X-RAY TOPOGRAPHY AS A PROCESS CONTROL TOOL IN SEMICONDUCTOR AND MICROCIRCUIT MANUFACTURE

by

Dr. D. L. Parker

and

Dr. W. A. Porter

Texas A& M University
College Station, Texas

SUMMARY

X-ray topography is currently widely recognized as the only practical, nondestructive method for the identification of crystal lattice defects in semiconductor materials. Unfortunately conventional methods have proved too expensive for any broad application in semiconductor process control. This paper gives a brief review of the conventional x-ray topographic techniques and a description of a new high speed camera which has demonstrated a considerable savings in cost-per-topograph.

INTRODUCTION

Early in this century several investigators demonstrated that the lattice of a single crystal can act as a diffraction grating for x-rays with wavelengths comparable to the atomic spacings. The phenomenon is due to the coherent scattering of specific x-ray waves by the individual atoms in the very regular array. The rather complicated geometrical relations governing this diffraction process are made formal and concise by Bragg's law of reflection: i.e.

$$N\lambda = 2d \sin \theta$$

where

N = an integer (the order of diffraction)

λ = the x-ray wavelength

d = the atomic plane spacing

θ = the angle of incidence required for diffraction (Bragg angle).

The word reflection is used to indicate that the outgoing diffracted ray acts as if it were a reflection of the incoming ray with the atomic planes acting as the mirror.

Bragg's law, of course, gives only the condition for maximum diffraction and hence gives no prediction of how much of the incident x-ray power is diffracted nor the shape of the angular window. In the case of an extremely perfect crystal these quantities can be calculated from first principles and agree fairly well with experimental results. However, the amount of diffracted x-ray power is found to vary strongly as the crystal deviates from perfect order. And further we have a paradox that the nearly perfect crystal can diffract more strongly (on the average) than the perfect crystal. This is the principle of x-ray topography: i.e., strained regions of an otherwise perfect crystal can be made visible by image contrast in the diffracted beam. The strains may be caused by substituted atom mismatch, point defects, dislocations, or film interface stresses.

CONVENTIONAL TOPOGRAPHIC CAMERAS

The first camera developed specifically to study crystal defects was the Berg-Barrett camera [1]. A schematic diagram of the camera is shown in Figure 1. The x-ray source is typically a diffraction x-ray tube with a small spot or line focus. These tubes have an anode made of a very pure metal and the electron bombardment produces x-rays with continuously varying wavelengths. However, they also produce a few spectral lines which are characteristic of the anode metal and are several thousand times more intense than the adjacent continuum wavelengths. One of the spectral lines (usually the strongest) is used to produce the diffracted image.

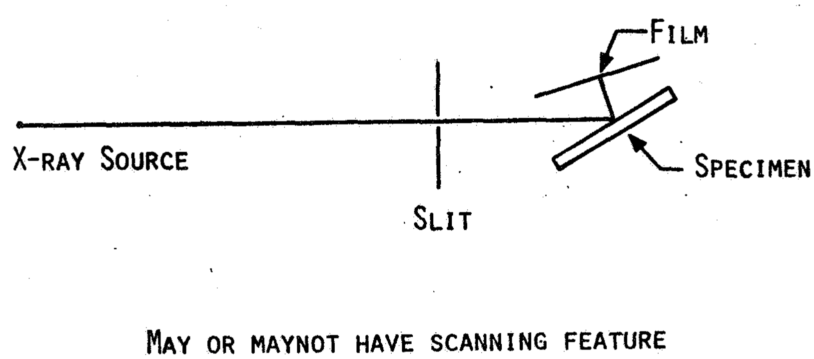

Figure 1. Berg-Barrett camera.

The slit is usually at the end of a long tube and serves to collimate the x-ray beam and thus shield the film and operator from all unnecessary direct and scattered radiation. Only a narrow vertical (perpendicular to the diagram) strip of the specimen receives the incident x-rays; however, they all strike the surface at approximately the same angle. The specimen is, of course, rotated to such a position that these rays satisfy the Bragg angle for some set of crystalline planes for the characteristic x-ray tube wavelength. The film (or photographic plate) then receives the diffracted image (with defect features) of the vertical strip of the specimen. Larger sections of the specimen can be imaged by translating the specimen and film during the exposure.

The camera most commonly used in semiconductor crystal analysis is the Lang camera [2]. A diagram of this camera is shown in Figure 2. This camera differs from the Berg-Barrett type primarily in that the diffracted rays are transmitted through the specimen. A second (stationary) slit S_2 is necessary to prevent the direct beam from exposing the film. The primary advantage of the Lang camera is that the detect image contrast may be enhanced significantly by a judicious choice of the x-ray wavelength for a given specimen thickness and composition.

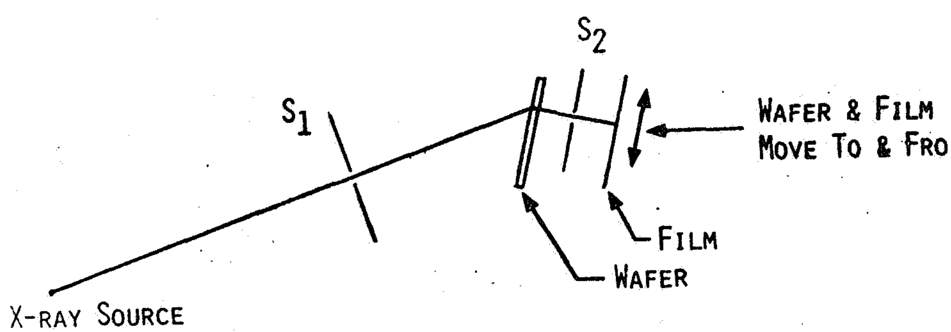

Figure 2. Diagram of the Lang camera.

Both cameras require long exposure times (at least several hours) in order to produce a useful topograph of a 2 in. diameter silicon wafer. They also require a rather expensive precision translator carriage for the scanning operation. The combination of long exposure times, expensive equipment, and highly trained personnel has prevented any significant application of x-ray topography to semiconductor device fabrication except in research and development.

THE NEW BENT WAFER CAMERA

A new high speed x-ray topographic camera has recently been developed in the Texas Engineering Experiment Station's Institute for Solid State Electronics (ISSE) at Texas A&M [3]. The new camera is identical to the stationary Berg-Barrett camera with the exception that the wafer is slightly bent in order that rays from the point source may strike all portions of the wafer at the Bragg angle simultaneously. This allows the image of the entire wafer to be formed in the same time that a single narrow strip can be formed by either of the conventional methods. A diagram of an early version of this camera is shown in Figure 3. This version uses a rigid spherically curved-vacuum chuck with multiple vacuum feed holes. The wafer is bent by applying sufficient partial vacuum to cause the wafer to conform to the chuck shape. The radius of bending required depends on the wavelength of radiation used, atomic lattice planes used for the particular diffraction, and the "cut" of the crystal. Typical radii of curvature are 100 to 200 in.; thus, the deformation is very small.

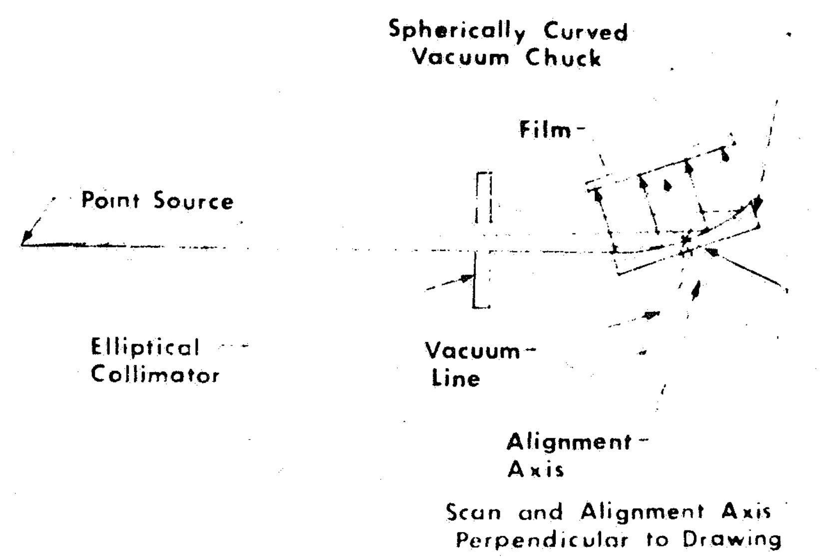

Figure 3. Early version of the Berg-Barrett camera.

Figure 4 is an x-ray topograph, made with the new camera, of a 2 in. silicon wafer. The wafer had completed all processing steps including probe evaluation. Each square pattern represents an integrated circuit whose overall dimensions are 0.10×0.10 in. The irregular light areas near the edge of this picture were caused by imperfect bending of the wafer.

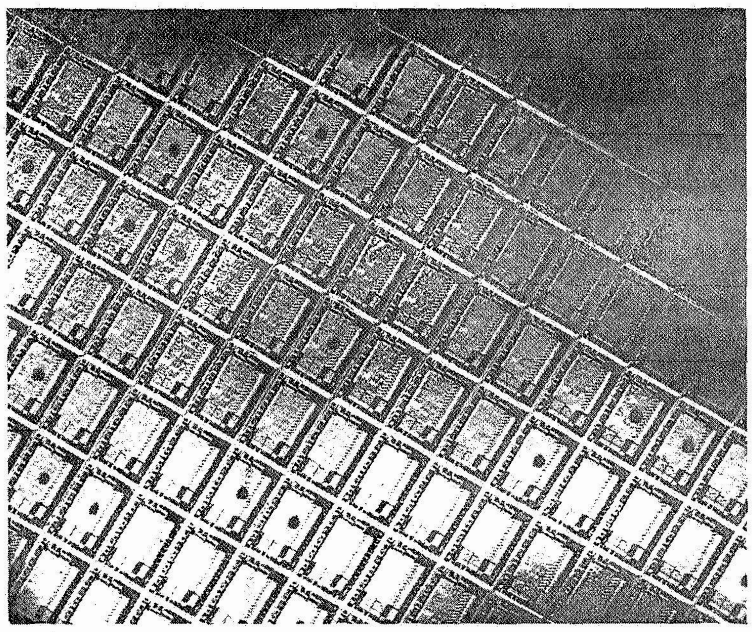

Figure 4. X-ray topograph, made with the new camera, of a 2 in. silicon wafer.

Figure 5 is a microscopic enlargement of an x-ray topograph. The numbers and letters are 0.001 in. tall. The numbers and letters, as well as all the other black geometrical shapes, show regions which have received a deliberate impurity diffusion. The regions are white because of the lattice disruption caused by the diffusion. The diagonal lines running through this picture are due to slip damage introduced during one of the many thermal processing steps this wafer received during fabrication. Slip damage is a line of dislocations and is known to contribute to low yields and poor performance in many integral circuits.

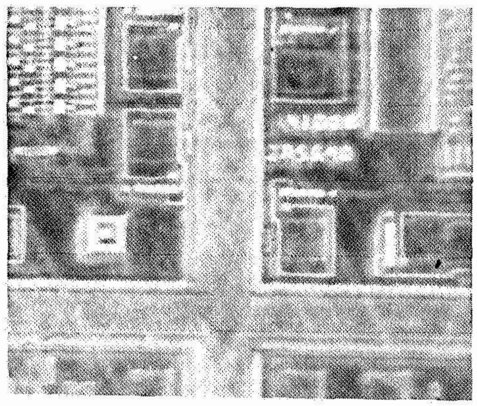

Figure 5. Microscopic enlargement of an x-ray topograph.

The topograph shown in Figures 4 and 5 was made with a Kodak high resolution plate with a 2 h exposure. Under similar conditions an exposure time of more than 30 h would be required using one of the conventional cameras. Nuclear track plates give contrast and resolution almost as good as high resolution plates (in this application) with about 1/10th the exposure time.

CURRENT RESEARCH

There are two primary objectives of current research with this camera: (1) to continue to improve its performance and (2) to demonstrate its utility in solving production process control problems.

A new deformable elastic chuck has recently been developed which allows continuously variable bending of the wafer by a controlled partial vacuum. This removes the requirement of having a multitude of fixed curvature chucks, each suitable for only one crystal and for one set of atomic planes and one x-ray target source. This chuck allows custom bending of each wafer for an optimum topograph (even those that are accidently or deliberately cut off of one of the major crystallographic axes). Also, the bending is more uniform with smaller washed out areas.

Also, under development is a real time TV system which will allow TV monitor viewing of the diffracted x-ray image. The system will use a fluorescent screen and a low light level TV camera. The feasibility of this technique has already been demonstrated with a 35 mm still camera.

Several experiments are currently in progress which are designed to correlate various types of lattice defects with performance, yield, and reliability of modern circuits and devices. These experiments involve wafers processed by several different manufacturers, as well as some of those processed in the ISSE facilities. Also, new applications of x-ray topography are being studied such as the determination of the degree and uniformity of impurity deposition.

CONCLUSIONS

The substantial reduction in the cost-per-topograph which has been realized by the development of this new camera demands a reexamination of the potential of x-ray topography used directly in semiconductor process control.

The technique has the unique ability to follow an individual wafer through the entire fabrication process with documentation of the process-induced damage created at each step. These considerations make 100 percent evaluation of high reliability parts, as well as routine quality control economically feasible.

REFERENCES

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