2. Separation methods

Low die strength due to an induced crack or chip is common to mechanical grinding separation techniques and can immediately yield a bad device or lead to premature failure. Currently, most manufacturers separate die by means of mechanical grinding via the use of a diamond saw or more commonly, a ‘dicing saw’. One problem that arises from use of this technique include chipping and cracking on the top and bottom edges of the substrate near the sawn grooves where bending stress will affect it most. Lowering the speed of the dicing saws traversing speed (10 to 15 mm s$^{-1}$) tends to reduce the amount of chipping and cracking of the substrate [3]. The groove width dimensions for a dicing saw, or kerf...
widths, for this type of separation technique are around 20 to 50 μm for thin wafers [1, 3].

Accompanying the edge chipping and cracking problem experienced, dicing saws also leave stresses in the sidewall surfaces that may cause die failure at low external loads. High-pressure cooling water, needed to cool the blade during diamond saw cutting, can damage sensitive mechanical and electrical devices via direct force or contaminate a device via diffusion [4]. Previous works have noted unacceptable chipping of die edges from dicing saws [5, 6], the extent of which is dependent on the cutting rate, blade width, etc [1]. Ways to protect these die from damage include using protective polymers [7] and glass caps [8].

Some other techniques are laser ablation, multi-laser beam dicing, scribe-and-break, dice by thinning, water jet dicing, and stealth (or, ‘Mahoh’) dicing [1]. Scribe-and-break is still a serial cutting method and works best on thinner substrates [9]. Laser ablation gives small kerf widths but tends to sputter material onto the top of the die and is also prone to water contamination [4, 10]. Stealth dicing is an emerging method and has the potential to give near zero kerf widths, fast serial cutting, and generates a low amount of debris. One of the downsides to stealth dicing are that it requires the substrate to undergo high thermal loading near the crack propagation site [11].

Dry etching alleviates a lot of problems when compared to mechanical dicing. Although generally more time consuming than dicing on wafers with few die, dry etching may offer benefits in the other areas of concern such as damage free surfaces, low residual stresses, and being a parallel cutting process. Some common gases that are used for etching silicon substrates in this manner are SF$_6$ and CF$_4$. Dry etchings performed by ionized gases are usually isotropic and leave very smooth surfaces. An advanced dry etching procedure is the Bosch DRIE and is considered to be highly anisotropic. In this method the substrate is etched similarly to simple reactive ion etching, but with passivation cycles mixed into the process. In the first phase of the process, ions from the plasma gas (F$^-$ and SF$_6^+$) bombard the surface and react with the substrate surface while removing silicon. During the second phase of the process, the sidewalls and bottom of the notch are passivated with a gas (C$_4$F$_8$) that forms a chemically inert layer that prevents the etch cycle from cutting into the sidewalls. Here, the plasma ions are forced down in the vertical direction, causing the passivated bottom of the notch to be etched more quickly than the sidewalls, thus lending to large aspect ratios.

High aspect ratios (depth-to-width ratio of the etched feature) are possible with the alternating etching/passivation cycles and are what distinguish DRIE from other dry etching methods. Aspect ratios of around 25:1 are not uncommon for the DRIE process [12] and will be very useful in this research area. Depending on the substrate and processing conditions, the DRIE method can etch at rates from 50 nm to 24 μm min$^{-1}$ [13]. Silicon substrates using SF$_6$/O$_2$ (etching/passivation gas) can have etch rates up to 10 μm min$^{-1}$, no scalloped walls, and have nano sized structures [14–16]. Another commonly used passivation gas is C$_4$F$_8$ which creates a polymer on the silicon surface.

Landesberger et al used an anisotropic plasma etch of SF$_6$ to achieve a robust dice by thinning technique [6]. Currently Panasonic has a commercial plasma dicer, the PSX800, that can achieve kerf widths about 1/3 that of a dicing saw and die fracture strengths of up to 3 GPa [15]. The PSX800 uses a plasma etch blocked by photoresist to separate individual die. Others have patterned trenches using DRIE on the back and front side of SOI wafers then used HF vapors to separate their dies [17, 18]. Of course the depth of the notch, given a certain number of cycles, is also a function of the feature size [19] which can complicate separation if not all trenches are the same width.

Constructing vertical sidewall features uniformly over large areas is a very attractive for the patterning and manufacturing of MEMS devices. However, little is known about the effects of the passivation process on the sidewalls, the effects of DRIE notch geometry on die separation, and the effects on overall die strength when the wafer is cleaved apart. The focus of this research is to investigate the strength effect of separating wafers at different depths using Bosch DRIE in comparison with standard separation methods.

2. Procedure

2.1. Overview

For this work, samples were prepared using both DRIE and a traditional dicing saw to create notches in silicon wafers to define individual dies. On these samples, two basic types of mechanical tests were performed: (1) die separation tests on notched wafers, in which samples cut or etched only a portion of the wafer thickness were loaded in three-point bending until fracture propagated from the notch-tip, and (2) individual die rupture strength tests, in which three-point bending tests were performed to determine the rupture stress for all individual dies, including those completely separated by cutting or etching (100% of wafer thickness) as well as those separated by the process of notching and subsequently separating via three-point bending.

2.2. Sample preparation

2.2.1. Dicing saw notched samples. All (1 0 0) silicon wafers were 525 ± 20 μm thick, P/Boron type, single sided polished, and originated from the same lot (Silicon Valley Microelectronics, Inc.). Specimens were notched via a dicing saw (Disco DAD321) to depths of 25%, 50%, and 75% of the total wafer thickness. Additionally, some specimens were completely separated into die (100% of wafer thickness).

The diamond composite dicing blade used for all mechanical grinding cuts had a nominal width of 70 μm. Five streets were cut aligned parallel to the (1 1 0) wafer flat, and then another five streets were cut perpendicular to the (1 1 0) wafer flat, figure 1 [20] so that square die could be obtained. Water jets helped keep the blade cool while the dicing took place. Each street was placed 17.07 mm apart, giving a die size of 17 mm square. In all cases, the dicing saw was operated at a
constant rate of 1 mm s\(^{-1}\). Each wafer package was carefully removed from the vacuum chuck, and the wafer and tape were cut apart from the metal support ring with a razor blade. Backside dicing tape was then sheared at an acute 0° to 10° angle so that minimal normal force was applied to the wafer and to avoid unintentional die separation. In the case of 100% cut wafers, the dies were simply pulled from the tape while attempting to avoid extra edge chipping.

2.2.2. Deep reactive ion etch notched samples. Substrates with identical mechanical properties and orientations as the diced wafers were used for the DRIE notched specimens. Photoresist masks were fabricated to produce similar trench spacing on the \(\langle 100 \rangle\) plane and the same final die dimensions as the diced specimens. A thick layer of photoresist (Shipley Microposit 1827) was used to protect the silicon that was not to be etched. The necessary resist thicknesses were found to be 3.2 \(\mu\)m for the 25% and 50% etch depth depths and 4.25 \(\mu\)m for the 75% and 100% etch depths. All samples were inspected and hard baked at 115°C for at least 5 min which hardened the photoresist and prepared them for a long DRIE process. The Bosch DRIE procedure was performed on an STS MESC Multiplex ICP, using SF\(_6\) and C\(_4\)F\(_8\) as the etching and passivation gases, respectively.

After 150 cycles (30 min) in the DRIE machine using a custom recipe, the samples were removed and put on a hot plate at 115°C for another 2 min. It has been observed that this additional hot plate treatment hardens and strengthens the photoresist even more and allows the substrate top surface to survive the deep etching process. The specimen wafers were then adhered to a support wafer which was coated with crystal bond, an adhesive, prior to being etched the remainder of the desired depth. Before all samples used for fracture data were fabricated, the etch rate of the DRIE equipment was calibrated on test wafers to determine the number of cycles required to reach each target notch depth. Optical microscope measurements were used to verify the actual notch depth of each sample.

2.3. Notch geometry modeling

ANSYS 12 and Solid Edge were used to derive the stress concentration factors for the various notch geometries under three-point bend loading. To determine the notch geometry formed by both the DRIE and dicing saw methods, scanning electron microscope (SEM) images were taken of the cross-sections for different notch depths, figure 2. The notch geometries formed by the two vary significantly for various reasons. DRIE trench geometry varies by depth as this method of material removal depends on the gas flow and heat transfer about the sample. Shallow trenches have a much flatter base than the deeper etched trenches. Shallow features have a much flatter bottom as the etching gas has a more uniform flow.
pattern of fresh ionized gas. As trenches become deeper, the profile becomes more rounded due to irregular ionized gas flow. Deep trenches and shallow trenches did show the same radii of curvature at the corner connecting the trench wall and the base. For the FEA modeling, it was assumed that the trenches are etched anisotropically, meaning that the walls are almost vertical. Dicing saw trenches had the same bottom radius and sidewall slope, regardless of cut depth. To determine the radii of curvature for all specimens, images were taken of the cross-section in a SEM and the curvature was fit to a circle (figure 2).

Models with varying cut depths were created in Solid Edge for the dicing saw and DRIE notch profiles. They were imported to ANSYS 12 and loaded so that the magnitudes and conditions were constant. This allowed for the calculation of the stress concentration factors needed to estimate the normal tensile stress experienced by the specimens. Since silicon is an anisotropic material it has a stiffness tensor (\(C\)) which relates stress and strain. The Hooke’s law relationship and stiffness properties are given by [21]:

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{xy} \\
\tau_{yz} \\
\tau_{xz}
\end{bmatrix} = \begin{bmatrix}
c_{11} & c_{12} & c_{12} & 0 & 0 & 0 \\
c_{12} & c_{11} & c_{12} & 0 & 0 & 0 \\
c_{12} & c_{12} & c_{11} & 0 & 0 & 0 \\
0 & 0 & 0 & c_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & c_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & c_{44}
\end{bmatrix} \begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{xy} \\
\gamma_{yz} \\
\gamma_{xz}
\end{bmatrix}
\]  \tag{1}

where \(\sigma\), \(\tau\), and \(\varepsilon\) are normal stress, sheer stress, and strain respectively. The values of \((C)\) in the (100) directions are \(c_{11} = 167.4\) GPa, \(c_{12} = 65.23\) GPa, \(c_{44} = 79.57\) GPa [21].

2.4. Die separation and rupture strength testing

Two types of bending strength tests were performed on the specimens in this study. The first series of tests involved three-point bending of specimens notched by both the dicing saw and the DRIE process. A custom three-point bend fixture, figures 3(a)-(b), with a linear crosshead velocity of 40 \(\mu\)m s\(^{-1}\) and a consistent bottom span of 15.0 mm, was used for all tests. The die separation tests were performed sequentially and in a consistent routine for each wafer, as detailed in figure 1. For the fully notched four-inch wafer, the specimen for the first separation test had a width of 97.4 mm, the second and third separation specimens had a width of 72.7 mm, and the width for the rest of the separation tests was 17.0 mm. For each test, the specimen notch was loaded in tension and arranged directly under the center load point using alignment marks on the backside of the wafer (figure 3(c)).

After the individual dies were all separated, a second series of three-point bending tests were performed using the same fixture and experimental parameters to determine the rupture strength of each individual die. For the rupture strength testing of the individual die, the top of the original wafer (the polished top surface that was trenched/diced) was always loaded in tension. The maximum nominal bending stress was calculated for both the rupture strength of each individual die, and the separation stress for the notched specimens by:

\[
\sigma = \frac{Mc}{I} = \frac{3FL}{2wt^2} \tag{2}
\]

where, \(M\) is the moment at the center of the beam, \(c\) is the distance to the neutral axis, \(I\) is the moment of inertia, \(F\) is the force applied to the beam, \(w\) is the width of the beam, and \(t\) is the thickness of the beam at the narrowest point (at the notch tip for separation tests and simply the wafer thickness for die rupture strength tests).

3. Results and discussion

3.1. Stress concentration derivation

Over a range of notch depths, the geometries found for the two wafer trenching methods were modeled under three-point bending loading using ANSYS. From these ANSYS simulations, stress concentration factors were determined to relate the maximum nominal bending stress, \(\sigma_{nom}\) from (2), to the maximum principal stress found:

\[
SCF = \frac{\text{First principal stress}}{\text{Nominal stress}}. \tag{3}
\]
3.2. Die separation

During die separation tests for both notch geometries, fracture was observed to initiate almost exclusively at the location of maximum principal stress. Results of the maximum principal stress at separation, and the corresponding Weibull cumulative distribution functions, are shown for the 50% notched samples in figures 6(a) (diced) and (c) (DRIE). For the dicing saw notched specimens, fracture consistently initiated at the very bottom of the notch root, but propagated along planes that varied from 0° up to ~55° from directly in front of the notch root. For DRIE specimens, fracture initiated at the fillet where the die sidewall meets the notch base, and typically propagated at a ~55° angle approximately along the (1 1 1) crystal plane.

The slopes of the Weibull plots in figure 6 indicate the precision of predicting when a failure will occur. Sharper slopes mean more consistent predictions whereas broader (lower) slopes lead to a higher variability in fracture stress. Consistent chipping and cracking of the diced samples allowed for a more repeatable region of fracture stress, thus resulting in a sharper slope for figures 6(a) and (b).

Die separation performed through the method of trenching followed by a bending test yielded different viable die quantities, depending on the notch type and depth. Specifically, the first three separation breaks (figure 1) for the 25% DRIE notched specimens yielded high-energy fractures, which resulted in higher defect rates and occasional premature separation of other die. A complete summary of die separation strength tests, as well as the resulting individual die rupture strengths and Weibull parameters is included in table 1. Values in table 1 include the stress concentration factor $K$, the scale parameter $\alpha$, the shape parameter $\beta$, and the correlation coefficient $\rho$. A high shape parameter indicates a sharper slope and better precision for failure prediction, the scale parameter sets the range for the Weibull function, and the correlation coefficient indicates how well the model fits the data. While the shape parameter correlates to consistency of failure, the scale parameter can indicate higher fracture strengths.
Figure 6. Weibull analysis showing the cumulative density function and experimentally determined maximum normal stress at separation during three-point bend tests for notches 50% of the wafer thickness created by dicing (a) and DRIE (c); the subsequent Weibull analysis of the rupture strength of the resulting separated individual dies are then shown for the diced (b) and DRIE specimens (d).

Table 1. Summary of Weibull parameters determined for die separation and die rupture.

<table>
<thead>
<tr>
<th>Notch method</th>
<th>Notch depth (%)</th>
<th>Die separation</th>
<th>Individual die rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Scale parameter, $\alpha$ (MPa)</td>
<td>Shape parameter, $\beta$</td>
</tr>
<tr>
<td>Dicing saw</td>
<td>25</td>
<td>2.45</td>
<td>243</td>
</tr>
<tr>
<td>Dicing saw</td>
<td>50</td>
<td>2.17</td>
<td>188</td>
</tr>
<tr>
<td>Dicing saw</td>
<td>75</td>
<td>1.69</td>
<td>256</td>
</tr>
<tr>
<td>Dicing saw</td>
<td>100</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>DRIE</td>
<td>25</td>
<td>4.22</td>
<td>869</td>
</tr>
<tr>
<td>DRIE</td>
<td>50</td>
<td>4.20</td>
<td>1242</td>
</tr>
<tr>
<td>DRIE</td>
<td>75</td>
<td>3.19</td>
<td>1212</td>
</tr>
<tr>
<td>DRIE</td>
<td>100$^a$</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>DRIE</td>
<td>100$^b$</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>DRIE</td>
<td>100$^c$</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

$^a$ Fully intact photoresist.
$^b$ Partial (edge) photoresist failure.
$^c$ Through-thickness photoresist failure.

3.3. Individual die rupture strength

A summary of the average separation stress and maximum stress at rupture for individual die is reported in figures 7(a) and (b), respectively. The Weibull analysis plots from the two 50% notched die rupture cases are shown in figures 6(b) (diced) and (d) (DRIE) above. A similar Weibull analysis was performed on the die rupture strengths for all specimen variations, the results of which are detailed in table 1 with the separation strengths.

Results in figure 7(a) show that separation stress for DRIE samples are much higher. This indicates that the plasma etching routine gives a cleaner and stronger cut, though the force needed to fracture the die is not necessarily higher due to the DRIE having small radii fillets and larger associated stress concentration factors. This is an inherent flaw in the DRIE etching mechanism, though can be avoided by dry etching all the way through a wafer or grinding the remaining material from the backside.

From figure 7(b), a number of general trends emerged. Most notched specimens showed little variation in final die rupture strength based on the notch depth or notching method, with the exception of the 25% DRIE notched specimens.
Figure 7. Summary of results for die separation stress (a) and individual die rupture strength (b) for both dicing saw and DRIE die separation methods (error bounds represent standard deviation).

Figure 8. Scanning electron micrographs showing the sidewall and top surface (die upside down) quality resulting for die completely separated by the DRIE process having a completely intact photoresist mask (a), edge initiated photomask failure (b), and complete, through-thickness photomask failure (c).

For this case, the high energy fractures due to the thicker specimens and location of the highest stress concentration near the notch edges tended to result in larger damage zones on the specimen back surface, thus lowering the rupture strength for these dies. Statistically, there was also minimal difference found in the rupture strength between samples that were 100% separated via dicing saw and samples that were partially cut then separated via three-point bend loading. For all die fabrication methods, there was also found to be no statistically significant correlation between the die rupture strength and the spatial location of the die on the wafer. This result is likely equipment-specific, and may not hold for other wafer dicing saw or DRIE systems.

During preliminary work on project [20], the initial specimens 100% separated via DRIE (last two columns in figure 7(b)) showed surprisingly low stress magnitude at the time of rupture. Careful inspection of these specimens revealed micro-pitting due to failure of the photoresist protection layer during the DRIE process. These specimens have been classified into two failure categories based on the DRIE damage observed; total mask failure and edge mask failure, figure 8. All specimens that were 100% DRIE processed showed grass structures at the bottom of the trenches and this is shown at the bottom edge (top of the pictures) in figure 8. The grass is most likely a result high SF6 flow rates [22]. Some specimens showed complete ‘through-thickness’ failure of the protective photoresist layer, resulting in widespread pitting across the entire die polished surface (figure 8(c)) that is loaded in tension during the three-point bend rupture tests. Depositing a thicker photoresist layer produced slightly better specimens (figure 8(b)), but some micro-pitting was still observed along the edge of the die. This phenomenon is
likely due to partial failure of the photoresist due to sloped sidewalls of this layer that are gradually eaten away by the DRIE process. A non-vertical sidewall will provide less protection at the base of the photoresist layer, leading to the initiation of micro-pitting just at the edge of the notch during a lengthy DRIE process as seen in figure 8(e). A third iteration of 100% DRIE samples used a modified exposure time and additional hard baking time with the thicker photoresist layer to produce a protective layer that remained completely intact throughout the entire DRIE process (figure 8(a)). The fully protected die that were 100% separated by DRIE showed a substantial improvement in rupture strength over all other fabrication methods tested, averaging more than double the strength of the nearest alternative, figure 7(b). The authors attribute this effect to the higher flaw densities and damage zones created on the surface by other methods. This result may also have relevance to the commonly used ‘dice-by-thinning’ procedure for die separation, for which partial DRIE notching may be preferable to partial notches created via a dicing saw. More statistics and preliminary data can be found in [20].

4. Conclusions

Partially notched silicon specimens were created by both a dicing saw and by a deep reactive ion etching process. Notch profiles were determined via scanning electron microscopy, and then modeled in ANSYS to determine the stress concentration factors associated with each notch profile under three-point bend loading. Accounting for the stress concentration factors, the maximum stress required to induce die separation was found to be much higher for the DRIE notched specimens. Specimens notched 25% by the DRIE process then separated by three-point bending performed poorly, producing lower yields and reduced die rupture strength. All other partially notched specimens showed only minimal variations in the die rupture strength. Specimens 100% separated by DRIE showed a substantial improvement in rupture strength compared to all other die separation methods tested. However, this is highly dependent on an adequate protective photoresist layer. Specimens in which the photoresist layer was compromised showed micro-pitting on the sample surface and greatly reduced rupture strength.

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References


