Optical Microscopy

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Introduction

Moore's Law has driven many circuit features below the resolving capability of optical microscopy. Yet the optical microscope remains a valuable tool in failure analysis. It is easy and gratifying to quickly examine a device under a nearby microscope, but effective use of the microscope requires some mastery of concepts, which we describe here. This author consistently hears requests from semiconductor engineers for resolving finer details, most frequently and incorrectly expressed as a request for more magnification. We will describe the physics governing resolution and we will describe useful techniques for extracting the small details. We will start with the basic microscope column and construction. These basic construction elements are hidden away but still fundamental to the most sophisticated million dollar instruments. We will discuss microscope adjustments, brightfield and darkfield illumination, and microscope concepts important to liquid crystal techniques. We will discuss solid immersion lenses, infrared and ultraviolet microscopy and finish with laser microscopy techniques such as TIVA and XIVA.

Some words about light

The term Optical Microscopy is commonly limited to light that can be manipulated and focused with lenses, i.e., the visible light spectrum, plus the infrared and ultraviolet. We will not address non-photonic microscopy, e.g., electron microscopes, focused ion beams, ultrasonic or atomic force microscopes, none of which use photonic light for image formation. All light propagates through vacuum at approximately $3x10^8$ meters/second and nearly the same speed in air. Light travels more slowly in other materials such as glass or water. Light travels approximately 50% more slowly in glass than in air.

If the air/glass interface is bent or curved a plane wave will strike and slow on one side first and thereby itself be bent and curved, turned and focused, giving rise to the optics industry and microscopy. The ratio of the speed of light in vacuum to the speed in some other medium is important to optics and is known as the index of refraction, given by:



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Figure 1: Typical Lab Microscope showing epi-illumination path.

Index of Refraction N =	Speed of Light in Vacuum	
	Speed of Light in Medium	

Equation 1:

Ultraviolet		0.2 - 0.4
		microns
	Violet	0.4 microns
Visible	Blue	0.45 microns
	Green	0.5 microns
	Yellow	0.56 microns
	Red	0.6 microns
	Near Infrared	0.75~2 microns
Infrared	Short Wave Infrared	~1~3 microns
	Mid Wave (Thermal)	3 - 5 microns
	Infrared	
	Long Wave (Thermal)	8 – 12 microns
	Infrared	

Some commonly used wavelengths of light as follows:

The energy in a photon is related to the wavelength λ is by:

$$E = \frac{hc}{\lambda}$$

where:

E is in $c = 3x10^8$ m/s (speed of light in vacuum) $h = 6.626x10^{-34}$ joules/s (Planck's Constant)

The Microscope Column

A simple compound microscope consists of an objective lens and an eyepiece. The objective creates an image of the



Figure 2:A simple 1920's microscope showing eyepiece, tube, objective, sample stage and illumination source. From Spitta, 3^{rd} edition [1].

sample in the space between the eyepiece and objective. The eyepiece acts exactly like a simple hand lens magnifier, to magnify the intermediate image for the eye. A well designed eyepiece makes the image appear as though coming from an infinite distance so the eye may work in a relaxed state. The lens in the users own eye performs the final focus of the image on the retina. If you remove the eyepiece from a common microscope and invert it so you look through the bottom, it makes a fine hand lens for quickly examining an object.



Adapted from Spitta, 3rd Edition

Figure 3: Schematic view of a simple microscope column showing the intermediate focus. In today's microscopes the intermediate focus occurs just inside the bottom of the eyepiece. The image can be directly examined in a dark room by removing the eyepiece and inserting a bit of lens tissue as a screen, into the eyepiece socket. From Spitta, 3rd edition [op. cit.].

A practical microscope requires an illuminator. The illuminator illustrated in figure 1 is an epi-illuminator, epi meaning 'above' in Latin; so it illuminates from above the sample. In a biological microscope the illuminator typically transilluminates the glass sample slide from below. The microscope in figure 1 is also equipped for transillumination as are the microscopes in figure 4. In figure 1 the epiillumination is coupled into the objective with a beam splitter. A beam splitter is a plane of glass that reflects some fraction of incident light, and passes the rest. Some given portion of the illumination light is reflected into the objective, and some of that will strike and be reflected by the sample. When it returns, a given fraction will pass through the beam splitter to the eyepieces. In figure 1 there is an additional beam splitter in the trinocular head to divert the some of the image light from the eyepieces to the camera.

Microscope Parts and Nomenclature

Reflected/Transmitted Light Microscope Configuration



Figure 4: Cutaway views of microscope showing nomenclature. adapted by permission from www.molecularexpressions.com.

Stereo Microscopes

One effective form of depth perception comes from having each eye view from a slightly different angle causing image shift or parallax to each eye. The stereomicroscope creates parallax by actually offering two microscopes in a common housing, one for each eye, each seeing the sample from a different angle. For compactness the left and right eye microscope often share portions of the final lens as shown in the CMO design in figure 5.



Figure 5: Two stereo microscope designs with erecting prisms. In the CMO design each eye has a distinct microscope path but they share portions of the objective. Adapted by permission from www.molecularexpressions.com.

Today most high magnification microscopes such as those in figure 4 offer two eyepieces, but not for depth perception, rather for the viewing comfort of the user. Many things cue the brain to see depth, but true stereomicroscopes offer depth perception by having separated optical paths for each eye. Nonetheless there are some situations possible with conventional microscopes like those in figure 4 to see true parallax depth perception. The situations arise when the user has improperly adjusted the interpupillary distance between binocular eyepieces. Then each eye will see a slightly different view and the brain will detect some depth perception.

Microscope Objectives

Expensive high magnification objectives have a great many lenses contained within to perfect the image. For any given manufacturer all objectives are deliberately designed so the back focus will fall at a given distance, usually 160 mm to 200 mm. This is done so every lens will remain at the correct distance from the camera and eyepieces when the nosepiece is rotated. Substituting a different manufacturer's lens into a microscope may not work well if the back focal lengths are different. The back focal length is often simply known as the tube length, for the length of tube required to separate the objective from the eyepiece.



Figure 6: The complexity of a lens may be seen from this 100x Objective from a US Patent roughly superimposed within a common lens housing. [2]

the field (sample) is parallel in the infinity space. Accessories such as beam splitters go into the infinity space area.

Newer microscopes are equipped with infinity corrected objectives. These objectives project the light in collimated or parallel rays, as though they are coming from infinitely far away. The final focusing is left to a separate lens called a tube lens. A single tube lens can serve all of the objectives in the nosepiece and is often embedded in the head that houses the eyepieces. The collimated or parallel ray space between the infinity lens and the tube lens is optically ideal for inserting options such as beam splitters or filters. Infinity corrected objectives perform better and more flexibly than direct focusing objectives. Infinity corrected objectives must be paired with the correct tube lens. The will not have the correct magnification (stamped on the lens) if they are paired with a tube lens of incorrect focal length. Infinity corrected lenses cannot be interchanged with fixed focal length lenses.

Key Concept: Numerical Aperture

Numerical Aperture (N.A.) is the single most important figure of merit in microscopy. The numerical aperature or N.A. of a lens governs ultimate resolution, image brightness, depth of focus, working distance and ultimately the price of the lens; lenses with higher N.A.'s are more expensive. It is a common misconception among microscope users that with a little more magnification they can resolve finer features. It isn't true, magnification has a secondary effect on resolution but numerical aperture determines the limit to resolution.



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Figure 7: This schematic shows how an infinity corrected lens works. Note that on the left, the light from any specific point of



Figure 8: A high N.A. has a short working distance and wide cone angle. A low NA has a long working distance and narrow cone angle. High N.A.'s offer the best resolution.

Most high quality objective have their numerical aperture value stamped on the side of the lens. N.A. can be thought of as the collection cone of the objective. Large collection angles correlate to large N.A. values, finest resolution and greatest light and signal collection. N.A. is mathematically defined as:

Numerical Aperture N.A. = $N \sin \theta$

Equation 2: Numerical Aperture where: N = index of refraction (between the lens and the sample) $\theta = the half$ angle of the acceptance cone of the lens

N.A. approaches a limit as the collecting half angle approaches 90°. In air where the refractive index is 1, the maximum N.A. is limited to 1 and in practice rarely exceeds 0.95. A lens with N.A.=0.95 will have an exceedingly short working distance, often impractical for failure analysis. Some lenses are designed for immersion in water or oil and in these cases the N.A. becomes 1.2 or 1.4 respectively.

Well made objectives of 50x magnification or greater are usually designed to be diffraction limited, meaning that the wavelength of the light and the collecting cone of the objective lens govern resolution. How does the diffraction limit work? When light from a point source passes through a circular aperture and is then focused, it spreads with a characteristic pattern as seen in figure 9, due to light bending around the edges of the aperture.



Figure 9: Illumination from a point source spreads at the focus due to diffraction. The spread is least for large N.A. This ultimately limits resolution. On film a well exposed Airy Disk would appear as in the upper right.

Diffraction is derivable from the Heisenberg Uncertainty principle (beyond our scope here) but suffice it to say that the smaller the aperture, the larger the diffraction spread and hence the larger the Airy disk. This means that a point source will always be imaged larger than a point, so diffraction effects ultimately limit the sharpness of an image. A large N.A. minimizes diffraction effects, so it pays to buy good lenses with large N.A.'s. The diameter of the Airy disk is proportional to the wavelength, and inversely proportional to the NA.



Rayleigh Resolved

Sparrow Resolved

Figure 10: Point sources just resolved by Rayleigh and Sparrow Criteria.

A simple, effective measure of resolution is the Sparrow Criteria, given as the just resolvable separation between two point sources as shown in figure 10. The relation between the Sparrow Criteria and the somewhat better known Rayleigh Criteria is also shown.

Rayleigh Criteria

Sparrow Criteria

$$D = \frac{0.61\lambda}{N.A.} \qquad D = \frac{0.5}{N.A}$$

Equation 3: Rayleigh & Sparrow Criteria give minimum separation of point sources to be resolved.

The Sparrow Criteria is defined as D=0.5*lambda/N.A., where D is the distance between the points, lambda is the wavelength and N.A. is the numerical aperture. Mid-visible, green light, is about $\frac{1}{2}$ micron wavelength and for an air immersed lens the NA is limited to 1, so using the Sparrow Criteria, typical FA lab microscopes working in air must be limited to, at best, about $\frac{1}{4}$ micron resolution. More commonly in FA microscopes, the N.A. is traded for increased working distance so the user can place micro-probes between the lens and the circuit. In that case the N.A. is more commonly limited to about 0.5 and the Sparrow resolution is about $\frac{1}{2}$ micron. There

are many merit figures for resolution, but it is substantially correct to say that the Sparrow Resolution is the maximum resolution of a lens. Note that magnification is NOT the limiting factor in resolution.

Role of Magnification on Resolution

Magnification doesn't limit resolution, at least not directly, numerical aperture does. But we know that if we increase magnification we can see smaller details. Magnification is actually about matching the resolution element to the detector, whether eve or camera. Imagine an objective with N.A. appropriate for our resolution task but with no magnification (1x). Then neither our eye nor a camera will be able to resolve the fine detail. The human eve has a resolution limit. often given at 1 minute of arc depending on age and individuals. That corresponds to about 76 microns at a comfortable viewing distance of 250 mm. Likewise cameras have a resolution limit imposed by distance between pixels, known as the pixel pitch, ranging from around 6 microns to 50 microns. The job of magnification is to make the image large enough so the resolved element can be seen by at least 2 or 3 detector elements, be they camera pixels or cones in the human eye.

For example, consider a pair of objects resolved per the Sparrow criteria at ¹/₄ micron separation. The job of magnification is to enlarge that just resolved dimension so that it fills two eye resolution elements.

$$M = \frac{eye_resolution}{Sparrow_resolution}$$

Where M is the required magnification. For our example:

$$M = \frac{2 (76 \text{ microns})}{0.25 \text{ microns}} \sim 600 \text{x}$$

In this example we need about 600x magnification to just resolve the objects with our eye. 600x is readily achieved with a 60x objective and a 10x eyepiece. It is common to use a 100x objective and 10x eyepiece for a total magnification of 1000x to make the job of the eye a little easier, particularly for those of us who are older. If the eyepiece is removed and replaced with a camera with a 12-micron pixel pitch, the required magnification is:

$$M = \frac{2 (12 \text{ microns})}{0.25 \text{ microns}} \sim 100 \text{x}$$

There is a minimum magnification that is appropriate to the

N.A. of the objective. Any magnification above the minimum is known as 'empty magnification' because it doesn't improve the resolution of the instrument, it renders the blurred detail a little larger, but not less blurred. It is customary to exceed this magnification a bit to make the job of the user easier, but it is pointless and we will show that it is deleterious to exceed the required magnification by too much.

Magnification & Pixel Pitch for UV or IR Applications

The Sparrow Criteria may be used effectively to choose appropriate magnifications and camera pixel pitch for ultraviolet and infrared applications. For example, consider a hypothetical air immersed microscope objective working at 200 nm in the deep ultraviolet. Assuming the numerical aperture is at the theoretical limit of N.A.=1, and the desired camera has 6 micron pixel spacing, what should the objective magnification be? From the Sparrow Criteria:

$$D = \frac{0.5 \text{ (.200 microns)}}{\text{NA:1}} = 0.100 \text{ microns}$$

Sparrow Criteria for Deep UV example

and using this result to compute the required magnification:

$$M = \frac{2 (6 \text{ microns})}{0.100 \text{ microns}} \sim 120 \text{x}$$

For this deep UV example it can be seen that a 100x lens just will not be enough.

For an infrared example, the author has used a thermal infrared microscope working at 3 microns wavelength to measure junction temperatures. The infrared detector pixels were spaced 24 microns apart and the objective had an N.A. of 0.5 to allow ample working distance to microprobe the circuits. The Sparrow Resolution in this case will be [0.5*3 microns / 0.5 = 3 microns]. So for this infrared example the limiting resolution is 3 microns. Applying the magnification formula, [2*24microns / 3 microns = 16x]. We can see from these two examples that microscope magnification must be increased for short UV wavelengths, but may be decreased for longer infrared wavelengths.

Downside to Excess Magnification

Most of us have noticed that microscopes used at high magnification must be protected from vibration or shock. Any lateral vibration that is present will also be magnified by the objective so that activity on the lab bench supporting the microscope can appear as an earthquake in the eyepieces. If the user increases the magnification beyond the useful resolution of the objective, the image will not become any clearer but any ambient shock or vibration will be magnified perfectly, possibly rendering the instrument useless. A very common example is when a microscope is coupled to a functional test head. Without mitigation, the fans in the test head will badly blur images from the high magnification lenses. In a later section we will also show that the throughput or signal at the camera plane is inversely proportional to the magnification squared. That is why the user must commonly increase the illumination when they switch to higher magnifications. A 100x objective tends to just match or exceed the capabilities of current tungsten halogen bulbs to illuminate the specimen. So loss of illumination is yet another penalty for excess magnification.

Field and Aperture Planes

A field plane is a location anywhere in the microscope where a focused image is located, whether virtual or real. The specimen plane, the camera focal plane and the retina of the eye are all field planes. There is also a field plane inside the tube at the focus of the eyepiece. There are additional field planes in the illumination path. These field planes are copies of one another, excepting in the illumination path, and are said to be joined or "conjugates". Some field planes are special, e.g., the eyepiece field plane is an excellent location for a cross hair reticle, since it will be in focus and superimposed on the sample image. One of the field planes in the illuminator often has a 'field diaphragm' so the user can adjust the size of the illuminated spot to match the field of the lens. When a field Diaphragm is adjusted the user can see the field of view shrink or grow, usually with the edges of the diaphragm vanes clearly visible.



Conjugate Planes in the Incident Light Optical System

Figure 11: Locations of Field (image) and Aperture Planes in an epi-illuminated microscope are designated with images of a specimen or lamp filament respectively. Used by permission from www.molecularexpressions.com.

There is another set of conjugate planes in a microscope known as aperture planes. The aperture planes limit the cone angle of light and occur at the iris of the eye, the back of the objective, the illuminator diaphragm and often at the lamp filament. The illuminator filament doesn't affect the cone angle but it is deliberately placed at an aperture plane to facilitate Koehler Illumination. Any object located at a field plane is imaged in sharp focus at the other field planes. Less obvious but likewise true, any object located at an aperture plane is imaged in sharp focus at the other aperture planes. Objects in focus in one set of planes are perfectly defocused, actually collimated, at the other set of planes. To illustrate, if you could somehow place a bit of paper at the back of the objective you would see a sharp image of the bulb filament. (If the microscope is the type with a ground glass diffuser, then an image of the diffuser will be there instead.) There is another sharp image of the lamp filament just at the iris of the user's eye but the filament is perfectly diffuse and unfocused at the retina. Likewise in the set of conjugate field planes there is a sharp image of the retina of your eye formed at focus of the evepiece and at the specimen. In the design and use of microscopes these conjugate planes come into play in various surprising ways. For example there is a Fourier Transform of the specimen at the back of the objective and unusual and powerful filtering tricks can be applied there in microscopes that allow access to that point. In the next section on Koehler Illumination, we show how to make the filament perfectly diffused and uniform at the specimen plane by deliberately focusing it in the aperture plane.

Illumination – Koehler Illumination

In 1893 Professor August Koehler published his brilliant technique for microscope illumination, now almost universally fielded on top quality microscopes. Koehler's technique requires that the filament be focused perfectly in the aperture planes, so that it will be perfectly collimated and therefore very diffuse and very uniform at the specimen plane. There are several adjustments on a top quality microscope for setting up Koehler illumination. In a multi-user environment these are often badly adjusted. Poor Koehler adjustment leads to reduced resolution, uneven illumination and diffraction artifacts, it is worth learning how to adjust the illumination. For an epi-illuminated system, the most important aperture adjustment is the field diaphragm located closest to the microscope body. When first adjusting the microscope and after each lens change, the user should adjust the field diaphragm so the vanes just barely disappear from the field of view. If the field diaphragm is opened too far, light spills uselessly inside the microscope tube and creates a veiling glare that reduces contrast and makes viewing difficult.

The aperture diaphragm (if equipped) controls the cone angle of the illumination light. It should typically be left wide open for epi-illumination. In principle, restricting the aperture diaphragm can lead to reduced resolution but the highly reflective surfaces of circuits tend to mitigate the effect. Nevertheless, it is prudent to leave the aperture diaphragm wide open.

In biological microscopes the illumination usually comes from below, to transilluminate the glass specimen slide. This requires a separate condenser below the sample stage that must be adjusted up and down on a stage to suit each objective lens. A good (expensive) substage condenser will also have a field and aperture diaphragm. For transillumination the adjustment of the aperture diaphragm is critical for achieving high performance. It should be opened wide for the high N.A. lenses (the high magnification lenses), to match the illumination cone to the lens N.A. cone. Failure to do so directly sacrifices the resolving capability of the high N.A. lens. This is easily demonstrated with biological microscopes and in theory it is true as well for the epi-illuminated microscopes in our failure analysis labs. However in practice the author finds that scattering due to reflection from epiilluminated samples often seems to compensate for badly adjusted (or missing) aperture diaphragms. As with the field diaphragm, an opening too large may causes excess light to spill in the microscope tube, creating glare and reducing contrast. Some microscopes permit and therefore require adjustment of the filament position. If there is no ground glass an image of the filament can be seen by removing the eyepiece and looking down into the barrel. This is difficult without a special tool called a Bertrand Lens. The image will be too bright and too small. Nevertheless the filament should be centered and focused in the tube.



Figure 12: Adjust the field diaphragm at each change of magnification so the vanes just disappear outside the illuminated field. Adjust the aperture diaphragm (if equipped) wider for high N.A lenses, and narrower for low N.A. lenses to optimize resolution and contrast.

Adjusting Binocular Eyepieces

Binocular eyepieces commonly provide two adjustments, and remarkably, casual users have difficulty with these. The first of these adjusts the interpupillary distance. Typically the user need only push or pull the eyepieces closer together or further apart until they are comfortably spaced. On some poorly designed microscopes this adjustment will change the distance from eyepiece to the objective, requiring some refocus.

A binocular head also provides a separate focus adjustment for each eye, since few of us have the same requirement for each eye. The adjustment is usually a ring surrounding the eyepiece that rotates, slightly raising or lowering that specific lens. In some cases only one lens is adjustable, for which case the eye without adjustment uses the main focus adjustment on the body of the microscope. To adjust, close the eye over the adjustable eyepiece and using the other eye, focus the microscope normally with the general focus knob. Then close this eye, and open the one over the adjusting ring. Then with the adjusting ring, focus for the remaining eye. If both eyepieces are adjustable adjust one eyepiece midway between the stops, to the mid-adjustment position and then treat it as though it has a fixed focus, performing the adjustments with only the other eyepiece.

Lens Aberrations / Correction for Backside Imaging through Si

The Airy disk and Sparrow criteria indicate the diffraction limit to resolution, based on the behavior of light when constrained by a finite aperture. Well-designed and typically expensive lenses will preserve the diffraction limit. Lesser microscopes may exhibit some of the following typical aberrations which will degrade the resolution to less than the diffraction limit.

Field Flatness

A simple lens naturally focuses an image to a curved surface and a correction must be applied to make the image suitably flat for CCDs or film. Inexpensive objectives are not corrected for field flatness and should be avoided for failure analysis. If the user notices that she can focus the center, or the edges of the field, but not both at the same time, that lens lacks field flatness. Better objectives with field flattening are usually designated so with the prefix 'plan', e.g., 'plan apochromat'.



Figure 13: A simple lens naturally focuses light to a curved surface. If the detector is flat, e.g., a camera, this results in poor focus at the corners and edges of the image. A 'Plan' type objective is corrected to project a flat image.

Chromatic Aberration

The index of refraction of glass varies slightly with the wavelength. That is why the classic equilateral prism can disperse light into a rainbow; each wavelength is bent by a differing degree. That creates a natural problem for imaging optics. Chromatic aberration occurs because a simple lens is unable to bring light of all colors to a common focus.



Figure 14: Chromatic Aberration blurs the image by causing light of different wavelength or color to focus at different locations.

Fortunately it can be corrected by a careful optical design, by pairing lenses with slightly differing dispersion. A greater degree of correction usually costs more, so the industry has created a labeling system, often stamped on the lenses, to identify the quality of correction. The most common designations are listed in the nearby table. The author suggests that for the high resolutions required for failure analysis work, the user should always insist on the plan-apochromat type lenses.



Figure 15: Simple achromat doublet corrects chromatic aberration by pairing lens powers and shapes so that each cancels the aberration of the other. Similar techniques are used to correct all aberrations.

Common Microscope Lens Descriptors			
Achromat	Least expensive and common in dental and physician offices and modest labs, they are corrected for 2 wavelengths, red and blue, slightly out of focus for green and other colors.		
Fluorite or semi- apochromat	Corrected for 3 wavelengths, sometimes corrected for flatness.		
Apochromat	Corrected for 4 or more wavelengths, effectively eliminating chromatic aberration.		
Plan Apochromat	Corrected for 4 or more wavelengths and corrected for field flatness. This is an expensive, superior lens and the only type that should be employed for high-resolution failure analysis.		

Coma, Astigmatism & Distortion

Coma is an unwanted variation of magnification related to where in the aperture the light enters. It causes a point source to look like a comet with a pointed tail. Astigmatism occurs when a lens has more focusing power in one direction, e.g., the horizontal, than another. Astigmatism correction often involves adding the equivalent of a cylindrical lens, which has focusing power in one direction only. Distortion is seen as pincushioning or barrel distortion where objects become misshapen at different parts of the field of view. Elimination of these aberrations and others require extra optical design effort and additional lenses in the interior of the objective, and additional manufacturing care. Higher quality, more expensive lenses make sharper images for a good reason.

Spherical Aberration & Backside Imaging through Silicon

Spherical aberration has special interest for Failure Analysis because it affects imaging through the backside of silicon. Spherical aberration causes energy from a point source to spread into a surrounding halo. Spherical aberration is from rays entering the edges of the aperture, which focus at a greater distance than rays entering the central part of the aperture.



Figure 16: Sperical aberation blurs the image by causing rays entering the lens off center to focus away from the paraxial focus.

A skilled optical designer can correct spherical aberration provided he controls all the refractive media. However when inspecting circuits from the backside of the wafer, the intervening silicon becomes part of the optical path. The silicon introduces spherical aberration whose severity depends on the thickness of the silicon and the numerical aperture of the examining lens. The aberration can be corrected provided the silicon thickness is known, or sometimes the correction is user adjustable. Biological microscopes have long faced this issue since the biologist places a cover-slip of glass on his slide to keep his specimen from drying out. High N.A. biological objectives are often designed with a correcting ring. The user can dial in the required compensation for the thickness of the cover-slip. If the failure analyst is performing a backside inspection with a high numerical aperture objective, the image will be degraded unless the lens is corrected for the intervening silicon.

Immersion and Solid Immersion Lenses (SILs)

Equation 2 shows that the numerical aperture increases directly with the index of the medium between the lens and the sample. Since the best available resolution depends on numerical aperture we can improve resolution considerably by employing an objective that is designed to be immersed in a high index medium. Biologists have long used water or oil immersion lenses to get a 20% or 40% improvement in resolution, respectively.



Figure 17: Specially designed fluid immersion lenses improve resolution by up to 40% over air immersed lens. The index of the immersion medium must match that of the 1^{st} lens.

Immersing a circuit in oil or water is usually undesirable and commercial oil or water immersion lenses are poorly corrected for looking through silicon; the author's experiments with them have been disappointing. However workers at Boston University [3] and others have revisited a technique known as solid immersion in which a portion of a hemispherical silicon lens is placed in intimate contact with the back surface of the wafer. Solid immersion lenses have long been used for making detectors; Warren Smith described the technique in 1966 in his text Modern Optical Engineering [4]. Now they are being applied effectively to failure analysis.



Figure 18: Solid Immersion Lens (SIL) in optical contact with the wafer gives a huge benefit in resolution for backside inspection. Note the hemisphere continues virtually, but not actually into the wafer.

Since the index of silicon is 3.5, the minimum resolution from the Sparrow Criteria (eq. 3) is

$$D = \frac{(0.5)(1.0)}{3.5}$$

$SIL_resolution = 143nm$

where we use 1 micron, the shortest wavelength that will pass through silicon, and we assume that the NA half angle is operating at 90 degrees, the theoretical maximum. In this case the Sparrow Criteria yields 143 nanometers minimum resolution. The high refractive index of the silicon pays off, yielding resolution considerably better than that available from air immersed lenses viewing from the front side. More realistically, we should plan on a maximum practical half angle of 72 degrees instead of 90 degrees, and a wavelength minimum of 1.1 microns. This still results in a Sparrow Criteria minimum of 165 nanometers, which is very respectable.

For the SIL technique to work, both the contacting lens and the wafer must be smooth and flat with no air gaps. Any air gaps of wavelength dimension will degrade the resolution from the theoretical. Few papers, perhaps none, have reported achievement of theoretical resolution for contacting SIL lenses. But nevertheless they have reported excellent resolution. From Smith, the SIL lens must have a hemispherical shape and must have a specific radius matched to the thickness of the wafer. This satisfies an optical condition, known as aplanatic, that eliminates spherical, coma and astigmatism aberrations. Smith gives the aplanatic condition as:

$$L = R \left(1 + \frac{1}{N} \right)$$

Where

L = the distance from the top of the SIL to the focus at the far side of the wafer.

R = the radius of curvature of the SIL lens.

N = the index of refraction of the SIL & wafer (N=3.5).

This constrains the SIL such that the SIL radius, height and diameter at contact all depend on the wafer thickness. Some example values are given here:

SIL Dimensions For θ = 72° and N = 3.5 (See figure 18 for definitions)

T um	D um	H um	R um
50	308	148	154
100	616	296	308
200	1231	592	616
300	1847	888	924
400	2462	1184	1232

500	3078	1480	1540
600	3693	1776	1848

The light emerging from the SIL must be collected by another lens in the turret. Workers using SILs report using common objective lenses for this. Note that since the SIL resolution is very small, the overall magnification of the SIL together with the collecting objective must be large or the camera pixels will be found too coarse to preserve the newly obtained resolution. The magnification should be about 150x to 200x depending on the CCD pixel pitch. The increased magnification will make the microscope much more sensitive to vibration, requiring more care with vibration isolation.

SIL focusing and navigating may be difficult. In normal microscope usage, the worker starts with a low magnification lens which is easy to focus and easy to find the area of interest. Then the worker progresses through greater magnification, at each lens improving the centering and focus. When the solid immersion lens is finally employed it must be placed, probably by hand, and the contact must be so good that it adheres or nearly adheres to the wafer, which requires a bit of fussing. Most likely the microscope must be lifted to perform this task, therefore the SIL cannot be automatically par-centered to the other lenses. Moreover, the field of view is very small because of the great magnification. So the user must hunt for the area of interest, all the while tapping or pushing the immersion lens to center it. Despite these difficulties, solid immersion lenses offer very improved resolution.

In a new SIL development, Koyama, et. al., from Renesas Technology [5] have machined a SIL lens directly into the backside of the silicon wafer. This has a huge advantage of insuring a continuous high index medium between the focus and the top of the SIL. Any air gap approaching a wavelength in dimension in the "placed" SIL will spoil the immersion effect, but the Koyama technique creates a continuous SIL interface directly in the wafer. The authors named this type of SIL "FOSSIL" for "Forming Substrate into Solid Immersion Lens". The Fossil technique has several interesting constraints:

- 1. The defect must first be located by other lower resolution techniques so the FOSSIL can be subsequently machined directly over the fault.
- 2. The machining process must be precise enough make an acceptable optical surface with spherical figure good to a fraction of a wavelength.
- 3. The aplanatic condition must be met with the material remaining in the wafer, which restricts the size of the FOSSIL lens.

When these conditions are met, the authors report enhanced throughput (NA^2/M^2) and the ability to resolve failures in or within single transistors.



Figure 19: Machining a FOSSIL type Solid Immersion Lens directly into the back surface of the wafer makes the optical contact perfect and creates the best possible SIL conditions.



Figure 20: Close up of FOSSIL type machined in place lens showing aplanatic conditions for the following table. In this case R must be chosen to satisfy:

$$T \ge R + \frac{R}{N}$$

Some machined in place (FOSSIL) solid lens values vs. wafer thickness for $\theta = 72^{\circ}$:

Thickness	Radius	R Diameter	Cut Depth
T um	um	(2X) um	C um
50	39	78	37
100	78	155	75
150	117	233	112
200	156	311	149
250	194	389	187
300	233	466	224
350	272	544	262
400	311	622	299
450	350	699	336
500	389	777	374
550	428	855	411
600	467	933	448

Brightfield / Darkfield

In brightfield microscopy, illumination light is introduced coaxially with the imaging path. This is accomplished with a

beam splitter, just above the objective. This causes the field of view to appear bright, hence the name. Objects of interest at the focus tend to reflect light out of the field of view, so that they appear dark in a bright field.



Figure 21: The left image of crystal defects is darkfield illuminated, the right image is brightfield. Light scattering objects show up well against the dark background.



Figure 22: In darkfield, objects illuminated from outside the field reflect light into the field of view, appearing bright against a dark field. In brightfield the field is illuminated, and objects tend to reflect light out of the field, and so appear dark.

In darkfield the specimen plane is illuminated from light outside the numerical aperture cone of the objective. It will not enter the objective unless diverted by feature of interest, so the field appears dark and areas of interest appear brightly contrasted. The contrast effects are quite different and a feature can appear quite different by each method. A very rough surface may appear dark in brightfield illumination, since it reflects light away from the collecting NA of the objective. Thus a rough surface could be mistaken for a absorbing material or circuit contaminate. Brightfield illumination requires a beam splitter (figure 12) or it requires a condenser if illuminating from below the specimen. Darkfield illumination can be introduced with a fiber illuminator or other bright source aimed right at the working distance between the sample and objective. Many top grade emission microscopes have a darkfield ring illuminator on the macro lens. The working distance for most high magnification objectives is too close, and the light requirement too great to introduce

darkfield light so casually. There are commercial darkfield objectives that deliver illumination from a surrounding housing reflected into the field from mirrors surrounding the final lens.

Polarized Light Microscopy and Liquid Crystal Hot Spot Detection

Most forms of natural and artificial illumination produce light waves whose electric field vectors vibrate in all perpendicular planes with respect to the direction of propagation. The electric field vectors may be restricted to a single plane with a filter. In that case the light is *polarized* with respect to the direction of propagation and all waves vibrate in the same plane. Polarized light microscopy employs 2 polarizing filters. The first, called a polarizer is placed inline near the illuminator. The second polarizing filter is materially identical to the first but is known as the analyzer. It is placed between the objective and the detector (human eye or camera). The analyzer (and sometimes the polarizer) may be rotated. Each filter blocks any light not polarized parallel to the axis of that filter. If the axes are arranged to be orthogonal, then all the light will be extinguished.

Polarization of Light Waves



Figure 23: Crossed polarizers extinguish light vectors not parallel to the axis of the polarizer. Used by persmission from www.molecularexpressions.com.

Polarization techniques are effective for investigating materials that have properties that change the polarization of light. One such technique is liquid crystal detection of short circuits or other hot spots. The technique exploits a characteristic phase change in the liquid crystal solution. The phase change occurs at a known temperature, characteristic of the particular liquid crystal solution. Below the phase change temperature, the nematic phase, the liquid crystal changes incident light polarization. Above the characteristic temperature the liquid crystal loses this property. When placed between crossed polarizers, the circuit will be visible in the nematic phase, but gray or black above the characteristic temperature. The trick is to adjust the circuit temperature with a thermal stage while looking for the hot spot as the crystals in that area change phase. The technique is effective and relatively inexpensive. Unfortunately it requires contact with

the heat-generating defect, so it is quite ineffective for backside inspection. Some labs are prohibiting the use of liquid crystal because the solvent, usually methylene chloride, may have properties harmful to humans.

UV Microscopy

The physics of microscopy favors short wavelengths for the most detailed resolution. Several commercial firms have offered deep ultra-violet microscopes with wavelengths as short as 200 nm. Below about 180 nm there is significant interaction between air and the UV photons, so vacuum must be employed between the objective and sample. There are significant technical difficulties with deep UV microscopy. There are not many glasses that can be used in the objectives. and UV photons are so energetic that some of these glasses and related cements are damaged with protracted UV use. The light sources are expensive and have short lifetime issues. Cameras for UV microscopy must be prepared by removing or replacing the protective glass window in front of the CCD, as the UV will not penetrate this faceplate. The author has heard a report that the deep UV wavelengths do not penetrate some semiconductor oxides. It is restricted to front side inspection since UV wavelengths do not penetrate silicon. UV wavelengths haven't made much headway in back end inspection. Nevertheless UV has been employed with great advantage for photolithography and simple calculation shows remarkable diffraction resolution, e.g., 100 nm at 200nm wavelength. We may vet see more UV in reliability and FA applications in the future.

Infrared Microscopy

For some FA labs, increasing numbers of metal layers and flip-chip packaging techniques are making front side circuit inspection impractical. However, silicon is transparent at infrared wavelengths longer than 1.1 microns so with infrared techniques, it is possible to examine the circuits from the back of the die or wafer. This has given rise to several infrared techniques for fault location and failure analysis. We use midwave infrared microscopes, from 2 to 4 microns to detect thermal infrared radiation, to locate short circuits by their joule heating. With careful calibration we can even measure junction temperatures from the front or back of the die. We use short wave infrared, from 1 to 1.6 microns, to detect recombination photoemission sites that indicate a variety of failures. We use a special form of a laser-scanning microscope, equipped with 1.34-micron wavelength lasers to generate micro-local heating from the backside. This is known variously as TIVA, OBIRCH or XIVA fault detection techniques. If an infrared laser much closer in wavelength to the silicon bandgap is employed, such as 1.064 microns, it can generate photo-carriers at micro-locations. That enables OBIC, LIVA and PC-XIVA techniques for locating faults from the backside.



Figure 24: Undoped silicon transmits infrared well.

Silicon Transmission & Surface Reflection

The plot for undoped silicon shows the transmission rising at about 1 micron wavelength, and rises to and stays about 54% to the end of the plot. The transmission is actually quite good to about 9 microns wavelength where there is an oxygen absorption dip, and it persists to longer wavelengths. Silicon is commonly used for lens material for 3 - 5 micron military night vision application. Silicon's very high index of refraction causes light to travel 3.5 times more slowly in silicon than in air. That causes an impedance mismatch at the silicon air interface that generates a vigorous reflection. The maximum transmission in the graph is limited by reflections at the surface. With proper anti-reflective coatings it has a transmission of 98% or higher. The failure analyst can improve their backside microscopy results by applying an anti-reflection coating but high performance vapor-deposited anti-reflection coatings are not trivial and are outside the scope of this tutorial. There are some commercial spin-on coatings that provide some benefit. Likewise, in a pinch you can apply a drop of extra virgin olive oil for some relief from reflection, and also as a quick and dirty means of smoothing a rough or poorly prepared silicon surface.

Doped Silicon Backside Thinning

Heavily doped silicon is much less transparent than undoped silicon because of band-gap shifts and because of free carrier absorption and scattering. Following absorbtion measurements by Aw, et. al. [6], Aaron Falk [7] gives empirical methods for calculating absorption and required thinning for doped silicon. Using his formulas, the following figures show calculated optical transmission for a 600, 100 and 50 microns thickness, including reflection loss from one surface. Figure 26 shows transmission less than one percent for 100 microns of heavily P doped silicon, and the spectral bandpass is limited to a region near the bandgap at 1.1 micron.



Figure 25: Transmission of P-Doped Silicon falls dramatically with increasing carrier concentration. Calculated from empirical formulas given by A. Falk [7].

In the case of heavily doped substrates, the silicon must be thinned to permit backside inspection. However many circuits employ lightly doped silicon substrates and no thinning at all is required on these. Calculating the opacity may not be necessary. It takes little time to examine a die for backside transparency. Substrates that must be thinned are typically reduced to about 100 microns thickness as a suitable compromise between transmission and thermal and mechanical fragility. Many labs are content to thin with a polishing disk. Others employ machines to open rectangular "pockets" in packages. These machines may be of the CNC Mill variety or much less expensive gravity feed grinders. The thinned surface ultimately becomes an optical surface. Take care to polish the surface at the end of the thinning process. Any remaining surface roughness will scatter light and degrade the image. For laser techniques, any residual waviness will cause interference artifacts that will impede the examination.



Figure 26:Transmission of Si improves with wafer thinning Note that transmission for 10^{20} cm⁻³ material through 100 microns is less than a percent . Calculated from empirical formulas given by A. Falk in [7].

Photoemission Infrared Microscopy

Many defects permit unwanted electron-hole recombination. An example would be a conducting path punched through an oxide by static damage. Electron-hole recombination is typically accompanied by photon emission, and these are known as recombination photons. Photon Emission Microscopy, sometimes known by the initials PEM, is a technique by which such failure sites are located by their photon emissions. The PEM is most often comprised of a very sensitive camera mounted on a microscope in a dark enclosure. Usually the camera employs a peltier or cryogenically cooled detector to reduce noise and improve sensitivity. The setup often includes a probe station or means to dock to a functional tester. Photoemission microscopy is so effective in locating failure sites that it is frequently the first failure analysis tool to be employed. The wavelength spectrum of recombination emissions tends to be near the silicon bandgap. Some emissions are blue shifted from hot electron effects, from added energy from impressed voltages. Most of the recombination emissions appear to be red shifted, that is, shifted to longer wavelengths, due to phonon energy losses. The figure shows emissions reported by Rowlette at LEOS, 2003 for V_{d-s} 1.2 Volts, on a 10-micron transistor [8].



Figure 27:Rowlette reports red shift of PMOS recombination emissions from a 10 micron length transistor.

The recombination spectrum is largely infrared, so ideally the photoemission camera should be optimized for near infrared (NIR) and short wave infrared (SWIR) detection up to about 1.6 microns wavelength. When photon emission microscopes first became available, and for about their first decade, there just weren't any reasonable SWIR detectors available. Instruments of that vintage relied on silicon CCDs or CCDs fielded with image intensifiers. They depended on detecting hot electron effects for blue shifted recombination signatures. Now thanks to funding from astronomy applications, there are suitable, if expensive, infrared detectors that are excellent for detecting recombination emissions. The most commonly fielded SWIR detector for emission microscopy is made from Mercury-Cadmium-Telluride, the trinary compound sometimes known as HgCdTe, MCT or regrettably just MerCad. HgCdTe has long been the material of choice for military infrared applications, but only at wavelengths longer than 3 microns, a region of no interest for detecting recombination emissions. The author knows of only 2 sources of HgCdTe detectors with the right stoichiometry for the failure analysis community, with spectral response and dark current suitable for emission microscopy and the detectors are breath-takingly expensive. Germanium and Indium Gallium Arsenide (InGaAs) materials have a suitable bandgap for detecting over the wavelengths of interest. However to date LN2 cooled InGaAs has not demonstrated the low darkcurrent noise required for emission microscopy. Most likely that is due to the detector readout circuitry "glowing" in the same wavelengths of interest and thereby uselessly filling the detectors with false signal. Perhaps by the time this is published the detector community will solve the readout "glow" problem and bring some price relief to SWIR emission microscopy. The current generation of SWIR detectors for emission microscopy are liquid nitrogen (LN2) cooled. Some of these require constant cooling, that is, the detector manufacturer requires that once cooled to cryogenic temperature, that the detector not be allowed to warm again. This is to prevent damage from thermal expansion and contraction over subsequent cooling cycles. Future generations may be LN2 cooled or they may utilize closed cycle cryogenic

refrigerating engines, already-developed (for the military) but as yet unfielded for PEM,.

Photoemission High NA Macro Lenses

Modern NIR or SWIR photoemission microscopes must employ NIR (near infrared) objectives, rather than the more common visible objectives. The NIR lenses are far superior for long wave microscopy compared to visible lenses. These objectives were never intended to work at wavelengths as long as 1.6 microns but they seem to have adequate performance in that band and they are reasonably priced and available. Common optical glasses do not work for Mid-wave, 2-4 micron infrared microscopy. Mid-wave infrared requires custom objectives with silicon and germanium lenses. Future requirements for photoemission microscopy may encourage us to develop similar custom lenses for SWIR work, but for now, commercial NIR objectives suit.

Specially designed high N.A. macro lenses have considerable value for photoemission work and the user should insist on them. Macro lenses offer 1x or less magnification and they are needed for canvassing the entire die at once to find a defect that could be anywhere. If the PEM is not equipped with a macro, the user is forced to systematically scan a large die with higher magnification lenses, a tedious and timeconsuming task. The macro must have a high NA to gather all available signal so as to reveal the emission sites. However most commercially available macro lenses compromise the NA terribly in order to make the lens mechanically compatible with the higher magnification objectives in the lens turret. The best macro objectives for photoemission work abandon mechanical compatibility in favor of extremely high signal throughput. The high NA macros are created by splitting the optical power between two equal or similar lens groups, one near the camera focal plane, and the other near the sample focal plane. A simple way to do this is to employ 2 matched 35mm camera lenses with equal or similar focal lengths and fast F/#s arranged per figure 28. A pair of lenses arranged this way has amazing light gathering power, and often the emission sites are most readily located with the macro. The technique is described in US patents 4,680,635, Khuruna, and 4,755,874 Esrig. The magnification of the paired lenses is given by the ratio of their focal lengths; hence if they are equal, the magnification will be 1x. If the lens nearest the camera has a focal length shorter than the lens nearest the sample, the magnification will be less than unity.



Figure 28:A pair of camera lenses used back to back makes an extraordinarily sensitive 1x macro for photo-emission detection.

Thermal Infrared Hot Spot Detection

In the past liquid crystal techniques served to find short circuits from the front surface. Liquid crystal techniques fail for backside inspection because the liquid crystals must themselves be warmed by the hot spot to work, and heat from the short diffuses too much to be to be detected from the backside. However all warm objects radiate some infrared photons according to the Planck blackbody law and this thermal photon emission may be used to detect short circuits from the front or back of the die.

Thermal infrared light from objects near room temperature radiates from the motion within and between molecules, from twisting, bending and coupled oscillations caused by thermal excitation. At higher temperatures the agitation is greater, increasing the radiation overall and blue shifting the peak radiation. At about 800 Kelvin the radiation peak wavelength is short enough to be visible to the eye as a kind of dull orange, seen in glowing coals in fireplaces.



Figure 29:All objects warmer than absolute zero emit infrared radiation according to the Planck blackbody law. This property may be used to detect heat from short circuits via infrared microscopy.

$$Q(T,\lambda) = \varepsilon \cdot \frac{2\pi c}{\lambda^4} \cdot \frac{1}{e\left(\frac{ch}{\lambda kT}\right) - 1}$$

Equation 4: Planck's law yielding the curves above where:

 $Q = Photons per second per cm² per \mu m$

 ε = emissivity constant of the material ranging from 0 to 1 c = velocity of light $3x10^{10}$ cm/s

 $h = Planck's constant, 6.63x10^{-34} watts • seconds²$

 $k = Boltzmann's constant, 1.38x10^{-23}$ watts•seconds per

Kelvin

 λ = wavelength in centimeters

T = source temperature in degrees Kelvin

$$Q = \varepsilon \sigma' T^3$$

Equation 5; The integral of Planck's law over all wavelengths known as the Stefan-Boltzman Law illustrates the cubic relationship of radiation to temperature, where:

Q = radiant photon emittance, photons per second per cm² ε = Emissivity constant of the material ranging from 0 to 1 σ' = 1.52x10¹¹ per second per cm² per °Kelvin³ T = Kelvin temperature of the source

Not all materials emit equally well according to the Planck laws. A perfect emitter is also a perfect absorber. A perfect absorber has no reflection so this type of source is called a blackbody source, and it was for a blackbody source that Planck formulated his laws. Any given material may be more or less efficient at emitting infrared radiation and the property that describes how closely a material approaches a perfect blackbody source is called emissivity, which ranges from zero to unity. Metals are poor emitters of infrared with emissivities near or below 10%. Semiconductor circuit materials tend to be about 40% to 60% emissive. Packaging materials, plastics, ceramics and epoxies usually have very high emissivities. Thermal infrared microscopes are very effective for locating current leaks from their heat signature, but less so if the leak is under metal or some low emissivity material. A thin layer of black paint applied to the surface of a circuit can enhance the emissivity and boost the infrared signature to reveal hard to find hot spots.



Figure 30: This is a thermal infrared image of a GaAs radio frequency amplifier. The circuit isn't powered and there is no external illumination. The detected infrared is all from the IC and all of the contrast is due to emissivity differences. The metal lines and pads emit much less infrared than does the junction areas or the packaging.

Thermal infrared has subtle but important differences from other sources of light. A dark box does little good for thermal microscopy, because the box walls themselves glow with infrared emissions. You cannot turn out the lights in the infrared, except by cooling the source. Normal glass lenses are opaque and will not work at thermal infrared wavelengths. Instead infrared optical workers use silicon or germanium for lens materials, or exotic compounds such as zinc-selenide, or magnesium fluoride. This makes thermal infrared objectives much more expensive than conventional objectives, and requires optical shops with special skills to grind the lenses. Thermal infrared is long wave, compared to recombination photoemissions, and so is limited by diffraction to relatively larger airy disks and less fine resolution.



Figure 31: Thermal infrared detected hot spot on a silicon IC, overlayed on a thermal infrared reference image. Normally the hot spot is displayed in false color to contrast vigorously with the black and white reference image. Courtesey of Quantum Focus Instruments Corporation.

Inspection of the Planck curves in figure 29 show that the peak radiation is near 10 microns wavelength. However the Sparrow Criteria favors shorter wavelengths for best resolution. The manufacturers of thermal infrared microscopes balance these requirements and the overwhelming vast majority of fielded instruments operate between 2 to 4 microns wavelength. By contrast, recombination photons detected in emission microscopy are limited to 1.6 microns wavelength or less.

In failure analysis the process of detecting a hot spot by thermal infrared is qualitative. It doesn't matter if the spot is barely detectible or so bright as to be completely saturated, so long as the defect is located. However the radio frequency IC (RFIC) community routinely employs a version of the thermal infrared microscope that is calibrated to compensate automatically for emissivity at each pixel, and to yield highly accurate, quantitative temperature values for the junctions of operating ICs.





Figure 32: Certain thermal infrared microscopes are designed to accurately measure temperatures on ICs. Upper left, thermal infrared reference image of a 5 watt high brightness LED (for illumination). Upper right, false color temperature image of the HBLED showing excessively hot regions. Lower, values of temperature in degrees celsius along the line. Courtesey of Quantum Focus Instruments Corporation.

Laser Signal Injection Microscopy

Shorts, junction defects, problem VIAs and other integrated circuit defects can sometimes be located from the front or backside with Laser Signal Injection Microscopy (LSIM). An LSIM works by scanning a laser beam through a microscope lens, crossing an integrated circuit while monitoring the circuit input and output for laser-induced changes. Various laser wavelengths induce different effects. Short wavelength lasers electron-hole pairs, (photo-carriers) in the produce semiconductor. These photo-generated carriers reveal failure sites in transistors and PN junctions. Longer wavelength lasers induce micro-local heating to reveal resistive and ohmic problems. Both photo-carrier generation and microthermal heating may be performed from the front or backside of the wafer. Various techniques have evolved for semiconductor fault location by Laser Signal Injection. The pioneer was OBIC in 1988. Since then other techniques have appeared known by names such as LIVA, TIVA, OBIRCH, SEI and XIVA. Each of these techniques generates either photocarriers or micro-local thermal heating to reveal defect locations. They differ in how the circuit under test is biased and connected to the measuring amplifier. The LSIM is actually an adaptation of a laser-scanning microscope (LSM). In the LSM, the injected laser light is scanned over a circuit in a raster pattern, and the reflection is detected and displayed.

An LSM image appears much like any light microscope image.



Figure 33: Laser Scanning Microscope (LSM) forms an image by detecting reflections from a raster scanned laser. The example is a backside image showing interference lines caused by laser light waves reflecting from both surfaces of the die, which causes destructive and constructive interference.



Figure 34: Laser Signal Injection Microscope (LSIM) forms an image by detecting laser induced changes in microcircuits. More commonly known by OBIRCH, TIVA, XIVA, etc. Note that an LSIM can simultaneously produce an image by reflection.

As can be seen in figure 33, images from laser microscopy from the backside often show interference patterns. These patterns result from the destructive and constructive interference of monochromatic light waves that are reflected from each surface of the die. The effect can be so pronounced that the circuit can be quite hard to see. It can be mitigated with antireflection coatings on the back surface of the die, or in some cases by regrinding the die back surface. Often the fringing is more evident at low magnifications.



Figure 35: Left: OBIC image from laser induced photocarriers, courtesey of Optometrix Inc. Right: Thermal XIVA image from microthermal heating showing current in a conductor. Scan direction on right image is vertical.

List of Laser Techniques:

Known	Full Name	Approx.	Physics	Application
as:		Intro-		
		duction		
OBIC	Optical	1988	Photo-Carrier	Junction
	Beam			Defects
	Induced			
	Current			
LIVA	Light	1994	Photo-Carrier	Open
	Induced			Junctions and
	Voltage			Substrate
	Alteration			Damage
OBIRCH	Optical	1998	Thermal	Locations of
	Beam			Shorts and
	Induced			defective
	Resistance			VIAs
	Change			
SEI	Seebeck	1999	Seebeck	Location of
	Effect		Effect	Opens
	Imaging			-
TIVA	Thermal	1999	Thermal	Locations of
	Induced			Shorts and
	Voltage			defective
	Alteration			VIAs
XIVA	External	2001	Thermal or	Junctions,
	Induced		Photo-Carrier	substrates,
	Voltage		per	shorts.
	Alteration.		wavelength	

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Special thanks to Michael W. Davidson of the National High Magnetic Field Laboratory at Florida State University for generous permission to use many of the excellent illustrations from <u>www.molecularexpressions.com</u>. The author encourages the reader to visit the Molecular Expressions website for an amazing wealth of information on microscopy.

Thanks also to Aaron Falk for providing his absorption calculations in the form of a spreadsheet, adapted here to generate the doped silicon transmission curves.

Additional Resources

Online: <u>www.molecularexpressions.com</u>. Excellent and voluminous microscopy tutorial from the Florida State University and the National High Magnetic Field Laboratory.

General Optics:

Optics, Eugene Hecht et, al. Excellent and well illustrated survey of optics.

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