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Beam-induced dislocations and their CL contrast

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ABSTRACT: Dislocations induced by high SEM beam currents in GaAs were studied by TEM and emission CL. They were found to consist of bowed segments and confirmed to have [001] Burgers vectors. The capacity of different SEMs to induce dislocations varied greatly. Methods for recording CL contrast profiles and a Monte Carlo based program for CL calculations are presented.

1. INTRODUCTION

Beam scanning can induce dark and bright squares visible in several modes of the SEM. Such effects are generally avoided and loosely ascribed to 'contamination' or to 'damage'. A quite different effect was found by Franzosi et al (1988, 1989). Beam currents above a μA induced dense grids of dislocation lines parallel to the surface, running across the scanned area in the two orthogonal <110> directions in (001) GaAs and InP. X–ray topography showed these dislocations to have [001] Burgers vectors. This was ascribed to the production of high densities of vacancies of the volatile constituent under bombardment with subsequent aggregation to produce dislocations. This paper reports TEM and initial ECL contrast studies of these unusual dislocations.

2. EXPERIMENTAL METHODS

At I.C.S.T.M. a JEOL JSM–840A SEM fitted with a Matelect ISM–5 conductive mode detection system was used to take the signal from a Si photodiode mounted above the sample for emission cathodoluminescence (ECL) panchromatic imaging. It was connected to a Kontron image processor for signal averaging, image recording, contrast enhancement and image analysis. At Maspec the TEM work was done using a JEOL 2000FX and the dislocations were induced in a Stereoscan 250 fitted with an EDS (Cuorgné) ECL/TCL (emission and transmission CL) detector. The specimens were cut from wafers grown at Maspec by Dr. R. Fornari.

The ability to induce dislocations was found to vary with the type of SEM. Attempts to beam–induce dislocations using the JEOL 840A on a dozen occasions at magnifications of a few hundred to well over a thousand times using currents up to 4 μA succeeded only once. The Stereoscan 250, however, easily and reliably induced dislocations on going above 1 μA at magnifications of a thousand or more (Fig. 1). The 250 can even produce visible patches showing spectral colours due to the grids of scan lines 'burned' into the material acting as gratings. Reversible changes in luminescent intensity were generally all that was produced by the beam in the 840A. The result of repeated scanning at slightly different magnifications was then to produce concentric areas that could be alternately brighter and darker i.e. show window–frame like contrast in subsequent ECL images (Fig. 2). Which difference or differences in electron optics or scan speeds are responsible for the difference between the two SEMs is not yet known.

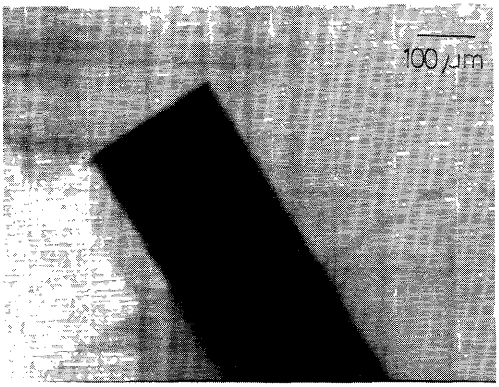


Figure 1. ECL micrograph of a number of patches in a GaAs specimen in which dislocations running in the < 110 > directions in the (001) material were previously beam–induced by the Stereoscan 250. The previous scan direction was inclined at 30° to the dislocations and to the scan direction in this micrograph. Part of a dark, damaged area can be seen at lower centre and a bright undamaged area at lower left. The low density grid of dislocations at lower right is the type that was selected for measurement in Fig. 4.

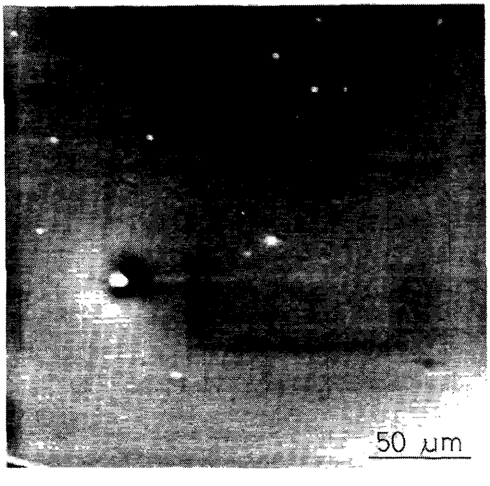


Figure 2. SEM ECL micrograph of a GaAs specimen. The effect of scanning at different magnifications was to induce brighter and darker emission (efficiency) in the scanned areas, resulting in window–frame contrast patterns.

3. RESULTS

A part of the scanned area in which dislocations were induced in the 840A is shown in a digitized Kontron 512 x 512 pixel image in Figure 3a. Numerous ECL greyscale contrast line scan profiles could then be extracted along the lines marked in Figure 3a, for examination at leisure (Figure 3b). This method avoids possible further changes due to continued beam scanning and allows rapid checking for changes in dislocation strength along their length due to local impurity decoration or alternating dissociation and constriction (e.g. along d3).

A higher–resolution but slower method for extracting more quantitative ECL line scan profiles for dislocation contrast analyses is provided by the Matelect ISM-5 with computer interface and software. A single isolated 250 beam–induced dislocation was selected from a low defect density area like that at bottom right of Figure 1. A set of line scan profiles at increasing magnification are shown in Figure 4. The shape of the dislocation profile could be made to appear asymmetric by slow, long–range changes of CL intensity (Figure 5) and care was taken to avoid such cases.

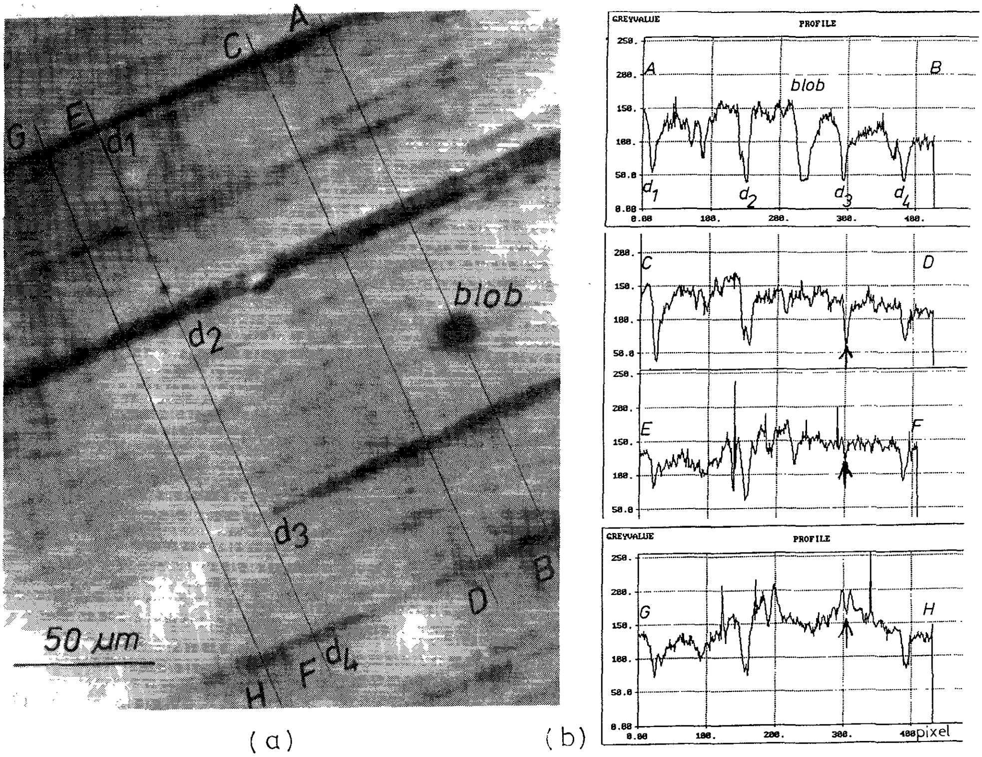


Figure 3. (a) part of a digitized 512×512 pixel ECL image of beam–induced dislocations in GaAs and (b) a number of CL intensity profiles for the scan lines marked in (a).

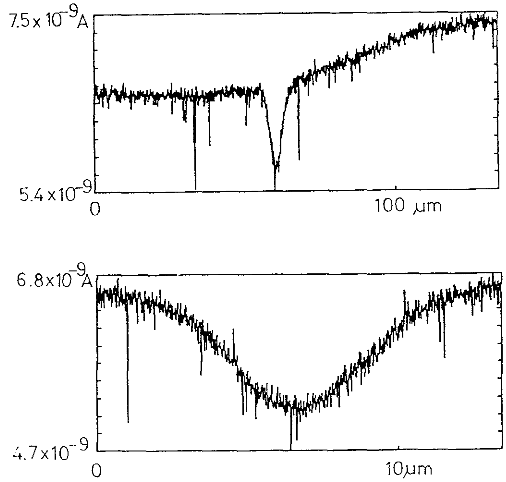


Figure 4. ECL photodetector current line scan profiles of a single beam–induced dislocation in the specimen of Figure 1 at one and ten thousand times.

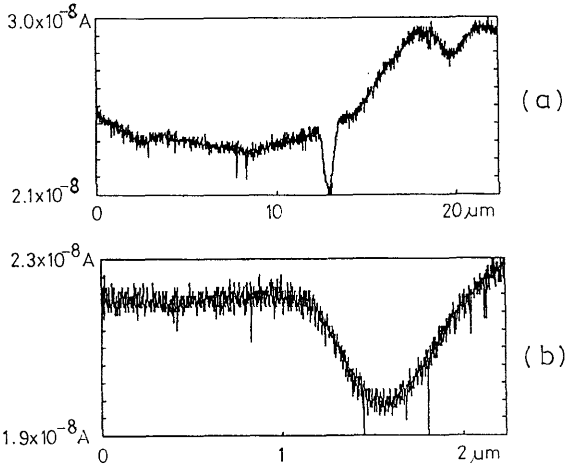
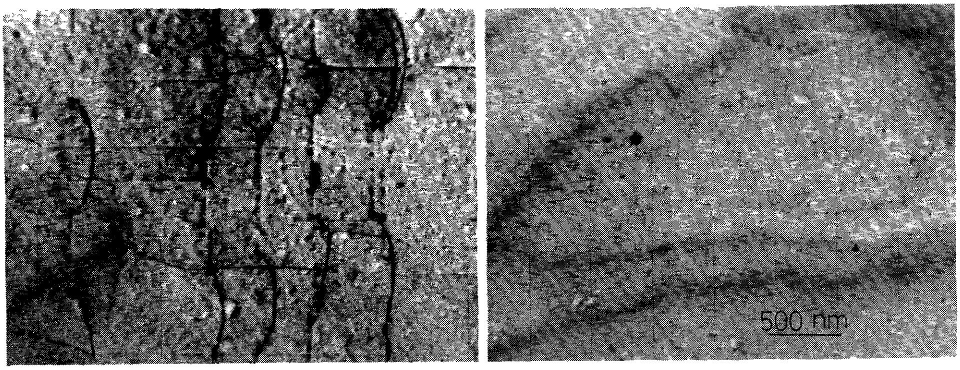


Figure 5. Line scan profiles across another dislocation in an area where the background ECL emission (efficiency) varied across the dislocation resulting in a distorted, asymmetric form of defect contrast. The magnifications were (a) 700× and (b) 6,000×.



(a) (b)

Figure 6. TEM plan view images of a beam-affected area crossed by orthogonal grids of beam-induced dislocations taken with reflections (a) g = $\bar{1}3\bar{1}$ and (b) g = 400.

TEM analysis showed the beam-induced material to be crossed by dislocations with [001] Burgers vectors (Figure 6). In such micrographs some dislocations could be seen to run down into the material and then along at a constant depth suggesting that they were introduced from the surface. Segments of the dislocations can be seen to be bowed out, perhaps suggesting the action of shear stresses and the presence of pinning points. This is also reminiscent of the beam activated motion of dislocations previously observed in the TEM (Cockayne et al 1987, Maeda et al 1987).

4. DISCUSSION

A program in C to run on PC compatible microcomputers was written using a simplified model of CL emission. This employs a depth dose distribution of hole-electron pairs derived from a Monte Carlo simulation of electron trajectories program (called MC–SET) adapted to deal with epitaxial multilayer materials and laterally limited device structures. This is an extended and modified version of that described earlier (Napchan and Holt 1987, Napchan 1988) and deriving from the Joy (Joy and Pimentel 1983, Joy 1987) and NBS (Mykleburst et al 1976) programs. The CL program was first tested by simulating the variation of ECL intensity (photodiode current) versus beam voltage for power constant and for current constant and found to give the correct shape of the curve and quantitative fit for reasonable values of the material parameters. It has now been used as the basis for simulation of dislocation ECL line scan profiles using the Donolato phenomenological model, previously applied to CL defect contrast by Lohnert and Kubalek (1983). Work is in progress to use fitting of experimental dislocation contrast data like that in Figures 3 and 4, to determine dislocation depths and strengths. The TEM results show that single ECL dark lines with widths of some μms, may be due to pairs or larger groups of dislocations and variations in effective recombination strength could arise in this way.

It is clear that at the beam powers used to induce the dislocations, preferential evaporation of the volatile constituent can occur since visible grating–like line structures can be produced in severe cases. Moreover, it is well known that the mobility of dislocations in glide can be enhanced by electron bombardment (Cockayne et al 1987, Maeda et al 1987). Hence it appears likely that point defect aggregation and climb and/or beam enhanced glide mobility are involved in introducing beam–induced dislocations.

Numerous line scan profiles can be extracted via image processing from a single ECL stored image thus avoiding inducing further damage during analysis. Higher–resolution quantitative line scans however require extended scanning to select the dislocation and the position(s) along its length for analysis and to record linescans (15 secs each for those in Figures 4 and 5).

Preliminary studies of microcomputer simulations of the strength of the emitted CL and the dislocation contrast profiles showed them to match measured data quite well.

Previous reports of beam damage in CL images were of a reduced CL brightness in ion–implanted Si ascribed to annealing effects (Myhajlenko el al 1983) and of large, slow increases in CL intensity with time in GaAs/AlAs quantum well specimens (Holt et al 1991). Both effects are probably due to electronic 'damage' as contamination films take much longer times to build up effective thicknesses (Wilson et al 1980). The electronic effects appear to involve changes in the numbers of surface states or in the charges on the surface or on point defects.

Dark (bright) patch contrast in ECL pictures is due to a reduction (increase) in radiative recombination efficiency, η_r. This can be written

$$\eta_r = \frac{\tau_{nr}}{\tau_{nr} + \tau_r}$$

where τ_{nr} and τ_r are the non–radiative and radiative recombination times. Hence, dark (bright) contrast implies a reduced (increased) non–radiative recombination time or an increased (decreased) radiative recombination time in the scanned area. Assume in the usual way that

$$\tau = \frac{1}{v_{th}\sigma N_t}$$

where v_{th} is the thermal velocity of the carriers, and σ and N_t are the capture cross–section and density of the non–radiative (radiative) recombination centres (traps) respectively. Suppose, to be specific, that the dark (bright) contrast is due to a reduced (increased) *non–radiative* recombination time. The contrast implies (i) an increase (decrease) in N_{tnr} or (ii) an increase (decrease) in σ_{nr}. Changes in the density of centres, N_{tnr}, are unlikely as knock–on displacements are not possible at the energies (keV) of SEM electron beams. Order of magnitude changes in effective capture cross section, σ_{nr}, however, can be produced by charge state changes in recombination centres (McKeever 1985) which beam irradiation is likely to produce and this seems a probable mechanism for damage effects.

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