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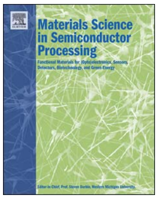

Crystalline damage in silicon wafers and 'rare event' failure introduced by low-energy mechanical impact

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ABSTRACT

We used X-ray diffraction imaging to detect and characterize mechanical damage introduced to 300 mm silicon wafers by low impact energy exerted on the wafer edge. Maps of crystalline damage show a correlation between the damage size, the magnitude of the impact energy and the location of the impact point. We demonstrate the existence of crystalline non-visual defects; crystalline defects that appear in the X-Ray diffraction images but not in optical microscopy or scanning electron microscope. We propose a mechanism of crystalline damage formation at low impact energies based on finite element analysis and high-resolution synchrotron white beam transmission X-ray topography. Finally, we propose the concept of 'rare-event' to described relatively low rate of occurrence of wafer failure by fracture within semiconductor manufacturing facilities.

1. Introduction

Wafers of brittle single crystal (BSC) materials such as silicon are ubiquitous in the high-tech industries and are the foundation for the micro-, opto-electronics and related industries. BSC wafers, usually, pass through many different processes with various equipment and hundreds of individual possessing steps to achieve the final product. The rates and costs of BSC wafer breakage are, naturally, kept confidentially by the manufacturers. Chen et al. [1–3] assessed that the average ratio of 200 mm silicon wafer breakage in typical fabrication plant in 2005 was ~25:1000, and that the costs associated to wafer breakage could approach $600,000 per month. In a fabrication plant in 2016, the average wafer breakage ratio of 300 mm silicon wafers is ~1:10,000. Economic loss follows due to the need to stop the process and to clean the tool in which the wafer broke as well as the lost productivity to identify and resolve the root cause of the breakage. An attempt to explain failure probability of such a ratio by statistical strength of brittle materials via, say, Weibull Statistics [4], is likely to fail, meaning that the failure events are not directly related to the intrinsic strength of a wafer. Instead, we introduce a concept of ‘rare event’ that can elucidate failure of the wafer during fabrication that poses extremely low failure probability. This concept suggests that several events should occur sequentially to end up with fracture failure of a wafer.

Parts of processing and handling equipment are, usually, in contact with the edges of BSC wafers for different purposes such as transferring the wafers between their carriers and processing tools and positioning the wafer within these tools. The forces applied to the wafer edges by the contacting parts are generally low, and as such, the BSC response is expected to be elastic. Thus, these low impact forces are commonly considered as non-destructive. Importantly, we found that these low impact forces are sufficient to generate crystalline defects that can reduce the residual strength of BSC wafers, and may lead to wafer breakage when the wafer passes though fabrication process that exerts sufficient tensile stress at a defected location.

Tanner et al. [5,6] have been applying X-ray diffraction imaging (XRDI) to study silicon wafer breakage phenomenon and suggested an XRDI technique for assessing the probability that individual microcrack will propagate and cause a catastrophic failure during rapid thermal annealing (RTA) process. Chen et al. [1–3] has performed fracture tests to study the strength of silicon wafers and found a statistical correlation between the probability of wafer breakage during processing and the shape of the wafer edge profile. These studies assumed that misaligned handling tools are sufficient to develop a crack at the wafer edge [7]. However, the mechanism that allows low impact forces applied by handling tools to generate crystalline damage at the silicon wafer edges has not been studied yet.

2. Experimental

To simulate low impact forces, we built a pendulum-like experimental system (Fig. 1a) that allows introducing a controlled amount of

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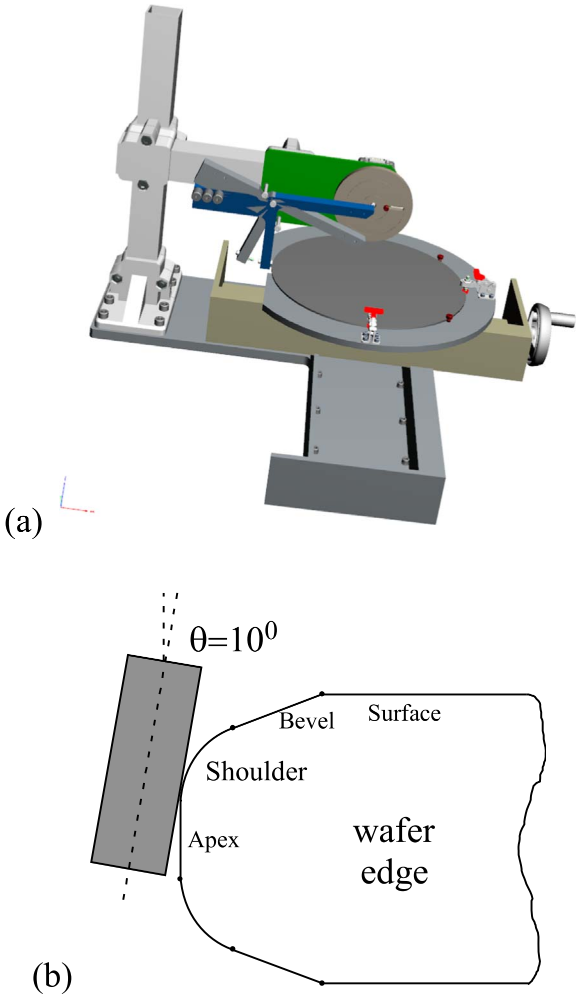

Fig. 1. (a) A pendulum–like experimental system used to simulate edge damage caused during wafer processing and (b) schematic presentation of the wafer edge and the impactor inclined by angle θ.

impact energy to a specific region on the wafer edge. Prime grade, 300 mm diameter (001) Si single crystal wafers were used as a model and technologically very relevant BSC material. A Si wafer was fixed on a circular aluminum plate attached to a stage that allows selecting the impact region around the perimeter of the wafer. Two stainless steel stoppers, fixed to the circular plate, were used to prevent lateral sliding of the wafer. The potential energy (PE) is transferred to the wafer edge by dropping an impactor with a mass m from a vertical distance h above the wafer surface such that PE=mgh. The portion of PE that is contributing to the defect formation is determined by the impactor shape and material. We performed experiments using different impactor shapes and materials, but we report here only on the results of the impactor that allowed generating enough wide range of defect area to describe the "rare event" concept. We report on the results of impact test performed using a cylindrical pin, 5.4 mm in diameter, made from stainless steel.

The profile of the Si wafer's edge consists of three main regions: apex, shoulder, and bevel. The contact zone between the impactor and the wafer edge can be characterized by the misalignment angle, θ, between the impactor and the normal to the wafer plane (Fig. 1b). In this study, we limited the experiments to low misalignment angles due to two reasons: 1) the geometry of the handling instruments, usually, does not allow reaching high misalignment angles, and 2) high misalignment angles (> 20°) are expected to create experimental difficulties that need to be addressed e.g. variation in the curvature of the "shoulder" region of the wafer edge and energy dissipation on wafer bending due to the geometry of the experimental system.

We performed several impact tests along the wafer's perimeter. To avoid possible effects of strain field generated by one experiment on the strain field generated by the adjacent experiments, we set the minimal distance between any two adjacent experiments along the wafer's perimeter to eight times the size of maximal damage size observed in preliminary tests, translated to one impact test each 6°, equivalent to 60 impact tests for each wafer.

To map the crystalline defects in silicon wafers introduced by the impact forces, we used a Bruker JVSensus XRDI system. The system consists of an X-ray source mounted on a rotation stage, X-ray cameras and mechanical stage to scan the wafer with respect to the stationary X-ray beam. The alignment, measurements, and defect detections were done automatically under computer control, the underlying principles were reported previously [8]. In this work, we used a point focus Mo tube operating at 2 kW and imaging CMOS X-ray detector with pixel size of 74.8 μm to image the diffracted beam. The incident beam angle was set to measure the 400 reflection in transmission geometry.

White beam transmission X-ray topography (XRT) was also used to characterize crystalline defects in silicon wafers introduced by the impact forces. We used the TOPO-TOMO beamline at the ANKA synchrotron for these measurements. The experimental setup used for these measurements was reported previously [9].

3. Results and discussion

The main finding reported here is the unexpected and significant correlation between the crystalline defect size induced by the impact force applied at the wafer edge and the misalignment angle between the impactor and the wafer's apex. Preliminary results showed that there is no XRDI observable mechanical damage at the wafer edge up to ~2000 mJ impact energy applied when using a stainless steel pin impactor and carefully aligning it with the wafer apex, i.e. θ=0°. However, relatively large defects (~10 mm^2) were observed in XRDI scans after applying only ~20 mJ impact energy (1% of the former) with same impactor but by allowing small misalignments (θ < 20°). To illustrate this correlation, we performed the following experiment on four prime silicon (001) wafers: each wafer experienced 60 impact tests at different positions along its perimeter, each test was done using stainless steel pin impactor set at height equivalent to impact energy of 20 ± 2 mJ. On each wafer, the misalignment angle was different, θ=0°, 5°, 7.5°, and 10°. The wafers were scanned by using XRDI before the impact test to ensure that there are no crystalline defects preceding the test. The XRDI scan of the wafer experienced the test when θ=10° is shown in Fig. 2d, and representative XRDI images of defects generated by different misalignment angles are shown in Fig. 2a-c. Image analysis of the four wafers in this experiment show that the average area of crystalline defects increase with the misalignment angle, Fig. 3a.

To further explore this phenomenon, we performed the following experiment on three prime silicon (001) wafers: each wafer passed 60 impact tests at different positions along its perimeter, each test was performed using stainless steel pin impactor set to impact the wafer edge at misalignment angle of θ=10°. The height of the impactor varies among the wafers to apply the following different impact energies: 10, 15, and 25 mJ. Image analysis of these three wafers together with the wafer from previous experiment with same misalignment angle and 20 mJ impact energy show that the average area of crystalline defects increases with the impact energy, Fig. 3b. The distribution of the crystalline defect area as observed by XRDI show no correlation with any preferred crystallographic orientation.

Visual inspection of the wafer edge surface near the crystalline defects allowed detecting defects larger than ~15 mm^2 even with naked eye, in some of the cases wafer chipping was observed. Both optical microscope and scanning electron microscope (SEM) allowed observing surface traces of cracks near portion of the crystalline defects with