Heterojunction PIN Diode Switch

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Abstract — **This paper describes the development of a heterojunction AlGaAs/GaAs PIN diode as a replacement for the homojunction GaAs PIN diodes commonly used in microwave systems as a control element for commercial and military switch applications up through millimeter wave frequencies. In particular, a single heterojunction PIN diode, when simulated at a bias of 10 mA in a 50 ohm series configuration, indicates a potential reduction in insertion loss of 37% (Rs) with no degradation in isolation (Cj).**

This paper describes a switch topology of choice which uses a Series-Shunt element at the main junction, since it offers the widest bandwidth due to the low zero bias capacitance of Series diode. This simple structure has an upper frequency limitation that is dependent on the electrical distance due to the physical location of the series diode relative to the center of the actual device junction and the maximum isolation achievable by the Cj of a discrete diode.

PIN switch circuits and RF probable test structures were processed through our GaAs Wafer Fab and later tested on wafer for broadband RF performance from 50 MHz through 40 GHz. A comparison between simulated and empirical results for insertion loss, return loss and isolation demonstrates excellent agreement for isolation and a 10% offset for insertion loss and return loss.

I. INTRODUCTION

The application of Bandgap engineering to produce novel semiconductor structures is a technique that has been in vogue in the microwave industry for several years. Utilizing the properties of multiple quantum wells, superlattices and heterojunctions, a new class of semiconductors grown by molecular beam epitaxy and metalorganic vapor phase epitaxy was created. In particular, the development of three terminal heterojunction devices in the form of HBTs and p-HEMTs has received a great deal of attention from manufactures of cellular telephones and other commercial applications. As a supplier of these devices, M/A-COM has invested heavily into this technology.

While the use of bandgap engineering has been applied to bipolar transistors fabricated in elemental silicon; group IV-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. To this day a majority of two terminal devices such as PINs, Gunns, varactors, IMPATTs and Schottkys are still manufactured from a single semiconductor material. Over the years some attempts have been made to explore ways to enhancement the performance of power generating diodes. The double drift IMPATT diode using a GaAs/AlGaAs heterojunction in place of the standard p-n junction and the Gunn diode with its heterojunction launcher are two examples of device enhancements resulting in increased efficiency and power at higher frequencies of operation. Not until recently has there been any significant changes made to the design of the PIN diode to enhance it's RF performance. It is our belief this paper is the first reported application of a wide bandgap heterojunction used in place of a conventional p-n junction contained in a PIN structure.

II. OVERVIEW OF THE DIGEST FORMAT

The basic principles of bandgap engineering, the bandgap being the difference in energy between the conduction and valance bands in a semiconductor material, center upon 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 I-region. This difference in bandgap enables a suitable barrier height difference to be created, 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.

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The use of bandgap engineering changes the essential equations that describe the basic P+ anode-I-region junction current injection and the P+ anode and I-region recombination rates. This results in a PIN structure that has a significantly higher concentration of charge carriers reducing the RF resistance in the I-region of the heterojunction PIN device.

Several simulations utilizing Silvaco BLAZE™ modeling software were performed on a combination of

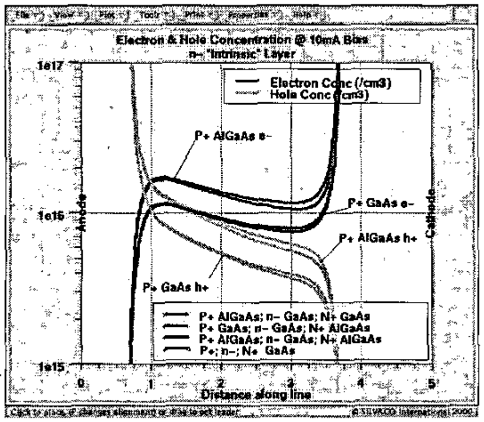

Figure 1: Simulation of the electron and hole concentration distributed within the four basic PIN structures.

single and double hetero-junction structures. The exact layer construction of four basic PIN structures that were simulated consists of a homojunction, a single P+ AlGaAs anode hetero-junction, a single N+ AlGaAs

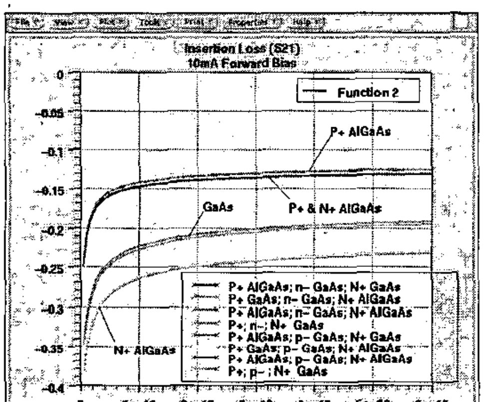

Figure 2: Frequency response plots of Insertion Loss show the best performance obtained by the single heterojunction P+ AlGaAs – I – N+ structure.

cathode heterojunction, and a double heterojunction, again employing AlGaAs.

The simulations predict a barrier height change in the conduction band energy of 100meV and the valance band energy of 20meV resulting from differences in the energy between the larger bandgap AlGaAs and the lower bandgap GaAs semiconductor materials. This resulting barrier height difference at the P+ heterojunction interface reduces the recombination rate for electrons and promotes the forward injection of holes into the I-region. It was found that the recombination rate for electrons at the P+ GaAs - I-region junction is sizable in comparison to the P+ AlGaAs heterojunction. The combination of lower recombination rates and higher carrier injection will yield a greater number of carriers thus lowering the effective resistivity of the I-region. Figure 1 shows the simulation results of the electron and hole carrier

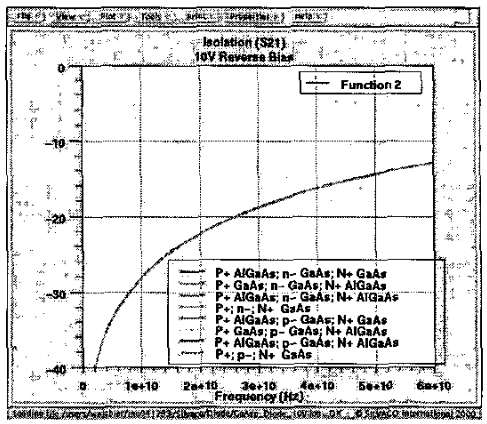

Figure 3: Frequency response plots of the reverse biased Isolation for every PIN structure layer combination.

concentrations distributed within the four modeled PIN diode structures.

Insertion loss simulations, displayed in Figure 2, of a double heterojunction PIN structure formed at the P+/I-region and I-region/N+ interface predict a significantly lower RF resistance in comparison to an all GaAs PIN structure. However, these same simulations indicate the P+ – I – N+ AlGaAs structure has the highest insertion loss among the four basic structures and the single heterojunction P+ AlGaAs – I – N diode offers the best performance with the lowest overall insertion loss. Lastly, Figure 3 shows the frequency response plots of the reverse biased isolation simulated for all PIN structures. These curves demonstrate no change in the reverse bias isolation due to the insensitivity of reverse bias capacitance for all PIN diode structures.

Presented in Figure 4 is the measured insertion loss of the series diode with 10 mA of forward bias current. This plot shows the IL the GaAs- homojunction PIN diode in comparison to the AlGaAs heterojunction PIN. The HJ-

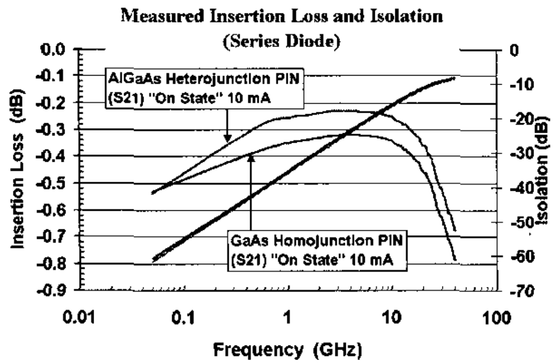

Figure 4: Frequency response plots measured data of series diode insertion loss and isolation showing the best performance obtained by the AlGaAs heterojunction verses the GaAs homojunction

PIN structure yielded a 27% reduction in IL whereas the BLAZE™ simulation predicted a 37% reduction representing a 10% offset. Also shown in Figure 4 is the measured isolation of the series diode in the "Off State" displaying two sets of curves. One for a 0 volt reverse bias and the other for a -10 volt reverse bias. In examining these plots it can be seen that no difference in the isolation is observed regardless of the junction type.

IV. Overview Of An AlGaAs PIN Diode Switch Design

The fundamental advantages observed above in the discrete heterojunction PIN diode structure can be seen to have unique advantages when applied to a standard PIN diode based MMIC switch topology. An analysis of the fundamental properties of a series/shunt PIN diode multi-throw switch and the resultant of applying this AlGaAs based heterojunction technology is presented below.

The Series Diode and Shunt Diode configurations are the two basic diode elements used to provide the control function in a PIN diode switch circuit. The combination of these two elements will form a Series-Shunt element commonly used in multi-port switches capable of large frequency bandwidths, a typical example of a 3P3T switch is shown in Figure 5.

First, the ***Series Diode*** performs the necessary ON and OFF switching operation of the RF signals through the diode's changes from low loss state (*forward biased*) to high loss properties (*reversed biased*), induced by a dc signal.

The design of the diode's junction capacitance will offer the necessary isolation (high loss) for the frequency of interest. Due to the geometry of the diode chosen to achieve the required junction capacitance the diode inherits a nominal Rs. As was seen in the discrete diode analysis above, this capacitance value for an AlGaAs PIN diode is unchanged as compared to an equal geometry GaAs homojunction PIN Diode. As a result, there is the freedom of designing an AlGaAs PIN diode with lower junction capacitance with identical Rs as seen in the standard homojunction GaAs Diode.

Second, the ***Shunt Diode*** performs its switching function in a reverse manner as the series diode. Isolation is achieved by dc forward biasing the diode.

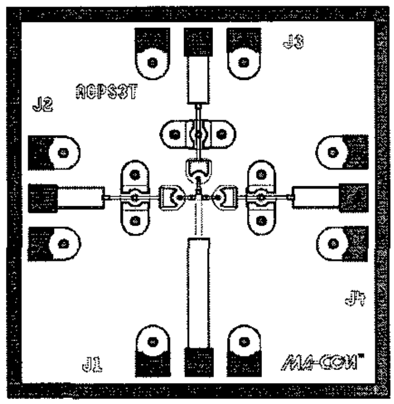

Figure 5: SP3T mmW Switch

Here, the advantage of an AlGaAs PIN Diode is observed by the isolation offered as compared to a GaAs device with equal geometries. Since the Rs is lower for an AlGaAs diode, the isolation will be greater.

Meanwhile, when the diode is operated in the low loss state, by applying a reverse bias, the diode's junction capacitance in conjunction with typical air-bridge interconnects will offer a low loss path. Also, since this capacitance is the same for equal geometries GaAs or AlGaAs PIN Diodes, another degree of freedom is observed in choosing lower capacitance diodes when designing Millimeter-Wave multi-port switches.

The structure of the series and shunt diodes were specifically designed to operate from 0.5GHz to 50GHz. The transmission line lengths of the interconnects to the series diode were chosen to minimize any parasitics associated with the device geometry and process used. While transmission lines interconnecting the shunt diode were carefully chosen to tune out the diode's junction capacitance in the low loss state, and improve the isolation frequency response of the overall switch.

For multi-port switching functions the AlGaAs advantage becomes evident when it is understood that a specific electrical length is required to interconnect each arm of the series diode of each arm to the center junction. This electrical distance, in conjunction with the diode's capacitance, dictates the functional bandwidth of the switch. Therefore making the diode's Cj smaller is of great advantage; enabling the electrical length associated with the diode's structure to function in millimeter wave applications.

Figure 6 shows the average measured Insertion Loss response for a Microwave SP3T, manufactured in GaAs and AlGaAs, from 1 to 30 GHz. The total insertion Loss difference can be observed (Loss Δ=0.12dB at 20GHz). It

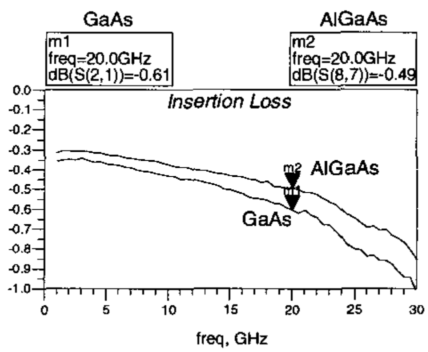

Figure 6: mmW SP3T Insertion Loss J1 to J2

should be noted that the original GaAs version of this

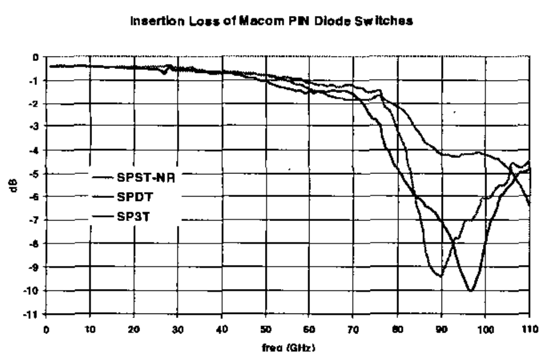

Figure 7: MA/COM's Multi-Port MMW Switch Family Typical Insertion Losses (Courtesy of Agilent Technologies)

switch was designed to operate from 2 to 18 GHz. Further design modifications and the incorporation of AlGaAs heterojuction diodes into the switch structures, as discussed above, increased the bandwidth up to 70GHz as shown in Figure 7.

The advantage of AlGaAs is also evident when the switch is utilized in high RF power environments. Since the series resistance for an AlGaAs device is lower, the power handling and linearity of the switch improves dramatically. This is tabulated in the Table I.

1 dB Compression Point, P1dB		
Measured at 8mA Forward, and 3.8V Reversed		
Frequency	**AlGaAs**	**GaAs**
2GHz	27.0 dB	21.0 dB
10GHz	29.0 dB	26.0 dB
18GHz	29.0 dB	26.5 dB

OIP3		
Pin=+10dBm, 7MHz Separation. Biased at 8mA Forward, 3.8V Reversed		
Frequency	**AlGaAs**	**GaAs**
2GHz	47.0 dB	34.0 dB
10GHz	50.0 dB	33.0 dB
18GHz	46.6 dB	34.5 dB

Table I: P_{1dB} and OIP_3 for GaAs & AlGaAs Switches

V. CONCLUSION

Recent simulations of AlGaAs/GaAs PIN diode structure indicate that significant reductions in the diode series resistance can be achieved by the use of this heterojunction configuration. This reduction in series resistance translates to a significant improvement in the diode insertion loss. The heterojunction modeling indicates that this reduction in diode loss can be achieved with no increase in the reverse junction capacitance; thus, the diode isolation will remain unchanged.

A comparison of the performance predictions based on BLAZE™ simulations for both a single and dual heterojunction PIN was presented in contrast to a comparable GaAs PIN structure. Further, it has been shown that mmW integrated GaAs PIN diode switches exhibit dramatic improvements in terms of reduced insertion loss with no penalty to pay in terms of isolation.

PIN based switch circuits and RF probable test structures fabricated from this material have been tested and have demonstrated broadband RF performance from 50 MHz through 50 GHz.

ACKNOWLEDGEMENT

The authors would like to thank W. Rousseau and E. Rousseau for the innumerable contributions in the hands-on efforts to realize the HJ-PIN device and to Joel Goodrich, M/A-COM Technology Fellow for advancing our understanding of the device physics.