THE DEVELOPMENT OF HIGH-POWER, LOW-FREQUENCY PIN DIODES

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ABSTRACT

The application of PIN diodes in high-power systems at frequencies as low as 500 kHz requires the use of diodes with intrinsic layers of long carrier lifetimes, operation at low rf-to-bias current ratios, and large reverse bias voltages. The development of suitable diodes, operating conditions, and test results in actual circuits are described.

Summary

The use of the PIN diode as a high-voltage switch at microwave frequencies is well established. By combining diodes, reverse breakdown voltages of over 2000 V have been achieved.[1] At lower frequencies, there is a need for a fast switch capable of handling high power to tune antenna couplers, switch antennas, etc., and thus replace the slower mechanical ones now in use. This paper will describe developments in PIN diodes that permit operation at as low as 500 kHz, and measurements made to discover the limitations peculiar to low-frequency performance.

I. Forward-Bias Operation

The carrier lifetime τ of a PIN diode operating in the forward bias mode is the characteristic that dominates its low-frequency operation. In forward bias, the high resistivity I-layer is converted onto a conducting medium and the number of excess charges maintained in the I region depends on the lifetime τ. At low frequencies where $\tau \ll T$ (T = rf period), the I region has little charge, and the diode becomes a rectifying pn junction. At high frequencies (where $\tau \gg 1/f$) the PIN diode acts like a fixed resistor (characteristic of the doped layers) in series with a variable resistor (characteristic of the I-region), mainly controlled by the dc bias current I_o. The minimum useful frequency has a strong dependence on τ.

It can be shown[2] that the total (ac and dc) resistance R of the I-layer of a PIN diode can be represented as:

$$\frac{1}{R} = \frac{1}{R_S}\,[1 + \alpha\cos(\omega t+\phi)]$$

where $R_S = W^2/[I_o\tau(\mu_e+\mu_h)]$, the dc resistance,

and I_o = dc bias current, W = I-layer thickness, μ_e,μ_h = electron, hole mobility, ω = rf radian freq., I_{rf} = peak rf current, τ = carrier lifetime.

The ac modulation term α is

$$\alpha \cong \frac{I_{rf}}{I_o \cdot \omega\tau}$$

The conductivity thus has an ac term at low frequencies. At f = 1 MHz, τ = 20 μs and I_{rf}/I_o = 10, the ac term $\alpha <$ .1. At more common values, τ = 1 μs and I_{rf}/I_o = 100, α can be greater than 10, and the ac resistance will dominate the dc resistance. In order for the diode to operate at kHz frequencies, the carrier lifetime must be very long and the diode design and operating conditions (such as I_{rf}/I_o) must be taken into account.

A. Improvement of Carrier Lifetime. The storage time of PIN diodes has been increased through various techniques. Martinelli and Rosen[3] have shown the increase of lifetime with increased diode diameters. In this paper, we report on the dependence of lifetime with I-layer thickness, and on the fabrication of planar diodes. Storage time limitation by carrier recombination can depend on (1) bulk, (2) surface (n-layer sidewalls), and (3) n-n+, p-n interface recombination. Surface recombination dominates and becomes less significant with increasing diode diameter.

The lateral surface recombination can be reduced further by using a planar construction. Planar diodes have been constructed which have lifetimes over twice as long as those of otherwise similar mesas. The voltage breakdown of such diodes is much lower than that of mesas, and a more elaborate guard ring construction is required.

A very practical technique to increase lifetime has been to increase the I-layer thickness so that the interfacial recombination at n-n+ and p-n junctions is reduced. Table I lists lifetimes measured as a function of thickness and diameter. It may be observed that lifetimes were increased by a factor of 2 with thickness increases of 100%. The increases with diode diameter previously reported[3] are also indicated. Diodes fabricated of 65-mil diameter and 12-mil thick I-layers were measured to have forward series resistances of 0.3 Ω. These diodes have been incorporated in antenna switches operating at 2 MHz, as will be reported.

Table I
Lifetime vs I-layer Thickness t

Diode Diameter	τ_e (μs) 50	100	200
thickness t(mils)			
4.4	13.0	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	23.0	33	
11	26	47	72

B. Forward-Bias Measurements. A resonant circuit allowed a moderate power source (50 W) to supply either high current for forward-bias operation or high-voltage for reverse-bias conditions across the diode. A voltage probe and/or current transformer was used to monitor the rf current value and wave shape, and a spectrum analyzer allows one to see the effects on the harmonic content caused by operating conditions and diodes (I_{rf}, I_o, τ). Figure 1 is a series of photographs showing the harmonic spectrum for an 8-A rf peak current at 1.9 MHz. Figure 1a is a reference spectrum of a short in the circuit. Figures 1b and 1c show the spectral response for diodes of different lifetimes in the same circuit. Figure 2 shows the reduction of harmonics caused by increasing the bias current from 210 to 1000 mA. The increase in harmonic content with decreasing I_o (Fig. 2) and diode τ (Fig. 1), predicted by the equations derived (increasing α) is demonstrated. However, the diodes described are capable of operation at frequencies as low as 500 kHz.

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(a)
short
circuit
refer-
ence

(b)
τ = 30 μs
A-5

(c)
τ = 53 μs
B-3

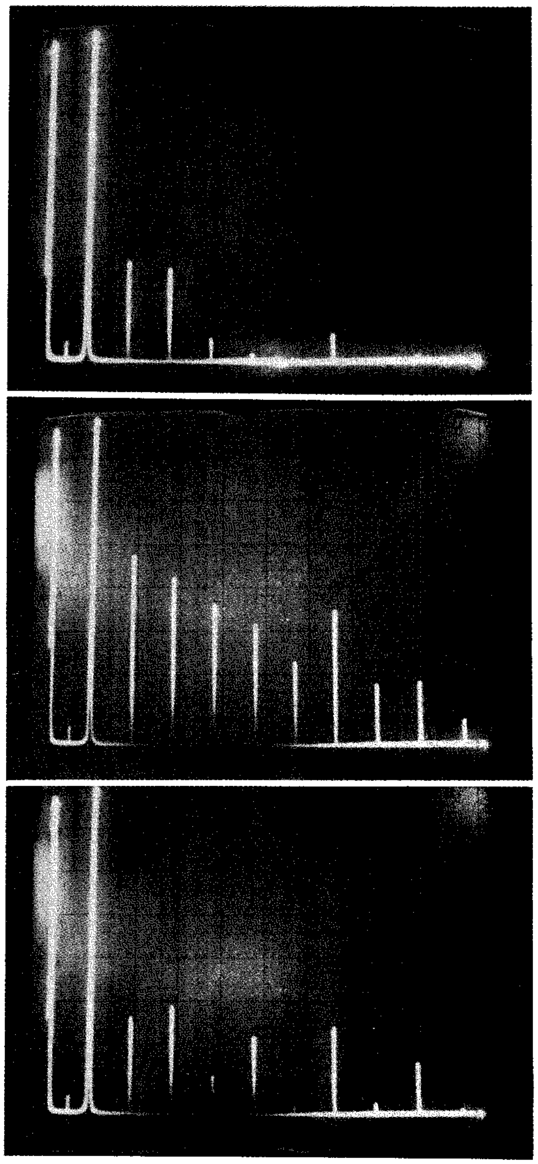

FIGURE 1: FORWARD-BIAS OPERATION - SPECTRAL RESPONSE VS. LIFETIME AT 1.9 MHz (10 dB/div.) I_o = 100 mA.

(a)
210 mA

(b)
1000 mA

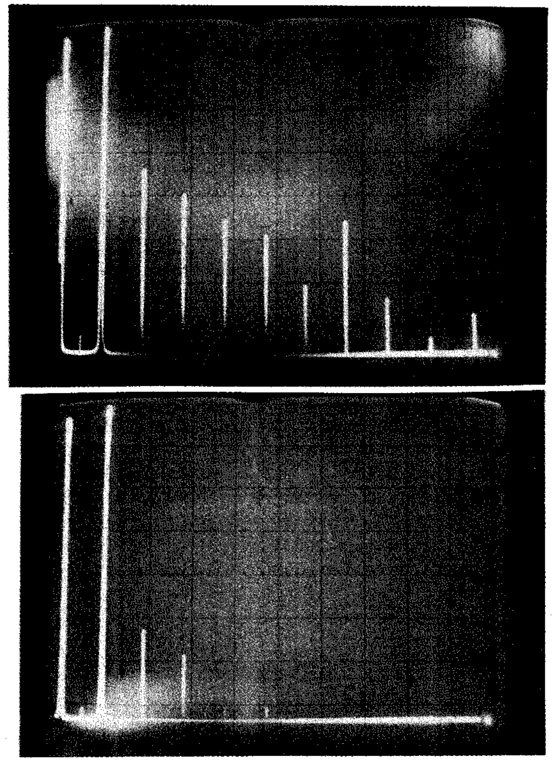

FIGURE 2: FORWARD-BIAS OPERATION - SPECTRAL RESPONSE OF DIODE A-5 VS. BIAS CURRENT I_o.

(a)
287 V

(b)
162 V

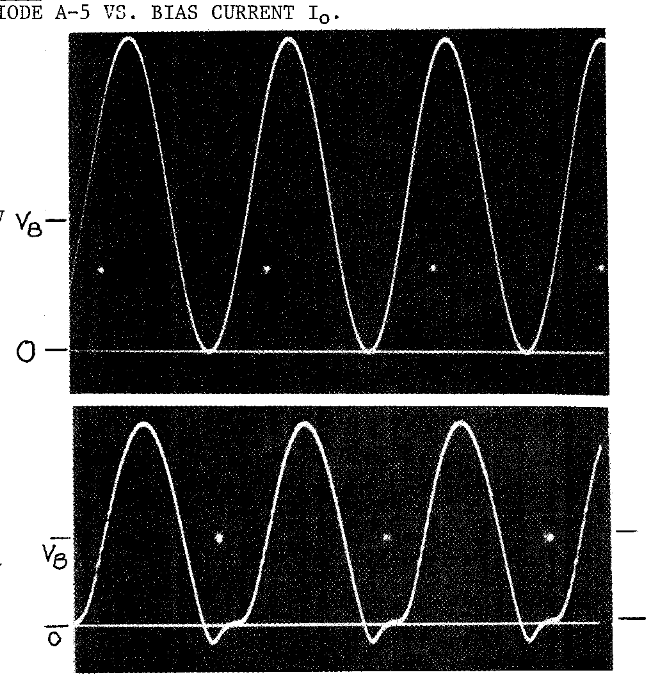

FIGURE 3: REVERSE-BIAS WAVEFORM OF 300 V PEAK 1.65 MHz SIGNAL AT BIAS VOLTAGES (a) 287 V, (b) 162 V.

II. Reverse-Bias Operation

Reverse-bias conditions were studied using the resonant circuit previously described, and Fig. 3 is an oscilloscope plot of the rf (1.65 MHz) voltage across a PIN diode for three different bias voltages. When the bias voltage is decreased, the peak 300 V swing is inhibited from going into the forward conduction region. Figure 4 presents a wave form of the forward current that can be forced through in a so-called reverse-bias operation, and this current will burn the diode.

Figure 5 schematically depicts the I-V characteristics of a PIN diode, locating reverse breakdown, zero bias, and applied reverse bias. At high frequencies, the applied bias can approach zero without forward conduction. At low frequencies, the reverse bias must at least equal the expected peak rf voltage. This comparison at the high frequencies is detailed by White[4].

By using a voltage transformer, the bias voltages of Fig. 3 were studied as a function of frequency. As the frequency was increased beyond 40 MHz, a 240 V p-p signal was able to swing into the forward conduction region without drawing current. Figure 6 is a plot of the minimum bias voltages required to keep the rf signal from compression. At frequencies below 10 MHz, the bias voltage must at least equal the rf peak voltage, so that rf voltage swing cannot go in the posi-

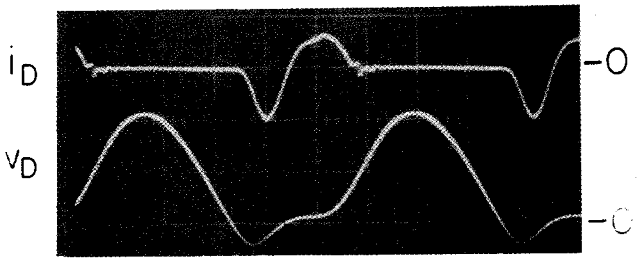

FIGURE 4: FORWARD CURRENT UNDER REVERSE BIAS: f = 1.9 MHz, V_B = 160V, i_D = 1A/div., V_D = 200 V/div.

tive region. The frequency at which the minimum bias voltage can approach zero was found to be related to the drift velocity of the carriers in the I-layer. In this figure the frequency limit is 40 MHz for 120 V peak reverse voltage.

The important consideration is that at low frequency operation, bias voltage must equal the maximum expected rf peak voltage in reverse-bias operation. Unfortunately this limits the maximum voltage swings permissible by almost 50%, and therefore requires a higher voltage bias supply.

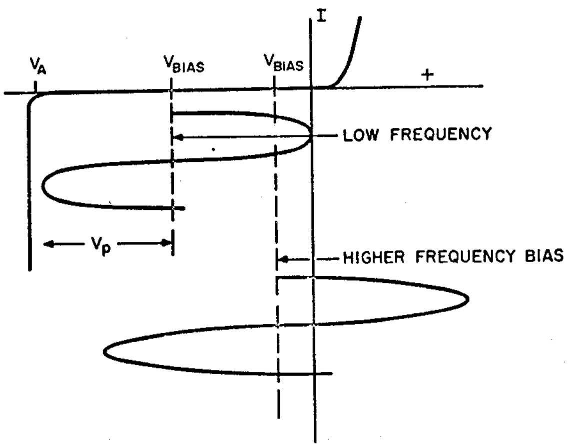

FIGURE 5: REVERSE BIAS - LOW FREQUENCY AND HIGH FREQUENCY VOLTAGE SWINGS SUPERIMPOSED ON THE I-V CHARACTERISTICS OF A PIN DIODE.

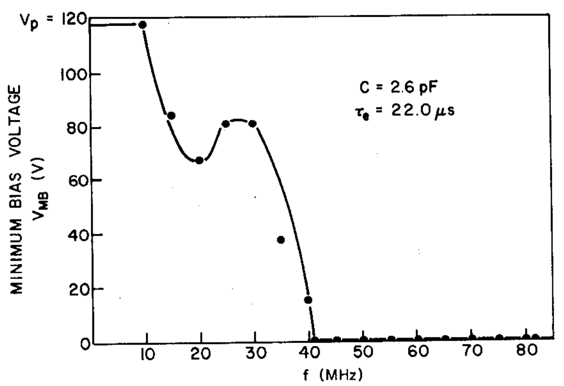

FIGURE 6: MINIMUM REVERSE BIAS VOLTAGE REQUIRED TO KEEP REVERSE-BIAS VOLTAGE SWING (V_P = 120V) FROM COMPRESSING IN THE POSITIVE VOLTAGE CONDUCTION REGION, AS A FUNCTION OF FREQUENCY.

III. Application in an Antenna Switch

PIN diodes were used in an antenna interface switching system[5] replacing rotary switches to select the desired interconnection. This system had 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

IV. Conclusions

PIN diodes, widely used at microwave frequencies, can be used for controlling high-power at HF frequencies, provided (1) the carrier lifetime is large enough, (2) operating conditions (rf and bias current) are appropriate, and (3) the reverse bias voltage is equal to maximum rf peak voltage.

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V. References

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