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A SCANNING DEFECT MAPPING SYSTEM FOR SEMICONDUCTOR CHARACTERIZATION

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ABSTRACT

We have developed an optical scanning system that generates maps of the spatial distributions of defects in single and polycrystalline silicon wafers. This instrument, called Scanning Defect Mapping System, utilizes differences in the scattering characteristics of dislocation etch pits and grain boundaries from a defect-etched sample to identify, and count them. This system simultaneously operates in the dislocation mode and the grain boundary (GB) mode. In the "dislocation mode," the optical scattering from the etch pits is used to statistically count dislocations, while ignoring the GB's. Likewise, in the "grain boundary mode" the system only recognizes the local scattering from the GB's to generate grain boundary distributions. The information generated by this instrument is valuable for material quality control, identifying mechanisms of defect generation and the nature of thermal stresses during the crystal growth, and the solar cell process design.

INTRODUCTION

Crystal defects such as dislocations and grain boundaries strongly influence the performance of all electronic devices. The influence of defects is particularly important for solar cells because the commercial silicon solar cells are fabricated on low-quality material that contains high densities of defects and impurities. In the large-grain polycrystalline silicon substrates, used for commercial solar cells, the dominant defect appears to be the intragrain dislocations. A knowledge of the distribution of defects is necessary for the following reasons: (i) the distribution of defects reflects the nature of thermal stresses generated during the crystal growth. It is known that dislocation formation can take place when the magnitude of thermal stresses during the crystal growth exceeds the yield stress, (ii) the degree of degradation in the device performance due to defects depends on their distribution as well as their density. This is because the localized regions of high dislocation density can produce a significantly higher effect on the cell performance compared to a case if the dislocations were uniformly distributed over the cell area, (iii) a knowledge of the defect distribution can allow a better design of the cell and the cell fabrication processes, (iv) determination of the variations in the defect distributions from wafer-to-wafer, and from ingot-to-ingot are essential for material quality control.

The two methods commonly used for determining the dislocation density in semiconductor materials are: X-ray topography and chemical etching. X-ray topography is typically only used for single crystal wafers of low dislocation density. The most commonly used method consists of etching the material in a chemical solution that produces etch pits at the dislocation sites. Subsequently, the etch pits are counted under an optical microscope. This procedure can be extremely tedious and time-consuming for large-area wafers (even with the help of image analysis attachments for the optical microscope). A similar procedure can be applied to polycrystalline silicon substrates. However, care must be exercised in selecting the suitable etches, because many of the etches do not work well for polycrystalline substrates. For example Wright and Dash etches produce etch pits of different shapes and sizes for different orientations (1, 2). A unique etch, known as "Sopori etch," was formulated for polycrystalline silicon to produce etch pits of the same size on all orientations (3). This isotropic etch consists of

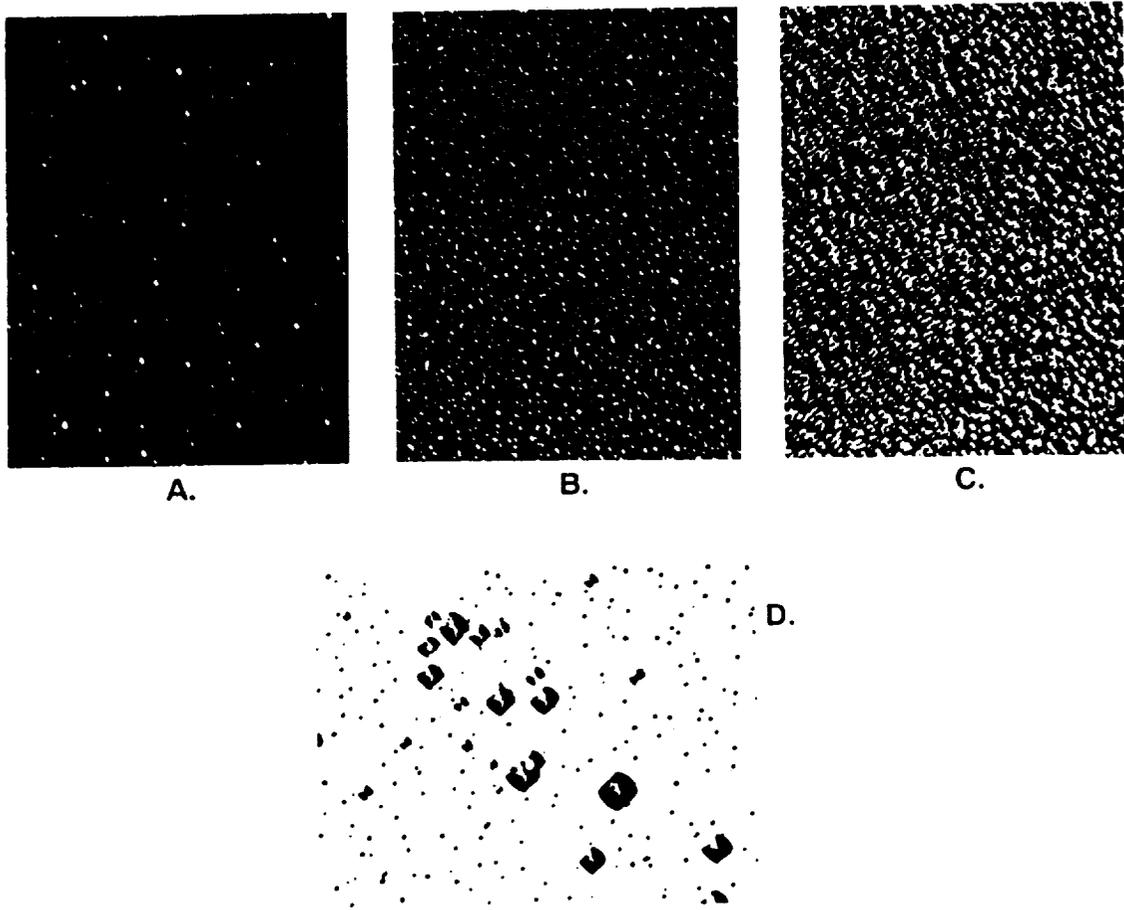


Figure 10. Photographs showing variation in the texture density and size due to different Optical Processing conditions (see text)

HF:CH₃COOH:HNO₃ in the ratio of 36:15:2. The shape of an etch pit produced by this etch depends only on the direction of the dislocation; circular etch pits are formed when the dislocation emerges normal to the surface, and elliptical when the dislocation is at an angle to the surface.

In order to facilitate the defect counting process we have developed a rapid, optical scanning technique that uses scattering from a defect-etched wafer to statistically count dislocations at the surface. This system called Scanning Defect Mapping System (SDMS) can simultaneously produce maps of the grain boundary distributions. This paper describes the principle of this new technique and some applications for semiconductor characterization.

PRINCIPLE OF THE TECHNIQUE

SDMS uses the characteristics of the light from a defect etched sample to recognize and statistically count the dislocation etch pits. When a silicon sample, defect-etched in Sopori etch, is illuminated with a collimated light beam, the reflected light from the etch pits is scattered into a narrow cone of about 20 degrees. Figure 1a shows a reflection pattern due to dislocation etch pits of circular geometry. The shape of the pattern is indicative of the shape of the etch pits. A photograph of the etch pits is shown in Figure 1b. If the etch pits are elliptical, the reflected pattern also shows elliptical geometry.

It has been shown previously that the total integrated light, scattered from an illuminated region of a defect-etched surface, is proportional to the number of dislocation etch pits in that area (4,5). This principle was previously applied to map dislocation density in large-area, single crystal semiconductor wafers. However, the usefulness of this technique for polycrystalline substrates was severely limited. It was found that grain boundary (GB) "grooving," which occurs during defect delineation by chemical etching, produced very strong signals that erroneously indicated a high dislocation density. This problem prevented application of the proposed technique to polycrystalline samples -- a domain where it is expected to be the most valuable. We have recently solved this problem and successfully applied this technique to produce maps of the dislocation distributions in commercial silicon substrates, typically 10 cm x 10 cm in size. Furthermore, this technique is extended to image the grain distribution of the wafer.

In the new approach the reflected light signal, due to the GB scattering, is separated from the dislocation signal. This is made possible by the fact that the divergence of the GB and the dislocation signals is different. The GB scattering occurs with a very large scattering angle and is primarily scattered as line pattern perpendicular to the direction of the GB. Whereas the scattering from the dislocations occurs within a narrower cone as discussed previously (4). These scattering features allow us to retrieve the dislocation and GB information from the scattered and near-specular components of the reflected beam, respectively. In the setup described in the next section, the input and output apertures are adjusted such that the first lobes of the light scattered by the GB's, accompanying the specular reflection, are allowed to emerge from the integrating sphere along with the specular beam. However, the light scattered by the dislocations is captured by the integrating sphere.

SYSTEM CONFIGURATION OF SDMS

Figure 2 is a schematic showing the major components of the SDMS. A light beam from a HeNe laser ($\lambda = 6328 \text{ \AA}$) illuminates the defect-etched sample at normal incidence. The light scattered by the sample is collected by two detectors referred to as the Grain Boundary Detector (GBD) and the Dislocation Detector (DD), shown in Figure 2. These detectors are positioned so as to differentiate between etch pits and grain boundaries as follows. When the laser beam is incident

on a group of etch pits, the light is primarily scattered into a well-defined cone with an angular spread of about 20° . This light is collected by the integrating sphere and is measured by the photodetector DD. The signal from the detector, which measures the integrated light intensity, is proportional to the local dislocation density of the sample. When the laser beam hits a grain boundary, the light is scattered as a one-dimensional streak, elongated perpendicular to the length of the GB. The near-specular component of the scattered light passes through the integrating sphere and is reflected by the beam splitter towards the GBD. The central stop of the annular aperture blocks the axial component of the beam, allowing the off-axis component to focus on the GBD. When the laser beam is incident on a defect-free area of the sample, the light is specularly reflected back out of the integrating sphere, giving no signal on the DD. This beam is then blocked by the annular aperture, thus producing no signal on the GBD either.

The sample is scanned under the light beam using an X-Y stage. The detector signal and the position signals from the X-Y stage are processed by the computer and displayed as defect maps. The SDMS acquires data simultaneously in two modes - the "dislocation" mode, and the "grain-boundary" mode. Electronic circuits are provided to minimize the cross-talk between GB and the dislocation signals. The signals from the two detectors are digitized and fed into a computer along with the x-y position signals from the scanning stage. The data are stored in high speed buffer memory. The electronic hardware and the computer software required for SDMS is developed at NREL. Having the information stored in the computer allows the user to perform detailed analyses of the distributions. Alternatively, the analog signals from the detectors are processed to directly display the defect and GB distributions on a storage oscilloscope.

RESULTS

Figure 3a is a dislocation density map of a 2.5 cm x 2.5 cm commercial solar cell substrate generated by the SDMS. The dislocation densities (corresponding to various colors in the original map) are identified by a gray scale; a calibration sample is used to establish this relationship. Figure 3b shows a grain boundary map of the same sample. Figure 4 is a photograph of the defect-etched sample whose dislocation and GB maps are shown in Figure 3a. In comparing these figures one can clearly note the absence of grain boundaries in Figure 3a and absence of dislocations in Figure 3b.

Due to short times required for mapping dislocations (typically 1 hour for a 10-cm x 10-cm wafer), SDMS can be used routinely to evaluate material quality of commercial photovoltaic silicon substrates. Figure 5a is dislocation map of a polycrystalline silicon wafer typically used for commercial solar cells. A photograph of the defect-etched sample is given in Figure 5b for comparison. It is seen that a large fraction of the total substrate area has very low dislocation density. However, a strong variation in the dislocation distribution seen in this figure is expected to degrade the cell performance due to the fact that heavily dislocated regions can act as "sinks" and shunts for the rest of the device.

In evaluating the material quality by this technique we consider two parameters: the average dislocation density, and the degree of spatial variation in the dislocation density. At this time it is not known how each of these parameters influence the cell performance. These issues are being addressed in our current research work that is being done in collaboration with a number of photovoltaic manufacturing companies.

The dislocation distributions determined by SDMS can also be used on a qualitative basis to determine the locations of high thermal stresses (above the yield stress level) during crystal growth. Figure 6 is a dislocation map of a 10-cm x 10-cm wafer that has a high dislocation density near the wafer edges, indicating a high level of stress at the sides of the casting. It is important to note that this information can only be obtained by extensive defect analyses, such as

by SDMS. Further details of the relationship between defect distributions by SDMS and the crystal growth conditions are given in a forthcoming paper (4).

CONCLUSION

An optical scanning technique for defect mapping of single and polycrystalline silicon substrates has been developed. This technique uses optical recognition of dislocations and grain boundaries and performs statistical counting of dislocation etch pits. These features make this technique rapid and accurate compared to any other technique currently available. Furthermore, the cost of the instrument is very low compared to other instruments based on imaging and electronic recognition. Although we have demonstrated use of this technique for silicon, this is also applicable to other semiconductors.

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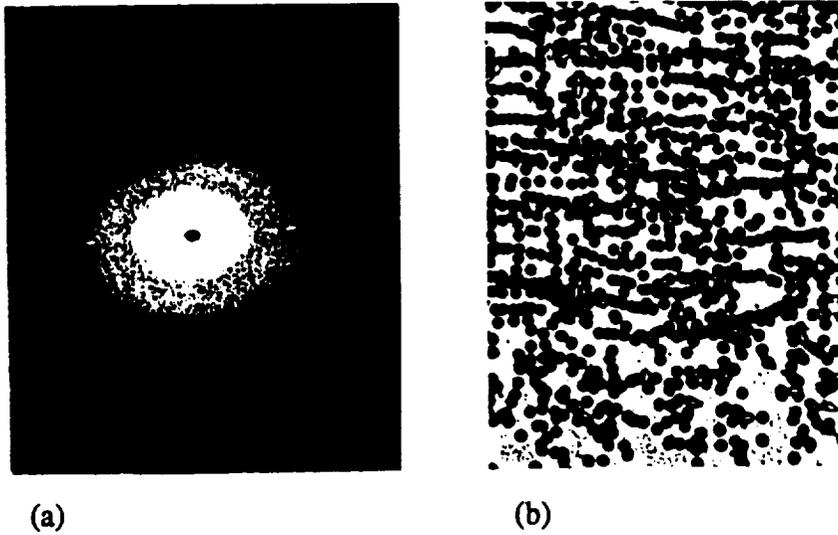


Figure 1a. Photograph of the reflection pattern from circular etch pits

Figure 1b. Photograph of the circular etch pits

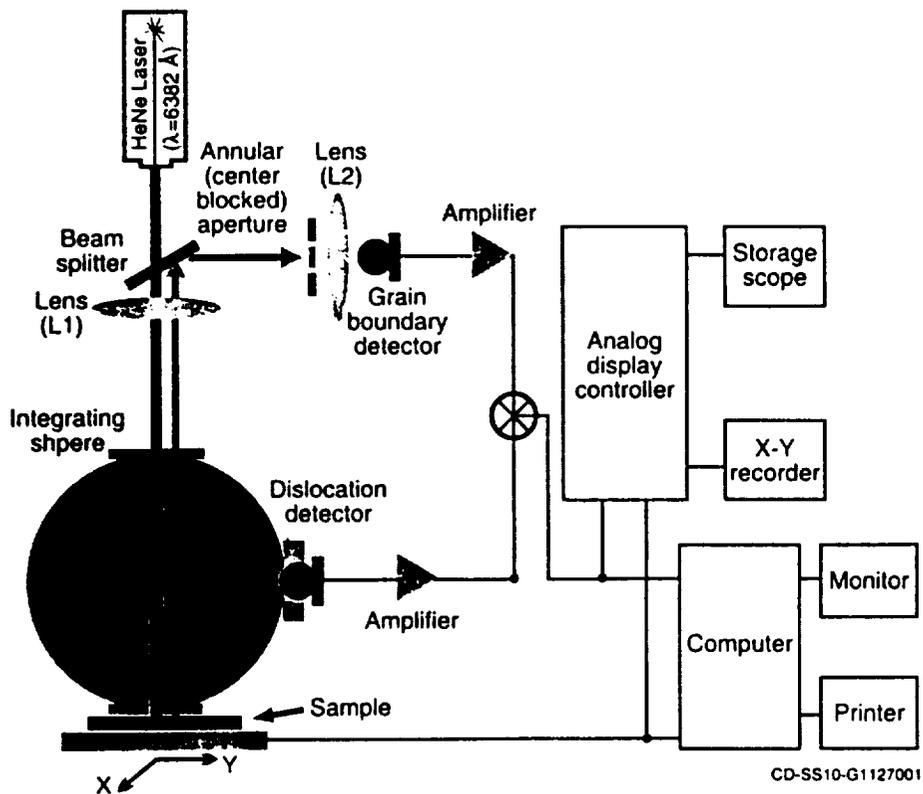


Fig. 2. A schematic of the Scanning Defect Mapping System

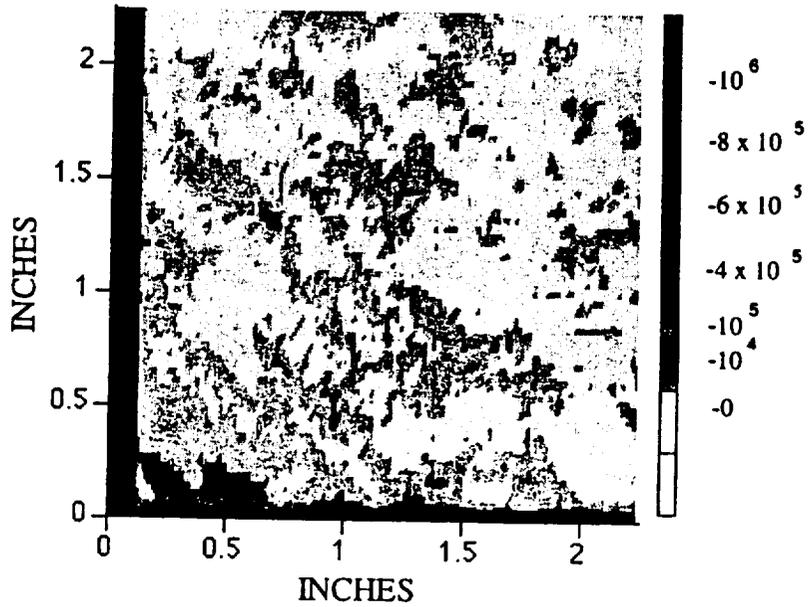


Figure 3a. Dislocation map of a 5-cm x 5-cm polycrystalline silicon substrate (shown in Fig. 4) produced by SDMS



Figure 3b. Grain-boundary map of the 5-cm x 5-cm sample shown in Fig. 4



Figure 4. Photograph of the defect-etched sample used in Fig. 3

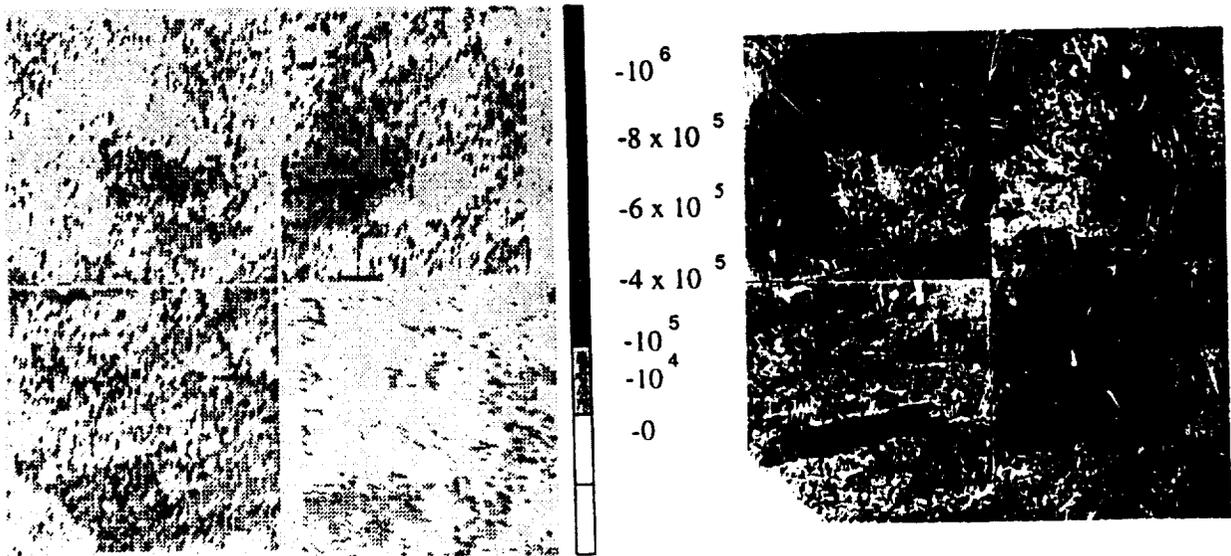


Figure 5a. Dislocation map of a 10-cm x 10-cm commercial silicon wafer showing non-uniform dislocation distribution

Figure 5b. Photograph of the defect-etched sample corresponding to the dislocation map of Fig. 5a

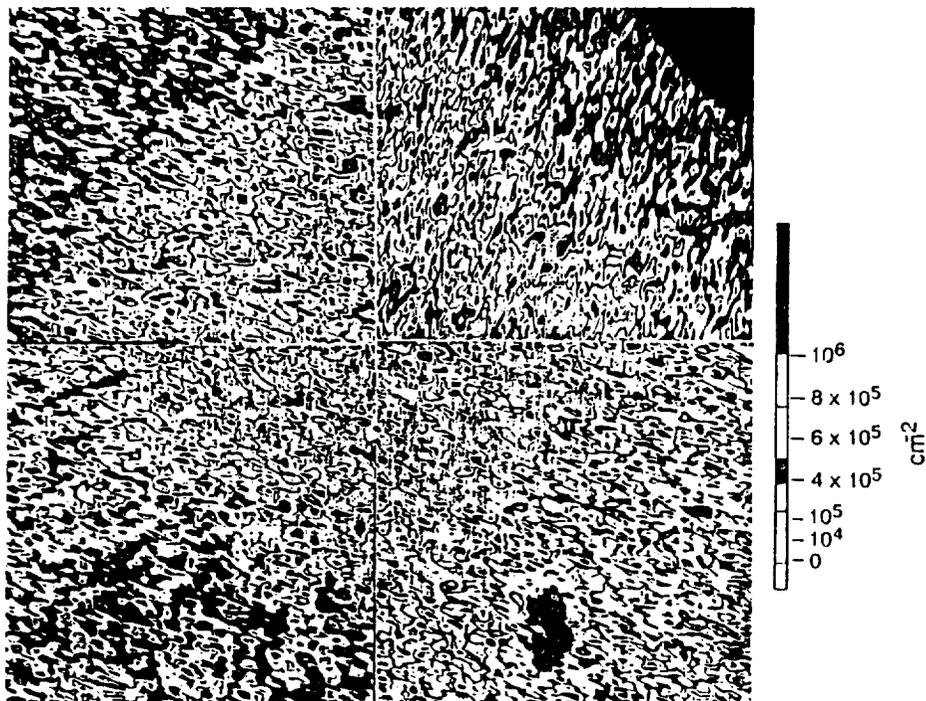


Figure 6. Dislocation density map of a 10-cm x 10-cm corner section of a cast wafer indicative of a high thermal stress at the edges of the casting as manifested by a high dislocation density around the edges.