Subsurface damage measurement in silicon wafers with cross-polarisation confocal microscopy

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Abstract: Silicon wafers are used as the substrates upon which over 90% of the semiconductor devices are manufactured. A series of processes are needed to manufacture silicon wafers. Some processes will induce SubSurface Damage (SSD) that should be eliminated by subsequent processes. Therefore, the assessment of SSD is critically important to optimise manufacturing processes and ensure high quality of silicon wafers. In this paper, a novel non-destructive method is introduced for measuring the SSD in silicon wafers, the cross-polarisation confocal microscopy. This paper also presents experimental results of using this method to measure the SSD in ground silicon wafers.

Keywords: cross-polarisation confocal microscopy; grinding; manufacturing; measurement; non-destructive method; silicon wafer; SubSurface Damage (SSD).


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1 Introduction

1.1 Industrial need of non-destructive evaluation methods for subsurface damage in silicon wafers

The impact of semiconductors on the economy and society is significant. Semiconductor wafers (more than 90% are silicon (Van Zant, 2000)) are the fundamental building blocks for Integrated Circuits (ICs). About 150 million silicon wafers of different sizes are manufactured each year worldwide (Tricard et al., 1998). In 2004, worldwide revenue generated by silicon wafers was $7.3 billion (Online Staff, 2005a) and worldwide semiconductor revenue was $213 billion (Online Staff, 2005b). Research activities are desirable to enable silicon wafer and IC manufacturers to enhance their manufacturing cost-effectiveness.

Semiconductor ICs are typically manufactured by the following processes (Bawa et al., 1995; Fukami et al., 1997; Pei and Strasbaugh, 2001, 2002; Pei, 2002; Tonshoff et al., 1990; Vandamme et al., 2000):

1. crystal growth: to produce crystal ingot
2. slicing: to slice the ingot into wafers of a thin disk shape
3. flattening (lapping or grinding): to flatten the wafer surface
4. etching: to chemically remove process-induced damage without introducing further mechanical damage
5. polishing: to obtain a mirror surface
6. cleaning: to remove the polishing agent or dust particles
7. feature developing: to develop circuits on the front side
8. back-grinding: to thin the completed device wafer to a required thickness
9. dicing: to separate the completed wafer into individual chips/dies by using very thin blades and
10. packaging: to complete the IC package with interconnection and protection.
For semiconductor wafer manufacturing, SubSurface Damage (SSD) induced by slicing and flattening must be removed by subsequent processes. For IC manufacturing, SSD induced by back-grinding must be kept below a certain level to ensure the wafers or dies (chips) possess sufficient strength. There is a critical need to assess the SSD induced by these mechanical machining processes.

Evaluations of subsurface cracks induced by mechanical machining processes have attracted much attention. Many techniques have been reported to observe/measure subsurface cracks in silicon wafers: angle polishing (Abe et al., 1994; Tonshhoff et al., 1997), angle lapping (Jeong et al., 2000; Oh et al., 1999), step polishing (Stephens, 1986), x-ray diffraction (Dupke and Reimers, 1994), step etching plus scanning infrared depolarisation (Lundt et al., 1994), SEM photography (Blake and Scattergood, 1990) and etching method (Tonshhoff et al., 1990). However, it is very difficult for these techniques to provide information about subsurface crack configurations in three dimensions. Cross-sectional transmission electron microscopy investigations have been conducted to reveal subsurface cracks (Abe et al., 1994; Mchedlidze et al., 1995; Zarudi and Zhang, 1996), but the full spectrum of subsurface crack configurations have not been provided. Pei et al. (1999) used cross-sectional microscopy method to obtain all possible crack configurations in ground silicon wafers. Thus, the above-mentioned methods either destroy the wafers or measure only localised areas instead of the whole wafer. Currently, there are no Non-Destructive Evaluation (NDE) methods that can measure the SSD across the whole wafer with high efficiency and low cost. Lack of such tools has hindered further reduction in manufacturing costs of semiconductor wafers and ICs.

1.2 Optical scattering techniques for surface and subsurface evaluation

Several optical scattering techniques have been reported to be capable of revealing subsurface defects. However, none of them can be used to characterise subsurface cracks in silicon wafers, because they either cannot provide the depth information at all or do not have sufficient resolution.

Most optical scattering methods, including Total Integrated Scatter (TIS) (Davies, 1954), Bi-directional Scatter Distribution Function (BSDF) (Nicodemus et al., 1977), and the speckle contrast measurement (Asakura, 1978), can only examine the 2D microstructure on a sample’s surface. When light is incident on a surface, most of the light coming back for measurement originates from the surface by surface reflection and scattering. The surface reflection results from the refractive index mismatch between air and sample material, while the scattering is due to the surface roughness. For metals, only surface reflection and scattering exist. For transparent materials, most incident light is transmitted into the internal of the material. For translucent materials such as ceramics, silicon and biological materials, a major portion of incident light can penetrate inside the material’s subsurface and the scattering induced by subsurface discontinuities (such as cracks, voids, etc.) can escape back out of the surface and be detected (see Figure 1). This internally backscattered light is, however, relatively weak compared to the light originating from the surface. All conventional optical methods cannot separate the weak subsurface scatter from the strong surface scatter, so they have low sensitivity for detection of subsurface discontinuities.
One technique to detect and resolve depth of the internal backscattering is Optical Coherence Tomography (OCT), developed during the last ten years (Dunkers et al., 1999). This technique is based on low-coherence optical gating of the backscattered light from different depths, relative to a reference beam using an interferometer. Interference occurs when the scattering depth is equal to the reference ‘depth’ determined by the position of a reflector. By moving the reflector and synchronously measuring the interference signal, the scattering data from various depths can be obtained. Typical axial and lateral resolution is over 10 \( \mu \text{m} \). This kind of resolution is not sufficient to measure subsurface cracks in silicon wafers.

1.3 Cross-polarisation optical scattering techniques for subsurface evaluation

One method to separate subsurface scattering from surface reflection/scattering is to utilise the polarisation property of light. In the plane perpendicular to the light travel direction, light can have two perpendicular components. When incident light is linearly polarised (i.e. with only one polarisation component), the surface reflected/scattered light has the same polarisation as the incident light. The subsurface scattered light, however, will become depolarised because of multiple scattering interactions with the subsurface discontinuities (Hecht, 1998). Using polarised optics to select the cross-polarised light (with respect to the incident light) that originates from the subsurface backscattering, the detected signal is only related to the subsurface microstructure variation.

This method, referred to in short as ‘laser scattering,’ has been successfully developed and used to detect subsurface defects in silicon nitride ceramic materials (Ellingson et al., 1993; Ellingson and Brada, 1995; Ellingson et al., 2001; Sun et al., 1997a,b, 1998, 1999). Defects such as voids, porosity, inclusion and cracks can be distinguished and characterised. However, this method itself has no depth resolution because the detector receives all cross-polarised light scattered from different subsurface depths within the measurable range.
1.4 Combination of laser scattering and confocal microscopy

Recently, a new method that combines the (cross-polarisation) laser scattering and the confocal microscopy was developed (Sun, 2003). It relies on the laser scattering method for subsurface detection sensitivity and the confocal method for the 3D spatial resolution. Confocal microscopy has been widely used to examine transparent biological materials such as cells and tissues (Pawley, 1990; Wilson and Sheppard, 1984). However, this method itself cannot be directly used to examine subsurface microstructure of dense materials such as ceramics and silicon.

Confocal optical imaging has been demonstrated theoretically and experimentally to obtain superior spatial resolution by eliminating contributions from out-of-focus illuminations (Pawley, 1990; Wilson and Sheppard, 1984). This is achieved by first applying a high-quality light source, that is, a point source, so a significant portion of the light is focused by the objective lens into a small (diffraction limited) spot in the sample. A spatially restricted point detector is further used to detect only the light emanating from the focus spot. The spatial resolution of confocal set-up is represented by the size of the focusing spot determined by the Numerical Aperture (NA) of the objective lens. With high NA objectives, 3D spatial resolutions (including depth) can be well below 1 \( \mu \text{m} \). When polarised laser and optics are used to selectively detect the cross-polarised scatter from the subsurface, the cross-polarisation confocal method can directly measure subsurface microstructure. This novel hybrid system overcomes the shortcomings of the individual systems: lack of depth resolution for cross-polarisation scattering and transparency requirement for confocal microscopy.

1.5 Outline of this paper

This paper reports an experimental study of using the innovative method (cross-polarisation confocal microscopy) to measure the SSD in ground silicon wafers. Following this introduction, the system set-up is described in Section 2. Section 3 presents the experimental results with discussion. Conclusions are drawn up in Section 4.

2 System set-up of cross-polarisation confocal microscopy

A schematic diagram of the cross-polarisation confocal microscopy system is shown in Figure 2. This set-up is similar to a conventional confocal set-up, except the use of a polarised laser (25 mW He-Ne laser at wavelength of 0.633 \( \mu \text{m} \)) and a Polarising Beam Splitter (PBS) necessary for cross-polarisation backscatter detection. The polarised laser beam is directed through the PBS cube and focused onto the sample surface. As discussed in the previous section, light scattered/reflected from the surface will not undergo change in polarisation unless the surface is extremely rough. Therefore, all surface-scattered light will be reflected in the PBS and directed back towards the laser. However, any light scattered from the subsurface material undergoes several reflections and refractions at grain boundaries and microstructural discontinuities (such as cracks), so the subsurface scattered light becomes completely depolarised. Half of the subsurface back scattered light will be reflected by the PBS and directed back to the laser; the other half will be transmitted by the PBS into the detection train, imaged by
a positive lens onto a polished stainless steel pinhole aperture, and recorded by the detector.

**Figure 2** Illustration of cross-polarisation confocal microscopy system

During a typical test, the sample is scanned in the x-y-z directions in a raster fashion, and the resulting 3D scattering data provide information about the subsurface microstructure of the sample. The data can be displayed as slices in any plane for easy visualisation, similar to the practices in displaying 3D x-ray Computed Tomography (CT) data.

### 3 Experimental results

Two types of scanning directions were used for experiments:

- **x-y scanning**: scans along the surface of specimen to detect the surface damage and
- **x-z scanning**: scans in the direction vertical to the specimen surface to detect the SSD.

#### 3.1 Silicon nitride specimen

Since the laser scattering has been successfully used to detect and characterise SSDs in silicon nitride ceramics (Ellingson et al., 1993; Sun et al., 1999), an NT551 silicon nitride specimen with known SSD was tested before measuring the SSD in a silicon wafer.

Certain regions of the NT551 silicon nitride specimen have undergone indentation tests. Two damaged regions with indentation loads of 2800 N and 3000 N, respectively are shown in Figure 3.

Figure 4 shows the x-y scanning result (scan step size 1.0 µm) for the two damaged regions. The two damaged regions exhibit portions of two rings, indicating the indentation-induced cracks with higher scattering intensities.

Furthermore, the x-z scanning with scan step size of 0.2 µm was conducted along two randomly chosen lines A and B, as shown in Figure 4. The scanned results are shown in Figures 5 and 6. From Figures 5 and 6, the depth of the indentation-induced cracks can be observed.
3.2 Ground silicon wafer

The silicon wafer used in the experiment was a single crystal wafer with (100) plane as the wafer surface. It was first ground by a #320 diamond wheel, then further ground by a #2000 diamond wheel. The details of wafer grinding process can be found elsewhere.
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An area (1 mm × 1 mm) of the wafer was scanned in the x-y direction first. Scan step size was 1 µm. As shown in Figure 7, the white speckles represent regions with excessive light scattering due to subsurface cracks, and the bright lines represent the cracks induced by grinding.

**Figure 7** Cross-polarisation confocal x-y scan image of an area on the silicon wafer

Figure 8 shows an x-z scanning image of the silicon wafer along the arrow direction indicated in Figure 7. The scanned length was 1 mm, and scan step size was 0.2 µm. Some bright speckles can be observed from this image, representing subsurface cracks.

**Figure 8** Cross-polarisation confocal x-z scan image on the silicon wafer

4 Concluding remarks

The cross-polarisation confocal microscopy method for SSD measurement of silicon wafers is introduced. The experimental results on a silicon nitride specimen with known defects and a ground silicon wafer are presented. This method has the following attractive features:

- it can obtain quantitative data on SSD depth
- it is capable of high spatial resolution (2 µm can be achieved with 40X objective lens)
- it is non-contact and non-destructive, and can be fully automated and scaled up to cover whole wafer surface and
it can be operated at high speed for entire wafer inspection (e.g. within few hours), while it usually takes days or weeks for the current destructive methods (such as cross-sectional microscopy, and step-polishing) to measure the SSD in silicon wafers.

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References


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