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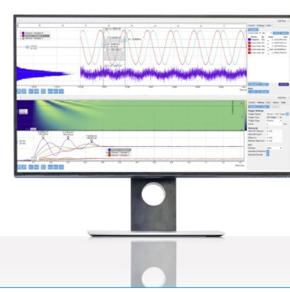

Full-Wafer Defect Identification using X-ray Topography

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Abstract. The timely identification of defects can lead to increased yields and significant cost savings in wafer production. X-ray topography (XRT) is recognized as being a powerful tool for directly imaging defects in single crystals, such as semiconductor substrates and epitaxial thin-films. In XRT, defects are imaged by measuring changes in the diffracted X-ray intensity across a wafer due to strain and/or tilt that the defects introduce into the crystal lattice. We have developed a novel, high-speed digital XRT method for non-destructive defect characterization of up to 300mm diameter wafers. This method, called BedeScan™, offers substantial advantages to conventional topography, especially for rapid, convenient defect identification in a wafer manufacturing/processing environment. X-rays from a microfocus source are diffracted from a wafer, which is translated with fast, high-precision motions in front of a fixed CCD camera and a sequence of images is recorded. A virtual scan of the camera in the computer is undertaken to place each of these images at the correct position (x,y) in the final image. The final image contains impressions of defects across the full-wafer, *e.g.* mechanical edge damage, misfit dislocations and slip bands. This method allows a limited area detector to be used to image specimens of any size. It is possible to record a low-resolution full-wafer topograph with subsequent high-resolution, small-area topographs in regions of special interest. BedeScan™ also offers the ability to measure only the periphery of a wafer for quick mechanical edge defect recognition. Quantitative maps of specimen distortion, *e.g.* wafer bowing as a result of thermal processing, can also be produced.

INTRODUCTION

The move to 300 mm silicon wafers as substrates for ULSI fabrication together with the development of new processes means that there is a continued need for new characterization methods capable of non-destructively imaging defects within large wafers. These methods should be sufficiently sensitive to image a variety of defects, such as: surface scratches and grinding marks, mechanical edge damage, slip bands, striations due to dopant variations and even single misfit dislocations at the interface with epitaxial layers deposited on substrates. X-ray topography (XRT) provides sufficient sensitivity to image these, and other, types of defects over the large areas of current production wafers.

XRT methods produce images of defects in wafers by measuring variations in the X-ray diffraction as a function of position across the wafer's surface using a position sensitive (imaging) detector. To obtain an XRT image, the wafer is oriented with respect to the incident X-ray beam such that a single set of planes, designated by the Miller indices (hkl), satisfy the Bragg condition for diffraction, namely

$$2d \sin \theta_B = \lambda \qquad (1)$$

where d is the spacing of the diffracting planes, θ_B is the Bragg angle and λ is the X-ray wavelength. For wafers that contain no defects, the crystalline lattice is essentially perfect leading to a constant X-ray intensity diffracted from the wafer. However, defects that disturb the perfection of the lattice (*i.e.* those defects that introduce strain and/or tilt) alter the d-spacing and/or Bragg angle, which give rise to variations in the diffracted intensity in the vicinity of the defects. For a detailed treatment of the theory of X-ray topography see the texts by Bowen and Tanner [2], or Authier [3] and the references contained therein.

The most commonly encountered XRT instruments are based on the design proposed by Lang [3] in 1959. The geometric arrangement is shown in figure 1. To date, the usage of XRT instruments by the semiconductor industry has been somewhat limited

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despite the industry's complete reliance on single crystal substrates. We believe that the most important factors limiting the use of XRT systems by industry are practical, namely:

- the long exposure times: typically 6 hours for a 200 mm wafer on a system using a rotating anode generator, with medium resolution film
- the large size of conventional Lang cameras: typically 1.5 x 2 x 3.5 m for a 200 mm system
- the complication of maintenance of rotating anode generators
- the time and inconvenience of photographic processing, especially in a fab environment
- the requirement to digitize the film images before automated interpretation can be applied
- the difficulty to change between reflection and transmission geometries

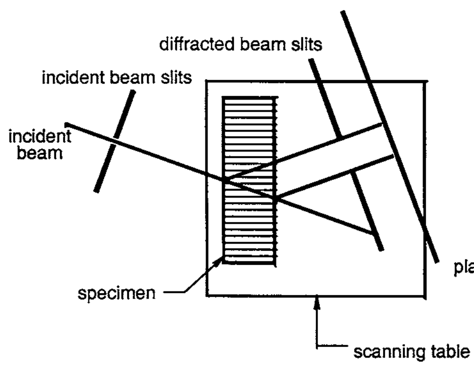


FIGURE 1. The geometric arrangement for Lang X-ray topography in transmission. A similar reflection arrangement is also available. The specimen and plate or film are rigidly coupled together and scanned through the X-ray beam while the diffracted beam slits stay fixed in space.

To overcome these limitations, we have developed a new XRT method that employs a scanning sample stage in front of a stationary CDD detector, which greatly simplifies the design of XRT systems capable of imaging up to 300 mm wafers.

THE NEW METHOD

Figure 2 illustrates the new XRT method that we have called BedeScan™. The X-ray beam is diffracted from the wafer in either reflection or transmission, and the diffracted beam recorded on a two-dimensional imaging detector.

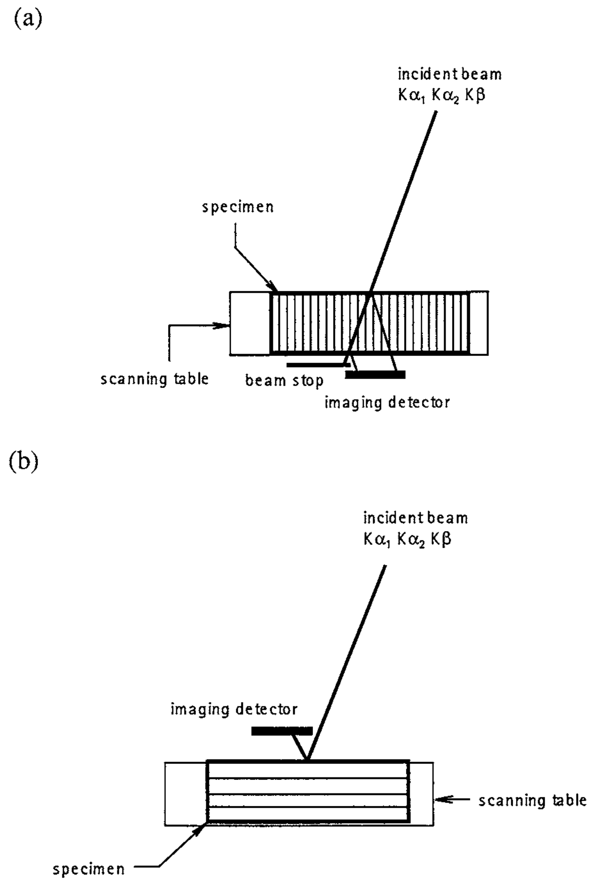


FIGURE 2. The new scanning XRT method in (a) transmission and (b) reflection. The imaging detector is fixed, and the wafer (specimen) scans through the beam.

In reflection using Cu radiation, the image at the detector is a double line of $K\alpha_1$and $K\alpha_2$ as shown in figure 3, with each line imaging a different part of the wafer. A bright dot is seen on the $K\alpha_1$ line in figure 3, which is the image of the cross-section of a defect; this is not seen on the $K\alpha_2$ line, which images a different area. In transmission, using Mo radiation, the image at the detector contains the $K\alpha_{1/2}$ and $K\beta$ lines.

In the Lang method, a slit is used to eliminate $K\alpha_2$ since it otherwise causes blurring of the image. Much shorter distances from specimen to detector can be used in the new method, since there are no diffracted beam slits to interfere. Using the new method, we can also completely eliminate the spectral blurring in reasonably good crystal. Therefore, significantly more intensity is available by including the whole of the $K\alpha_1$ and $K\alpha_2$ lines.

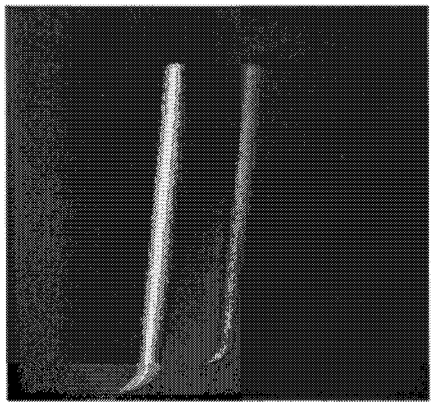


FIGURE 3. Single "frame" image showing Kα_1 (left) and Kα_2 (right) lines. These two lines image slightly different parts of the wafer.

When the wafer is scanned by a mechanical step, the new image is superimposed on the previous one. In order to integrate each frame into a complete image, we therefore undertake a *virtual scan* of the detector in the computer. This is illustrated in figure 4.

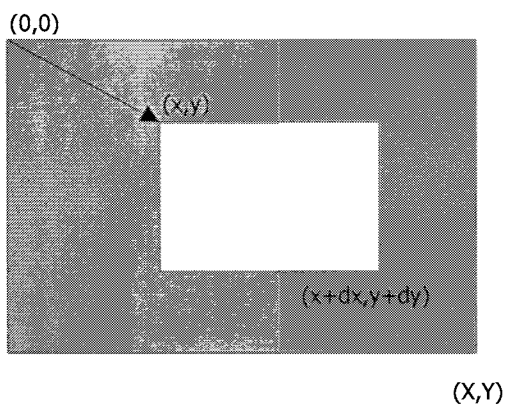


FIGURE 4. Illustration of principle of "virtual scan" of detector.

The area (x, y) to (x+dx, y+dy) is the image acquired in single frame. The area (0,0) to (X, Y) is the full image of the wafer, held in computer. The frame currently received from the detector is mapped into the correct part of computer memory, so that scanning across the whole wafer builds up the image of the wafer. This principle can in fact be applied to any kind of image (*e.g.* an optical micrograph or X-ray radiograph) and allows a limited area detector to be used to image a specimen of unlimited size. In addition to the image contrast information, the absolute position of the Kα_1 and Kα_2 lines on the detector are a sensitive measure of the local orientation of the wafer, specifically its deviation about an axis normal to the incidence plane. These orientation data may also be conveniently stored and mapped to give a quantitative map of specimen distortions, *e.g.* bowing or distortion in processing.

INSTRUMENTATION

Figure 5 shows a prototype BedeScan™ instrument. X-rays are produced using an 80W microfocus source. The incidence angle (θ) of the X-ray beam on the wafer is adjusted to satisfy the Bragg condition by rotating the source, which is carried on a curved mechanical slide above the surface of the wafer.

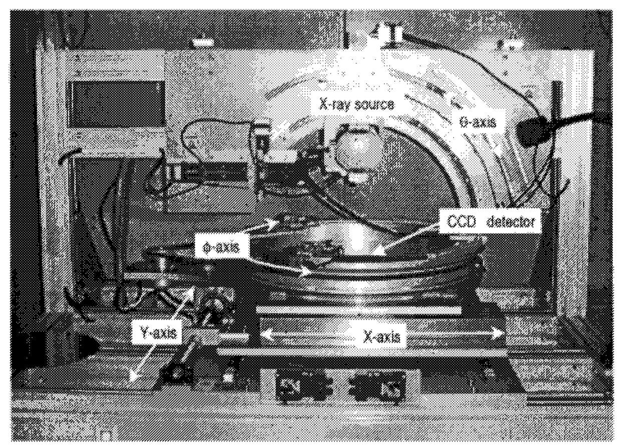


FIGURE 5. Prototype BedeScan™ instrument configured for transmission XRT measurements.

In the transmission geometry (shown), the CCD detector is mounted below the surface of the wafer with a beam-stop placed between the wafer and the active area of the detector so as to occlude the direct X-ray beam. In the reflection geometry, the detector is mounted above the wafer.

The wafer is horizontally mounted using a three point kinematic clamp. The wafer clamp is carried on two high-precision translation (y and x) axes and a rotational (ϕ) axis, ordered from bottom to top of the instrument. The wafer is aligned by rotating the ϕ-axis until that the diffraction stripes (as shown in figure 3) are parallel to the y-axis.

Under full computer control, the wafer is scanned through the incident X-ray beam using the x-axis and stepped using the y-axis in order collect a partial topograph (stripe) with a height approximately equally to the height of the active area of the CCD detector. These stripes are then stitched together to create the final X-ray topograph.

All topographs shown in the next section were measured in the transmission geometry using Mo Kα radiation ($\lambda \approx 0.07$ nm) and the Si(220) reflection. A small area (~10×12 mm^2) CCD detector with a 20 μm resolution setting was used unless otherwise stated.

RESULTS & DISCUSSION

A detailed treatment of image properties of this method has been published elsewhere [4], but for the purpose of this paper we note the following properties:

- Image contrast shows geometrical diffraction or orientation contrast [5]
- The contrast of the images as shown is conventional for topography, *i.e.* darker corresponds to higher intensity.
- The resolution is limited only by the detector, down to a resolution of < 0.5 μm.
- Exposure time is shorter than on a conventional film system.

A topograph of a 300mm silicon wafer is shown in figure 6. The faint periodic horizontal lines are artifacts introduced by an early version of the stitching algorithm used to create the full wafer image and are not due to defects. In addition to high temperature processing, an ~19 nm thick epitaxial SiGe layer (Ge fraction ~9.5%) was deposited on the substrate, thereby leading to misfit dislocations and slip bands in the single crystal. Most mixed dislocations along <110> crystal directions appear around the wafer edges. A few shorter dislocations are visible away from the edges. These dislocations are believed to have nucleated late during the annealing process, thus leading to shorter lengths of the detected dislocation bundles. X-ray topography in reflection geometry would help determine the depth spread of dislocation bundles inside the wafer and would thus help distinguish between misfit and thermal slip dislocations. This was, however, outside of the scope of this study. At the laser mark close to the notch (top), dislocation bundles running along a <100> type direction are visible, which indicates that these dislocations are not mixed type dislocations but pure edge dislocations. Pure edge dislocations come into being only during processes that cause a very high stress in the crystal, *e.g.* thermal annealing. All detected defects show a very strong contrast. Thus, for standard monitoring of thermal annealing or epilayer growth processes, low resolution scanning is recommended, with high-resolution topographs taken in the areas where defects are found at in the quick pre-scan.

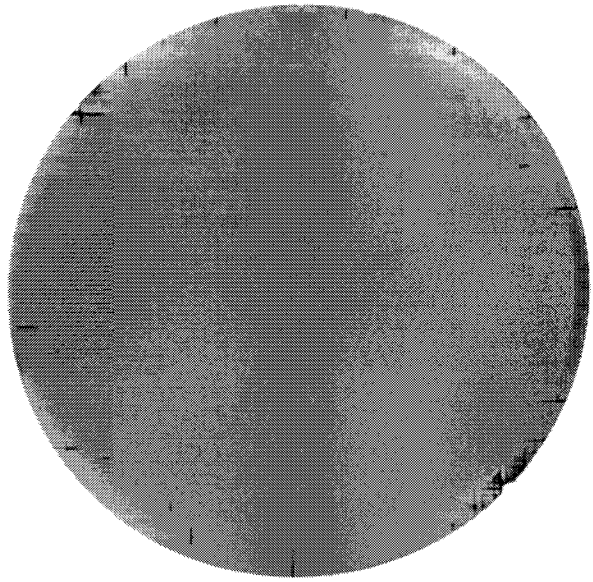
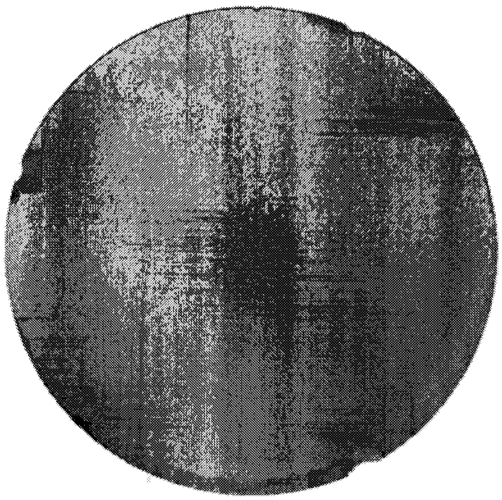


FIGURE 6. Dislocations and slip bands in a 300 mm wafer with an epitaxial SiGe layer deposited on the substrate.

A topograph of a 200 mm wafer after thermal processing is shown in figure 7. The bulk oxygen in Czochralski silicon wafers enhances gettering by forming bulk micro defects (BMDs) from the precipitated oxygen atoms. The high oxygen content in this sample introduced large lattice strain and dislocations. A magnified region of the wafer is provided in figure 7(b) to show the resolution of the topographic image at detector setting 10μm resolution. Single dislocation lines and their curved threading ends can easily be distinguished. The wafer is slightly miscut, which is why orthogonal dislocation lines are not exactly perpendicular.

Non-destructive defect recognition in early stages of processing allows wafers to be sorted based on their potential to meet final product quality requirements. Identification of residual edge damage, slip lines, tilted domains and similar defects can provide significant cost savings. A topograph of an etched 150mm diameter silicon wafer provided by Wacker Siltronic Inc. is shown in figure 8. Etching is a very early point in wafer processing. A low-resolution, annular topograph was measured in order to survey the wafer for edge damage, which is known to act as slip line and misfit dislocation nucleation sites during further wafer processing [6]. A high-resolution (10 μm resolution setting) topograph was measured where a dark spot at the wafer edge was present (shown). It is apparent that most of the edge and surface area of the wafer is free of defects.

(a)



(b)

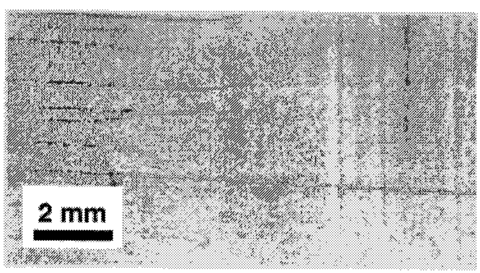


FIGURE 7. Slip bands and dislocations lines in a 200 mm wafer after thermal processing.

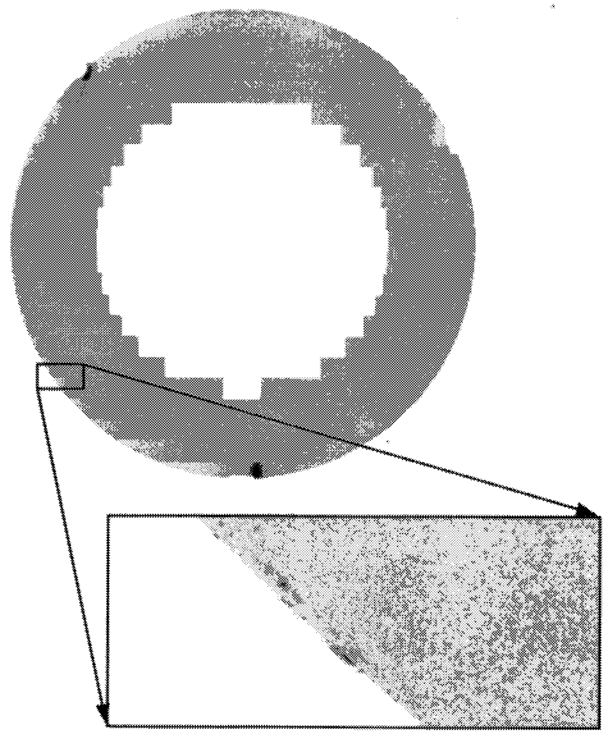


FIGURE 8. Mechanical edge damage in an etched 150 mm wafer.

CONCLUSION

We have presented a new X-ray topography method, which we have called BedeScan™. The method offers substantial advantages compared to traditional Lang topography, especially for the rapid, convenient characterization of large wafers as used in ULSI fabrication. It gives good contrast for defects, such as dislocations, slip bands and subgrain boundaries. The resolution is limited only by the detector, and may displace film methods entirely as detectors improve. The method offers substantial advantages over film methods in convenience and the application of digital image processing techniques and in the extraction of quantitative information, such as orientation maps.

ACKNOWLEDGMENTS

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REFERENCES

1. Bowen, D. K., and Tanner, B. K., *High Resolution X-ray Diffractometry and Topography*, Taylor & Francis, 1998.
2. Authier, A., *Dynamical Theory of X-ray Diffraction*, Oxford Univ Press, 2001.
3. Lang, A.R., *J. Appl. Phys.* **29** 597 (1958).
4. Bowen, D.K., Wormington, M. and Feichtinger, P., *J. Appl. Phys. D* (in press).
5. Dudley, M., Huang, X.R., and Huang, W., *J. Phys. D* **32** A139 (1999).
6. Feichtinger, P., Goorsky, M. S., Oster, D., D'Silva, T., Moreland, J., *J. Electrochem. Soc.* **148**, G379 (2001).