A W-BAND MONOLITHIC GaAs PIN DIODE SWITCH*

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ABSTRACT

A state-of-the-art performance has been achieved for a W-band monolithic single-pole-single-throw PIN diode switch. An insertion loss of less than 0.5 dB with return loss greater than 15 dB (transmission mode) and an isolation greater than 11 dB (isolation mode) have been measured over a 6 GHz bandwidth (80 to 86 GHz).

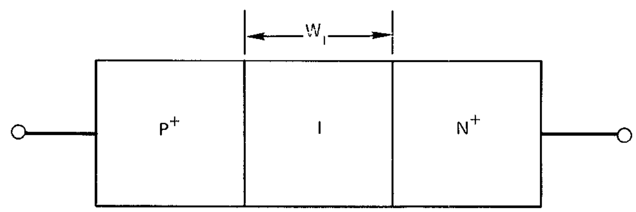
INTRODUCTION

The recent advances in solid state millimeter-wave devices, power combining technique(1), and high power thermionic sources have helped millimeter-wave systems gain wider acceptance and applications. The millimeter-wave radar systems offer certain favorable characteristics that are lacking in their counterparts - the microwave systems. The advantages of millimeter-wave systems are: high spatial resolution; large bandwidth; superior atmospheric penetration of fog, smoke, and dust; physically small size and lightweight. These and other unique propagation characteristics have led millimeter-wave systems for use in specific applications, such as missile and smart munition guidance and other radar applications.(2) Currently, all the existing millimeter-wave systems have been integrated using hybrid circuits. These can be very costly and time consuming when a large quantity is involved, as in the case of weapon guidance sensors.

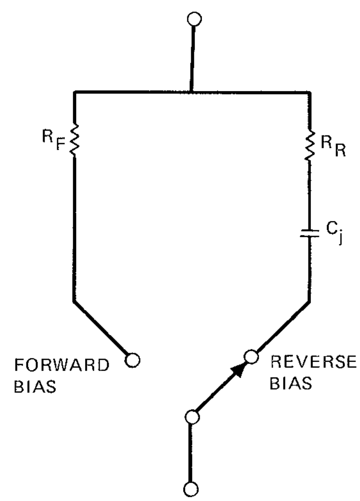
The key to reducing component cost is through large volume production.(3) The future of millimeter-wave systems relies heavily on increasing usage of monolithic integrated circuits for their implementation.(4-6) The monolithic circuits are small, light weight, low parasitic reactances; in addition, they offer the potential of cost reduction through batch processing. A broadband monolithic PIN diode switch, using 4 mils thick GaAs substrate, has been designed, successfully fabricated and tested at W-band. The design, fabrication process, and state-of-the-art performance of this PIN diode switch will be presented in this paper.

SWITCH DESIGN

The PIN diodes are commonly used for microwave/millimeter-wave switching applications because of their ability to absorb many watts of RF power without damage and with little change in impedance. For



(a)



(b)

Figure 1 (a) Basic pin diode configuration. The "I" layer is sandwiched between the heavily doped P^+ and N^+ ohmic contact layers, (b) simplified equivalent circuit model of a PIN diode for two different bias conditions.

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switch design purposes, the basic PIN diode structure and the simplified equivalent circuit under different bias conditions are shown in Figure 1. The intrinsic resistance of the PIN diode under forward bias state can be calculated using Equation 1.[7]

$$R_I = \frac{4KT}{qI_F} \sinh \frac{W_i}{2L_o} \left[\tan^{-1}\left(\exp \frac{W_i}{2L_o}\right) - \frac{\pi}{4}\right] \qquad (1)$$

where

- W_i = thickness of the intrinsic region
- k = Boltzmann's constant
- T = diode temperature
- q = electron charge
- I_F = forward bias dc current
- L_o = $\sqrt{D_o \tau_o}$, ambipolar diffusion length
- D_o = $(2D_n)/1 + \mu_n/\mu_p$), ambipolar diffusion constant
- μ_n, μ_p = mobility of electrons and holes
- τ = effective carrier lifetime in the "I" region

For $W_i \leq 2L_o$, which is typical for millimeter-wave PIN diodes, the above expression for forward bias "I" layer resistance may be simplified to

$$R_I \approx \frac{W_i^2}{4\left[(\mu_n \mu_p)/(\mu_n + \mu_p)\right]} \quad \frac{1}{I_F \tau} \qquad (2)$$

The total resistance of the diode consists of the intrinsic layer resistance, R_I, in series with an ohmic contact resistance, Rc. Rc is inversely proportional to the area of the ohmic contacts and is often the dominating factor in millimeter-wave frequency range.

The PIN diode presents a constant junction depletion capacitance to an RF signal at reverse bias. This capacitance is given by

$$C = \varepsilon (A/W_i) \qquad (3)$$

where

- A = area of the PN junction
- W_i = width of the intrinsic region
- ε = dielectric constant of the depletion layer material

The switch operation is based upon difference in impedances between the forward bias and the reverse bias states. By operating the switch in a reflective mode, a small PIN diode can be used to control relatively large amounts of power.

The GaAs monolithics PIN diode switch circuit is shown in Figure 2. This SPST switch utilizes four PIN diodes to perform the switching function. The diodes are in shunt with the transmission line, with a quarter-wavelength spacing between two pairs of diodes for maximum isolation. For diodes in shunt-mounted configuration, minimum loss is obtained for the reverse bias condition and the maximum isolation for the forward bias condition. The theoretical diode series resistance, including ohmic contacts, is calculated to be approximately 2.07 ohms when forward biased with a current level of 10 mA. The overall dimensions of this monolithic SPST switch circuit chip are 24.5 mm x 1.43 mm.

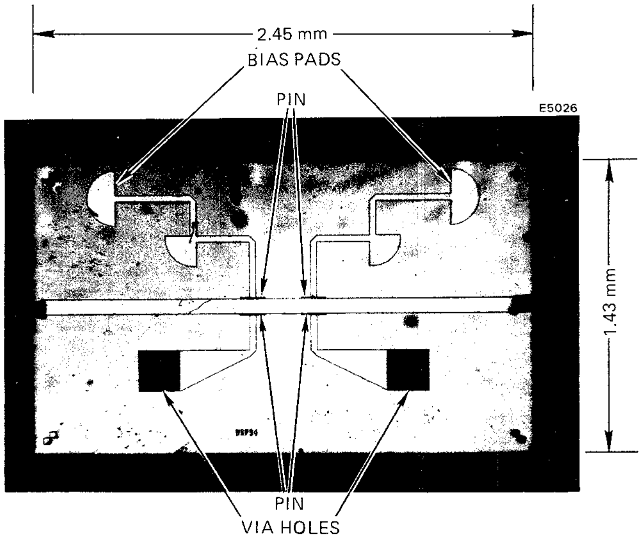


Figure 2 W-band monolithic PIN diode switch circuit fabricated on 4 mils thick GaAs substrate. The diodes are mounted in anti-parallel configuration, with quarter wavelength between two pairs of diodes.

PIN SWITCH CIRCUIT FABRICATION PROCESS

The monolithic PIN switch devices were fabricated on undoped semi-insulating LEC substrates. Processing sequence can be described in steps as shown in Figure 3. The n+ and p+ regions were formed by selective ion implantation of silicon and beryllium. The n+ and p+ regions are in the form of a narrow strip measured 125 µm by 2 µm. The implants were simultaneously activated using rapid thermal annealing. After annealing, p+ ohmic contacts were formed using Pt-Ti-Pt-Au metallization and photolithographic lift-off technique. This was followed by using standard alloyed eutective AuGe metallization for the n+ ohmic contacts. Transmission line patterns were then accurately aligned to the p+ and n+ contacts thus formed, and overlay metals were metallized and lifted off using Ti-Au, with Au being 1 µm thick to reduce contact resistance. The contact metal pads on the front side were gold plated to 3 µm thick to provide for rigid mechanical contact to through substrate via hole ground plane metallization (Figure 4) on the back side of substrate. The via holes were formed by chemical etching after the substrate was polished/etched to 0.1 mm final thickness.

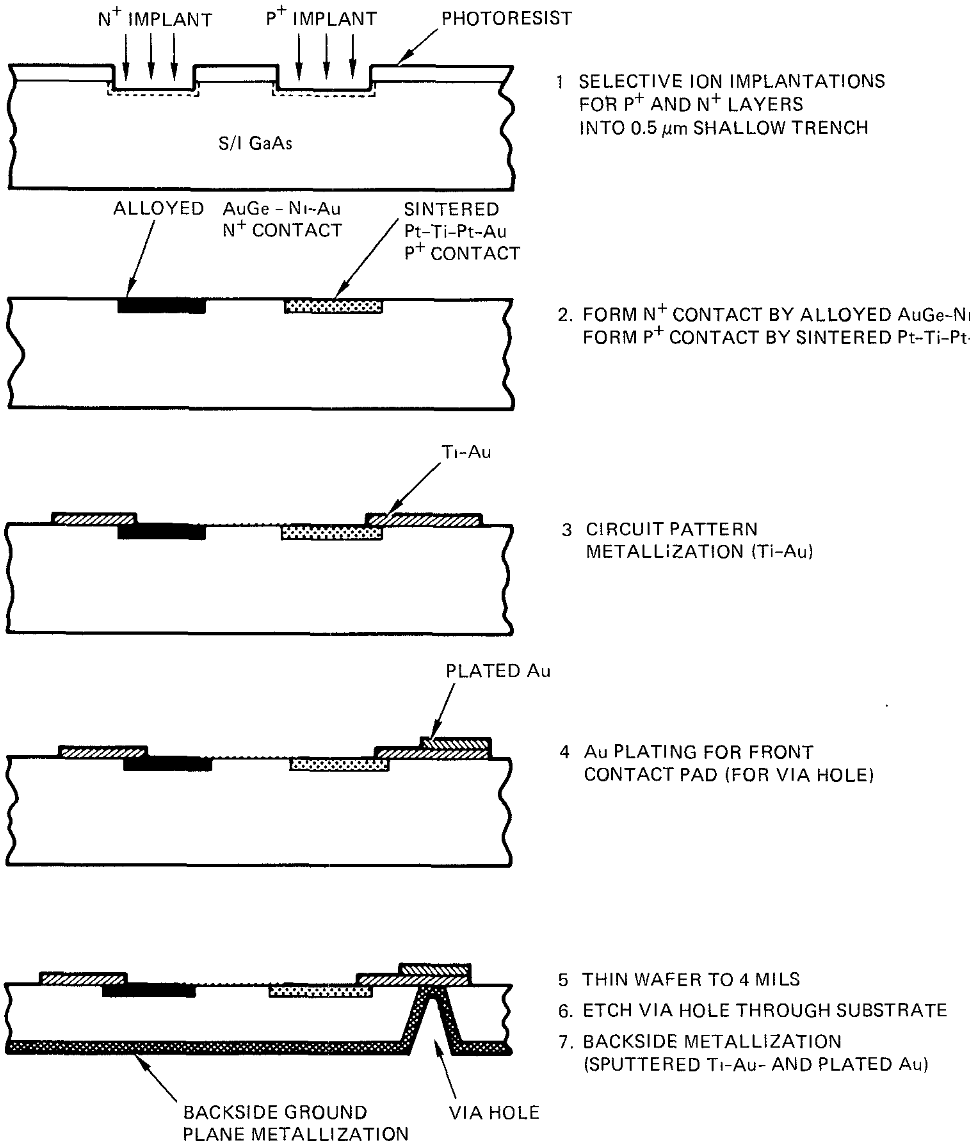


Figure 3 Schematic diagram for MMIC PIN switch processing.

EXPERIMENTAL TEST RESULTS

Broadband waveguide-to-coax-to-microstrip transitions have been developed for evaluating the electrical performance of this monolithic PIN diode switch. With a straight 50 ohm microstrip transmission line chip (same size as the switch circuit) mounted on the test fixture, the insertion loss and the return loss are measured to be approximately 2 dB and 10 dB, respectively, across 19 GHz bandwidth (Figure 5).

A state-of-the-art performance has been achieved for the broadband monolithic PIN diode switch circuit. The insertion loss and reurn loss for switch-on and switch-off conditions are shown in Figure 6. At the switch-on state (transmission mode), an insertion loss of less than 0.5 dB and return loss greater than 15 dB have been measured from 80 to 86 GHz. Over a broader frequency band (80 to 93 GHz), the average insertion loss is approximately 1 dB. The 2 dB test fixture loss was substrated from the above insertion loss data. Maximum insertion loss for the switch-off state (isolation mode) is obtained when the diodes are forward biased with a total current level 23 mA. No additional isolation improvement was observed for a current level of greater than 23 mA. A minimum on/off ratio of 11 dB was measured from 86 to 92 GHz. Figure 7 shows the PIN switch mounted in the test fixture.

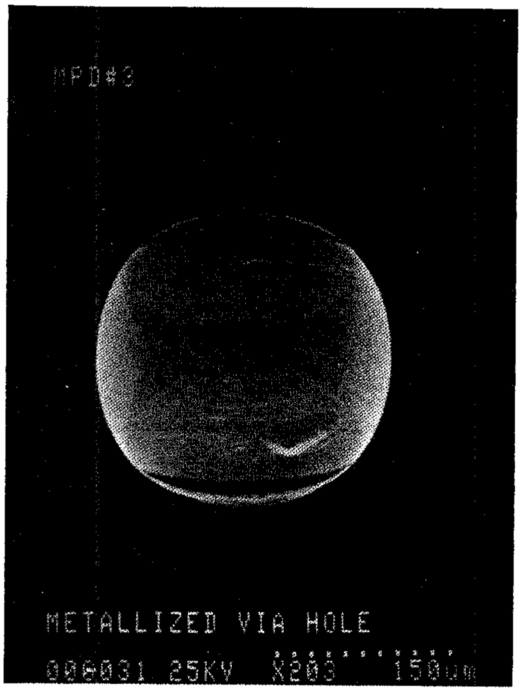


Figure 4 SEM micrograph showing metallized through substrate via hole.

CONCLUSIONS

Utilizing advanced semiconductor processing techniques, excellent test results have been obtained for the GaAs monolithic PIN diode switch circuit. A maximum insertion loss of 0.5 dB and return loss greater than 15 dB have been measured for this monolithic PIN switch over a 6 GHz bandwidth. Currently, the evaluation is in progress to determine the switching speed of this monolithic PIN switch. Additional circuit optimizations are under way to further improve the electrical performance of this switch circuit.

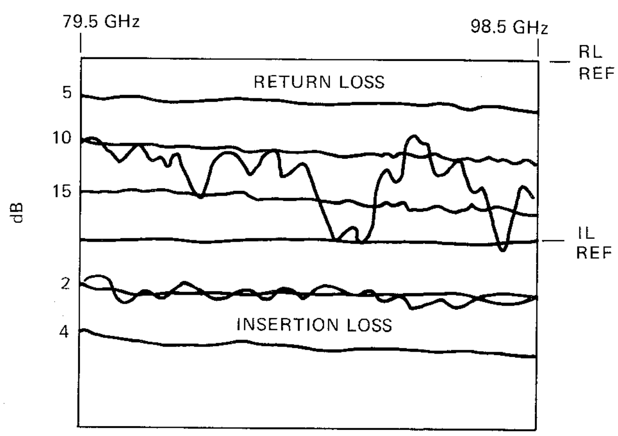
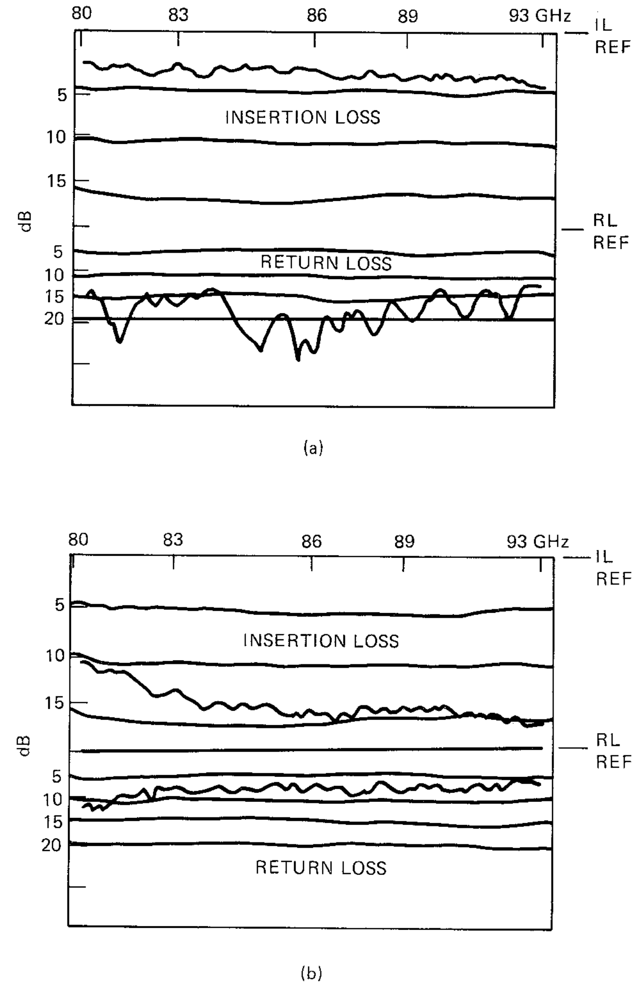


Figure 5 RF performance of the waveguide/coax/50 ohm GaAs microstrip/coax/waveguide transition.



(a) SWITCH-ON STATE, REVERSE BIAS CONDITION V = 0V

(b) SWITCH-OFF STATE, FORWARD BIAS CONDITION

V = 3.06V I = 23 mA

Figure 6 Total insertion loss (including 2 dB test fixture loss) and return loss of a W-band monolithic PIN switch at two different bias states.

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Figure 7 W-band monolithic PIN switch circuit embedded in the test fixture.

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