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THE USE OF LASERS TO SIMULATE RADIATION-INDUCED TRANSIENTS IN SEMICONDUCTOR DEVICES AND CIRCUITS

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The study of transients induced in semiconductor devices and associated circuitry when exposed to high levels of ionizing radiation requires simulation of these environments. Pulsed X-ray machines and linear accelerators are available for this purpose; however, they require relatively large installations and have a high cost of operation. High levels of ionization can be created in semiconductor devices by irradiating the devices with short pulses of light. If the light frequency is properly selected, sufficient and uniform energy deposition is obtained which results in ionization rates orders of magnitude above those presently attainable from other sources. It is shown that a pulsed infrared laser can be used as a relatively simple, inexpensive and effective means of simulating the effects caused by intense gamma-ray sources on semiconductors.

Calculations based upon published as well as experimental absorption data for silicon show that energy deposition is very nearly uniform for the neodynium wavelength (1.06 microns - 1.17 ev photons). Dose rates in excess of 10¹² rads/sec (silicon) in 40 x 10⁻⁹ seconds over an area of 50 cm² have been obtained from a Q-switched 10 megawatt neodynium laser. This compares favorably to maximum dose rates of 1010 rads/sec (silicon) over approximately 1 cm2 attainable from Linac sources. Experimental results presented show that the transients induced in various types of silicon transistors when exposed to the laser are essentially identical to those obtained when using pulses of 25 MeV electrons from a linear accelerator. Good agreement exists between the peak photocurrents obtained using the two sources over a dose range of 10⁻¹ to 10⁴ rads.

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In contrast to defocusing a high energy laser beam to cover relatively large areas, a low energy pulsed laser has been focused through a microscope to a spot size of 10 microns and used as a probe to generate ionization in selected regions of semiconductor devices. Data are presented which show the magnitude of the photocurrent resulting from ionization introduced at various points in the wafer geometry for a diffused mesa transistor. Also, some preliminary studies of a monolithic circuit indicate that the infrared probe is a valuable tool in understanding the responses obtained from integrated circuitry and developing hardened versions of these circuits.

Introduction

The study of transients induced in semiconductor devices which are exposed to penetrating and ionizing radiation such as gamma rays or high energy electrons is well documented 1,2,3. Energy is transferred from the incident photons to the material through several processes and causes ionization and excitation of electrons with the result that hole electron pairs are generated uniformly throughout the material. Some of the carriers generated near the device junctions will traverse the junction and produce transient currents at the device terminals. In general, at exposure levels below that required to conductivity modulate the bulk material, only those carriers generated within the depletion regions and within one diffusion length of the junction are collected; the other carriers recombine before reaching the junction and do not contribute to the transient current. At much higher exposure levels, the currents resulting from changes in the resitivity of the bulk material must also be considered. If the approximate carrier lifetimes, diffusion lengths and geometry are known, mathematical models can be formulated which predict the observed transient.

An important part of radiation effects studies is the experimental determination of the transients produced by ionizing radiation and thus simulation of the environments is required. Pulsed X-ray machines and linear accelerators are available for this purpose; however, they require relatively large installations and have a high cost of operation. High levels of ionization can be created in semiconductor devices by irradiating the devices with short pulses of light. If a proper light frequency is selected, sufficient and reasonably uniform energy deposition is obtained which results in ionization rates orders of magnitude above those presently attainable from other sources.

The generation of photocurrents in diodes which are exposed to radiation in the form of visible light has been studied to some extent in conjunction with solid state photodetector design. In general, the mathematical model becomes more complicated because absorption characteristics of semiconductors at optical wavelengths are rapidly varying functions of frequency.

The use of monochromatic light in the infrared alleviates this problem and at infrared wavelengths penetration depths sufficient to give nearly uniform energy deposition in typical silicon devices can be obtained. A Q-switched laser is a particularly well-suited source because it has the desired monochromativity, collimated beam, and the ability to deliver high energies in Very short times (typically 20-50 nanoseconds). In addition, through the use of ordinary optics, it can be focused or defocused to cover a desired area with varying amounts of energy flux. It is a relatively simple, inexpensive and compact laboratory tool, capable of simulating the high ionization levels in semiconductor devices that are of interest in radiation effects work.

Generation of Carriers in Silicon by Photon Absorption

Consider a flux of monochromatic light, I (watts/cm²), impinging upon the surface (x = 0) of a material. If the wavelength of the incident light is λ (cm), the number of photons Q (Photons cm² sec) striking the surface will be

$$Q = \frac{I}{hv} = \frac{\lambda I}{hc}$$

 $Q = \frac{I}{h\nu} = \frac{\lambda I}{hc}$ where c = volocity of light (cm/sec)

h = Planck's constant

v = the frequency of the light.

If the reflection coefficient of the surface is R, the flux entering the surface will be

The photons are absorbed while traveling throughout the material and in accordance with Lambert's law of absorption, the flux F at a distance x from the surface will be given by

where $\alpha(\lambda)$ is the absorption coefficient of the material. If only intrinsic absorption is considered and if the quantum yield is m (ratio of the hole electron pairs produced to the number of photons absorbed) the number of hole electron pairs per cm³ per second generated in the semiconductor at a distance x will be

$$g = mFo\alpha e^{-\alpha x}$$
 pairs/cm³sec

Figure 1 shows the absorption coefficient of intrinsic silicon and its re--ciprocal, penetration distance-(point-at which intensity has decreased by 1/e), 0.01 ohm cm at which point free carrier absorption^{8,9} becomes prominent and the absorption coefficient increases with increasing carrier concentrations. Fortunately, expect for the emitter regions of some transistors, most devices employ carrier concentrations within the above limits.

Figure 3 shows the percentage of input energy at 1.06 microns deposited in silicon as a function of wafer thickness for an average absorption coefficient of 40 cm⁻¹. Typical transistors and integrated circuit wafers thicknesses range from several microns to about 100 microns. For 100 microns, the uniformity of deposition obtained throughout the wafer is about 30% a reasonable value for simulation of energetic radiation sources.

It is informative to compare the absorption coefficient of silicon at X-ray wavelengths, shown in Figure 4, to the previous results for light. As indicated on the curve, the penetration distance obtained in silicon with the ruby and neodynium laser corresponds to the penetration of 2 KeV and 10 KeV X-rays respectively, and thus the laser would accurately simulate the energy deposition profile obtained at these energies.

plotted as a function of photon energy. Because the energy band gap (E_g) in silicon at room temperature is approximately 1.08 ev, very few hole electron pairs can be generated by photons with energies hv < \mathbf{E}_{σ} . In the region of the absorption edge, where photon energies are approximately equal to \mathbf{E}_{σ} , electrons in the valence band can be excited across the forbidden gap to the conduction band and consequently the absorption coefficient increases rapidly as $(hn' - E_g)^{2.5}$. The upper limit of usable wavelengths for simulation is thus given by $\lambda < \frac{hc}{E}$; the lower limit is determined by the energy deposition profile desired

For optimum uniformity of energy depositon in silicon, the photon energy should be slightly greater than the band gap energy where the absorption coefficient has relatively low value. The degree of uniformity obtained will be influenced to a great extent by the device dimensions, the radiation dose levels of interest, and the impurity doping concentration present in the silicon. At relatively low doses, before the onset of conductivity modulation, the active carrier generation depth of a transistor extends only through the emitter and base depths plus a diffusion length into the collector region. At high ionization levels the peak photocurrent response is determined by the change in resistivity of the bulk material in the collector region and hence the entire wafer thickness is important. The effect of doping concentration will be considered later for the laser frequency of interest.

Although an ever increasing number of available laser frequencies are reported in the literature, there are at present only two solid state lasers available with sufficient energy output for simulating radiation over large areas: the ruby (wavelength - 0.6943 microns; photon energy - 1.8 ev) and neodynium-doped glass (wavelength - 1.06 microns; photon energy - 1.17 ev). It will be shown that the latter is a reasonable choice for simulation of penetrating radiation in silicon.

Because the absorption coefficient in silicon is extremely wavelengthdependent for photon energies slightly greater than E,, experimental values were determined at 1.06 microns for P- and N-type samples with various doping impurity concentrations. Figure 2-and 3 shows the results of these measurements for phosphorous-doped and boron-doped silicon, respectively. It is seen that the absorption remains essentially constant from 100 ohm cm to approximately.

Calculated Energy Deposition

In this paper, the radiation exposure is referred to in terms of the dose or the dose rate depending upon which is appropriate for the discussion. The unit of dose used is the rad and is defined as an absorbed energy of 100 ergs/gm of the material. Because a rad is defined by the energy deposited in the material, it is independent of the radiation spectrum. Furthermore, for gamma rays and high energy electrons it is assumed that uniform generation of hole-electron pairs takes place and that the average energy required to create a hole-electron pair in silicon is approximately 3.6 ev, which corresponds to a generation rate of 4.3 x 10¹³ pairs/cm³ sec for a dose rate of one rad/sec.

If a light energy flux of E_0 joules/cm² impinges on a silicon wafer the energy deposited per unit volume is given by

$$E_d = (1-R)\alpha E_0 e^{-\alpha x} j/cm^3$$
.

For $\alpha x << 1$, the deposition will be nearly uniform and the expression becomes

$$E_d = (1-R)\alpha E_o j/cm^3$$
.

(The assumption of uniform deposition at 1.06 microns for a typical wafer thickness of 100 microns results in a 30 percent error of calculated dose.) At 1.06 microns $\alpha \simeq 40~{\rm cm}^{-1}$ and R=0.32 so that $E_{\rm d}=2.72~E_{\rm c}{\rm j/cm}^3$ or 1.08 x 10⁶ $E_{\rm o}$ rads over an area equal to that of the laser rod. Because the quantum efficiency in silicon at optical wavelengths is nearly unity⁹, for laser irradiation, one hole-electron pair is created for every absorbed photon leading to a generation rate of

 $g = \frac{3.6 \text{ eV}}{1.17 \text{ eV}} \times 4.3 \times 10^{13} \text{ pairs/cm}^3 \text{ sec} = 1.32 \times 10^{14} \text{ pairs/cm}^3 \text{ sec}$ for an absorbed dose of 1 rad/sec. Thus, when comparing laser-induced transients to those obtained using nuclear radiation, the respective doses must be weighted accordingly.

In a Q-switched laser the gain per unit length of rod, which is proportional to the exponent of population inversion achieved, is very high at the instant of switching. This causes multimode operation in which the laser output will be phase coherent in the direction of propagation but will not be of uniform phase across the wave front. Under these conditions the energy flux emerging from the laser is relatively constant over the cross-section of the laser rod. To check this experimentally the laser beam was diverged by a short focal length lons and flux measurements were made across the beam front at a point where the beam diameter was a factor of 16 greater than the rod diameter. The results ere-depicted in Figure 5 and show the uniformity to be within a factor of two across the diameter. The degree of uniformity obtained is dependent on the homogeneity of the laser rod material, the pumping configuration and the quality of the other optical components in the system. In the experimental apparatus used here no attempt was made to select optimum components and hence it is felt that the above variation in uniformity could be made considerably less. Moreover, Figure 5 shows that if only the center portion of the laser output is used, thus eliminating the nonuniformity at the edges (caused by nonuniform pumping of the laser rod), the variance is held to a more reasonable value.

In general, if the laser output energy is considered nearly uniform over the cross-sectional area of the laser rod, it can be focused or defocused to give any desired energy flux at the target. The energy that can be deposited E(rads) over an area A is given by

$$E = 1.08 \times 10^6 E_0 \frac{A_L}{A} \text{ rads}$$

where $A_{T_{i}}$ is the area of the laser rod.

For a typical laser rod of 1 cm² cross-sectional area delivering a one joule Q-switched output, a dose of 1.08 x 10⁶ rads can be obtained over 1 cm². This corresponds to an equivalent gamma dose of approximately 3 x 10⁶ rads and compares favorably to the maximum attainable dose of about 2 x 10³ rads(silicon) over 1 cm² available from a linear accelerator. Plotted in Figure 6 are curves of the equivalent gamma dose; that can be delivered over various areas as a function of laser output power. The range of power outputs considered is representative of standard laboratory-type lasers that are currently available. The curves point out the fact that entire circuits can be irradiated at substantial dose levels with relative ease in the laboratory.

Experimental Results

To experimentally determine the effectiveness of infra-red laser radiation in simulating high ionization rates caused by energetic gamma rays or electrons, the time responses of the transient emitter currents induced in three types of double diffused mesa silicon transistors when exposed to pulses of 25 MeV electrons and to a pulsed laser were measured over a dose range extremely from 0.1 rad to 2 x 10³ rads. The devices were operated in the common collector configuration (shown in Figure 7) with constant current base drive. This configuration eliminates from the measurements the secondary electron current arising from electron bombardment of the transistor header and container. Because geometrical considerations are important at optical wavelengths, scale drawings of the wafers are shown in Figures 8 through 10, to indicate the percentage of base area covered by metallic strips and contacts. This percentage varies from 25 percent for the 2N1051 to 75 percent for the 2N1675.

Figures 7 and 8 which depict the transient emitter current waveform obtained with the two sources at a low dose and high dose for the 2N1051 demonstrate the similarity in response for comparable peak currents. The faster risetime noted with laser irradiation is believed due to slightly greater absorption in the base and emitter regions of the device. The initial peak is the high dose waveform due to conductivity modulation of the collector region demonstrates that the laser is effective in penetrating the entire depth of the wafer. Figures 8 and 10 which have similar waveforms for the 2N1675, indicate that that the percentage of occluded area has little effect on the device time response, except to lower the saturation current denoted by the flat-portion of the waveform immediately after the initial peak in the high dose results. This is to be expected since there is considerable shadowing of the collector region and hence the effective area in the expression R = C1 / A is decreased—leading—to—higher—value—of—collector registance.

Plots of peak collector current versus dose, shown in Figures 10, 11 and 12 for two of each of the three types of transistors, indicate good agreement for doses extending over four decades. To account for the unit-to-unit variation in dose due to occluded areas the dose in each case was decreased by the ratio of occluded base area to the total base area. Also, for purposes of comparison, the calculated laser dose was increased by an amount equal to the ratio of carrier generation rates obtained with the two sources so that the abscissa represents the equivalent gamma-ray dose delivered by the laser.

A diagram of the experimental apparatus used to expose the transistor to short pulses of 1.06 micron light is schematically shown in Figure ./6. The laser used in the experiment employed a 6" x 1/2" neodynium-doped glass rod which was Q-switched by a rotating prism rotating at 800 rps to obtain 30 nanosecond pulses. The laser output was monitored by PD₁, an IT&T planar photodiode which had previously been calibrated to a TRG Model 401 calorimeter. A 5 cm focal length lens was used to diverge the beam to a lower energy density at which point gelating filters were used to vary the dose to the target in discrete steps. PD₂ serves as the relative dosimeter by measuring the energy density immediately preceding the target.

Laser Probe

Geometrical studies of transistor and monolithic circuits can be facilitated by the use of narrow beams of penetrating ionization to isolate the effects caused by various components or regions of a semiconductor wafer. Extremely narrow collimated radiation sources are nonexistent and present design of X-ray and machines does not produce beams with the consistency and directivity necessary for collimating to very small diameters externally. Shielding of areas on a wafer where ionization is unwarranted is extremely difficult because of the small dimensions involved.

A relatively low power continuous-wave laser can be used in conjunction with a microscope to create ionization in minute regions of semiconductors. Because a laser is a well-collimated and coherent light source, it can be focused to a spot size determined by the diffraction limit of the optical system. With some choice of operating frequencies available, the penetration depth of the ionizing radiation can also be chosen to allow energy deposition in thin layers of a device or in a nearly uniform manner. If an optical shutter such as a Kerr cell is used to modulate the laser output, any desired pulse width can be six selected and at a repetition rate limited only by the characteristics of the shutter, typically 60 pulses per second.

The approximate expression for the minimum diameter to which light with a uniphase wave front can be focused in a given optical system is

$$D = \frac{1.2 \, \lambda f}{d}$$

when λ = wavelength of light, f = focal length of the lens, and d = diameter of laser beam (this assumes that the diameter of the laser beam is smaller that the lens aperture). For a typical Helium Neon Gas Laser (6328Ű) with a beam diameter of several millimeters and focused through a relatively low power microscope objective (l6x), the theoretical spot size would be about one micron. This is difficult to achieve in practice because of imperfections in the optical components and a certain amount of laser beam divergence; however, a spot size of 10 microns can be obtained with relative ease.

The absorption coefficient in silicon for 6328Å° is 5 x 10^{-3} cm, equivalent to a penetration distance of 2 microns. In this distance, over a diameter of 10 microns, a 3 mw laser will produce a dose rate of approximately

$$E = 10^{12} \text{ rads/sec.}$$

At these extremely high ionization rates created nonuniformly in very small difficult volumes it is and to predict precisely the movement of all the carriers generated. Lifetimes of the carrier definitely will be reduced and surface combinations will take place with the result that a quantitative analysis of resulting transient currents at the device terminals would be impractical. However, a visible wavelength laser probe can be used in a qualitative manner to determine geometrical characteristics of devices. The measurement of effective lifetime in regions of a device is possible since a penetration depth and of 2 microns allows carrier generation only in volumes immediately adjacent to the surface of the wafer. In particular, effective base lifetime in a transistor can be obtained from the decay of the collector current response when the probe energy is deposited in the base region of the device.

The study of integrated circuitry requires the ability to deliver uniformly deposited doses of ionizing radiation to individual components of the wafer and thus an infra-red probe must be used. It is desirable to focus a continuous wave laser rather than a Q=switched laser through a microscope to facilitate the alignment problem at the invisible wavelengths. With a continuous output, infra-red film can be used to record the position of the exposed wafer portion.

Short

Infra-red film sensitivities are much too low to record shot pulses of light and the repetition rate of a Q-switched laser is limited to pulses. the extent that it is not practical to expose the film to a train of pulses.

The expression developed for the infrared laser dose calculations shows that to obtain a dose rate of 10⁸ rads/sec an incident light flux (at 1.06 microns) of about 100 watts/cm² is required. Typical areas of individual laser monolithic components are about 0.04 mm² yielding a laser output power of

percent loss associated with the Kerr cell shutter (polarization losses) and another 50 percent loss associated with the internal optics of the microscope so that the total laser output of 130 millivolts is required to produce an ionization rate of 10 rads/sec. The largest continuous wave infrared gas lasers have output powers of only 25 mw. There is, however, a continuous wave solid state material, such as neodynium-doped ittrium iron garrate, presently capable of producing up to 500 mw at 1.06 microns. In general, they do not have uniphase wave fronts and thus cannot be focused to into the diffraction limit of an optical system but spot sizes sufficiently small for irradiation of monolithic components can be obtained.

If higher ionization rates are desired there exists the possibility of operating an ittrium iron garrate laser rod in a dual purpose cavity where Q-switched or continuous operation could-be-used. This configuration would allow positioning of the beam as well as the high peak powers obtained in the Q-switched mode. Advances in the laser state of art are numerous so that in the near future many of the present limitations will be nonexistent.

Experimental Probe Results

A 6328A gas laser was used in conjunction with a microscope to determine the magnitude of photocurrents resulting from ionization produced at various points on the wafer of a 2N1051 diffused mesa type transistor. The laser beam, gated with a Kerr cell to give 100 nanosecond pulses, was focused to a spot size of approximately 10 microns at the surface of the wafer and the collector current response measured when ionization was produced at 70 points on the wafer,

Figure 19 shows a cross sectional sketch of the double diffused mesa transistor. Because the base depth is 5.8 microns, essentially no penetration of the collector region occurs. This is evidenced in the collector current response obtained whom the trailing edge decoy time constant is that of the base layer lifetime, about 100 nanoseconds for the 2N1051. A plot of the peak collector current obtained as a function of the point of energy desposition in the wafer is shown in Figure & C. The current is zero everywhere except in the base mesa where it remains relatively constant. This is essentially a measure of the active volume which must be used in mathematical predictions of the transient response of transistors to ionizing radiation. If only the effective base layer thickness and emitter junction areas were known, it might be assumed that the base layer carriers which are effective in producing a response are generated in a volume equivalent to the product of the emitter collector spacing and the area of the base collector junction. The above measurements show that the total base volume must be used and substantiate the results obtained in computer predictions of the photocurrents in the above transistor where it was found that a factor of 3 errors in the base layer component of primary photocurrent resulted if the smaller volume was used.

The large currents obtained when ionization is introduced in the emitter region do not agree with the normal assumption made in transient effects predictions that the emitter region lifetime is very short and hence carriers generated there have a negligible effect on the total photocurrents. Indications that carriers generated in the emitter region are as effective as those in the base region and consequently the emitter lifetime is much longer than believed. More sophisticated measurements could possibly lead to a value for this lifetime.

More useful measurements could be made with a larger laser output power. or a lower noise system where primary photocurrent measurements could be made. The experimental apparatus used was limited in sensitivity due to electrical noise generated by the high voltage switching (50KV) necessary to generate the Kerr cell shuttle.

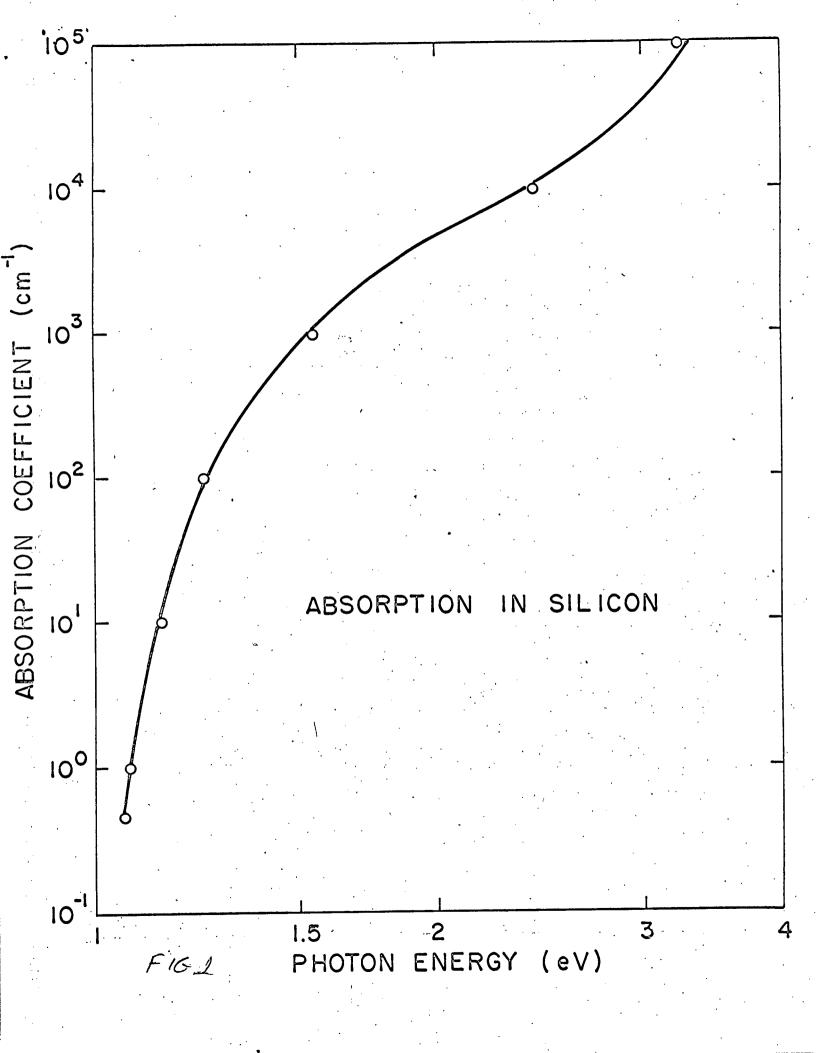
Conclusion

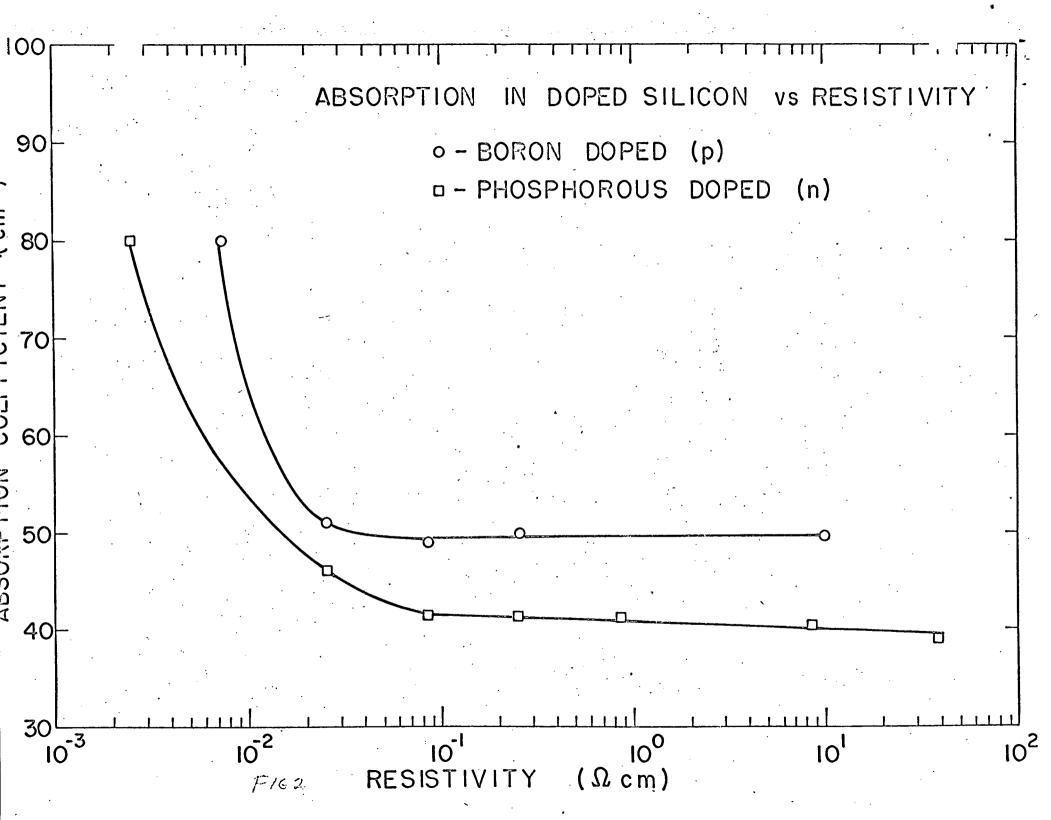
Because the study of transient radiation effects in electronic systems involves primarily silicon devices, the laser could be a valuable asset to the many who must concern themselves with radiation effects and yet have no large testing facility of their own. Much preliminary testing could be done with a laser to eliminate the many wasted hours at testing facilities and in the field because of improper advance experimental planning. If the user fully realizes the limitations of laser simulation techniques, it is a relatively inexpensive and effective means of obtaining high ionization levels in silicon devices. The ability to focus or defocus the laser beam makes possible the irradiation of entire circuits or the smallest component of a monolithic integrated circuit wafer. The added flexibility of varying penetration depths provides the user with an excellent tool for studying device characteristics, such as surface phenomena, shock and thermal damage, and localized ionization effects.

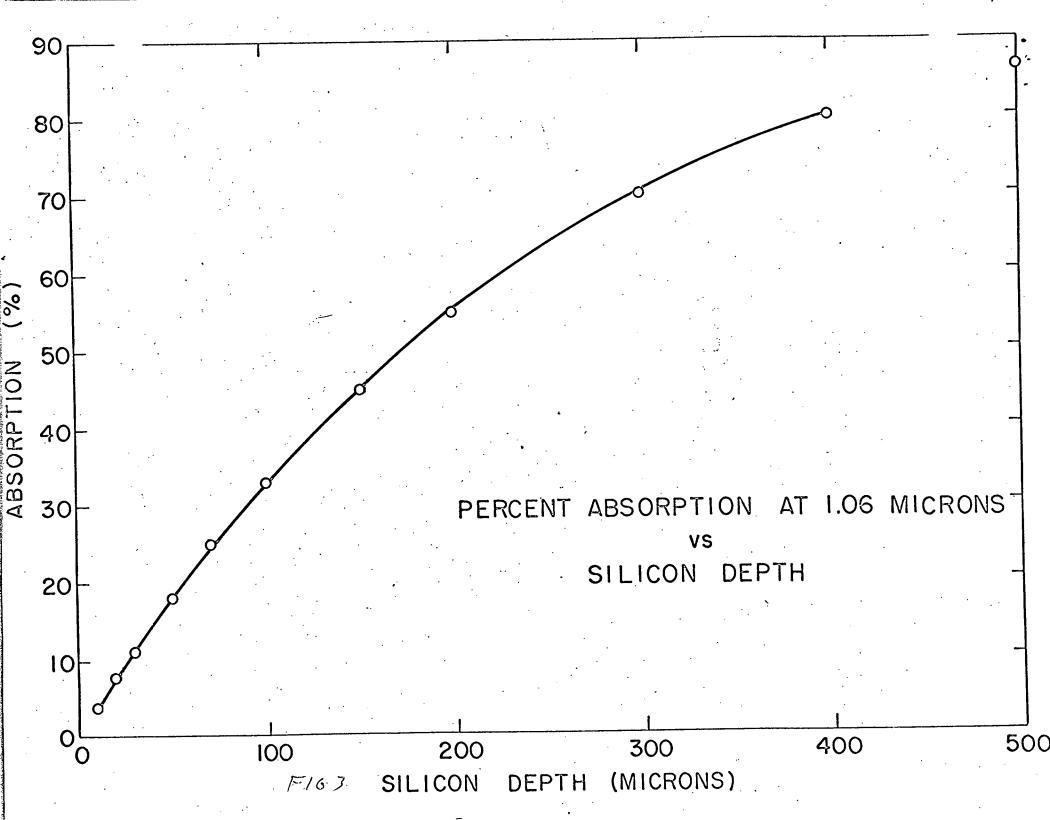
Although lasers can be a helpful and powerful laboratory tool in the—circulation of rediation effects to semiconductors, they certainly cannot replace X-ray machines or particle generators. Lasers are light sources and as such cannot penetrate or ionize most materials in a manner similar to that obtained with gamma rays or high energy particles. There are many instances especially at high dose levels, where the effects on components other than semiconductors, such as capacitors and resistors, must be considered. The laser offers no help in this area. The most serious drawback of laser simulation in silicon devices is the dependence of the absorption coefficient on the impurity doping concentration. This is felt most severely in high frequency, low voltage breakdown devices where doping concentrations are usually very high. Some caution must be exercised when considering the simulation effectiveness in such devices.

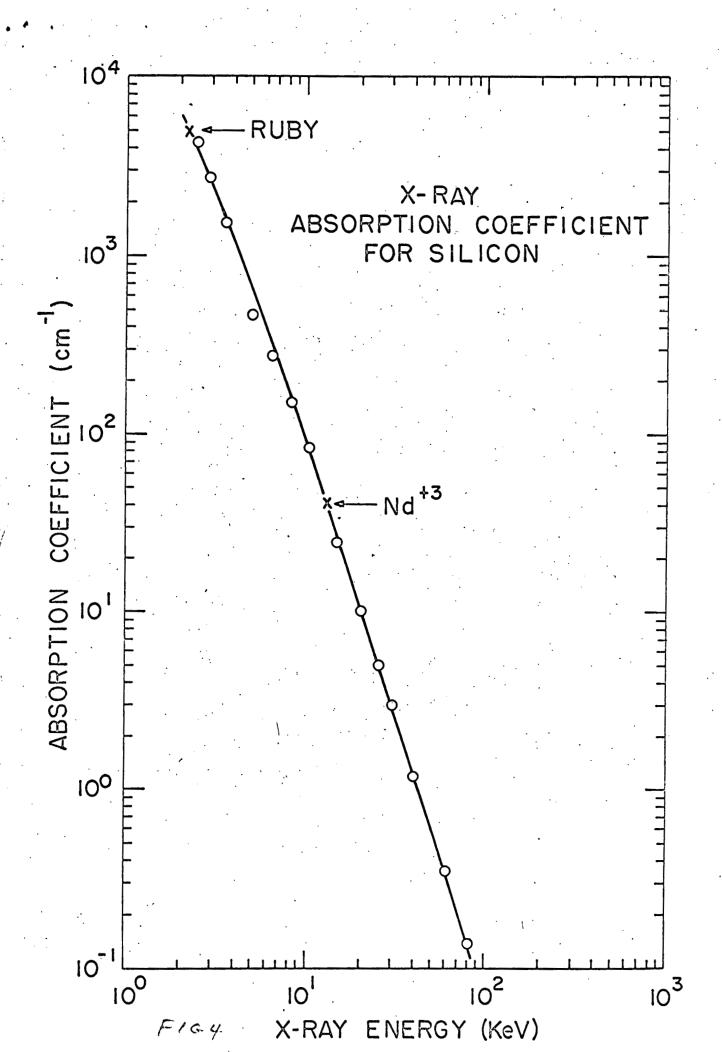
References

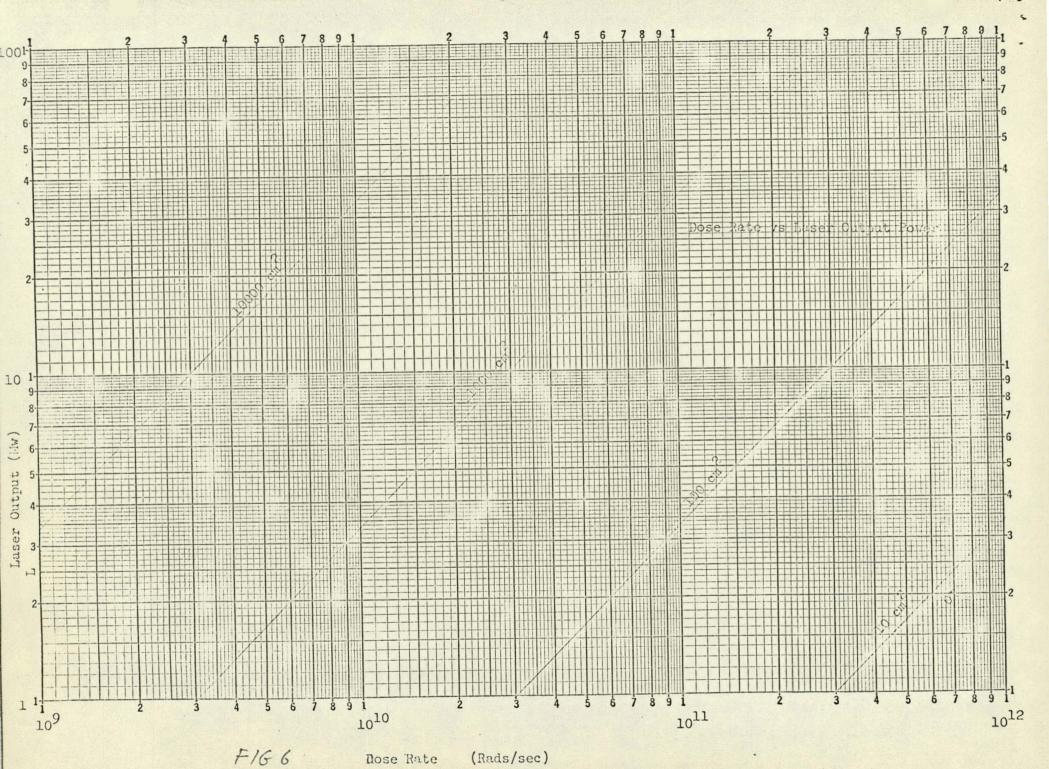
- 1. R. S. Caldwell, D. S. Gage and G. H. Hanson, "The Transient Behavior of Transistors Due to Ionizing Radiation Pulses," Communication and Electronis, No. 64 (January 1963).
- 2. J. L. Wirth and S. C. Rogers, "The Transient Response of Transistors and Diodes to Ionizing Radiation," IEEE Trans. on Nuclear Science NS-11, No. 5, 24 (November 1964).
- 3. A. G. Jordan and A. G. Milnes, "Photoeffect on Diffused P-N Junction with Integral Field Gradients," IRE Trans. on Electronic Devices ED6-7, 242-251 (October 1960).
- 4. J. N. Shive, <u>Semiconductor Devices</u>, D. Van Nostrand Co., Inc., Princeton, (1959).
- 5. T. S. Moss, Optical Properties of Semiconductors, Butterworths, London (1961).
- 6. McFairlanc and Roberts, "Infrared Absorption of Silicon Near the Lattice Edge," Phys. Rev. 98, 1715 (March 1955).
- 7. H. Y. Fan, M. L. Shepherd and W. Spitzer, "Infrared Absorption and Energy Band Structure of Germanium and Silicon," <u>Photoconductivity Conference</u> (Held in Atlantic City, November 1954), Wiley & Sons, New York (1956).
- 8. N. B. Hannay, Semiconductors, Reinhold Publishing Corp., New York (1960).
- 9. V. K. Subashiev and G. B. Dubrovskii, "Indirect Transitions and the Structure of the Valence Band of Silicon," Soviet Phys-Solid State $\underline{6}$, No. 5, 1017-1022 (November 1964).
- 10. W. Schroen, W. W. Hooper, H. J. Queisser, Failure Mechanisms in Silicon Semiconductors, Rome Air Development Center (Prepared by Shockley Research Laboratory), Technical Documentary Report No. RADC-TDR-64-153 (May 1964).

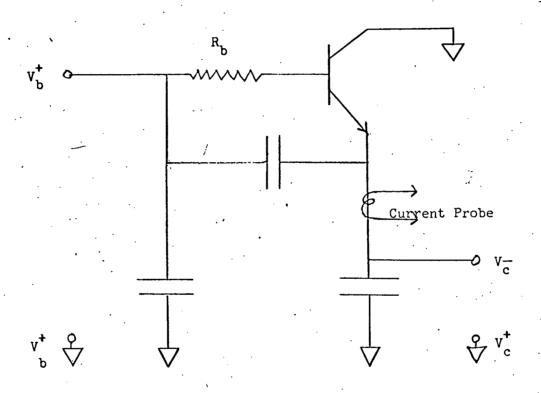




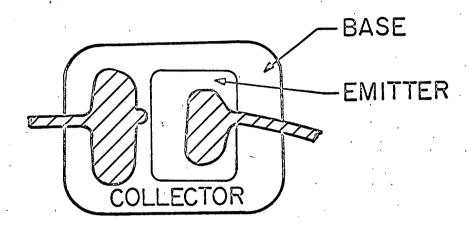








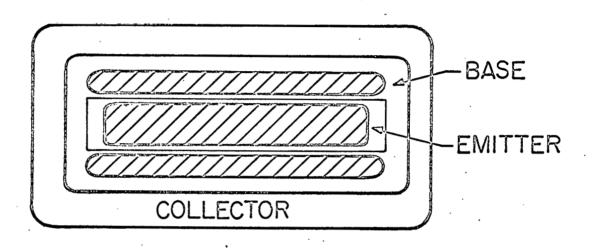
F167 Transistor Test Circuit





SCALE - O.OI mm/div

TOP VIEW OF 2NIO51 WAFER





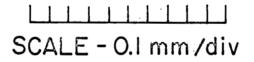
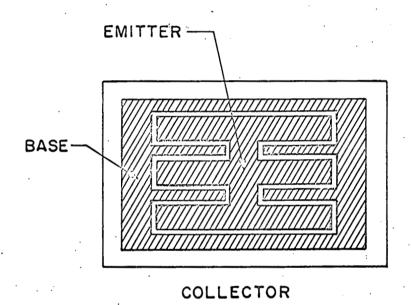
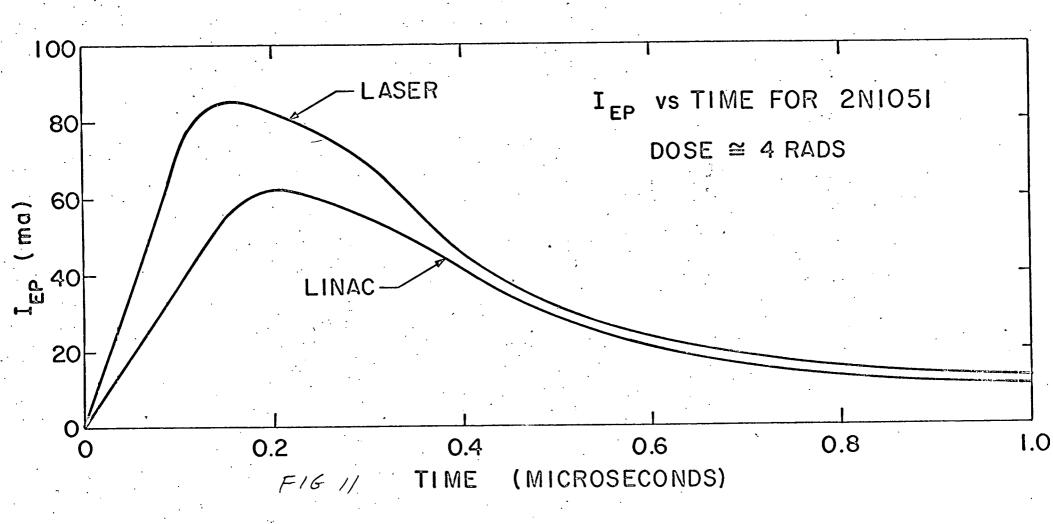


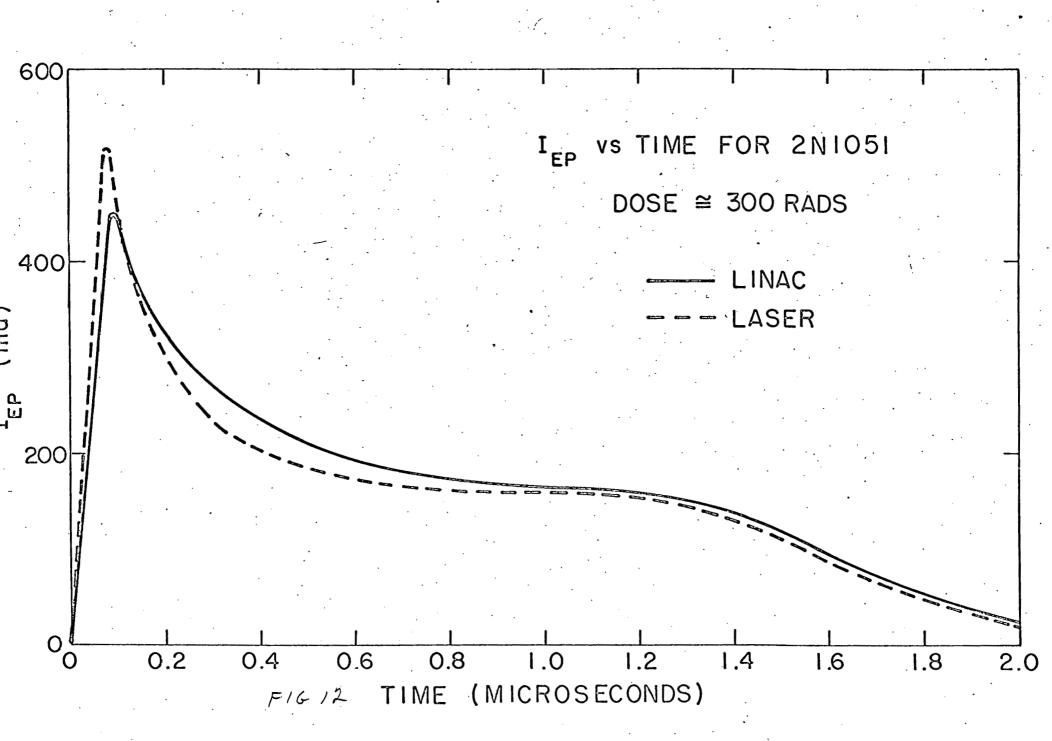
FIG 9 TOP VIEW OF 2N1841 WAFER

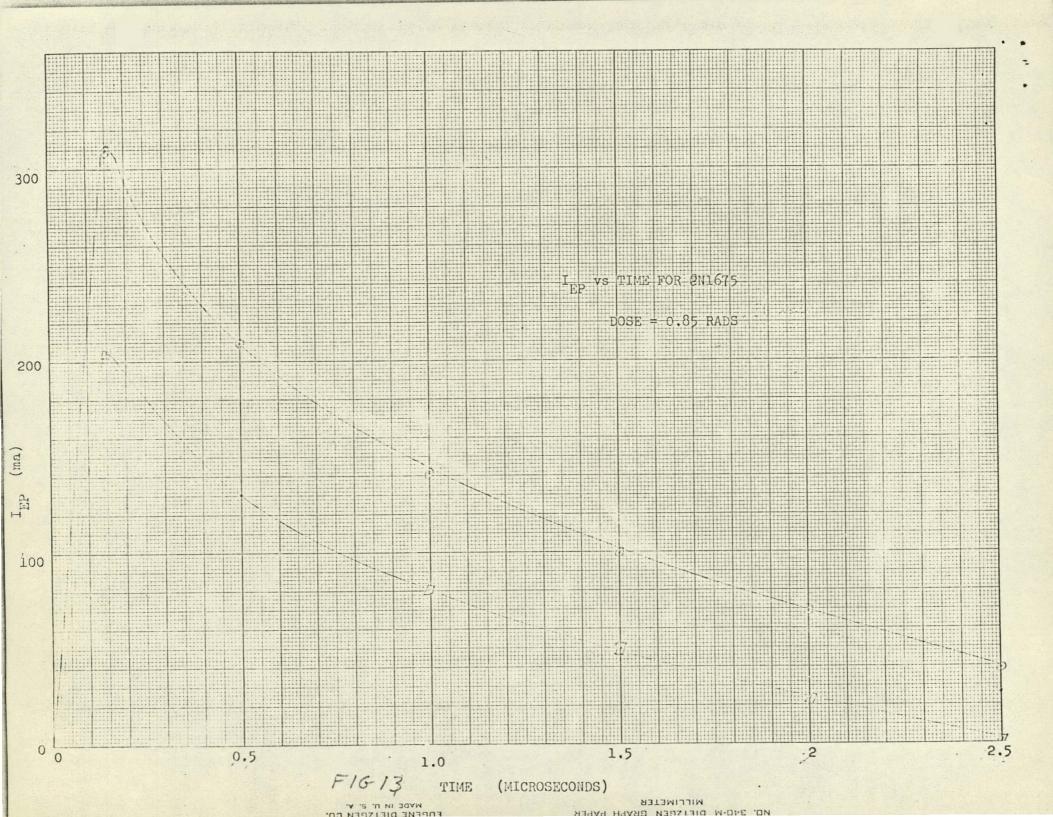


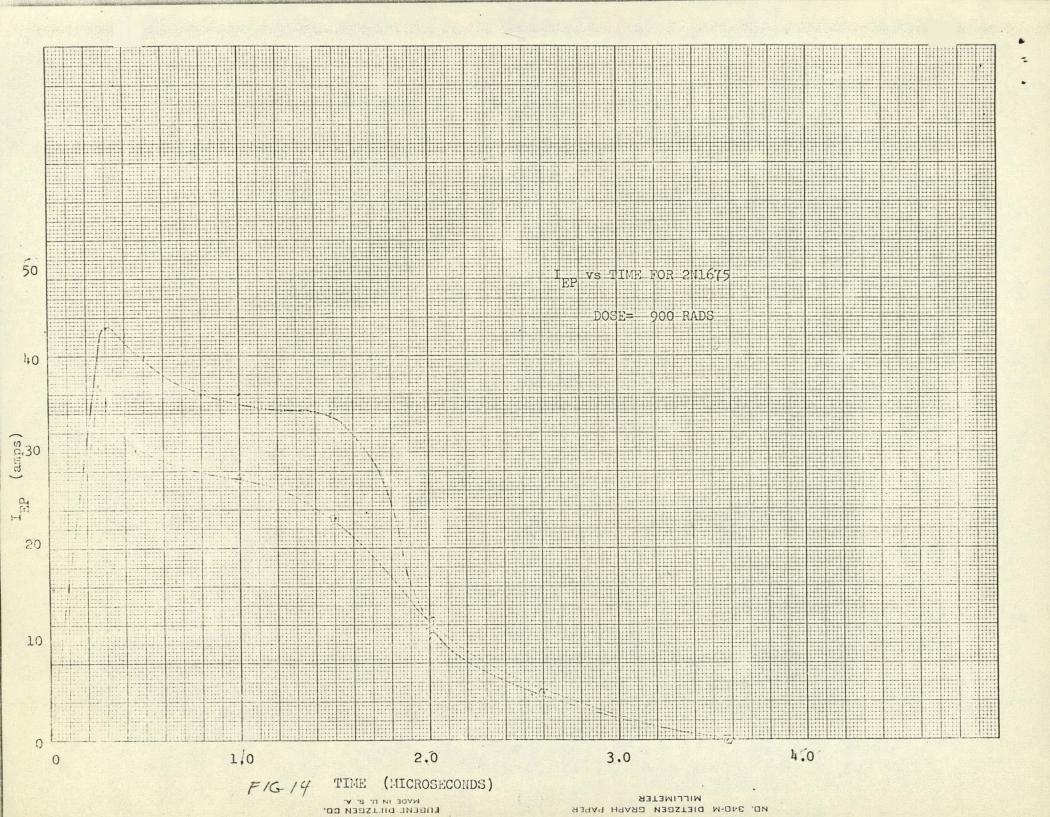
SCALE: I.O mm/div METAL

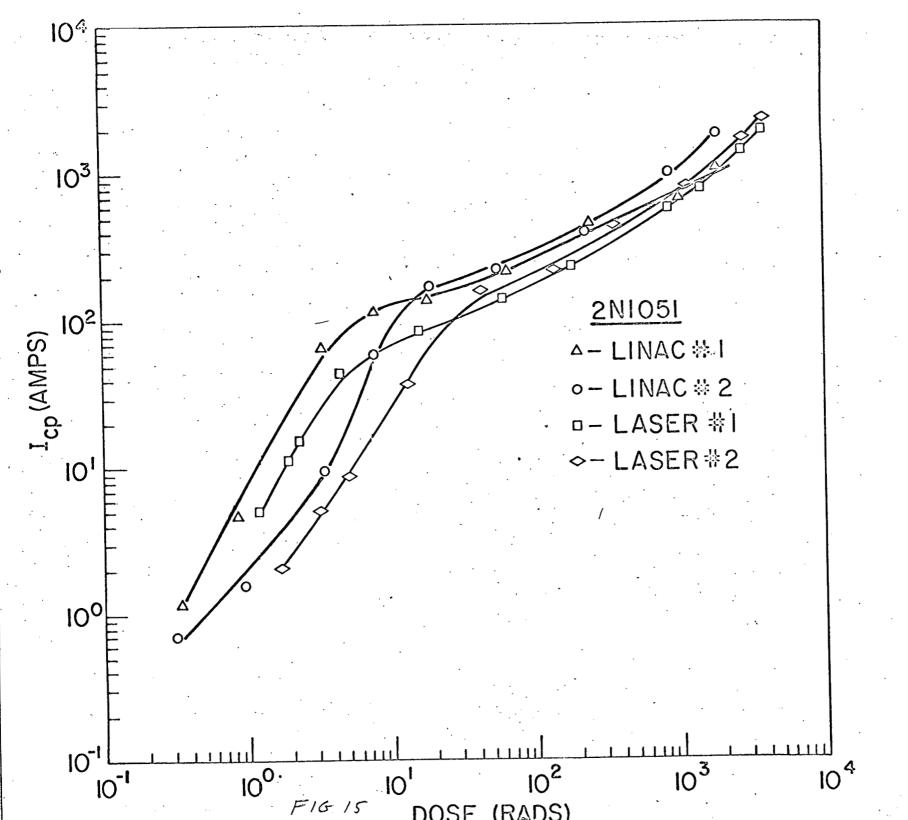
FIG 10 TOP VIEW OF 2NI675 WAFER

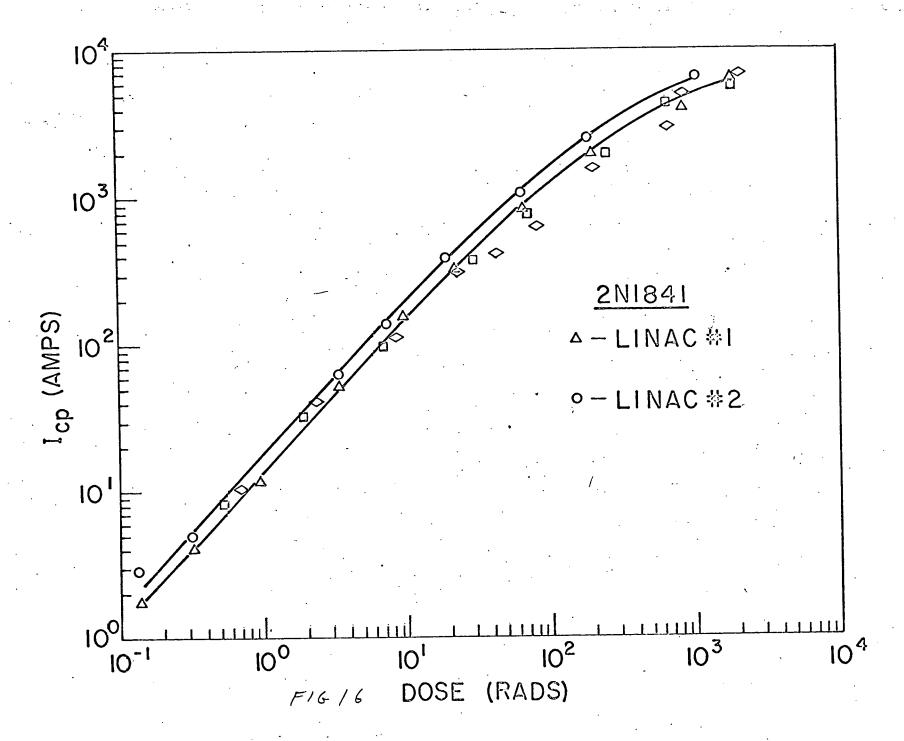


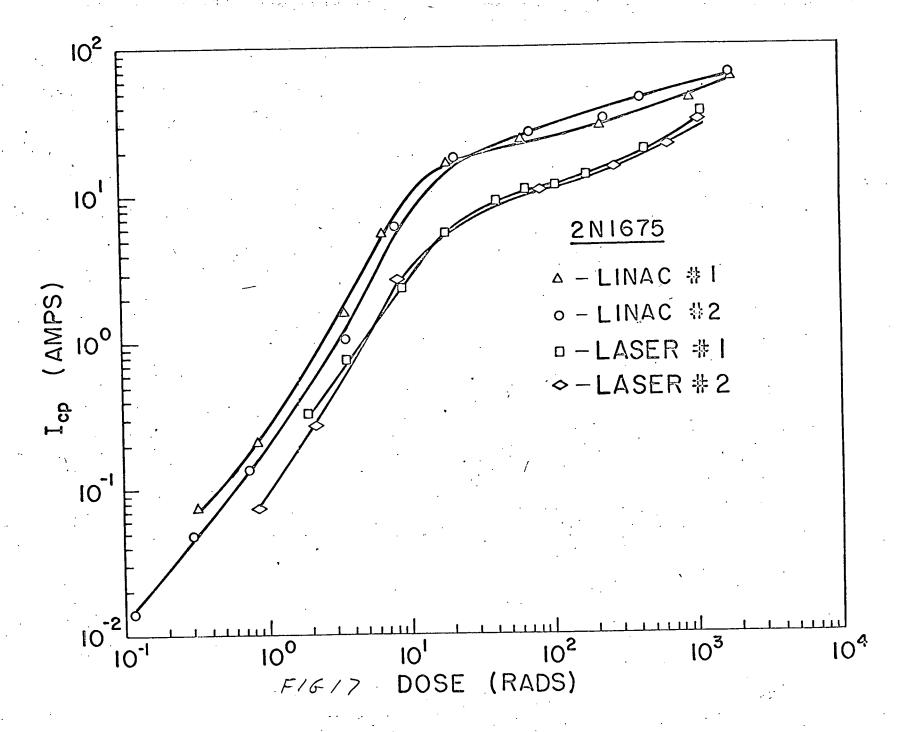












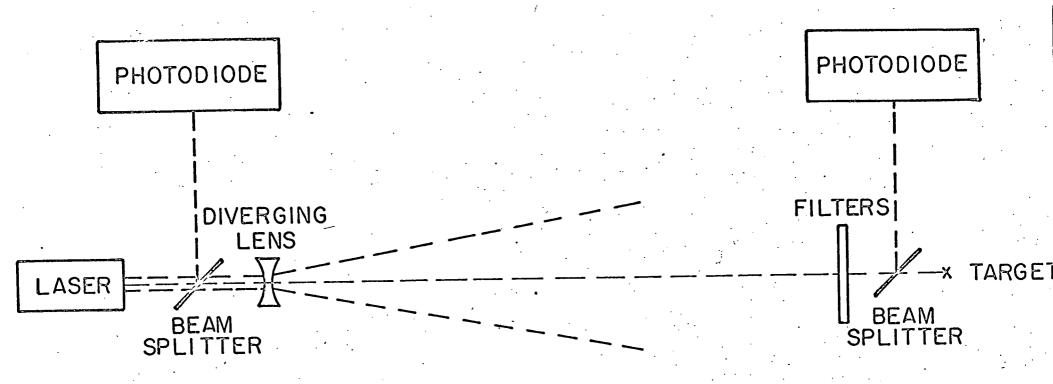


FIG 18 EXPERIMENTAL LAYOUT

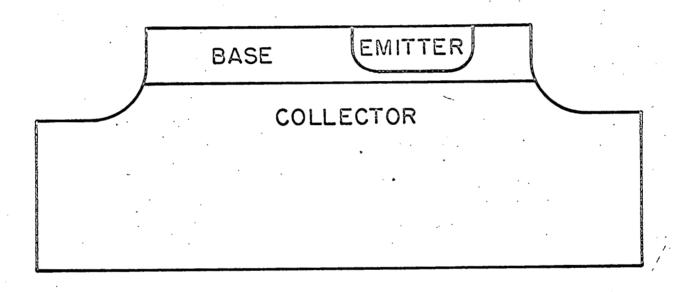
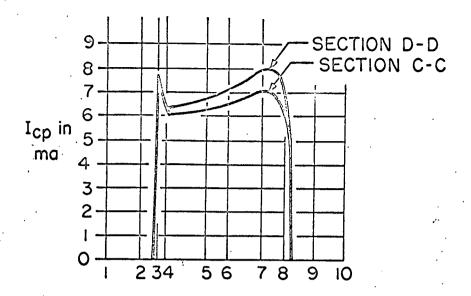
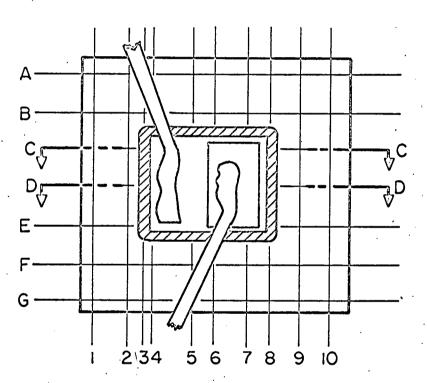


FIG 19 CROSS SECTION OF A DOUBLE-DIFFUSED MESA TRANSISTOR





FIGDO I_{CP} v.s. POINT OF ENERGY DEPOSITION FOR 2NIO51