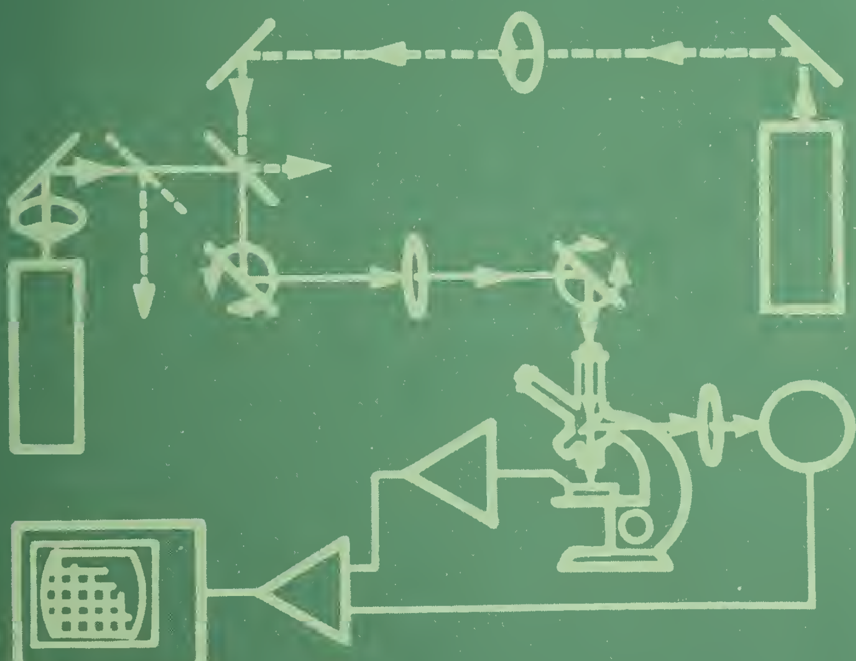
SPECIAL PUBLICATION 400-27

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Semiconductor Measurement Technology:

Laser Scanning of Active Semiconductor Devices



Videotape Script

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Semiconductor Measurement Technology:

Laser Scanning of Active Semiconductor Devices—Videotape Script

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PREFACE

This is the script for the second in a series of videotape presentations being distributed on loan without charge in order to disseminate more effectively to the semiconductor community the measurement technology improvements developed under the Semiconductor Technology Program in the Electronic Technology Division of the National Bureau of Standards (NBS).

The Semiconductor Technology Program serves to focus NBS efforts to enhance the performance, interchangeability, and reliability of discrete semiconductor devices and integrated circuits through improvements in measurement technology for use in specifying materials and devices in national and international commerce and for use by industry in controlling device fabrication processes. Its major thrusts are the development of carefully evaluated and well documented test procedures and associated technology and the dissemination of such information to the electronics community. Application of the output by industry will contribute to higher yields, lower cost, and higher reliability of semiconductor devices. The output provides a common basis for the purchase specifications of government agencies which will lead to greater economy in government procurement. In addition, improved measurement technology will provide a basis for controlled improvements in fabrication processes and in essential device characteristics.

The Program receives direct financial support principally from three major sponsors: The Defense Advanced Research Projects Agency (ARPA),* the Defense Nuclear Agency (DNA),† and the National Bureau of Standards.× The ARPA-supported portion of the Program, Advancement of Reliability, Processing, and Automation for Integrated Circuits with the National Bureau of Standards (ARPA/IC/NBS), addresses critical Defense Department problems in the yield, reliability, and availability of integrated circuits. The DNA-supported portion of the Program emphasizes aspects of the work which relate to radiation response of electron devices for use in military systems. There is considerable overlap between the interests of DNA and ARPA. Measurement oriented activity appropriate to the mission of NBS is a critical element in the achievement of the objectives of both other agencies.

Essential assistance to the Program is also received from the semiconductor industry through cooperative experiments and technical exchanges. NBS interacts with industrial users and suppliers of semiconductor devices through participation in standardizing organizations; through direct consultations with device and material suppliers, government agencies, and other users; and through periodically scheduled symposia and workshops. In addition, progress reports are regularly prepared for issuance in the NBS Special Publication 400 sub-series. More detailed reports such as state-of-the-art reviews, literature compilations, and summaries of technical efforts conducted within the Program are issued as these activities are completed. Reports of this type which are published by NBS also appear in the Special Publication 400 sub-series. Announcements of availability of all publications in this sub-series are sent by the Government Printing Office to those who have requested this service. A request form for this purpose may be found at the end of this report.

*Through ARPA Order 2397, Program Code 6D10 (NBS Cost Center 4257555).
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Semiconductor Measurement Technology:

Laser Scanning of Active Semiconductor Devices

Videotape Script

by

David E. Sawyer

and

David W. Berning

This is the script of a videotape presentation which describes new and powerful applications for laser scanning in semiconductor device design and reliability work. The design of the scanner is described in detail and many of its applications are displayed and discussed. The optical scanner can, in a completely nondestructive way, reveal the inner workings of semiconductor devices. For example, it is shown that the scanner can (1) map dc and high-frequency gains in transistors, (2) reveal areas of the device operating in a nonlinear manner, (3) electronically map temperature in the transistor, and (4) detect the location of hot spots that can develop for certain operating conditions. The vehicle used to show these capabilities of the scanner is a bipolar interdigitated UHF transistor. A dual input NAND gate is used to demonstrate the use of the scanner to determine internal logic states and otherwise observe internal operation of the circuit. To show the ability of the scanner to examine MOS devices without detectable degradation, a MOS shift register is used. The location and progress of internal logic in the register is clearly shown by the scanner. Not only can internal logic be mapped and marginally-operating logic cells detected, but individual logic states can be changed by the scanner without affecting other elements.

Key Words: Failure analysis; hot spots; integrated circuits; laser scanner; measurement method; nondestructive test; nonlinear operation; optical scanner; reliability; transistors.

<u>Sawyer</u>

Hello. My name is David Sawyer, and seated next to me is David Berning. We are staff members of the Electronic Technology Division at the National Bureau of Standards, Washington, D. C., and we would like to tell you about our work with an optical scanner which we developed. This scanner has been used to reveal, in a completely non-destructive way, the inner workings of semiconductor devices by taking advantage of the photosensitivity of semiconductor materials. We have looked both at discrete devices and at integrated circuits (IC's) with it. **(000)***

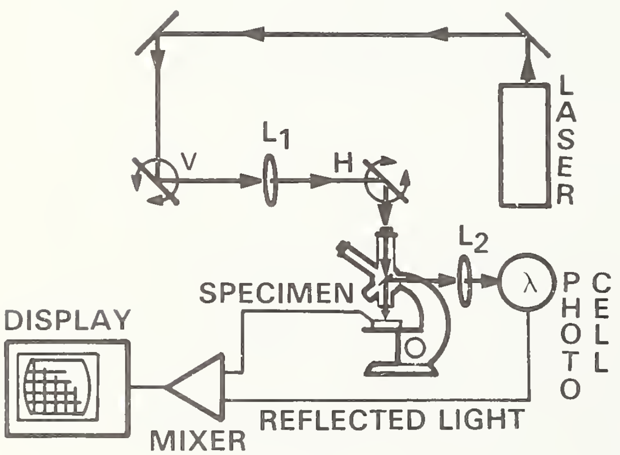
The effect of scanning a device is to create current-carriers inside to excite it electrically, and this allows us to map the operation of the device over its active

*Tape counter setting.

area. In many cases, this can be done while the device is functioning in its usual (018) manner in a circuit. We will demonstrate this with photographs showing the results of scanning bipolar and MOS IC's to reveal internal logic states, and we will show that the scanner may also be used to change the state of an embedded logic cell reversibly. Then a discrete device, a UHF transistor, will be used to demonstrate some of our newer scanner applications by revealing the location of hot-spots, and mapping regions where the transistor is operating in a nonlinear fashion. Some of our latest work with the same transistor type suggests that the scanner can be used also to map electronically the temperature variations within functioning devices. During the presentation, we will be making suggestions as to how scanner setups such as this might be used in device design and also used to assist in evaluating device reliability. But first, we would like to tell you briefly how the scanner works and list some of its attributes. David?

Berning

In the design of the scanner we have incorporated ideas from Sawyer's previous efforts [1], as well as ideas obtained from other sources [2]. The scanner is quite simple in principle. Let me show you how it works. [Graphic 1] On the upper right, optical radiation from a low-power cw helium-neon laser is reflected in sequence from four mirrors. The first two fold the optical path to make the scanner more compact and rugged. The second two, labeled V and H, are vertical and horizontal deflection mirrors, respectively, which oscillate in orthogonal directions. The laser beam is directed through the camera tube of a standard microscope onto the specimen. The beam is focussed to a small spot on the specimen and is deflected across it in a raster pattern. The same electrical sources that drive the deflection mirrors also deflect the spot on a cathode ray display screen in synchronism with the laser scan. The display screen is on the lower left of the chart. By electrically connecting the scanned specimen to modulate the spot on the display screen, a map of the device's photoresponse is obtained. Let's go back to the mirror scanning



Graphic 1

[1] Potter, C. N., and Sawyer, D. E., A Flying-Spot Scanner, *Rev. Sci. Instrum.* 39, 180-183 (1968).

[2] McMahon, R. E., Laser Tests IC's with Light Touch, *Electronics* 44, 92-95, (April 12, 1971).

system. The lens L_1 between the vertical and horizontal deflection mirrors refocuses the vertical deflection, from V, onto the horizontal mirror, H [3]. The beam diverges from the horizontal deflection mirror, H, to form the scanning raster. Mirror H is located at the exit-pupil point of the microscope camera tube. The scan raster typically covers all of the field of view that can be seen with the eye when the microscope is used in its usual manner. For the microscope which we have, it is not possible to scan the specimen and observe the specimen with the eye at the same time. Switching between these two functions is performed by moving a prism within the microscope. Perhaps this is a good thing, for even though the lasers we use are low-powered there always is the possibility that under certain conditions the laser beam might be reflected directly into the eye and cause some discomfort. But it would be useful if we could always know which portion of a specimen is being scanned, and this is one of the main functions of the reflected-light circuit. The reflected-light circuit makes use of a half-silvered mirror in the microscope, lens L_2, and a photocell. The mirror comes as an integral part of the microscope vertical illuminator. Laser radiation reflected from the specimen is directed by the half-silvered mirror onto the lens and photocell. The photocell signal modulates the display screen to present a picture of the device surface topography. Used this way, we could call the apparatus a "flying-spot microscope". It is useful in its own right, and of course no electrical connections to the specimens are required. But the main purpose of the flying-spot scanner is to learn the specific details of device operation by monitoring the electrical effects of electron-hole pairs photogenerated within the device, and so the primary purpose of the reflected-light circuit is to pinpoint the device response with relation to surface features such as metallization areas. This is accomplished simply by mixing together the signals from the scanned specimen and the photocell. (080)

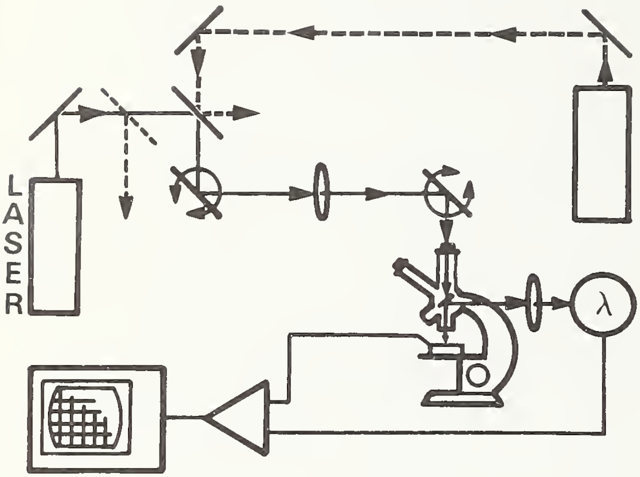
Sawyer

We extended the capability of our scanner by adding a second dedicated laser. [Graphic 2] We can change between them by sliding a mirror — which carries the second laser beam from the left — in or out of the path of the first laser beam. I will tell you the reason for having two lasers in a moment. But let us first finish the description of the entire scanning system. [Graphic 3] This is the schematic of the complete system and shows a few items which did not appear before. The laser on the left operates at 0.633 μm, in the visible red, and the right one at 1.15 μm, in the near infrared. They both are cw helium-neon lasers, one is equipped with mirrors to permit it to oscillate at 0.633 μm, and the other with mirrors for 1.15 μm operation. The system also has a rotatable analyzer in the 0.633-μm laser path on

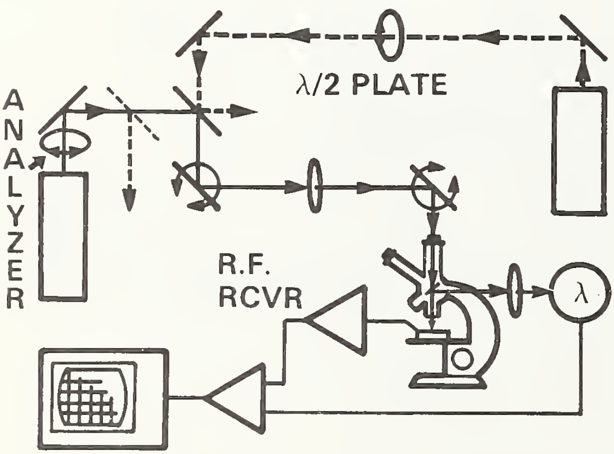
[3] Beiser, L., Laser Beam Scan Enhancement through Periodic Aperture Transfer, *Applied Optics* 7, 647-650 (1968).

the left, a half-wave plate in the 1.15-μm path, on the upper right, and a radio-frequency receiver in the specimen signal path, just to the left of the microscope specimen stage. (150)

Now let us show you what the scanner actually looks like. [Graphic 4] This is a photograph of the scanner in our laboratory. A frame holding all of the optics for the system is rigidly attached to the microscope stand. One of the lasers is easily identified in the view. It is mounted on the right hand side of the frame. An 8 X 10 display screen, on the left, provides a large display that can easily be seen by several persons. The signal generators that provide the vertical and horizontal deflection signals for the scanning mirrors and the display can be seen above the display screen. A preamplifier and mixing amplifier are located above the generators. The shelf above the scanner holds some supporting electronics for the system. These include the radio receiver, scanning mirror power amplifiers, laser power supplies, a dc to 100 kHz laser modulator, and some other power supplies used for specimen excitation.

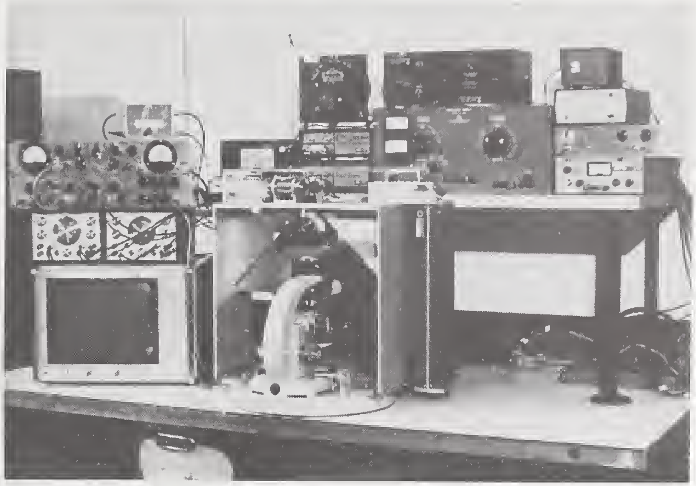


Graphic 2



Graphic 3

We added the second laser to the scanner to give us greater measurement flexability. This flexability comes from the difference in penetration depths of the radiation from the two lasers. Light and near-infrared radiation incident on silicon creates electron-hole pairs with a generation rate which exponentially trails off with distance into the material. The penetration depends on the wavelength of the incident radiation. For each wavelength we can associate a characteristic penetration length as that distance required to decrease the pair generation rate to 36.8% of its value at the surface. This 36.8% value is simply the reciprocal of e, the base of the natural logarithm system. The 0.633-μm visible light from the first laser mentioned has a



Graphic 4

characteristic penetration depth in silicon of about 3 micrometers [4]. Because (198)
most modern silicon devices have their active regions within a few micrometers of the surface, the 0.633-μm laser is quite effective in mapping active regions of operating devices. For this reason, this laser has been our "work horse" for device scanning. The light from the laser is already polarized, and so the rotatable analyzer I mentioned earlier provides a convenient way to adjust the illumination intensity. The intensity at the specimen can be varied to produce junction photocurrents over the range from about 10 picoamperes to about one-tenth of a milliampere.

Silicon at room temperature is almost transparent to 1.15 μm infrared radiation from our second laser. The characteristic penetration depth of this radiation is about one centimeter [4]. Because of this weak absorption we need to utilize as much of the laser intensity as we can. There are several air-glass interfaces within the microscope which can attenuate the infrared radiation selectively, depending on the specific angle of polarization at each interface, and so it is helpful to be able to rotate the plane of polarization of the laser to find the optimun incident polarization angle through the system. This is the purpose of the half-wave plate I mentioned earlier. The half-wave plate is rotated to yield a maximum specimen signal.

We use the infrared laser for two classes of measurements, both of which make use of the penetrating nature of the radiation. In the first, we can use the reflected light circuit to look through the silicon wafer and observe irregularities at the silicon-header interface. This application uses the scanner in the

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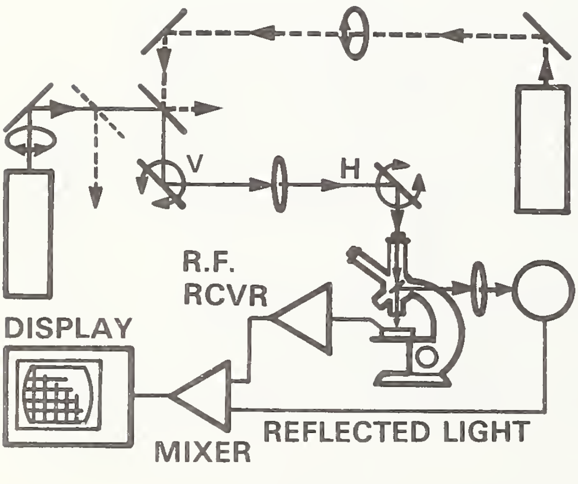
[4] Dash, W. C., and Newman, R., Intrinsic Optical Absorption in Single-Crystal Germanium and Silicon at 77° and 300°K, *Phys. Rev.* 99, 1151-1155 (1955).

"flying-spot microscope" mode we mentioned earlier. The second application makes use (238)
of the temperature sensitivity of the silicon absorption. It produces a larger signal on the display screen for those device portions which are warmer than others. Utilizing this sensitivity, we have an electronic technique for thermal mapping of devices which appears to have a number of advantages over the more traditional methods. We will show you an example of this application later on.

Since the scanner's optical system uses refractive optical elements, one has to refocus the scanning raster with the use of the reflected light circuit when one changes from one wavelength to the other. But this is not too bothersome, although a system using only reflecting optics would obviate this minor inconvenience.

During normal operation, the lasers produce optical radiation not at just one discrete wavelength but at a series of discrete wavelengths centered about the nominal wavelength. These wavelengths correspond to the individual allowed axial modes of the laser. Mixing of these wavelengths has the effect of modulating the light simultaneously at several frequencies. The modulation frequencies are multiples of a fundamental one, and for our visible laser, the light is self-modulated at 500 MHz and 1.0 GHz to a degree adequate for determining the response of devices to light modulated at these frequencies. The corresponding frequencies for our infrared laser are 385 and 770 MHz. We can determine the response of a specimen to optical radiation modulated at these frequencies. Looking again at the diagram of the scanning system, [Graphic 5] we determine this response by inserting a radio receiver between the specimen on the microscope stage and the mixing amplifier and tuning the receiver to the desired modulation frequency. This technique has been used to map the frequency dependence of device characteristics and also R-C effects in distributed passive structures.



Graphic 5

To complete the coverage of the important attributes of the scanner we need to describe briefly the deflection circuits, mixing amplifier, and display screen. And, we should make some statements about the optical resolution of the system. David, if you will summarize these items, then we will move along to show some results we have obtained using the scanner on operating devices.

The keynote of our scanner design was flexibility. We did not want the range (287) of applications to be limited by the equipment, so we designed the scanner to be as versatile as possible. For example, the rate of the horizontal or vertical mirror deflection sweeps, either or both may be varied between 3 mHz and 1.1 kHz. The upper frequency is established by mechanical resonance of the mirrors. The low-frequency range allows us to observe phenomena which are intrinsically slow, carrier trapping for example. But this is not a consideration in much of our work. We generally use a 1 kHz horizontal sweep frequency and a 3 Hz vertical sweep. This gives us a 330 line scan which yields adequate definition.

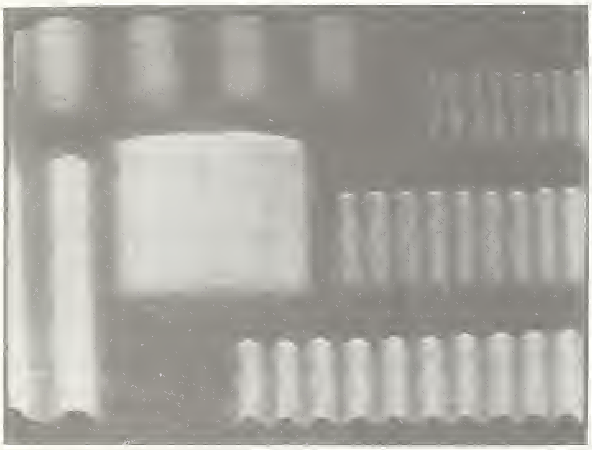
The mixing amplifier was designed by us, and it is flat from dc to about 2 MHz. Filters are built-in which provide low-frequency roll-off when desired. The dc capability is a necessity when slow sweeps are employed. Its use is generally desirable at other times as well, since it yields a more accurate display; however, drifting and noisy specimens necessitate using the filters sometimes. The mixing amplifier contains three channels, which permit us to perform algebraic operations on the amplifier inputs. For example, we can obtain the specimen output for the unmodulated component of the laser radiation. We call this the specimen's video response. Simultaneously we can pick off the specimen output at the laser R.F. frequency component with the R.F. receiver, and can subtract the two to present on the screen only the difference to show the change in device behavior with frequency. At the same time, we may add the reflected light signal so that the net change in electrical response is superimposed on a picture of the surface of the device. The display mode also may be varied. One mode modulates the intensity of the electron beam on the 8 X 10 inch screen in the conventional manner while the other mode injects the signal into the vertical deflection amplifier. This latter, "Y-axis", modulation mode produces pictures that appear to have a three-dimensional quality. One of the advantages of the vertical-deflection mode is that it allows the specimen response to be quantified, since the screen vertical deflection can be calibrated in terms of specimen signal current or voltage. The next chart [Graphic 6] demonstrates a mixture of both the intensity modulation and the vertical deflection display modes.

This is a photograph of the display screen where the specimen scanned is a chrome-on-glass pattern test target placed over a photodiode which generates the electrical signal monitored. You see only a very small portion of the test pattern. The display was generated using the visible laser. The finest pattern of lines shown here is on the upper right. This pattern consists of 2-μm wide bars spaced 2 μm apart which are clearly resolved. So we say that our optical resolution is somewhat better than 2 μm. The same measurements made using the infrared laser results in a slight degradation of detail. We associate with the infrared laser usage a resolution of better than 3 μm, referred to the specimen.

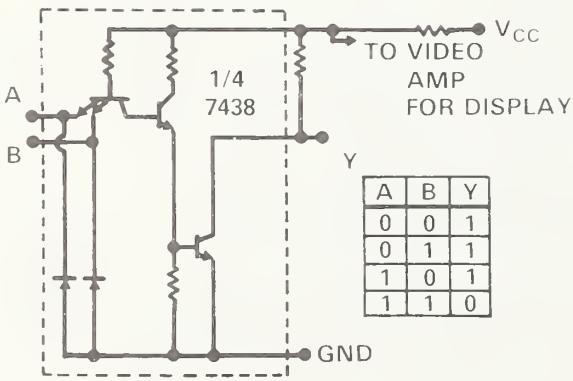
One further point before we move on to devices, all the device results which (347) we will show are qualitative. But we believe the scanner also can provide quantitative information if we determine, with a calibrated photodiode, for example, the photon flux at the scanned specimen and if we calibrate the display screen in terms of photovoltage or photocurrent from the specimen. We could then attach numbers to the input-output interactions and in this way quantify specimen behavior.

Sawyer

Now that we have described the scanner to you in some detail, let us move on to show you some of the ways the scanner can be used. A good example of the capabilities of the scanner is shown by the results we obtained some time ago with a type 7438 dual-input NAND gate scanned with visible light. In this chart [Graphic 7] we have a schematic of the 7438. It is a bipolar IC with the output transistor normally in its high or nonconducting state. To switch the output transistor to its low state, that is into saturation, requires that both inputs be in their high state. The inputs are labeled A and B and the output is labeled Y. In the truth table on the lower right, the designations 1 and 0 tell, respectively, whether the specified circuit state is high or low. The circuit state is specified by a trio of numbers representing A, B, and Y, in that order. For example, the case in which both A and B are high to cause the output to go low is listed in the truth table as 110.



Graphic 6

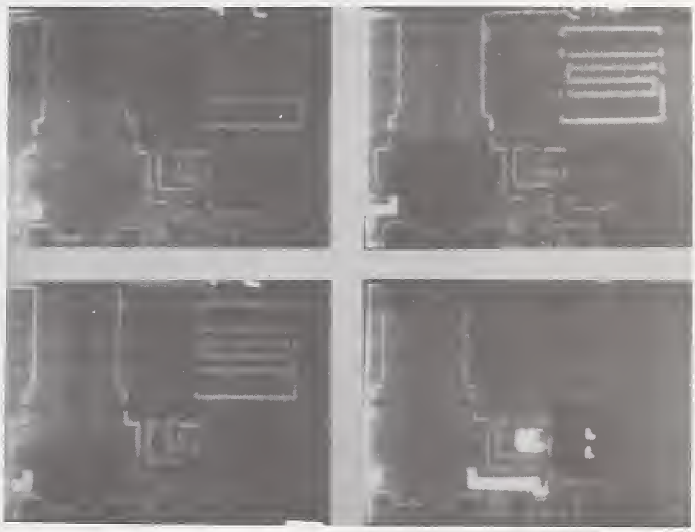


Graphic 7

The electrical response of the circuit to the scanning light spot is revealed in the following manner. The effect of the light spot is to generate current carriers in the silicon. When these current carriers are generated near active elements they may alter the current through the supply bus, depending on the operating condition of the element scanned. This change in current is detected as a change in the voltage drop across a resistor inserted in the supply bus, which is shown in the upper right. The voltage signal serves as the input to the mixing amplifier and display screen. For example, a transistor operating so that it has significant small-signal current gain will show a large photoresponse to the scanning light spot and consequently produce a bright image on the display screen. On the other hand, a transistor operating with little small-signal current gain, such as when it is in saturation, will produce no image. Thus, from the photoresponse of the elements in the circuit, the different logic states can be deduced. Naturally, changing the state of the NAND circuit yields a new photoresponse display of the active elements. (390)

The next graphic [Graphic 8] shows photographs of the display screen for the four different states. The photograph on the upper left shows the image on the display screen for the 001 condition. The large rectangular pattern of horizontal stripes in the upper right is the output transistor's base-collector region scanned by the laser. The transistor is in its high state and, as expected, an appreciable photoresponse is obtained because the photocurrent is amplified by the small-signal current gain of the transistor. In order for the output transistor to be in its high state, the truth table predicts that the input transistor have one or both emitter inputs in their low state. The input transistor is located directly below the output transistor, and as can be seen, no photoresponse is obtained in this area. This is because no amplification of the photogenerated current in the input transistor can occur in the circuit unless both inputs are in their high state.

The two photographs on the upper right and on the lower left are for the 101 and 011 states, respectively. For neither of these two states are both emitters of the input transistor in their high state, and so amplification occurs. The last photograph, on the lower right, is for the 110 state. The output is in saturation and so no photoresponse is seen in this area. The two L-shaped lighted areas on the lower right quadrant are the base-collector regions around the two emitters of the input transistor. The illuminated region to the left is the interstage transistor, and the horizontal bar below this transistor is the 4-kΩ load resistor for the input transistor. This diffused resistor shows up on the display screen because the resistor material, silicon, is photoconductive. In order for this photoconductivity to be observed, a current must flow through the resistor, and be amplified by the interstage transistor which occurs only in the 110 state.



Graphic 8

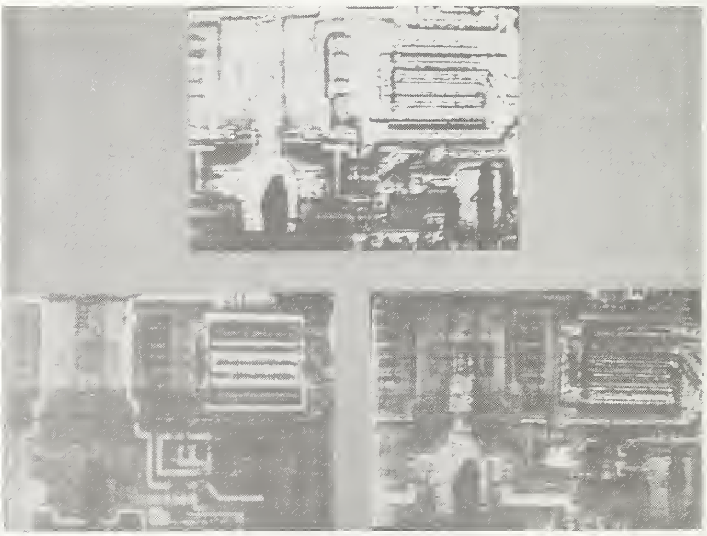
It is sometimes useful to see the surface of the circuit to identify various areas on such displays. In the next graphic [Graphic 9] we have three photographs of the same circuit but now with the reflected light mode added. On the top, is a display generated solely from reflected light. In the other two, the electrical signal from the supply bus has been added to the display. The photo on the lower left is for the 001 state, and the one on the right is for the 110 state.

The fact that a diffused resistor could be detected by its photoconductivity led us to believe that we might be able to tell which transistors in an MOS array were ON by observing channel photoconductivity. We were successful in doing this and David Berning will describe the results.

Berning

The scanner was used with visible light to observe logic information passing through a MOS shift register. The shift register was a static dual 128-bit P-MOS ion-implanted device and the operation of the circuit was easily observed without altering the device characteristics. In order to be able to observe the logic flow in the device with the laser scanner, the package leads are connected as appropriate for normal circuit operation. The information which describes the circuit operation is extracted by monitoring variations in power supply current to the device, as was explained for the bipolar NAND gate.

To prepare you for viewing the shift register scanned in real time, I would like to first show you some photographs of the display screen when the scanner was used to view the shift register. [Graphic 10A] The upper left photograph shows about one third of one of the 128 bit registers and some associated input/output circuitry on the far right of the photograph. In the main part of the register a



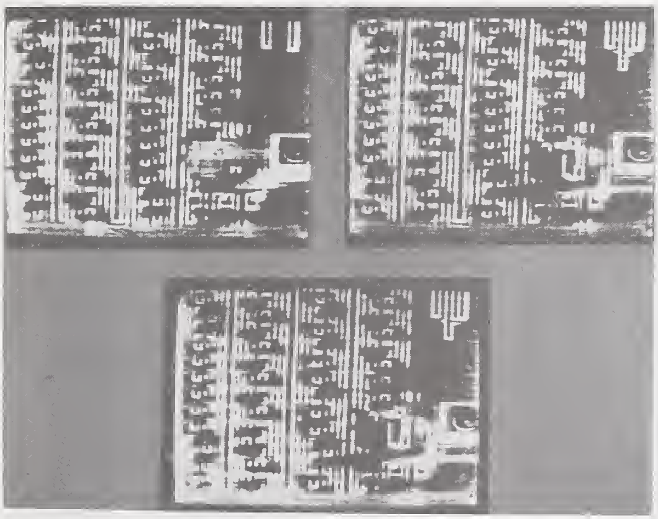
Graphic 9

random pattern of logical 1's and 0's can be seen which appear as arrangements of dark and light areas along four columns, starting from the left. The logic flows in the register along a snake-like path which begins in the left hand column at the bottom. It flows up this first column, then down the second column, up the third, and down the fourth to where it switches the output circuitry at the bottom of the fourth column. The logical 1's and 0's are easily identified in this particular shift register: if we look along the direction of motion, and this would be the vertical direction for the first column, the 1's are those elements bounded on the right by two parallel light bars, and the 0's are the elements bounded on the left by two parallel light bars. So, for example, in the first column on the left and starting from the bottom, the first two cells are 1's and the next six are 0's.

The upper right photograph shows the same register after a single clock pulse has been injected through the clock input and a logical 1 injected through the data input. To help you see how the logical 1's and 0's have shifted, we have labeled them in the first column of the two upper photographs. [Graphic 10B] The output has also switched states.

Demonstrated here is the operation of a good device. Our laser scanning technique should be able to detect sections of the device which are marginal. When this circuit was operated with reduced power supply voltage, it was observed that some logic cells did not always function properly. In looking at a defective circuit, we have been able to detect improper internal operation.

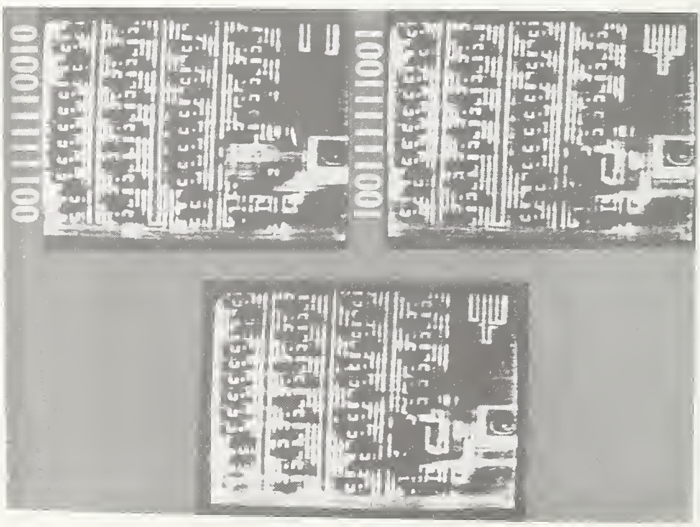
It was also found while scanning this MOS device that internal logic states can be changed non-destructively by increasing the laser intensity with the polarizer-analyzer. In fact, the laser has to be attenuated before stable logic states can



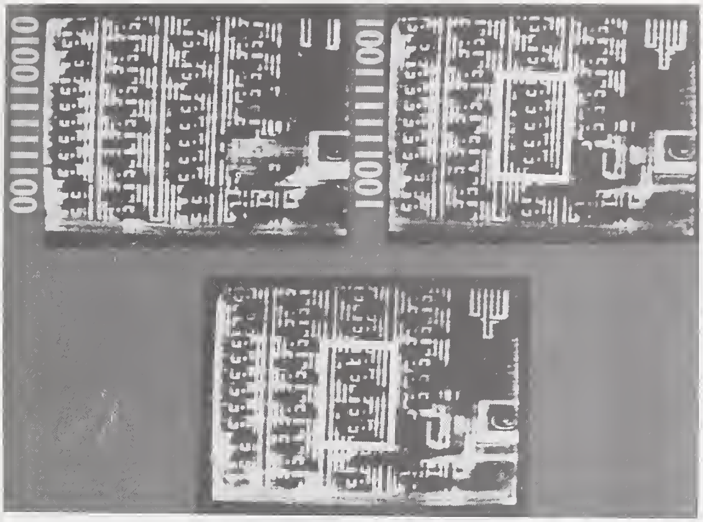
Graphic 10A

exist in the register. Logical 1's can be selectively changed to 0's and vice versa. We do this by first decreasing the laser scan raster to a region on the logic cell where a change is desired. The scan raster is decreased by electronically decreasing the excursion of the laser deflection mirrors. The laser intensity is then increased to change the state of the cell, after which the beam is returned to its previous intensity. The laser raster scan then can be restored to its original size. This operation changes the state only of the desired cell and does not affect the state of any other cells in the register. In this case aiming the laser to one side of the logic cell changes a 0 to a 1, and aiming to the other side changes a 1 to 0. Aiming the laser is accomplished by moving the microscope stage on which the device rests. The bottom photograph shows the register as it appeared in the upper right except that the laser was used to selectively change one of the logic cells. The cell changed is the center one in a group of five logical 1's located in the third column. The group is enclosed with a white line to help you see them. [Graphic 10C] You may be able to note that no other logic cell has been changed and no input pulses were injected into the device. The ability to change internal logic states non-destructively may have far reaching benefits in the testing of LSI devices which have internal processing blocks which are not accessible externally. (487)

Now that you have had a chance to become acquainted with what the shift register looks like as revealed by the scanner, let's look at a videotape we made in our laboratory of the progression of logic through the MOS shift register. [Videotape begins] This was taped in real time from the scanner's display screen. You see here as you saw in the previous photographs a random pattern of logical 1's and 0's. The device can easily be moved on the scanner to see the areas of interest. All 128 storage units in this register can easily be located.



Graphic 10B



Graphic 10C

We are now going to enter a series of logical 1's into the register by using the clock and data inputs on the device. These can be observed moving into the register at the bottom of the first column. As each logical 1 is injected all of the other logical states move along the register as they should — up the first column, down the second, up the third, and down the fourth to where the output stages receive either a 1 or a 0, and switch as appropriate. (525)

To observe the logic levels in this delicate device, the laser beam had to be attenuated with the polarizer-analyzer. If the laser intensity is increased by a small amount, one can observe the logic elements switching randomly. As was stated before, if the scanning raster is reduced to a point and aimed at any individual cell, the cell's state can be changed predictably.

If the laser intensity is increased still further, the logic cells appear to saturate.

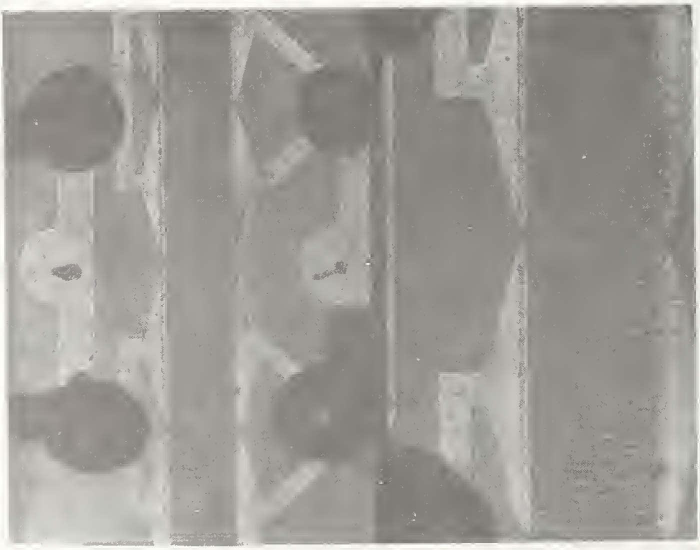
When the laser intensity is restored to its original level, once again stable states form in the shift register, and these states can be moved through the circuit as before. [Videotape ends]

Sawyer

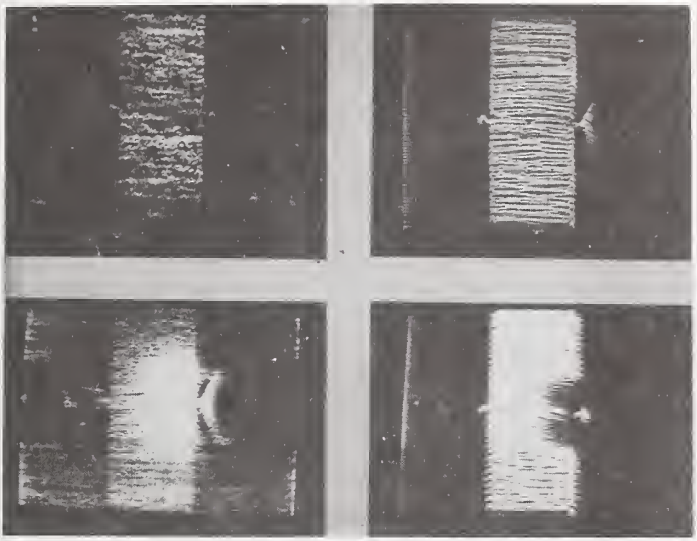
We would like to show you next how the scanner can be used to map, almost simultaneously, low-frequency electrical characteristics, the high-frequency electrical characteristics, and the thermal behavior of a device, and also tell about the uniformity of operation over the device area when it is working within its normal frequency range. We will demonstrate this with a type 2N4431 UHF transistor. This widely available transistor type is designed to furnish 5 watts at UHF frequencies up to 1,000 MHz. The surface topology for the transistors we have worked with is shown next by the photomicrographs in the next graphic. [Graphic 11] There are four in-line cells electrically connected in parallel, and these are shown in the left photograph. The total active area of the transistor is a rectangle 1.2 mm long and 0.15 mm wide. The photograph on the right is an enlargement. You may be able to see that the emitter and base fingers are interdigitated with the emitter fingers coming in from the right, and the base fingers coming in from the left. The finger metallization is 2 μm in width, and the stripe separation is 8 μm. The metal stripe separation allows the active device regions to be accessible to laser irradiation. For the results that David Berning will show, the devices were scanned while they were connected and biased in the common-emitter configuration. The signal for the display screen image was taken from a 60-Ω resistor which served as the collector load. For several of the transistors, we found that regions of high temperature, so called "hot-spots", would form within the bias range listed in the manufacturer's data sheet. We used this observation to aid in understanding the many things the scanner can tell us about the way a device really works. (571)

Berning

This [Graphic 12] is an array of observations on a 2N4431 transistor. The upper left image is the infrared response for a collector-emitter voltage of 26 V and a collector current of 250 mA. The transistor is operating just outside of the hot-spot regime. Not much of the incident optical energy is absorbed in the device active regions and so the display screen signal is weak. The infrared response was actually quite uniform over the device, and the apparent nonuniformity captured in



Graphic 11



Graphic 12

this photograph was due to system noise which had the effect of modulating the presentation of the photoresponse. The lower left photograph was made for the same scanning conditions but with the bias adjusted slightly to put the transistor into hot-spot operation. The region of enhanced photoresponse, the white area, is the hot-spot region as confirmed with the use of a passive infrared microscope. The photoresponse is proportional to the number of electron-hole pairs photogenerated in the device active region. For radiation from the infrared laser, which is lightly absorbed at room temperature, the number of the pairs photogenerated increases with temperature because the optical absorption coefficient increases with temperature. This is due primarily to the well-known change in the silicon bandgap with temperature [5]. (600)

The upper right photograph is for the same hot-spot conditions, but it was made using the video response to the visible laser instead of to the infrared laser. The optical absorption for the visible wavelength is large enough so that essentially all of the incident light is absorbed in the active regions at room temperature and no enhancement in the hot-spot portion is observed. The lower right photograph is for the same bias and optical wavelength except that now we have used the radio receiver, and the image produced is the response of the transistor to the component of the laser light modulated at 500 MHz. We interpret this image as the spatial map of the 500 MHz gain of the transistor. The hot-spot area is revealed quite dramatically, and we see that there are actually two hot spots symmetric about a cell boundary.

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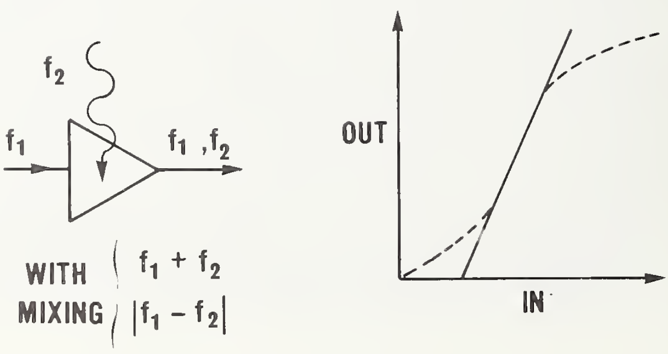
[5] Smith, R. A., *Semiconductors* (Cambridge University Press, 1961) 204-207.

Although the results shown here, both for the thermal mapping and the mapping of transistor gain at 500 MHz, were obtained with static biasing, similar measurements with the transistor operating in its own RF circuit should be feasible. (623)

Now we would like to show that the scanner can be used to detect regions where nonlinear behavior is occurring within functioning semiconductor devices. As far as we know, this has never been done before.

The demonstration vehicle is the same group of 2N4431 transistors that was used for the low- and high-frequency mapping, and for the electronic thermal mapping described. But, before we show the results, we first should describe how the method for mapping nonlinear behavior works. This [Graphic 13 — drawn at blackboard] is a general representation of an amplifying element, such as a transistor or an entire integrated circuit. For simplicity, let's show the element amplifying at the single frequency f_1, although other frequencies may also be present, such as side-bands, if f_1 were modulated. But generality is not lost by considering f_1 alone. To describe our technique, let us assume that a portion of the specimen is operating in a linear manner; that is, the local minority carrier concentration is proportional to the input current, and the input-output characteristic is shown by this solid-line. [Graphic 13, right half] Other portions of the device may behave in a nonlinear manner as shown by this dashed line. The overall behavior will lie somewhere between these two curves. By monitoring the electrical output and changing the operating conditions, we will know that nonlinearity is occurring but we will not know whether it is occurring uniformily or only in certain, as yet unspecified, portions of the specimen.

But the scanner can tell us which portions are behaving nonlinearly. We optically scan the specimen with the laser output modulated at the frequency f_2, and with the electrical input at f_1 as before. For the portions that are behaving linearly, the electrical output will contain the two input frequencies f_1 and f_2 only. One can always represent a curved line, such as the dashed line, by a power series; and, the output for the portion specified by this curve will consist of frequency



Graphic 13

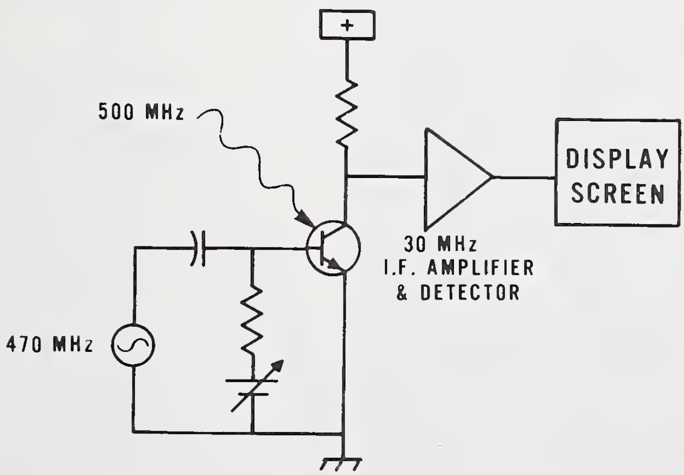
components other than just f_1 and f_2. The first term after the linear term in the power series is the square term, and this will produce an output at both the sum frequency, f_1 plus f_2, and the difference frequency between f_1 and f_2. If we now connect a radio receiver to the output of the scanned specimen and tune to either the sum or difference frequency, we will get an output from the receiver only when the laser is incident on a portion of the specimen that has some nonlinearity in its electrical characteristics; and, if we connect the receiver to the display screen, then we will present only those nonlinear portions on the screen. (663)

David Berning will show you a set of photographs, showing nonlinearities in a 2N4431 revealed in this manner after some introductory remarks.

Berning [At Blackboard]

We used a 2N4431 which could be put into hot-spot operation, as revealed both by the use of a passive IR scanner and by the electronic techniques previously described. The transistor was connected [Graphic 14 — drawn at blackboard] in a simple common-emitter circuit with a 60-Ω collector load resistor and a variable dc base current supply. A UHF signal generator was used to furnish R.F. base drive, and a 30 MHz I.F. amplifier and detector was connected across the 60-Ω collector load. The detector output was fed into the display screen's mixer-amplifier. The signal generator was set at 470 MHz, which is within the operating frequency range of the transistor. If nonlinearities are present within the transistor, then the 470 MHz electrical input and the 500 MHz optical modulation of the visible laser will mix to produce an output on the display screen from the 30 MHz I.F. amplifier.

We have a plot of the low-frequency input-output characteristics for the 2N4431 scanned. [Graphic 15] The curve was obtained from a recorder trace of the dc

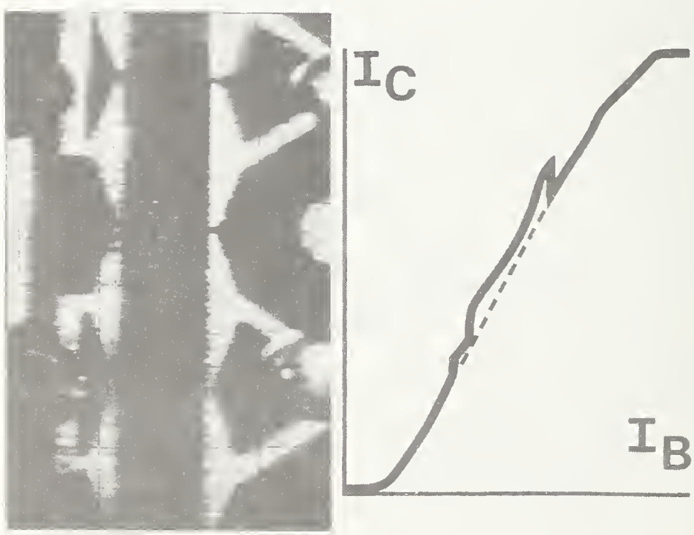


Graphic 14

collector-current, base-current characteristics. The base current range is from 0 to 13 mA, and the collector range is from 0 to 520 mA. The deviation from linearity in the center is associated with hot-spotting, as we established by thermally mapping the device. Had the device been linear, its characteristics would have followed the dashed line, which we have sketched in. If the transistor's R.F. characteristic is similar to the static characteristic shown here, then we should obtain a signal on the display screen when the transistor is biased near cut off, in the hot-spot region, and near saturation; and, we should see relatively little when the transistor is biased at the various linear regions in between. (696)

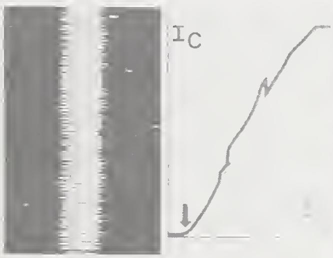
The photograph on the left-hand side shows the topology of the transistor, and this photograph was made using only the reflected light circuit of the scanner. The active region appears dark in this photograph and it is bounded by the reflective base and emitter contacts at the ends of the interdigitated fingers.

In the next series of graphics we will show the results of using the I.F. output of the scanner for various operating points on the input-output characteristic, going from cut off to saturation. So, the central region in the photograph that now appears dark will be light when there is significant I.F. output which indicates nonlinear operation. With that introduction let's look at the next graphic [Graphic 16] which is a combination of the display screen photograph for the transistor near cut off and the collector-current base-current graph with the dc operating point indicated by the arrow. We obtain a strong I.F. output because of the strong electrical nonlinearity. In the next graphic [Graphic 17] we have moved into the first linear region, and the signal has decreased. Moving on, [Graphic 18] the hot-spot region has been entered. It is interesting to observe that hot-spotting can influence electrical linearity in cells other than just the one or ones with a hot spot.

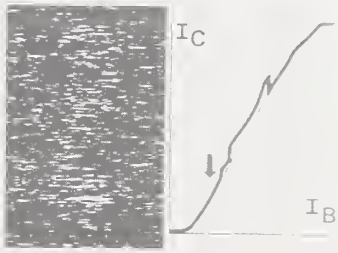


Graphic 15

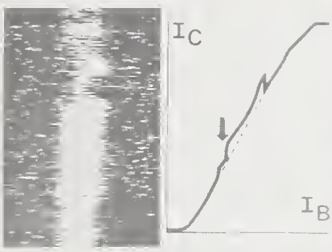
As you can see, the nonlinearity is fairly uniformly distributed over the entire active area of the four cells. Perhaps this is due to coupling in the common collector substrate. As we move up the characteristic, [Graphic 19] the behavior is still quite nonlinear. Here, [Graphic 20] even though the device is still operating in the hot-spot regime, the recorder trace shows that the input-output characteristic is fairly linear, and so not much frequency-mixing occurs. Now, [Graphic 21] we are approaching the high-current boundary for hot-spotting, and the nonlinearity increases. Here, [Graphic 22] the operating point is outside of the hot-spot region, and the characteristic again is fairly linear and so little mixing occurs. Finally, for the last condition, [Graphic 23] the device is near saturation, and again nonlinearity is observed on the display screen. You may be able to see that the nonlinearity is somewhat more pronounced along the right-hand emitter side. We suspect that this is so because the base contact is on the left, and a small amount of debiasing of the right-hand emitter side is occurring due to the dc voltage drop along the base fingers. (723)



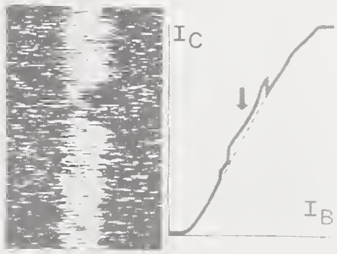
Graphic 16



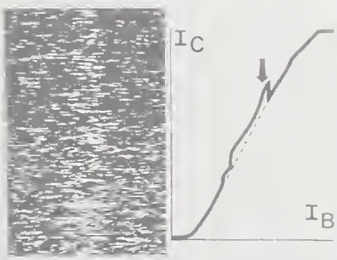
Graphic 17



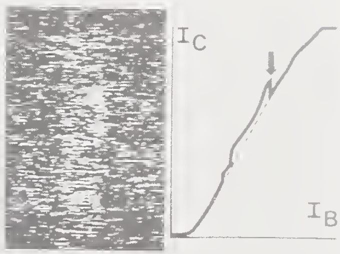
Graphic 18



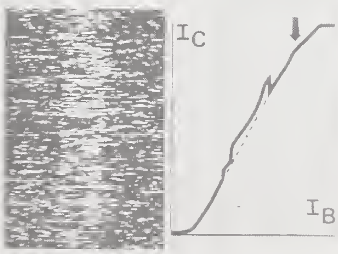
Graphic 19



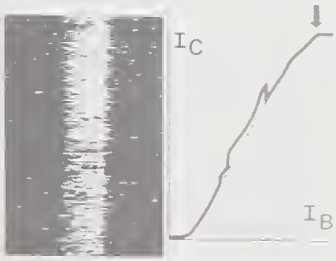
Graphic 20



Graphic 21



Graphic 22



Graphic 23

Although the observations were made on a transistor operating in the UHF region, (738) there should not be any problem using this technique to detect operating nonlinearities in either higher or lower frequency ranges, or even at audio frequencies; it should only be necessary to choose appropriate laser modulation and I.F. frequencies, and to modulate the laser at the required frequency.

One of the requirements, of course, for applying any of the scanning ideas that we have demonstrated is that one has to get light into the device. But, the trend in bipolar device design appears to be toward interdigitation, now even for power supply transistors, and this allows optical access. Optical access to IC's is facilitated when polysilicon is used in place of metal, and polysilicon is widely used now. For these two reasons, it is generally easier to obtain scanning results from devices now than it was just a few years ago.

Most of our scanning work has been on devices for which the chips have been mounted on a header. But some of these can be scanned at the wafer level; that is, before the chip is mounted. This is most feasible for low power devices which do not require optimum heat-sinking during testing.

All of the work shown today was performed on silicon devices. However, we also have scanned devices made from other semiconducting materials, germanium and indium arsenide, for example.

To sum up the work which we have shown today, we make use of the fact that semiconducting materials are photosensitive in an electrical sense as part of their basic nature. Thus, semiconductor devices such as diodes, transistors, and entire integrated circuits made from these materials can be studied using optical radiation. The effect of the optical radiation is to generate electron-hole pairs in a non-damaging way within the specimen. These current-carriers can stimulate device behavior by taking the place of signal current-carriers which are normally supplied by leads fixed to the device. In contrast to signals applied via the leads, which are fixed in position, the optical excitation can be moved over the surface and within the bulk, and the response of the structures can be studied on a point-by-point basis to learn the inner workings of the device.

We have developed a versatile optical scanner that can be applied to a variety of device problems. In several cases we have observed device phenomena which one has not been able to study before. The scanner can map the flow of logical information in MOS and bipolar IC's, it can map the operation of transistors at ultrahigh frequencies, it can electronically map the temperature distribution, and it can pinpoint the portions of operating devices which are operating in a nonlinear manner. These are just some examples of the applications of the scanner we have developed which we felt would be of greatest interest to you.

If you have questions about the suitability of laser scanning for these or any (777)
other applications, to shed light on YOUR problems, or if you would like to explore with us the possibility of assembling such a scanner at your facilities, please telephone or write us. Contact either David Berning or me, David Sawyer. Our address is Electronic Technology Division, National Bureau of Standards, Washington, D. C. 20234.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This is the script of a videotape presentation which describes new and powerful applications for laser scanning in semiconductor device design and reliability work. The design of the scanner is described in detail and many of its applications are displayed and discussed. The optical scanner can, in a completely nondestructive way, reveal the inner workings of semiconductor devices. For example, it is shown that the scanner can (1) map dc and high-frequency gains in transistors, (2) reveal areas of the device operating in a nonlinear manner, (3) electronically map temperature in the transistor, and (4) detect the location of hot spots that can develop for certain operating conditions. The vehicle used to show these capabilities of the scanner is a bipolar interdigitated UHF transistor. A dual input NAND gate is used to demonstrate the use of the scanner to determine internal logic states and otherwise observe internal operation of the circuit. To show the ability of the scanner to examine MOS devices without detectable degradation, a MOS shift register is used. The location and progress of internal logic in the register is clearly shown by the scanner. Not only can internal logic be mapped and marginally-operating logic cells detected, but individual logic states can be changed by the scanner without affecting other elements.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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