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MULTI-WATT POWER GENERATION AT MILLIMETER-WAVE FREQUENCIES USING EPITAXIALLY-STACKED VARACTOR DIODES

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ABSTRACT

High power varactor diodes capable of generating watts of power at frequencies as high as 100 GHz are described. These devices show cutoff frequencies in excess of 900 GHz and breakdown voltages greater than 100V. Output powers (and associated efficiencies) of frequency doublers built with these devices are 9W at 22 GHz (60%), 5.5W at 35 GHz (60%), 5W at 44 GHz (50%) and 280 mW at 88 GHz (14%). The last result is nearly 10 dB better than any previously reported multiplier power in that frequency range, but is preliminary in the sense that it is new data with an as yet non-optimal circuit. Thermal response simulations reported here show low operating junction temperatures for these devices.

INTRODUCTION

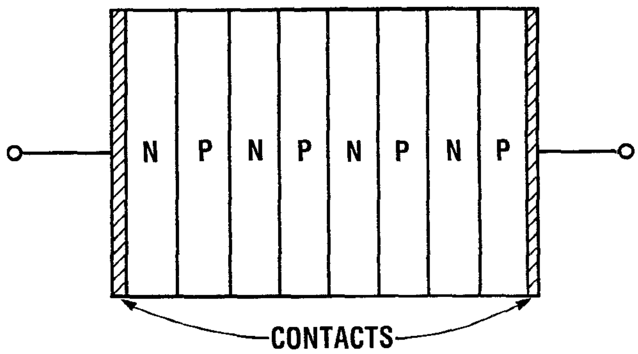
Historically, varactor diodes have provided the thrust of solid-state technology for power generation in transmitter applications for the microwave range. They still dominate the field in terms of continuing applications, having proven to be economical and reliable. With the advent of the GaAs FET in the 1970s and early 1980s, new applications for microwave varactor power sources have declined. IMPATT diodes as alternatives have failed to achieve wide acceptance for communications applications, but have dominated the millimeter wave field by default. The new ISIS varactor described here offers an alternative for the mm-wave bands, providing equivalent power levels at substantially reduced operating temperature.

In this paper we discuss methods of achieving watts of power from frequency multipliers at frequencies up to at least 100 GHz using discrete, single crystal, multi-junction varactor diodes. Devices, circuits and results are described in the following. A significant operational feature of the device is that its high conversion efficiency allows low operating junction temperatures using standard plated-heatsink technology, suggesting applications where reliability at low fabrication costs is important.

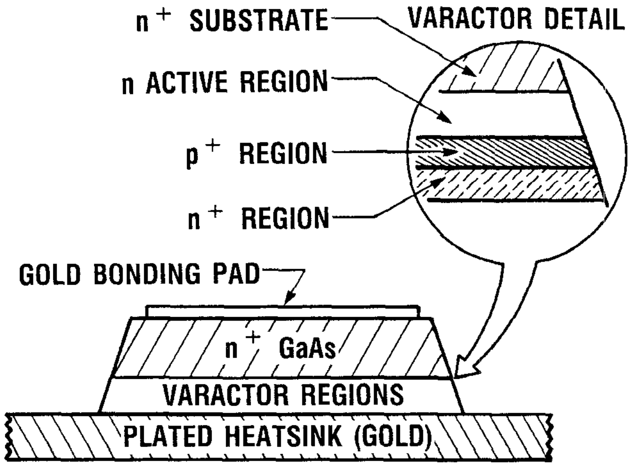
DIODE DESCRIPTION

The type of diode discussed here is based on a concept proposed in 1958 by A. Uhlir, Jr. [1] who directed early developments in high-quality diode capacitors while at Bell Laboratories. The diode is a "stacked" device grown by epitaxial techniques on a single crystal wafer containing two, three or more active varactor diodes in series. Uhlir's representation is reproduced in Figure 1a.

As controlled epitaxial growth techniques in semiconductors matured, device fabrication became possible. T.B. Ramachandran of M/A-COM initiated device development in the early



a)



b)

FIGURE 1. Representation of series (stacked) varactor structures. a) Uhlir's concept of multilayer device [1]. b) Present epitaxial implementation of mm-wave diode showing plated heatsink and junction detail of varactor region nearest to substrate.

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1980s. He suggested the acronym ISIS (Integrated Series IMPATT Structure) since first device attempts were directed at fabricating a high voltage IMPATT structure. The acronym persists even though the varactor has proven to be the device most easily realized in practice.

A sketch shown in Figure 1b illustrates a three-stack ISIS varactor diode chip in cross-section. It is a "flip chip" design and uses standard plated heat sink wafer processing technology to provide a low loss thermal path to the diode mount. The technique yields a chip which has a total thickness of approximately .001" with the substrate almost entirely removed. The result is a parasitic series resistance small compared to the conventional mesa diode fabrication technique and a device with useful operation to output frequencies of 100 GHz.

Theoretical description of varactor multiplier performance as originally presented by Penfield and Rafuse [2] applies; when compared with a single-layer conventional varactor with the same doping profile and the same capacitance, an N-stack ISIS will have N^2 times the power-handling capability of the single layer device. This is easy to see from the expression for (input) junction power to a single-junction device [2]:

$$P_{in} = \beta (V_B + \phi)^2 \omega_0 C_{min}$$

where V_B and ϕ are the breakdown voltage and contact potential of the device, ω_0 is the input radian frequency, and C_{min} is the minimum junction capacitance. β is a multiplicative constant depending on the doping profile in the active region and upon the drive level. In stacking N junctions so that the total capacitance C_{min} of the structure does not change, the power increases by N^2.

Figure 2 shows a C-V plot of a three-stack packaged device sized for use at Ka-band. This device has a breakdown voltage of 100V; cutoff frequency measured by the deLoach technique [3] is 1000 GHz at five volts reverse bias. This compares favorably with the highest quality figures of GaAs Schottky diodes developed for low power applications such as parametric amplifiers.

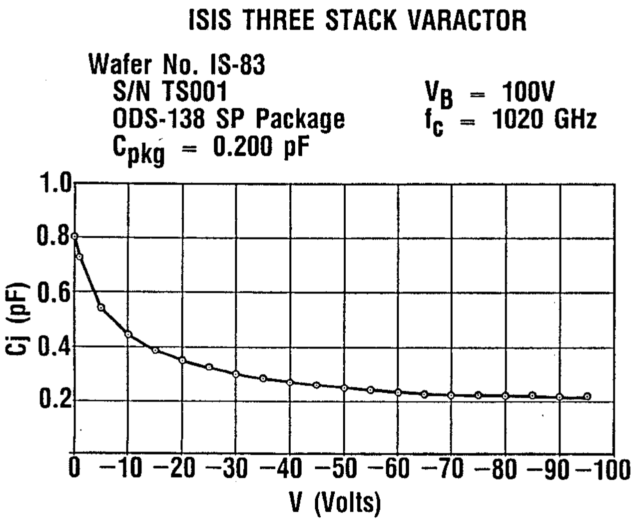

FIGURE 2. Typical C-V plot of three-stack packaged device. Breakdown voltage for this device is 100V and cutoff frequency is greater than 1000 GHz.

CIRCUIT DESCRIPTION

Two-diode circuits used to achieve the results described below use mounting techniques which achieve frequency separation by symmetry. The circuit shown in Figure 3, used for a 22-44 GHz multiplier, excites the diode pair in waveguide in series as viewed from the source, but takes the second harmonic from the midpoint of the structure using stripline, thus rejecting the fundamental component. The stripline extends into the output waveguide, where it acts as an antenna.

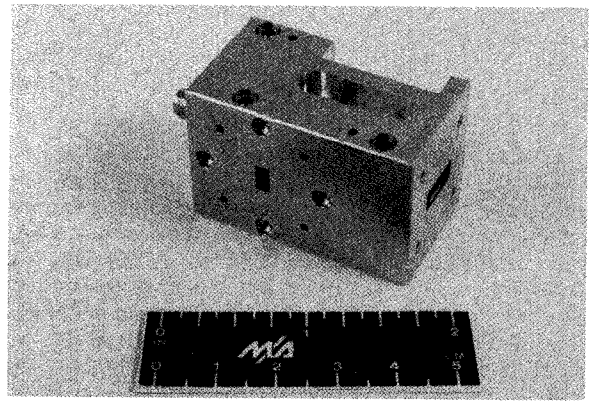

FIGURE 3. Two-diode (balanced) circuit used for 22-44 GHz multiplier.

The single-diode circuit of Figure 4 has its output in waveguide, which is below cutoff at the input frequency. A radial choke in the input coax section provides output to input isolation.

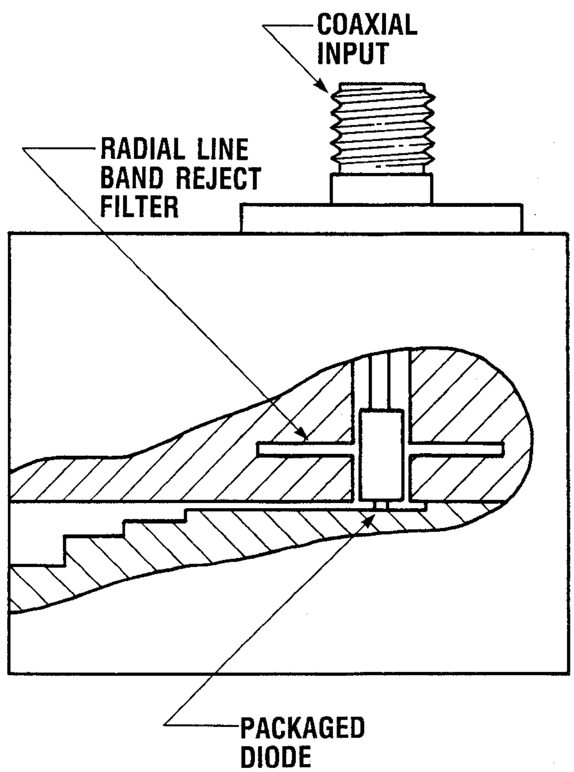

FIGURE 4. Single diode circuit. A band-reject filter in the input circuit provides output-to-input isolation.

CIRCUIT RESULTS

Shown in Figure 5 as solid and broken lines is solid-state CW power capability of IMPATTs and FETs as a function of frequency [4]. Single-device-equivalent power numbers for ISIS diode frequency doublers are shown on this figure as obtained from the circuit results summarized in the following table:

Output Frequency (GHz)	P_{out} (CW) (Watts)	Multiplier Circuit Description	Efficiency
22	7.3	Single-diode X2	50%
35	5.5	Single-diode X2	60%
44	5	Two-diode X2	50%
88	0.28	Two-diode X2	14%

The last result was achieved in a non-optimized circuit, but represents nearly a 10 dB increase in power over previously reported two-diode results in this frequency range [5] (also shown in Figure 5). This doubler circuit should be capable of over 1W output with at least 30% conversion efficiency [6]. Figure 6 shows output characteristics of the 35 GHz doubler. This unit shows a 1dB bandwidth of 6%.

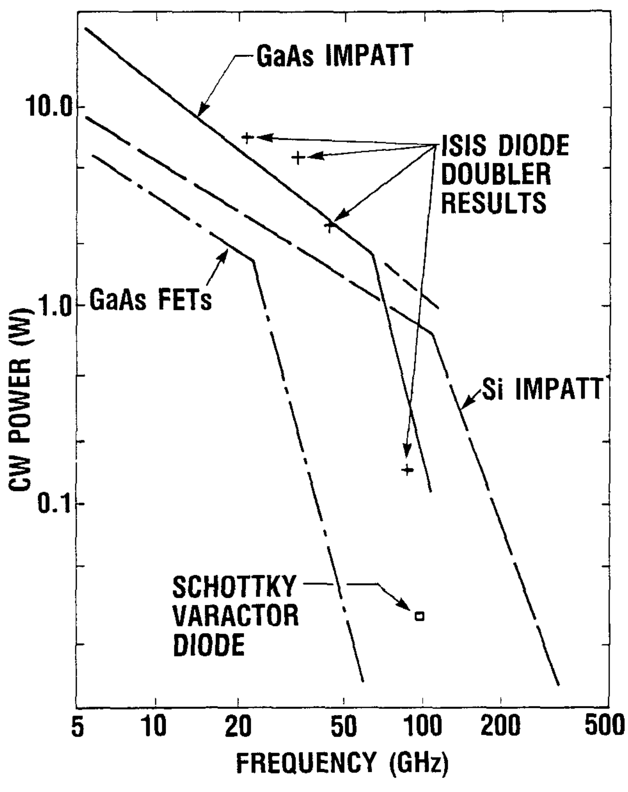

FIGURE 5. CW power output achieved by single device IMPATTs [4], FETs [4] and ISIS varactor diodes as a function of frequency. The Schottky varactor data is for a balanced (two-diode) configuration [5].

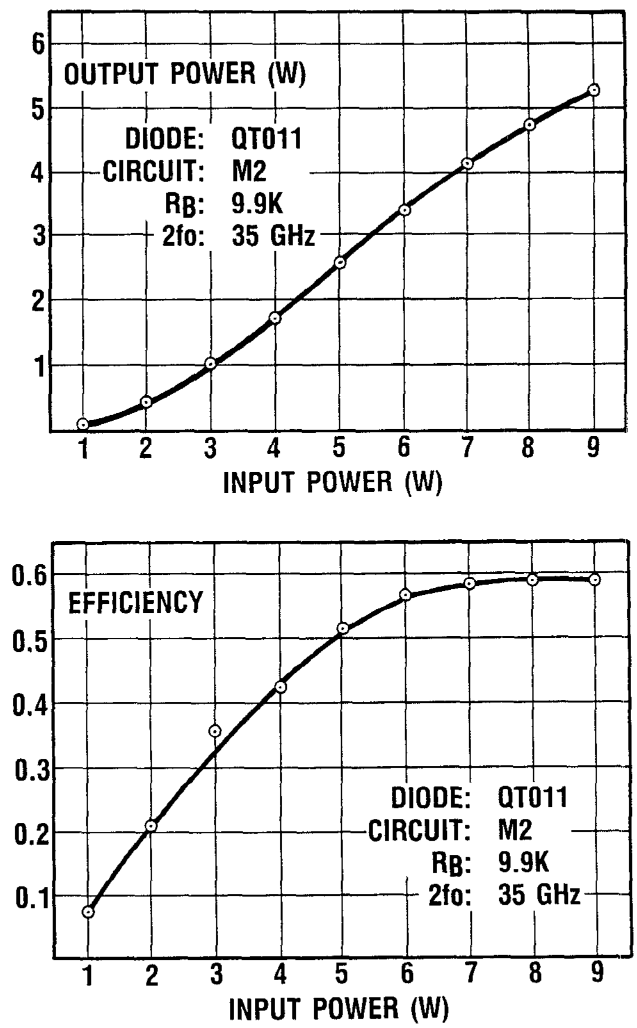

FIGURE 6. CW output power and conversion efficiency of a single (three-stack) diode 17.5-35 GHz doubler. One dB bandwidth of this unit is 6%. A fixed resistor in the varactor dc return path provides (self) bias.

THERMAL PERFORMANCE

Figure 7 shows thermal performance simulations [6] for a three-stack ISIS diode designed for operation at 35 GHz. The model shows three heat-generation "nodes" corresponding to the varactor junctions. The steady state temperature is calculated for a total dissipated power of 1W distributed equally among the three junctions, and is shown for the warmest (node 2) and coldest (node 4) junction as a function of diameter in Figure 7.

The coldest junction curve also represents the thermal resistance of a single junction device which would be the same as an IMPATT diode using the same heat sink technology.

The curves of Figure 7 indicate that the hottest part of an ISIS diode is roughly two times as hot as such an IMPATT (same heat sink, diameter) on a per-dissipated-watt basis. Power dissipation, P_{diss}, is related to output power, P_{out}, and conversion efficiency, η by:

$$P_{diss} = P_{out} (1 - \eta)/\eta$$

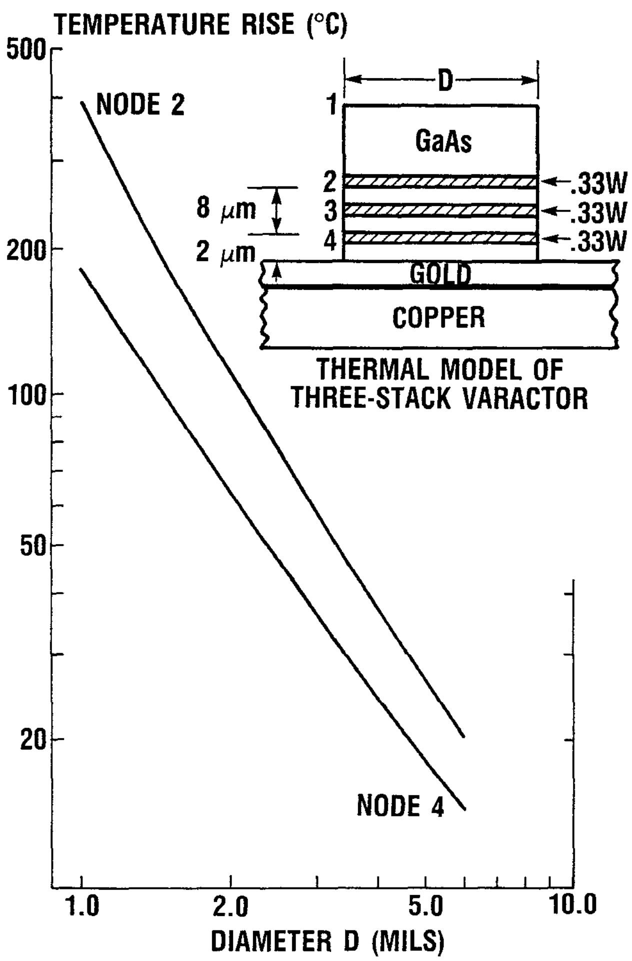

FIGURE 7. Geometry used to simulate thermal characteristics of three-stack 17.5-35 GHz doubler, and thermal response of warmest and coldest active junction as a function of diameter. One watt total power is assumed equally distributed among 3 junctions.

To generate the same output power, then, the varactor, with 60% conversion efficiency has one-sixth the dissipated power of an IMPATT with (an assumed) 20% conversion efficiency. The associated thermal rise of this varactor is one-third that of the IMPATT, on a per-generated-watt basis.

CONCLUSION

Device results of series-stacked epitaxial varactor diodes show power and efficiencies as frequency multipliers at millimeter wave frequencies that suggest use as system building blocks where reliability and prime power are important.

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