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Report No. 03-67-23

SECOND INTERIM ENGINEERING REPORT

for

DEVELOPMENT AND FABRICATION OF SOLID-STATE HIGH-SPEED OPTICAL DETECTORS

This Report Covers the Period

16 November 1966 to 15 February 1967

Texas Instruments Incorporated

13500 North Central Expressway

Dallas, Texas 75222

Navy Department
Bureau of Ships
Electronics Division

Contract No. NObsr 95337

Project No. SF021-02-01

Task No. 9349

March 1967

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ABSTRACT

Work continued on development and fabrication of a high-speed silicon avalanche photodetector optimized for operation at 0.9 μm. During this quarter the work was concentrated on design and fabrication problems.

The inversion-stopper ring formed by P-diffusion and the alloyed aluminum ring proved to be completely ineffective in preventing inversion layers and correspondingly high reverse leakage currents. The problem has been solved by a separate P^+-diffusion.

The high electric field at the sharp radius of the N-diffusion in the NPπ [illegible] cture was found to be the cause of the edge breakdown.

Preliminary indications are that fabrication of the structure with the original dimensions requires better control of diffusions.

Good avalanche photodiodes have been fabricated using a graded guardring structure. Uniform gains of greater than 150 across the diode active area were observed.

W. N. Shaunfield,
Project Engineer

J. R. Biard,
Program Manager

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SECTION I

TECHNICAL REVIEW

A. PURPOSE

Texas Instruments is conducting a program of development aimed at fabricating photodiodes which satisfy the following goals:

1) An NPπP photodetector will be developed which utilizes the avalanche mechanism.
2) The detector will be optimized to operate at 0.9 μm wavelength.
3) Design goals for the detector will be a response of 0.15 ns with a sensitivity equal to or better than that of a photomultiplier tube used at the same wavelength.
4) The photodiodes will operate at and above room temperature and will not be affected by 100°C storage temperature.
5) The photodiodes will be capable of providing amplification of 100 or greater.

The program consists of two phases: I, design and fabrication of the avalanche photodiodes; II, testing and characterization. Phase II will begin with completion of the first diffusion runs to determine whether any modifications in the original design are necessary to achieve the desired characteristics. Specific steps of the program are:

1) Obtain photomasks
2) Determine optimum diffusions
3) Produce experimental epitaxial slices
4) Fabricate experimental planar epitaxial diodes
5) Characterization of experimental diodes, including quantum efficiency, gain characterization, noise performance, and frequency response.

B. GENERAL FACTUAL DATA

Personnel and Hours Worked

Professional	Hours
W. N. Shaunfield	214.0
John Blair	57.0
Jim Lewis	15.0
Total Professional	286.0

Technician	
Jerry Reid	154.4
Norris Tidwell	274.0
Sam Provenzano	4.5
Sam Angelo	16.0
Billie Housewright	17.0
Total Technician	465.9

C. DETAIL FACTUAL DATA

1. Inversion Layers

During the first quarter, inversion layers on the surface of the diode were found to be the cause of high reverse leakage currents. The original design of the photomask included a P-type inversion-stopper ring which was diffused with the P-diffusion in the active region. However, the impurity concentration required in the active region proved to be too low to be completely effective in the inversion-stopper ring. Surface concentration of the P-diffusion is approximately 10^{17} cm $^{-3}$, while that required for the inversion stopper is 5×10^{18} cm $^{-3}$.

Two possible solutions were discussed in the first quarterly report:

1) Perform a separate P^+-diffusion in the ring;
2) Alloy an aluminum contact to the existing diffusion.

Aluminum, which is a P-type dopant in silicon, when alloyed to the ring should prevent inversion layers from forming over the inversion-stopper ring. The second approach was selected, since this could be done during application of contacts and would not require an additional processing step.

The additional photomask required for the aluminum ring was received during the second quarter, and several runs were made with this approach. Results were not as good as expected. Leakage current was high, and there was drifting of the current with time at high reverse-bias voltages.

Traces made with an optical microprobe showed that under reverse bias an inversion layer was formed under the aluminum inversion-stopper ring. In making an optical-microprobe trace the diode is contacted between the P-contact on the back of the slice and the N-contact on the active region, and the photocurrent due to a 0.2-mil-diameter spot of light traced across the surface of the diode is measured. In addition the light is modulated at 400 Hz and the current is synchronously demodulated to avoid errors due to dark leakage currents. Magnitude of the signal is plotted versus distance on an X-Y recorder.

Figure 1 shows several plots made at different bias voltages on a diode with the aluminum inversion-stopper ring. The large photoresponse between the N^+-diffusion and the inversion-stopper aluminum indicates that inversion layers are present on the surface. The diode formed by the N-type inversion layer and the π-type bulk

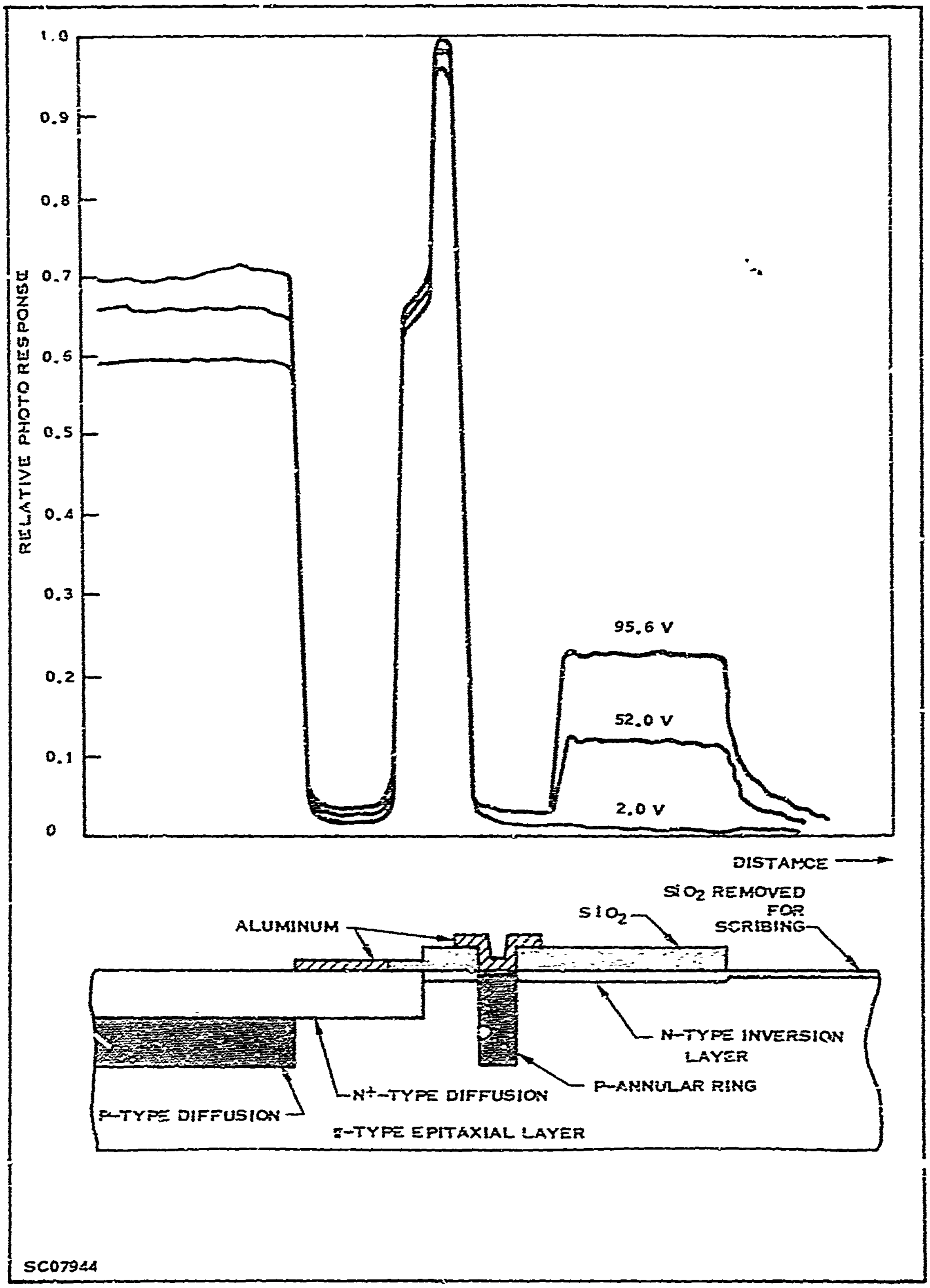

Figure 1. Relative Photoresponse Across Surface of NPπP Structure for Different Bias Voltages

is light-sensitive like a conventional diode. Note that at 2.0 volts bias the inversion-stopper ring is effective in isolating the diode's active region from the inversion layer outside inversion-stopper ring. However, as reverse bias is increased, photoresponse is observed outside the ring, indicating formation of an inversion layer under the ring connecting the inside and outside inversion layers. Inversion-layer photoresponse outside is lower than that inside, apparently because of series resistance under the ring. Note that photoresponse falls off where the oxide was removed along the scribe line, indicating that this removal reduces the inversion layer's adverse effect. At bias voltages near breakdown (180 - 240 V) the leakage current was still too large, typically 200 μA.

Because of the problem with aluminum alloyed to the P-ring, the other approach, requiring a separate P^+-diffusion, was tried. Although an additional processing step is necessary the diffusion is not critical. A photomask with only the inversion-stopper ring was obtained, and several runs were fabricated by this method. Results were very encouraging. An optical-microprobe trace showed no photoresponse outside the ring, and leakage currents typically were less than 100 nA at 150 volts bias. In addition no drifting of the leakage current was observed.

2. NPπP Structure

During the second quarter seven runs of the NPπP structure were processed. Each run had breakdown at the edge of the junction instead of in the active region. Breakdown location was determined by the light emission from the edge when diodes were biased into sustained breakdown. Possible reasons for the edge breakdown and the solutions are discussed in the following paragraphs.

During the last quarter, calculations were made to determine the P-diffusion concentration, N_p. These calculations showed that the acceptable range of N_p was very critical (3 to 6 x 10^{16} cm^{-3}). When edge breakdown was first detected it was suspected that the P-diffusion concentration was too low; however, when the concentration was increased the diodes still had edge breakdown. Additional runs are being processed, with P-diffusion concentration increased further.

In the calculations on required impurity concentrations the effect of junction curvature on the electric field was neglected. Along the edge of the planar-diffused junction a cylindrical junction is formed with radius approximately equal to junction depth. As a result the electric field is greater than in a plane junction, and breakdown voltage is reduced. For the case where the junction depth is small compared to depletion width the breakdown voltage is significantly reduced [1].

For the case where depletion width extends to a P^+ substrate, as in the NPπP structure, edge effects are not as significant. This can be illustrated graphically if several simplifying assumptions are made:

1) assume that the depletion region can be represented by a capacitor with plates separated by the plane junction depletion layer width;

2) assume that there is no charge between the plates.

Assumption 1 is not valid, since the depletion width of the cylindrical junction is not as wide as that of a plane junction for the same applied bias; neither is assumption 2. since there is charge in the depletion region.

1. S.M. Sze and G. Gibbons, "Effect of Junction Curvature on Breakdown Voltage in Semiconductors," Solid State Electronics, Vol. 9, pp. 831-845 (1966).

Although these assumptions are not valid for a depletion region, they do allow the effects of a P^+ substrate on the peak electric field to be illustrated by the graphical field-mapping technique. It should be pointed out that, although the field in a PN junction could be graphically mapped, the complication would not add to understanding of the effect.

Using the assumptions above, the electric field for a diffused junction is shown in Figure 2a. Note that the highest electric field, represented by close spacing of the flux line, occurs at the junction edge. In Figure 2b the field is shown for the same potential applied to a junction with a P^+ substrate under the N^+-diffusion. Note that the electric field at junction edge is not appreciably changed, while that at the plane portion of the junction is significantly increased. Ratio of edge breakdown voltage to center breakdown voltage would be much less in (b) than in (a).

In the NPπP structure the peaking of electric field in the active region is further aided by the P-diffusion; however, the edge effect puts closer limits on the already critical dimensions. To prevent edge breakdown in the NPπP structure it is necessary that the epitaxial layer width be small compared to breakdown depletion layer width in a concentration equal to that of the epitaxial layer. This requirement is contradictory to the wide expitaxial layer widths required for high quantum efficiency and the impurity concentrations possible with epitaxial techniques. It is felt that the NPπP structure will work with the concentrations and dimensions discussed in the first quarterly report; however, this will require more accurate control of diffusions.

Two additional techniques can be employed to reduce edge effects in the NPπP structure. The first is to make the N-diffusion deeper. This results in a larger radius of curvature at the junction edge, reducing the peak electric field. There would be some reduction in quantum efficiency. The other technique would be to etch a moat into the region which normally is depleted. If there were no material to be depleted the electric field could not rise to the high value normally at the edge. Also, the

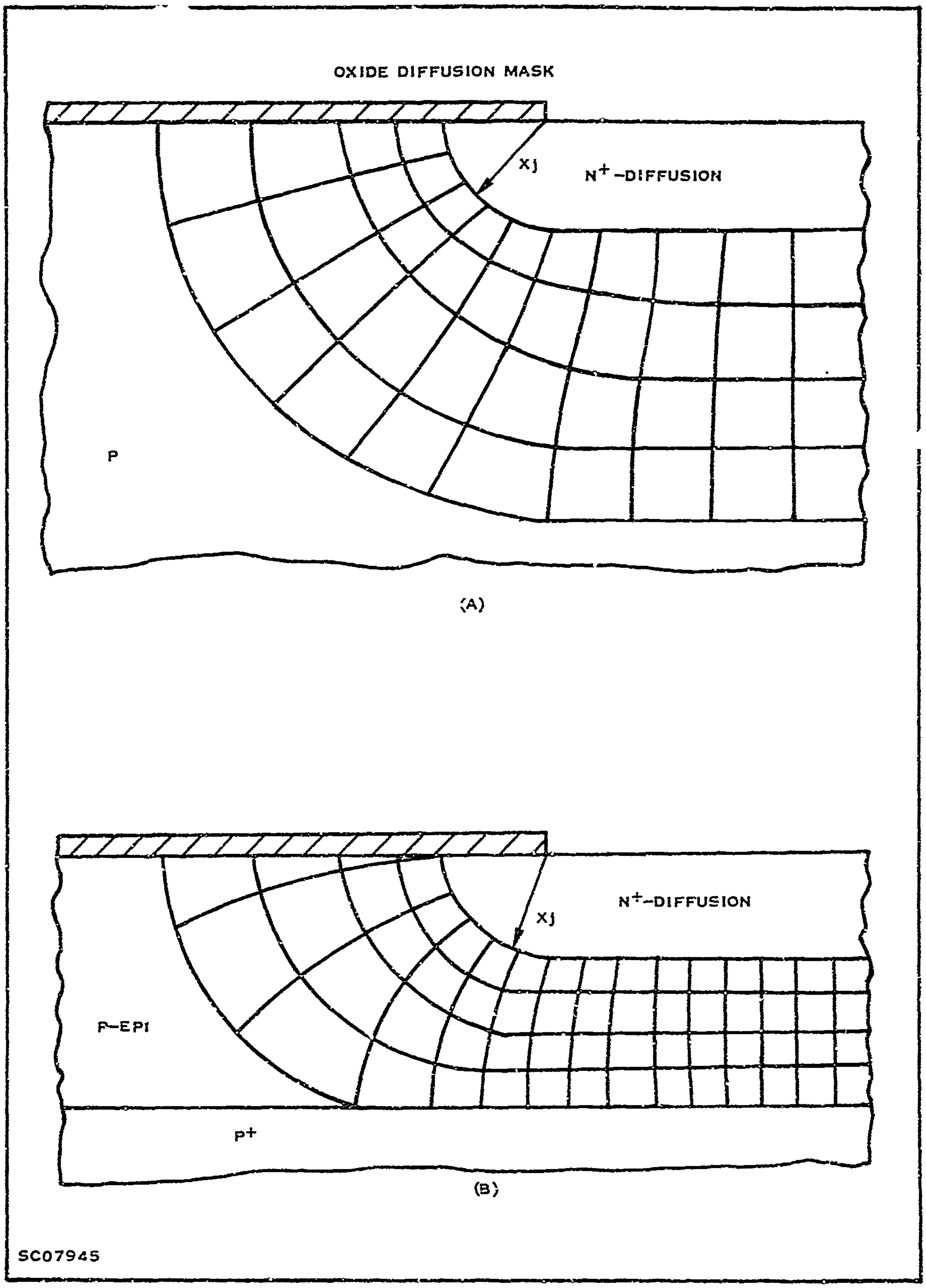

Figure 2. Simplified Representation of Electric Field at Junction Edge

moat could be etched through the edge of the junction, forming a mesa junction. The etched surface could result in higher leakage currents. Each of these techniques will be investigated in the effort to fabricate an acceptable NPπP structure.

3. Graded Guardring Structure

Because of the problems discussed in the preceding paragraphs, another structure is being fabricated in addition to the NPπP structure. The diode uses a simpler N^+P structure with graded guardring to prevent edge breakdown [2].

A cross-section of the diode is shown in Figure 3. The edge has a higher breakdown than the active region because the guardring junction is graded and it has a large radius of curvature. Diode has a 10-mil-diameter active region. A composite photomask layout is shown in Figure 4.

First run of the graded guardring structure was completed during the second quarter. Substrate resistivity was 6.5 Ω cm. A guardring diffusion 5 μm deep, and an active region diffusion 1.0 μm deep, formed the diode. Also, a P^+ inversion-stopper-ring diffusion around the diode was used. The 6.5-Ω cm material results in a 10-μm depletion layer width at average breakdown voltage of 170 volts.

Results of the first run are very encouraging. No edge breakdown was observed, and the yield of good diodes was greater than 50 percent. Gain of the good diodes was very high and uniform. Optical-microprobe traces across the surface of a typical diode for several values of gain are shown in Figure 5. Traces were made before contacts were applied; therefore photoresponse is recorded across the entire diffused area for the trace where $M = 1$. Also, photoresponse due to a surface inversion layer was observed out to the inversion-stopper ring.

---

2. A. Goetberger, B. McDonald, R. H. Haitz, and R. M. Scarlett, "Avalanche Effects in Silicon P-N Junctions: II, Structurally Perfect Junctions," J. Appl. Phys., Vol. 34, pp. 1591-1600 (June 1963).

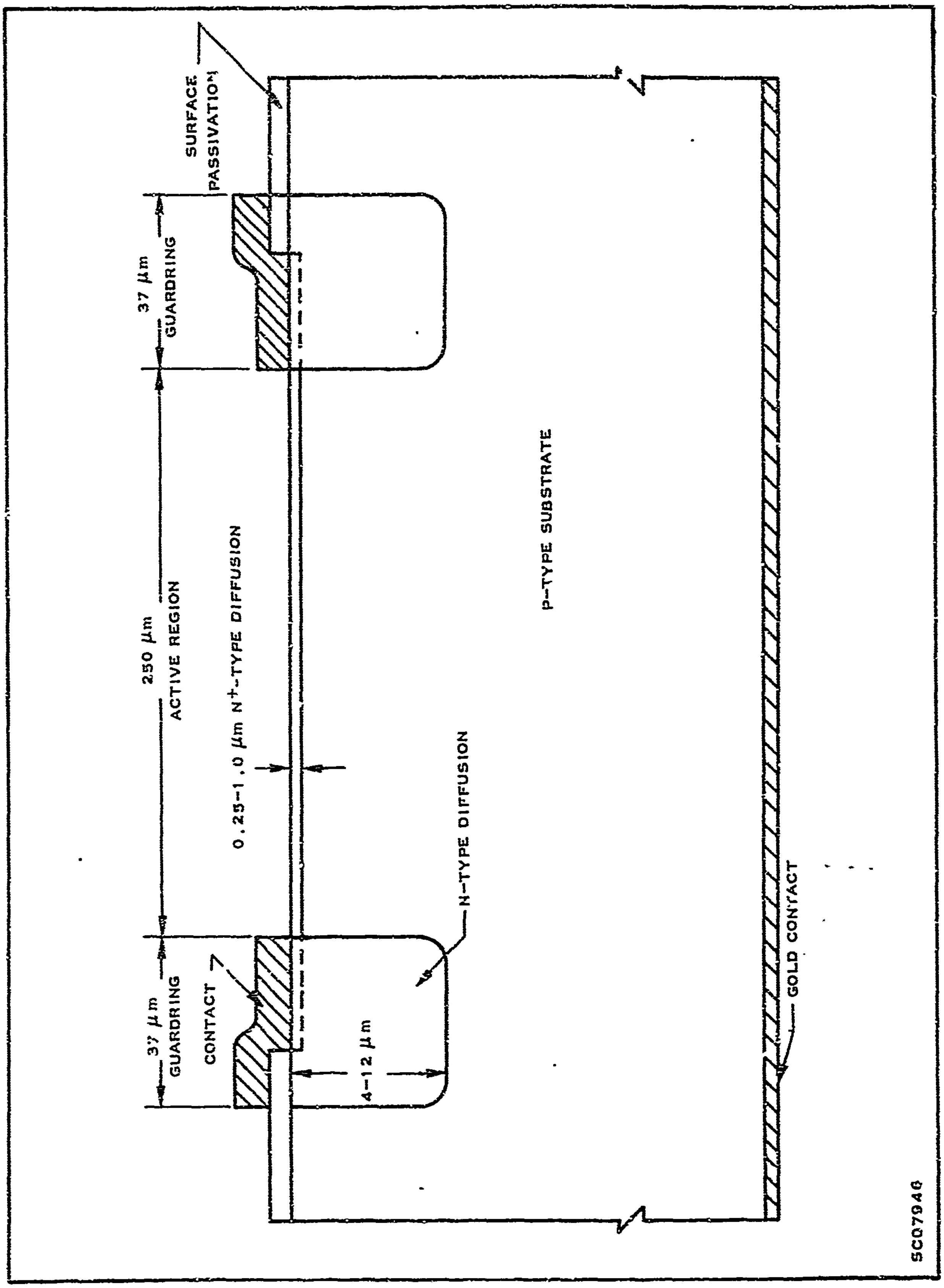

Figure 3. Graded Guardring Avalanche Photodiode

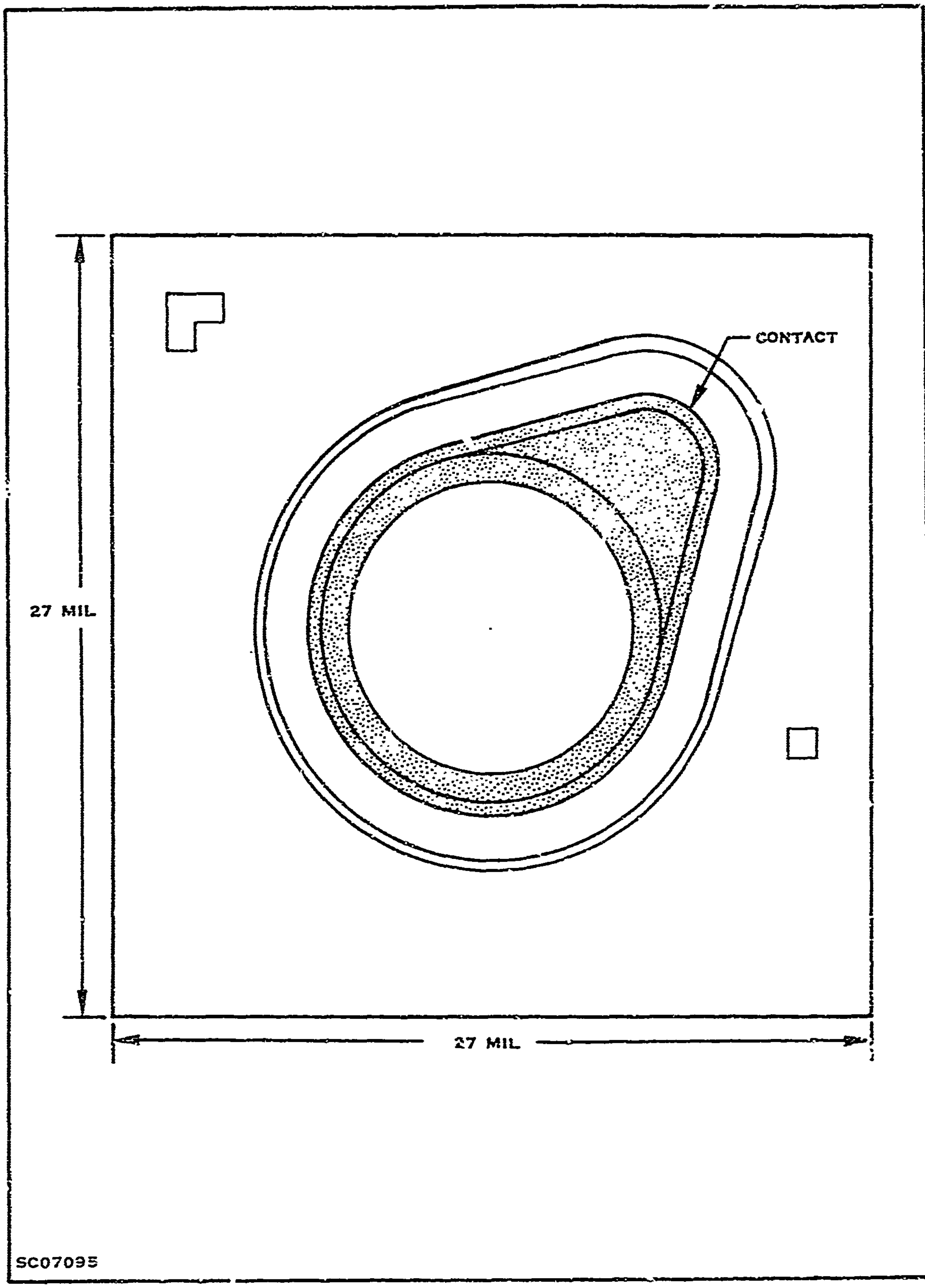

Figure 4. Composite Photomask Layout for Graded Guardring Avalanche Photodiode

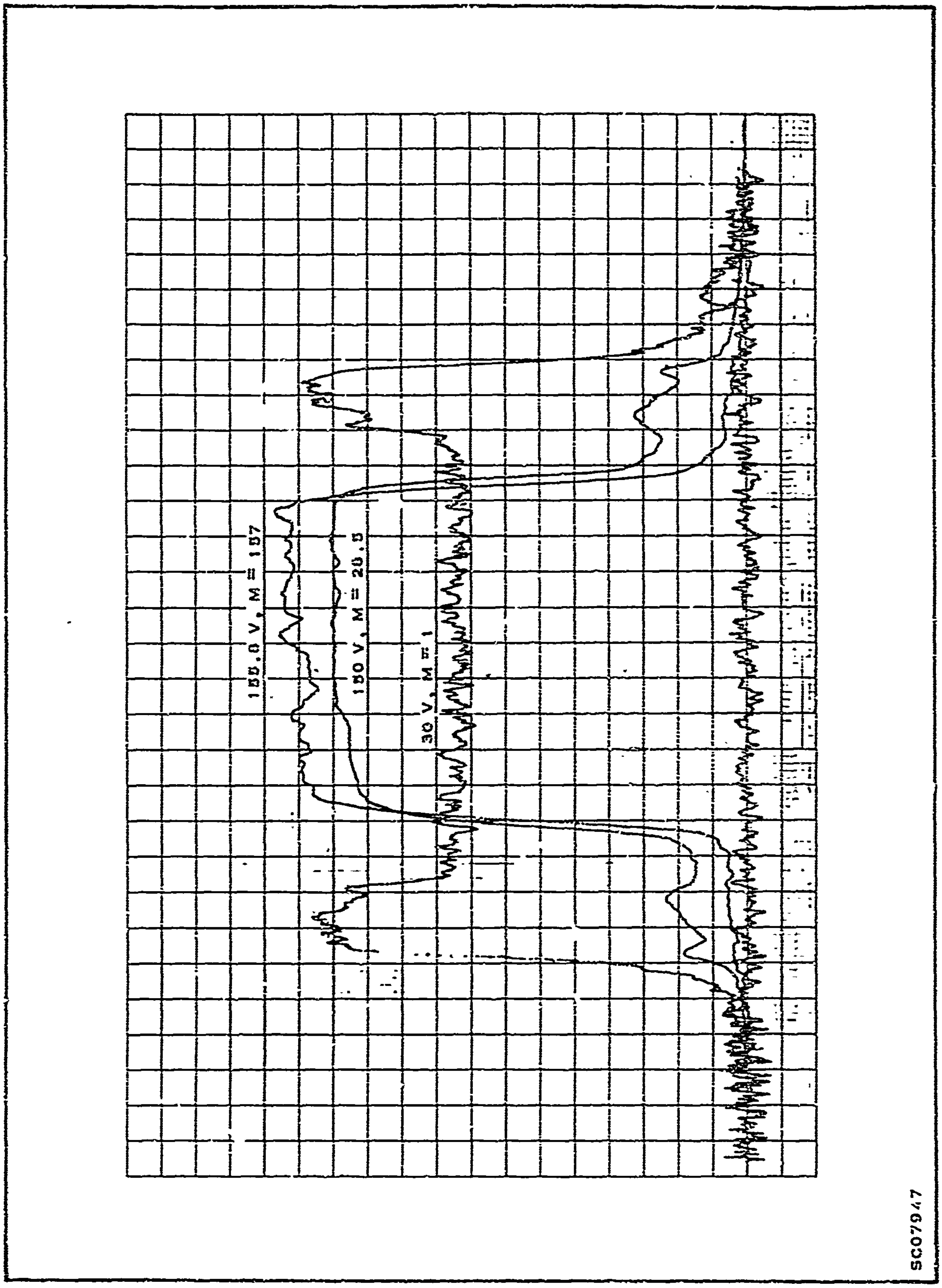

Figure 5. Photoresponse Across Surface of Graded Guardring Structure

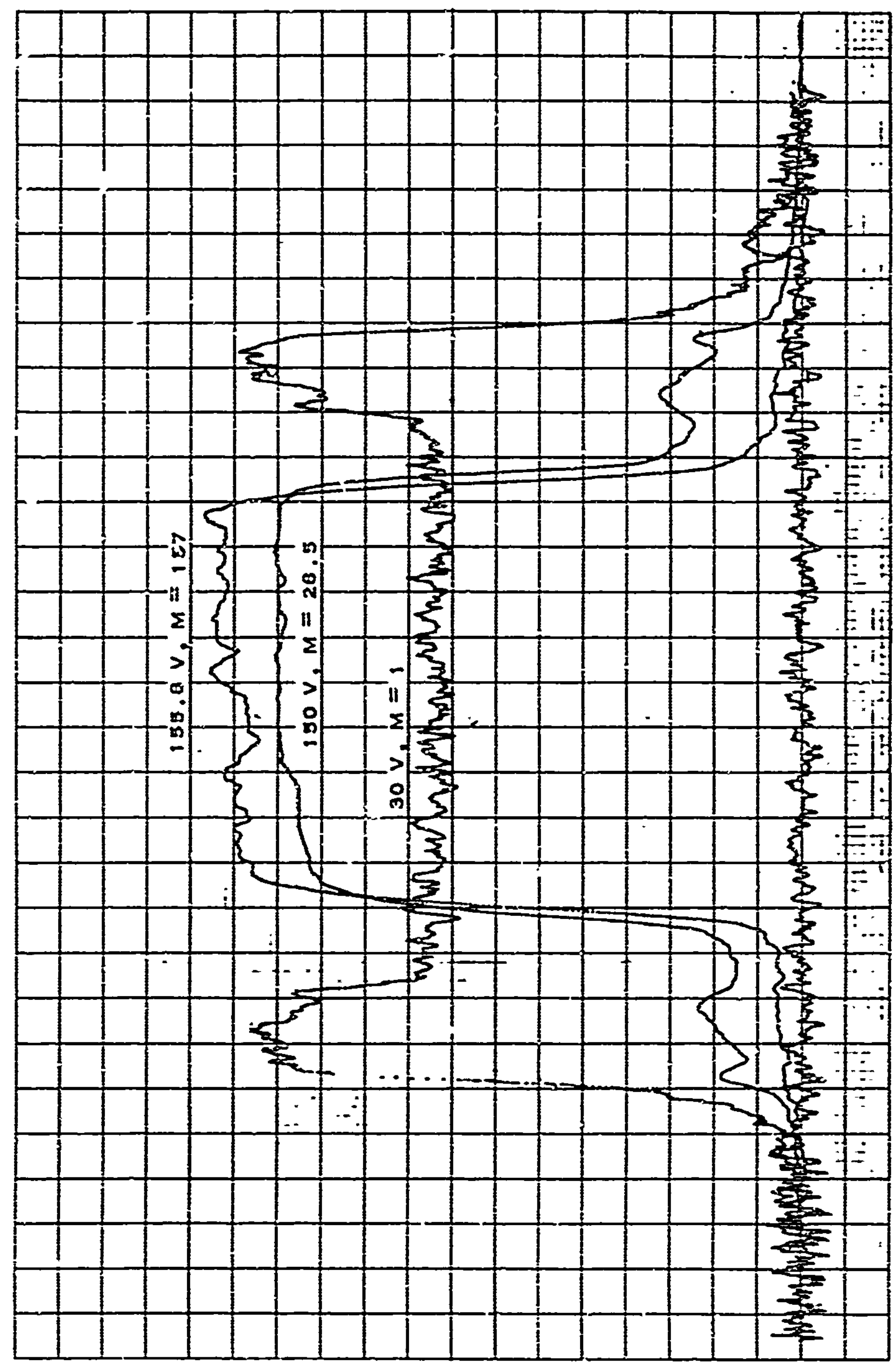

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Figure 5. Photoresponse Across Surface of Graded Guardring Structure

Another indication of the inversion-stopper ring's effectiveness was low reverse leakage currents (typically 70 nA at 130 volts). The top trace of Figure 5 illustrates the uniformity of avalanche gain across the diode surface. Improved signal-to-noise ratio of the traces, with gain over the trace for M = 1, illustrates the advantage in using avalanche gain.

Although the graded guardring structure is simple and resulted in a high yield of uniform avalanche photodiodes, it has one disadvantage as a high-frequency detector. Series resistance is much larger than that of the NPπP structure because of the high-resistivity substrate material. Calculated series resistance is approximately 100 ohms for the 6.5-Ω cm material 6 mils thick. Although this could be reduced by mechanically thinning the slices or by epitaxial techniques, it is unlikely that the 1-ohm series resistance of the NPπP structure could be obtained. Capacitance of the junction at breakdown is approximately 1.0 pF. Therefore the diode could be operated into a resistive load of several hundred ohms and have a 200-MHz bandwidth.

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4. Project Performance and Schedule

Texas Instruments Incorporated

Contract No. NObsr 95337 (Report) Date: March 1967

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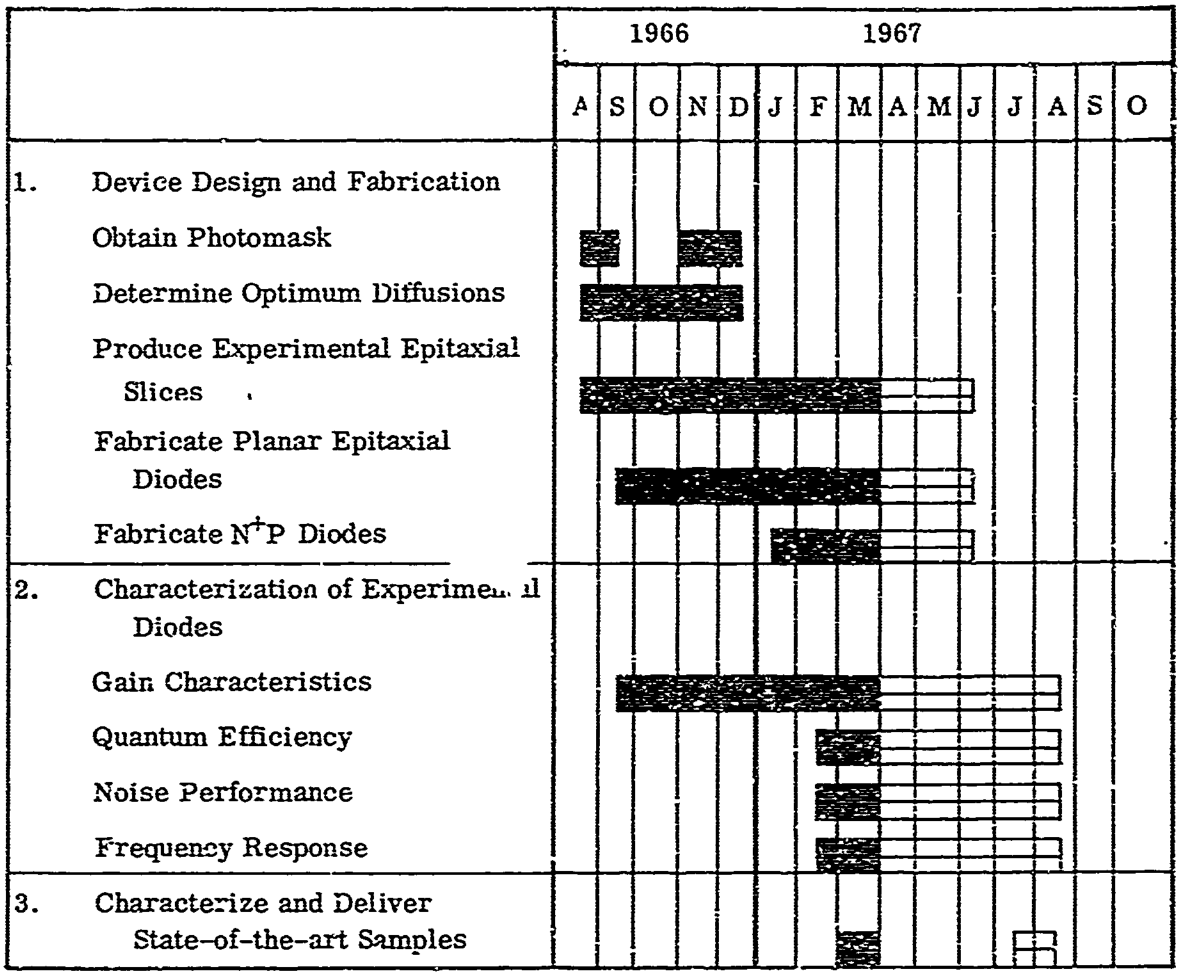

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Legend:

Work Performed

Schedule of Pro;ected Operation

Item: Estimated completion in percent of total effort expected to be expended (not chronological):

1.	Obtain Photomasks	100%
2.	Determine Optimum Diffusions	70%
3.	Produce Experimental Epitaxial Slices	80%
4.	Fabricate Planar Epitaxial Diodes	50%
5.	Determine Gain Characteristics	40%
6.	Determine Quantum Efficiency	20%
7.	Determine Noise Characteristics	20%
8.	Determine Frequency Response	20%
9.	Characterize and Deliver Samples	20%

Notes and Remarks:

Because of difficulties in fabricating acceptable avalanche photodiodes the characterization and delivery of the samples will be delayed thirty days.

D. CONCLUSIONS

The inversion-layer problem was solved with a separate P^+-diffusion in the inversion-stopper ring.

Continued edge-breakdown problems prompted an investigation of the edge effects on the electric field. The investigation showed that the acceptable diffusion tolerances were closer than expected.

Because of problems with the NPπP structure, work on a graded guardring structure was begun. The first of these diodes fabricated had high, uniform gain.

SECTION II

PROGRAM FOR NEXT INTERVAL

For the next quarter we plan the following work:

1) Continue fabrication of NPπP structure with emphasis on elimination of edge breakdown.

2) Fabricate additional runs of graded guardring structure.

3) Produce additional lots of epitaxial material for diffusion runs.

4) Complete characterization of state-of-the-art samples.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
High-speed photodetector Avalanche photodiode Silicon photodetector Low-noise photodiode						

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