SYSTEM AND METHOD FOR INSPECTION OF SILICON WAFERS

BACKGROUND OF THE INVENTION

Field of the Invention

This present invention relates generally to systems for nondestructive inspection of silicon wafers in semiconductor industries and, more specifically, to systems and methods for inspections for detecting defects on a surface and sub-surface of a silicon wafer by combined optical interferometry and phase shifting interferometry.

Description of the Related Art

Silicon wafers are widely used in semiconductor and microelectronics industries. The quality tolerances in these industries are extremely tight, and there is an immense need to obtain silicon wafers with a highly polished, defect-free surface for improved yield in the production process and performance of the subsequent micro-components. The Semiconductor Industry Association's International Technology Roadmap for Semiconductors identifies the inspection and characterization of defects and particles on wafers to be a potential barrier to device miniaturization. The Roadmap specifies that by 2005, 30 nm particles must be detectable on bare silicon and nonmetallic films, 39 nm particles must be detectable on metallic films, and 100 nm particles must be detectable on wafer backsides. Presently, no inspection systems exist to detect such small particles. With the need to detect smaller defects, the costs of inspecting wafers are skyrocketing. For new advances to be implemented in production environments, improvements in defect detection sensitivity must be achieved.

The management of processing costs of silicon wafers, including the control of defects (at sub-micron size and especially at sub-surface locations) on these wafers, is critical to wafer fabrication/reclamation industries. The wafers produced by wafer fabrication processes are known as "prime" wafers. Wafers which fail to meet production quality standards are rejected at various stages of the wafer fabrication process. These rejected wafers are known as "test" wafers. "Test" wafers are useful for monitoring the operation of the device manufacturing process during trial manufacturing runs prior to beginning the actual device manufacturing using the "prime" wafers. "Test"

wafers can be used five or six times for trail runs before being discarded; but these "test" wafers must be processed, or reclaimed, prior to each trial run by such exemplary processes as stripping, lapping, or polishing.

The current practice in the semiconductor industry is to inspect the wafers for any surface defects only at the end of final polishing stage of the wafer fabrication process. At this stage, the sub-surface defects are visible (as they have been exposed by polishing) as minute spots forming spiral rings or swirls. These sub-surface defects, which are not detected before the reclamation process or wafer fabrication process, cause a high wafer rejection rate at the end of the wafer finishing stage. It has been reported that millions of dollars have been lost each year by failing to detect these defects in silicon wafers prior to the wafer fabrication/reclamation processes. Unfortunately, there is no instrument currently available to inspect the "prime"/"test" wafers at the sub-surface level prior to the wafer fabrication/reclamation processes.

U.S. Patent No. 6,157,444 to Tomita et al. discloses an inspection apparatus for detecting defects in silicon wafers subsequent to the wafer production process, the contents of which are incorporated herein by reference. The Tomita et al. apparatus directs two light beams of differing wavelengths onto and into a wafer surface and analyzes the light scattered back from the wafer to detect defects on and inside the wafer. A more complex inspection system is disclosed by U.S. Patent No. 6,020,957 to Rosengaus et al., the contents of which are incorporated herein by reference. The Rosengaus et al. system provides for a plurality of monochromatic light sources to illuminate the surface of a wafer in parallel and filters the light scattered back from the surface of the wafer to detect defects on and below the surface of the wafer. Yet a third wafer inspection system is disclosed by U.S. Patent No. 6,424,733 to Langley, the contents of which are incorporated herein by reference. The Langley inspection system can inspect wafers during the production process by attaching an inspection station to a cluster tool but is limited to inspecting only the surface of each wafer. A single light source, such as a laser, is beamed onto the surface of the wafer; and the reflected light is compared against a known good image for the detection of any surface defects.

Typically, a semiconductor wafer can have a large number of defects, of varying patterns, such as swirl, cluster or random particles, voids, scratches, cracks or damages

etc., which may have resulted from any number of causes, such as crystal pulling during crystal growth or improper control of process parameters during the lapping, etching, or polishing processes. To increase the yield in the manufacturing process and to control the defects during the production process, such defects should be detected early in the wafer production process.

Along with defects inspection, the surface quality, such as surface topography, flatness, and total thickness variation, of the produced wafer will also affect yield management in semiconductor industries. There are a number of commercial wafer inspection devices currently available in semiconductor industries to inspect the surface of wafers for defects at the end of the wafer fabrication process. These devices include the KLA Tencor instrument, the Atomic Force Microscope, laser interferometers, and laser-scanning profilometers. There is no single "in-line" inspection system that can inspect the wafers before the wafer reclamation/fabrication step in the wafer production line for surface and/or sub-surface defects and for quality analysis.

Figure 1 shows a typical "swirl" surface defect in a silicon wafer revealed by the KLA tencor instrument after final polishing. Such an anomaly is a microdefect, located in a spiral pattern in wafers cut perpendicular to the crystal growth direction. Swirl defects are classified into two types: "A" (larger) and "B"(smaller). Swirl defects were at first attributed to vacancy clustering, such as voids or vacancy-type dislocation-loops, until the discovery of the same by an electron microscope. In 1975, "A" defects were identified as interstitial-type dislocation-loops by electron microscopy, although "B" defects could not be detected by this method. The practitioners in the production lines prefer designations such as "crystal originated particles," or pits, or "light point defects." Recently, crystal originated particles have been recognized as surface defects or micro-pits generated during the crystal ingot growing process and have been detected by a particle counter after surface cleaning processes. Crystal originated particles have attracted much interest because they can decrease the reliability and manufacturing yield of semiconductor devices. These defects, which cannot be detected by existing instruments before the wafer fabrication /reclamation, have resulted in high wafer rejection rates at the end of final polishing stage. The rejection rate is estimated by the

International Semiconductor Products Pte. Ltd., Singapore, to be approximately ten percent of the fabricated wafers, amounting to one million dollars per year.

One known method for the nondestructive testing of objects is the use of optical interferometric techniques. Two of these techniques are electronic speckle pattern interferometry and speckle shearing interferometry, also known as shearography. These techniques have been used to detect hidden defects in aircraft parts, turbine blades, space vehicles, automobiles, and many other products. Shearography is a laser optical method, which is suited for both nondestructive testing and for strain analysis. Contrary to holography, which measures surface displacements, shearography measures derivatives of surface displacements. One such application of shearography to detection of material defects and damage is disclosed in U.S. Patent No. 6,040,900 to Chen, the contents of which are incorporated herein by reference. The Chen device provides for a thermal stressing unit to induce a temperature difference between a localized area of the material and the surrounding region. Dual laser sources directed toward the material produce reflected surface images, the out of plane displacement derivatives of which can be measured to determine surface defects in the material.

In shearogarphy, two laterally displaced images of the object, in the form of random speckle patterns, are made to interfere to form a pattern of fringes. The pattern is random and is dependent on the characteristics of the surface of the object. When the object is deformed (by temperature, pressure, or other means), the random interference pattern will change. The amount of the change depends on the soundness of the object. A comparison of the random speckle patterns for the deformed and undeformed states, and their respective fringe patterns, provides information about the structural integrity of the object. The method is called shearography because one image of the object is laterally displaced, or sheared, relative to the other image.

Digital speckle shearing interferometry, or digital shearography, uses a charge-coupled device camera and computer image processing to produce the fringe patterns of anomalies in objects. The application of shearing interferometry to measure deformations can be further enhanced using phase shifting (also called phase stepping). Under equal conditions, phase shifting interferometers have a higher sensitivity than systems without phase shifting. Phase shifting interferometers calculate the phase

distribution from several interference patterns, which can then be displayed on a video monitor. One application of phase shifting interferometry is discussed in B.K.A. Ngoi, et al., "Instantaneous Phase Shifting Arrangement for Microsurface Profiling of Flat Surfaces," Optics Communication, vol. 190, pp. 109–16 (2001), the contents of which are incorporated herein by reference. Another discussion of this technology, as applied to measuring thickness variations in acrylic pipe with X-rays, is presented in Koichi Iwata, et al., "Phase Shifting X-Ray Shearing Interferometry," Japanese Journal of Applied Physics, vol. 38, pp. 6535-39 (1999), the contents of which are incorporated herein by reference.

Although the phase shifting technique has many advantages, it is marred by inaccuracies from the vibration and mechanical movement of the phase shifter itself. One method to eliminate these errors was proposed in Smythe and Moore, "Instantaneous Phase Measuring Interferometry," Optical Engineering, vol. 23(4), pp. 361-64 (1984), the contents of which are incorporated herein by reference.

SUMMARY OF THE INVENTION

The present invention relates to surface quality inspection and a surface and /or sub-surface defects inspection system for semiconductor industries and particularly to an inspection system for checking surface quality such as roughness, flatness and total thickness variation of smooth wafer surfaces and also for defects such as swirl defects and groups of particles in an unpolished silicon wafer before the wafer reclamation and/or the wafer fabrication process, using combined optical interferometry and real-time instantaneous phase-shifting shearography and/or holography. The method described here relates specifically to semiconductor wafers, but can be generalized to any other samples.

One of the embodiments of the present invention is to make use of ground, lapped or etched wafer surface to inspect for sub-surface defects by digital shearography or holography techniques. Swirl defects and groups of defects can be easily detected both qualitatively and quantitatively by whole field measurement of the wafer surface in few seconds. The serial automatic measurement on a small area (approx. 1mm by 1mm) can be carried out using a macro focus lens at different locations of the wafer for detecting distributed sub-surface wafer particles of micron and sub-micron size.

In exemplary embodiments, instantaneous phase measuring interferometry can be applied in combination with a carefully designed real time digital shearography and holography system for high resolution, high speed, robust, accurate, highly stable whole field measurement for defect inspection in unpolished silicon wafers for semiconductor/reclamation industries. Such a system can also be used to measure the surface quality of smooth surfaces such as polished wafers. The phase measuring interferometry can utilize either four cameras or one camera interchangeably.

According to exemplary embodiments, surface and sub-surface defects are detected and evaluated by stressing the silicon wafer while looking for defect induced anomalies in a fringe pattern, generated by the interference of two speckle patterns, utilizing one or more charge-coupled device camera and digital image processing. In one embodiment, the wafer is stressed using a vacuum stressing unit to provide a slight pressure difference between exposures, with the change in pressure being used to reveal any defects or voids. Instantaneous phase-shifting technique is developed to obtain a good quality interference fringe patterns and quantitative analysis. The system is designed in such a way, to perform as an optical interferometer and profiler for surface quality checks such as roughness, flatness and total thickness variation of silicon wafer.

Exemplary embodiments are directed toward a system and method for inspection of silicon wafers, including applying a stress to a silicon wafer secured in a mount; illuminating the stressed wafer with two or more light beams, wherein a reflected image beam from the stressed wafer is created from the illumination; shearing the reflected image beam to form an interference fringe combined beam according to optical interferometry; splitting the combined beam into four phase shifted beams by applying phase shifting interferometry to the combined beam; acquiring images of the four phase shifted beams and computing a wrapped phase map of the wafer from the acquired images; and displaying the computed wrapped phase map on a monitor, indicating the location of any defects on the wafer.

BRIEF DESCRIPTIONS OF THE DRAWINGS

These and other objects and advantages of the present invention will become more apparent and more readily appreciated to those skilled in the art from the following

description of the preferred embodiments, taken in conjunction with the accompanying drawings, wherein like reference numerals have been used to designate like elements and wherein:

Figure 1 shows a surface image of polished silicon wafer with a "swirl" defect as seen by the KLA tencor instrument.

Figure 2 is shows a component diagram of a system for inspecting silicon wafers in accordance with an exemplary embodiment of the invention.

Figures 3A and 3B show the arrangement of optics for digital shearography and holography configurations.

Figure 4 shows an optical head including an instantaneous phase shifting head and an image shearing head.

Figure 5 shows an alternate embodiment for an optical head.

Figure 6 shows a component diagram for measuring the flatness of a polished wafer surface in accordance with an exemplary embodiment of the invention.

Figure 7 shows an exemplary pattern of line and area scans for evaluating a wafer backgrind process.

Figure 8 shows a diagram of an exemplary wafer mount with a vacuum-loading device.

Figure 9 shows an exemplary wafer reclamation process cycle.

Figure 10 shows a block flow chart incorporating an exemplary method for inspection of silicon wafers during the wafer production process.

Figure 11, consisting of Figure 11A and Figure 11B, shows sub-surface defects in an unpolished silicon wafer in Figure 11A and shows a good wafer in Figure 11B.

Figure 12 shows the surface micro-defects of the wafer from Figure 11A after surface polishing, as measured by a KLA tencor instrument.

Figure 13, consisting of Figures 13A – 13E, shows surface defect displays for a silicon wafer according to an embodiment of the invention, with Figure 13A showing nano-scale defects, Figures 13B and 13C showing a single defect on a lapped surface, and Figures 13D and 13E showing a single defect on a fine polished wafer surface.

Figure 14 shows a component diagram of an X-ray interferometer system according to an exemplary embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 2 illustrates a computer-based system for inspecting silicon wafers according to an exemplary embodiment of the invention, including a sensor head consisting of an image shearing head 6 and an instantaneous phase shifting head 7 for shearing the image and forming real time phase shifting strain fringes, a turret head 24 to hold imaging optics, a vacuum stressing device 12, and linear 14 and rotary 13 stages. These different heads and devices are interfaced to a computer 25, a power supply, and control electronics. The sensor head enables combined digital shearography and holography capability with instantaneous phase shifting optics that measure the out of plane displacement and its derivative in real time with respect to an image shearing direction and simultaneously records four real time phase shifted fringes.

The vacuum loading or stressing device 12 is used to provide a uniform vacuum pressure on the wafer surface 5, with the wafer's edge held firmly in a wafer mount attached to the vacuum chamber. Alternate wafer loading or stressing methods such as pressure stressing, thermal stressing using an infrared lamp or a flash lamp, and microwave stressing can be used without detracting from the inventive features of the embodiments. Additionally, thermal or microwave stressing can be used to locally stress the wafer 5 for serial automatic measurement on a small area to detect micron-size defects. A change in vacuum pressure induces stress concentration at the vicinity of defects in the wafer 5 and reveals wafer defects and voids in the form of flaw–induced anomalies in the generated fringe pattern. The fringe pattern is generated by the interference between two coherent laser beams 3 produced from the image shearing head 6 and digital image processing performed on the computer 25. Accordingly, a system and method is provided for whole field nondestructive inspection and evaluation of a wafer before the wafer polishing and/or reclamation processes.

The turret head 24 includes imaging objectives and a beam expanding lens 51 for measuring defects, surface topography, total thickness variation, and flatness of the wafer surface 5. The electronic subsystem includes a computer 25, a power supply, a frame grabber for simultaneous and real time image acquisition, and an instantaneous phase shifting assembly for implementing phase shifting with respect to quantitative fringe

analysis. While a personal computer 25, with an attached monitor or screen 26, is shown in Figure 2 as being proximately located to the inspection apparatus of the inventive system, any processing device can be utilized without detracting from the inventive features of the system and can be connected to the inspection apparatus through hard-wiring, radio transmissions, across a network, or the like.

In Figure 2, the diode laser 1 coupled with fibers 2 through a collimator and beam splitter assembly 4 produce beams 3 to illuminate the diffuse wafer surface 5. One of the sides of the wafer 5 is ground, lapped, or etched prior to the polishing or the reclamation process. A ground or lapped wafer surface 5 is more diffuse in nature than an etched surface. This diffuse nature of the wafer surface 5 helps in measuring and detecting sub-surface defects by a speckle interferometric technique. The double illumination mode shown in Figure 2 is adopted to illuminate the surface of the wafer 5 more uniformly. The scattered light 8 reflected from the wafer enters the instantaneous phase shifting head 7 (shown in more detail in Figure 4) through the image shearing head 6. The image shearing head 6 can be a Michelson-type shearing device, comprised of a polarizing beam splitting cube 9, two quarter waveplates 10 and 11, and two mirrors 15 and 16. Four charge-coupled device cameras (shown in Figure 4) are used in the instantaneous phase shifting head 7 to simultaneously record four real time phase-shifted fringes. The charge-coupled device cameras, with, for example, 2048 x 2048 pixel capability, are connected to an image processing board of the computer 25 for calculating the phase distribution at video speed (e.g., 25 frames/sec). A wrapped phase map can be obtained either after the phase shifted fringe acquisition process or by using a dedicated digital holographic processor, which displays the wrapped phase in real time on the monitor 26. Alternatively, as few as one charge-coupled device cameras can be used, as discussed below with Figure 5.

The surface deformation of the wafer 5 under inspection can be directly obtained by observing the phase change before and after stressing the wafer 5 by the vacuum stressing device 12. The phase images from these two different loading states of the wafer are subtracted in real time by the computer 25, providing a phase change image modulo 2 pi (wrapped phase) that can be displayed in real time on the monitor 26. Phase unwrapping can then be carried out to remove the 2 pi phase jumps. After successful

unwrapping, further filtering can be applied for smoothing and removing the effects of local and global tilting and bending of the tested wafer. A color-coded map of the wafer displacement and strain field is viewable continuously on the monitor 26, indicating the locations of any defects.

The wafer 5 mounted on a vacuum stressing device 12 can be rotated and translated laterally by a rotating stage 13 and a linear stage 14, respectively, to perform serial measurements on a small area of the wafer 5 and also to perform total thickness variation measurements on whole area of the wafer 5. The positioning of the wafer is further adjustable vertically by means of a movable table 23. Respective motion encoders monitor the rotational and linear co-ordinates of the stages. Software operating on the computer 25 can be used to control and correct any fluctuation or eccentricity error of the stages during the wafer measurements and inspection.

The image shearing head 6 can be used in alternate embodiments utilizing digital shearography and/or holography techniques, as shown in Figures 3A and 3B. Figure 3A shows the arrangement of image shearing head 6 for digital shearography, which can utilize the Michelson interferometric principle as the shearing device. The interference takes place between the two laterally shifted object beams coming from the movable mirror 15 and the tilted mirror 16 fitted to a piezo-electric transducer 17. The direct object beam 27 reflected from the mirror 15 and the sheared object beam 28 reflected from the mirror 16 will form an interference fringe at the instantaneous phase shifting head 7. The amount of image shearing can be controlled by the piezo-electric transducer 17 through a piezo-electric transducer controller (not shown) connected to the computer 25.

In another embodiment, as shown in Figure 3B, with reference also to Figure 2, the mirror 15 can be translated linearly to transform the image shearing head configuration to a digital holography or a digital speckle interferometer configuration. In this embodiment, the object beam 19 reflected from mirror 16 at no the tilt position and a reference beam 18 from the diode laser 1 passing through the fiber 20 and a collimator 21 (as shown in Figure 2) are made to interfere at the charge-coupled device cameras in the instantaneous phase shifting head 7. A filter 22 is used to reduce the intensity of the reference beam 18.

Figure 4 shows an instantaneous phase shifting interferometric setup in accordance with an exemplary embodiment to measure wafer surface quality and surface/sub-surface defects. The combined beam 29 from the image-shearing head 6 is directed through the three non-polarizing beam splitters 30, 31 and 32 attached as shown in Figure 4. The advantage of attaching the three beam splitters together is that the effect of the environment and of vibration affects all the three beam splitters similarly. Hence errors due to the environmental effect are reduced. The beam 29, as it passes through the combination of beam splitters 30, 31, and 32, is split into four beams 33 of equal intensity. For phase shifting interferometry, the main requirement is that there should be three or more equally phase shifted images so that the phase value of the image can be calculated. In conventional phase shifting, the reference object is made to move by a piezoelectric actuator, which provides the necessary phase difference between the reference and measurement beams. However in embodiments of the present system, the phase shifting is instantaneous and non-mechanical. To ensure that the four beams 33 are phase shifted to the required value, a combination of quarter waveplates and polarizers are used in the paths of all the beams. Accordingly, the four beams 33 exiting from the three non-polarizing beam splitters 30, 31, and 32 have the same phase difference, α, between the two polarizations, as they travel through the same path length.

The phase difference, α, is from the path length difference between the object and the reference beam in the interferometric arrangement. By introducing a polarizer 39 at 45° in the beam path of Arm 1, both angles of linear polarization are rotated by 45°; and the phase difference still remains α. By introducing a polarizer 40 at 135° in the beam path of Arm 3, both angles of linear polarization are rotated by 135°; and the phase difference becomes $180^{\circ} + \alpha$. By introducing a quarter waveplate 41 at 45° in the beam path of Arm 2, a phase shift of 90° is achieved between two polarization states and the total phase shift after the quarter waveplate becomes $90^{\circ} + \alpha$. Then, by introducing the polarizer 39 at 45°, there is no additional phase shift; and the total phase shift is $90^{\circ} + \alpha$. By introducing a quarter waveplate 41 at 45° in the beam path of Arm 4, a phase shift of 90° is achieved between two polarization states; and the total phase shift after the quarter

waveplate becomes $90^{\circ} + \alpha$. Then, by introducing the polarizer 40 at 135°, there is an additional phase shift of 180°; and the total phase shift is $270^{\circ} + \alpha$.

Accordingly, the phase of the combined beam can be shifted by increments of 90° depending on the orientation of the quarter waveplate 41 and the polarizers 39 and 40. The basic advantage of this type of phase shifting is that it does not rely on any moving objects. Additionally, there is no ambiguity in phase shifting as the intensity of both beams will be the same and the interference fringes will be sharp at these angles. Since there are no mechanical devices and no ambiguity, the system once setup need not be calibrated with time, thereby increasing the accuracy and reliability of the phase shift. Moreover, the probability of errors induced due to motion is eliminated. It can be noted that not all the beams are similar, but two beams are the mirror images of the other two beams. As seen from the position of the cameras CCD 1 – 4 in Figure 4, the cameras CCD 2 and 3 are the mirror images of cameras CCD 1 and 4. For accuracy, the images from cameras CCD 2 and 3 should be mirrored before wrapping and unwrapping of the same. The four charge-coupled device cameras CCD 1 – 4 can be aligned by pixel to pixel resolution in the x and y-axis to better ensure a high degree of accuracy.

An alternate embodiment is shown in Figure 5 wherein one charge-coupled device camera 37 is utilized instead of four cameras as shown in Figure 4. The size of the system setup is accordingly greatly reduced. The combined beam 29, with different polarization states, leaves the shearing head 6 and is divided into two optical paths by a beam splitter 34. A quarter waveplate 35, placed in one of the two optical paths after the beam splitter 34, produces the required phase shift. The beam leaving the quarter waveplate 35 has two components that are mutually orthogonally polarized, differing $\pi/2$ in phase from each other and is combined with the sheared object beam at the beam splitter 36. Two speckle pattern images are formed at the charge-coupled device camera 37 after passing through the polarization splitter 38. From the two sets of two images, one set taken before, and one after stressing the wafer 5, the phase change due to stressing can be calculated; and an unwrapped phase map can be presented in real time on the monitor 26 showing the presence of sub-surface defects in the wafer 5.

In another exemplary embodiment, the system can be used to measure total thickness variation of the wafer surface 5. This embodiment utilizes a piezo-electric

transducer driven objective lens to function as a confocal microscope to obtain surface height data at equal radii of the wafer surface 5. During the measurement, a charge-coupled device camera in the instantaneous phase shifting head 7 is used to measure the peak intensity reflected from the wafer surface 5. During the surface height measurement, the rotary stage 13, the linear stage 14, and the movable table 23 are automatically employed to position the wafer 5 below the focus spot. The wafer 5 is scanned from its center to its outer edge concentrically at equal intervals (see Figure 7) to measure the height variations over the entire wafer surface 5, and the software of the computer 25 calculates the total thickness variation by removing errors due to the tilt in the rotary 13 and linear 14 stages with the input from the corresponding stage encoders.

In another embodiment, as shown in Figure 6, the system can be used for measuring the flatness of the polished wafer surface 5. An achromatic doublet lens 42 with a clear aperture equal to the diameter of the wafer 5 is concentrically fitted at the top of the wafer mount 43. The lens 42 placed over the wafer surface 5 will collimate the rays from the lens 51, positioned at the turret head 24. The reflected light 44 from the wafer surface will pass through the same lens and interfere with the beam reflected from the reference mirror 16 (Figure 2) to form the interference fringe at the charge-coupled device cameras in the instantaneous phase shifting system. The software will evaluate the flatness and present the results on the monitor along with two dimension and three dimension representations.

In another embodiment, the system can be used to measure surface topography of the wafer by phase shifting and vertical scanning interferometry technique. This makes use of an objective lens 51 in the turret head 24 to allow the collimated beam to pass through and focus on to the wafer surface 5. The objective lens 51 is mounted on a piezo-electric transducer. This is used for measuring the rough back surface of the wafer 5 by a vertical scanning interference technique. This embodiment allows various objective lenses 51 to be changed easily to accommodate different fields of view on the measuring surface. This avoids use of costly interference microscope objective lenses needed to be mounted on the turret head 24 to change the field of view as is done with commercial optical profilers. The wafer surface 5 can also be adjusted vertically by moving the table 23.

Embodiments of the inspection system utilizing the confocal technique can also be used to measure surface roughness of wafer backgrind surfaces. Backgrinding is a process that thins a wafer 5 from its normal thickness to accommodate various packaging requirements (e.g., on the order of 12 mils or 300 μm). Applications for smart cards and hand held devices are leading the trend for thinner packages and correspondingly thinner wafers 5. The overall process of backgrinding of the wafer 5 thins the wafer 5 before dicing and packaging. The process is to grind away wafer material on the backside of the wafer 5. Roughness control for the backgrinding process is important to ensure quality control for subsequent processes. The wafer surface roughness must be within tolerances after backgrinding. A wafer 5 that is too smooth or too rough will be considered out of specification. Additionally, the uniformity of the surface roughness is important, so being able to measure surface roughness at several locations on the wafer is useful. Embodiments of the inspection system facilitate a fast, optical-based system for the measurement of roughness of backgrind surfaces. Included features are the controlled automatic focus by the piezo-electric transducer for scanning across very thin backgrind wafers 5; a large number of data points per wafer scan for good spatial resolution independent of the scan length; two-dimensional and three-dimensional measurement capability; and rotational, lateral, and vertical motion control of the wafer placement. Figure 7 shows an exemplary pattern of line and area scans for evaluating the surface roughness of a wafer following a backgrind process, wherein measurements are taken perpendicular to a radius of the wafer 5. Four exemplary scan paths, numbered 1 – 4, are shown; although more or fewer paths are possible within embodiments of the system as well as asymmetric paths.

Figure 8 shows two views of a wafer mount incorporating a vacuum-stressing device. Other methods such as thermal stressing or microwaves can be utilized within embodiments of the inspection system to apply stress to the wafer 5 while holding the wafer 5 securely. The mount shown in Figure 8 includes a vacuum chuck 45 with a chamber fitted with a flange with pipe sockets 46 and 47 for connection to a vacuum pump (not shown) and a venting valve (not shown), respectively. The flange with pipe socket 46 is also connected to a vacuum gauge 48 and a controller for controlling the

pressure. The wafer 5 is placed on the vacuum chuck 45, sealed using an o-ring 49, and clamped with a circular plate 50 to prevent any rigid body motion of the wafer 5.

Figure 9 shows an exemplary wafer reclamation process cycle. Reclamation is a reprocessing technology on rejected wafers during wafer fabrication. As discussed above, the reclaimed wafers are used as monitor or "test" wafers during the semiconductor device manufacturing processes.

Figure 10 illustrates the in-line inspection of silicon wafers at steps 106 and 118 in semiconductor industries in accordance with exemplary embodiments. The system can be used to detect sub-surface defects in two cases: at step 106 before the wafer fabrication processes at step 106 (i.e. after the ingot sliced into wafers) and at step 118 before the wafer reclamation processes in case of reclamation industries or processes. This system can also be used to inspect wafer surface quality parameters for such characteristics as roughness, flatness, and total thickness variation before or after any of the processes subsequent to the slicing of the ingots at step 104. Any bad wafer rejected from the inspections at steps 106 and 118 can be routed to a recycle bin for subsequent processing or disposal.

Defects and flaws in silicon wafers 5 induce strain concentrations on the wafers 5. Shearography reveals these defects by translating the defect-induced strain concentrations into anomalies in the fringe patterns. Typical defect indications depicted in fringe patterns include: bull's eyes; abrupt curvature changes; abrupt fringe density changes; and fringe discontinuity. Some of these anomalies can be seen in the fringe pattern of a typical defective wafer as shown in Figure 11A. Whereas in Figure 11B, for good wafers, the fringe patterns show lines of equal out-of-plane derivatives of displacement from loading or stressing; and there are no abrupt changes of curvature and/or discontinuity of fringes. The results are repetitive, and the technique can differentiate the good wafers from defective wafers before the wafer reclamation/fabrication processes. In reclamation industries, a general rule is that a sub-surface defect at depth of approximately 15 μm and a defect of more than 10 μm in diameter are considered to constitute a defective wafer. To visualize the micro sub-surface defects and for quantitative analysis, a small area on wafer is imaged using a macro focus zoom lens 51 adopting the phase shifting method. A defect size of about 10 μm and larger can be

easily detected by embodiments of the inspection system. The defective unpolished wafer 5 of Figure 11A has been sent for polishing to verify the presence of sub-surface defects. After the polishing process, the wafer was inspected using the KLA tencor instrument for surface defects. The defect map obtained by the KLA tencor instrument on final polishing shows in Figure 12 defect particles more than 2000 μm in diameter. The sizes of defects in the wafer 5 can vary from tens of nanometer to hundreds or thousands of micrometers.

Figure 13A shows the characterization of surface defects on a silicon wafer. Exemplary embodiments of the inspection system can be used to check for wafer surface quality and defects characterization. A three-dimensional representation of the surface topography displayed by exemplary embodiments provides a clear indication of size, depth, and shape of defects. The defects on an unpolished (lapped) wafer surface 5 are often almost circular (or rectangular) in shape at the surface and taper down like a cup to a depth of about 205 nm, as shown in Figures 13B and 13C. The diameters of the defects can vary from 10 to 15 μm. The depth and shape of the defects found on the wafers change as the wafer fabrication/reclamation process changes from lapping to fine polishing. The defects on the polished wafer surface are irregular (or elliptical) in shape at the surface and taper down like conical or pyramidal to a depth of about 5 nm, as shown in Figures 13D. The size (diameter) of the defects typically varies from 1 to 5 μm at the surface as shown in Figure 13E. Table 1 shows the surface topography parameters of silicon wafers during various reclamation processes. There is a considerable decrease in the size and depth of defects in the silicon wafer from the lapping to the fine polishing process. However, these even these smaller defects affect the final performance and decrease reliability and manufacturing yield of semiconductor devices.

Table 1. Surface topography parameters of processed Si-wafers
(Measurement area: 225.7 × 296.7 μm)

Sl. No	Parameters/ Processes	R_a (nm)	R_q (nm)	R_z (nm)	R_t (nm)	Defect Diameter (μm)	Defect Depth(nm)
1	Lapping	1.92	6.31	221.1	296.5	10-15μm	200
2	Etching	1.44	1.99	44.61	67.09	5-10 μm	50
3	Stock polishing	1.10	1.32	8.10	11.84	2-8 μm	10
4	Fine Polishing	0.85	1.08	7.94	8.53	1-5 μm	5

The detection of nano-size individual sub-surface defect particles in silicon wafers can not be revealed by laser digital shearography or holography alone because of limitations of the wavelength of the laser light source. Exemplary embodiments of the inspection system can detect nano-size defects or particles at the wafer surface and at the wafer sub-surface level. The system utilizes phase shifting X-ray digital shearography or holography and makes use of soft/hard X-rays of a lower wavelength. Hard x-rays are more powerful because they are transmitted through many types of material with low absorption, and they travel straight even at the boundary of objects. These features cause X-rays to be a useful tool for inspecting the internal structures or defects in an object, including a silicon wafer. Figure 14 shows a schematic diagram of an exemplary embodiment utilizing X-ray interferometry. The advantage of this technique is that there is no need for external excitation or loading/stressing the object to be tested. The inspection is based on the phase variation of X-rays that travel through the wafer 56. This phase variation is caused by the spatial variation of the refractive index of the wafer 56 for X-rays. This gives an image of the refractive index by measuring the phases of X-rays.

In the exemplary embodiment shown in Figure 14, two slightly sheared X-ray beams 51 are produced and each is transmitted through the wafer 56. The two beams are superposed and interfere after they are transmitted through the interferometer. The main part is cut monolithically from a silicon block 52 consisting of two parallel plates 53. The plates 53 are cut in such an orientation that the plane surfaces of the plates 53 are perpendicular to the lattice planes, which diffract X-rays, as shown in the figure. The spacing between the paired plates 53 is the same in both pairs. Since the distances between the two-paired plates are small, the two interfering beams travel almost along the same path. The X-ray beam 54 produced from an X-ray source 64 incident on the first plate 55 at the Bragg angle is divided into transmitted and diffracted rays. Both beams 51 are transmitted through the wafer 56 to be measured and diffracted by the third 57 and fourth 58 plates. The two diffracted beams are superposed and interfere and seen by the X-ray charge-coupled device camera 59. The other two beams are blocked by the aperture 60 placed in front of the camera 59. The interfered beams show intensity variation due to the phase difference between the sheared beams. To measure the phase

difference, the phase shift method can be introduced. To obtain a phase shift, a wedge plate 61, or rotating polariser or an instantaneous phase shifting method, can be adopted as discussed above. To detect the spatial phase variation, the wafer 56 can be translated in x and y direction, perpendicular to the X-ray beams 51 with a computer controlled stage using a controller 62 connected to the computer 63. The output from the camera 59 is fed into the computer 63, and the image can be processed using image processing software. The phase difference between the rays is caused by the spatial variation of the refractive index in the wafer 56. Thus the sub-surface nano-defects of the wafer 56 can be revealed on the monitor 65 as an abrupt intensity change from an abrupt change of refractive index distribution along the X-ray paths.

Although preferred embodiments of the present invention have been shown and described, it will be appreciated by those skilled in the art that changes may be made in these embodiments without departing from the principle and spirit of the invention, the scope of which is defined in the appended claims and their equivalents.

CLAIMS

What Is Claimed Is:

1. A method for inspection of silicon wafers, comprising:

applying a stress to a silicon wafer secured in a mount;

illuminating the stressed wafer with two or more light beams, wherein a reflected image beam from the stressed wafer is created from the illumination;

shearing the reflected image beam to form an interference fringe combined beam according to optical interferometry;

splitting the combined beam into four phase shifted beams by applying phase shifting interferometry to the combined beam;

acquiring images of the four phase shifted beams and computing a wrapped phase map of the wafer from the acquired images; and

displaying the computed wrapped phase map on a monitor, indicating the location of any defects on the wafer.

2. The method according to claim 1, wherein stress the wafer is accomplished by application of vacuum, pressure, microwaves, or temperature to the wafer.

3. The method according to claim 1, wherein the wafer mount is an adjustable mount and wherein the wafer mount is adjustable rotationally, laterally, and vertically.

4. The method according to claim 3, further comprising:

positioning the wafer surface rotationally, laterally, and vertically such that the wafer surface is located below the focus spot of the light beams;

scanning the surface of the wafer from center of the wafer to the outer edge of the wafer concentrically at equal intervals to measure the height variation over the entire wafer surface; and

calculating the total thickness variation of the wafer, including removing errors from any tilt in placement of the wafer.

5. The method according to claim 1, wherein the light beams are two laser beams.

6. The method according to claim 1, wherein the method of optical interferometry used to shear the reflected image beam is selected from a list including speckle shearing interferometry, digital shearography, digital speckle interferometry, vertical scanning interferometry, confocal microscopy, profiling, and holography.

7. The method according to claim 1, wherein the combined beam is split into two beams and images, the images representing the wafer before and after stressing, and wherein an unwrapped phase map is computed and displayed.

8. The method according to claim 1, wherein the displayed map reveals surface and/or subsurface defects on the wafer.

9. The method according to claim 1, including displaying wafer quality information of surface roughness, wafer flatness, and/or wafer total thickness variation.

10. A system for inspection of silicon wafers, comprising:

a vacuum stressing device securing a silicon wafer in a mount;

a laser illuminating the secured wafer with two or more beams, wherein a reflected image beam from the wafer is created from the illumination;

an image shearing head forming an interference fringe combined beam from the reflected image beam according to optical interferometry;

a phase shifting head splitting the combined beam into four phase shifted beams by applying phase shifting interferometry to the combined beam;

cameras acquiring images of the four phase shifted beams

a processor computing a wrapped phase map of the wafer from the acquired images; and

a monitor displaying the computed wrapped phase map, indicating the location of any defects on the wafer.

11. The system according to claim 10, wherein the vacuum stressing device can apply stress to the wafer by means of vacuum, pressure,

12. The system according to claim 10, including motion controllers to control adjustment of the wafer mount rotationally, laterally, and vertically.

13. The system according to claim 10, wherein the phase shifting head comprises three beam splitters attached together.

14. The system according to claim 10, wherein rough surfaces of the wafer are profiled by a vertical scanning interference technique by scanning the wafer vertically downward so that each point on the wafer surface produces an interference signal and frames of interference data imaged by the cameras are captured and processed to determine surface height profile.

15. The system according to claim 10, wherein the surface of the wafer is profiled by a confocal technique by focusing an optic lens onto the surface of the wafer and continuously measuring of the lens position to determine height variations of the surface of the wafer.

16. The system according to claim 15, wherein a piezo-electric transducer is used to move the objective lens to focus on the surface of the wafer.

17. The system according to claim 10, wherein the image shearing head comprises at least one beam splitter and at least one mirror for shearing the combined beam according to a digital shearography technique.

18. The system according to claim 10, wherein the phase shifting head comprises optics and charge-coupled device cameras for simultaneous phase shifting to generate four real time phase shifted fringe patterns characteristic of defect induced anomalies.

19. The system according to claim 10, including a turret head with a interchangeable lens selected from a list including an imaging lens for whole field wafer measurement, a macro lens with extension tubes for serial automatic measurement on very small areas with digital speckle interferometry, and a piezo-electric transducer-mounted objective lens.

20. The system according to claim 10, wherein the image shearing head and the phase shifting head are contained in a unit separate from the vacuum stressing device to avoid vibration.

21. A method for detecting defects in a silicon wafer, comprising:

vacuum stressing a silicon wafer, wherein the wafer is mounted in a mount attached to a vacuum chamber;

illuminating the back side of the wafer by two coherent laser beams through polarization maintaining fibers;

generating a fringe pattern characteristic of defect-induced anomalies in the wafer in real-time through digital shearography and instantaneous phase shifting optics by:

measuring the surface strain or the derivative of out-of plane displacement with respect to an image shearing direction;

subtracting phase shifted speckle patterns obtained before and after vacuum stressing the wafer loading; and

simultaneously generating in real time four phase shifted fringe patterns with defect anomalies by an instantaneous phase shifting head;

processing the generated phase shifted fringe patterns to generate a phase map image of the wafer;

converting the phase map image to an unwrapped phase image showing the wafer defects;

generating wafer defect statistics, depths, and locations; and

displaying the defects and statistics in a phase contour map and three dimension image on a monitor.

22. The method according to claim 21, wherein each defect can be characterized by one or more of: the position of the defect in the wafer, the shape of the defect, and the size of the defect.

23. The method according to claim 21, wherein wafer surface and/or sub-surface defects are detected before a wafer fabrication process or a wafer reclamation process.

24. A method for measuring surface roughness of a silicon wafer, comprising:

directing a coherent laser beam from a diode laser to a surface of a silicon wafer through an objective lens mounted on a piezo-electric transducer;

forming four phase shifted fringe patterns from the interference of light reflected from the wafer surface with a direct reference beam;

processing the formed phase shifted fringe patterns to generate surface parameters and surface topography images in two dimension and three dimension; and

displaying the generated images and parameters.

25. The method according to claim 24, wherein smooth wafer surfaces are measured by an instantaneous phase shifting technique.

26. The method according to claim 24, wherein back side wafer surfaces and backgrind wafer surfaces are measured by a vertical scanning interferometry technique or a confocal microscope technique.

27. A method for measuring the flatness of a silicon wafer, comprising:

directing a light beam onto a silicon wafer through an achromatic doublet lens with clear aperture equal to the diameter of the wafer, wherein the lens is concentrically fitted at the top of a mount securing the wafer;

collimating and reflecting the directed light beam back from the surface of the wafer through the doublet lens;

directing the reflected light beam into an instantaneous phase shifting system, wherein the reflected light beam interferes with a direct beam from a reference mirror to form an interference fringe at one or more charge-coupled device cameras; and

processing images from the charge-coupled device cameras to find the flatness error of the wafer surface.

28. A method for detecting nano-scale defects in a silicon wafer, comprising:

shearing an X-ray beam within an X-ray digital shearing interferometer;

directing the sheared X-ray beams onto the surface of a silicon wafer, wherein the wafer is not subject to external stress;

superimposing and interfering the two sheared X-ray beams with each other after the beams have passed through the wafer;

forming an interference fringe pattern of the interfered beams at an X-ray charge-coupled device camera showing intensity variations from a phase difference between the sheared beams;

measuring spatial phase variation differences according to phase shifting interferometry; and

displaying nano-scale defects in the wafer as abrupt wafer image intensity changes, wherein the image intensity changes reflect phase variation differences.

29. The method according to claim 28, wherein the digital shearing interferometer includes two parallel thin plates cut monolithically from a silicon block.

30. The method according to claim 28, wherein phase shift between the sheared beams is obtained by passing the beams through a transparent wedge plate, by passing the beams through a rotating polarizer, or by applying an instantaneous phase shifting interferometry method.

31. The method according to claim 28, wherein the spatial phase variation is detected by translating the wafer in x and y directions, perpendicular to the X-ray beams, with a computer controlled stage.