and from this I_{dss} may be obtained from the value of I_{ds} at 0-V bias.

REFERENCES

[1] J. J. Pan, "Wideband MESFET frequency multiplier," in *IEEE MTT-S 1978 Int. Microwave Symp. Dig.*, June 1978, pp. 306–308.

[2] P. T. Chen, C-T Li, and P. H. Wang, "Dual-gate GaAs FET as a frequency multiplier at *Ku*-band," in *IEEE MTT-S 1978 Int. Microwave Symp. Dig.*, June 1978, pp. 309–311.

[3] P. T. Chen, C-T Li, and P. H. Wang, "Performance of a dual-gate GaAs MESFET as a frequency multiplier at *Ku*-band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 411–415, 1979.

[4] M. S. Gupta, R. W. Layton, and T. T. Lee, "Frequency multiplication with high-power microwave field-effect transistors," in *IEEE MTT-S 1979 Int. Microwave Symp. Dig.*, pp. 498–500, Apr. 1979.

[5] M. S. Gupta, R. W. Layton, and T. T. Lee, "Performance and design of microwave FET harmonic generators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 261–263, 1981.

[6] H. A. Willing, C. Rauscher, and P. deSantis, "A technique for predicting large-signal performance of a GaAs MESFET," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 1017–1023, 1978.

[7] P. Penfield, Jr. and R. P. Rafuse, *Varactor Applications*. Cambridge, MA: MIT Press, 1962.

[8] J. C. Decroly, L. Laurent, J. C. Lienard, G. Marechal, and J. Vorobeitchik, *Parametric Amplifiers*. New York, NY: Wiley, 1973.

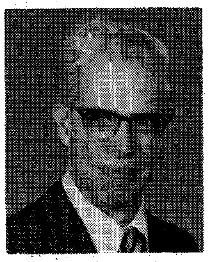
[9] C. W. Gear, *Numerical Initial Value Problems in Ordinary Differential Equations*. Englewood Cliffs, NJ: Prentice-Hall, 1971.

[10] R. A. Pucel, H. A. Haus, and H. Statz, "Signal and noise properties of Gallium Arsenide microwave field-effect transistors," in *Advances in Electronics and Electron Physics*, vol. 38, L. Marton, Ed. New York: Academic, 1975, pp. 195–266.

Anand Gopinath (S'64–M'65) received the degree of B.E. (electrical) from Madras University, India, in 1957 and the degree of M. Tech. from the Indian Institute of Kharagpur, West Bengal, India, in 1961. He received the degree of Ph.D. from University of Sheffield, England in 1965 and was awarded the degree of D.Eng. in 1978, by University of Sheffield.

He was Graduate Apprentice at the Metropolitan Vickers, C., Manchester, England, from 1958 to 1960, Engineering Assistant at Jessop &Co., Calcutta India, from 1960 to 1962, and was Research Assistant at University of Sheffield, Sheffield, England, from 1965 to 1966. He was appointed Lecturer in Electronics at the University College of North Wales, Bangor, Wales, in 1966, and in 1978 became Reader in Electronics. He joined M.I.T. Lincoln Laboratory, Lexington, MA, in 1979.

Dr. Gopinath is a member of the Institution of Electrical Engineers (London), graduate member of the Institution of Mechanical Engineers (London), and a member of Sigma Xi.



J. Bruce Rankin (S'49–A'51–M'58) was born in Baltimore, MD, in 1923. He received the B.S. degree from Harvard University, Cambridge, MA, in 1947, the B.S.E.E. degree from the University of Delaware, Newark, in 1948, and the M.S.E. degree from Princeton University, Princeton NJ, in 1957.

In 1950 he joined the Technical Staff of RCA Laboratories, Princeton, NJ, where he worked on antennas, waveguides, and propagation. He was later transferred to the RCA Missile and Surface Radar Division, Moorestown, NJ. In 1961 he joined the staff of MIT Lincoln Laboratory, Lexington, MA. He has been involved with antennas for satellites, with optical propagation, and optical satellite communication. At Lincoln Laboratory he was a Personnel Representative from 1973 to 1979. Currently he is engaged in computer programming of microwave circuit and radar problems.

p-i-n Diodes for Low-Frequency High-Power Switching Applications

MARTIN CAULTON, FELLOW, IEEE, ARYE ROSEN, SENIOR MEMBER, IEEE, PAUL J. STABILE, MEMBER, IEEE, AND ANNA GOMBAR

Abstract —**The development of high-power low-frequency diodes, conditions for their operation, and results measured in actual circuits are described. Harmonic distortion at 500 kHz and 2 MHz has been found to decrease with increasing diode lifetime and forward-bias current. Large reverse bias voltages are necessary at low frequencies to keep the RF voltage swing from penetrating the forward conduction region. The improvement of p-i-n diode lifetimes with thicker I-layers or with planar construction has been studied and the performance of these diodes in a routing switch is reported.**

Manuscript received July 24, 1981; revised February 1, 1982. Part of the material in this paper was presented at the 1981 IEEE International Microwave Symposium in Los Angeles, in June.

The authors are with RCA Laboratories, David Sarnoff Research Center, Princeton, NJ 08540.

I. INTRODUCTION

WITH the successful design and fabrication of p-i-n diodes for high-voltage switches at microwave frequencies [1], their application at lower frequencies can now be investigated. This paper stems from the successful effort

0018-9480/82/0600-0875$00.75 ©1982 IEEE

to use the diodes at frequencies as low as 500 kHz. The applications considered include their use to tune antenna couplers and for routing switches, among others. Ultimate goals were to develop p-i-n diodes that would withstand currents as large as 10-A rms without distortion or burnout, and also sustain reverse bias RF voltage swings of 1000 V or more.

In the forward bias condition, with a dc current of 100 mA, a p-i-n diode should have a low dc series resistance R_s on the order of 0.2 Ω. Upon application of a dc back-bias, the diode should be represented by a high resistance (100 000 Ω) and a capacitance of less than 3 pF. Thus by the application of forward or reverse bias we can produce approximations to open or short circuits. For instance, in use as a routing switch, the open-circuit resistance and capacitance reduce the isolation, while the finite forward resistance causes loss.

We have investigated the properties of the diodes particular to low-frequency operation. We have found, as expected, that in the forward-bias mode the p-i-n diode serves as a low resistance only when the carrier lifetime τ_e of the I-layer is long compared to the period of the RF signal. In addition, the ratio of RF to dc control current also influences the diode forward-bias characteristics. In the reverse bias mode, the frequency of operation and the diode transitions set limits on the voltage required for safe and efficient operation.

Measurements and some analyses of p-i-n diode operation (reverse and forward) at these low frequencies will be described, as well as new requirements for proper operation. In addition, p-i-n diode characteristics have been studied and new p-i-n structures which have been fabricated (improving the carrier lifetime and reverse-bias limits) will also be included in the discussions.

II. Diode Performance and Analysis

A. Forward-Bias Operation

1) Background: p-i-n diodes are composed of p^+ and n^+ semiconductor regions separated by an intrinsic I-layer of n-material 2000-Ω·cm (or higher) resistivity, having a reasonably long lifetime τ (Fig. 1). Upon application of a forward bias current, holes and electrons are injected into the I-layer from the p^+ and n^+ layers. The mobile carriers form a dense plasma of charges which can convert the high-resistivity I-layer into a conducting medium. The number of excess carriers maintained in the I-region depends on the lifetime τ and the dc bias current I_0. At high frequencies, where $\tau \gg 1/f = T$, the resistance of the diode is due to the number of excess carriers and the p-i-n diode resistance has a dc term only. The minimum useful frequency is mainly determined by τ and the ratio of the peak RF current I_{RT} to the dc bias current I_0.

It is shown in Appendix A that the forward-biased diode can be approximated by a resistor of conductivity G [2], [3]:

$$G = \frac{I_0 \tau(\mu_e + \mu_h)}{W^2} + \frac{I_{RF}}{W^2} \frac{\tau(\mu_a + \mu_h)}{\left[1 + (\omega\tau)^2\right]^{1/2}} \cos(\omega t + \phi) \tag{1}$$

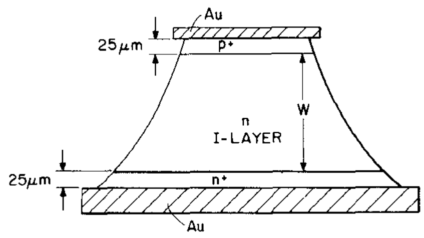


Fig. 1. p-i-n diode diagram.

where

I_0	dc bias current,
W	I-layer thickness,
μ_e, μ_h	electron, hole mobility,
I_{RF}	peak RF current,
ω	radian RF frequency.

Defining the dc resistance as

$$R_s = \frac{W^2}{I_0 \tau(\mu_e + \mu_h)} \tag{2}$$

and a modulation term α

$$\alpha = \frac{I_{RF}}{I_0\left[1 + (\omega\tau)^2\right]^{1/2}} \cong \frac{I_{RF}}{I_0 \omega \tau} \tag{3}$$

for $\omega\tau \gg 1$.

For total resistance may then be written

$$\frac{1}{R} = \frac{1}{R_s}\left[1 + \alpha \cos(\omega t + \phi)\right]. \tag{4}$$

According to this approximation, the conductivity thus has a dc resistance R_s which is determined by the material thickness and bias current, and an ac term which helps to predict the harmonic effects at low frequencies. At $F = 1$ MHz, $\tau = 20$ μs, and $I_{RF}/I_0 = 10$, the ac term $\alpha < 0.1$. At a lower τ of 1 μs and I_{RF}/I_0 approaching 100, this analysis does not apply. The α term is then a guide to the simpler harmonics.

It is apparent that in order for the diode to operate at kilohertz frequencies, the carrier lifetime must be large and the diode design and operating conditions (I_{RF}/I_0) must take this into account. As will be seen in the next section, α is not a meaningful term for diodes of different construction.

2) Measurement: The performance of p-i-n diodes has been measured at low frequencies, and the previously described relations have been compared with experimental results. A series resonant circuit [4] (Fig. 2) used an amplifier of moderate power (50 W) to apply either a large RF current (at low voltage) or a high voltage for reverse-bias studies. A wide-band (35-MHz) current transformer is used to measure and display the RF current. Fig. 3(a) is the spectral response of a reference short circuit in which the spectrum analyzer is connected across the current transformer output. Figs. 3(b) and 4 demonstrate the spectral response of a diode with three different bias currents. Fig. 3(b) and (c) show the improvement (reduction in harmonic content) with a larger lifetime diode (under similar biasing conditions). Diode B-1 also has larger diameter and capaci-

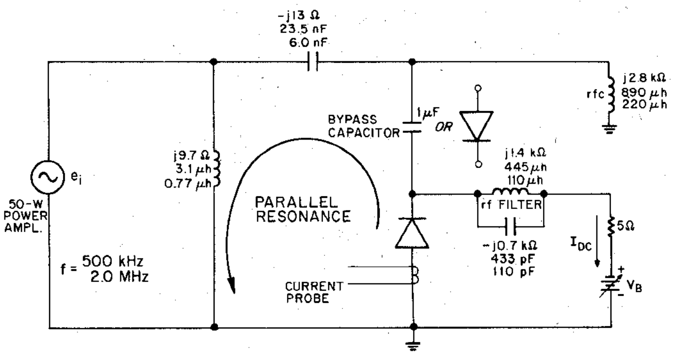
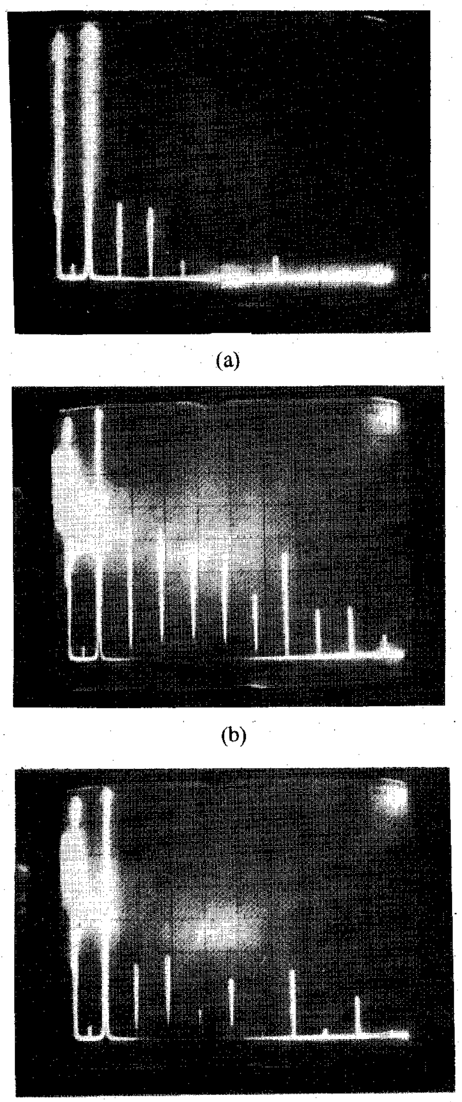


Fig. 2. Circuit diagram of the forward-bias test circuit.



(a)

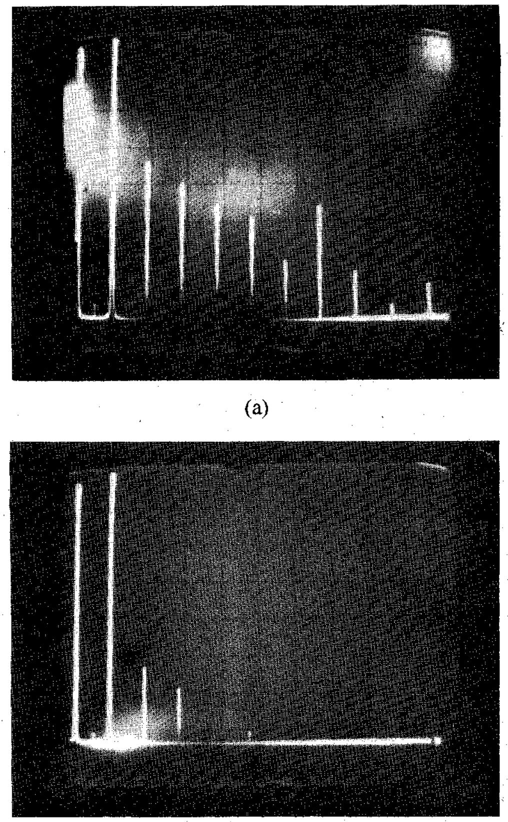
(b)

(c)

Fig. 3. Forward-bias spectral response of p-i-n diodes with $I_0 = 100$ mA, $I_{RF} = 8$-A peak. Scale: 10 dB/cm. (a) Reference short circuit. (b) $\tau = 30$ μs (diode A-5). (c) $\tau = 53$ μs (diode B-1).

tance. The significant reduction of harmonics in diode A-5 with decreasing I_{RF}/I_0, as predicted by the modulation equation, is demonstrated in Fig. 4.

Table I tabulates the spectral response for three diodes at different RF and bias currents. The diode lifetimes are indicated and two RF currents, 4- and 8-A peak, can be compared. For each diode, both the modulation index and the current ratio I_{RF}/I_0 describe the change of spectral response. However, for different diodes α is not too meaningful, and other factors come into consideration. It is



(a)

(b)

Fig. 4. Forward-bias spectral response of diode A-5 ($\tau = 30$ μs), $I_{RF} =$ 8-A peak. Scale: 10 dB/cm. (a) $I_0 = 210$ mA. (b) $I_0 = 1000$ mA.

TABLE I
SPECTRAL RESPONSES FOR THREE DIODES

Diode τ(μs)	I_{RF}(A) peak	I_0 (mA)	P_2(dB)	P_3(dB)	P_4(dB)	I_{RF}/I_0	α
A-5	4	57	−33	−41	−45	70	0.196
		108	−35	−44	−46	37	0.103
30		205	−42	−52	−53	20	0.054
		403	< −51	< −52	< −73	9.9	0.028
	8	210	−34	−40	−45	38	0.106
		428	−39	−45	−50	19	0.052
		809	−54	< −55	−68	9.9	0.028
		1000	< −54	< −55	< −71	8.	0.022
	10	1010	−48	−42	−64	9.9	0.028
		1210	< −55	< −42	< −74	8.3	0.023
B-1	4	4	−43	−50	−51	1000	1.58
53		25	−51	< −52	−60	160	0.253
	8	108	< −51	< −52	< −73	37	0.059
		27	−46	−47	−57	296	0.468
		100	< −54	−53	−71	80	0.126
A-6	4	112	−35	−44	−43	36	0.272
		220	−40	−50	−49	18	0.138
11		405	< −51	< −52	−73	9.9	0.075
	8	720	−38	−35	−50	11	0.08
		1000	< −52	< −52	< −76	6.2	0.045

< indicates special responses less than the system value. Note diameters of A-5 and A-6 are equal. Fundamental frequency = 2 MHz.

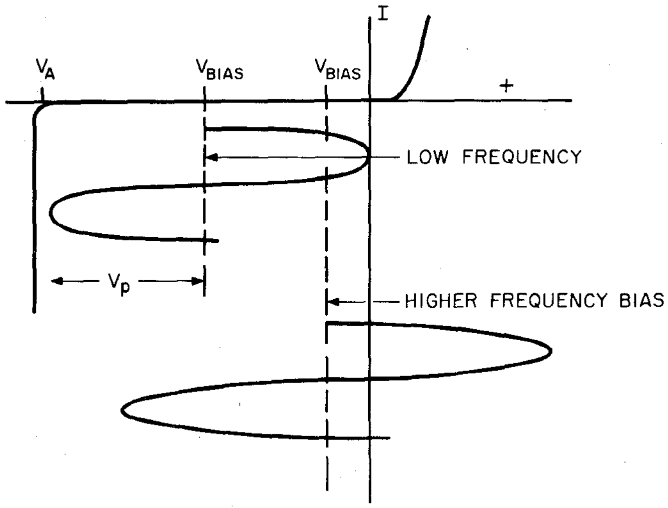


Fig. 5. Reverse-bias waveforms: low- and high-frequency voltage swings superimposed on the $I-V$ characteristics of the p-i-n diode.

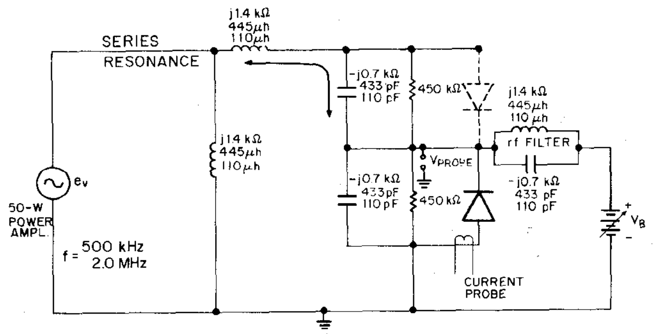


Fig. 6. Circuit diagram of reverse-bias test circuit for p-i-n diodes.

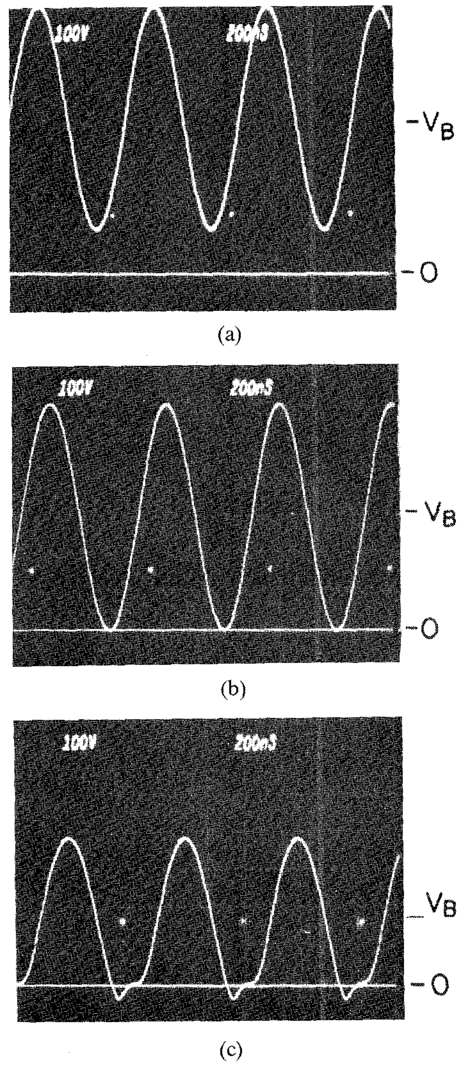


Fig. 7. Reverse-bias waveforms for $V_P = 300$ V and $f = 1.65$ MHz. (a) $V_B = 400$ V. (b) $V_B = 287$ V. (c) $V_B = 162$ V.

obvious that the lower the current ratio and/or the higher the diode lifetime, the less the distortion, as evidenced by the spectral response. This data relates to a single diode. Two diodes placed in a front-to-front orientation, as indicated in Fig. 2, will reduce the harmonics even further.

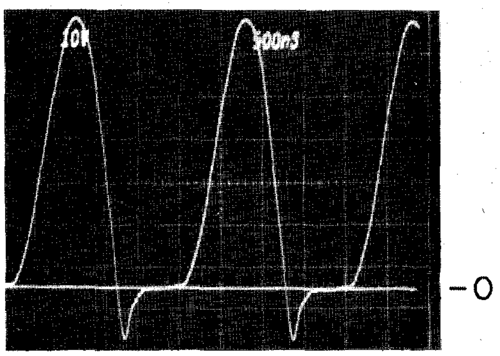
B. Reverse-Bias Operation

Fig. 5 schematically depicts the $I-V$ characteristics of a p-i-n diode locating reverse breakdown, zero bias, and applied reverse bias. Operation at a high RF voltage is shown with the voltage swing going in the forward conduction region (see lower swing labeled high frequency). According to White [5] the RF voltage swing in the forward region is allowable within limits; no carriers reach the electrodes because the period of the swing is too short. However, ionization can occur and the voltage swing should be limited. Fig. 6 is a schematic of the circuit [4] that was used to provide a high RF voltage.

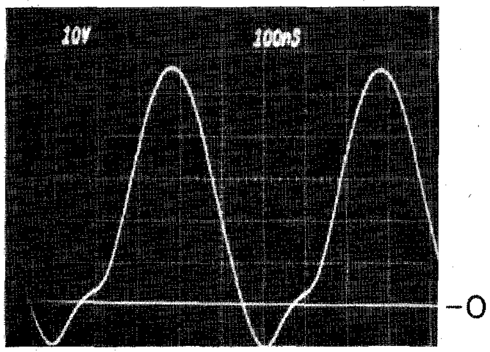
Fig. 7 is an oscilloscope photo of the RF voltage at 165 MHz across a p-i-n diode with three different bias voltages. The forward conduction region is below the zero voltage mark. The bias voltage V_B is noted. As the bias voltage is decreased toward zero (Fig. 7(b)) the peak voltage swing (~ 300 V) is unchanged, but at a bias voltage of 162 V (Fig. 7(c)) the voltage swings are inhibited from going to the forward conduction region. Fig. 8 is a similar display at two different frequencies, 500 kHz and 2 MHz, with the same bias and RF voltage. Note that the higher frequency was less distorted. The forward current that results under insufficient bias is displayed in Fig. 9. This current will soon burn out the diode. As seen in Fig. 9, forward currents of over 1 A can ensue during the forward voltage swing under these conditions.

This effect at low frequency requires the application of a reverse bias voltage equal to the largest expected peak RF voltage (1.4 V_{rms}). Fig. 5 diagrams the bias voltage required at low-frequency operation. As seen, the RF voltage is significantly limited to one-half of that of high-frequency operation.

A simple step-up transformer was constructed to test the diodes at different frequencies (under reverse bias conditions). By setting up a voltage transformer across the diode, the authors were able to measure the voltage as the frequency was increased. As expected, at higher frequencies (>40 MHz) the RF voltage could penetrate the forward conduction region. The authors examined 200-V peak voltage swings at 60 MHz across a diode biased to only 20



(a)



(b)

Fig. 8. Reverse-bias waveforms for a constant peak voltage and $V_B = 2$ V (where $V_P > V_B$). (a) $f = 500$ kHz. (b) $f = 2$ MHz.

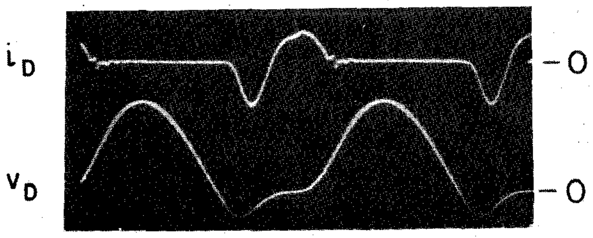


Fig. 9. Reverse-bias p-i-n diode current (i_D) and voltage (v_D) at $V_B =$ 160 V and $f = 1.9$ MHz (i_D-1 A/div.; V_D-200 V/div.)

V. Even at less than 5-V bias the display was unchanged. We lowered the frequency and recorded the bias voltage at which the signal voltage in the forward direction compressed by about 10 percent. This varied with diode size and package. Fig. 10 shows the results for a particular diode. AT 41 MHz, a minimum bias voltage was required to keep the signal from compression in the forward direction. Fig. 11 is a scope display of a 41-MHz signal exhibiting slight forward compression with a 4-V bias. The anomaly of Fig. 10 at 25–30 MHz varied with different diodes, and is believed to be due to resonances in the system.

Note that the minimum required bias voltage reached the peak applied voltage below 15 MHz. Some diodes of different construction differed in the frequency at which compression set in. Lifetime did not seem to play a role but the transit time in the I-layer appears to be a controlling aspect. This time (w divided by the drift velocity) should be longer than the period of the signal. Some of the

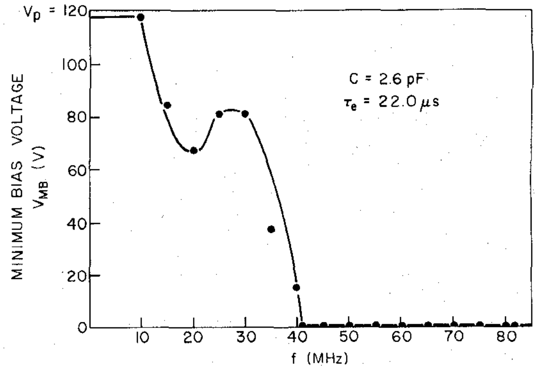


Fig. 10. Minimum reverse-bias voltage, required to keep the RF peak voltage ($V_P = 120$ V) from compressing more than 10 percent as a function of frequency.

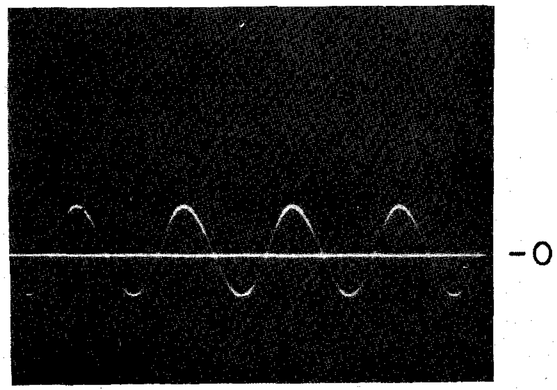


Fig. 11. Reverse-bias waveform of a p-i-n diode at $f = 41$ MHz, $V_P = 120$ V, $V_B < 5$ V, and with the RF peak voltage compressing 10 percent.

ramifications of this are under study.

The high-frequency bias voltage set by the depletion voltage is now replaced by the need at low frequency to keep the RF voltage swing from going into the positive region, as indicated in Fig. 5. In summary, the criterion for operation at these frequencies is that the bias voltage must be at least equal to the peak voltage. Unfortunately, this lowers the p–p RF voltages to values below the reverse breakdown voltage. At higher frequencies, maximum allowable p–p RF voltage would be closer to twice the reverse breakdown voltage.

III. Improvements of Carrier Lifetime

The low-frequency performance in forward-bias conditions is dependent on the lifetime achieved in the diode, as pointed out in Section II-A. Lifetime and storage time measurement procedures and dependent parameters are discussed by Rosen *et al.* [1]. The lifetime of a p-i-n diode is limited by carrier recombination, which depends on at least three mechanisms: 1) bulk, 2) surface of the n-layer sidewalls, and 3) interfacial at the n–n^+ and n–p^+ boundaries.

A. Approach

Surface recombination is extremely large. Fig. 12 [6] is a plot of lifetime versus diode diameter. The increase of lifetime τ_e with diode diameter takes place when τ_e is

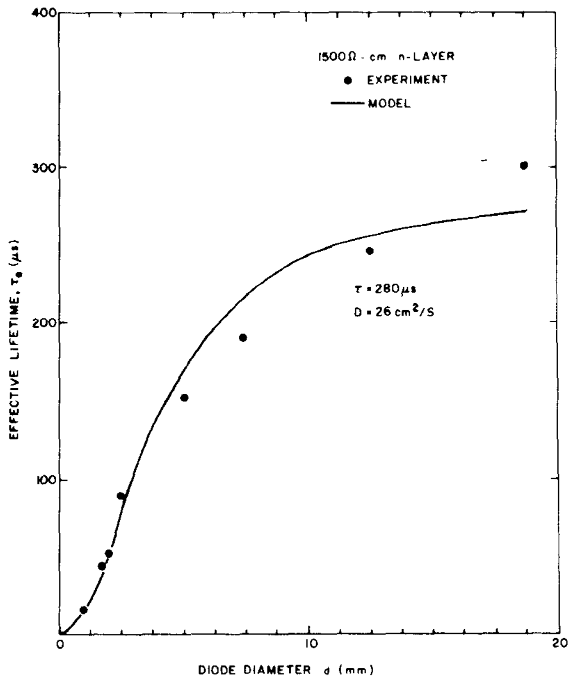


Fig 12. Lifetime versus diode diameter (fig. 7 of Martinelli and Rosen [4]).

dominated by surface recombination (diode diameters under 10 mm). Large-diameter diodes have larger capacitance, and the improvement in lifetime with diameter and increase in capacitance are part of the compromise required with diode design. Stacking diodes [1] in series is a technique used to permit increasing diode diameter (and thus the lifetime) while keeping the capacitance within limits. The stacked diode comprises two or more diodes in series. This reduces the capacitance as the number of diodes, n, but increases the thickness by n and the resistance by n rather than $(n)^2$. Another advantage of combining diodes is the increase of reverse voltage breakdown. However, combined diodes must have identical electrical characteristics. The charge in each should be identical. Batch-stacked diodes described in [1] provide a technique to enable combining identical diodes.

The lateral surface can be brought further away by a planar construction. The bulk recombination should then be the major mechanism. However, the increase in lifetime is expected to be accompanied by a decrease in reverse bias breakdown due to the high field at the curvature of the p–n junction. There are techniques [7] of using guard rings which can improve this. Initial results show a doubling of lifetime for planar diodes compared to mesa diodes of similar dimensions, with lower reverse-voltage breakdown.

B. Thickness Variations

p-i-n diode interfacial recombination is higher than that of silicon bulk. On that basis, it was proposed to increase the I-layer thickness so that the interface boundaries are more widely separated. A series of wafers of varying thicknesses were prepared and diodes of different diameters were fabricated.

Table II lists the lifetimes measured as a function of I-layer thickness and nominal diameters. With the mask used it was difficult to obtain many samples of 200-mil diodes and the values are averages. Over nine diodes of the smaller diameter were available for measurement on each wafer. As may be observed, the lifetime increased by a factor of two with thickness increases of 200 percent. The capacitance decreased, voltage breakdown increased, and the series resistance of a 12–13-mil diode, 65 mils in diameter, was measured to be on the order of 0.3 Ω at $I_0 = 100$ mA.

TABLE II
LIFETIME VERSUS I-LAYER THICKNESS W

Diode Diameter (mils)	50	$\tau_e(\mu s)$ 100	200
thickness W(mils)			
4.4	13.	20.1	31.1
5.	14.1	23.4	36.2
6.2	20.6	35.8	53.5
7.	21.2	42	60
8.5	23.	33	
11	26	47	72

A serious problem was encountered in attempting to fabricate mesa diodes from these thick substrates. Scribing and sawing the diodes apart was found to degrade the lifetime and the voltage breakdown. Etching the diodes through caused a large undercut, and the lifetime was degraded by a decrease in diameter. It was found that designing the diameter to allow for the undercut permitted etching. Laser scribing was more successful: 6-mil depth or more in the cut permitted separation without great degradation of lifetime or reverse breakdown, when followed by some clean-up etching.

IV. Application in Switches

The antenna interface switching system, commonly in use, uses ratchet motors driving rotary switches to select the desired interconnection among antennas, transmitters and receivers. The limitations of this system are:

1) slow response time,
2) poor characteristic impedance,
3) limited life due to wear.

High-voltage p-i-n diodes with long carrier lifetime (described above) are required to produce high performance switches.

p-i-n diodes described in this paper were used [8] in an antenna interface switching system replacing rotary switches to select the desired interconnection. This system has the following specifications:

Frequency range	2–30 MHz
DC bias current	100–300 mA
Maximum RF voltage	450-V rms
Isolation (min)	27 dB
Insertion loss	< 0.5 dB
Harmonic content	< -50 to -60 dB.

V. Results and Conclusions

We have demonstrated the requirements for the operation of p-i-n diodes at low frequency and high power. A long lifetime diode is an important requirement for distortion-free operation. Operating conditions (RF and bias current) must also be appropriate. Techniques to improve the lifetime, such as increasing diode diameter and I-layer thickness, allow successful compromises with increasing capacitance and series forward resistance. An important consideration at low frequency is the reverse bias voltage needed to keep the reverse voltage swing from penetrating the forward conduction region. This in turn limits the voltage swing allowed and requires higher voltage bias supplies.

Appendix A

Derivation of Conductance Modulation

The following derivation is paraphrased from that carried out by Kokkas and Assour [3]. The stored charge in the p-i-n diode I-layer is related to the forward current I by the charge continuity equation.

$$\frac{dQ}{dt}+\frac{Q}{\tau}=I \tag{A-1}$$

where $Q=$ stored charge and $\tau=$ lifetime of electrical carriers in the I-region. We assume that the forward current consists of an RF signal sumperimposed on a dc bias current I_0.

$$I=I_0+I_{\mathrm{RF}}\cos\omega t. \tag{A-2}$$

In our application, I_{RF} is often greater than I_0.

The steady-state stored charge determined from (A-1) is given by

$$Q=I_0\tau+I_{\mathrm{RF}}\frac{\tau}{1+(\tau\omega)^2}(\cos\omega t+\tau\omega\sin\omega t). \tag{A-3}$$

The conductance of p-i-n diode is

$$G=\frac{\sigma A}{W}W \tag{A-4}$$

$$\sigma=q(n\mu_e+p\mu_h) \tag{A-5}$$

$\sigma=$ conductivity of the diode's I-region, $A=$ area of diode, $W=$ thickness of I-region, n, $p=$ electron and hole densities, $q=$ electrical charge, μ_e, $\mu_h=$ electron hole mobility.

For injected carrier densities greater than the equilibrium carrier density in the I-region, $n=p$ and the stored-charge under bias and conductance are given by

$$Q=qAnW \tag{A-6}$$

$$G=\frac{qAn}{W}(\mu_e+\mu_h)=\frac{Q}{(W)^2}(\mu_e+\mu_h). \tag{A-7}$$

Substituting (A-3) for the stored-charge Q in (A-7):

$$G\cong\frac{I_0\tau(\mu_e+\mu_h)}{(W)^2}+\frac{I_{\mathrm{RF}}\tau(\mu_e+\mu_h)}{(W)^2\sqrt{1+(\tau\omega^2)}}\cos(\omega t+\phi) \tag{A-8}$$

and

$$\phi=-\tan^{-1}\omega\tau.$$

The total conductance is thus seen to approximate both a dc and an ac term. Interpretation of (A-8) leads to the following results: First, at a fixed value of carrier lifetime τ, the ac conductance term decreases to zero for $\omega\tau\gg1$. This condition is practically satisfied with RF signals above 60 MHz. The resulting conductance becomes independent of frequency and varies only with dc bias.

Limitations: The use of (A-2) limits the application of (A-8) to the high-frequency domain. At this low-frequency application our approach and that of Leenov [2] may not remain so simple. In our application our dc bias is not negligible, our frequency is low, and our ac currents are high and do modulate the conductance of the diode as evidenced by the harmonic distortion under high level drive conditions. Equation (A-2) as used gives an approximation to predict how harmonic content will vary as per (A-8) within limits. Because of the constraints discussed, its use is limited in (1)–(4) when they are applied to low-frequency, high-current switching.

Acknowledgment

The authors wish to acknowledge the technical expertise of W. Janton, from the Device Technology Group, whose skills were invaluable in the design of the various diodes' packaging. The help of A. Booz of Quantronix, to lazer scribe thick silicon, was also an asset.

In addition, the authors also appreciate the support of H. Huang during the course of the program.

References

[1] A. Rosen, R. U. Martinelli, A. Schwarzmann, G. J. Brucker, and G. H. Swartz, "High-power, low-loss PIN diodes for phased-array radar," *RCA Rev.*, vol. 40, p. 22, Mar. 1979.

[2] D. Leenov, "A silicon diode as a microwave radar protector at megawatt levels," *IEEE Trans. Electron Devices*, vol ED-11, pp. 53–61, Feb. 1964.

[3] A. Kokkas and J. Assour, "Silicon PIN diodes:—Part II, theoretical analysis," Internal Publication, RCA Labs. PTR 2556, Aug. 1968, unpublished.

[4] P. Farnum, private communication RCA, Camden.

[5] J. White, *Semiconductor Control.* Dedham, MA: Artech House, 1977, p. 84.

[6] R. Martinelli and A. Rosen, "The effects of storate time variation on the forward resistance of silicon p^+-n-n^+ diodes at microwave frequencies," *IEEE Trans. on Elec. Devices*, vol. ED-27, p. 1728, Sept. 1980.

[7] T. Matsushita, H. Hayasi, and H. Yagi, "New semiconductor devices of ultra-high breakdown voltage," *IEEE Trans. EDM*, p. 109, 1973.

[8] P. Basile *et al.*, "Solid-state antenna switching," *RCA Rev.*, vol. 42, p. 752, Dec. 1981.

[9] J. White, *Semiconductor Control.* Dedham, MA: Artech House, 1977, p. 254.

Martin Caulton (M'61–SM'65–F'80) received the B.S., M.S., and Ph.D. degrees, all in physics, from Rensselaer Polytechnic Institute, Troy, NY, in 1950, 1952, and 1954, respectively. He completed the doctoral research at the Brookhaven National Laboratories in high-energy nuclear physics. From 1954 and 1955, he was a Fulbright scholar at the Imperial College of Science and Technology in London.

In 1955, he joined the Technical Staff at Bell Telephone Laboratories working in research and development of low-noise microwave tubes. In 1958, he became Assistant Professor of Physics at Union College, Schenectady, NY. In 1960, he joined RCA Laboratories as a member of technical staff. There he engaged in research on microwave power tubes, multivelocity flow problems in electron beams and plasmas, and microwave solid-state devices. He has been directing projects in microwave integrated circuits since 1966, and has authored numerous papers in this field. He has worked on the basic design and measurement of microstrip circuits and integration methods based on the use of lumped elements for the miniaturization of high-power amplifiers and microwave circuits, including FET devices. He has coauthored a textbook, *Physical Electronics* (John Wiley & Sons, Inc., NY 1967), and has also taught courses in microwaves and modern physics as Adjunct Professor of Electrical Engineering at Drexel Institute of Technology. During 1971–1972, he served as Visiting Professor at the Technion (Israel Institute of Technology) in Haifa, Israel.

Dr. Caulton was the recipient of RCA Laboratories' Achievement Awards for his work in microwave integrated circuits in 1968 and 1971. From 1970 to 1975, he served first as Cochairman and later as Chairman of the Committee on Microwave Integrated Circuits of IEEE Microwave Theory and Techniques Society and was formerly an Associate Editor of IEEE TRANSACTIONS OF MICROWAVE THEORY AND TECHNIQUES. He is a member of the American Physical Society and Sigma Xi.

Arye Rosen (M'77–SM'80) received the B.S.E.E. degree cum laude from Howard University in 1963 and the M.Sc.E. degree from Johns Hopkins University, Baltimore, MD, which he attended on a Gillman Fellowship, in 1965. He received the M.Sc. degree in physiology at Jefferson Medical College, Philadelphia, PA.

During the years 1963–1964, he was an instructor at John Hopkins. From 1964 to 1967, he was concerned with systems design at General Telephone and Electronics International, and with antenna and circuit design at Channel Master, Inc., and American Electronics Laboratories, Inc. In 1967, Mr. Rosen joined RCA Laboratories, where is is presently engaged in the study of development of microwave circuits and devices. From 1970 to 1971, on leave of absence from RCA, he was engaged in research in the Division of Cardiology at Jefferson Medical College in Philadelphia, PA, where he presently holds an appointment as an Associate in Medicine. He is the author of over 35 technical papers and presentations and holds 20 patents in the microwave field; he is also the author of several papers and presentations in the field of echocardiography.

Mr. Rosen is the recipient of a 1972 RCA Laboratories Outstanding Achievement Award for a team effort in the development of *S*-band TRAPATT amplifiers. He is a member of Tau Beta Pi, Sigma Xi, and the Association of Professional Engineers of British Columbia.

Paul Stabile (S'75–M'79) received the B.E. degree in electrical engineering summa cum laude from Manhattan College, Bronx, NY, in 1979.

Afterward, he entered the Engineering Rotation Program at RCA. His assignments included microwave amplifier design, digital circuit development, and a study of VLSI computer-aided design techniques. In October 1979, he joined RCA Laboratories, where is is presently an Associate Member of technical staff. There he has been engaged in research of high power, low-frequency p-i-n diodes, and silicon millimeter-wave devices and integrated circuits. He is also the author of several technical papers.

Mr. Stabile is a member of Eta Kappa Nu, Tau Beta Pi, and Epsilon Sigma Pi of Manhattan College.

Anna M. Gombar was born in Hungary. After attending the Technical University in Budapest, she came to the United States in 1956.

In 1960, she began textile research at F.M.C. in Princeton, NJ. Transfering to RCA Laboratories in 1973, she was engaged in research in the field of silicon devices such as high-power p-i-n diodes, high Q varacter diodes, and lately, millimeter-wave device technology. She is the holder of several U.S. patents and the author of several technical publications.

Coupling Characteristics Between Single-Mode Fiber and Square Law Medium

RYOZO KISHIMOTO, MEMBER, IEEE, AND MASAKI KOYAMA, MEMBER, IEEE

***Abstract*—The coupling characteristics between a single-mode fiber and a square law medium are theoretically and experimentally discussed in order to obtain the optimum coupling design for a variety of single-mode fiber optical devices using square law media. In theoretically analyzing coupling efficiency, it has been possible to evaluate a Gaussian beam, in a dielectric, which has passed through a square law medium with the help of mode-expansion technique and one of the generating functions of the Hermite polynomials. As a result, it has been possible to analytically obtain coupling efficiency even when the output beam from the single-mode fiber is off-axis and tilted. Through this analysis, it has been made clear that the ray matrix analysis used previously agrees with the analysis without the**

Manuscript received October 8, 1981; revised December 30, 1981.

The authors are with the Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation, 1-2356, Take, Yokosuka-shi, Kanagawa-Ken, 238-03, Japan.