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Development of a Scanning Optical Microscope for Examination of Radioactive Specimens.

by M.A. Brearley.

SUMMARY

Microscopic examination of radioactive samples is undertaken by WNL's Post-Irradiation Examination Department using, among others, conventional (compound) microscopes. These are modified to enable them to be installed in shielded cells and operated remotely. The modifications and the subsequent cost of maintenance are becoming prohibitively high and ways are being sought of reducing them. This report describes a prototype scanning optical microscope (SOM) constructed at WNL by the Instrument Section of the Development Engineering Group. The equipment, which has been specifically designed for remote operation uses a laser light source.

The report describes the equipment, presents the photographic results obtained, and compares its performance with other remote microscopes. It is concluded that a system based on the laser scanning optical microscope could provide an inexpensive alternative to present equipment.

CONTENTS

1. INTRODUCTION

The equipment used at WNL for examination of radioactive specimens includes 8 conventional objective/eyepiece (compound) microscopes. These are enclosed in shielded lead cells and modified so that the controls (focus, stage movement etc) are located outside the cell wall. An extension tube is interposed between the objective lens and the eyepiece so that the image can be safely viewed outside the shielding.

The modifications virtually quadruple the cost of the original equipment and the resulting installation is maintenance intensive. In addition some loss of image quality is incurred by adding the extension tubes.

In looking for ways to reduce these costs, the Metallurgy Section in March 1981 asked the Instrument Section to assess the potential of a laser optical microscope and build a prototype.

Examination of radioactive samples by a scanning optical microscope is attractive because such a microscope would produce an image output in the form of an electronic signal which can be viewed remotely from the cell on a video monitor by any number of observers.

A market survey showed that no suitable instruments were available commercially despite the idea of a scanning or flying spot microscope being around since the late 1950's. Various prototypes are described in the literature[1,2] but early versions suffered from lack of availability of a suitably bright light source or sufficiently sensitive detector. The development of inexpensive lasers and semi-conductor photo detectors has meant that these problems no longer apply and that theoretical performance can more nearly be achieved in

practice. Recently workers at Oxford University[3,4] have claimed that a type of scanning optical microscope called the confocal system is capable of resolution over and above that achievable from a conventional microscope. They say that when the optical system of scanning microscope is confocal (Fig. 3(b)), then the size of the scanning spot can be made smaller, by spatial filtering at the detector, than any other optical microscope or, in fact, a conventional microscope operated with vidicon tube detector. Scanning optical microscopes can be operated in either a refelection or a transmission mode. Generally the image is of higher contrast with better edge definition than the conventional microscope equivalent. Special types of detectors have been used [5], to enhance contrast even further. SOM's have a tendency to reject unfocussed images [6] so that in a transmission mode a two-dimensional plane can be imaged in a 3-D object. A version has been reported [7] which detects reflections from the sample at harmonics of the incident wavelength. These are produced by non-linear processes in certain crystal structures and enable a video image mapping the distribution of these crystals to be produced.

2. EQUIPMENT DESCRIPTION

Figure 1 shows the equipment schematic and Figure 2 is a photograph of the prototype. Light from a 1 milliwatt helium neon laser R1 of wavelength 0.63 um is focussed by an objective lens L1 to a diffraction limited spot on specimen S1. Light reflected from the specimen is collected by the same lens, deflected by the beam splitter M1 and brought to a focus at detector D1. The specimen is oscillated back and forth* by electro-mechanical vibrators V1 and V2, powered by amplifiers A1 and A2. In order to ensure that the laser is kept in focus throughout the full amplitude of the scan, the stage is clamped to the mid-points of four piano wires so that movement in only one plane is permissible. In step with the motion of the specimen stage, a spot on an oscilloscope screen is moved so that, when the output from the detector is caused to modulate the Z axis of the spot, a magnified reflectance image of the specimen is displayed on the screen.

A unique feature of the proptotype equipment described in this report is the means by which synchronisation of the scanning spot on the oscilloscope is achieved with the focussed laser spot, described as follows:-

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* Vibrating the specimen was never seen to be a practical way of operating a microscope using radioactive samples and in all but the first prototype the laser spot is caused to oscillate by vibrating the focussing lens.

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The position of the moving stage is measured by two orthagonal position sensors C2 and D2, Figure 1, mounted under the sample table. The devices work by sensing small capacitance changes between a central electrode E1 and a pair of plates P1 and P2 [8]. The position signals are fed to the oscilloscope X and Y inputs and cause the spot to deflect horizontally and vertically in step with movement of the stage. The advantages claimed are:-

(a) This system is simpler and more accurate than the normal video system of using a composite video signal (ie synchronisation pulses added to the video signal).

(b) It allows flexibility of scan mode eg spiral scan, random or a radar type scan can be used.

(c) It provides some immunity to spurious vibrations, since movements of the stage from whatever source are tracked by movements of the imaging spot on the screen.

3. THEORY OF IMAGE FORMATION

3.1 THE OPTICAL SYSTEM

The theory of the scanned image formation has been extensively studied by others [3, 4, 9, 10, 11, 12, 13, 14]. They define two distinct types of scanning optical microscopes, Types 1 and 2), (Figure 3). The Type 1 or 'flying spot' type is formed by moving the point source off the optical axis usually by using mirrors (15). The second, simpler system, which we have adopted is the present design they call the Type 2 or confocal system.

These differences in the optical systems result in the following:-

(a) By the reprocicity theorum a Type 1 system is equivalent to a conventional (compound) microscope fitted with a scanning detector such as a TV vidicon. In other words the quality of the image produced by a 'flying spot' microscope is the same as a conventional microscope and that moving the point source is equivalent to moving the point detector.

(b) That in a Type 1 system the only function of Lens L_2 is as a collector of light and it does not contribute to the resolution whereas in Type 2 confocal system L_2 contributes to and increases the resolution.

(c) That in a Type 1 system Lens L_1 is required to image points such as X off the optical axis so that the system suffers the usual lens aberrations of astigmatism and coma. In the Type 2 system however, the rays of light are always centred on the optical axis, hence the lens aberrations are not present.

The SOM microscope based on a Type 2, confocal system has potential therefore to yield resolution over and above that of the conventional microscope.

3.2 SPOT SIZE AND DEPTH OF FOCUS

The beam emitted from a laser has a near perfect plane wavefront and a Gaussian transverse profile [16]. It quickly, however, acquires curvature and begins to spread[17] according to:-

$$R(Z) = Z \left[1 + \left(\frac{Wo^2}{Z}\right)^2\right] \quad \ldots\ldots\ldots\ldots (1)$$

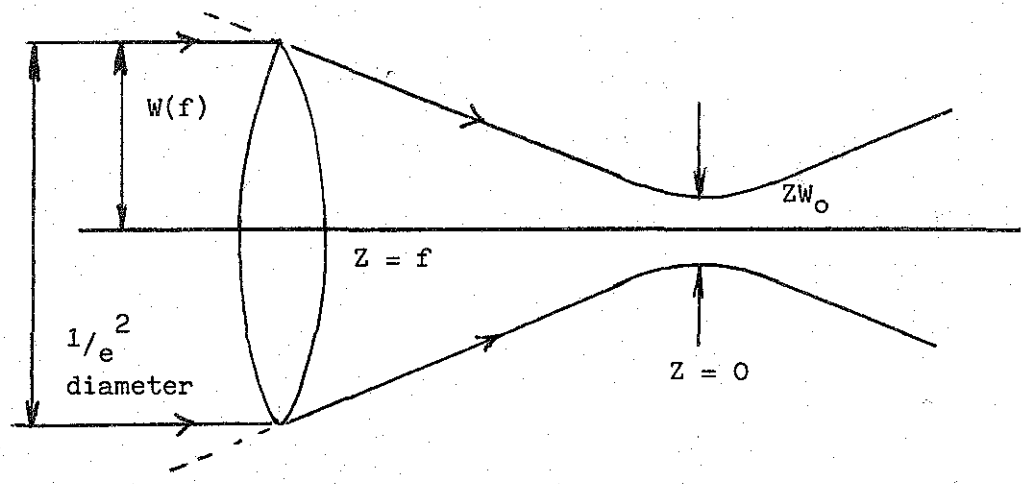
$$W(Z) = Wo \left[1 + \frac{Z}{Wo^2}^2\right]^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots (2)$$

Where W is the beam diameter at the point where the intensity has dropped to $1/e^2$ or 13.5% of its maximum value.

R(Z) is the wavefront radius after propagating a distance Z.

W(Z) is the radius of the $1/e^2$ contour after the wave has propagated a distance Z.

W_o is the radius of the $1/e^2$ contour when the plane wave was flat.



For large Z R(Z) approaches Z

W(Z) approaches $\frac{\lambda Z}{\pi Wo}$ ..... (3)

One can use equation (3) to find the size of the focal spot formed when a perfectly colimated laser beam is focussed with an aberration free lens.

In this case Z becomes, f, the focal length of the lens and Wo is the contour radius of the new waist formed near the lens focal point thus:-

$$Wo = \frac{\lambda f}{\pi W}$$

As an example if f = 4 mm

W = 0.75

then $Wo \quad \frac{0.63 \times 4}{\pi \times 0.75} \approx 1\ \mu m$

The depth of focus $\pm \Delta Z$ can be derived from (2) by setting $W(Z) = 1.05\, Wo$ (to allow for 5% increase and solving for Z = Z the result is

$$\therefore \Delta Z \simeq \pm \frac{0.32\ Wo^2}{\lambda}$$

$$\Delta Z \simeq \pm \frac{0.32\ \pi}{0.63} \approx 2\ \mu m$$

Thus the lens of focal length 4 mm and diameter 0.75 will focus a parallel helium-neon laser beam down to, approximately, a spot size of 1 μm and a depth of focus of 2 μm.

4. THE CASE FOR A SCANNING OPTICAL MICROSCOPE

4.1 LOW COST

The total cost of a fully engineered version of the prototype at 1982 prices is anticipated to be £25,000, fully installed, in cell, compared to over £0.2M for a compound microscope. As an example of the substantial cost savings the new microscope only requires one focussing lens at £300 compared to a conventional system which requires a set of at least 3 with an auto change system costing £3,000.

4.2 REMOTE OPERATION

The scanning type of microscope has been chosen because it is, inherently remotely operated. The only connection between the control panel and the parts located in cell is the bundle of control cables. The optical extension tubes used to bring the image from a conventional microscope out of the shielded cell have been eliminated

4.3 VIDEO OUTPUT

The output is in the form of an electronic signal which can easily be interfaced with a computer for automatic measurement, image analysis or processing.

4.4 MAINTENACE COSTS

The equipment is much smaller, more compact and not bound to the cell wall. Unlike conventional 'in cell' microscopes it can be unplugged from its cables,

moved around in the cell, replaced or removed as required. This will have a large impact on maintenance costs, and will simplify health physics procedures for preparation for maintenance.

4.5 IMPACT ON CELL DESIGN

Figure 4 depicts how the microscope might look in cell. The operator now only stands in front of the cell for a short time while the sample is positioned on the microsocpe. This may allow a re-think on the design of any new cells with potentially a saving in lead shielding.

4.6 IMAGE BRIGHTNESS

The SOM uses helium neon laser light source. The power level can be chosen from the wide range now available and can be orders of magnitude brighter than other conventional microscope lamps. (High power lasers are not used to illuminate conventional microscopes because of the risk of damage to the eye). All the light is focussed down to a spot of the order of 1 μm in diameter so that the refelected signal even from a poor reflector can be large compared to any other type of microscope.

This leads to two advantages of the laser SOM.

(a) Less gain needs to be applied to the detector amplifier and hence the signal to noise ratio of the image is higher.

(b) The usual blackening of the objective lens of a microscope on exposure to radiations eventually reduces image intensity down to such a level where the objective lens has to be replaced. This is not a problem with the SOM since sufficient light is available to enable it to be automatically controlled to provide constant intensity throughout the working life of the microscope.

The properties of the SOM mentioned above are particularly important when the sample is being observed in polarised light with "crossed polars" (dark field).

In this situation it is not unusual for image intensities to be many orders of magnitude less than the normal and quite often the performance of conventional equipment is severely limited.

4.7 RELIABILITY

The new microscope has no requirement, unlike the conventional microscope, for lens changing controls. The parts of the SOM located in cell are of low cost and small size. It is therefore envisaged that a spare unit would be kept on stand-by in the cell. This would mean that a microscope would always be available for use.

4.8 EASE OF OPERATION

When using a conventional microscope the operator has only limited control over the image in the eyepiece. To change the magnification he has to change either the eyepiece or the objective. On a microscope located behind shielding this is a time consuming operation if it is required to go up and down in magnification frequently. However, in the SOM, the magnification is not a function of the lens focal length but is controlled quickly and easily from the control panel by altering the sensitivity of the position measuring transducers. This causes the video signal to be displayed over a large or smaller area of the screen.

5. RESULTS

Photomicrographs are presented in Figures 5, 6, 7 and 8 as follows:

Figure 5(a) An integrated circuit imaged with the SOM

5(b) A similar integrated circuit imaged using a conventional microscope.

6(a) A sample of Magnox, SOM image.

6(b) Same sample as 6(a) but conventional microscope image.

7(a) A prepared sample of Zircaloy SOM image, polarised light.

7(b) Same as 7(a) but conventional microscope image, dark field.

7(c) Same area of sample as 7(a) SOM image, bright field.

8(a) 1.6 μm rulings on glass, SOM video signal recorded on a cathode ray tube.

The equipment and settings used to obtain the photographs are detailed below:

Laser	-	Helium-neon 1 mwatt output
Laser focussing lens	-	Reichert X90, NA0.75
Detector	-	Silicon photodiode BPX65
Detector preamplifier	-	3100E (bandwidth approx. 1 MHz)
Line scan frequency	-	50 Hz sinusoidal
Frame scan	-	0.01 Hz triangular
Display system	-	Hewlett Packard 1301 CRT
Photograph exposure	-	100 sec (1 frame) on Polaroid 120B film.

6. DISCUSSION OF RESULTS

6.1 IMAGING CHARACTERISTICS

By comparing Figures 7(a) and (b) it can be seen that the imaging characteristics of the two microscopes are quite different. The laser microscope shows more detail between the grains. This example illustrates the fact that new information may be obtained from samples. It is planned as soon as possible to provide microscopists with a version of the equipment for more trials so that its full potential can be evaluated.

6.2 RESOLUTION

Figure 8(a) is the video signal output displayed on an oscilloscope of a glass grating with line spacing equal to 1.6 μm. From this it can be deduced that the spot size and hence the resolution of the laser microscope is about 2.0 μm. By comparing Figures 7(a) an image from the laser microscope and 7(b) an image of the same area using a conventional microscope it can be seen that the resolution of the new microscope is as good as, if not better than the conventional microscope.

6.3 INSTALLATION IN CELL

Although the new microscope has not been installed in cell yet and the results so far presented are obtained on an inactive rig, no reduction in resolution will result from installation in cell. Figures 5(b) and 6(b), however, were obtained using a conventional microscope out of cell and some deterioration of resolution would occur if it were installed in cell due to the extension tubes

which would be required to bring the image out of the cell.

7. FURTHER DEVELOPMENT

7.1 ENGINEERING

Figure 4 shows how the new microscope could be used for examination of radioactive specimens. The equipment can be packaged into a cabinet no larger than $0.6m^3$. Because this is much smaller than existing equipment one can envisage that a stand-by unit could be kept in the cell ready to be plugged in if one fails.

7.2 SCANNING MODE

Although in the present prototype the sample is vibrated, a second stage is being developed at WNL which allows the sample to be stationary. Instead the lens is vibrated. In both systems the beam is always perpendicular to the lens axis so that the laser is focussed to as small a spot as possible. The new scanner also eliminates the need for the four vertical suspension wires. This development gives better access to the stage for positioning the sample with manipulators.

7.3 IMAGING CHARACTERISTICS

The results achieved so far and presented in this report indicate that the image is qualitatively different from those produced by other microscopes. In order to quantify this it is intended that a prototype will be made available to users so that more information can be obtained as quickly as possible in order to quantify these differences and evaluate the potential of the microscope to yield more sample information than hitherto obtainable.

7.4 RESOLUTION

(a) By careful choice of the laser focussing lens it is expected that a spot size as small as 0.8 μm can be achieved with the helium neon laser. The possibility of using a nickel-cadmium laser, which emits light in the UV region, to obtain even higher resolution, will be investigated.

(b) It is proposed that possibility of using a 'harmonic scanning microscope' (7) on radioactive metallurgical samples be investigated. This adaptation of the basic SOM is claimed to yield resolution above the classical limit set by the illuminating light. Its operation is based on the properties of certain crystals, which lack a centre of symmetry, to generate harmonic light frequencies, at high light intensities. Light reflected from the sample at the fundamental frequency is filtered out and an image of the sample built up in the normal way using the harmonic light.

7.5 IMAGE PROCESSING

The SOM produces an output in the form of an electronic signal so not only can it be displayed on the cathode ray tube to be viewed by any number of observers but also it can be interfaced to a computer for functions such as:-

1. Archive storage in digital memory.

2. Production of hard copy in less time than photographs.

3. Electronic processing such as image enhancement.

4. Automatic operations such as particle counting.

8. CONCLUSIONS

A scanning optical microscope using a laser beam as light source has been developed principally for use in Post Irradiation facilities at WNL. The advantages offered by the development of this type of microscope, are listed as follows:

1. Operational Advantages

The output is an electronic signal. The following operations can now be carried out more easily or quickly..

- Remote viewing of image in order to reduce radiation dose to the operator and allowing centralising of operations in one control room.

- Interfacing of the microscope to other hardware to facilitate

  (a) image enhancement by computer;
  (b) large archive storage in computer memory;
  (c) production of 'hard copy' from video printer rather than photographs;
  (d) Measurement of image parameters, automatic particle counting etc using software programs.

2. Quality of Image

(a) Micrographs of inactive metallurgical samples obtained using the experimental equipment have shown the resolution to be approximately 2 μm, very close to the resolution limit set by the wavelength of the illuminating light. This is equal if not better than that produced by existing 'in-cell' equipment.

(b) The SOM image shows details of metallurgical features in a way different to other microscopes. This may be useful in imaging objects which have hitherto been difficult to observe using existing equipment (eg oxide layers).

(c) The system does not suffer from degradation of the image due to radiation effects on the lens. The high intensity obtainable from the laser allows any lens blackening to be compensated for.

(d) The high intensity of light available from the laser results in a higher quality image than other systems with less electrical noise on the displayed image, particularly, when image intensity is low, such as when viewing in dark field using polarised light.

3. Economics

(a) The capital cost is less than any other comparable system.

(b) The installation costs are less, largely because, unlike present equipment, no modifications are necessary.

(c) Lower maintenance costs will result because the microscope has been designed to be used in the difficult environment of the shielded cell. The 'in-cell' components of the microscope represent no more than 10% of the total cost of the instrument.

(d) Lower operations costs will result from the use of a spare scanner unit installed in cell so that there will always be an instrument available for use.

The Appendix summarises the features and compares performance of the SOM with other types of equipment.

9. ACKNOWLEDGEMENTS

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APPENDIX

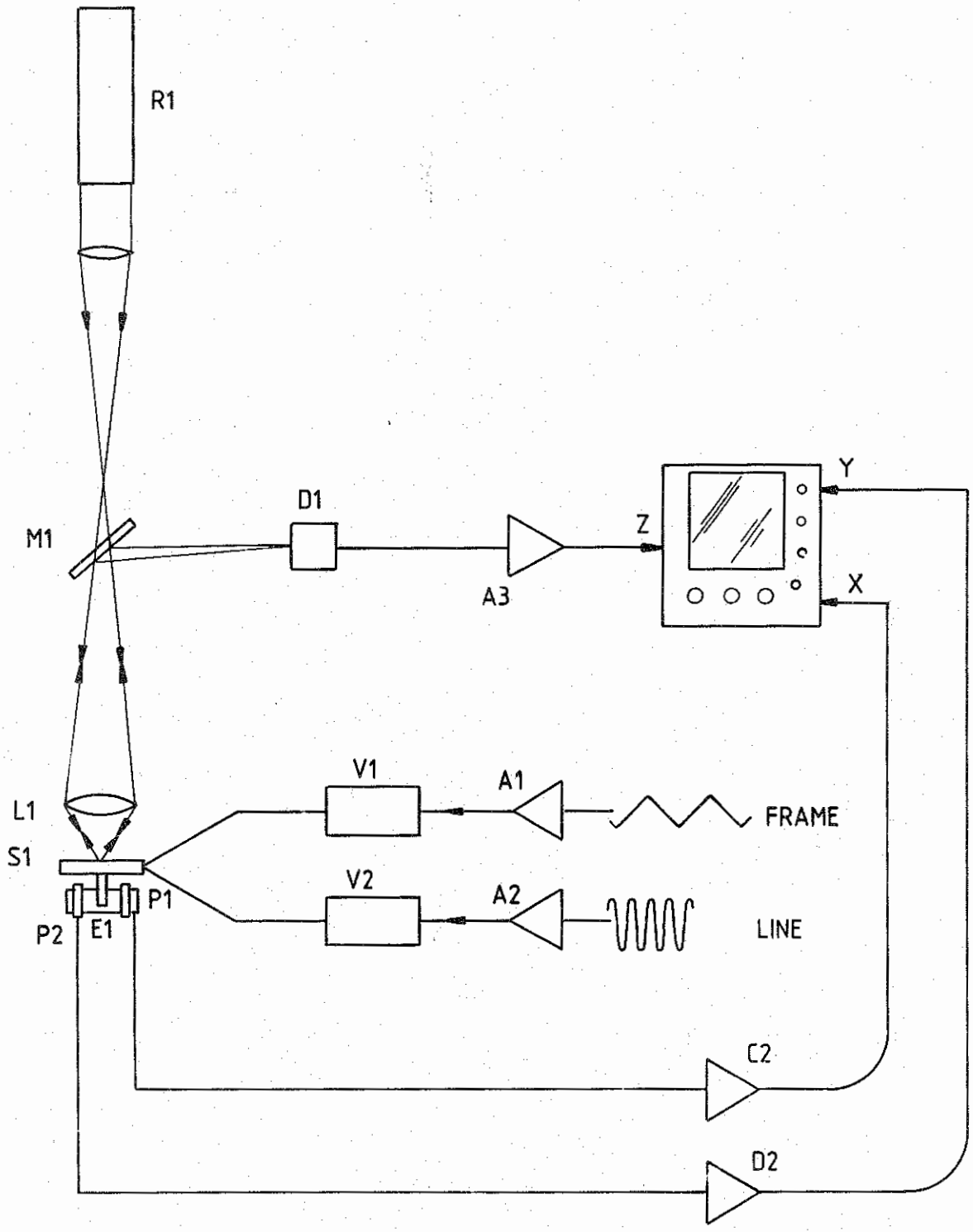
Comparison of microscopes suitability for PIE

	Conventional objective eyepiece	Video (objective and vidicon)	SOM (Scanning optical microscope)	SEM (Scanning electron microscope)
Example equipment	Neophot, Riechart etc	Hamamatsu C1000	WNL prototype	Hitachi X650
Estimated installed capital cost	£150K	£35K	£22K	£200K
Resolution (limit in cell) Centre (um)	2	1	1	Better than 0.1µm
Resolution (limit in cell) Edge (um)	3	2	1	
Image parameters				
(a) No of scanning lines	500 (Polaroid photograph)	1000	2,000	2,000 lines
(b) Noise bandwidth	NA)(low light levels-NA) often a problem)	15MHz	1MHz	5MHz
(c) Detector efficiency		.1	.6	Not known
(d) Image brightness	Poor in polarised light	Limits performance	Does not limit performance	Does not limit performance
Imaging speed				
(1) Low-quality image	Instantaneous	1 field/.02 sec	1 frame per 5 sec	1 frame/.02 sec
(2) High-quality image	"	1 frame/.04 sec	1 frame per 30 sec	1 frame/30 sec
Image qualitative characteristics	Soft image reducing effects of surface topography. Imaging in colour.		High contrast - good edge definition	Low grain contrast. Topography shows up well. X-ray analysis is optional feature.
Can unit be interfaced with computer?	No (separate image detector required)	Yes	Yes	Yes
Cell volume required	$2M^3$	$1M^3$	$.6M^3$	$3M^3$

NA - Not Applicable

FIG 1

LASER SCANNING OPTICAL MICROSCOPE



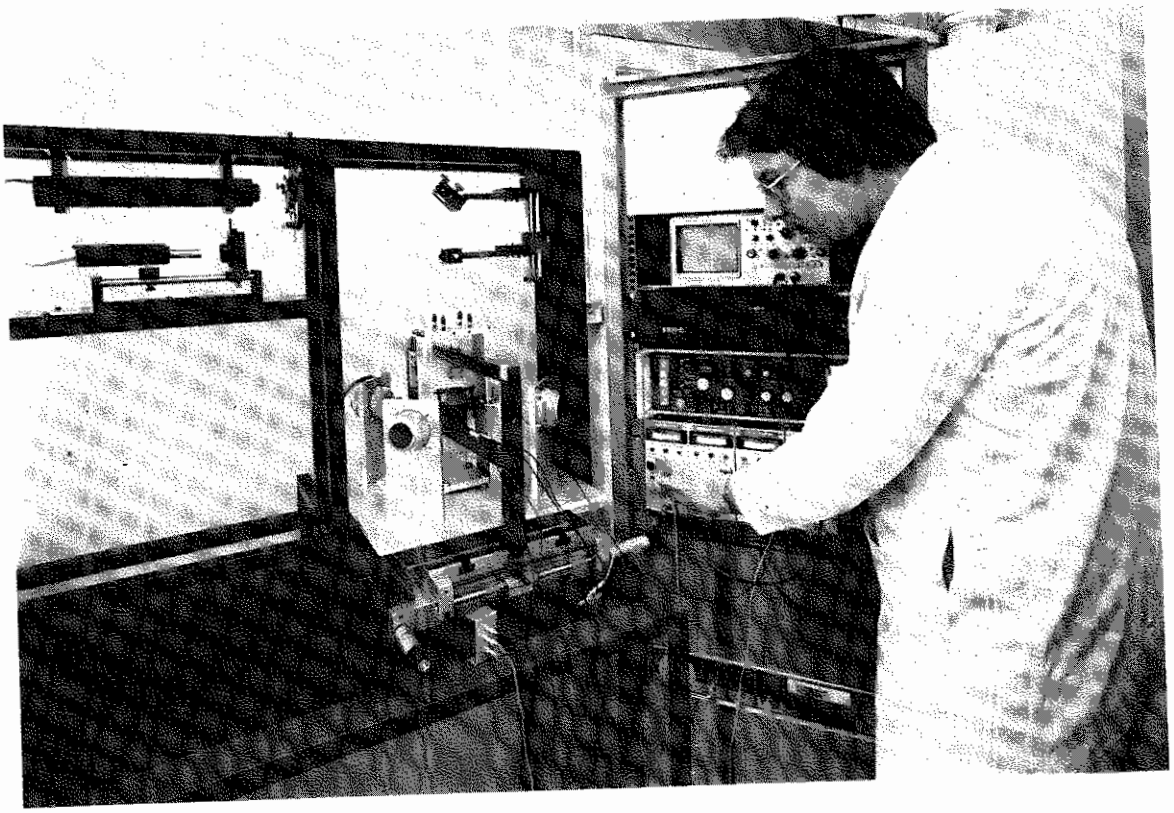


FIGURE 2: THE PROTOTYPE LASER SCANNING OPTICAL MICROSCOPE

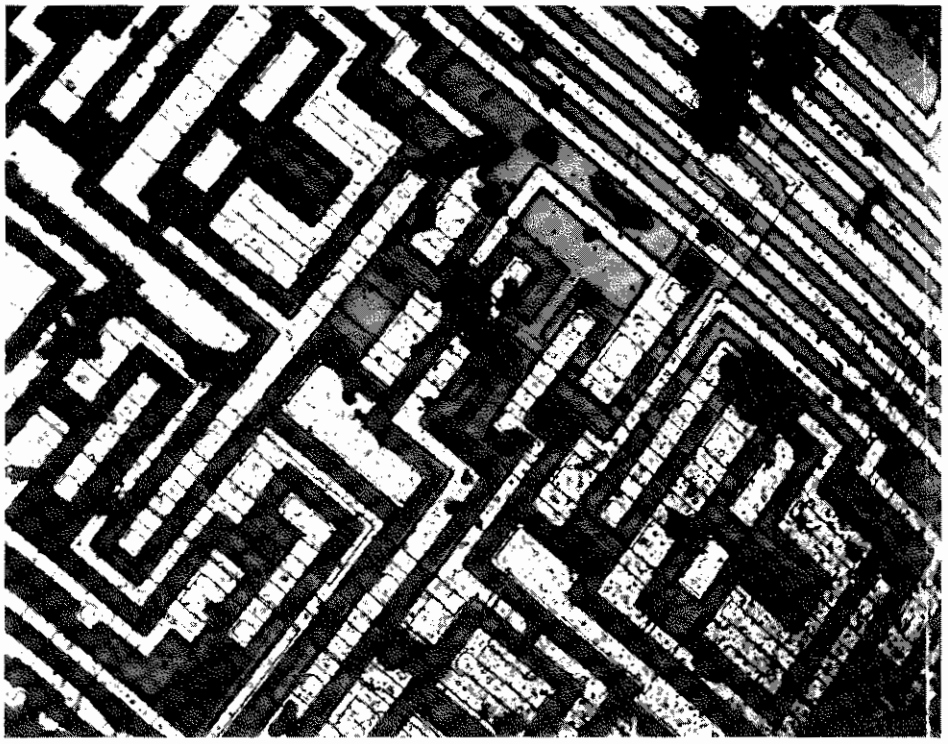


FIGURE 5 (a): AN INTEGRATED CIRCUIT IMAGED WITH THE S.L.O.M
MAGNIFICATION X200

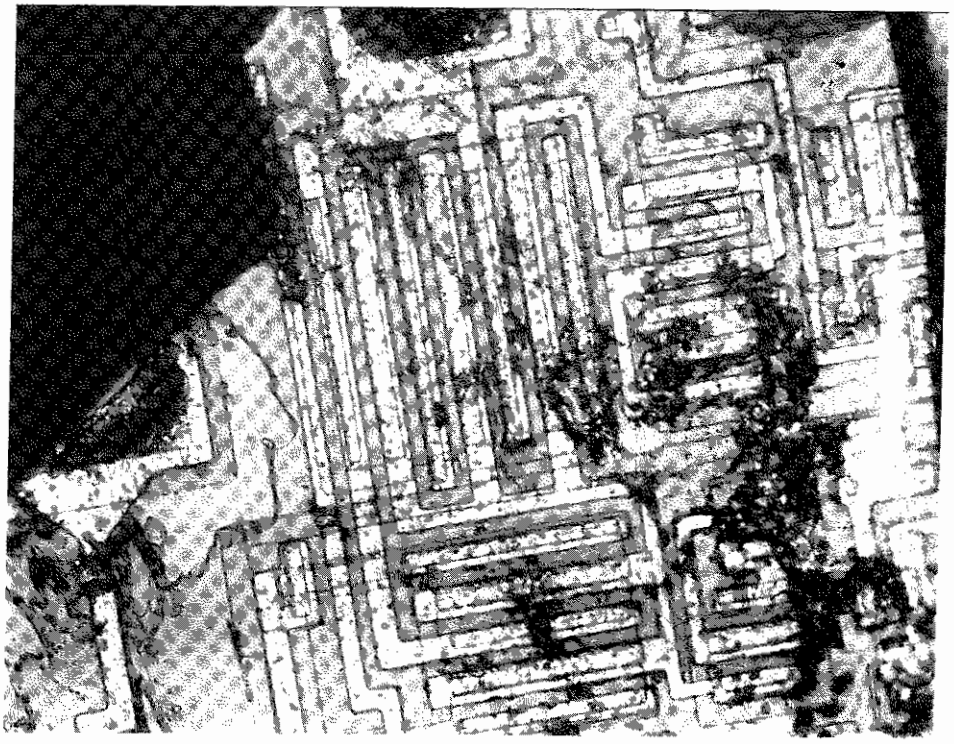


FIGURE 5 (b): A SIMILAR INTEGRATED CIRCUIT IMAGE USING A CONVENTIONAL MICROSCOPE
MAGNIFICATION X200

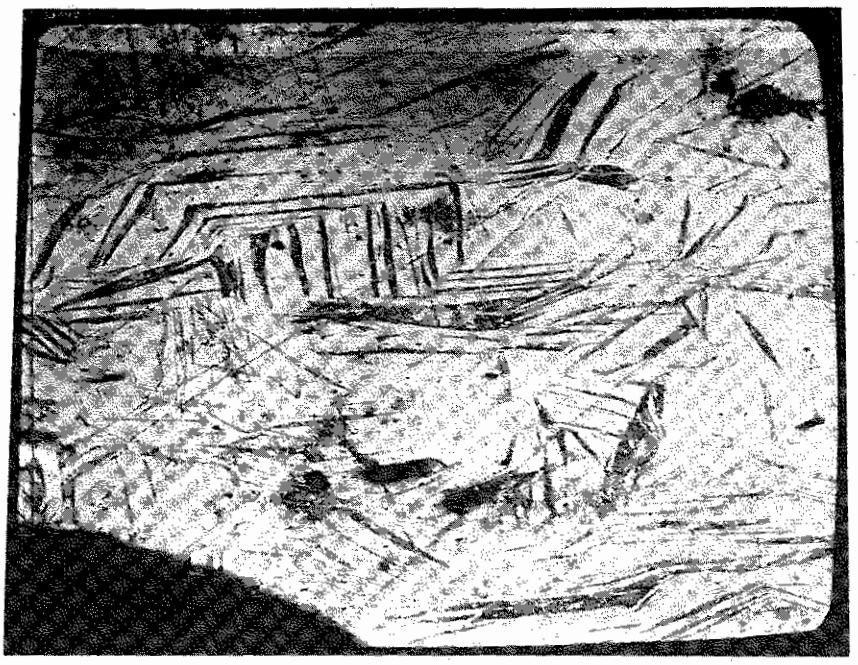


FIGURE 6 (a): ETCHED SAMPLE OF MAGNOX
S.L.O.M IMAGE X200

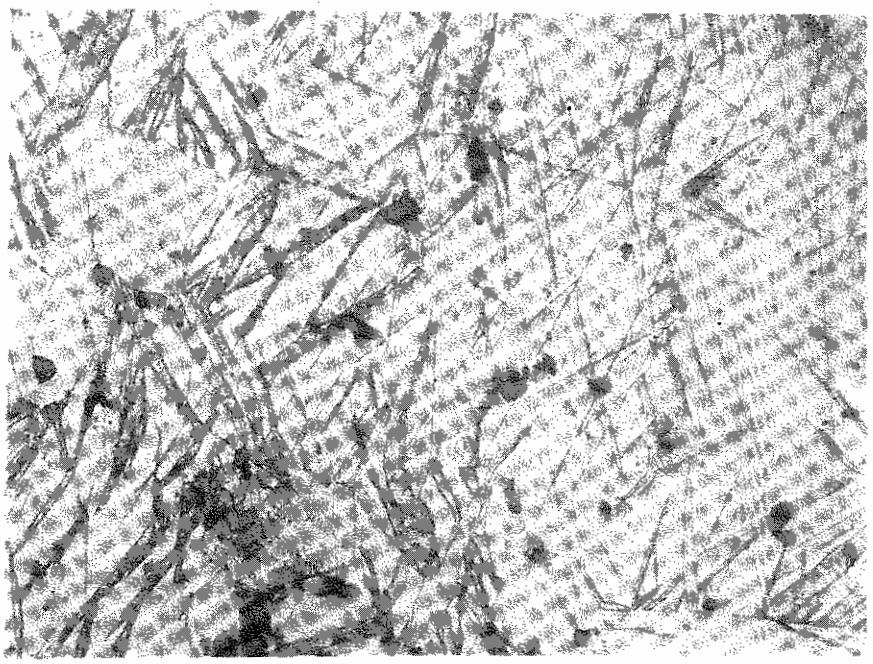


FIGURE 6 (b): SIMILAR AREA OF ETCHED MAGNOX
CONVENTIONAL MICROSCOPE IMAGE X200

FIGURE 7 (a): ETCHED ZIRCALOY IN POLARISED LIGHT
(S.L.O.M IMAGE X200)

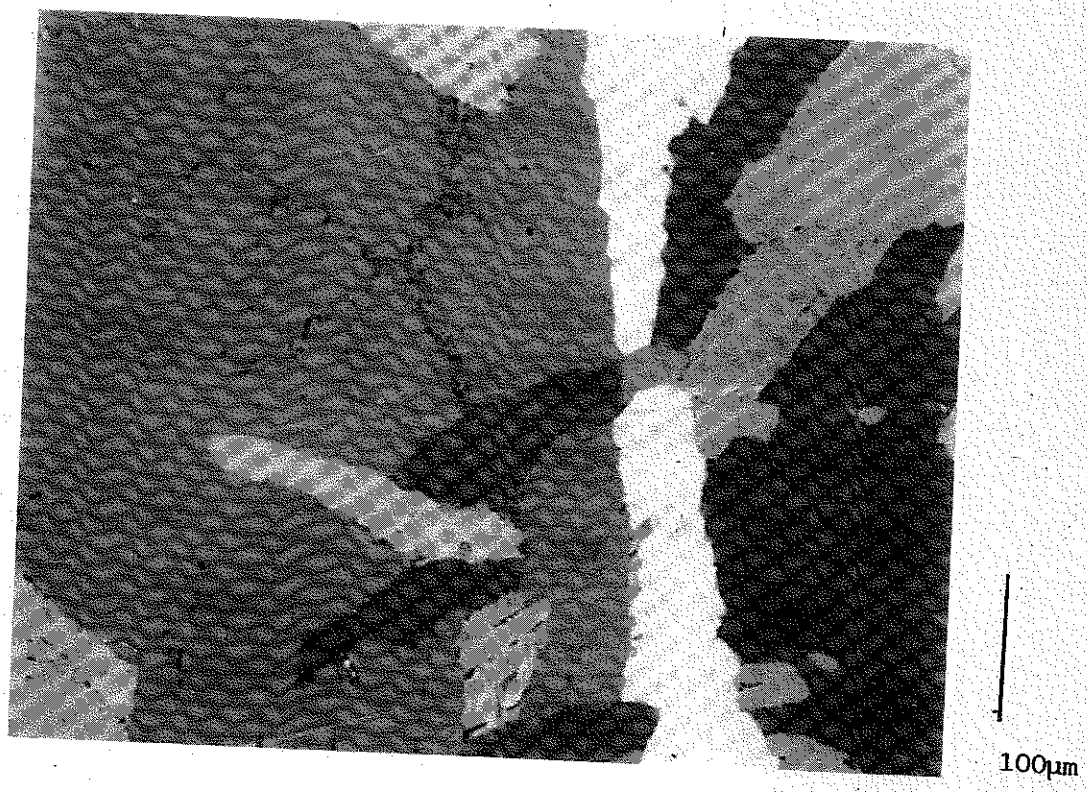


FIGURE 7 (b): ETCHED ZIRCALOY IN POLARISED LIGHT
(CONVENTIONAL MICROSCOPE IMAGE X200)

FIGURE 7 (c): ETCHED ZIRCALOY - BRIGHT FIELD
S.L.O.M IMAGE X200

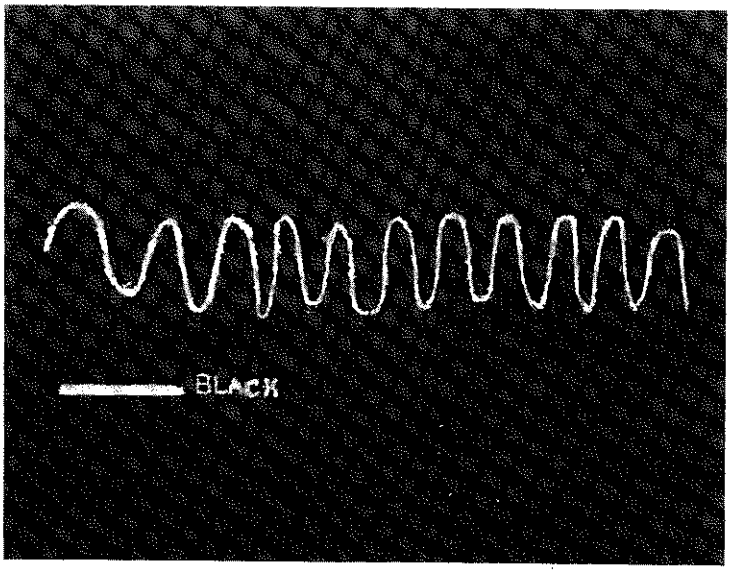


FIGURE 8 (a): GRATICULE SCALE (600 LINES PER MM)

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