AlGaAs PIN Diode Multi-Octave, mmW Switches

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***Abstract* — The novel use of an AlGaAs/GaAs heterojunction to form a PIN diode, with reduced RF resistance (R_S) and no change in junction capacitance (C_T)[1]-[3], has been analyzed and employed in the development of several different PIN diode switches of various circuit topologies. Series designs demonstrate improved insertion loss, shunt designs improved isolation, and series-shunt designs improvements in both parameters.**

These switches demonstrate superior broadband performance, with low insertion loss and high isolation from 50MHz to almost 80GHz, and series-shunt switches exhibit 50% increased input power capability over equivalent homojunction GaAs PIN diode switches.

***Index Terms:* — Heterojunction Devices, mmW Switches, Monolithic Switches, PIN Diode Switches**

I. INTRODUCTION

While the use of bandgap engineering has been widely applied to bipolar transistors fabricated in elemental silicon and group IV materials, i.e. SiGe, SiC, SiGeC, etc.; and III-V compounds, i.e. GaAs, AlGaAs, InGaAs, InGaP, InP, etc., the application of this technology to high frequency and microwave diode structures has largely been ignored. At present, the majority of two terminal devices, such as PINs, Gunns, varactors, IMPATTs and Schottky diodes, are manufactured from a single bandgap semiconductor material. Not until recently has there been any significant changes made to the design of the PIN diodes to enhance its RF performance. MA-COM Technology Solutions' patented development of the heterojunction AlGaAs/GaAs PIN diode is one of those rare improvements, the first reported application of a wide bandgap heterojunction used in place of a conventional p-n junction, contained in a PIN diode structure that only enhances the diode RF and microwave performance with no trade-off in any other characteristic.

Bandgap engineering principles, as presented in Fig. 1, were used to create a structure using two dissimilar semiconductor materials which have different Fermi levels to produce a device that has a wider bandgap in the P+ anode region as compared to the adjacent Intrinsic region (I region). This difference in bandgap enables a barrier height to be generated, which both enhances forward injection of holes from the P+ anode into the I-region and retards the back injection of electrons from the I-region into the P+ anode. This results in a P-I-N structure that has a significantly higher concentration of charge carriers reducing the RF resistance in the I-region of the heterojunction PIN device. The off state capacitance of the diode will remain unchanged since the thickness and resistivity of the I-region are unchanged. Measurements of fabricated diodes demonstrated a 37% reduction of RF resistance in an appropriately formed AlGaAs/GaAs PIN diode vs. a GaAs PIN diode under forward bias. The RF capacitance of the same two diodes under reverse bias was

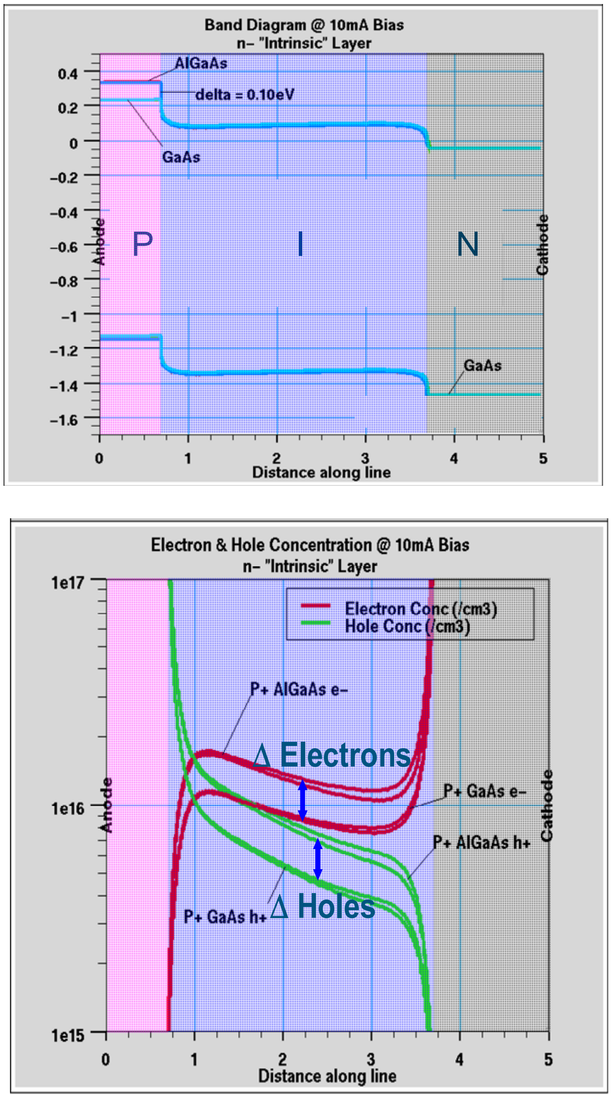

Fig. 1 Band Diagram for Heterojunction PIN Diode & "I" Region Charge Confinement

identical, as expected. These measured results for a series configured discrete PIN diode are shown in Fig, 2.

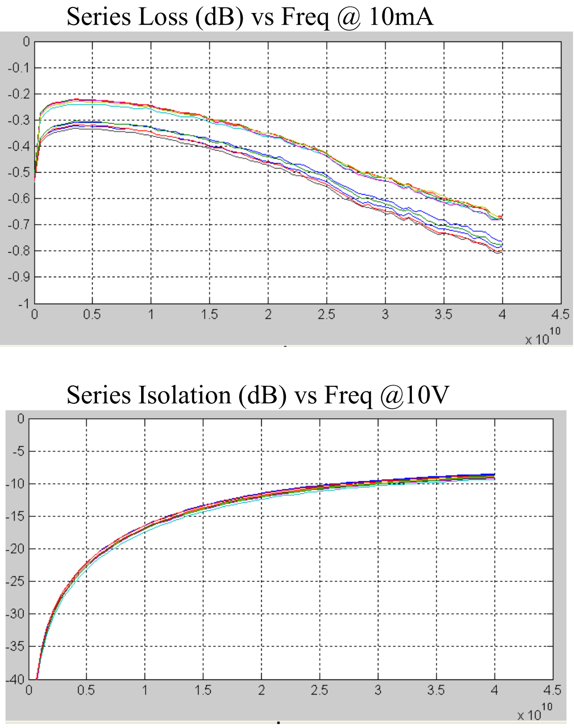

Fig. 2 Measured Insertion Loss & Isolation for Series Configured Heterojuction AlGaAs vs GaAs PIN Diode

Utilizing three dimensional EM software and a device structure simulator, ADS compatible models of AlGaAs heterojunction series and shunt configured PIN diodes were built up as shown in Fig. 3 and Fig. 4. In the development of these models special care had to be taken in consideration of the three dimensional nature of the PIN diode mesa structure and the associated airbridged interconnections.

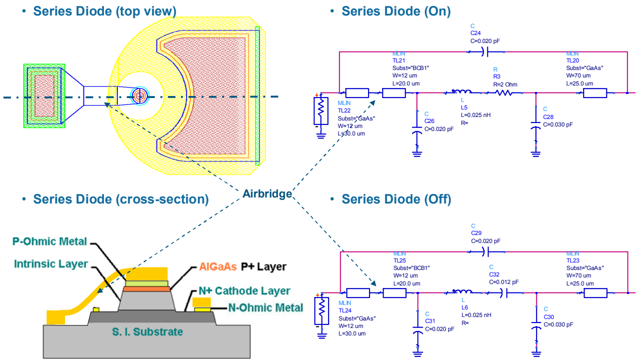

Fig. 3 Model of Series Configured Heterojunction PIN Diode

A number of multi-octave switches capable of operating well into mmW frequencies were designed utilizing shunt, series-shunt, and series switch configurations, encompassing a family of designs that included a SPST, SPDT, SP3T, SP4T, SP5T, and SP8T. This paper will discuss and contrast the design, high frequency performance aspects, and bandwidth tradeoffs of insertion loss, isolation, and return loss for these categories of switch designs.

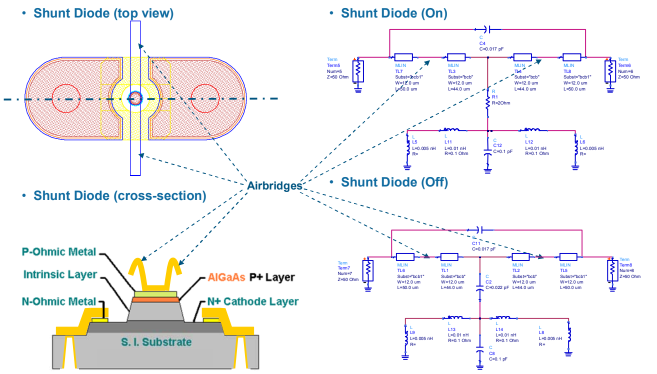

Fig. 4 Model of Shunt Configured Heterojunction PIN Diode

II. DISCUSSION

Single-pole-multi-throw switches may be designed in a number of topologies, all of which are some version of three main types: “series” where series elements (in this case diodes) are the gating devices in each arm of the switch, “shunt” where shunt diodes are the gating devices in each arm, and “series-shunt” with pairs of series and shunt diodes in each arm.

Textbook analysis of the simplified impedances presented by a PIN diode at microwave frequencies, resistance R_S under forward bias and capacitance C_T under reverse bias, leads to basic equations for insertion loss (IL) and isolation (ISO) of each topology of switch, as given below [4], with the assumption that R_S and C_T of both series and shunt diodes is identical. These are first-order approximations that do not include diode and interconnect parasitics, nor the effect of adding multiple arms to the switch. In practical designs, these secondary effects at the diode level are taken into account by utilizing the extracted models presented in Fig 3 and Fig. 4. In addition, advantage can be taken of the ¼ wave transformations in the case of shunt diode designs and impedance matching in all cases.

It will be immediately noticed in these equations that any reduction in R_S, without changes in C_T will reduce the insertion loss of a series switch, increase the isolation of a shunt switch, and improve both parameters of a series-shunt switch. The isolation of a series switch and insertion loss of a shunt switch would show no improvement or degradation.

Plots of typical insertion loss and isolation are shown in Fig. 5 and Fig. 6, respectively, based on equations (1) through (6), assuming representative values of R_S and C_T.

Table I displays the relative suitability of particular PIN diode switch configurations to optimize various switch parameters, including loss, VSWR and isolation[5]. These

$$\underline{\text{Series}}\quad IL = 20\cdot\log_{10}\left[1+\left(\frac{R_S}{2\cdot Z_0}\right)\right] \tag{1}$$

$$\underline{\text{Series}}\quad ISO = 10\cdot\log_{10}\left[1+\left(\frac{X_C}{2\cdot Z_0}\right)^2\right] \tag{2}$$

$$\underline{\text{Shunt}}\quad IL = 10\cdot\log_{10}\left[1+\left(\frac{Z_0}{2\cdot X_C}\right)^2\right] \tag{3}$$

$$\underline{\text{Shunt}}\quad ISO = 20\cdot\log_{10}\left[1+\left(\frac{Z_0}{2\cdot R_S}\right)\right] \tag{4}$$

$$\underline{\text{Series-Shunt}}\quad IL = 10\cdot\log_{10}\left[\left(1+\frac{R_S}{2\cdot Z_0}\right)^2+\left(\frac{Z_0+R_S}{2\cdot X_C}\right)^2\right] \tag{5}$$

$$\underline{\text{Series-Shunt}}\quad ISO = 10\cdot\log_{10}\left[\left(1+\frac{Z_0}{2\cdot R_S}\right)^2+\left(\frac{X_C}{2\cdot Z_0}\right)^2\cdot\left(1+\frac{Z_0}{R_S}\right)^2\right] \tag{6}$$

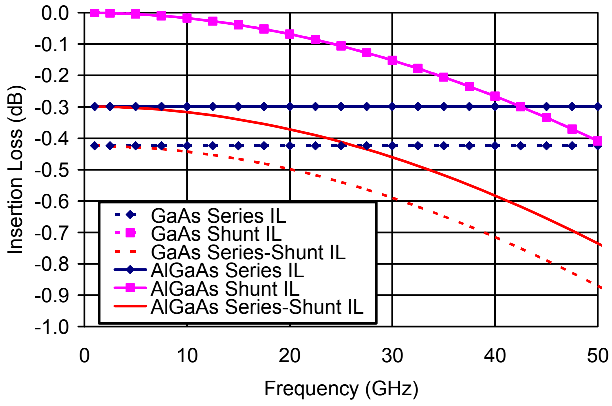

Fig. 5. Insertion loss of various PIN switch configurations.

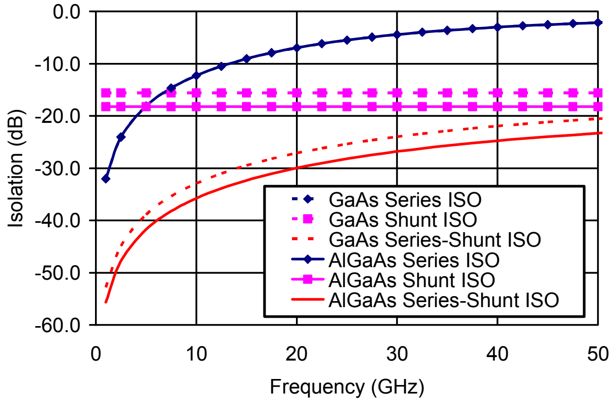

Fig. 6. Isolation of various PIN switch configurations

rules of thumb may be used as a starting point when considering design of a PIN diode switch, but careful analysis of the selected topology must be made using EM and circuit design tools and models such as HFSS, Momentum and ADS.

TABLE I

RELATIVE SUITABILITY OF PIN SWITCH CONFIGURATIONS

	Switch Design Configuration		
Parameter	**Series Diodes**	**Shunt Diodes**	**Series-Shunt Diodes**
Insertion Loss	Best @ hi freq	Best @ lo freq	Moderate
VSWR	Moderate	Worst	Best
Isolation	Worst	Moderate	Best

III. RESULTS

An SPST switch was designed with two shunt diodes, having, as shown in Fig. 7, zero-electrical length transmission lines and spacings between the diodes, and a minimal overall dimension from input to output. These features combine to provide extremely high performance from 50 MHz through at least 70 GHz – at 50 GHz insertion

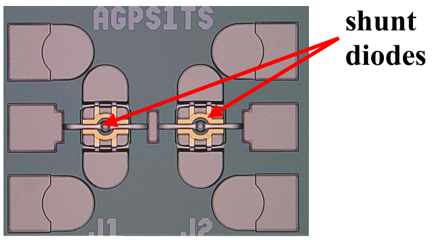

Fig. 7 SPST switch utilizing 2 shunt diodes

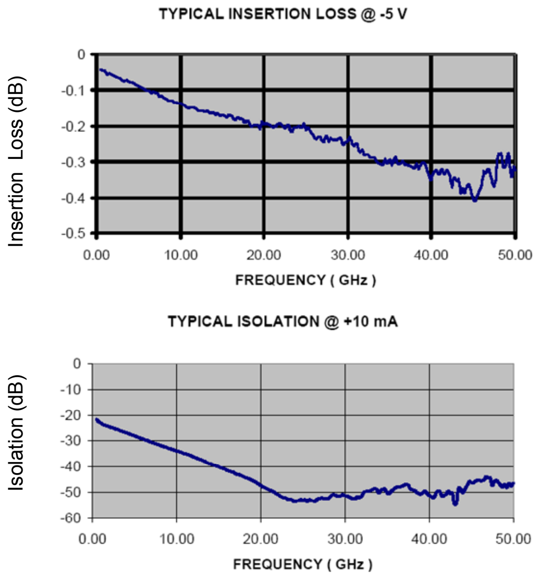

Fig. 8. Broadband performance of the SPST shunt switch

loss is 0.35dB and isolation is 46 dB, with only -5 V and +1 0mA bias, respectively (Fig. 8).

A photomicrograph of a SP2T series-shunt is shown in Fig. 9. Isolation and insertion loss characteristics of this series-shunt SP2T are plotted in Fig. 10. It can be seen that the insertion loss is less than 0.7 dB at 50 GHz and less than 2.0 dB almost to 80 GHz (data courtesy of Agilent Technologies). This excellent insertion loss performance is accomplished while achieving over 35 dB of isolation at 50 GHz.

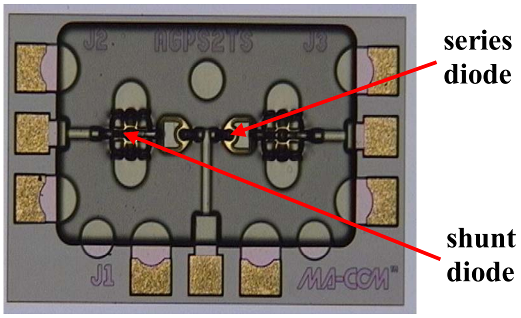

Fig. 9. An SP2T switch utilizing series-shunt configured diodes

A single-pole-eight-throw series only switch, shown in Fig. 11, was designed with all series diodes. Internally the switch is actually a combination of one SP2T and two SP4T switches. This design optimizes broadband relatively flat insertion loss of the series switch design, while improving isolation by chaining 3 diodes together in each arm of the switch. At 40 GHz, typical 3-diode insertion loss is <2.0 dB and isolation is >30 dB. Broadband performance is shown in Fig. 12.

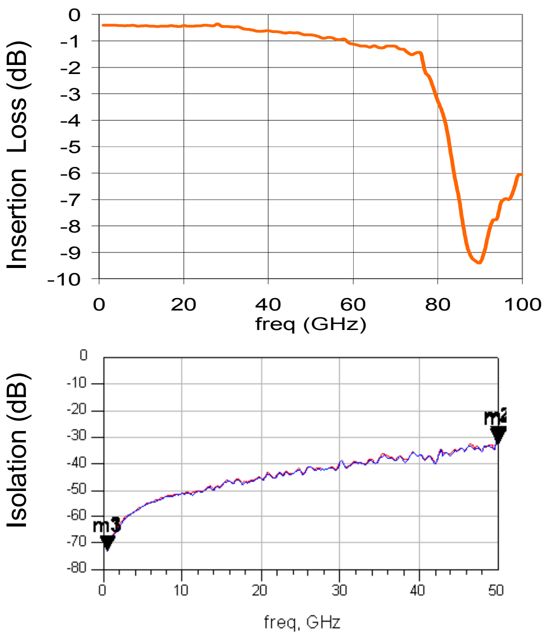

Fig. 10 Broadband performance of the SP2T series-shunt switch

In the MA-COM Technology Solutions’ AlGaAs/GaAs PIN process, both series and shunt diodes are formed on a semi-insulating GaAs substrate, as shown in Fig. 3 and

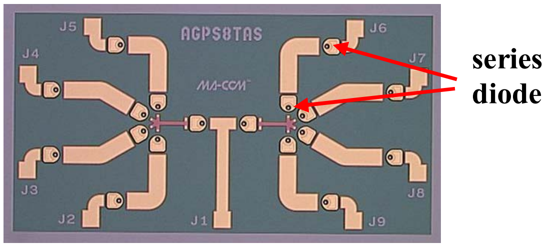

Fig. 11. An SP8T switch utilizing only series diodes

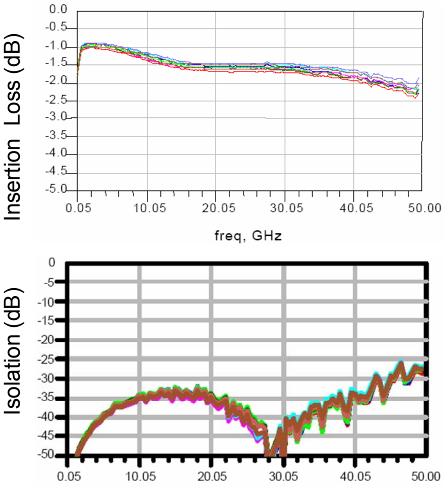

Fig. 12. Broadband performance of the SP8T switch

Fig, 4. Since the back-side of the device is a full-area metal ground-plane, it can be mounted to thermal as well as electrical ground.

$$\frac{Pdiss(W)}{Pin(W)} = \left(1 - 10^{-\frac{IL(dB)}{10}}\right) \qquad (7)$$

In series and series-shunt switches, power handling is limited by the high frequency series resistance of series element biased in the on-state. Since the AlGaAs/GaAs construction reduces the on-state resistance of the series diodes, in addition to reduced insertion loss the dissipated power Pdiss (relative to input power Pin) is also reduced.

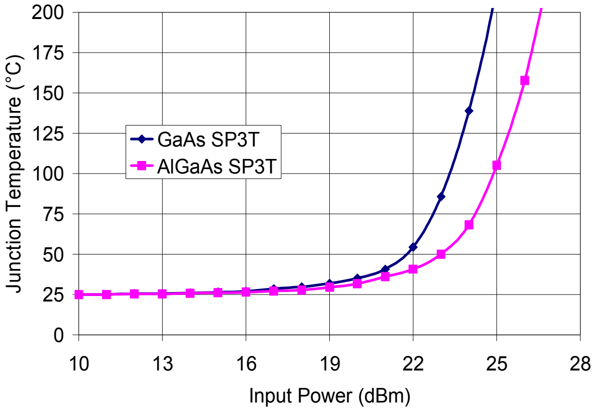

Fig. 13. Series Diode Junction Temperature vs. Input Power in SP3T series-shunt switches

Since thermal resistance of the AlGaAs/GaAs diode is identical to the GaAs diode, effectively the switch can handle higher input power, as can be seen in equation (7). A 37% decrease in insertion loss (dB) that was observed in the heterojuction PIN diode equates to approximately 50% increase in maximum input power.

The plot of series diode junction temperature vs. input power of the SP3T series-shunt switches in Fig. 13 demonstrates that the AlGaAs/GaAs switch reaches 125°C at approximately 50% more input power (+1.8 dB) as compared to the homojuction GaAs case. In addition, this maximum safe operating temperature is reached at an absolute incident power of +26 dBm (0.4 watts).

IV. CONCLUSION

Implementation and a full model extraction of a heterojunction AlGaAs/GaAs PIN diode with lower RF on-state resistance has resulted in the development of various extremely broadband switches with superior insertion loss and isolation from 50MHz through almost 80GHz, as well as, improved maximum input power ratings when compared to homojunction diode structures.

A family of multi-throw broadband mmW switches have been developed and the RF performance described. These switch variants consist of a multiple-series-diode SP8T switch with <2dB insertion loss and >30dB isolation at 40GHz; a double-shunt-diode SPST switch with ~0.35dB insertion loss and ~46dB isolation at 50GHz; and a number of multithrow series-shunt switches were also discussed with excellent loss and isolation figures. All of these switch configurations demonstrated an approximate 50% increase in input power capability over homojunction GaAs switches.

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