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SPATIAL INTENSITY DISTRIBUTION AND COLOR ANALYZER

ROBERTA L. URSCHEL
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SOLID STATE PHYSICS RESEARCH LABORATORY

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OFFICE OF AEROSPACE RESEARCH
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FOREWORD

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ABSTRACT

Research leading to new and more advanced imaging devices requires extensive study of large quantities of different semiconductor plates. Very useful in this endeavor is the Spatial Intensity Distribution and Color Analyzer (SIDCA) which, if used properly in connection with a stigmatic spectrograph, reduces the number of spectrographic plates needed for analyzing a target plate from a prohibitively large number to a reasonable one. SIDCA is a specially designed and built opto-electronic scanner using three photomultipliers in connection with suitable filtering, nonlinear amplification techniques, and an analog computer. It can be used in an intensity or spectral analyzing mode. In spectrographic plates, SIDCA can detect information which is not readily perceivable by the human eye. Furthermore, it can map the flaws and spatial uniformity of potential target plates or optical elements by directly scanning them in a transmission or reflection mode. Also, it can show the spatial distribution as a result of diffusion when employing spot doping and can be used for studying spatial effects of emissions from excited semiconductors. Furthermore, it may be used for determining the spatial homogeneity of optical elements such as interference filters, etc. When using appropriate filter-photomultiplier combinations, SIDCA can identify colors in the standardized CIE color triangle; then, the analog computer performs the mathematical operations which result in the presentation of the appropriate locus in the triangle on an oscilloscope, where the parabolic portion of the triangle is obtained by scanning a low leakage verlauf filter or using a suitable, variable monochromator. In

addition, artificial color triangles, produced by using closer spaced spectral filters, provide a way to distinguish smaller increments in hue or wavelength. When scanning spectrographic plates with this instrument, oscillographic records or new plates may be made that show detectable information too low in contrast on the original plate to be perceived by the unaided eye. Spatial expansion can be used in the new recording and provides easy evaluation of structures within an apparent line, but errors may be introduced by the adjacency effects in the original plate. For mapping a specimen, the signal obtained may be recorded, line by line, with conventional oscillographs or may be depicted using an image storage reproducer, displaying otherwise unperceivable detail.

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I. INTRODUCTION

Semiconductor research concerned with investigations that lead to crystal target plates suitable for use in highly sensitive imaging devices involves analysis for spatial homogeneity in spectral behavior, absorption, reflection, etc. Semiconductive plates, when used in opto-electronic image detecting devices, are commonly called target plates. Electrical read-out of the optical image focused onto them may be achieved by scanning them in a vacuum with an electron beam. This causes a time sequential signal over a resistor which is connected to a semitransparent metallic coating on the light receiving side of the target plate. Homogeneity is especially important if the target plates have been doped in such a manner that detection occurs only over a narrow spectral region, which for example, might have to match the wavelength of the radiation from a laser source used as illuminator. The necessary analysis often demands laborious spectrographic work, since large numbers of samples are usually involved. For obtaining meaningful results from experimental research on target plates using processes such as doping, samples with known characteristics must be used. Research in this area must lead to target plates which are highly uniform, since any spatial nonuniformity in the final target plate which affects the detection characteristic may show up as shading, bars, etc., in the image reproduced on the monitor. Since the probability of detecting information is a function of the ratio of information to shading, the homogeneity of the target plate may determine the permissible amount of signal modification which can be used for obtaining contrast enhancement in the reproduced image, because even minute spatial changes in the target plate may then become visible on the reproducer screen. Such spatial defects, or nonuniformities, might be introduced in the vapor phase when growing the platelet or the bulk crystal from which the target plate was cut, or they might be the result of uneven doping, etching or other modifications of the crystal after it was grown. This is of great interest, for example, in a diffusion doping process used by us, by which CdS platelets or plates cut from bulk crystals are doped with PbS in order to achieve infrared sensitivity with these crystals. One method of determining which doping method yields crystals that are uniform enough or have a suitable characteristic to be used in infrared sensitive vidicons is to actually mount them in a workable tube. However, this process is a costly one, since too many samples have to be investigated to obtain all the pertinent data.

Spectrographic analysis of these prospective target plates in their different stages often yields spectrographic plates which may contain information not easily recognizable because it consists of almost imperceptable density differences in the plate. Further, what often appears to the unaided human eye to be a single spectral line on the photographic plate may actually be several very closely spaced ones which form a composite line. When using a spectrograph suitable for stigmatic imaging (one where each point on a spectral line on the spectrogram represents a specific location on the crystal) to survey a complete target plate by conventional means, one has to take at least as many spectrographic plates as scanning lines used for that target plate. The spot resolution of the spectrogram then must at least match the spot resolution of the target plate. Since ther vertical loci on the spectrographic plate represent the individual resolution points of the specimen and the horizontal their wavelength dependency, any spatial difference in the intensity of the image focused on the slit of the spectrograph will show up in the lines, respectively, and any spatial spectral inhomogeneity will cause lines which are not straight.

An obvious solution to the problem of analyzing such spectrographic plates was to design an opto-electronic scanner in which the electrical signal, obtained by scanning the spectrographic plates, is recorded by a suitable oscillograph to permit comparison of the spectral behavior of the different resolution points of interest and also precise comparison of different target plates. For this, apertures of suitable configuration, rectangular for covering the whole length of the spectral line, or round for analysis of a portion of the line which corresponds to the size of a given resolution element on the target plate, etc., may be used. When building the instrument, consideration was given not only to scanning the spectrographic plates obtained from platelets or plates cut from bulk crystals, but also to scanning the specimens themselves or optical elements by using a suitable opto-electronic arrangement in modes where light may be reflected as well as transmitted. The realization of these ideas resulted in the instrumentation called SIDCA (Spatial Intensity Distribution and Color Analyzer), which may be operated in an intensity or spectral analyzing mode, as expressed by its name. SIDCA resulted from consideration of means by which color perception may be achieved.[1,2,3] It fulfills the previously stated task of scanning the spectrographic plates and, by using an analog divider, suitable filtering, variable nonlinear amplification, and a suitable reference, can produce a new plate of desired density or a useful oscillographic recording which shows only a negligible spectral gradient background caused by the lamp that was used with the spectrograph. Thus, information is shown which may be too low in contrast on the original spectrographic plate for direct perception by the human eye; obviously, only information above the noise can be detected. Furthermore, when scanning spectrographic plates, if the spatial resolution of the signal is sufficient to resolve structures within an apparent single line and if the recording device operates at a faster speed than that of the scanner, the reproduction obtained is an expansion of the original and readily provides direct visual observation and convenient evaluation of any structure within a line.

Also, SIDCA is capable of determining all colors which can be sensed by the human eye by identifying their position in the standardized CIE (Commission International de l'Eclairage) color triangle, independent of intensity, and also can distinguish smaller increments in chromaticity or wavelength than can the eye. Further, the instrument permits mapping by line sequential scanning of a specimen, and any of the spatial inhomogeneities, nontransparent areas, etc., are recorded. Usually the number of spectrograms which have to be taken with the spectrograph can be reduced considerably, because now one can first determine with SIDCA the location of the areas of interest on the potential target plate, and then may obtain a stigmatic spectrographic plate of these areas. The areas which deviate from the rest of the target plate may be further investigated by other means such as x-ray diffraction, electron microscopy, etc. If different dopings are to be tried on the same potential target plate and if sufficiently uniform specimens are scarce, then the nonuniform areas found on the target plate by SIDCA, if few enough, can be avoided when applying the dopant. In addition, the spatial dependency of the homogeneity and leakage as well as the spatial uniformity of the transmission of interference filters or similar optical elements, can be checked efficiently with this instrument. The term "leakage" is usually used for the non-negligible fraction of the overall transmission which is represented by the tail of the curve of the filter characteristics. This tail may continue over a wide wavelength interval.

SIDCA may also be used for studying the spatial effects of radiation emitted by cooled crystals when exicting them with light of different wavelengths.

THE ARRANGEMENT OF SIDCA AND TECHNIQUES INVOLVED

The basic schematic of the SIDCA is shown in Fig. 1. Essentially, the SIDCA comprises the following:

1. The optical section, consisting of a light-tight compartment containing - -(a) various light sources, (b) a movable sled on which specimens are mounted, (c) the necessary optical elements for focusing the light from the appropriate source onto the specimen, (d) a semitransparent mirror which permits either transmission or reflection measurements, (e) a beam-splitter arrangement using 30-30 dichroic mirrors so the detectors can receive light from the illuminated area of the specimen simultaneously, (f) the necessary filters, (g) three photomultipliers for transducing the information light beam from the specimen and (h) one photomultiplier for producing a reference signal which is needed for suppressing the gradient lamp background on processed spectrograms.

2. The electronic section, consisting of: (a) a variable nonlinear amplifier[4] permitting modification of the intensity signal, (b) an analog divider which derives a new signal by dividing that signal obtained by scanning a spectrogram by that obtained from a reference, and (c) an analog computer which may be used to form, from the photomultiplier output signals $-x^+$, $-y^+$, and $-z^+$, the signals X, Y, and Z, and the sum M, and the ratios $X' = \frac{X}{M}$, and $Y' = \frac{Y}{M}$, (color coordinates).

3. The recording section, consisting of: (a) a three channel recorder, (b) a direct writing multichannel recorder, (c) an oscilloscope-camera combination, and (d) a glow discharge tube modulated by the nonlinear amplifier used

to expose a photographic plate on another movable sled.

4. The programmer, which consists of switches that permit selecting the desired operational modes.

The light sources used must have sufficient wattage to avoid problems of conversion noise, pertinent when operating with weak signals. The configuration of a straight single conductor filament, which can be matched with an optical slit, is preferable, since, in some operational modes, such a slit either is used in front of the specimen or is imaged on it. Hence, such a filament will give the most usable light for the least heat dissipation. For L 1 and L 3, the tungsten filament lamp, GE 18 A/T 10/1-6V, Sr 8, was found suitable to provide polychromatic light and, with selected filters, nearly monochromatic light. For L4, the mercury lamp, Osram HB 0/100/W/2, 1325 KC, operated at 5.0 amperes and 20 volts with appropriate filters for its various spectral lines, was used. A fast changeover between L 1 and L 4 is possible through the use of a flopping mirror arrangement (S 1). L 2 can be either a tungsten or a mercury lamp, depending on the task.

The specimens to be scanned are mounted on a motor-driven sled which has a reversible variable speed of 0.25 to 1 mm per second. The sled can be moved in the x and y directions and the effective y position of the aperture must be changed after each line of scan by its y dimension when performing a line sequential scan with a small aperture. Position indicators of various design may be used for the movable sleds for determining the x and y positions. For example, an electrical contact can be intermittently activated by the specimen sled and the sequence of the pulses coded to indicate the position of the specimen and the y position of the aperture. Alternatively, a photocell can be used to produce the identification pulses by receiving light coming through a sequence of holes in the sled, which are also affected by the y position of the aperture. At the reproducer a glow discharge tube may be used to reproduce the code sequence.

The optical system was designed for maximum adjustment in all planes with enough precision to assure good resolution and uses visual observation for focusing, necessary especially for spectral line structure study.

The lens arrangements (Fig. 1) used for illuminating the specimen for transmission measurements obviously may be used in a manner which illuminates the specimen with the largest possible amount of light or may serve as a collimator. When investigating a specimen in which the reflection, transmission, etc., depends on the angle of the light in reference to the specimen axis, it may become necessary to illuminate the specimen with light parallel enough for the intended purpose. However, one has to realize that when illuminating areas with a side length of a few microns with well collimated light, even when using the most powerful light sources, the effective quanta flux for such areas may be too small to yield a usable signal-to-noise ratio, since most of the light from the source is not used when forming a well-collimated beam. Fortunately, when analyzing axis-dependent semiconductors, if the light does not diverge from the beam axis by more than 5°, the error in the measurements is usually negligible. Therefore, collimating is not necessary and the source or the opening of an aperture acting as source can be imaged on the specimen by keeping the divergence of the individual rays within the permissible 5° by employing suitable pupils in the design. Then, an adequate quanta flux can be obtained for the specimens with most of the light sources and filters used.

Using L 2 instead of L 1 or L 4 makes easy conversion from transmission studies to reflection studies possible. In this case, it is also required that the light focused on the specimen must be within 5° of the perpendicular to the specimen. Since, in this mode, it is difficult to place an aperture before the specimen in a suitable manner and since placing an aperture too far away would increase the effective area illuminated on the specimen because of diffraction, etc., the specimen is illuminated by projecting on it the minified lighted area of a small aperture. This aperture receives its light from a large area light source and acts as a source. Then the effective pupil of the optical system has to be chosen so that none of the rays which form the image on the specimen diverges more than 5° from the beam axis. The semitransparent mirror, placed between the image lens and the specimen, should be such that the reflectance is about 10%, thus permitting use of the largest possible amount of light during transmission measurements of a specimen.

When scanning spectrographic plates, loss of resolution, complications caused by diffraction, etc., which could occur if an area restricting aperture is placed close to the spectrographic plate, are avoided by placing the necessary aperture before the photomultiplier tube and by focusing an enlarged image of the spectrogram on this aperture. When using a slit as aperture, its parallel alignment to the spectral lines is critical for best resolution. The linear magnification used was about 15, which is easily obtained. Thus, a rather large aperture of 75 μ gives, with a suitable lens, the possibility of observing 5μ on the plate. The divergence of the rays, which occurs behind this aperture, does not affect the resolution since the photocathode integrates all the light.

It is possible to use the same system for the spectral scanning by employing three properly aligned apertures before each photomultiplier, or using a single aperture in the focal plane of the imaging lens and placing the beam splitter between this aperture and the photomultipliers which must have large area photocathodes. However, the last two solutions constitute some design difficulties and also the large area photocathodes yield a larger amount of dark current. That is, they give a lower signal to noise ratio, which in turn requires a more powerful light source. Obtaining enough light is a problem in most cases. Therefore, for spatial spectral analysis of larger areas (> 50μ), for simplification, one may attempt to solve the problem of restricting the area under observation by using a single aperture close to the light receiving side of the specimen and by keeping the aperture at no greater distance than 0.3 mm. However, when analyzing very small areas(5 to 50μ) of the specimen, imaging the minified lighted area of an aperture on it, where again the aperture acts like a source as in the case of the reflection measurement, will best define the boundary of the illuminated area. The minification can be accomplished in two steps by using two separate lens systems, which usually results in a shorter or more suitable physical arrangement for the same minification. For the reproduction for the spectral lines on new plates, a similar arrangement may be used by employing a large area glow discharge tube in connection with a slit of about 200μ , which is imaged with a width of about 10μ on the recording photographic plate. Since obtaining enough light for proper exposure is no problem in such an arrangement, one may well use a sled speed for the reproduction which will record a line that was the limit in resolution of the original plate with a new line width of perhaps 50μ or more, which gives results more easily perceived.

The light from the monochromator (Fig. 1) can be injected into the system at several different places. The solution shown in the basic schematic has been chosen so that the light from the monochromator will pass through all the important elements which are usually involved in the measurements. Then, using an intensity-calibrated monochromator and the three-channel recorder, one can conveniently check the overall intensity response as a function of wavelength for the entire system.

For determining colors with SIDCA, as with the human eye, the X, Y, and Z responses of the eye can be sufficiently well represented by the following filter-photosensor combinations:

X-(X_{450} and X_{600}) X_{450} is used to refer to the portion of the X curve with a peak at about 4400A and X_{600} is used to refer to the portion of the curve with its peak at about 6000A. Since, at present, there seems to be no single filter available which gives both peaks, and, hence, can be used with a single photomultiplier, the combined output of #48 Kodak filter with a 1P28 photomultiplier (S-5) and #23A Kodak filter with a 1P21 photomultiplier (S-4) is a solution.

Y - #106 Kodak filter and #600 Optics Technology shortwave pass filter with a 1P21 photomultiplier.

Z - #48 Kodak filter with 1P28 photomultiplier.

Since only 3 photomultipliers had been incorporated in SIDCA, the omission of the 1P28 photomultiplier with the #48 filter for X_{450} was made possible by substituting a portion (0.17) of the Z signal and mixing this with the X signal obtained with the 23 A filter. The proper proportions between the signals were maintained through the use of neutral density filters, amplifier gain adjustments in the computer, and gain adjustments of the photomultipliers by adjusting the voltage of their power supplies within the range over which the relative spectral response was sufficiently constant.

The common failure of 30 - 30 dichroic mirrors (Fig. 1) to transmit and reflect with flat spectral responses must be considered in choosing the appropriate filter-photosensor combinations.

Neutral density filters must be used with the filter-photodetector combinations to balance the values of X, Y, and Z, with respect to each other, although additional adjustment can be made in the computer if the necessary supplementary amplifiers and potentiometers are available. The signals X, Y, and Z must be balanced to make up for differences in photomultiplier responses, failure of filter-detector combination response peaks to have the same relationship as the desired X, Y, and Z peaks, differences in the length of the paths of the light through the beam splitter, and differences in light losses for the mirror arrangements in the paths of the light through the beam splitter. A separate stabilized power supply with a controllable voltage output is used for each photomultiplier to permit individual control of the gain of the photomultipliers and permit selection of a voltage which will yield a linear performance.

The choice of filters for the crystal analysis depends on the width of the energy gap of the specimen to be examined and on the wavelength of the expected absorption due to doping. When using the three-detector arrangement, in order to get optimum signal changes from any spatial inhomogeneities, the three filters used for this should be very closely spaced, very narrow bandpass filters. Their peaks should be separated by a value equal to their half-intensity bandwidths, with the center peak very near the wavelength corresponding to the energy gap of the crystal or the wavelength at which absorption will occur because of doping. Using additional filters to restrict the spectral range of the radiation, as much as possible, to the region where absorption occurs will prevent any possible reduction in signal indications caused by leakage in the characteristics of the three closely spaced bandpass filters. When duplicating the color perception of the human eye, or in similar work, suitable infrared and/or ultraviolet cut-off filters should be used with all the detectors to prevent erroneous results due to leakage.

The analog computer must be made up of drift free amplifiers, dividers, etc. Frequency response of the computer was not a particularly important factor at the scanning speeds used. Philbrick vacuum tube equipment was used in the SIDCA, a UPA-2 for the adder and an MU/DV for the ratios. Several K2-W amplifiers with chopper stabilization provided by K2-P units were also used for other amplification and summation purposes. Solid state equipment was not used because, for a basic research tool, it was desirable to keep the cost as low as possible and space was not an important factor. In the voltage ranges encountered, some bias on the adder was occasionally necessary to prevent attempted division by zero. Supplementary amplifiers were used to obtain needed signal combinations, signals with the correct polarity for operation of the MU/DV, and positive outputs at the recorders (Fig. 1).

The recorders used were a multi-channel oscillograph (Honeywell Visicorder) and an X - Y oscilloscope (Tektronix Type 536), both with a sensitivity of 0 to 50 volts full scale. The recorders must have adequate frequency response to record the transient changes expected. The following reasoning is usually used to determine adequate frequency response. For optimum resolution, the sled should be run with its slowest speed, which in our instrument is 250μm sec^{-1}.

The smallest effective slit width in our instrument is 5 μm. Hence, a transient is achieved in $\frac{1}{250/5}$ = 20 msec. In practice, it has been found that the numerical value of the upper frequency cutoff of the amplifier should be 4 - 5 times the reciprocal of the input transient time for sufficiently maintaining the original waveform. This, in our case, is 200 to 250 cps; the visicorder used has a frequency response of 0 to 200 cps which fulfills this condition. The visicorder utilizes a mirror galvanometer deflecting an ultraviolet beam of light which is then recorded on ultraviolet sensitive photographic paper (trace visible a few seconds after exposure without further development; however, to obtain very good traces, chemical development may be used). Appropriate electrical filters had to be inserted between the computer and the recording devices to prevent recording of the high frequency signal from the oscillator in the multiplier of the analog computer. A polaroid camera may be attached to the oscilloscope and will provide, in a convenient way, photographic records when the slow speed sweep generator is used. In many cases, such recording may be sufficient; however, the records obtained with the visicorder are more accurate. When using the oscilloscope for recording, a dual beam scope may be used, where the trace of the second beam is used to indicate the position of the movable sled by pulsing the second beam on and off. Storage reproducers may be used in addition to the other recording devices shown in Fig. 1. Thus, the signals from the scanning of a specimen may be stored and then reproduced simultaneously when scanning is completed. For some applications, this type of recording may be more desirable than the time sequential record.

In the following paragraphs a few of the techniques for the various uses of SIDCA are discussed at length. Since a transmission or reflection spectrogram represents the overall spectral composite of lamp and specimen, and the emission from the lamps usually used has a high spectral dependency which causes a gradient in the plate background density, easy and precise recognition of faint information superimposed on this background is often a problem. With the help of SIDCA, one may produce spectrograms within certain spectral regions which show the information of the specimen, but only a very small amount of the background caused by the lamp. One method for achieving this requires taking a spectrogram of the lamp by itself on the same photographic plate as the composite spectrogram. Both spectrograms are then scanned simultaneously, using two photomultipliers. The signals obtained this way are divided, one by the other, and then, using the nonlinear amplifier as a variable threshold limiter, yield a signal which may be free of the lamp background. Obviously, the effective light flux used for the reference and the composite spectrograms should be as nearly identical as possible to minimize the influences of any nonlinearities in the photographic process. If the new recording does not have to express the ratio of the incident flux on the specimen to the flux received by the spectrograph for the composite, but merely is needed for correctly determining the wavelength of the spectral lines of interest, then a simple subtraction of the two signals may be made by feeding the two photomultiplier outputs to a ground symmetrical amplifier, acting as a differential amplifier, before using the nonlinear amplifier. In some cases, a simpler method may be used in which appropriate changes in the threshold of the variable nonlinear amplifier may be sufficient for reducing the background.

When performing opto-electronic processing of spectrographic plates, one should not overlook the following limitations of the photographic process and the spectrographic arrangement. When exposing a photographic plate to a fine pattern of light, the congruency of the reproduced pattern to the original is not determined by the size of the developed grains alone, but also by other factors. Furthermore, the location of a point image may not be exactly identical with the location where the light was focused. (Kodak quotes that these apparent image movements rarely exceed 10 micron). Whenever the intensity of an image focused on a photographic plate has sudden spatial changes, the recording shows a spatial transient for each spatial change in illumination, which is related to the type of configuration of the pattern and affected by the developing conditions. Since this may falsify the accuracy of the results, it must be considered when recording fine spectrographic lines and cannot be neglected in the evaluation of certain spectrographic plates. The different effects, which can cause such a spatial dependency as a function of configuration and developing method, have been collectively called the adjacency effects. (Kodak Photographic Plates for Scientific and Technical Use, by Eastman Kodak Comp., Rochester, N.Y.) These effects are mainly due to chemical reaction products which are produced during the developing process and which diffuse from a region of heavier exposure into one of lesser exposure and, likewise, of the diffusion of fresh developer from a less exposed area into regions of higher exposure. Furthermore, the reaction products accumulate in certain regions to a greater extent than in others. This all results in a gradient pattern of effectiveness of the developing action over the entire plate, which yields unequal results for equal exposure of light. That is, it introduces a spatial nonlinearity in the faithfulness of the recording.

Nonlinearities in density resulting from the failure of reciprocity may be calculated into the results when determining the original light flux from a photographic plate; but, to compensate for errors introduced by the adjacency effects is nearly impossible because of the different and complex situations which may exist and cause different kinds of distortions. Heavy agitation of the developer will considerably reduce the adjacency effects, but not completely eliminate them. When evaluating structures of spectral lines or closely spaced spectral lines, a test of the entire process and instrumentation should be performed by exposing the plate with a line of known structure and with close lines of known spacing and intensities.

Spectrographic plates made with the better grating spectrographs (grating with $N \approx 220{,}000$ lines) usually have a plate factor (this factor times linear distance between centers of lines on spectrograms gives wavelength difference between lines) of 2 Å per mm. Monochromatic light, no matter how narrow its true bandwidth, is treated by the spectrograph, because of its limiting angular resolution, as light having a minimum bandwidth of

$$\Delta \lambda = \lambda/(m N)$$

(m = spectral order). Therefore, when using light with λ = 4400 A and m = 1, the smallest possible linear width W_{Min} of a line on a spectrographic plate taken with an instrument with the above specification is 10 micron, regardless of how narrow the true bandwidth, and thus, the same as if caused by monochromatic light with a bandwidth of 0.02A. Hence, in such an instrument one source at λ and the other at $\lambda + \Delta\lambda$ will appear as one single line with a width of $2\, W_{min}$ (20 microns for the above example). Obviously, when several spectral lines fuse, the structure of the resulting line depends on their true separations, true bandwidths, and the intensity ratios of the sources. To prevent fusing as in the above example, one would have to use a higher m or increase N.

Scanning fused lines on a spectrographic plate with SIDCA, by setting the threshold limiter to an appropriate level, may show single lines on the new recording, if the line caused by the fusing had a suitable structure for this process, even if the true separation of the sources was less then $\Delta\lambda$.

The smallest obtainable line width in the above example matches the maximum value of the apparent image movement on the spectrographic plate, which means the uncertainty of the location of the line is that quoted by Kodak. To reduce the effectiveness of this apparent image movement and the previously explained adjacency effects, one would have to increase the plate factor; but, since an increase in the plate factor spreads the available number of quanta over a larger area, failure of photographic reciprocity may become a problem when recording weak lines. This may make the use of light amplification or the Lallemand Electronic camera[5] necessary, where the latter gives a gain in sensitivity of 100 or more and no failure of photographic reciprocity occurs.

A line sequential scan, which requires a small suitable aperture, should be used when scanning optical elements, platelets, or crystal plates for spatial effects to assure highest detectivity of flaws and inhomogeneities, even if this operation may require considerable time for large area specimens. To find specimens free of defects, one may be inclined to determine their flawlessness by a single scanning of the specimen by using a rectangular slit which has the length of the side length of the specimen. But any uniform striations extending across the specimen in the direction of the line of scan (parallel or nonparallel) would not be detected. Even turning the specimen 90° and scanning it a second time will not detect homogeneous diagonal striations in a rectangular specimen. Scanning such a rectangular specimen by turning it 45° is obviously no solution because the slit length must equal the y dimensions of the specimen, which would change constantly in this position. Hence, for the purpose of mapping the flaws of a specimen, it is useless to consider correlating the results of a first scan with a 90° scan by a computer. In addition, such a mapping method would deliver ambiguous results in cases where many small area flaws of different size and contrast exist since a different number of spots may result in the same signal and hence, no computer can conclude from the cross correlation the correct original formation. The most serious objection against using a rectangular slit with the length of the y dimension of the specimen is that it would give considerable impairment in detectivity, in comparison with the results obtained by using a small aperture, since detectivity is determined by the amount of change in light. When scanning a specimen which has only a few small flaws, by using a rectangular aperture, obviously, the change in light is only a fraction of that obtained when using a sequential line scanning with a small aperture. However, to find perfect specimens, it may be possible to eliminate some of them which are not obviously defective to the eye by first scanning with a rectangular slit which has the sidelength of the specimen. Then line sequential scanning with a small aperture is only necessary for the ones which did not appear defective in the rectangular slit scanning. Such a combined method may save time. If the dimensions of the aperture are not chosen sufficiently small, very small surface defects (minor scratches, etc.) may not show up in the signal when scanning.

To check the spatial uniformity in the intensity of transmission of interference filters, independent of their spectral distributions, the photodetector must have a flat spectral response over the wavelength region in which the deviation may occur. This can be achieved over a wide spectral region by using all three photomultipliers in parallel (S4C in the block schematic of Fig. 1) and selecting photomultipliers with photocathodes which have spectral characteristics that result in a sufficiently flat response for the combination over the desired (or achievable) spectral region. Using a single photomultiplier with a corrective color filter is also a possible solution for achieving a flat response over some portions of the spectrum. However, the latter solution will not yield the same signal-to-noise ratio since the flat response can only be achieved by reducing the amount of light which reaches the photocathode in the spectral region of higher sensitivity of the photomultiplier. A wider wavelength coverage may be needed if one wants to test the spatial uniformity of neutral density filters or to test interference filters for several spectral regions without changing detectors, and in the former case, the whole spectral region of interest should be covered by the spectrum of a polychromatic light source as well as the spectral characteristic of the detector. (Table of Modes).

For studies of radiation emitted by cooled crystals, the computer section of the analyzer is not used. The three photomultiplier outputs are connected directly to a three channel recorder. Thus, the crystal can be examined for emission in three different spectral regions at once. The cooling of the crystals in such an arrangement is not easy, since the crystals must be cooled in a vacuum chamber to prevent frosting. (Mode G). An arrangement is then used where, instead of moving the crystal and keeping the light source and the aperture stationary, the crystal and the vacuum chamber are kept stationary, but the light source, the slit, and some parts of the optical arrangement are moved to cause scanning of an illuminated area over the crystal. This requires the use of large area photocathodes for the photomultipliers to permit sufficient displacement of the area of light.

An alternative system consisting of three cascaded photodetectors may replace the beam splitters and photosensors of Fig. 1.[1] This system has several advantages but is more difficult to obtain by the present state of the art in semiconductor property knowledge. Three successive photoconductive or photovoltaic detectors with the desired spectral responses may be used, where light transmitted by the first and second stimulates the third. Of course, many problems exist in the selection of these detectors. They must all have an adequately high photoconductive or photovoltaic response, with suitable spectral peaks. The first and second detectors must have adequate transmission in the proper spectral region to sufficiently stimulate the detectors following them and the photoconductive or photovoltaic spectral response curves of the second and third will depend on the transmission curves for the preceding detectors. This system has the following advantages of simplification: few parts, low maintenance, low cost, and small size. It can be used for infrared research where the external photoeffect (photocathodes) fails.

Table of Typical Operational Modes for the SIDCA

Specimen under Investigation	Light source, Filters, etc., used for operation	Switch Programming
A. Spectrographic Plate:		
Scanned for information from low contrast plates, detection of finer structure and separation of information from stigmatic plates into separate spectrograms for individual resolution elements.	L1 on, L2 off, no interference filters or spectral correction filters. Suitable neutral density filters to prevent overloading of photomultiplier. Height of effective aperture adjusted for vertical resolution element size on stigmatic spectrographic plate, width of aperture adjusted for selected spectral resolution. Suitable reference spectrogram and with divider or with variable threshold limiter.	S1a; S2a; S3b; S4b; S5c; S6b; S9a; S10a; but position of S8 depends on mode of read out.
B. Monochromator:		
Calibration of SIDCA for spatial spectral measurements. This calibration forms the perimeter of the CIE color triangle on the scope and permits calibration of the visicorder.	L3 on, L2 off. Monochromator changing its selected wavelength over the visible spectrum. Suitable spectral correction filters used in connection with spectral characteristics of photomultiplier to match tristimuli curves of human eye. Suitable neutral density filters to prevent over-loading.	S2b; S3c; S4a; S5a; S6a; S7a; S9 on d for perimeter of color triangle and S10C for calibration of the visicorder, S9 on c for X' trace, S9 on b for Y' trace.

	Individual power supply voltages for photomultipliers and/or C_x, Cy and C_z at computer section set for proper values to obtain correct X, Y, and Z.	
C. Neutral Density Filters <u>Interference Filters, etc:</u>		
Scanning for intensity changes in signal.	L1, L4 or L2 on depending on desired measurement, transmission or reflection and monochromatic or polychromatic. No interference filters. Suitable neutral density filters and spectral correction filters to provide a flat response over the spectral range under consideration.	As in A but S4c and S6c. S1a for L1, S1b for L4.
D. Verlauf Filters, Crystals, <u>etc.</u>		
Scanning for general data.	As in B but L1 on instead of L3. Spectral correction filter I selected for desired color temperature of source.	As in B, but S2a; S1a.
E. <u>Points on Color Triangle:</u>		
Check of correct positions of some points on the perimeter of the CIE color triangle.	No specimen, as in D, but L4 on instead of L1 and suitable interference filters used for selection of desired spectral line of the mercury source.	As in D but S1b
F. <u>Crystal, etc:</u>		
Scanning specimen for determining exceptionally small spatial inhomogeneities by using narrow artificial color triangle.	L1 on, L2 off. No neutral density filter I. Interference filters II, III, and IV selected for desired configuration of artificial color triangle. No spectral correction filters. Neutral density filters II, III, and IV selec-	As in D.

	ted for proper balance between outputs of P_x, P_y, and P_z.	
G. <u>Crystal Emission</u>		
Scanning of cooled crystal for emission caused by ultraviolet excitation.	L4 on, L2 off. Interference filter I or spectral correction filter I matched for selected ultraviolet spectral region emitted by L4. Neutral density filter I selected for degree of excitation. For recording entire spectral regions: No interference filters II, III, and IV. Spectral correction filters II, III, and IV selected for chosen spectral regions to be recorded. For recording narrow bands: Interference filters II, III, and IV selected for chosen narrow bands. No spectral correction filters.	S1b; S2a; S3a; S4b; S5b; S6b.
H. Various Specimens:		
Scanning by using reflected light.	L2 on, L1, L3, L4, off. Filters, etc., selected in accordance with task as shown in previous examples.	Switches operated in accordance with task as shown in the previous examples.

Comments on Crystal Analysis with SIDCA

In using SIDCA for color analysis one must remember that different compositions of light can cause the same ratios, X'' and Y', depending on the spectral characteristics selected for the detectors, and, therefore, more than one artificial color triangle may have to be used for the same specimen in some cases in order to reveal inhomogeneities. Further, one must consider that, when scanning an interference filter with SIDCA for spatial changes in the percentage of transmission, where no change in the relative spectral response occurs, such density changes will not cause a change in the X', X'', or Y' signals, if suitable filter combinations are used for the detectors and SIDCA is set for operational Mode D. On the other hand, if several identical longwave pass filters are superimposed, the steepness of the edge of the characteristic increases. This changes the effective weight of the polychromatic light on the detectors and, hence, the ratios formed by the computer, and a spectral change is recorded. It is necessary to consider this, because crystals of uniform composition but of varying thickness will cause the same effect. Whether the recorded inhomogeneities are caused by a thickness change or a true change in the spectral composition of the crystal may then be determined by taking a stigmatic spectrogram of the areas involved. Obviously inhomogeneities of either type may cause a crystal to be unusable for a target plate.

When using single interference filters to produce nearly monochromatic light, their leakage plus the spectral characteristic of the specimen (crystal) plus the wavelength dependency of the light source may shift the effective spectral region of the light reaching the photomultiplier considerably away from the peak of the interference filter. Often in such a set-up the dominant element which determines the spectral distribution of the light reaching the photomultiplier may be the specimen and not the interference filter. Hence, in order to effectively use light within the band pass of the interference filter only and to avoid erroneous results from the leakage, multiple interference filters or a monochromator may have to be used. When checking crystals for changes in the absorption coefficient effective at the wavelength of the gap or at donor levels, the spectral region of the light should be restricted, as much as possible, to the spectral interval involved. Then, if suitable filters are not available for such specific wavelengths, it may be necessary in many cases to use a monochromator, so that optimum results can be obtained if changes in the absorption coefficient do exist.

Typical Examples of Results Obtained with SIDCA

Figure 3 shows the visicorder traces obtained by scanning spectrographic plates with SIDCA. Several spectral lines, too faint to be visually distinguished with certainty from the background of the original plate, can be recognized in Fig. 3a. Figure 3b shows the structure of a spectral line which appears to the unaided human eye as a single line on the original. Figure 3c shows a trace obtained by scanning, in a conventional manner, a plate with a reflection spectrum obtained by using a tungsten lamp. Figure 3d shows the trace obtained by scanning the plate used for 3c and using a changeable threshold in the threshold amplitude limiter to compensate for the spectral fade-out of the illuminating source. Figure 3e depicts the deviations in the spectral characteristic of different resolution elements on the same crystal by showing a series of spectrograms made by scanning the same stigmatic spectrographic plate and using an effective aperture of 10 μ width by 100μ length for SIDCA. The true limiting vertical spatial resolution of the spectrograph was determined to be 20μ by imaging a fine mesh screen on the slit of the stigmatic spectrograph. When performing these measurements, one must not overlook the limitations set by the adjacency effects, discussed earlier under techniques.

In another use of SIDCA, a verlauf filter (4000Å to 7000Å $\approx$ 3 cm) was used to obtain visicorder traces of X' and Y' and an on-scope color triangle (Fig. 4) closely resembling the CIE standard. An interference filter which changes its wavelength spatially in a continuous manner is often called a verlauf filter or, for short, verlauf. However, this color triangle fell inside the true color triangle due to leakage of the verlauf filter, the fact that the slit used (0.25 mm effective resolution) will pass a fairly wide spectral band (≈25Å) from a verlauf of the size used, failure of the detector responses to exactly duplicate the human eye responses, and failure of the source to duplicate CIE standard "white light". Correcting all the above errors would give the true color triangle.

With the same arrangement, commercial interference filters were tested for their uniformity. Surprisingly, deviations in wavelengths of as much as ± 12 Å were found in some of the better quality filters. The instrument was sensitive enough that the small amount of leakage in a filter with a half intensity bandwidth of 100Å caused the oscilloscope record to fall inside the CIE color triangle, rather than on its perimeter, but, closer to the true perimeter of the CIE color triangle than with the verlauf filter. Figure 4 also shows the trace of a heat damaged interference filter. Figure 5 shows the visicorder trace of the spectral effect caused by a scratch on a high quality optical glass, using (before the photomultipliers) close spaced interference filters which had their peaks at 4660, 5000 and 5330Å.

Figure 6a shows the change in the intensity of the transmitted light through a CdS platelet with striations, using a single 1P21 photomultiplier and a 5000Å filter.

Figure 6b shows the visicorder recording of the X' and Y' signal of the same platelet. The previously described close spaced interference filters (4660, 5000 and 5330Å) were used and the trace shows spectral effects caused by thickness changes not perceivable by the unaided eye or in a scanning mode using the human eye tristimulus responses. The foregoing experiments with SIDCA indicate that it should become an extremely useful research tool, especially for crystal analysis. It will do many different tasks in spatial analysis of both intensity and spectral variations and, when used in conjunction with a stigmatic spectrograph, can reduce the time required for surveying a large number of samples to a fraction of what is otherwise needed.

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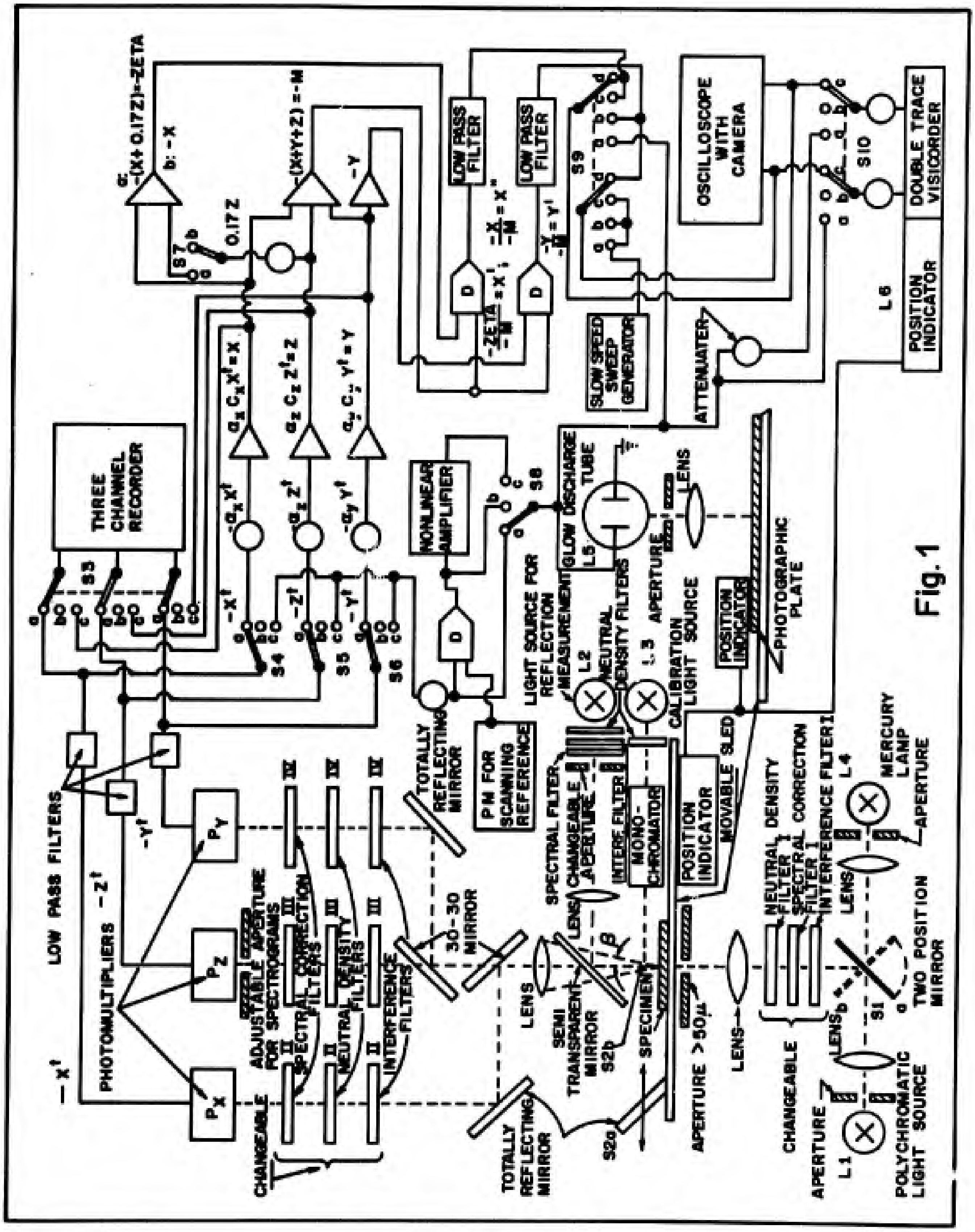
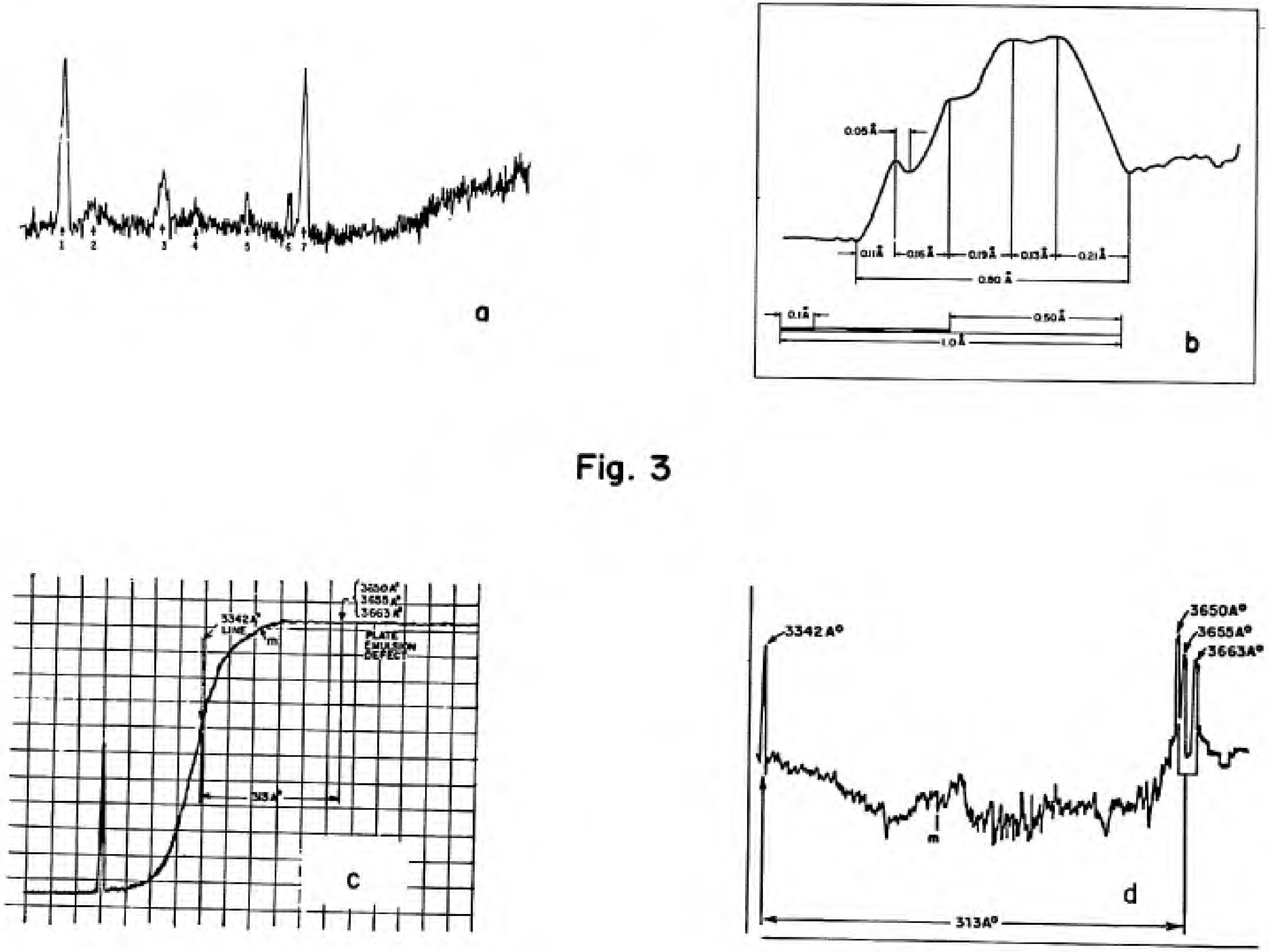


LOW PASS FILTERS
PHOTOMULTIPLIERS
THREE CHANNEL RECORDER
CHANGEABLE
ADJUSTABLE APERTURE FOR SPECTROGRAMS
SPECTRAL CORRECTION FILTERS
NEUTRAL DENSITY FILTERS
INTERFERENCE FILTERS
TOTALLY REFLECTING MIRROR
30-30 MIRROR
LENS
SEMI TRANSPARENT MIRROR
SPECIMEN
APERTURE >50μ
PM FOR SCANNING REFERENCE
NONLINEAR AMPLIFIER
LIGHT SOURCE FOR REFLECTION MEASUREMENT
GLOW DISCHARGE TUBE
SPECTRAL FILTER
CHANGEABLE APERTURE
INTERF. FILTER
MONO-CHROMATOR
POSITION INDICATOR
MOVABLE SLED
NEUTRAL DENSITY FILTERS
CALIBRATION LIGHT SOURCE
PHOTOGRAPHIC PLATE
NEUTRAL DENSITY FILTER I
SPECTRAL CORRECTION FILTER I
INTERFERENCE FILTER I
MERCURY LAMP
APERTURE
TWO POSITION MIRROR
POLYCHROMATIC LIGHT SOURCE
SLOW SPEED SWEEP GENERATOR
ATTENUATER
LOW PASS FILTER
OSCILLOSCOPE WITH CAMERA
DOUBLE TRACE VISICORDER
POSITION INDICATOR

Fig.1

Fig. 2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a
0.05 Å
0.11 Å
0.16 Å
0.19 Å
0.13 Å
0.21 Å
0.80 Å
0.1 Å
0.50 Å
1.0 Å
b
3342 A°
LINE
m
3650 A°
3655 A°
3663 A°
PLATE
EMULSION
DEFECT
313 A°
c
3342 A°
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3655A°
3663A°
m
d
313A°

Fig. 3

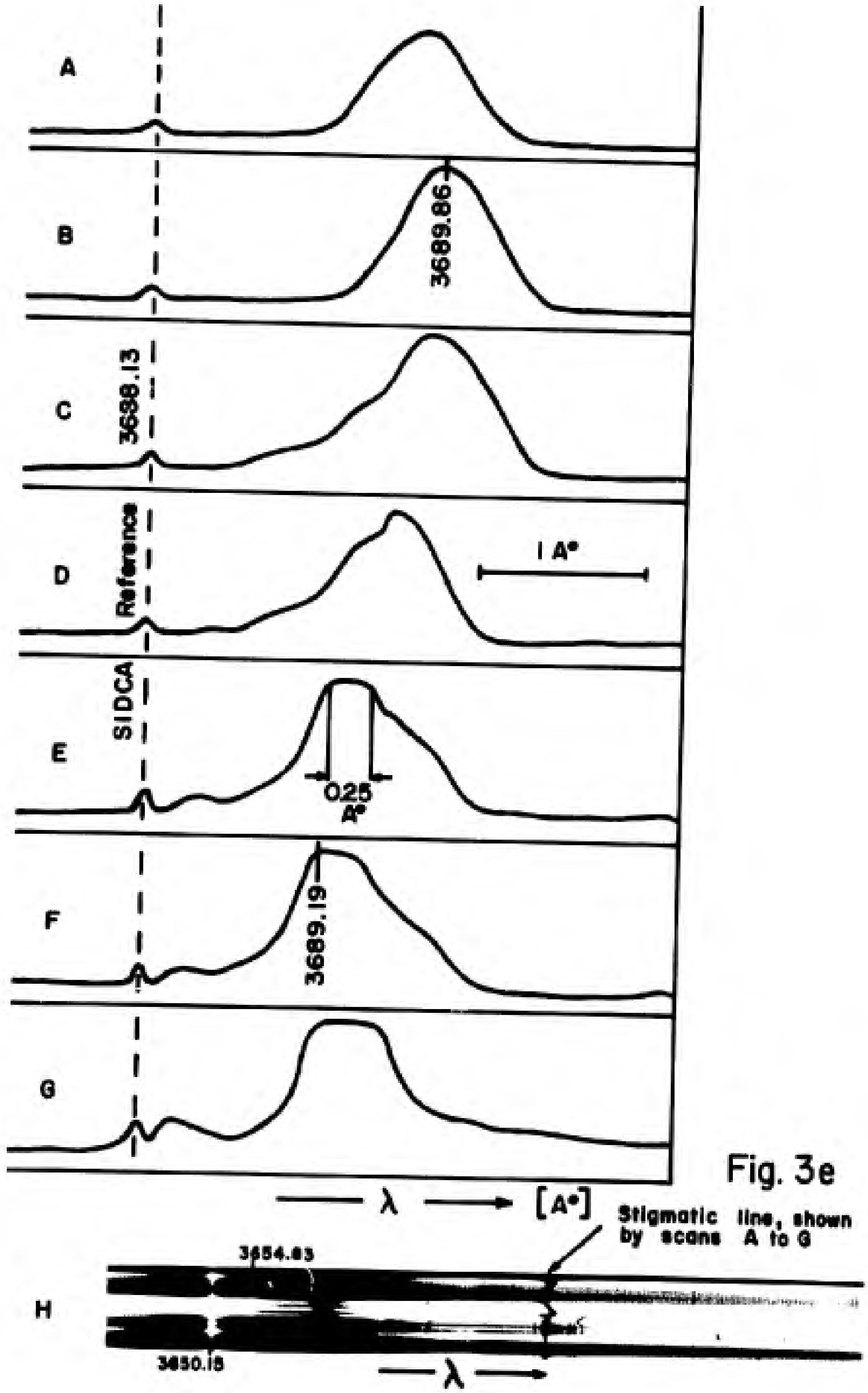
A
B
3689.86
C
3688.13
D
Reference
1 A°
E
SIDCA
0.25 A°
F
3689.19
G
λ [A°]
Stigmatic line, shown by scans A to G
H
3654.83
3650.15
λ

Fig. 3e

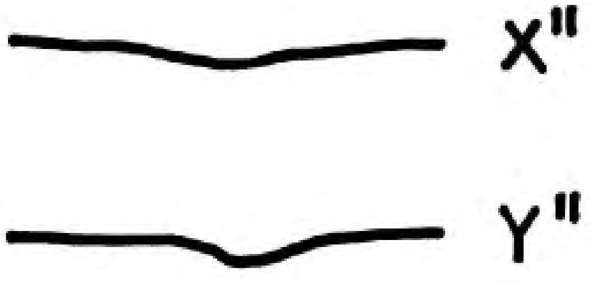

Fig. 5

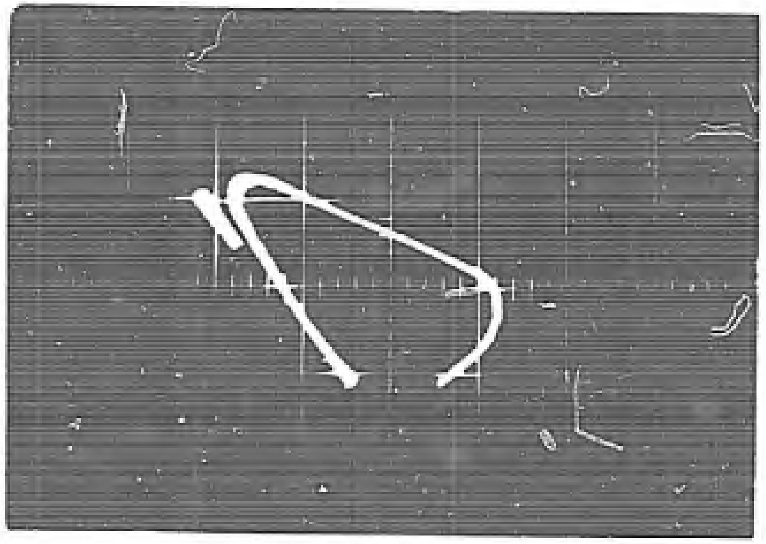

Fig. 4a

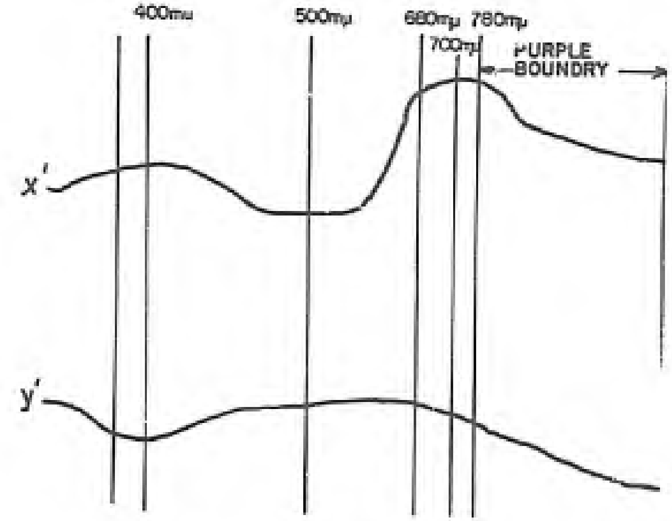

Fig. 4b

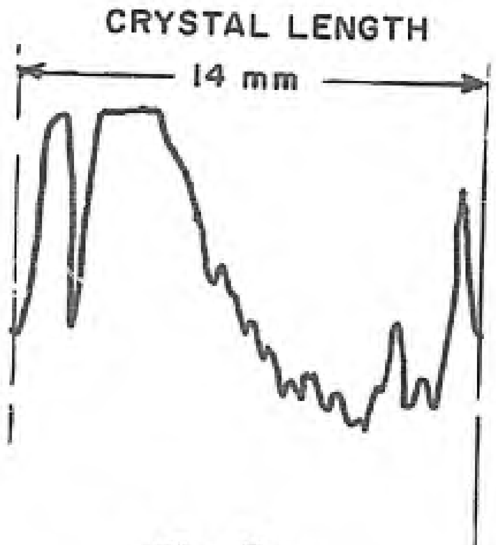

Fig. 6a

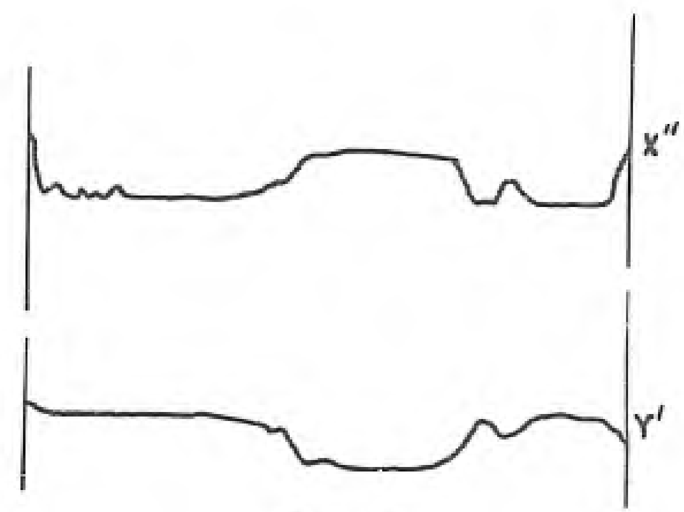

Fig. 6b

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13. ABSTRACT

Research leading to new and more advanced imaging devices requires extensive study of large quantities of different semiconductor plates. Very useful in this endeavor is the Spatial Intensity Distribution and Color Analyzer (SIDCA) which, if used properly in connection with a stigmatic spectrograph, reduces the number of spectrographic plates needed for analyzing a target plate from a prohibitively large number to a reasonable one. SIDCA is a specially designed and built opto-electronic scanner using three photomultipliers in connection with suitable filtering, nonlinear amplification techniques, and an analog computer. It can be used in an intensity or spectral analyzing mode. In spectrographic plates, SIDCA can detect information which is not readily perceivable by the human eye. Furthermore, it can map the flaws and spatial uniformity of potential target plates or optical elements by directly scanning them in a transmission or reflection mode. Also, it can show the spatial distribution as a result of diffusion when employing spot doping and can be used for studying spatial effects of emissions from excited semiconductors. Furthermore, it may be used for determining the spatial homogeneity of optical elements such as interference filters, etc. When using appropriate filter-photomultiplier combinations, SIDCA can identify colors in the standardized CIE color triangle; then, the analog computer performs the mathematical operations which result in the presentation of the appropriate locus in the triangle on an oscilloscope, where the parabolic portion of the triangle is obtained by scanning a low leakage verlauf filter or using a suitable, variable monochromator. In addition, artificial color triangles, produced by using closer spaced spectral filters, provide a way to distinguish smaller increments in hue or wavelength. When

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scanning spectrographic plates with this instrument, oscillographic records or new plates may be made that show detectable information too low in contrast on the original plate to be perceived by the unaided eye. Spatial expansion can be used in the new recording and provides easy evaluation of structures within an apparent line, but errors may be introduced by the adjacency effects in the original plate. For mapping a specimen, the signal obtained may be recorded, line by line, with conventional oscillographs or may be depicted using an image storage reproducer, displaying otherwise unperceivable detail.

Unclassified

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