WHITE BEAM SYNCHROTRON X-RAY TOPOGRAPHY OF GALLIUM ARSENIDE

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INTRODUCTION

The defect structure of gallium arsenide is being examined using white beam transmission topography. The specimens under examination are cut-and-polished, three inch diameter, single crystal substrates from various suppliers in the "as received" condition. The goal of this continuing program is to first document the existence of various crystallographic defect structures and then to establish their effect on the performance of microwave integrated circuits subsequently fabricated on the wafers. Success in establishing such a correlation might permit the use of an x-ray diffraction measurement to screen incoming material, eliminating marginal substrates and achieving a corresponding increase in yield.

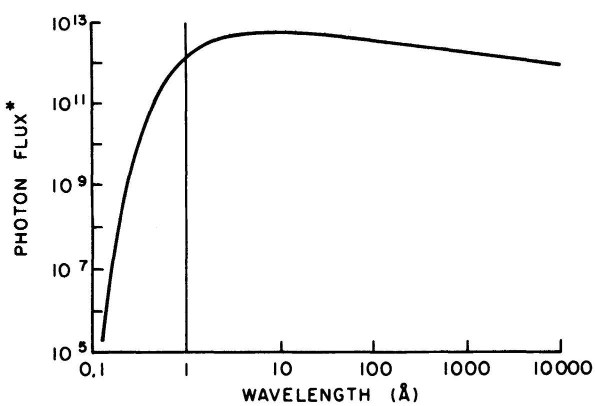
WHITE BEAM TRANSMISSION TOPOGRAPHY

The principles of white beam transmission topography are essentially identical to those of a classical Laue x-ray diffraction experiment. Both methods involve illuminating a stationary single crystal with a continuous spectrum of x-rays, (a white beam). In both cases diffraction will occur only for those particular sets of lattice planes which can find a match between their specific lattice spacing, their particular angular orientation to the incident beam, and some appropriate wavelength in the incident spectrum which will satisfy the Bragg condition.

Despite the above similarities, white beam transmission topography and the Laue diffraction experiment differ in several significant respects. The Laue method traditionally is used to determine the orientation of a single crystal from its pattern of Laue "spots". (A "spot" is the photographic image of the diffracted beam from one particular set of lattice planes - and the "spot" is characterized by the particular set of Miller indices which identify that set of planes.) To obtain orientations with good angular resolution requires small Laue spots. So a typical traditional Laue diffraction experiment will minimize the cross-section of the (highly collimated) incident beam to minimize the size of the resulting Laue spot. Consequently, the volume of the single crystal probed by the x-rays is minimized. In contrast, white beam tranmission topography seeks to maximize the area illuminated by the incident beam of x-rays, as discussed below.

White beam transmission topography could be viewed as a large number of Laue experiments, each adjacent to one another, so the incident beam covers a large area of the specimen, [1]. Each of these Laue experiments will probe its own limited volume, giving rise to a pattern of Laue spots. An adjacent Laue experiment will probe a volume adjacent to the first, and generate its adjacent pattern of spots. If the lattice planes corresponding to a given set of Miller indices are crystallographically perfect, two adjacent Laue spots with the same Miller indices will merge into a larger spot of uniform intensity. If there is some angular misalignment between adjacent portions of planes of the same indices, some of the diffracted energy will go in the wrong direction, causing a non-uniformity in intensity within the merged spot. So crystallographic misalignments will give rise to contrast in the individual images which make up the pattern generated by a large number of adjacent Laue experiments. It then follows that if the goal is to probe the defect structure of a single crystal, the method should maximize the area illuminated by the incident beam, so that the resulting image of any particular set of lattice planes will represent the defect structure from as great a portion of the specimen as allowed by experimental limitations. Therefore white beam transmission topography seeks to maximize the area of the specimen illuminated by the incident beam, as stated above.

Unfortunately, most laboratory x-ray generators are not able to generate enough photons per second in a non-divergent beam to permit large area transmission topography of even the thinnest foils of metals and alloys with reasonable exposure times. The problem can not even be solved by replacing photographic film with more sensitive imaging detectors, such as the image intensifier systems generally appropriate for "photon-poor" dynamic studies, [2]. A solution to the problem is to make use of the much higher x-ray photon flux available from the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. A typical x-ray photon spectrum for the NSLS x-ray ring is shown in Fig. 1.



*UNITS ARE: PHOTONS $(SEC)^{-1}$ $(MRAD)^{-1}$ $(100\ MA)^{-1}$ $(0.1\%\ BAND)^{-1}$
WHERE MRADS REFER TO HORIZONTAL APERTURE (2 MRAD MAX)
100 MA REFERS TO PRIMARY RING CURRENT
0.1 % BAND REFERS TO $\Delta E/E$

Fig. 1. Typical x-ray photon spectrum available from the National Synchrotron Light Source at 2.52 GEV.

A schematic of the experimental arrangement for white beam transmission topography is shown in Fig. 2. The specimen is held firmly within its plastic container by a plastic spider. The plastic container is positioned in the incident x-ray beam by seating its rim into a recess machined into the lead shield. The container is held in place with spring clips similar to those found on a microscope stage. The lead shield has a three inch diameter aperture cut in it immediately behind the specimen, to permit the primary and diffracted beams to pass. The primary beam is totally absorbed in a lead beam stop in front of the film package. The diffracted beams pass through the film package, forming the images which become the topograph. Direct comparison of topographs taken with and without the plastic container have shown its presence has no discernible effect on the topograph. This is very convenient, since it permits handling substrates in the relatively dirty environment of the NSLS without compromising their clean-room level of cleanliness.

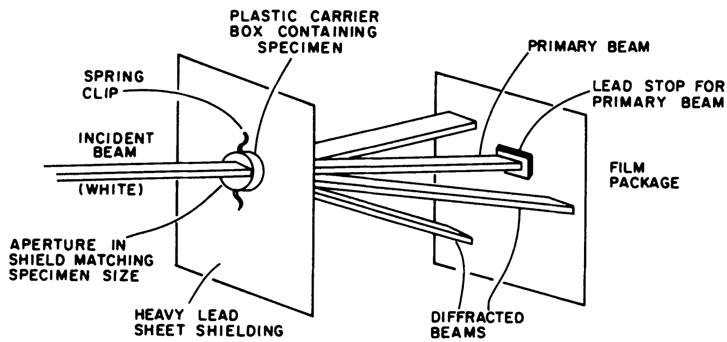


Fig. 2. Schematic for white beam transmission topography.

A typical topograph is made on an 8 inch by 10 inch sheet of Kodak SR-5 Photographic Film, with a nominal exposure time of 2 minutes for an x-ray flux corresponding to 120 ma of primary ring beam current. Just such a topograph for a gallium arsenide substrate is shown in Fig. 3. Each "bar" (of a lighter shade) is the image created by diffraction from one particular set of lattice planes, and, as such, may be identified by a particular set of Miller indices. The size and shape of these images is merely a reproduction of the size and shape of the "footprint" of the incident x-ray beam on the specimen. The dark outline at the center is the portion of the film masked by the beam stop. Since a continuous spectrum is used, a large set of diffracted images (actually, each is a topograph by itself) is generated in a single exposure. Each of these images contains information on the defect structure of the original crystal, as projected upon its particular set of lattice planes and as subsequently imaged by diffraction.

Figure 4 shows an enlarged view of the image indicated by the white arrow in Fig. 3. The range of intensities recorded on the original topograph far exceed the capability of the print to show the same detail, so the fact that Fig. 4 comes from the indicated location in Fig. 3 should not be surprising. Crystallographically, the image is from the $\bar{1}11$ lattice planes.

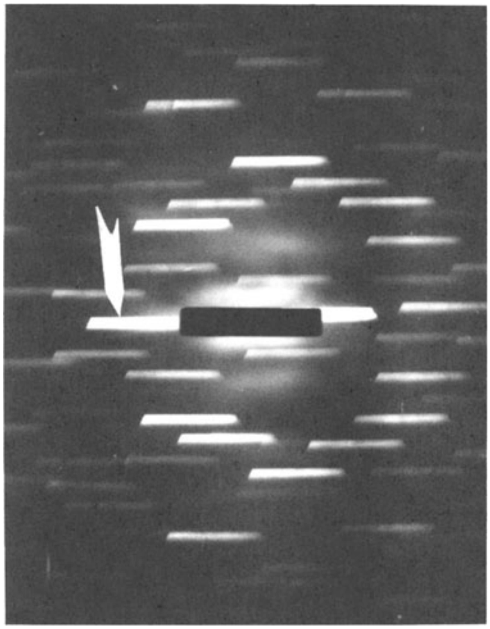


Fig. 3. Full size (8 x 10 inch) topograph of gallium arsenide substrate.

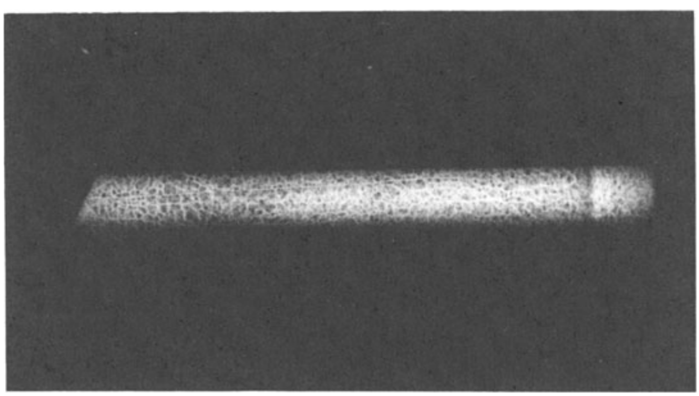


Fig. 4. Enlarged view of image marked by arrow in Fig. 3.

Figure 5 shows, in turn, an enlargement of part of Fig. 4. At this level of magnification, the wealth of information recorded in the topograph becomes more apparent. There are, however, some complications in interpreting the images. First, the diffraction process is such that the images are formed in reciprocal space. Consequently, the reconstruction of

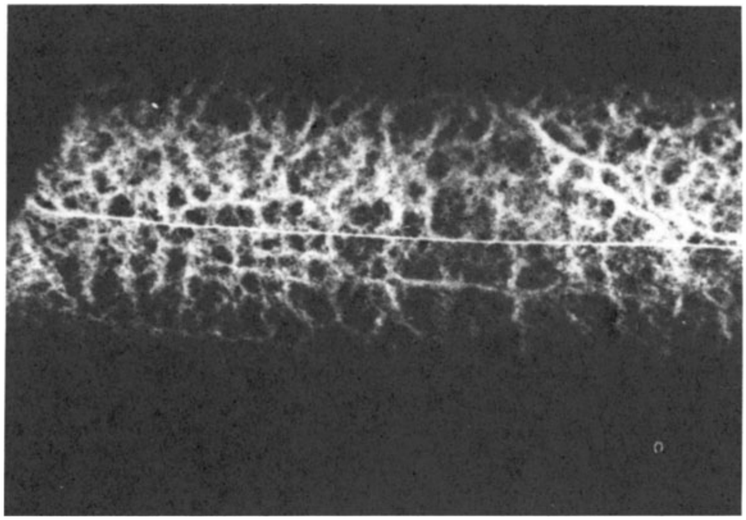


Fig. 5. Enlargement of Fig. 4.

defect structures from their apparent images as diffracted from various sets of lattice planes is not a simple operation. This problem is currently being addressed as an image processing problem in the authors' laboratory.

A MONTAGE OF TOPOGRAPHS

The second complication is that only a part of the three inch diameter specimen is illuminated by the incident beam (because of the inherent limitations on the beam dimensions available at the NSLS). This complication has been addressed by making a succession of topographs, each with the incident beam incrementally stepped in its narrow direction, so that the resulting series of topographs represent a series of incident beam positions sweeping from the center of the substrate to its outer perimeter. One particular image corresponding to one particular set of Miller indices has then been selected for enlargement, (the same one from each topograph), and a montage of images has been constructed using the resulting series of images. Each image in the montage is incrementally shifted in its narrow direction an amount corresponding to the amount the beam was initially shifted on the specimen. Figure 6 shows a section of this montage, where the outer perimeter of the gallium arsenide wafer can be seen at the upper left. Figure 7 shows a different section of the same montage, revealing what appear to be two linear arrays of dislocations running somewhat radially out from the center of the substrate. Figure 8 shows yet another view of a linear array at slightly higher magnification.

DISCUSSION

There appear to be two basically distinct defect structures which appear with variations in all the gallium arsenide topographs examined to date. First is a fairly isotropic cellular network or mosaic-like structure which seems ubiquitous throughout the specimens. Second are the more striking highly linear arrays which are localized to a few areas, and generally appear to run radially. The authors speculate the former

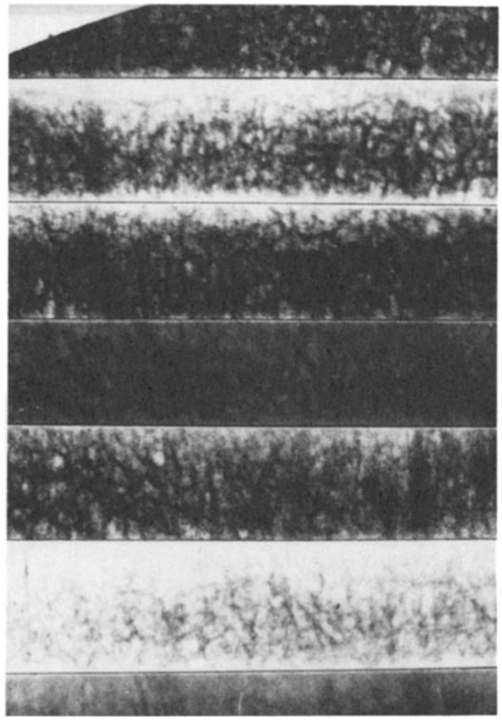


Fig. 6. A section of the montage ot topographs of gallium arsenide. Note the outer edge of the three inch diameter substrate at upper left.

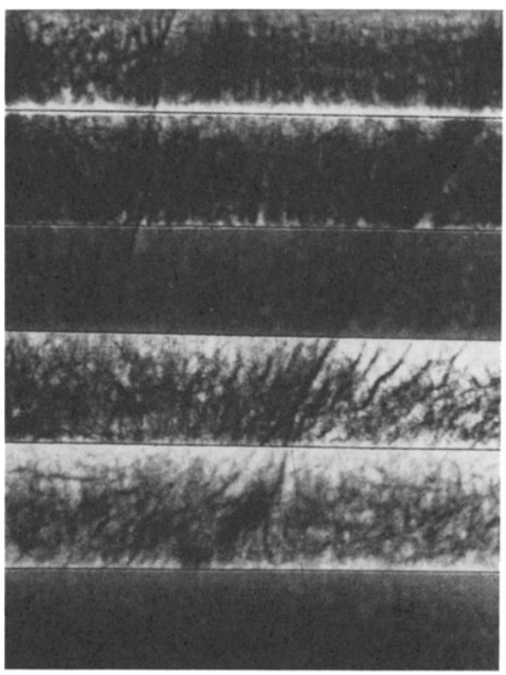


Fig. 7. A different section of the montage of topographs of gallium arsenide. Note the large linear arrays.

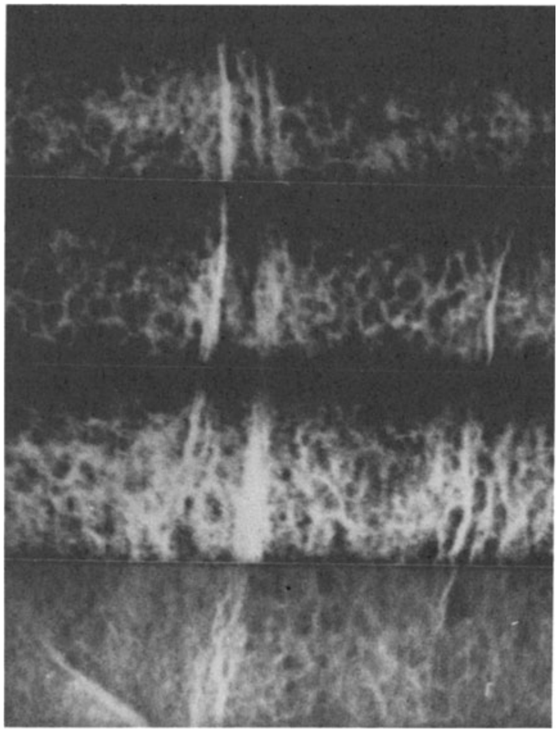


Fig. 8. Enlarged view of linear arrays in the montage of gallium arsenide topographs.

structures are artifacts of the solidification process, being reminiscent of cellular structures encountered when studying such processes. The linear arrays in the second category are more likely associated with plastic deformation encountered after solidification. If true, the latter may be susceptible to better control by close examination of the cutting, polishing, and subsequent handling practices.

CONCLUSIONS

White beam transmission topography is a valuable tool for the examination of the defect structure of single crystal gallium arsenide substrates. Significant anomalies have been easily imaged in substrates otherwise considered the very best of production quality material. It still remains to establish the correlation between some of the detailed features which have been recorded and the performance of microwave circuitry fabricated on top of those features, but it seems probable that the linear arrays in particular will cause trouble. An important consideration in assessing the value of the method is the time required to obtain data per substrate. In the work reported here, a substantial part (nearly 30%) of a substrate area is covered by stepping the incident beam along in order to make thirteen separate 8 inch x 10 inch topographs. This generates thirteen sets of data on literally dozens of individual topographs at a time (each corresponding to a different set of Miller indices). If further work were to show that images from just one or two of these sets is enough, then there are other experimental geometries which should speed the operation up considerably.

ACKNOWLEDGMENT

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