Active Solid-State Devices

By H. E. ELDER

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This paper describes the electrical and physical characteristics of 20 new solid-state devices developed for TD-3. Among them are new high-frequency planar, epitaxial, NPN silicon transistors which are used in intermediate-frequency amplifiers and in the FM deviator. The microwave power for the transmitter and receiver is supplied from a three-stage varactor multiplier chain which uses three new epitaxial silicon varactor diodes. A high-quality epitaxial silicon varactor diode pair is the up-converter in the transmitter modulator. A new epitaxial gallium arsenide Schottky barrier mixer diode assures a low noise figure for the receiver modulator. Two point-contact silicon IF and RF monitor diodes were developed using the same miniature package in which the transmitter modulator and receiver modulator diodes are encapsulated. Two very stable diffused silicon diodes provide a stable output from the FM deviator; in-process preaging at accelerated conditions is used to assure satisfactory stability. Two new epitaxial silicon Schottky barrier diodes are used in the IF amplifier-limiter and discriminator circuits, which require a nonlinear resistance with negligible capacitance and recovery time. Stringent voltage breakdown, corona and mounting requirements for the high voltage power supply rectifiers were satisfied by molding two high-voltage diode rectifier assemblies in a high-dielectric plastic. The need for a pure variable resistance in the IF variolosser was satisfied by the development of a new silicon PIN diode.

INTRODUCTION

Twenty new solid-state devices were developed to meet the TD-3 requirements. The FM terminal transmitter needed a variable capacitor diode (457A) as the active element in the deviator, a very stable voltage regulator diode (446AC), and a transistor oscillator (44A). A family of medium-power varactors (473A, B, and C) was required for the microwave carrier supply. A high-quality silicon varactor diode pair (471A) was developed for the transmitter modulator. Two new rectifiers (463A and 464A) were developed for the high voltage power supply for the traveling wave tube.

For the receiver, a low-noise gallium arsenide Schottky-barrier mixer diode (497A) and a low-noise IF preamplifier transistor (45J) were developed to assure the low-noise figure required of the TD-3 repeater. The second stage of the preamplifier required a transistor that could handle a large signal without harmful distortion (45G). The FM receiver also needed a transistor with controlled input impedance (45B) and a silicon Schottky-barrier diode (479A) in the IF amplifier-limiter, and a similar diode (479B) in the discriminator. The 45C transistor was developed for locations where the signal level exceeds the level at which the 45B transistor can maintain sufficiently low distortion. A silicon p-i-n diode (474A) was developed for the variolosser. Two silicon point contact diodes (488A and 493A) were developed for use in IF and RF monitor circuits.

I. TRANSISTORS By N. J. Chaplin and R. M. Jacobs

Concurrent with the conception and design of the TD-3 system, major advances in transistor technology occurred which have been exploited to reduce system noise, distortion, and power consumption, and to improve system reliability.

These advances resulted in the development of a family of high-frequency, planar, epitaxial, npn silicon transistors for use in the various intermediate-frequency amplifiers of the repeaters and terminals, and the FM terminal deviator. Typical values of important electrical characteristics of these transistors are given in Table I.

1.1 *General Description*

The family of transistors developed for the TD-3 system are characterized by a 1 Ghz gain-bandwidth product and have been designed to yield optimum performance in the various applications. The 45A transistor, illustrated in Fig. 1, is the basic transistor of the family and is designed for operation at collector currents in the range of

TABLE I—TRANSISTORS FOR THE TD-3 SYSTEM

Parameter	Transistor					
	44A	45A	45B	45C	45G	45J
	Typical values					
Gain bandwidth product (mHz)	1000	1000	1000	1000	1050	1000
NF (dB)	—	—	5.5	4.5	3.5	2.0
C_{ob} (pF at 5 V)	1.2	0.9	1.2	1.9	3.5	4.0
C_{ib} (pF at 1.5 V)	0.8	0.8	1.6	3.2	6.0	4.5

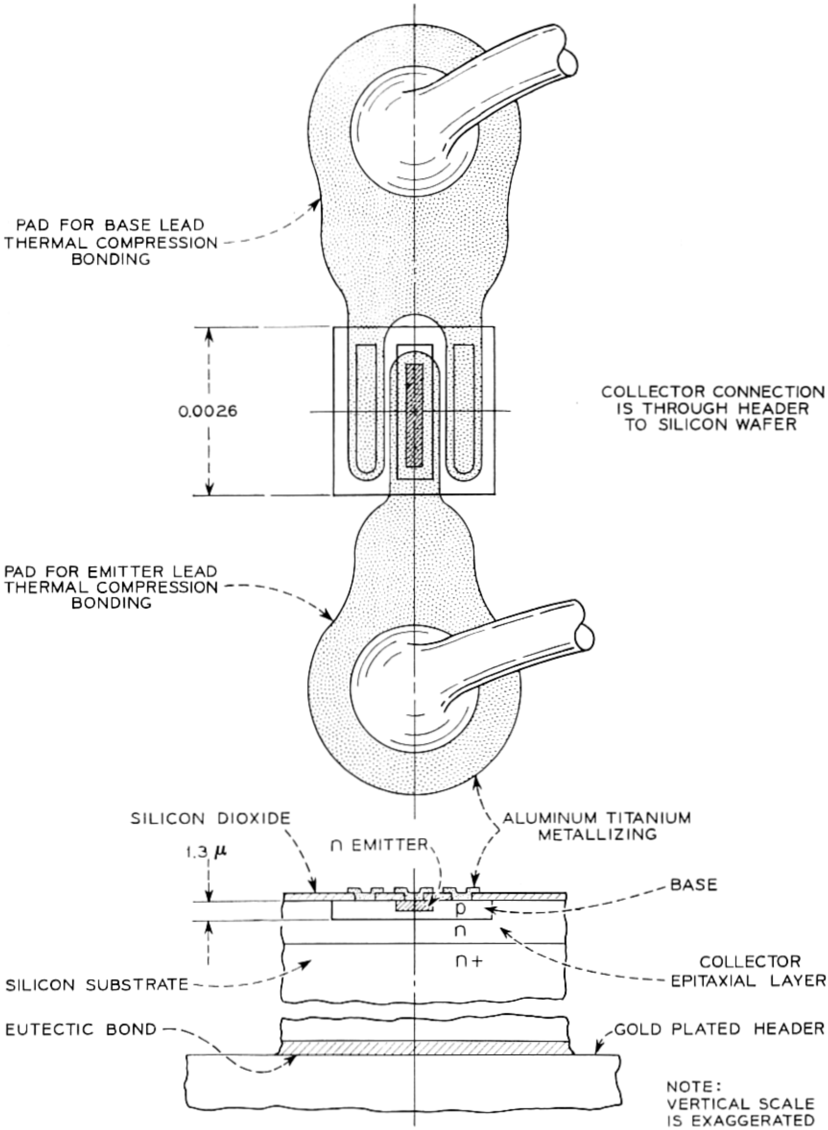

Fig. 1 — 45A transistor.

5 to 10 milliamperes. Other transistors of the family are fabricated by increasing the number of emitter stripes in order to increase the current handling ability and decrease the base resistance. The 45B, 45C and 45G transistors have twice, four and eight times the collector current rating and one half, one fourth and one eighth the base resistance of the 45A.

The transistor wafers are encapsulated in the metal-ceramic package illustrated in Fig. 2. This package was designed specifically for this transistor family to minimize parasitic capacitance, lead inductances, and to provide a relatively low thermal impedance. In addition, the package insulates the transistor collector from the heat sink. This package has been registered with the Joint Electron Device engineering Council and is designated TO-112. A transistor electrically similar to the 45A type has been encapsulated in a conventional TO-18 package for use in the FM deviator cavity and is designated the 44A. The collector of the 44A is connected directly to the deviator cavity through the metallic package. This method of connecting the collector to the cavity minimizes collector inductance and so maximizes the deviation range.

1.2 *Main and Limiter IF Amplifiers*

The stringent requirements of the TD-3 system IF amplifiers are discussed in Ref. 1. These requirements determine the critical tran-

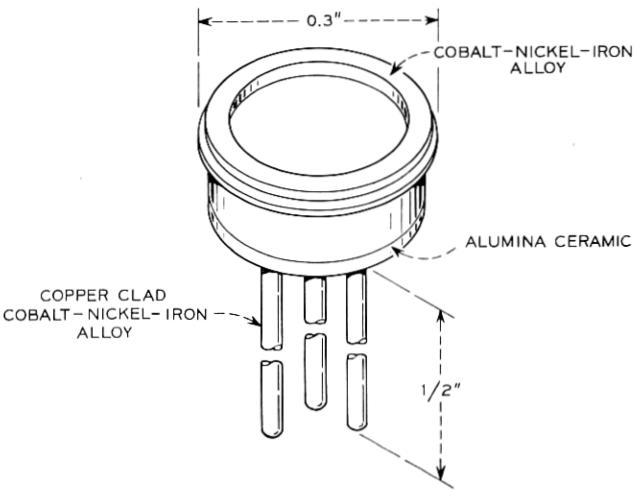

Fig. 2 — JEDEC TO-112 package.

sistor parameters, such as low noise figure, low output capacitance, controlled input impedance, high gain-bandwidth product, and the allowable distortion level.

To illustrate these parameter values, the 45B must have an output capacitance of less than 1.4 picofarads, a gain-band product of 1000 ± 200 MHz, and common base input impedance at the operating frequency of not more than 5 ± j5 ohms. The 45C transistor is used where the signal exceeds the level at which the 45B transistor can maintain sufficiently low distortion.

1.3 *IF Preamplifier*

As discussed elsewhere in this issue the low noise first stage of the preamplifier together with the low noise performance of the 497A Schottky-barrier diode have made it possible to meet the TD-3 system specifications for noise figure without radio frequency or parametric amplification.[1]

The needs of the preamplifier first stage were met by the development of a completely new transistor that has noise figures considerably lower than those previously attainable at the relatively high bias currents required for satisfactory TD-3 system performance. A bias current of 12 milliamperes is required to limit the distortion during the large signal condition of "up-fade" in short hop operation.

The 45J transistor was designed for this application. A typical noise figure of 2 dB at a 12 milliampere bias current was achieved by decreasing the base resistance of the transistor to five ohms. This reduction in base resistance was achieved by reducing the emitter width and increasing the total emitter length.

This lowering of transistor base resistance results in a considerably lower noise figure as evident from Fig. 3.* The new design also uses low resistivity diffused (five ohms per square) p type conductors in place of the usual metal base stripes. This structure permits covering the entire base-emitter inter-digitated structure with emitter metallizing. The metallized emitter contact is sufficiently large for wire bonding without an extension over the collector silicon and hence creates no parasitic collector-emitter capacity.

Figure 4 shows the structure of this transistor, designated 45J.

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* Figure 3 has been plotted using Nielson's equation and the assumptions shown. (See Ref. 2.) The equation is:

$$\text{N.F.} = 1 + \frac{re}{2\,Rg} + \frac{rb'}{Rg} + \frac{(Rg + re + rb')^2}{2\alpha_0 \cdot Rg \cdot re}\left[1/h_{FE} + \frac{I_{co}}{I_e} + \left(\frac{f}{f_\alpha}\right)^2\right]$$

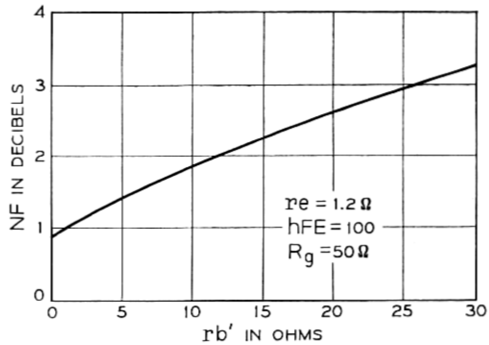


Fig. 3 — Calculated noise variation (re = 1.2 ohms, hFE = 100, RG = 50 ohms).

Table II compares characteristics of the 45J and 45G transistors. The lower noise and base resistance of the 45J are evident.

While the noise figure of the preamplifier comes largely from the first stage, a smaller contribution occurs from stage two. Because of the 17 decibel gain of the first stage, the 3.5 dB noise figure of the 45G is adequate for the second stage, but the bias current is increased to 38 milliamperes in order to handle the larger signal level without harmful distortion.

1.4 *Terminals*

Transistor requirements for the intermediate-frequency amplifiers in the TD-3 terminals are similar to those discussed in Sections 1.2 and 1.3. It has been necessary to use an additional transistor, the 44A, in the oscillator cavities of the FM deviator.

The 44A transistor uses the wafer of the 45A transistor mounted in a standard TO-18 package. This package is conveniently mounted in the resonant cavity since the collector is electrically connected to the metal package as described in Section 1.1.

The FM deviator requires devices stable with respect to capacity variation for the lifetime of the device.[3] Transistor samples were subjected to accelerated aging tests which predicted typical output capacitance variations of 0.01 pfd or less over life. Since the deviator diode capacitances are many times larger than those of the transistors. The contribution of capacitance variation caused by the transistor is negligibly small.

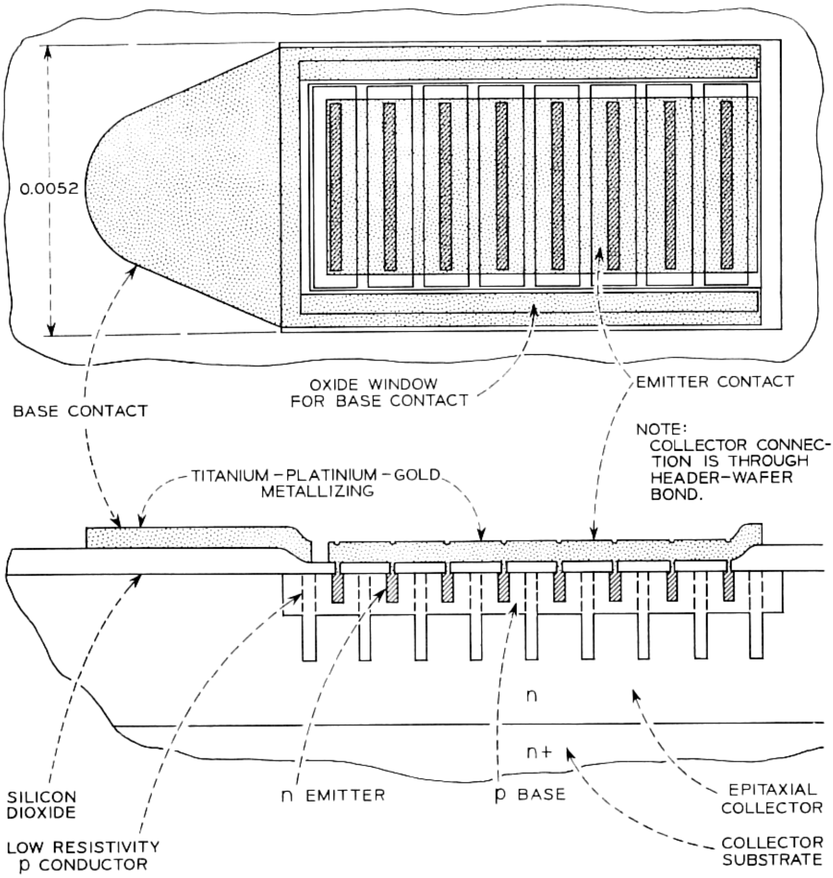


Fig. 4 — 45J transistor.

TABLE II — COMPARISON OF 45G AND 45J TRANSISTORS

	Typical values	
Transistor	45G	45J
Noise figure (dB)	3.5	2.0
Base resistance (ohms)	20	5

1.5 *Transistor Reliability*

During development of the 44 and 45 type transistors, several thousand models were subjected to accelerated aging under conditions of both power and temperature stress. Extrapolation of these data justifies a predicted transistor failure rate of less than ten failures per 10^9 transistor operating hours over a twenty-year period at junction temperatures of 125°C for all transistors except the 45J.

Similar data for the 45J transistor, which is fabricated with platinum-titanium-gold metallizing[4] predicts ten failures per 10^9 device-hours at 250°C.[5] Using this contact, junction operating temperatures are no longer limited by system reliability considerations, rather they are limited by the values of transistor parameters at such elevated temperatures.

The reliability information obtained through system use at this early date agrees with the extrapolated accelerated aging results.

1.6 *Conclusion*

44A, 45A, 45B, 45C and 45G devices have been developed and placed in manufacture to meet stringent requirements of the TD-3 system.

A vastly improved design in noise figure and reliability (45J) has been developed which, in combination with the Schottky diode, has permitted elimination of an expensive parametric amplifier or microwave preamplifier.

II. HARMONIC GENERATOR VARACTOR DIODES FOR THE MICROWAVE CARRIER SUPPLY By F. W. Crigler and D. R. Decker

The microwave beat oscillator power for the microwave transmitter and microwave receiver of the TD-3 radio-relay system[6] is supplied by an all-solid-state circuit incorporating a crystal-controlled oscillator, a transistor amplifier, and a three-stage varactor-multiplier chain. Three codes of medium power, high efficiency varactor diodes were needed for this circuitry since there were no suitable diodes at the beginning of the TD-3 project. The 7-watt output* of the transistor amplifier at 125 MHz is converted to about one-half-watt at 4 GHz by the varactor multipliers. The design requirements for the

* As described in Ref. 7, the output of the transistor amplifier is adjustable over the range of 7 to 10 watts.

beat oscillator supply (microwave generator) include adequate frequency stability and power capability, and very low noise.

2.1 *Circuit Requirements*

The three multiplier stages each contain a single varactor diode. The differences in operating frequency and power level between multiplier stages call for differences in diode characteristics. However, all three diodes must combine high power handling capability with efficiency and reliability.

A 473C diode in the first multiplier stage converts 7.0 watts from the transistor amplifier at 125 MHz to 2.8 watts at 500 MHz. The output frequency of the first stage is doubled to a nominal power of 1.2 watts at 1 GHz by a 473B diode multiplier circuit. The multiplier stages are decoupled from each other with isolators and frequency selective networks to minimize interaction during tuning and to eliminate undesired harmonics. A narrow band filter is used between the first and second multiplier stages to attenuate noise sidebands. Finally, the 1 GHz output is quadrupled to a minimum power of 400 mW at 4 GHz with a 473A diode circuit. The over-all efficiency of conversion from 125 MHz to 4 GHz is about 6 per cent. The efficiency includes all the losses of the interstage isolation and frequency selective circuitry that provide stable tunability and low noise performance.

2.2 *Diode Requirements*

The diode parameters that must be controlled to specified limits in order to assure desired multiplier performance include junction capacitance C_j, series resistance R_s, breakdown voltage BV, and thermal resistance θ_{J-C}. An equivalent circuit of the 473 diode is shown in Fig. 5a. Since the construction of the wafer and package is such that the fringing capacitance C_f is small enough to be neglected, a simplified circuit may be used as shown in Fig. 5b. The total capacitance C_t includes the package capacitance C_c and the junction capacitance.

The diode junction capacitance is determined by two considerations. First, the capacitance must be large enough to allow the diode to handle the desired power without being driven into avalanche breakdown. Second, a choice of circuit characteristics determines what range of diode capacitance will provide high efficiency multiplier operation. Typically, the junction capacitance is chosen on the basis

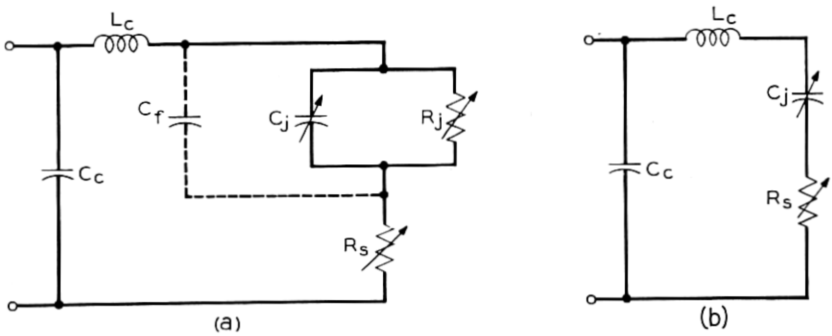


Fig. 5 — (a) Diode equivalent circuit. (b) Simplified equivalent circuit. C_c, package capacitance; L_c, package inductance; C_f, distributed fringing capacitance; C_j, junction capacitance; R_j, junction resistance; R_s, diode series resistance.

of circuit design considerations, and the breakdown voltage is chosen to provide adequate power handling capability and good efficiency. Noisy performance may be encountered if the diodes are allowed to operate into the breakdown region because of the inherently noisy avalanche process.

The diode series resistance is the only lossy element of the varactor. For frequency multipliers it is desirable to make the series resistance as low as possible. For prescribed capacitance, the lowest usable breakdown voltage gives the minimum obtainable series resistance.

The power dissipation capabilities required for each of the 473A, B, and C diodes can be derived from the maximum input power and maximum conversion loss for each stage of multiplication as shown in Table III.

2.3 *Diode Design and Construction*

The 473A, B, and C harmonic-generator diodes are diffused, planar, epitaxial, silicon diodes in the V package. (Section 2.4 describes the V package.) All three device codes are manufactured by the same

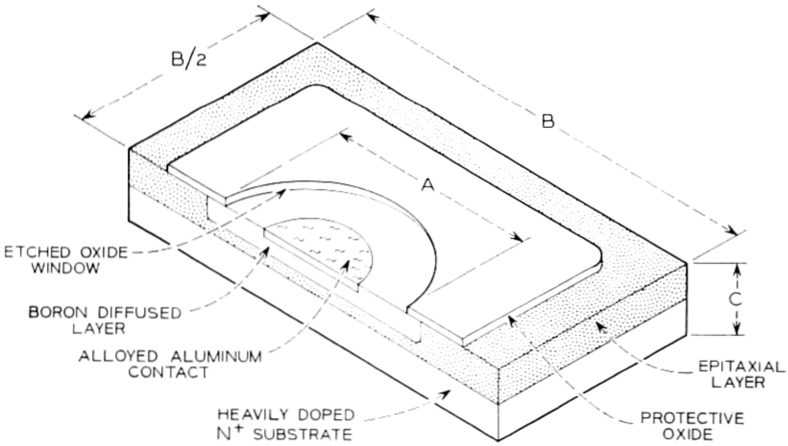
Table III—Multiplier Conversion Loss and Power Dissipation

Stage multiplier	Diode	Maximum diode conversion loss (dB)	Maximum power (W)	
			Input	Dissipated
125–500 MHz	473C	2.5	7.1	3.1
0.5–1.0 GHz	473B	2.0	2.0	0.8
1.0–4.0 GHz	473A	4.0	1.1	0.7

process. The differences in final device characteristics are controlled by choice of epitaxial starting material and by a difference in junction area. Figure 6 shows a cross-section of the planar 473 wafer.

The use of epitaxial silicon material for these devices is dictated by the need for a high breakdown voltage and a low series resistance. The epitaxial layer furnishes the lightly-doped region needed for high breakdown voltage while the heavily-doped substrate provides support and electrical contact for the lightly-doped layer without adding appreciably to the series resistance of the diode.

The intrinsic series resistance of an epitaxial diode is determined by the required epitaxial layer thickness and resistivity to sustain the breakdown voltage.[8] The parasitic resistance contributed by the substrate and package amounts to only 0.1 to 0.3 ohms. The breakdown voltage of an epitaxial diode is determined mainly by the epitaxial layer resistivity and the distance between the junction and the region of rapidly rising impurity concentration near the substrate. There is thus a compromise that must be made between a wide region



473	Dimension (inches)		
	A	B	C
	Window size	Wafer size	Wafer thickness
A	0.0072	0.020	0.0050–0.0070
B	0.0150	0.030	0.0050–0.0070
C	0.0284	0.040	0.0050–0.0070

Fig. 6 — Planar wafer cross section.

of high-resistivity material to sustain a high breakdown voltage and a narrow region of low-resistivity material to minimize the series resistance. The 473 design is an engineering compromise in this respect for the specified breakdown voltage.

The diode capacitance is governed mainly by the epitaxial layer resistivity and the junction area.[9] The 473A, B, and C diodes are designed by first tailoring the epitaxial material characteristics and the diffusion process to achieve the desired breakdown voltage with the least series resistance, and then adjusting the junction area to obtain the proper junction capacitance.

These diodes are fabricated by standard planar-photolithography.[10] An oxide film 8000 to 10,000 Å thick is first grown on the epitaxial silicon slice. Windows are etched in the oxide through a mask of photoresist, and boron is diffused into the slice to the desired junction depth. After diffusion, the windows are reopened and an alloyed aluminum contact is applied. The slice is scribed and broken into wafers, and the individual wafers are gold-silicon-eutectic bonded into a metal-ceramic V package. A gold tape is bonded by thermal compression to the wafer contact and to the package rim. The subassembly is vacuum baked before sealing the package by brazing on the end cap.

2.4 *Device Characteristics*

The V package is one of several standard microwave diode packages used in the Bell System. (The "V" is simply a sequential designation assigned by Bell Laboratories.) Figure 7 shows a cutaway view. The primary characteristics of this package are low shunt capacitance, low series inductance, good power dissipation, and low cost. One figure of merit of a microwave diode package is the self-resonant frequency computed from the capacitance and inductance of the package. For this package, the self-resonant frequency is 15.9 GHz using 0.25 pF and 0.4 nH for the shunt-capacitance and series-inductance, respectively. The package contribution to power dissipation capability (thermal resistance) is dependent mainly on wafer bond area. For the 473A, B, and C, the package contribution is less than 30 per cent of the total thermal resistance.

The primary characteristics of the 473 type varactors are listed in Table IV. Figure 8 shows distributions of breakdown voltage for diodes meeting these characteristics. Since there is no upper limit on breakdown voltage, the spread of the distribution is mainly deter-

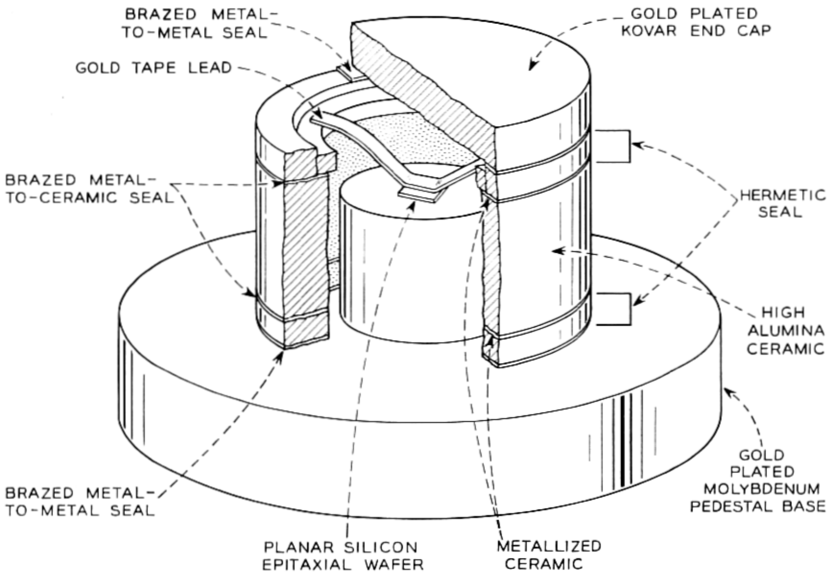


Fig. 7 — Cutaway view of V package.

mined by the capacitance and resistance limits for each code. As mentioned previously, these parameters are controlled by the characteristics of the epitaxial material and the diffusion profile. Typical dc forward and reverse-voltage characteristics are shown in Fig. 9a. High dc impedance is maintained in the operating region between breakdown voltage and forward conduction with a rapid rise in current occurring in the avalanche region for a small change in voltage. The forward voltage is exponential over many decades of current, producing a straight line plot on the log-linear scale shown.

In Fig. 9b are 473A junction capacitance and series resistance as functions of bias. The 473B and C diodes exhibit similar characteristics. The nonlinear capacitance-voltage characteristic shown is typical for a reverse-biased varactor. However, in the TD-3 genera-

Table IV — 473 Characteristics

	473A	473B	473C
BV (V) at $I_r = 10\ \mu A$	>60	>80	>70
C_T (pF) at $V = 0, f = 1$ MHz	3.0 to 6.0	11.0 to 19.0	46.0 to 68.0
R_s (ohms) at $V = 0, f = 1.3$ GHz	<1.5	<0.9	<0.5
θ_{J-C} (°C/W)	<38	<22	<18

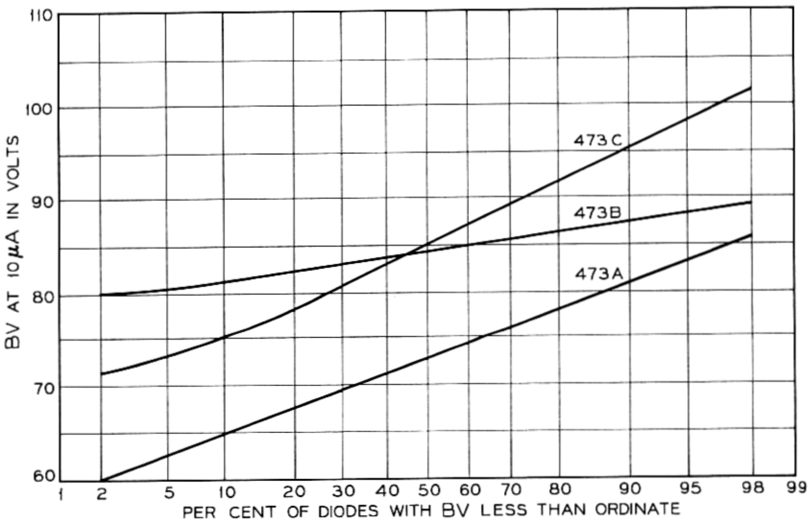


Fig. 8 — Breakdown voltage.

tor, the devices are driven into forward bias as well, and minority carriers are injected across the junction. These carriers are stored during the forward cycle and contribute to a large injection capacitance. The relative importance of charge storage effects on circuit performance is being investigated.

Total capacitance distributions are shown in Fig. 10. The capacitance of the 473A diodes falls in the upper part of the allowable range as a result of making the junction area as large as possible to assure a low series resistance. Capacitance measurements at 1.3 GHz or higher would require inductive reactance corrections for the B and C diodes. This problem has been avoided by using a capacitance bridge at 1 MHz.

The series resistance is obtained from measurements of voltage standing-wave ratio at 1.3 GHz. Reflections from the diode, terminating a coaxial line, are measured with a slotted line. A solid coin-silver slug in the shape of the package (short) is used to determine line losses, and a package without the silicon wafer (open) is used to establish the reference plane of the diode. The diode series resistance is calculated by computer using the following equation:[11]

$$R_s = Z_0 \frac{S(1 + \cot^2 \beta d)}{S^2 + \cot^2 \beta d}$$

where:

Z_0 is the characteristic impedance of the transmission line.
S is the voltage standing-wave ratio corrected for line and holder losses using the solid package short
β, the phase constant of the line, is $2\pi/\lambda$, where λ is the wavelength
d is the distance between the voltage minimum of the diode and a reference plane established at the voltage minimum for the open package.

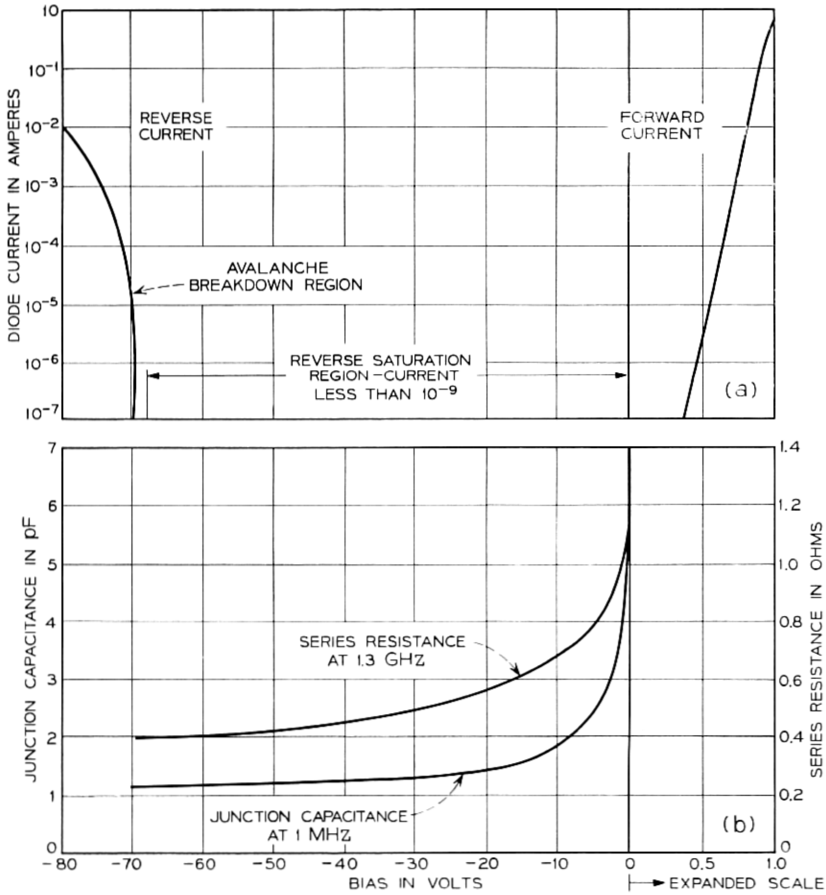


Fig. 9 — (a) 473A varactor forward and reverse current as a function of bias voltage. (b) Varactor junction capacitance and series resistance as a function of bias voltage.

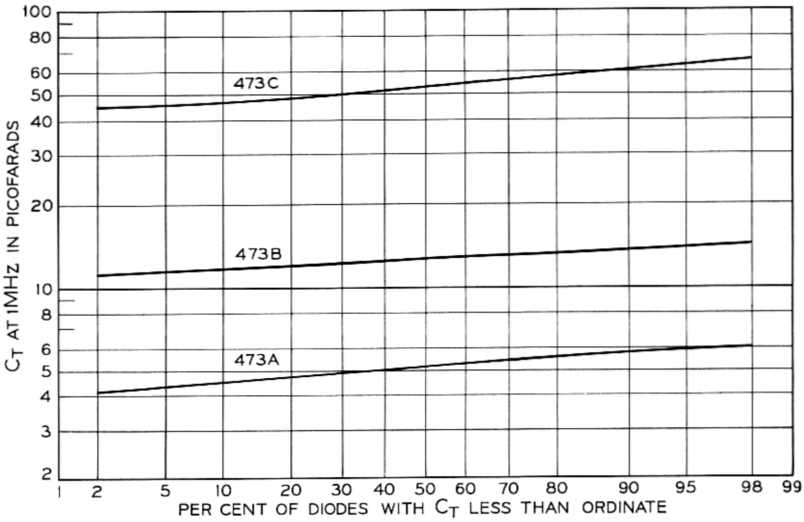


Fig. 10 — Diode total capacitance.

Figure 11 shows distributions of series resistance at zero bias. Typical values of resistance which are obtained at 100 mA forward current, on devices meeting the above specifications, are 0.25, 0.20, and 0.15 ohms for the 473A, B, and C diodes, respectively. These low resistances assure low diode losses during multiplier operation.

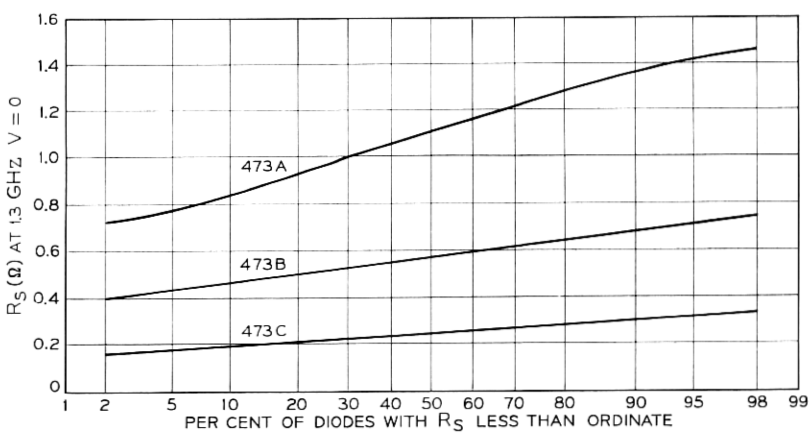


Fig. 11 — Diode series resistance.

Since relatively large power is dissipated by the 473 diodes, it is necessary to limit the diode thermal resistance to avoid degraded performance which would result from excessive device temperature during operation. Typical distributions of thermal resistance are shown in Fig. 12.

2.5 *Reliability*

Both temperature and power-aging experiments have been used throughout device development to evaluate designs. Analysis of temperature-step-stress aging[12] data on early developmental models led to the introduction of a more reliable wafer contact. High-temperature aging under reverse bias to evaluate the effectiveness of the oxide in stabilizing the surface of the wafer is a standard reliability test. Improved oxides have been obtained by using information from these tests and from metal oxide semiconductor measurements.

Manufacture of highly reliable devices requires constant attention to cleanliness in fabrication to assure a clean environment for the wafer. All devices are given a process screening at 220°C for 72 hours to weed out unreliable products. Temperature cycling is also used as a screening test. Encapsulations are tested for leaks in two steps. One uses a radioactive-source-tracer to detect very small leaks; the other

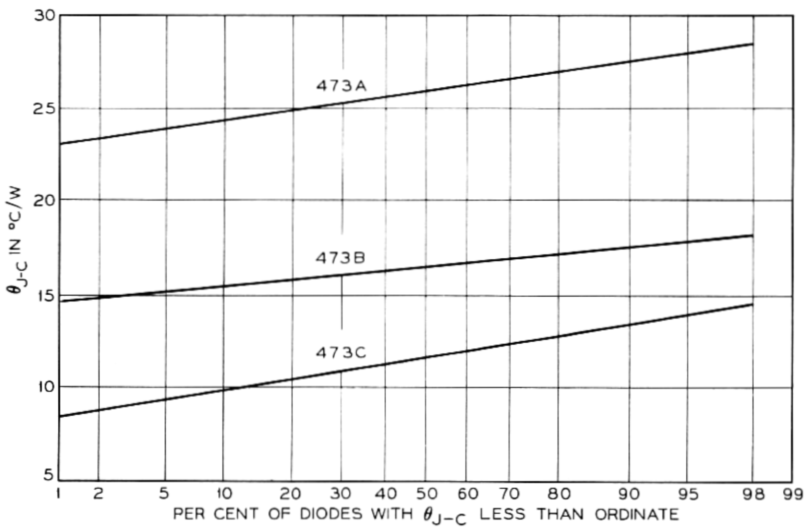


Fig. 12 — Thermal resistance.

TABLE V—100-HOUR POWER AGING REQUIREMENTS

Diode	Power (W)		V_R (V)
	Rated	Aging	
473A	2.0	3.0	50
473B	3.0	4.5	70
473C	4.0	6.0	60

uses pressurized dye to indicate larger leaks; combined they assure a hermetically sealed package. All devices undergo a 16-hour test at 175 per cent of rated power to assure reliable operation in the multiplier circuit. A centrifuge test at 20,000G and a shock test at 1,500G complete the screening.

A sample lot of devices is required to pass 100-hour power aging tests as indicated in Table V. Diodes are switched between forward conduction and reverse-bias operation ($V_R = BV - 10V$) at 60 Hz during aging. The forward current is adjusted to obtain the correct aging power. About 1 per cent of the diodes in a sample from a properly manufactured lot fail under the conditions of Table V.

2.6 *Summary*

The 473A, B, and C are medium power varactor diodes that are useful as harmonic generators in the range 0.1 to 10 GHz. The diodes are planar, passivated structures encapsulated in a miniature pill-type ceramic package. Process screening tests assure high quality. In the TD-3 microwave generator circuitry, these diodes generate the desired beat oscillator power while meeting additional requirements of low noise and tunability.

III. U-PACKAGE MICROWAVE DIODES

By H. E. Elder, T. P. Lee, F. H. Levien, D. C. Redline and N. C. Vanderwal

The 471A transmitter modulator diode pair, the 488A IF monitor diode, the 493A RF monitor diode, and the 497A receiver modulator diode are encapsulated in the "U package." The "U" is a sequential designation assigned by Bell Laboratories.

The U package was designed to fill a need for a hermetic microwave package with low parasitic inductance and capacitance. Figure 13 shows a U-package silicon varactor. The other diodes which use the U package differ in semiconductor wafer material, processing, and internal contacts. The 488A and 493A diodes have internal tungsten

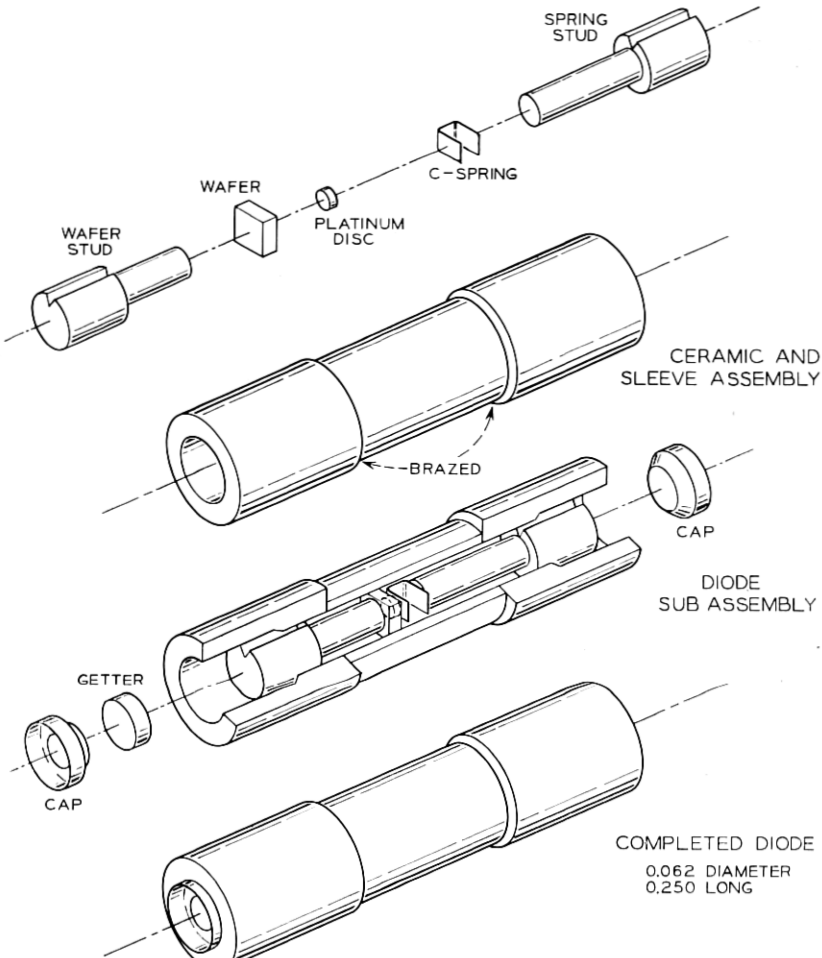


Fig. 13 — 471A diode in a U package.

wire S-spring point contacts on the top of the silicon wafer, and the 497A gallium arsenide diode uses the basic gold-plated platinum disk contact and C-spring shown for the 471A in Fig. 13. The 488A diode has external nickel wire leads welded to the endcaps of the U package.

3.1 *Silicon Varactor*

The 471A diffused epitaxial silicon mesa varactor was developed to satisfy the need for an upconverter diode that would give about

8.5 dB conversion gain in the TD-3 transmitter modulator.[13] A satisfactory Western Electric diode did not exist before the 471A was coded. In order to provide the desired transmitter modulator performance, the 471A diode was developed with the following characteristics:

Semiconductor wafer

$C_{j(OV)}$ (pF)	$R_{s(OV)}$ (Ω) max.	BV (V) min.	$f_{c(OV)}$ (GHz) min.
0.68 to 1.08	3.0	15.	75.

Package parasitics		Pairing requirements	
C_c & C_f (pF)	$L_{s(\text{nh})}$	$\Delta C_{T(OV)}$ max.	$\Delta R_{s(OV)}$ (Ω) max.
0.12	1.4	0.1	0.5

$C_{j(OV)}$ is the zero-bias junction capacitance, $R_{s(OV)}$ is the zero-bias microwave series resistance, BV is the dc breakdown voltage, $f_{c(OV)}$ is the zero-bias cutoff frequency, C_c is the case capacitance (about 0.07 pF) and C_f is the fringing capacitance (about 0.05 pF) between the contact spring and the silicon wafer.

The series inductance, L_s, is about 1.4 nh in the 4 GHz, 0.090-inch high waveguide circuit used with the transmission resonance method for measuring inductance and microwave resistance of diodes as described by B. C. DeLoach.[14] The pairing requirements, needed in the balanced hybrid transmitter modulator circuit to suppress the carrier, are that the two diodes may differ by no more than 0.1 pF in total zero-bias capacitance and no more than 0.5 ohm in zero-bias series resistance.

Varactor action is assured by the wafer design and the manufacturing processes which lead to the following C-V relationship

$$C_j = \frac{C_{j(OV)}}{\left(1 - \dfrac{V}{0.6}\right)^{1/3}}$$

where

C_j is the junction capacitance,
$C_{j(OV)}$ is the junction capacitance at zero-bias

and

V is the applied voltage.

Studies showed that the transmitter modulator output power correlated well with diode resistance and capacitance, as Fig. 14 shows. In both cases, the plotted diode parameter is the average value of the two diodes involved. For a minimum total output power of 6 dBm from the transmitter modulator, the maximum series resistance for each diode was set at 3.0 ohms. The corresponding total capacitance ranged between 0.8 and 1.2 pF.

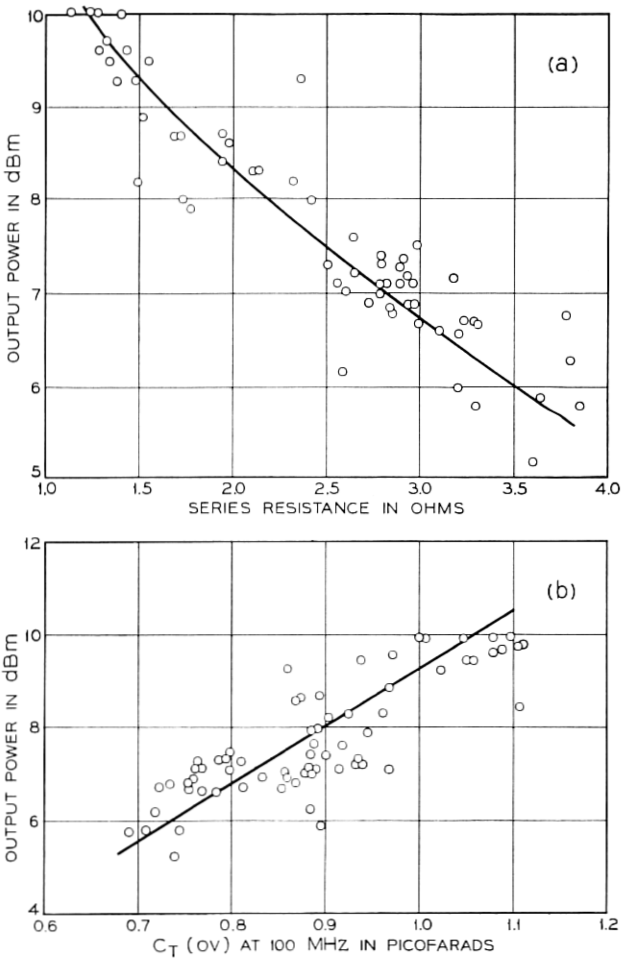


Fig. 14 — Transmitter modulator output power with (a) diode series resistance and (b) diode capacitance.

3.1.1 *Wafer Design*

The TD-3 transmitter modulator circuit requires diodes with zero-bias capacitance of about 0.9 pF, and series resistance less than 3 ohms. The difficulty in fabricating such diodes arises from keeping this low resistance in a diode with such low capacitance and consequent small junction area. In addition, this application requires that the diodes have a 15 volt minimum breakdown.

The breakdown voltage and series resistance tend to be mutually incompatible and are normally met only by compromising. In conventional diodes, the resistivity of the silicon wafer is chosen to lie between a lower limit set by the *BV* and an upper limit set by R_s. However, in the 471A design only a lower limit on resistivity is necessary. As Fig. 15 shows, cross-diffusion between a p-type doping impurity deposited on the surface and an n-type doping impurity from the substrate is produced within the epitaxial layer. This cross diffusion provides a low R_s which is independent of the original resistivity of the epitaxial layer.

A typical slice has a 7 micron layer of 0.3 ohm-cm silicon grown on a 5 mil thick phosphorous-doped substrate of about 0.001 ohm-cm resistivity. The slice is boron diffused to form a cross-diffused p-n junction midway in the epitaxial layer as shown in Fig. 15. The incoming boron atoms produce a diffusion gradient which meets the phosphorous doping impurity diffusing out from the substrate. Since both phosphorous and boron have about equal diffusion constants, the profiles meet about halfway through the epitaxial layer. The p-n junction thus formed has a small enough doping gradient to sustain the *BV* desired, yet the gradient provides a heavily doped region on either side of the junction regions to reduce diode resistance.

Another stringent requirement for this diode is the tight tolerance on diode junction capacitance, $C_{j(OV)}$. To meet the $\pm$ 0.2 *pF* allowable variation, a method of chemical etching was developed that allowed for precise control of diode junction area. The initial step is to prepare 0.001-inch thick platinum disks with diameters from 0.0006 to 0.0021 inch, and a thin evaporated layer of gold and palladium.

After the capacitance per unit area of a particular lot of wafers has been determined, the diameter is chosen and a disk is alloy bonded to the surface of the diffused epitaxial silicon wafer while the wafer itself is simultaneously alloy bonded to the gold plated stud. The wafer-stud assembly is then immersed in an acid mixture, which attacks the bare silicon wafer. That portion of the wafer under

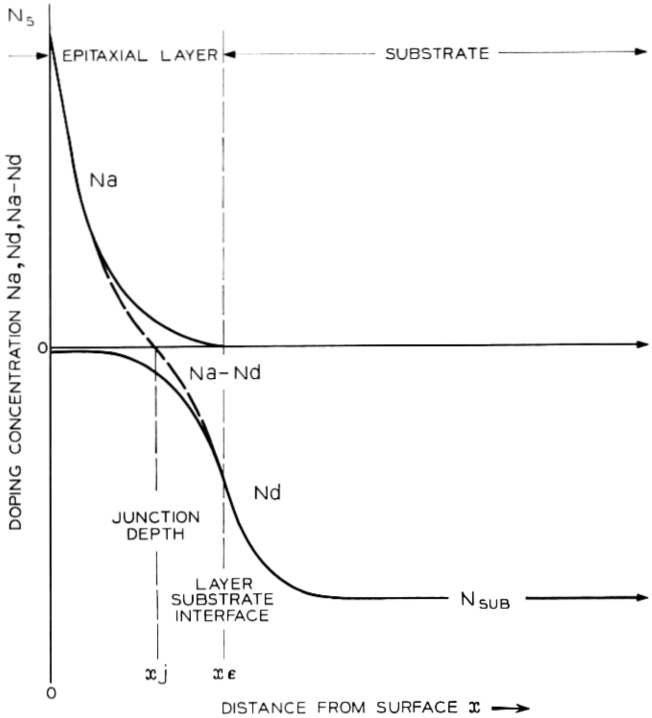


Fig. 15 — Schematic doping distribution for cross diffused junction.

the disk is protected and remains intact. The result is a mesa, the diameter of which controls the area of the junction and therefore the junction capacitance.

Now the wafer junction capacitance is carefully measured. If it is above the desired value, another brief acid immersion is sufficient to bring the capacitance within specifications. Thus, the ability to control the disk size and etching time, permits control of junction capacitance.

3.1.2 *Diode Reliability*

Device reliability is achieved first by careful attention to cleanliness in manufacturing, and second, by screening finished devices to eliminate weak units.

To insure that all volatile contaminants are driven off the interior surfaces of the diode, they are heated in a vacuum at 300°C for two hours, then pure, dry nitrogen is allowed to enter the diodes which are then hermetically sealed.

To prevent deleterious effects of unwanted gases evolved during the closure weld and during subsequent aging, a glass frit gas-absorber is placed in one end of the unit before final welding.

To identify completed diodes that may, however, still be unstable because of some chemical or ionic contaminants, all diodes are "process aged" by subjecting them for three days to a 220°C temperature after which they are electrically tested. All diodes which shift out of the electrical limits are discarded.

To eliminate mechanically weak diodes, all are subjected to the following tests:

(*i*) Centrifuge at 27,000g for 1 minute in each of 3 directions.
(*ii*) Temperature cycle from −65°C to +150°C, 5 times.
(*iii*) Mechanical shock at 1,500g, 5 times in each of 3 directions.

Each diode is then leak tested to insure that a diode is still hermetically sealed. Only those devices which survive all of these screening tests are used in TD-3. Step stress power aging data indicate the failure rate to be less than 100 failures per 10^9 device-hours at 50 mW per diode in the TD-3 transmitter modulator. Field data in a military parametric amplifier at slightly lower power levels (about 20 mW) indicate that five diodes out of 4000 apparently changed in total capacitance enough to necessitate their removal in the first 10^8 device hours. This indicates that a rate of 100 failures per 10^9 device-hours is a reasonable upper limit (with a 95 per cent confidence limit) for the 471A diode.

3.2 *Silicon Point Contact Detectors*

The 488A and 493A silicon point contact diodes were needed for IF and RF detector circuits because there were no hermetically sealed diodes available with the required detector characteristics. The gallium arsenide diode which ultimately became the 497A diode could have been used; however, it will probably always cost significantly more than silicon point contact diodes.

The 488A and 493A diodes are very similar. Both are in the U package and they use the same basic aluminum doped silicon material, but the wafers are processed differently. The 488A wafer is oxidized at 975°C and the 493A wafer is oxidized at 927°C. The ultimate desired results, caused by different out-diffusion profiles, are a higher reverse impedance for the 488A diode and a lower forward resistance for 493A. A more obvious difference is that the 488A diode has 0.020-inch nickel leads welded on each end of the package and the 493A diode has no leads.

The diode specifications, based on applications studies are:

	I_F at 1.0 Vdc (mA)	I_R (μA)
488A	20 min.	100 max. at −2 Vdc
493A*	20 min.	100 max. at −1 Vdc

As with the 471A varactor diode, the 488A and 493A diodes are vacuum-baked at 300°C for two hours. The final end cap weld is made in dry nitrogen. The assembled diodes are given a 72 hour process aging at 220°C. Leads are welded axially to the 488A end caps after aging. Both diodes are then given shock, temperature cycle, and acceleration tests before their final electrical tests.

Reliability tests indicate that the failure rate of the 488A and 493A diodes will be negligible. The diodes are rated at 30 mW; however, the various TD-3 applications are at significantly lower power levels (less than 10 mW). Temperature step stress aging indicates a failure rate of less than one failure per 10^9 device-hours. Long term power aging at 250 mW and 310 mW on 14 and 15 devices, respectively, has resulted in no failures after 6000 hours of aging. At 390 mW, eight out of 17 diodes failed after 6000 hours. There are no significant trends in diode parameter changes at the two lower powers, therefore the tests must continue for some time to get a good estimate of the failure rate.

3.3 *Gallium Arsenide Schottky-Barrier Diode*

The 497A gallium arsenide Schottky-barrier diode has been designed to replace the 416C silicon point-contact diode as the nonlinear resistor element in the receiver modulator or downconverter of TD-3. The 497A in an improved downconverter circuit, followed by a new low-noise transistor IF amplifier, has so improved receiver noise that

* The 493A specification also requires application tests in a 61A detector with minimum values of rectified current in a 1200 ohm load resistor at two different TD-3 power levels and two different TD-3 frequencies. Also, an input return loss of 20 dB minimum is required at both extremes of the TD-3 frequency band.

no microwave preamplifier is necessary to achieve TD-3 thermal noise objectives.

3.3.1 *Required Electrical Characteristics*

The present theory of downconverter diode operation uses approximations appropriate to small-signal analysis;[15] the 497A diode is driven in a large-signal mode by the TD-3 local oscillator and dc bias currents. Therefore, a new detailed characterization of the semiconductor wafer interaction with the circuit is needed. Further, this knowledge should be used to develop a more refined and appropriate general theory of downconverter operation. Such work is in progress in many laboratories, including our own, but is not complete. The only adequate measure now of downconverter diode suitability is a test of its performance in the microwave circuit.

This empirical approach was used to design a suitable diode for TD-3. First, an evaporated-metal Schottky-barrier diode was chosen because stored-charge effects which would degrade the desired varistor action are negligible,[16] and because there are well understood and controlled processes for fabricating such devices. Second, a readily tunable, low-loss, narrow-band downconverter circuit was built and used to search for the optimum semiconductor doping level and junction diameter for wafers packaged in the U encapsulation. Third, a suitable fixed-tuned, low-loss, broad-band downconverter circuit was designed using the apparent optimum device from this study.[17] Finally, using the broad-band circuit, the acceptable range of diode parameters was determined. They are shown in Table VI.

The forward series resistance, R_{sf}, is the resistance appearing in the diode current-voltage relationship $I = I_S \exp\left[(q/nkT)(V_A - IR_{sf})\right] - I_S$ where n is an experimental constant near 1.

The graphical determination of R_{sf} for a typical 497A diode is illustrated in Fig. 16. Unlike the $R_{s(OV)}$ common in varactor charac-

TABLE VI—ELECTRICAL REQUIREMENTS FOR THE TD-3 RECEIVER MODULATOR DIODE, TYPE 497A

Noise figure (f = 3.95 GHz NF_{IF} = 2.4 dB, I_D = 8 mAdc)	NF	6.9 dB maximum
Capacitance (V_A = 0 volts)	C	0.2 pF minimum 0.6 pF maximum
Reverse current (V_A = −6 volts)	I_R	10^{-4} A maximum
Forward series resistance	R_{sf}	2 Ω maximum
Power dissipation	P	0.05 W maximum

terization,[9] R_{sf} includes the resistance of most of the zero-bias depletion region, since the depletion region collapses almost completely under forward bias.* R_{sf} is discussed further in Sections 3.3.4 and 3.3.5.

3.3.2 *Structure*

The U encapsulation was chosen for the 497A diode, resulting in assembly processes represented by Fig. 13. A gold-tin solder preform is used for low resistance contact to the back of the GaAs wafer,

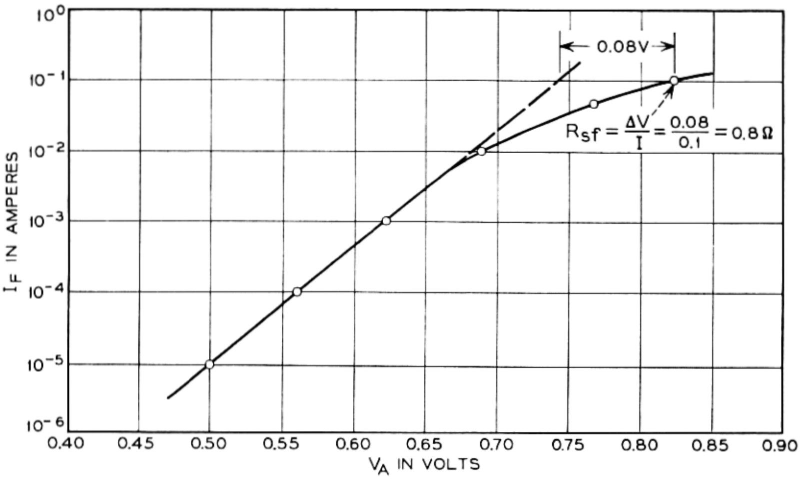


Fig. 16 — Forward current-voltage relationship for a typical 497A diode illustrating the graphical determination of R_{sf}.

and a 0.0018-inch diameter by 0.001-inch thick gold-coated platinum disk is used to reduce fringing capacitance between the front of the wafer and the C-spring contact.† Both contacts are effected during a single heating cycle under about 50 gm-wt compressive force. Use of the platinum-disk raised contact requires that an overlay contact on a protective insulator be used between the disk and the smaller-diameter metal-semiconductor Schottky-barrier junction.

Figure 17 is a cross-sectional drawing of the junction designed to

* Measurement of R_{sf} in *p-n* junction diodes at low frequencies measures only the resistance of the wafer substrate and contacts, since injected charge modulates the conductivity of the epitaxial layer in this case. This modulation is not significant in Schottky-barrier diodes at normally-encountered current densities.

† The platinum disk is used only for contacts. The disk size in the 471A silicon mesa diode described in Section 3.1 is chosen as an etching mask to control junction capacitance.

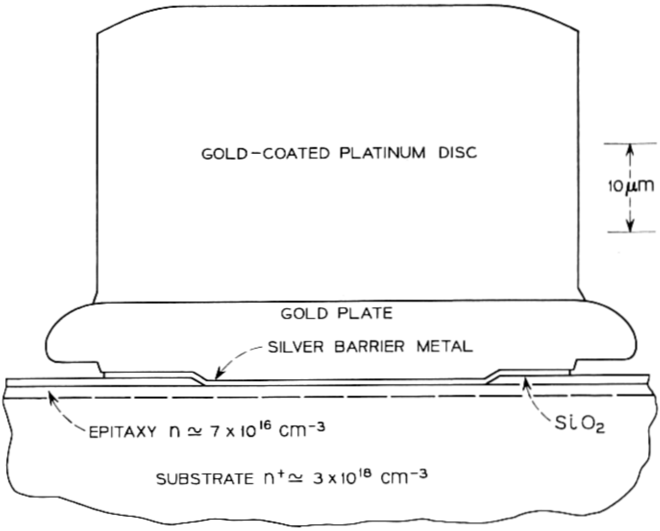


Fig. 17 — Cross section of gallium arsenide Schottky-barrier diode junction.

meet both the requirements of Table VI and the mechanical requirements imposed by the encapsulation.* A deposited layer of SiO_2 serves as the overlay insulator. Junction windows are etched through the SiO_2 photolithographically, after which a thin layer of titanium is evaporated onto the slice to improve the adherence of the silver barrier metal which is next evaporated onto the slice. A second photolithographic process defines apertures through which the gold contacts are electroplated. These contacts serve as etching masks during removal of silver and titanium from areas where they are not needed. This etching is the last operation before wafering and contact bonding.

3.3.3 *Advances in Technology*

Significant advances in control and characterization of thin n-on-n^+ GaAs epitaxial layers were required to meet the 497A device requirements. A silicon-doped, water-vapor-transport system[18] and tin, tellurium, or selenium-doped halide-transport systems[19, 20] have all achieved the required steep doping gradient between substrate and epitaxial layer doping levels. A sample chip from each slice is evaluated for doping profile and for effective electron mobility using large and small-area evaporated Schottky-barrier diodes, respectively.

* Prototype Schottky-barrier junctions on gallium arsenide developed by J. C. Irvin contributed to this junction design.

A computerized dC/dV technique[21] has been adapted for use on GaAs to obtain doping profile plots such as the typical one shown in Fig. 18. The R_{sf} of a sample of 0.001-inch diameter diodes is measured, using a pulse-formed alloyed-tin substrate contact, to insure adequate electron mobility.

In the complex, interdependent series of heating cycles required during processing, reverse-current degradation resulting from oxide contamination, and R_{sf} increases caused by contamination of the epitaxial layer with an acceptor (probably copper), are problems which have been brought under control during diode development.

To achieve adequate adherence of the photolithographic medium to the silver barrier metal during gold electroplating, the photolithographic process is carefully controlled and the time in the plating bath reduced to a minimum.

3.3.4 *Wafer Design*

Because devices commonly used as downconverters have barrier heights (Φ) varying from 0.1 to 0.9 volts, and are all forward-biased to similar current levels in downconverter operation, zero-bias cutoff

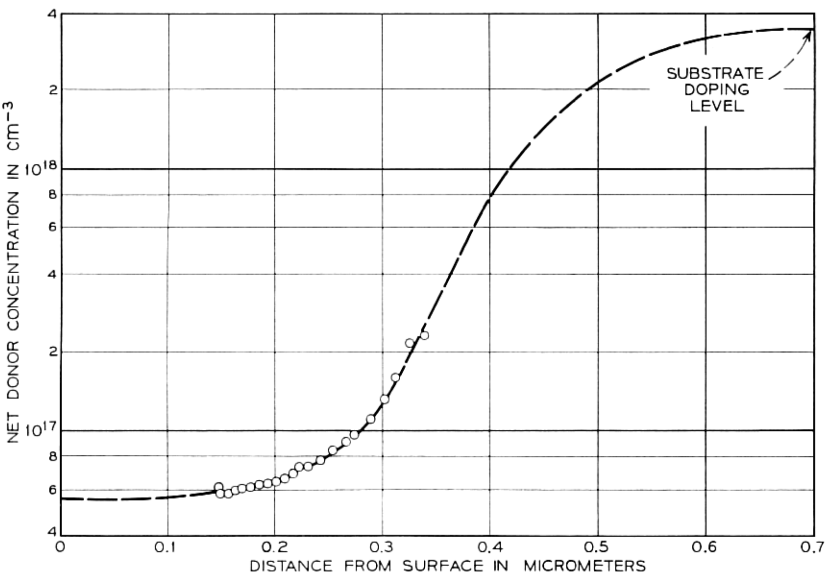


Fig. 18 — A typical doping vs distance profile for the epitaxial gallium-arsenide layers used for the 497A diode.

frequency is not a useful characterization parameter. A more meaningful parameter is the forward-bias cutoff frequency

$$f_{cf} = \frac{1}{2\pi C_{jf} R_{sf}}.$$

C_{jf} is defined at $V_A = \Phi - 0.1$ Vdc and can be calculated from the more common $C_{j(OV)}$ as $C_{jf} = C_{jo}\ (10\ \Phi)^{1/2}$ by making the reasonable approximation of uniform doping within the zero-bias depletion layer. The bias point $V_A = \Phi - 0.1$ Vdc is chosen since for many Schottky-barrier diodes, approximately this voltage produces the forward current at which the junction resistance $R_j = R_{sf}$, where $R_j = nkT/qI$.

Figure 19 shows the calculated f_{cf} as a function of epitaxial doping density for n-type gallium arsenide Schottky-barrier diodes. Curves for several junction diameters are shown. A curve for p-type silicon is also included, since this is used in the 416C point-contact diode. A contact resistance of 0.1 Ω and a 0.5 μm-thick epitaxial layer are assumed. For GaAs, layers having practical values of electron mobility on substrates of 0.002 Ω-cm resistivity are assumed. In practice, the lightly-doped layer

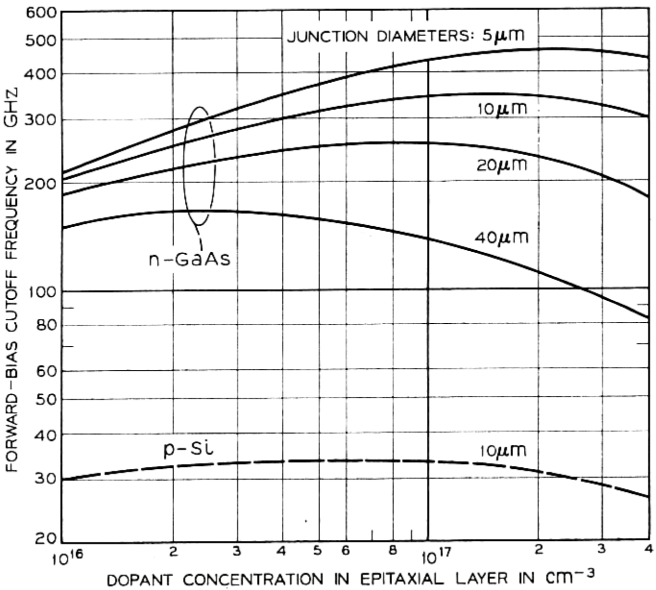


Fig. 19 — Theoretical forward-bias cutoff frequences of Schottky-barrier varistors in n-type GaAs and p-type Si, as a function of doping impurity density in a 0.5μ-thick epitaxial layer.

in the 416C is formed by out-diffusion of impurities and by "tapping," and is ≈ 0.2 μm thick, resulting in a nominal f_{cf} of 50 GHZ.

If there were no fringing capacitance or burnout constraints, a 5 μm-diameter junction on a GaAs epitaxial layer doped near 2×10^{17} cm^{-3} would be near optimum. However, the thermal resistivity of GaAs is triple that of silicon,[22, 23] and the outside diameter of the overlay is fixed by the choice of encapsulation and contacting technique. These considerations, coupled with the case capacitance of 0.12 pF, change the optimum to a junction diameter near 25 μm, a doping level near 5×10^{16} cm^{-3}, and an epitaxial layer thickness of 0.2 μm. Manufacturing tolerances force a range of epitaxial thicknesses, doping levels, and junction diameters varying from these optima toward thicker layers, higher doping, and smaller junctions.

3.3.5 *Results*

Figure 20 shows the experimental relationship obtained between f_{cf} and over-all noise figure for a tunable 6 GHz downconverter with reflected image and NF_{IF} = 1.1 dB, and for fixed-tuned downconverters with absorbed image and NF_{IF} = 2.4 dB, suitable for use in TD-3. The left end of each curve is based on measurements of

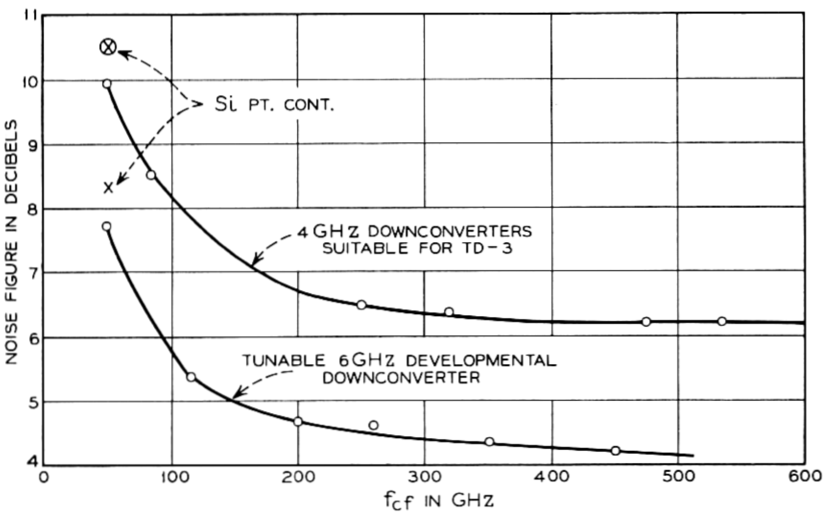


Fig. 20 — Overall noise figure vs f_{cf} for a 6 GHz reflected-image downconverter with NF_{IF} = 1.1 dB, and for a 4 GHz absorbed-image downconverter with NF_{IF} = 2.4 dB.

silicon point-contact diodes with junctions like the 416C. The excess noise characteristics of such junctions causes these points to be about 0.6 dB higher than the curve, which is drawn for Schottky-barrier junctions. All the other experimental points are median values for groups of diodes fabricated during the development of the 497A.

Based on these experimental curves, the design of the downconverter diode for TD-3 must provide a value of f_{cf} somewhat above 175 GHz to assure NF below 6.9 dB. For a typical total capacitance of 0.45 pF, this requires $R_{sf} \leq 1.1\ \Omega$ (overlay capacitance $\simeq 0.05$ pF, $\Phi \simeq 0.8\ V$). Lack of control of electron mobility in thin epitaxial layers of GaAs prevents calculation of the resistance expected from the measured doping-versus distance profiles. However, assuming contact resistances of 0.1 Ω, and calculating the spreading resistance from a 25 μm diameter junction in the substrate [24] to be 0.2 Ω, we find that for a 0.5 μm thick epitaxial layer, uniformly doped at 5×10^{16} cm^{-3}, the average electron mobility must be at least 1600 cm^2 V^{-1} sec^{-1}.

Referring to the requirements for the 497A diode listed in Table VI, typical values of parameters for the device being manufactured are:

NF	6.5 dB
C	0.45 pF
I_R	10^{-9} A
R_{sf}	0.8 Ω
$BV(I_R = 10\ \mu A)$	12 V

The mechanical and thermal process stresses used to screen 471A diodes are also used for the 497A. Figure 21 shows the step-stress aging curves for temperature and 60 cycle, 6 volt peak-reverse-voltage power stressing. For use in TD-3, a rate of less than 10 failures per 10^9 device-hours is predicted. These data are being supplemented by long-term aging tests.

IV. HIGHLY STABLE DIODES FOR THE IF DEVIATOR

By S. M. Forst, G. F. Foxhall, and G. A. Kelley, Jr.

This paper discusses the development of two semiconductor diodes to be used in the IF deviator of the 3A FM terminal transmitter. These devices have been coded 446AC, an 8.2 volt regulator diode, and 457A, a variable capacitance diode. While the two may be thought of as dissimilar device types, the system requires a like feature in each: great stability of electrical characteristics.

The heterodyne deviatior contains two voltage controlled Colpitts

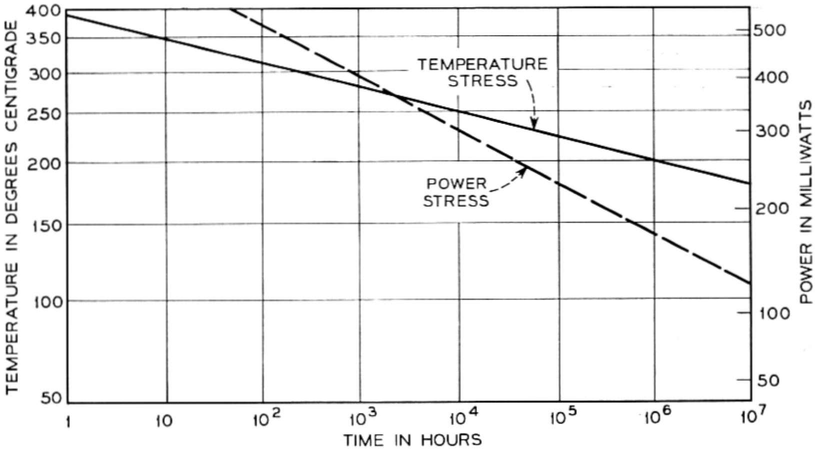


Fig. 21 — 497A stress aging: median-failure stress vs time.

oscillators operating at 186.67 and 256.67 MHz. The output frequencies are mixed, and the difference frequency of 70 MHz is extracted. The latter must have a drift instability of ±100 kHz maximum for a three-month interval.

An ultrastable 5 volt regulated supply using the 446AC diode provides bias for the 457A diodes in the oscillator tank circuits. (See Fig. 22). The baseband signal superimposed on this bias modulates the capacitance of each 457A diode, and consequently the output frequencies of the oscillators as well.

Since the stability of every component in the deviator system will affect the eventual stability of the output, an allowable range of frequency drift was assigned to each code.[3] For the 446AC diode, the allotted drift of 7 kHz means that the breakdown voltage must be stable to within 7 millivolts. The allowable drift of 43 kHz by the 457A diode places requirements on two characteristics. The reverse leakage current must be stable to within 2.3 nanoamperes to prevent excessive loading of the bias supply, and the capacitance must be stable to within 0.0078 pF.

4.1 *446AC Diode*

4.1.1 *Desired Characteristics*

The 446AC diode was the simpler of the two devices to develop since it is an extension of the existing 446T diode design. The 446T

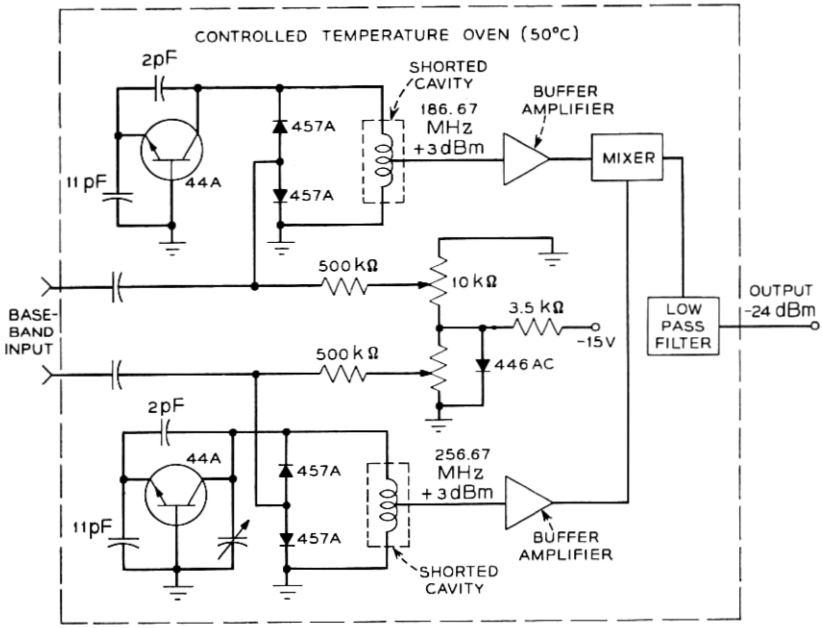


Fig. 22 — Simplified diagram of the 3A FM terminal transmitter deviator.

is an 8.2 volt regulator diode with a 5 per cent range on breakdown voltage. It was the additional requirement of 7 mV stability which necessitated the new code.

4.1.2 *Description and Fabrication*

The 446AC is a member of a family of K package devices. This implies a hermetic metal encapsulation as shown in Fig. 23. The body of the device is coated with grey paint; the leads are solder coated.

Manufacturing begins with the diffusion of an n-type layer (phosphorus is used as the doping impurity) into a slice of p-type silicon. An undesired n-layer is removed from the back side of the slice when the latter is lapped to give a final thickness of 0.007 inch. Metallic contacts are applied to the slice through plating and sintering; the outer coating is gold to facilitate subsequent wafer and wire bonding.

Individual diode wafers are formed by a stream of airborne abrasive. Round metal discs are held against the slice during this operation to protect those areas on the slice which will eventually become

0.035 inch diameter wafers. The portion between the discs exposed to the abrasive stream is eroded away. Etching removes damaged material from the edge of the wafer.

Next the wafers are bonded to a leaded platform and a wire is bonded to the top of the wafer by compressive force at elevated temperature. Finally, a tubulated case is placed down over the wafer onto the peripheral portion of the platform and welded in place. The wire which had been previously bonded to the wafer extends into the tubulation. Electrical connection is made when the tubulation is pinched off to provide the final seal. The assembly is shown in Fig. 24.

4.1.3 *Electrical Characteristics and Reliability*

The electrical requirements which were eventually placed on the device are shown in Table VII. Figure 25 shows a typical reverse characteristic at two different temperatures. Notice that at the lower voltages, reverse current increases with temperature, while at higher voltages the breakdown voltage increases with temperature.

Preaging to assure stability consists of 250 hours of storage at 250°C and 750 hours of reverse dc power aging at 400 mW. The breakdown voltage is measured at 0, 250, 500, 750, and 1000 hours, and those devices with less than 50 mV drift are considered accept-

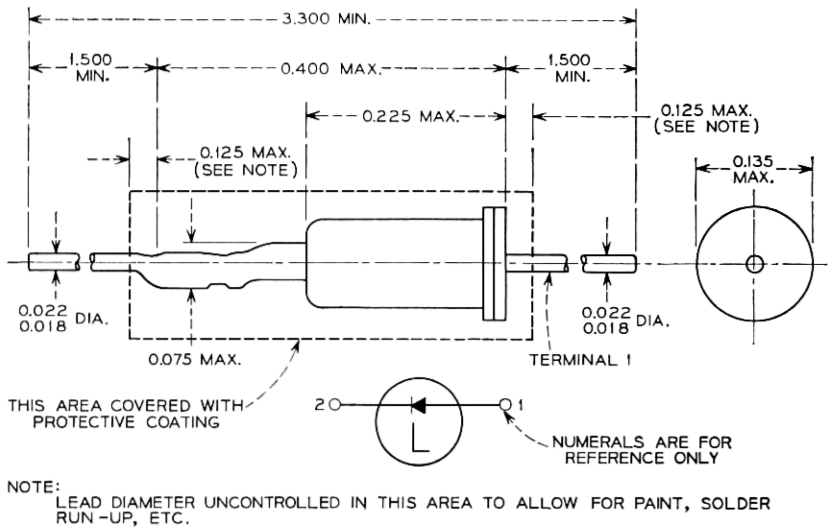


Fig. 23 — K-package encapsulation. All dimensions are in inches.

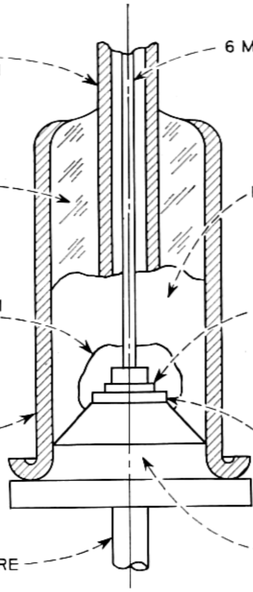


Fig. 24 — Internal structure of the K package assembly.

able. The relatively large tolerance on drift used for these accelerated test conditions is sufficient to provide a 7 mV stability at 16 mW use.

The expected failure rate of K package diodes is normally considered to be about one failure per 10^9 hours at a junction temperature of 60°C. The results of initial attempts to measure failure rate under an end point requirement of 7 mV stability were unfortunately obscured by variations in ambient temperature while readings were being taken. The experiment did show, however, that the device was indeed capable of meeting the requirement. This is verified by 10

Table VII — Electrical Characteristics of the 446AC Diode

		Min.	Max.	Typical	Units
Breakdown voltage (I_R = 10 mAdc)	BV	7.8	8.6	8.2	Vdc
Forward voltage (I_R = 400 mAdc)	V_F	—	1.0	0.9	Vdc
Saturation current (V_R = 6.5 Vdc)	I_S	—	2.0	0.3	μAdc
Breakdown impedance (I_R = 10 mAdc)	bz	—	7	5	ohms
Stability, breakdown voltage (I_R = 1.3 mAdc)					
Accelerated tests	ΔBV		50		mVdc
Use conditions	ΔBV		7		mVdc

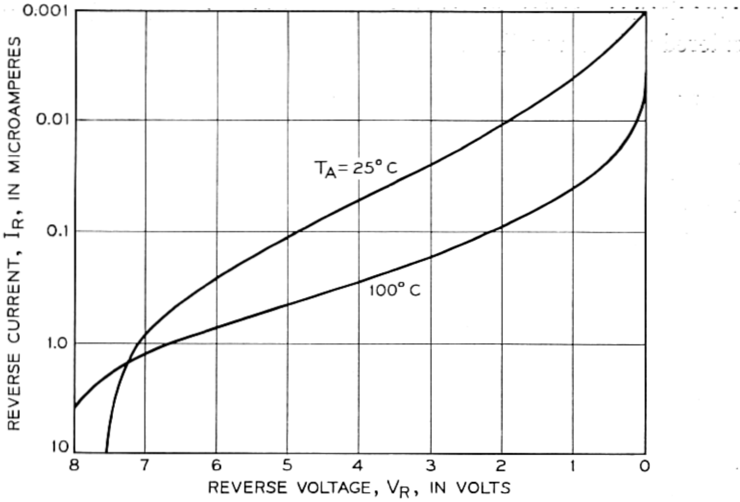


Fig. 25 — Reverse characteristics of the 446AC diode.

months of field experience during which no system failures have been recorded. A redesigned experiment to give more accurate values is under way.

4.2 *457A Diode*

4.2.1 *Desired Characteristics*

It was immediately apparent that many of the objective requirements for the 457A diode would make necessary the development of an entirely new code. Table VIII lists these requirements, of which

TABLE VIII — PROPOSED CHARACTERISTICS FOR THE 457A DIODE

		Min.	Max.	Units
Capacitance (V_R = 8 Vdc)	C	18	22	pF
Sensitivity ($C = V^{-n}$)	n	1/3		
Inductance	L		1	nh
Series resistance	R_S		0.5	ohms
Breakdown voltage (I_R = 5 μAdc)	BV	25		Vdc
Reverse current (V_R = 11 Vdc)	I_R		10	nAdc
Stability				
Capacitance	ΔC	as stable as possible		
Reverse current	ΔI_R			

capacitance, series resistance, inductance, and stability were considered to be controlling.

4.2.2 *Description and Fabrication*

An S-package design was selected primarily because of its low inductance. This incorporates two stud lead assemblies sandwiching the wafer, with a glass sleeve sealed along the major portion of the length of the studs. (See Fig. 26.) Because the body is so small, colored coding bands replace the usual alphanumeric identification.

Manufacturing is similar to that for the 446AC. An n-type slice is simultaneously diffused with both p and n layers on opposite sides of the slice. This leaves a very thin region in the middle of the slice where the silicon resistivity is high. This technique provides the low series resistance necessary to obtain high Q. Plating and sintering apply a metal contact to the slice.

The diode wafers are formed by an abrasive stream, but the stream is focused to cut a restricted kerf, and the resulting wafers are square.

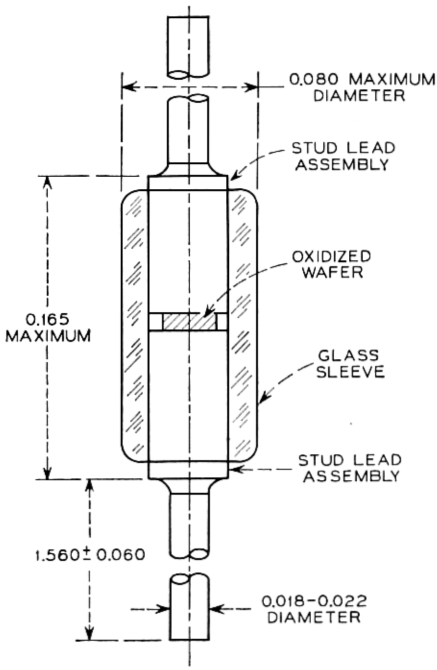


Fig. 26 — S package assembly.

The damaged edges are etched, and then an oxide is grown on the exposed silicon for passivation and protection. (See Fig. 27.) It is this oxide which prevents damage to the wafer during sealing, which is done at 830°C, and provides the required stability of electrical characteristics.

4.2.3 *Electrical Characteristics and Reliability*

As the development program progressed, it became evident that some of the requirements would have to be modified slightly to be compatible with manufacturing. For example, Fig. 28 shows distributions of series resistance achieved over successive runs. Based on these curves, a value of 0.7 ohm was specified as a maximum for series resistance, slightly greater than the 0.5 ohm requested. Table IX shows the final electrical characteristics. Figures 29 and 30 show the dependence of capacitance on voltage and temperature, respectively.

As with the 446AC diode, preaging assures that the 457A meets the stability requirements. All devices are subjected to 1000 hours of stress at a reverse bias of 5 volts and an ambient temperature of 150°C. Characteristics are measured at 250 hour intervals, and those devices drifting more than 0.1 pF or 2.3 nanoamperes are rejected.

A measuring system and associated facilities to detect capacitance changes as small as 0.0001 pF has been constructed. An experiment is under way to determine the expected failure rate at 5 volts reverse bias use condition and 50°C ambient temperature. At the time of this writing, no system failures caused by the 457A have been re-

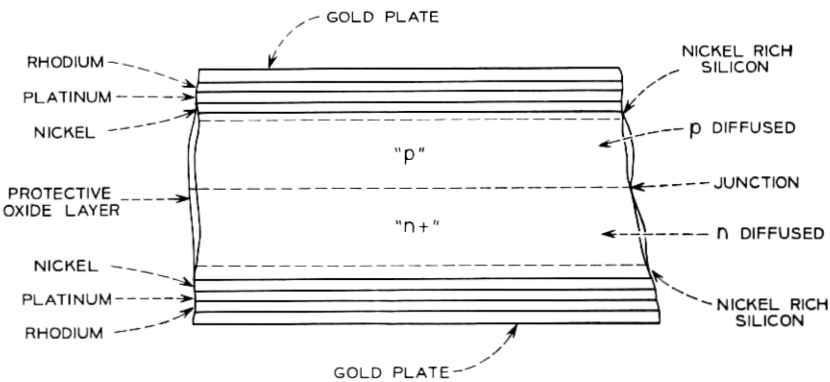


Fig. 27 — Completed 457A wafer.

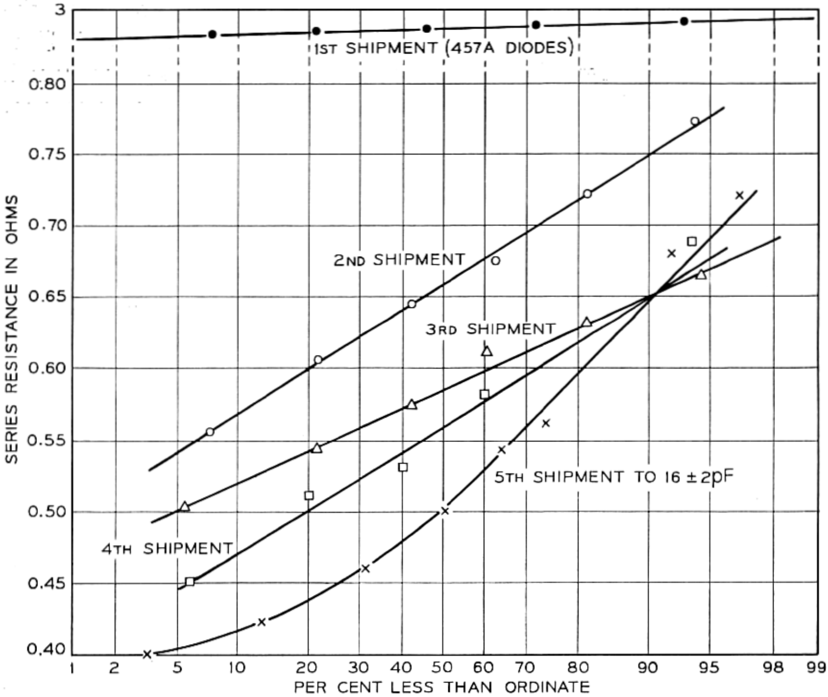


Fig. 28 — Series resistance (ohms) per cent less than ordinate. $f = 100$ MHz, $V_R = 5$ volts, $R_s = 1/(2\pi f c Q)$.

Table IX — Electrical Characteristics of the 457A Diode

		Min.	Max.	Typical	Units
Breakdown voltage ($I_R = 5\ \mu$Adc)	BV	50	—	60	Vdc
Forward voltage ($I_F = 100$ mAdc)	V_F	—	1.0	0.82	Vdc
Reverse current ($V_R = 5$ volts)	I_R	—	0.010	0.0005	μAdc
Capacitance ($V_R = 5$ volts, $f = 100$ KHz)	C	15	17		pF
Quality factor ($V_R = 5$ volts, $f = 100$ MHz)	Q	130	—	175	—
Series resistance ($V_R = 5$ volts, $f = 100$ MHz)	R_S	—	0.7	0.6	ohms
Inductance	L	—	—	3	nh
Stability					
Capacitance ($V_R = 5$ volts, $f = 100$ KHz)					
Accelerated tests	ΔC	—	± 0.10	—	pF
Use conditions	ΔC	—	± 0.0078	—	pF
Reverse current ($V_R = 5$ volts)	ΔI_R	—	± 2.3	—	nA

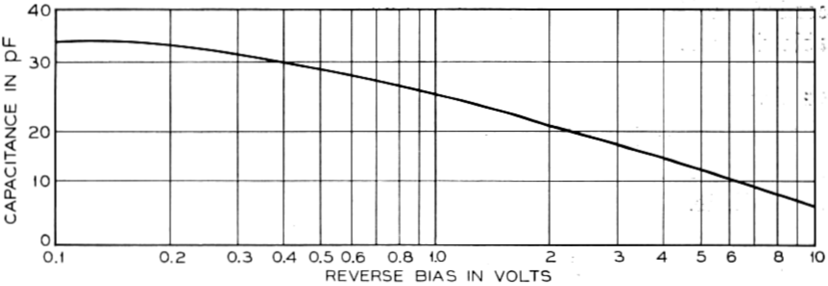


Fig. 29 — Dependance of the 457A diode's capacitance on reverse voltage.

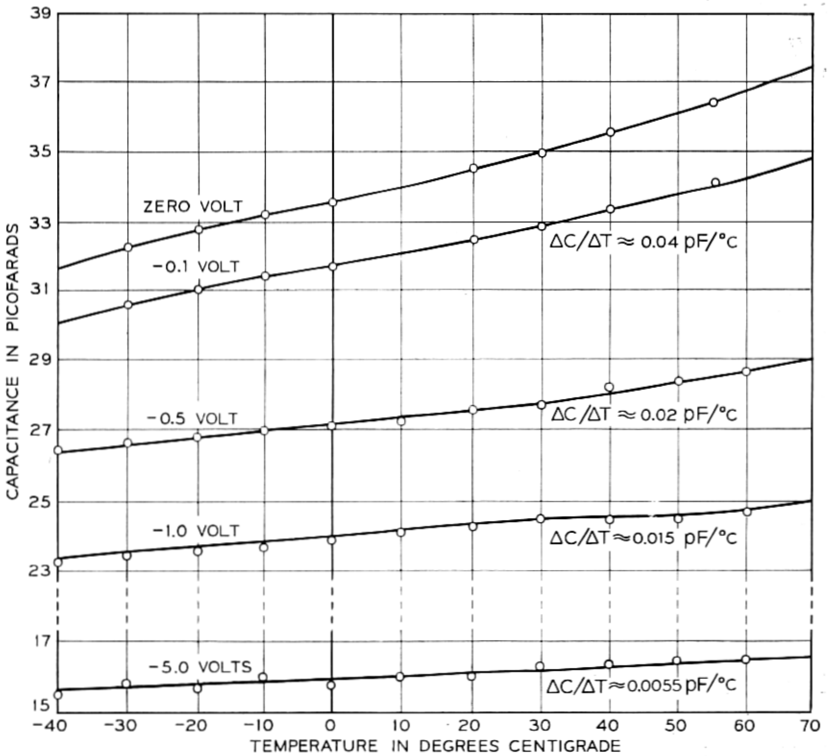


Fig. 30 — Dependance of the 457A diode's capacitance on temperature.

corded, verifying that the screening procedure is passing only acceptable devices.

4.3 *Summary*

Two devices have been developed for the 3A FM deviator. They are the 446AC, an 8.2 volt regulator, and the 457A, a variable capacitance diode.

Over the 3-month system maintenance interval, the breakdown voltage of the 446AC must be stable to within 7 millivolts; and the capacitance and reverse current of the 457A must be stable to within 0.0078 pF and 2.3 nanoamperes, respectively. Accelerated preaging assures such compliance with these requirements that to date there have been no system failures because of drift in either diode.

V. SILICON SCHOTTKY BARRIER DIODES By H. J. Lory

5.1 *Applications and System Requirements*

The 479A and 479B diodes are planer epitaxial silicon Schottky barrier diodes developed for the TD-3 system.

The 479A is used in the IF limiter of the TD-3 microwave transmitter[1] and in the TD-3 FM terminal receiver.[3] To provide the required limiting, a diode was needed with low capacitance (less than 0.6 pF), low recovery time (less than 500 ps), and moderate breakdown voltages (greater than 10 volts). Since a diode with all these characteristics was not available, the 479A was developed.

The 479B is used in discriminator circuits of the FM terminal receiver and transmitter.[3] Here, a high rectification efficiency is required at 70 MHz; this condition also calls for low capacitance and reverse recovery time. The bias on the diode is normally less than ten volts, but may sometimes go as high as 15 volts during certain testing procedures. Hence, the 479B has a higher reverse bias voltage specification than the 479A (20 volts vs 10 volts, respectively). Point contact diodes have suitably low capacitances and reverse recovery times, but their reverse breakdown is low. Hence, a Schottky barrier device is used.

In this class of device, conduction is almost entirely by majority carriers, so that there is negligible reverse recovery time. The desired low forward impedance can be achieved simultaneously with low capacitance by using epitaxial silicon with a closely controlled thickness and a doping level consistent with the breakdown voltage requirement.

5.2 *Configuration*

Initially, an evaporated gold dot on bare silicon was used. While this diode performed system functions satisfactorily, it was sensitive to ambient moisture and high temperature during fabrication. Moreover, the fragility of the gold-silicon bond led to low shock and centrifuge endurance compared with other configurations.

The configuration finally used is a modification of that developed by Kahng and Lepselter.[25] Figure 31 shows a cross section of the 479A diode wafer. (The 479B is fabricated similarly to the 479A, but with different epitaxial film parameters.) The principal features are:

(*i*) A Schottky barrier junction, 0.001-inch in diameter, between silicon and an "alloy" formed by a solid-solid reaction of silicon and palladium at 475°C.

(*ii*) A protective steam-grown SiO_2 passivated layer.

(*iii*) A protective overlay of platinum and palladium, 0.002 inch in diameter, sealed to the oxide by a thin (~300 Å) layer of chromium.

This yields a die which has little sensitivity to ambient moisture and which may be eutectically bonded to the gold plated header without deteriorating electrical characteristics.

5.3 *Choice of Package*

In order to reduce capacitance shunting the diode, the die was isolated from the metal platform of the TO-18 package, which was then grounded with a third lead. Figure 32 illustrates the package

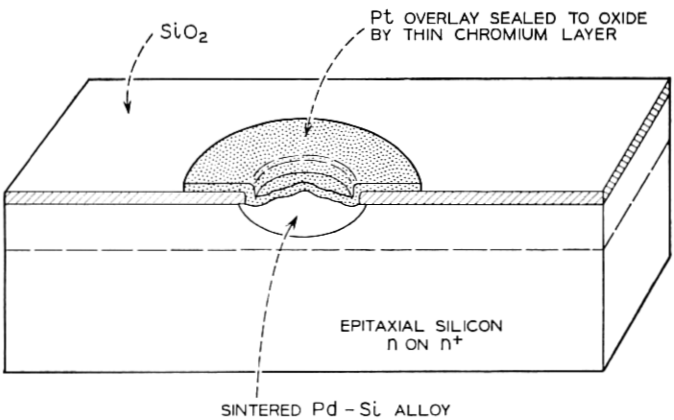


Fig. 31 — Cross section of Cr-Pd-Pt Schottky barrier diode wafer (not to scale).

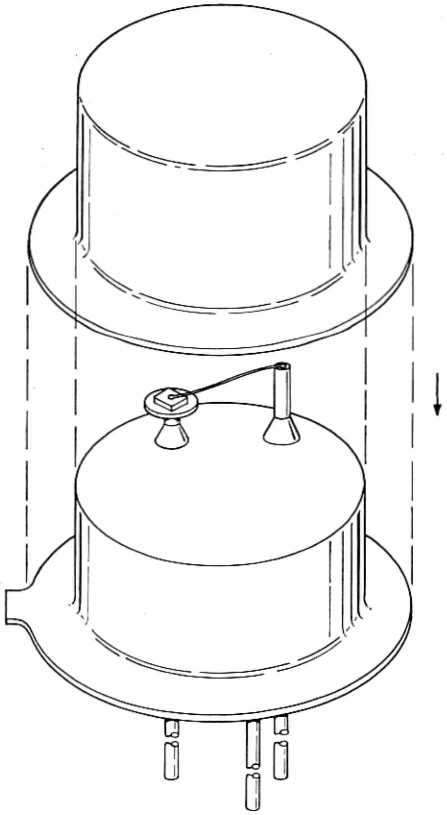


Fig. 32 — Packaged 479A diode.

used. The wafer die is mounted on a "nail head" lead, and a 0.7 mil wire connects to the second lead. This configuration leads to a typical diode zero bias capacitance of 0.35 pF, of which 0.05 pF is case capacitance.

5.4 *Electrical Characteristics*

Figure 33 illustrates the total zero bias capacitance distribution for a sample of 476 randomly selected units. The $\pm 1\ \sigma$ points cover a range of 0.075 pF.

The reverse recovery times of most 479A diodes are too low (less than 200 ns) to measure with available techniques. Testing to the 500 ns test specification limit is performed by switching from a for-

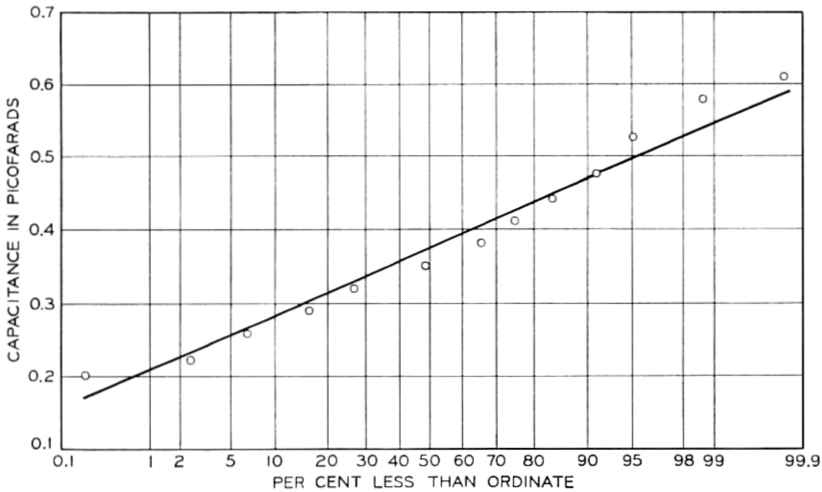


Fig. 33 — Distribution of capacitance for 479A diode.

ward bias of 10 mA to a reverse current of 10 mA while monitoring the waveform on a sampling oscilloscope. Figure 34 shows this waveform. The reverse peak is caused by the shunt capacitance; the ringing is associated with the lead inductance (approximately 2 nH) and the shunt capacitance. The reverse recovery time associated with minority carrier injection is not detectable here; it is less than 200 picoseconds.

Figure 35 shows the forward current-voltage characteristic of the

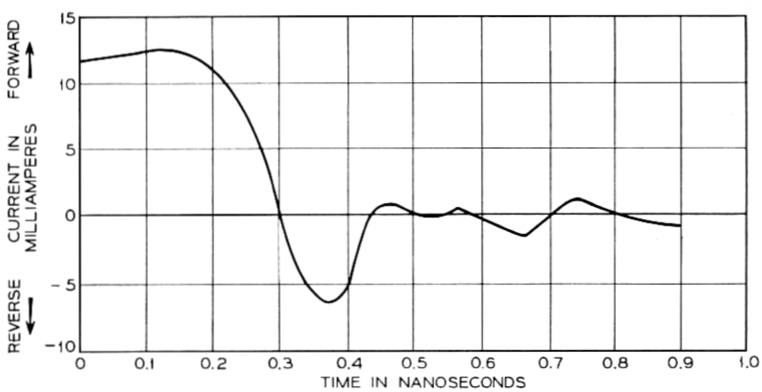


Fig. 34 — Reverse recovery characteristic of 479A diode.

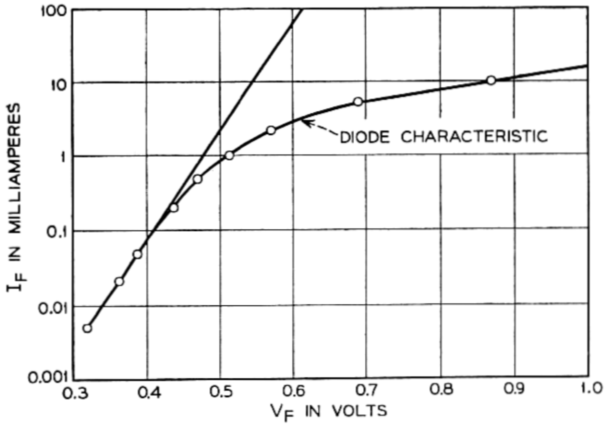


Fig. 35 — Forward characteristic of a typical 479A diode.

479A diode. At lower current levels, the characteristic fits the curve $I = I_o\ [\exp(qV/nkT) - 1]$. The number n varies from 1.01 to 1.30; the theoretical value[25] is 1.03. At higher current levels there is a deviation from the exponential relationship which is only partly explained by resistive drop in the expitaxial film. The problem of identifying the mechanisms affecting Schottky barrier current-voltage characteristics is complex and has been considered by many authors.[26–30] A quantitatively accurate model for the 479A diode has not been derived.

Reverse currents for the 479A and 479B are typically ~0.002 microamperes. Breakdown voltage is a function of the material and of the minimum curvature radius of the metal-semiconductor junction; it ranges typically from 15 to 25 volts.

5.5 *Aging and Reliability*

In order to test the basic susceptibility of the wafer to environmental influences, 29 diodes were aged in steam at 250 and 300°C on unencapsulated headers for 65 to 161 hours. Table X shows the results. No failures occurred at 250°C, and only three failed from environmental causes at 300°. In some cases, a high V_F reading occurred because of deterioration of the ohmic back contact; in every such case, rebonding brought the unit back within specifications.

Representative temperature aging data on encapsulated diodes is shown in Fig. 36. Four groups of 40 or more units were subjected to

TABLE X—AGING 479A AND 479B DIODES*

Temperature (°C)	Time (cumulative hours)	Number tested	Number failures	V_F	I_s	BV	Open	Short	Damaged in testing
250	120	29	0						
250	160	29	0						
300	65	29	4		1			1	2
300	161	25	3		1				2

* Steam, unencapsulated, complete overlap.

aging for fixed times at increasing temperatures from 150 to 450°C. The time intervals chosen were 2, 16, 168 and 1000 hours.

Failures at the lower temperatures most often resulted from breakdown voltage deterioration, while failures at higher temperatures were caused by high V_F, open circuits, or a combination of these with low BV. The median failure temperatures generally lie at or above the silicon-gold eutectic temperature. In many cases, diodes with low breakdown voltages tended to heal; that is, a diode would go below the BV specification on one temperature and then return to specification at a higher temperature. In all cases, however, regression curves were plotted using the criterion that, once a diode failed, it was con-

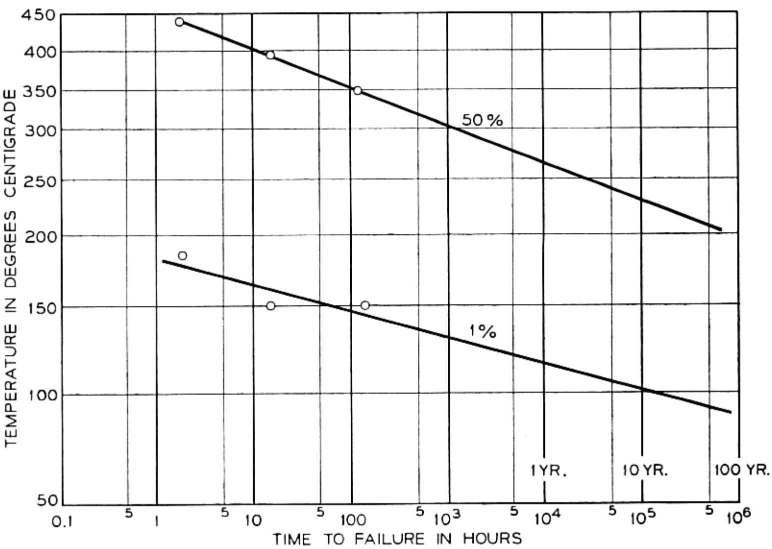


Fig. 36 — 479A aging curve, no in-process aging.

sidered defective for all subsequent measurements. Subsequent forward bias and high-temperature reverse bias aging revealed no bias-dependent modes of failure. The thermal impedance of the diode is about 1000°C per watt, and the maximum power to which the diode is subjected in use is 10 mW. This leads to a predicted failure rate of less than 10 failures per 10^9 device-hours for all TD-3 applications.

VI. HIGH-VOLTAGE RECTIFIER DIODES By I. C. Savadelis

Two new high voltage diode rectifier assemblies were required for the traveling wave tube power supply. High altitude operation imposed stringent voltage breakdown and corona requirements on these diode rectifiers. Multiple diodes were necessary to attain the high voltage requirements. Molding the multiple diodes in a single high dielectric constant plastic encapsulation assembly enhanced high altitude operation and simplified the mechanical mounting problem.

Type 426J one watt diodes were selected for the higher voltage diode requirements. Since these diodes were to be used in a voltage doubling circuit and in a full-wave bridge configuration, it was advantageous to mold four of them into a single package. The voltage doubling circuit required a breakdown voltage of 4800 volts in each leg. Therefore, two pairs of diodes were used in each leg with a third solder terminal between each leg. This allows the diode pairs to be used also in a full-wave bridge. The maximum forward voltage drop required across each pair of the 426J diodes was 7.5 volts at 300mA. The power rating of the assembly is 5.0 watts. This assembly was coded the 463A diode (multiple semiconductor type).

The molding concept was carried over to the other diode rectifier in the power supply. A bridge rectifier was needed with a minimum breakdown of 1200 volts between the terminals of each leg. Four 426G diodes molded into a four-terminal bridge configuration fulfilled this requirement. The power rating of the assembly is 5 watts and has a maximum forward voltage drop of 2.1 volts at 600mA. This assembly was coded 464A.

It was necessary that the molded assemblies mount easily and have a thermal impedance to the mounting surface lower than the individual lead mounted diodes. The molded assemblies are rectangular, with two mounting ears diagonally opposite each other. This gives a package that is approximately 2.75 inches long, 1.5 inches wide and 0.8 inch deep, as shown in Fig. 37.

The assemblies are fabricated using the diodes, a high dielectric

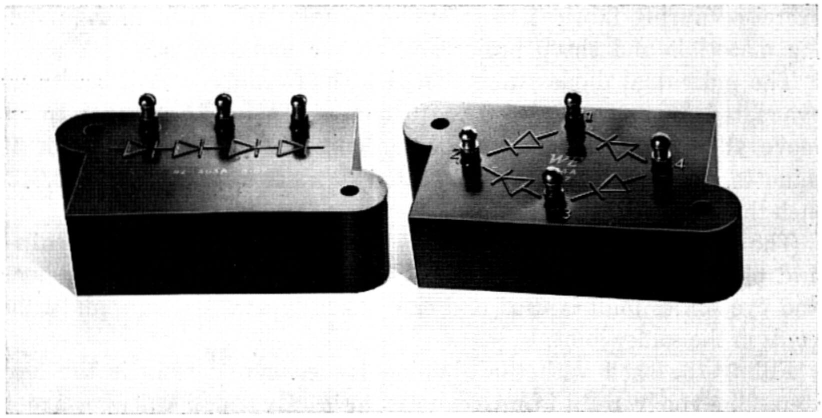


Fig. 37 — The 463A and 464A diodes.

constant silicone resin, an alumina filled epoxy, and a premolded silicone shell with terminals. Figure 38 shows the general assembly structure. The silicone resin serves as a high dielectric insulator across the glass seal area of the diode and mechanically decouples the diode from the epoxy resin. The epoxy supports the diode and wiring structure, and seals the diode from moisture. An alumina filling agent in the epoxy lowers the thermal impedance of the package, resulting in lower diode junction temperatures. The shell, although not required for the design of a molded assembly, was used to reduce fabrication cost. Because the 463A and 464A are high voltage diodes, care was

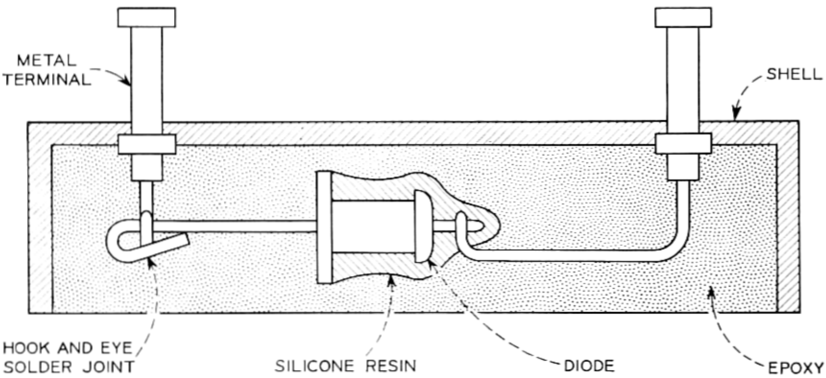


Fig. 38 — Cross section of 463A and 464A diode assembly.

exercised during fabrication to avoid pinholes and voids in the molding materials and sharp projections on the metal parts.

The individual diodes were coated with the silicone resin and were evacuated to a vacuum of 5 to 10 mm of Hg for 15 minutes to remove all air bubbles. The resin was cured in a 150°C oven for 15 minutes. The operation was repeated 3 times resulting in a 0.012-inch thick coating.

The coated diodes are then assembled into the desired circuitry and placed in the silicone shell. Where the diode leads join, a hook and eye solder joint is used and care taken to avoid sharp points and voids in the solder joint.

Filling the shell with the alumina loaded epoxy resin is the next step. The epoxy resin is mixed with the catalyst or hardening agent, thoroughly blended, and subjected to a vacuum of 5 to 10 mm of Hg to remove any gas. Then the epoxy resin is poured into the shell and the assembly degassed at 200 microns of Hg. The assembly is cured for 6 hours at 85°C, which is sufficient to harden the epoxy; and then at 150°C for 16 hours. Both curing steps are performed in an air atmosphere. This two-step cure is necessary to keep epoxy shrinkage to a minimum.

The completed assemblies are ac corona tested. For this test, all the terminals are connected and the corona is measured between the shorted terminals and a grounded plane adjacent to the assembly mounting surface. The observed corona voltage, for a charge transfer of 20 picocoulombs, is in excess of 6000 volts rms.

The standard 1 watt (426 type) diode used in fabricating the molded assemblies has a junction-to-ambient thermal impedance of approximately 50°C per watt. However, when molded into an assembly this thermal impedance is lowered to 32°C per watt. This improved heat conductance has allowed the molded assemblies to be conservatively rated at 5 watts.

Environmental tests were performed on the molded diode assemblies. These included temperature cycling from −65 to 125°C for five 90-minute cycles, thermal shock from 100 to 0°C, ten day moisture, accelerated moisture for 3 cycles and storage at 150°C for 1000 hours. The molded assemblies adequately met these tests, which are in excess of the environmental conditions encountered in TD-3 operation. Based on aging data of the 426G and 426J diodes, the reliability estimate of the 463A and 464A diodes for the TD-3 operating conditions is better than 100 failures per 10^9 device-hours of operation.

VII. PIN DIODE By R. J. McClure

An ultraflat IF amplifier using a variolosser stage is required for the TD-3 system.[1] In the variolosser stage a diode whose impedance is a pure resistance independent of frequency is needed. The diode must be capable of carrying a peak signal current of 3 ma (for 5 dB loss) without affecting the diode resistance. Any nonlinear resistance will generate harmonics. Available diodes exhibited too much frequency dependence of the forward impedance, so development of the 474A pin diode (p type-intrinsic-n) was required.

The pin diode is a semiconductor device which exhibits a resistance that varies with the forward bias current. The resistance under forward bias is roughly inversely proportional to the bias current (see Fig. 39). The resistance is nearly independent of frequency and can be controlled by very low currents.

To achieve 5 dB loss at the 3 ma peak current, the diode resistance must be 126 Ω. From Fig. 39 the dc bias must be 0.35 mAdc. The ratio of the peak ac to the required dc is 8.57. Even at this high ratio, the ac does not appreciably change the resistance of the pin diode.

The 474A pin diode is a diffused silicon, mesa-etched device mounted in a TO-18 package. The resistance of the i-layer cannot follow the instantaneous variations in the IF signal because of the

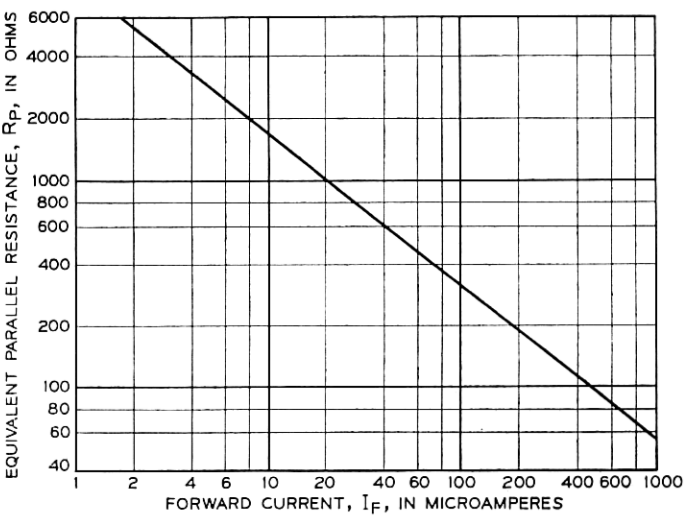


Fig. 39 — Typical resistance vs forward current characteristic for the 474A pin diode.

long transit time of the i-layer and the lifetime achieved after processing. At frequencies above which the junction impedance (which is frequency dependent) is small compared to the i-layer impedance, the pin diode acts as a linear resistor whose value is controlled by the direct current.

Design of the 474A has been optimized to achieve small frequency dependence of the total diode impedance above 5 MHz. Figure 40 shows a comparison of the normalized insertion loss versus frequency for the 474A diode and for the 1N100 germanium point contact diode which had been used before the pin diode was developed. The 474A diode with its superior frequency response provides improved transmission characteristics for the IF amplifier.

The equivalent circuit for the 474A diode is shown in Fig. 41. The circuit consists of the impedance of the p-i and n-i junctions, the impedance of the i-layer, and stray reactances associated with the package and the diode wafer itself. Stray reactances and the junction impedances should be as small as possible in order to minimize the frequency dependence of the IF amplifier transmission as the loss is varied.

The frequency dependence of the total diode impedance stems from the junction impedance Z_j, which varies inversely as $I_o(\omega\tau)^{\frac{1}{2}}$, where I_o is the diode dc, ω is the angular frequency, and τ is the lifetime in the i-layer. For small frequency dependence of the total diode impedance, the frequency dependent Z_j should be small compared with the i-layer impedance. Clearly, for a given I_o and ω, Z_j will be as small as possible if the lifetime in the i-layer is as high as possible. The lifetime in the i-layer is 1 to 2 microseconds after processing is completed.

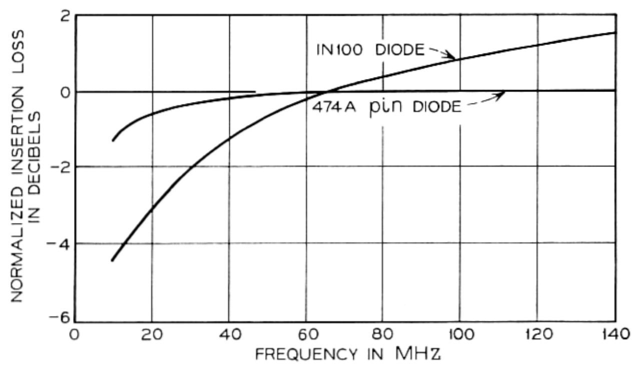


Fig. 40 — Frequency response of a commonly used diode compared with that of a specially designed pin diode.

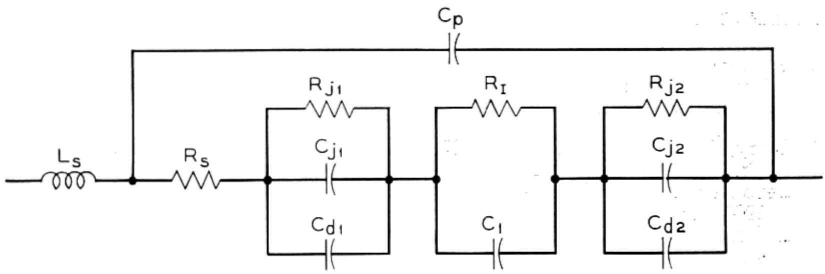


Fig. 41 — Equivalent circuit of a pin diode. L_S = series inductance, C_P = package capacitance, R_I = I layer resistance, C_I = I layer capacitance, C_{J1} & C_{J2} = two junction capacitances, R_{J1} & R_{J2} = two junction resistances, C_{d1} & C_{d2} = two diffusion capacitances, and R_S = diode series resistance.

The other alternatives available to minimize Z_j are to increase I_o and to decrease the junction diffusion voltages. The diode current may be increased while keeping the total impedance constant by making the i-layer width close to $2L_o$ (L_o is the dc diffusion length for current carriers in the i-layer). The decrease in junction impedance is compensated for by an increase in i-layer resistance. The i-layer width cannot be increased much beyond $2L_o$ without losing conductivity modulation and thus impairing the diode variolosser action.

As a result of these considerations, the i-layer width is designed for 4.0 mils for the 474A diode. The junction diffusion voltages are decreased by decreasing the junction doping gradients. The gradient at the p-i junction cannot be decreased too much since, below some value of the gradient, a depletion layer will cease to exist and injection at the junction will be lost. The optimum gradient for the p-i junction is achieved by a complementary error function boron diffusion to a depth of 0.4 mils. The n-i junction depth is about 1.2 mils.

Care is required in the fabrication of the 474A diode to obtain the required i-layer width of 4.0 mils. Phosphorus is first diffused into p-type silicon ($\rho > 5000$ Ω-cm) to the required junction depth. Then the back side of the slice is lapped to a final thickness such that, after a boron diffusion, the final i-layer thickness is 4.0 mils. After these two diffusion steps the i-layer resistivity has decreased from greater than 5000 Ω-cm to about 2000 Ω-cm. After the boron diffusion, aluminum contacts are evaporated and alloyed to the phosphorus side of the slice. Finally, 12 mil circular mesas are etched into the slice, and the slice is diamond-scribed into wafers. The wafers are packaged using conventional wafer and wire bonding techniques in gettered TO-18 cans.

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