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SCANNING OPTICAL MICROSCOPY OF SEMICONDUCTOR MATERIALS AND DEVICES

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Abstract

In the scanning optical microscope a focused light spot is used to illuminate the object and some property monitored as the spot is scanned relative to the object to build up an image. By monitoring different properties it is thus possible to use the scanning optical microscope in a wide range of imaging modes, which can be used to give much information concerning the structure and properties of semiconductor materials and devices. In the optical-beam induced current method the focused light spot generates electronic carriers in a semiconductor specimen, and the resultant current monitored. The technique can be used to study defects in semiconducting materials and to measure electronic properties. If instead the reflected light is monitored we can obtain images in which resolution, contrast and depth of focus are all improved relative to conventional optical microscopy. Using the confocal imaging mode surface topography of thick structures can be investigated. In the scanning optical microscope we gain all these advantages whilst avoiding the disadvantageous effects of an electron beam and the necessity for a vacuum environment.

Key Words: Optical microscopy, laser microscopy, confocal imaging, characterization, surface profiling, optical-beam induced current.

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Introduction

Optical microscopy has a number of desirable features which make it preferable to electron microscopy for a wide range of applications. Specimen preparation may be simplified, in many cases no special preparation at all being necessary, thus avoiding problems from preparation-induced artifacts. The radiation is of low energy, thus minimizing specimen damage, and there are no complications from charging-up of the specimen during observation. A vacuum environment is unnecessary, which simplifies instrumental design, avoids contamination problems, and improves operational convenience. The interaction of light with the specimen may be modelled theoretically in a simple manner, in many cases analytical expressions being obtainable, because photons unlike electrons are absorbed without energy loss. (Here we are ignoring scattering involving a frequency shift, which can be filtered out spectroscopically.) And in many cases light is a useful radiation because we are interested in the optical properties of the specimen.

Optical microscopy also of course suffers from severe drawbacks compared with electron microscopy, although in fact the performance can be improved greatly by using a scanning method. Contrast, resolution and depth of field can all be increased, whilst three-dimensional images can be formed, accurate quantitative data recorded and electronic and material properties studied. These improvements stem from a number of different imaging modes of the scanning optical microscope system [43,44,56]. For the investigation of semiconductor materials and devices the most important techniques are:

1) the optical-beam induced current (OBIC) method, which can be used to observe defects and obtain quantitative data on electronic properties, 2) the confocal imaging technique, which results in improved resolution as well as allowing images to be formed of thick and multilayer structures and surface profiles to be investigated, 3) the differential phase contrast method, which gives topographical images of specimen structures, and 4) spectroscopic methods, giving chemical and

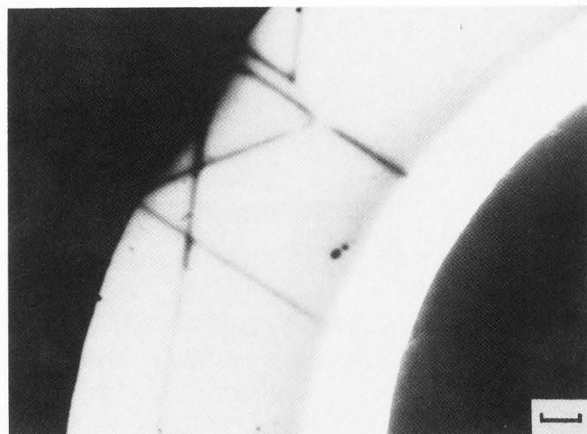


Fig.1. Defects in a silicon transistor using the OBIC mode. Bar = 10 μm.

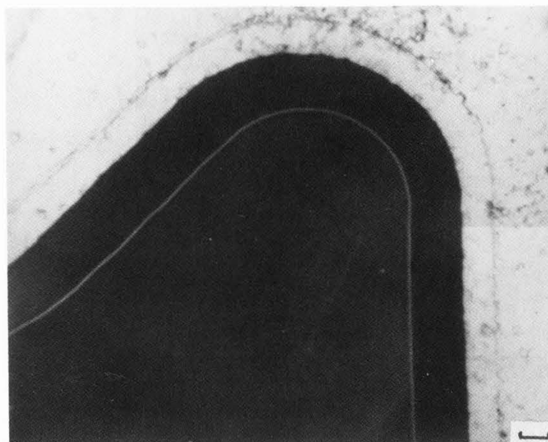


Fig.2. Incident light image of damage caused by exposure to the electron beam in an SEM. Bar = 100 μm.

material information.

In all these techniques the same basic procedure is used. Light, conveniently supplied by a laser, is focused to a small spot on the specimen, and some resultant signal monitored as the spot is scanned relative to the specimen in order to build up an image.

Scanning can be achieved either by scanning the beam or by mechanically scanning either the objective or the specimen. The last method has the advantages that imaging is space-invariant, resolution maintained over the whole field and variations in illumination avoided. In Oxford, although we have constructed microscopes using all three of these scanning methods, most of our work has been performed on specimen-scanned systems. A review of the various available methods is given in [44].

The OBIC method

In the OBIC technique the focused optical beam excites electrical carriers in a semiconducting specimen, and the photoinduced current signal used to produce an image [58]. Applications have included the investigation of photoconductors, photodiodes, photocathodes and solar cells, but also both discrete electronic devices and integrated circuits. The strength of the current varies as a result of changes in minority carrier diffusion length, junction depth, surface recombination velocity or the presence of crystal defects such as dislocations, grain boundaries or trapping centres. Quantitative data concerning these properties may thus be obtained, and in addition by using a moving or chopped beam the carrier lifetime can be investigated.

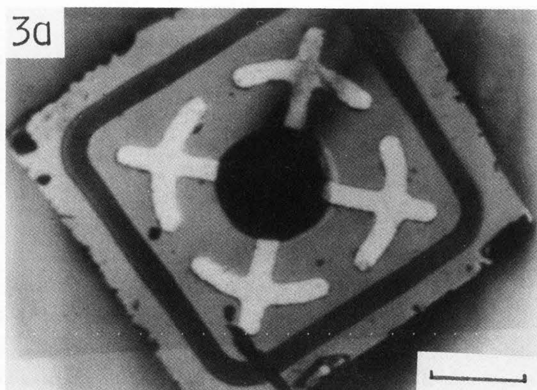
An example of an OBIC image of defects in a transistor is shown in Fig.1. This was produced using light from a HeNe laser (633nm), as are all the subsequent images in this paper. HeNe light is useful for semiconductor investigations as it usually has a reasonable penetration depth. Contrast and resolution of images of dislocations produced using the OBIC method have been shown to be similar to those in the analogous EBIC techinque [57].

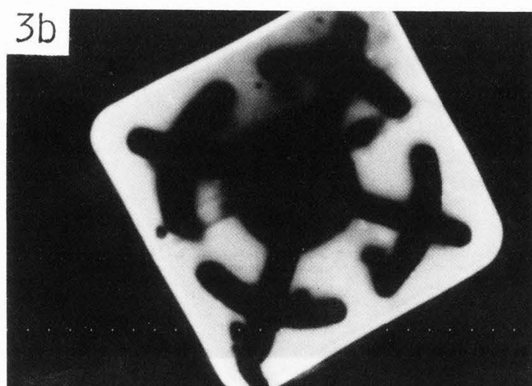
Advantages of the optical method are that problems of contamination, beam induced damage and specimen charging are avoided. It is also possible to study the effects of different atmospheres on electrical properties [53]. Fig.2 shows an example of electron-beam induced contamination of a device observed using the brightfield incident-light mode of scanning optical microscopy. Electron-beam induced damage in semiconductors has actually been proposed as a method of data storage [38].

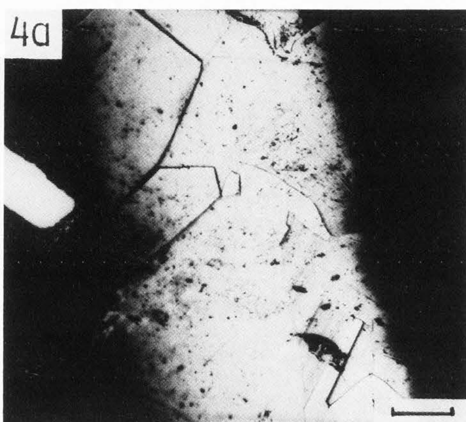
The OBIC technique has been used to observe the formation of microplasmas [18,53] and investigate leakage channels [51]. Logic states and gain of integrated circuit transistors can be determined and the transistors switched by the laser to test logic function [35,40].

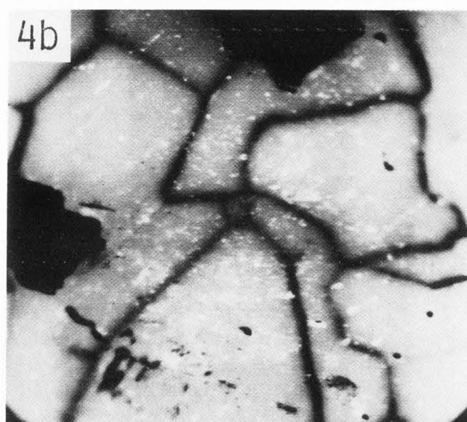
The optical technique is also particularly suitable for study of optoelectronic devices, such as solar cells [29,39,42] and photodetectors, and also light-emitting diodes, as illustrated in Fig.3, and semiconductor lasers [31,33]. Fig.4 shows examples of a reflected light and OBIC images of a polycrystalline silicon solar cell, grain boundaries showing up as dark lines on the OBIC image. Much information can be gained from comparison of such image pairs. Biasing either electrically or optically can also give more information, in particular in separating the effects of internal resistance and quantum efficiency [42]. The recombination velocity of grain boundaries has also been investigated [29].

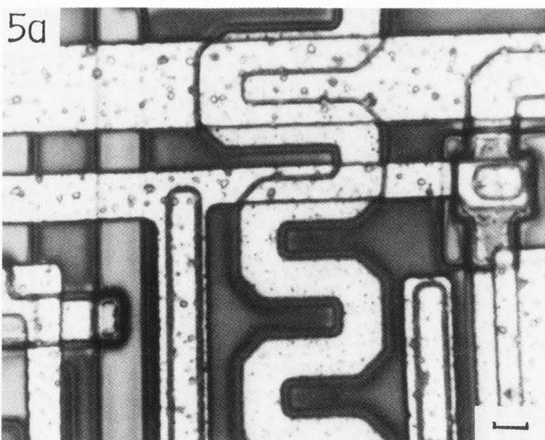
Instead of using photon energies great enough to excite carriers directly, images can also be produced from the photocurrent generated by a laser beam with photon energy smaller than the band-gap of the semiconductor [31]. In this case if a deep level is present within the band-gap an electron may be excited to the conduction band by a two-step process,











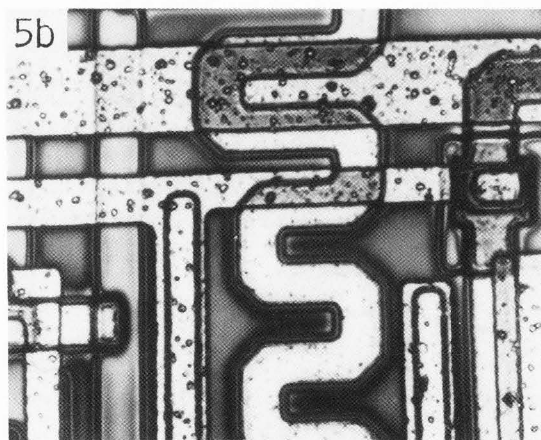


Fig.3. A polycrystalline Si solar cell in (a) reflected light, and (b) OBIC modes. Bar = 200 μm.

Fig.4. A GaP LED in (a)reflected light, and (b) OBIC modes. Bar = 100 μm.

Fig.5. An integrated circuit in reflection in (a) conventional, and (b) confocal modes. Bar = 10 μm. (Courtesy D.K. Hamilton, unpublished).

giving information complementary to that obtained with the normal OBIC technique.

The OBIC method can be performed on plain semiconductor materials either by preparing a Schottky barrier junction [32] or either a pressure [32] or electrolytic liquid [15] contact. Information on material properties including surface excess carrier density and the charge in the electron traps can be obtained from study of surface photovoltage. This method does not require contacts on the device, the signal being detected capacitively. Images have been produced from wafers without metallization [52] and also from plain wafers without junctions [37].

Confocal imaging

In a conventional microscope the image can be measured point-by-point by scanning it

relative to a point detector. Alternatively in a scanning microscope the object is probed point by point by the focused image of a point source. The imaging properties of these forms of microscope can be shown to be equivalent. In the confocal microscope these two forms are combined, so that a point source illuminates a small region of the specimen, whilst a point detector also collects light only from a small region. In practice the point detector is constructed by placing a small pinhole in front of a photodiode or photomultiplier tube. In the confocal microscope the imaging properties are modified substantially from those in the previous two geometries. The resolution is improved by a factor of up to two [46], according to the particular resolution criterion, which may be very significant in examining structures close to the resolution limit. This is also appreciable when compared with the improvement to be gained by using a very expensive, rather than a modest, conventional microscope.

The comparison images of Fig.5 demonstrate the improved definition of the confocal mode. The improved crispness of the confocal image is partly attributable to the rejection of flare by the confocal pinhole, the ratio signal/flare being improved by several orders of magnitude compared with a conventional system [11,45]. No electronic contrast enhancement has been used in these images. However in a scanning microscope contrast enhancement of one hundred times or more can be achieved. The improvement in contrast gained by electronic processing also has its effect on resolution. In a conventional microscope the condenser must often be stopped down at the expense of resolution in order to gain adequate contrast. Contrast enhancement also allows fine details, which may be imaged only weakly, to be enhanced and hence made visible.

The properties of a confocal microscope may be investigated by assuming an object which is thin so that it may be described by an amplitude transmittance function $t(x,y)$, assumed complex to account for variations in both reflectively (or absorption) and phase. Consider first imaging by a single lens with amplitude point spread function given by $h(x,y)$.

The intensity in the image of a single point object is given by:

$$I(x,y) = |h(x,y)|^2 \qquad (1)$$

For a circular pupil in the absence of aberrations the image is circularly symmetric and given by the well-known Airy disc:

$$I(v) = [2J_1\,(v)/v]^2, \qquad (2)$$

where J_1 is a first-order Bessel function, and v is a dimensionless radial optical coordinate:

$$v = kr\,\sin\alpha \qquad (3)$$

Here $\sin\alpha$ is the numerical aperture of the objective, k the wavenumber $(=2\pi/\lambda)$ of the radiation and r the radial coordinate in image space.

For any object other than a single point it is necessary to consider the spatial coherence of the illumination. For the limiting case of coherent illumination the image intensity is:

$$I = |h \otimes t|^2, \qquad (4)$$

where the symbol $\otimes$ denotes notes convolution. For incoherent illumination:

$$I = |h|^2 \otimes |t|^2. \qquad (5)$$

In the confocal microscope with lenses of point spread function h_1 and h_2 the image intensity is given by:

$$I = |(h_1\, h_2) \otimes t|^2, \qquad (6)$$

so that the microscope behaves as a coherent system with an effective point spread function h given by:

$$h = h_1 h_2. \qquad (7)$$

For two equal aberration-free circular objectives the image of a single point is:

$$I(v) = [2J_1\,(v)/v]^4, \qquad (8)$$

the central peak being sharpened up by a factor of 1.4 relative to the conventional microscope, and the strength of the outer rings drastically reduced thereby eliminating optical artifacts.

In an image-forming system a varying object transmittance $t(x)$ (assumed constant in the y direction) can be considered to be made up of spatial frequency components of strength $T(m)$. A coherent imaging system behaves as a filter with transfer function $c(m)$, so that the strength of the component in the resultant image is $c(m)T(m)$. The conventional coherent microscope behaves as a low-pass filter with constant transmission up to the cut-off frequency. In the confocal microscope the cut-off frequency is doubled, resulting in improved resolution. Similarly if we compare the confocal system with a general, partially-coherent, conventional microscope, the maximum frequency present in the confocal image is twice that in a conventional image.

The confocal microscope has a very strong optical sectioning property [47,25]. This is of an entirely different nature from the restricted depth of field in conventional microscopy. The difference is that in a conventional microscope out-of-focus information is blurred and hence confuses the image. In the confocal system the out-of-focus information is actually detected much less strongly. The mechanism is illustrated in Fig.6: light scattered by the specimen in a plane axially displaced from the focal plane is defocused when it reaches the pinhole and hence fails to pass through to the detector.

Consider an object comprising of a perfect reflector normal to the optic axis. It can be shown [48] that the intensity varies with axial position as:

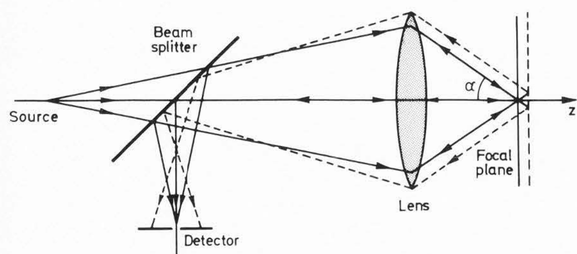


Fig.6. The mechanism of optical sectioning in the confocal mode.

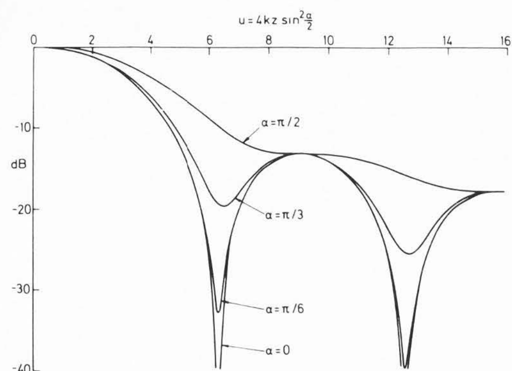


Fig.7. Theoretical intensity variation with defocus of a perfect reflector.

$$I(u) = [(\sin u/2)/(u/2)]^2 \qquad (9)$$

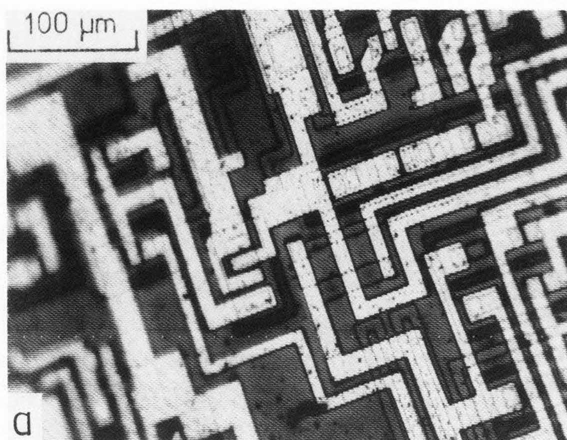
where u is a dimensionless axial optical coordinate ($k = 2\pi/\lambda$)

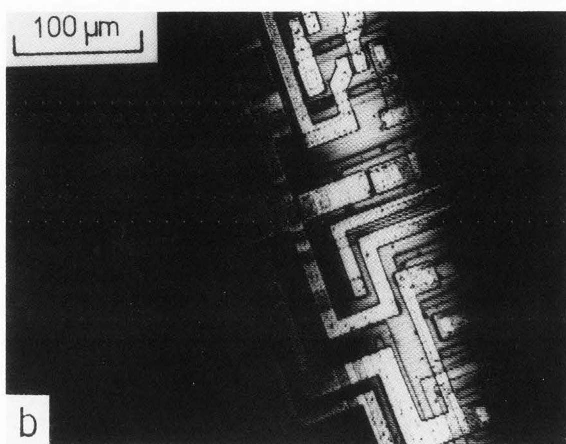
$$u = (4kz \sin^2\alpha/2) \qquad (10)$$

In fact this is only true for a system of low numerical aperture [48], the response for high aperture systems being shown in Fig.7. The response from a plane reflector depends (weakly) on the optical properties of the material [12], and may thus be used to distinguish different materials. Similarly it depends on the presence of aberrations in the optical system.

Fig.8(a) shows a conventional image of a planar microcircuit which was mounted with its normal tilted, in which the out-of-focus parts of the object appear blurred. In the confocal image of Fig.8(b) those parts of the object appear black rather than blurred. Furthermore the confocal image appears to be in focus throughout the width of the visible band, demonstrating that the optical sectioning property is dominant over the depth of focus. This is important, as it means that any detail that is imaged efficiently is in focus. Thus using a confocal microscope a series of image slices through a thick object may be obtained [6].

If the object is scanned axially and the series of axial slices summed an extended focus image, which is a projection of the thick object in a particular direction, is formed. The depth of focus is thus increased as is illustrated in Fig.8(c) [55], whereas if we attempt the same method using a conventional system the out-of-focus information produces a blurred image. The extended focus method results in a depth of focus which is in principle unlimited: in practice depths of





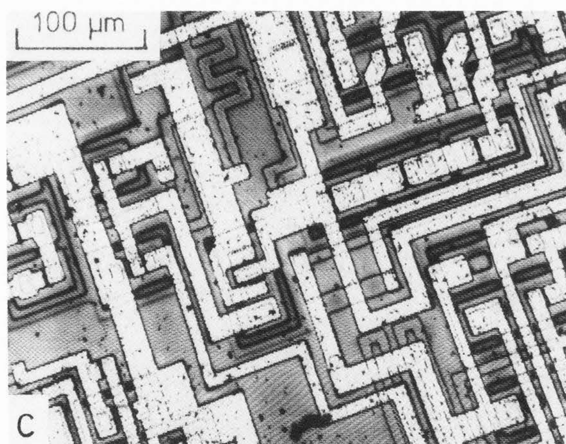


Fig.8. A tilted integrated circuit in reflection; (a) conventional, (b) confocal and (c) extended focus modes.

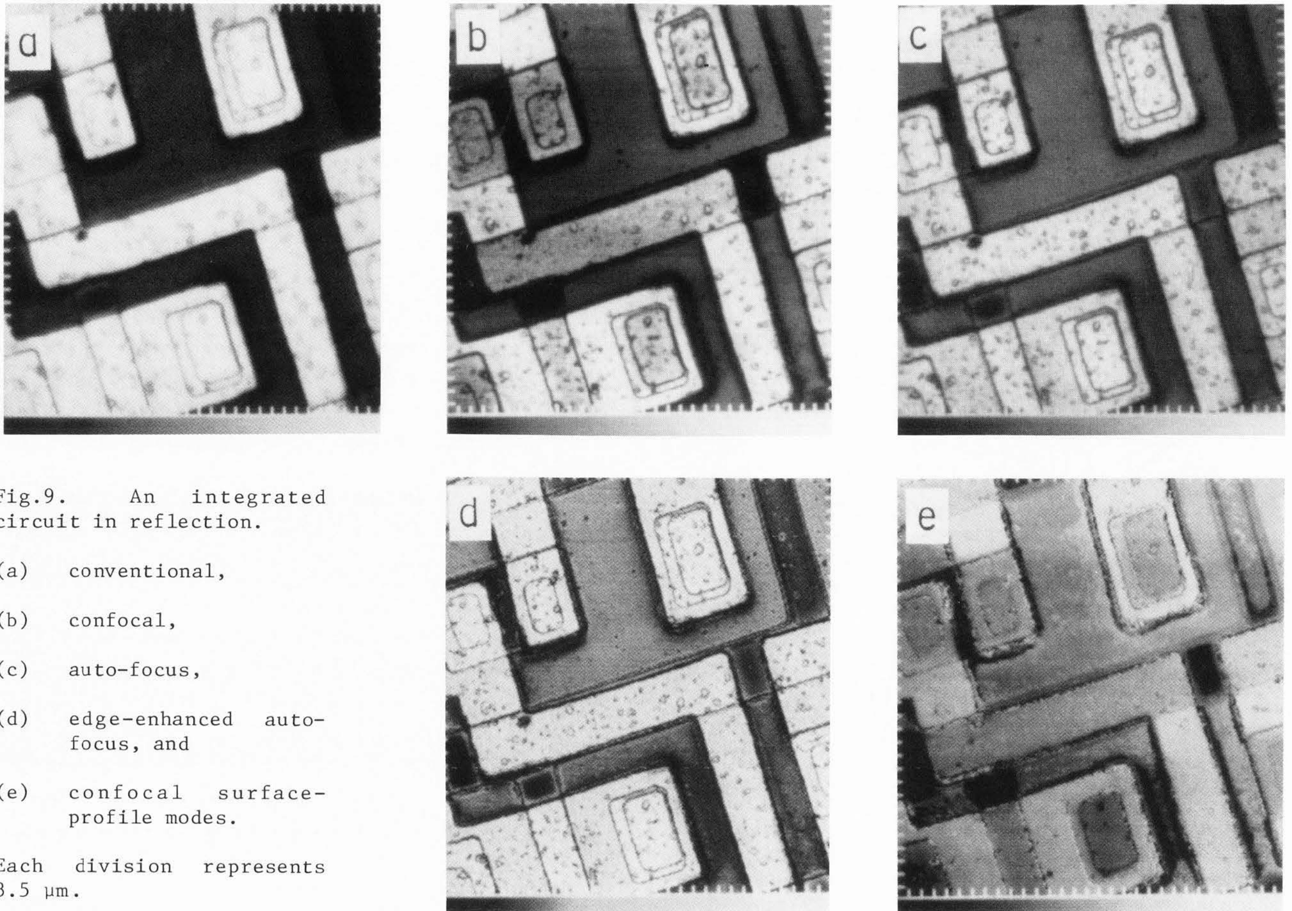


Fig.9. An integrated circuit in reflection.

(a) conventional,

(b) confocal,

(c) auto-focus,

(d) edge-enhanced auto-focus, and

(e) confocal surface-profile modes.

Each division represents 3.5 μm.

field of several hundred microns have been achieved [49]. The integration can be performed very simply in an analog manner by photographic recording [49,55], or by digital techniques.

An alternative method for obtaining increased depth of focus is the confocal auto-focus method [8]. In this, instead of integrating the image signal over axial position, the maximum intensity obtained when the local surface coincides with the focal plane is recorded. Fig.9 shows conventional, confocal and auto-focus images of an integrated circuit. Notice that in the confocal image of Fig.9(b) the metallization varies in brightness as the surface height changes as a result of the optical sectioning property. In the auto-focus image this shading is no longer present as each individual pixel is brought into focus. The auto-focus image may be edge enhanced digitally [9], as is demonstrated in Fig.9(d), the improvement in definition compared with the conventional image of Fig.9(a) being very pronounced. The auto-focus and extended focus methods result in substantially similar images. giving high-resolution diffraction-limited imaging with a depth of focus vastly greater than in a conventional microscope.

If as well as recording the axial maximum in intensity, we record the distance moved from some datum to achieve the maximum intensity, we obtain a measure of the surface height. This confocal profiling method allows non-invasive investigation of surface topography. This can be used to produce one- or two-dimensional plots of surface height with a sensitivity of better than 100nm. The maximum intensity can be determined either using analog [23,24] or digital [8] techniques. Fig.10 shows the surface profile of a metal strip on a microcircuit shown in the form of an isometric plot [24]. The reflectivity of the metal and semiconductor is quite different but does not affect the height measurement substantially. Fringing at the edges of the step is an optical artifact: theoretical calculations suggest this is less pronounced at high numerical apertures. Fig.9(e) shows the surface profile of an integrated circuit recorded digitally and displayed as grey levels: lighter areas represent regions closer to the observer.

The confocal method can be used to investigate the three-dimensional structure of thick objects. Data can be recorded as image slices, three-dimensional images, projections in different directions or as stereoscopic pairs [9]. Such methods are particularly useful for metrology of integrated circuit or multilayer structures.

The sensitivity of the confocal profiling method can be improved by using interference methods [21,20,36]. The object can be

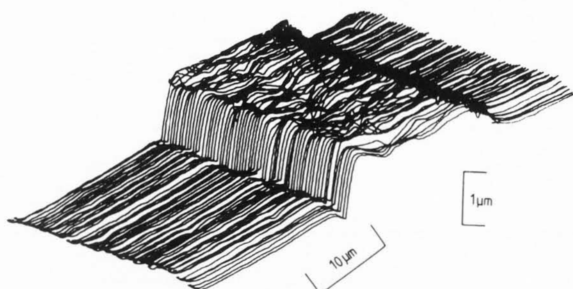


Fig.10. Confocal surface profile of a line of metallization.

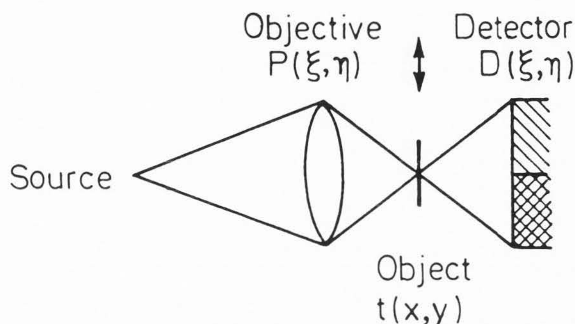


Fig.12. Geometry of the split detector method for differential phase contrast.

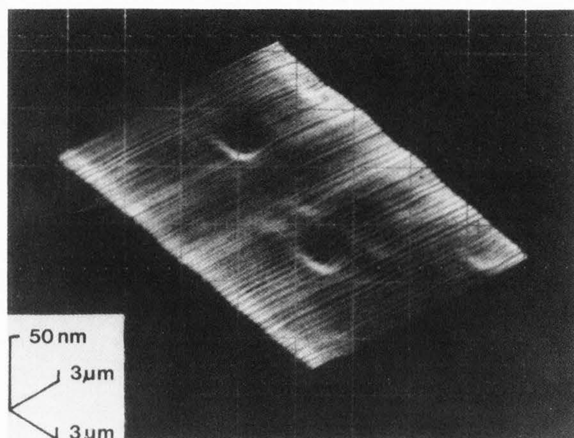


Fig.11. Surface profile of an aluminium film using confocal interferometry.

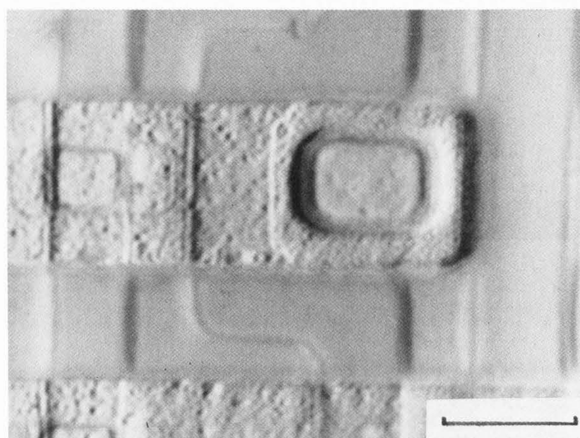


Fig.13. An integrated circuit in the differential phase contrast mode. Bar = 10 μm.

maintained in focus by locking on to a dark fringe, or alternatively the reference beam phase can be changed. Both methods have their own advantages: the former can cope with large height changes, whilst the latter, although it has only a limited range, has a sensitivity of better than 1nm. and high speed. An example of a profile produced using the phase-shifting method is illustrated in Fig.11, which shows the surface of an aluminium film.

Differential phase contrast

In a scanning microscope a detector array can be used to modify the imaging properties. A number of signals can be recorded simultaneously and processed in real time either using analog or digital techniques. The weighting of a detector element can also be made negative. An important example of a detector array is shown in Fig.12, in which the detector is split into two halves along a diameter. In the absence of an object each detector gives an equal signal so that their difference is zero. If an object comprised of a weak phase gradient is inserted the difference signal is proportional to the phase gradient [14,22]. The technique is called differential phase contrast, so that if the object can be represented in terms of the amplitude a and phase ϕ:

$$t = a \exp j\phi \qquad (11)$$

the difference signal is an image of:

$$I = a^2 \partial\phi/\partial x. \qquad (12)$$

In reflection the phase gradient results from a surface slope so that a level surface is imaged as mid-grey, a sloping surface being represented by bright or dark according to the direction in which the surface slopes. Fig.13 shows an image of an integrated circuit produced using this method, which is a convenient way of showing up surface topography. This method has a number of advantages over the Nomarski method [22].

It is apparent from (12) that by dividing an ordinary amplitude contrast image (given by the sum of the signals from the detector halves) the absorption (or reflectivity) cancels out (approximately) to give the phase gradient which can be integrated electronically to produce a pure phase image. Other forms of detector array also have useful properties [26].

Spectroscopic methods

In the scanning microscope there are a whole range of imaging modes in which the focused light produces an effect in the specimen which is monitored to produce an image. The OBIC technique is one example of such a method.

Another of these techniques is fluorescence or luminescence microscopy, in which radiation of a longer wavelength than that of the incident light is detected. One advantage of the scanning geometry for such spectroscopic methods is that the detection system, because it need not image, can have higher wavelength resolution, and greater sensitivity and stray light rejection. There is also an improvement in spatial resolution because the incident, shorter wavelength, radiation is used for imaging. Confocal fluorescence microscopy results in further improvement in spatial resolution and stray light rejection [13,45], and also allows the formation of three-dimensional images of thick objects [7,54].

Fluorescence or luminescence microscopy can give information about spatial variations in excitation states, binding energies, band structure, molecular configuration, structural defects and the concentration of different atomic and molecular species [4,5,27]. Use of a pulsed laser allows the investigation of transient effects such as the lifetime of excited states, capture and emission cross-sections and other time-resolved spectroscopy. Other examples of spectroscopy which can be performed using scanning techniques include absorption spectroscopy, Raman spectroscopy, resonance Raman spectroscopy, coherent anti-Stokes Raman spectroscopy and two-photon fluorescence.

In photoacoustic microscopy a chopped laser beam produces periodic heating of the specimen and the propagation of thermal waves, resulting in imaging of thermal properties and sub-surface imaging [59]. The imaging properties are in general a complicated mixture of the optical, thermal and acoustic effects [10]. Instead of detecting the resultant acoustic radiation, the emitted infra-red radiation can be collected [34], the resultant thermal expansion measured using optical interference methods [1], or a pyroelectric effect observed [19].

Other effects which may be detected include photoelectron imaging [2,3,43], which can show up variations in work function, and photodesorption [30], giving information about surface properties and band structure.

If the energy density in the focused spot is sufficiently high, non-linear optical effects such as harmonic generation [16], generation of sum frequencies, coherent Raman scattering, parametric oscillations and two-photon fluorescence can give information on crystal orientation and perfection, molecular structure and surface properties.

The range of wavelengths which may be used in scanning microscopy is much larger than the visible spectrum. Use of infra-red radiation allows semiconductor materials and devices to be viewed in transmission. Free-carrier absorption gives information on doping and diffusant variations and impurity precipitation [17,50]. Impurity variations can also be observed as a result of the Burstein shift in the band edge with doping level [28]. The variations in absorption also give information on temperature and hotspots in devices [40,41]. Deep-lying impurity levels can be investigated by photoionization microscopy, in which deep-lying impurity levels are ionized resulting in absorption of the beam. The presence of crystal imperfections in III-V materials can also be observed using infra-red polarization microscopy. The infra-red emission of LEDs or laser diodes can also be mapped using scanning microscopy.

Summary

A wide range of alternative imaging modes are available in scanning optical microscopy for study of semiconductor and other electronic materials and devices. In this way various disadvantages of the electron microscope can be avoided. In particular, the confocal imaging mode results in images of improved definition and allows investigation of thick structures in three-dimensions. In addition defects in semiconductors can be studied using the OBIC mode, which can also give data on their electronic properties.

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Discussion with Reviewers

C. Munakata: I have an objection to the word "OBIC". It sounds funny for us in the field of semiconductors because we have already a popular word "photocurrent". Moreover different people use "OBIC" for optical-beam induced conductivity, contrast or current. Therefore I strongly suggest use of "photocurrent" (PC) rather than "OBIC". The term "OBIC" has come from, I think, "EBIC". The reason why "EBIC" is used is that we don't have a popular word analogous to "photocurrent" in the field of electron beams, although some other words have been proposed. In some applications moreover a photovoltage (PV) instead of a photocurrent is observed.

Author: I agree with your objection. My use of the term "OBIC" is because this is now widely used in the literature. Presumably it originated from electron microscopists. Indeed "OBIC" is used misleadingly for optical-beam induced conductivity, whereas the beam does not really alter the conductivity, or contrast, whereas the contrast is not really induced. On the other hand there is not really a fundamental distinction between photocurrent and photovoltage observation. These are just special cases of termination with an arbitrary load resistor. What we really need is a term which encompasses both - perhaps "photoresponse".

Reviewer 3: What are the relative advantages, with references, of (a) photographic reading and (b) digital techniques in handling extended focus images?

Author: There is not much to choose between the two methods. All we are doing in each case is summing a series of sections. The photographic method [47,53] avoids expensive computing hardware, but may be more difficult to get the correct exposure. We routinely use the digital method but results have not been published.

Reviewer 3: Your review covers many technical and scientific contributions, particularly those from your own laboratory. There will undoubtedly be more interest generated from applications papers, so far as the majority of users are concerned. Could you therefore please indicate the following? How many commercial manufacturers of the various types of scanning optical microscope are there? Who are they? What might such an instrument cost? As a function of various degrees of capability? What would it cost to build? What level of expertise would be necessary to do it yourself? What would the DIY CSLM cost? (apart from the pain!) Can you predict the rate of expansion of these methods? Will the production costs rise or fall, and why?

Author: We set up the company Oxford Optoelectronics Ltd which offered the first commercial confocal scanning microscope in 1983. Systems based on the Oxford instrument are now manufactured by Biorad Lasersharp. As with many new techniques (for example SEM) it has been quite slow to develop commercially, but now there are at least seventeen manufacturers of various types of scanning optical microscope. Costs vary from about $50,000 up to maybe $200,000. Major contributions to the cost may be expensive lasers and computing capabilities. The cost of building a system yourself depends very much on what it must do. A low resolution system may not be too difficult to make yourself, but if it is intended to achieve high resolution considerable attention must be paid to the scanning system. The cost of the hardware may be perhaps only a few thousand dollars, to which must be added the cost of the electronics or computer. But in practice it would save a lot of effort to use commercial precision mechanical components, and even more effort to buy a commercial microscope which has benefitted from years of development. It is of course very difficult to predict future sales: 1987 is the first year in which more than a few scanning microscopes have been sold, and sales are now growing extremely rapidly. It seems likely that production costs will fall in the future. Partly this will occur as computing costs reduce, but also as production increases the cost of some components will come down. In particular the cost of the optics may reduce as it becomes viable to use specially designed components.