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Comparison of dislocation images obtained using the scanning optical microscope and scanning electron microscope

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Dislocations in a silicon specimen containing a p–n junction have been imaged with a scanning optical microscope (SOM) and a scanning electron microscope (SEM) using the induced carrier mode. Examination of the same dislocations by the two methods has shown that virtually identical images are obtained and the spatial resolution is 1 μm.

1. Introduction

Dislocations present in semiconductor materials and devices can adversely affect their electrical and luminescent properties. A method which has been used for many years to investigate the electrical behaviour is to inject carriers into the specimen with the electron beam of a scanning electron microscope. These carriers diffuse in the specimen and on reaching the depletion region of a p–n junction, generally located parallel to and a few micrometers below the specimen surface, they increase the reverse-bias junction current. This current is amplified and used to modulate the brightness of the SEM display screen scanned in synchronism. If the specimen is homogeneous, a uniform bright image is obtained. On the other hand, if electrical trapping centres such as dislocations are present between the surface and the junction, there is a local reduction in the junction current as the electron beam scans across the dislocation, and individual dislocations appear as dark lines in the resulting image [1]. A spatial resolution of 1 μm can be obtained, with contrast levels down to 0.1% directly displayed [1]. The technique has been known as the electron beam induced conductivity (EBIC), charge collection or barrier electron voltaic method. The analogous technique whereby the injected carriers recombine to produce photons, and the emitted photons are collected to give the image, is termed the cathodoluminescent method. Individual dislocations are again revealed but the resolution is generally poorer than for the EBIC method [2].

During the last few years several investigators have obtained information concerning dislocations in semiconductors by using laser beams to inject carriers into the specimens. Either the carriers were collected at a p–n junction, which might be analogy be termed the optical beam-induced conductivity (OBIC) method, or the emitted photons were collected, termed the photoluminescent (PL) method. For example, Heinke [3] used a stationary laser beam and recorded PL spectra at different distances from individual dislocations in GaAs. Suzuki and Matsumoto [4] rapidly switched off a stationary laser beam and measured the PL decay to determine the minority carrier lifetime for local regions of a GaP specimen corresponding to different dislocation densities. They also used a scanning laser beam and displayed PL images which showed individual dislocations in the GaP as dark blobs. DiStephano and Cuomo [5] used a scanning laser beam and the OBIC method to reveal grain boundaries in polycrystalline Si specimens. However, in none of these studies using laser beams to inject the carriers was the resolution better than 10 μm, and in most cases it was considerably poorer.

In the present work, the same areas of silicon specimens containing dislocations were examined with a scanning optical microscope [6–9] using the OBIC method, and with an SEM using the EBIC method. This paper briefly describes the

SOM which was used, reports the results obtained, and discusses the relative merits of the two instruments for dislocation studies and semiconductor measurements in general.

2. Experimental details

An SOM has been constructed for the inspection of electronic devices [6]. In this instrument a 3 mW HeNe laser beam (wavelength 0.633 μm) is focused down into a diffraction limited spot which is scanned relative to the specimen in a T.V. type raster. A signal is derived from, for example, the reflected light or photo-induced currents and this is used to brightness modulate a cathode ray tube spot which is scanned in synchronism with the laser beam (Fig. 1). In this way a magnified picture is displayed on the screen [7].

In this microscope, scanning is achieved by supporting the specimen between four taut piano wires and mechanically vibrating it across a stationary spot. With this arrangement, the light through the lenses is always on-axis thereby avoiding off-axis aberrations. The line frequency is typically 80 Hz with frame scan times between 1 and 30 sec. By altering the drive to the vibrators, the magnification can be varied continuously in the range × 30 to × 10 000. The image contrast can be electrically enhanced by subtracting background signal in the usual way.

The resolution which can be obtained for reflected light with the instrument described above (type 1) is limited by diffraction effects to a value of 1 μm or less, which is the same as can be obtained with a conventional microscope working at the same wavelength. However, if the reflected light is collected by a lens and focused onto a pinhole placed in front of the photodetector, both the objective and collector lenses contribute equally to the imaging and the resolution is improved [8, 9]. This arrangement has been termed a type 2 microscope.

The specimen used for the present dislocation studies arose during the development of a Si bipolar transistor. The base was B-implanted and the emitter P-diffused. The e/b and c/b junctions were typically 1.8 and 2.4 μm, respectively, below the specimen surface. In the emitter region, isolated groups of dislocations occurred at a depth of ~ 1 μm below the specimen surface. For the present dislocation studies, the e/b reverse-bias junction current was used to obtain both the OBIC and EBIC images. For all of the examinations there was a 0.3 μm thick SiO_2 film on the emitter surface.

For the OBIC images, the carrier generation depth in the specimen corresponds to the absorption length for the incident laser beam, which for light of wavelength 0.633 μm and Si is ~ 3 μm. A convenient number of collected carriers was obtained by inserting a neutral density filter (1% transmission) in the optical system. For the EBIC images, a Cambridge Scientific Instruments Stereoscan Type S4-10 was used operated at 30 kV. The carrier generation depth depends on the range of the incident electron beam, which for 30 keV electrons and Si is ~ 5 μm. A convenient number

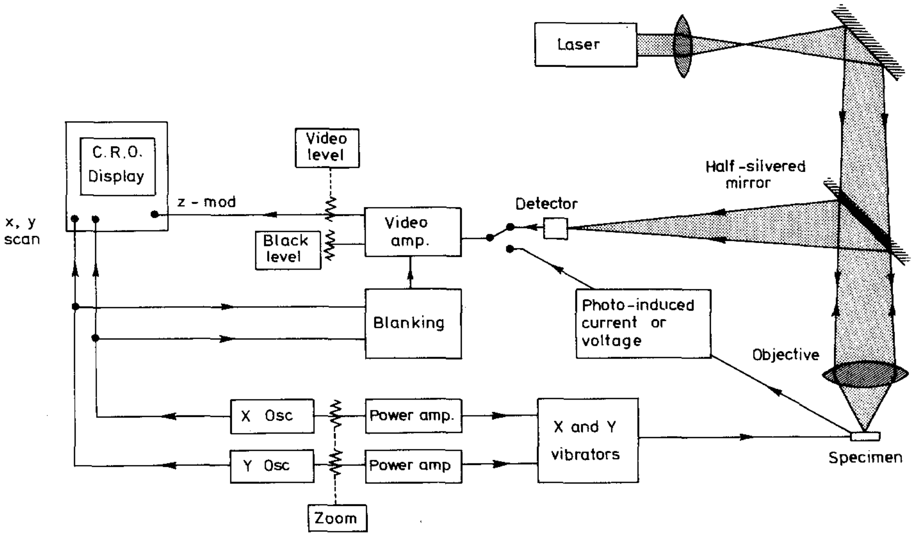

Figure 1 Schematic diagram of scanning optical microscope.

of collected carriers was obtained by using a 1 nA incident electron beam, which corresponded to a beam diameter of ~0.2 μm.

3. Results

The emitter and base regions of the specimen examined are shown in Fig. 2. This is a low magnification micrograph taken with the SOM using reflected light. When the magnification was increased the emitter showed no structure other than occasional surface features.

However, when the emitter was examined using the OBIC method (Fig. 3a), the isolated groups of dislocations lying beneath the specimen surface were immediately revealed as small clusters of dark lines. These dislocation lines were extremely clear and showed a variety of configurations, including intersections to give both three-fold nodes and small hexagonal arrays. The smallest line widths were 0.5 μm. Moreover, closely spaced lines could be resolved as separate down to a centre-to-centre line spacing of 1 μm. The line contrast, defined as $(I_{\mathrm{max}} - I_{\mathrm{min}})/I_{\mathrm{mean}}$, varied from line to line, and measurement showed the range to be 1 to 4%. The contrast at the intersection of lines was often greater than this.

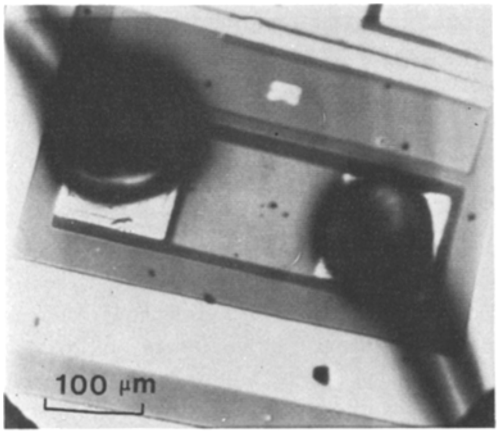

Figure 2 Portion of a Si bipolar planar transistor showing emitter-base area and electrical leads. Low magnification micrograph obtained with the SOM using reflected light.

When the same area of the emitter was examined using the EBIC method (Fig. 3b), the dislocations were again revealed as dark lines, and there was a precise correspondence between these lines and those observed by the OBIC method. In particular, the line widths, separations and contrast were the same within the error of the experimental measurements. For example, for the line-scan trace along PQ in Fig. 3a, the contrast on crossing dislocations X and Y was measured as 4 and 2% respectively for both the OBIC and EBIC images.

The dark line PQ that can be seen running across the full width of the OBIC image of Fig. 3a arises because the specimen was previously examined in the SEM to make the EBIC measurements. The electron beam was then scanned along the line PQ for 10 min, and this caused a line of contamination to build up on the surface of the SiO_2 film, an effect generally attributed to an interaction between the electron beam, organic vapours present in the vacuum system and the specimen surface.

4. Discussion

This work was performed because it was thought that it should be possible to use an SOM to obtain

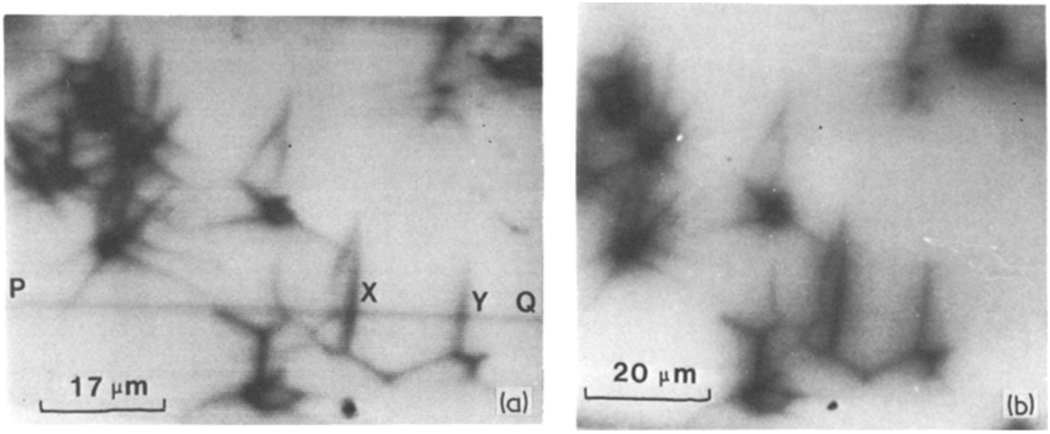

Figure 3 Portion of emitter of Fig. 2. High magnification micrographs obtained using beam generated carriers. (a) SOM and OBIC method, (b) SEM and EBIC method. Dark lines are dislocations lying ~ 1 μm below specimen surface.

OBIC images of dislocations of a quality considerably better than any that have hitherto been obtained, and that these images should be closely similar to those that can be obtained by the analogous EBIC method. Our experimental results have shown for the particular specimen and conditions chosen that this is indeed the case.

The reasons for this are as follows. Image quality depends on resolution, contrast, and signal/noise ratio. For the particular specimen used, the resolution and contrast obtained depends on the lateral spread of the carriers at the depth of the dislocations. This will, in turn, depend on the shape, size and depth of the generation volume, and the subsequent diffusion behaviour of the generated carriers. The generation volume is determined in the SEM by the scattering of the incident beam in the specimen, and in the SOM by the diffraction-limited spot size and the focus position. In the present work, the limiting factor for the OBIC images is probably the incident beam diameter, and for the EBIC images the scattering of the beam. Nevertheless, for both the OBIC and EBIC images and the conditions used, this spread is likely to be $\sim 1\,\mu$m, and this agrees with the experimentally observed resolution in both cases of $\sim 1\,\mu$m. For both the OBIC and EBIC images, the dislocation contrast was relatively large (1 to 4%) and the collected signal more than adequate, and so no difficulties were encountered due to signal/noise problems.

In view of the comparable performances of the SOM and SEM for such dislocation studies, it is of interest to consider other possible advantages and disadvantages of using these two types of microscope for such work. The SOM is a much simpler, cheaper instrument which does not require a vacuum system, and the electronic signal processing techniques used in the SEM can be incorporated in the SOM.

The SEM has a smaller minimum probe size, about $0.01\,\mu$m, and a very large depth of focus, but in this application the effective probe size is increased due to the scattering of the electrons inside the specimen. The probe size of the SOM depends on the wavelength used, but could be between 2 and $0.3\,\mu$m and can be maintained below the surface of the specimen.

The depth of penetration in Si [10] can be varied continuously over a range of about 0.5 to $60\,\mu$m in the SEM by varying the beam energy from 5 to 100 keV. In the SOM the depth depends on the wavelength used and so at present can only be at specific values where a laser line is available. Continuously variable penetration as in the SEM could be obtained by using a tunable laser. Penetration depths varying from 0.5 to $1000\,\mu$m can be obtained in silicon using available laser wavelengths [11] (0.4 to $1.06\,\mu$m). The use of a wavelength beyond the band edge affords a means of measuring free carrier absorption, and, therefore, the material doping level [12].

The distribution of carriers generated with depth is different for both methods, peaking below the surface for the SEM, and decaying exponentially from the surface for the SOM. Since the carrier lifetime varies with depth due to surface effects and the varying doping level, some carriers will recombine before reaching the junction and not contribute to the conduction current. This will modify the generation distribution and produce an effective distribution which peaks below the surface for both the SEM and the SOM.

Both methods can measure carrier lifetimes by pulsing the probe beam and observing the decay of the junction current. When surface contamination is present, it is more noticeable by using the OBIC mode in the SOM, than EBIC in the SEM.

There can be charging problems with the SEM due to the surface oxide layers on the device which may have to be removed, and the electron beam in conjunction with the organic vapours in the vacuum system can also deposit lines of contamination on the specimen (Fig. 3a). The SOM, however, does not alter or damage the device in this way and so could be used as a means of inspecting/testing production devices.

5. Conclusions

Dislocations in Si have been examined with a laser beam SOM using the OBIC method, and a standard SEM using the EBIC method. The SOM gave high quality dislocation images with a resolution of $1\,\mu$m, similar to the corresponding SEM images. The SOM has some advantages over the SEM for such studies, e.g. the instrument is simpler and the light beam has fewer detrimental effects on the specimen. However, the SEM has many advantages and further work is necessary to determine the ultimate resolution of the OBIC and EBIC methods for such studies.

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