AlGaAs Anode Heterojunction PIN Diodes

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Abstract

This paper describes the development of a heterojunction AlGaAs/GaAs PIN diode as a revolutionary improvement as compared to the homojunction GaAs PIN diode commonly used in microwave systems for commercial and military applications. In a heterojunction device the injected carriers from the junction are confined by the bandgap discontinuity between the AlGaAs/GaAs layers. This confinement effectively reduces the series resistance within the I-region of a PIN diode. Simulations of both single and double heterojunction PIN diodes predict a significant improvement in the return loss and insertion loss as compared to an equivalent GaAs PIN structure. In particular, the single heterojunction PIN diode, when simulated at a bias of 10 ma, indicates a factor of two reduction in high frequency insertion 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 pHEMTs has received a great deal of attention from manufacturers of RF, microwave, and mmW systems for both commercial and military applications.

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 enhance 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 its RF performance. This paper is reports the results of the developmental efforts of a patented AlGaAs/GaAs heterojunction structure in place of a conventional p-n junction in a PIN diode.

II. Discussion

Bandgap engineering principles, the bandgap being the difference in energy between the conduction and valance bands in a semiconductor were used to create a P+ anode region and an adjacent Intrinsic region (I region) diode structure using two dissimilar semiconductor materials. The 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.

Several simulations were performed on a combination of single and double hetero-junction structures to investigate the effect of employing different energy band gaps at the P+-

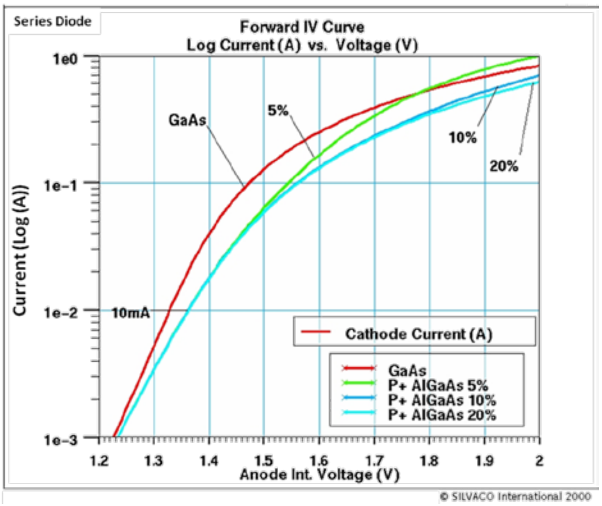

Figure 1 - Slope of Forward Voltage (DC Resistance) shows virtually no difference above 5% AlGaAs concentration

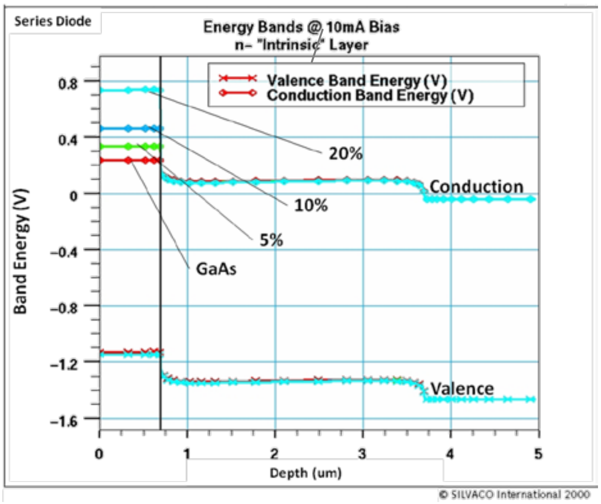

Figure 2 - Band Diagram showing resultant barrier heights with addition of AlGaAs to P+.

I junction. 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 cathode heterojunction, and a double heterojunction, again employing AlGaAs. The aluminum concentration contained in the P+ layer was varied and model extractions were carried out of the forward current/voltage characteristics for three different P+ AlGaAs heterojunction structures using 5%, 10% and 20% composition. The modeled results contained in Figure 1 show virtually no difference in the slope of forward voltage, equivalent to the DC Resistance, above 5% AlGaAs concentration when compared at 10ma of forward current.

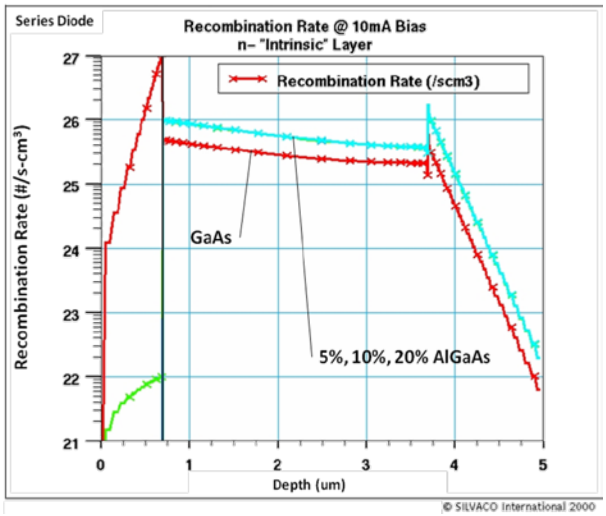

Figure 3 - Electron and hole recombination rates simulated from the four basic PIN structures

Displayed in Figure 2 is the 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. As shown in Figure 3, 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 4 shows the simulation results of the electron and hole carrier concentrations distributed within the four AlGaAs aluminum fractions in the PIN diode structures.

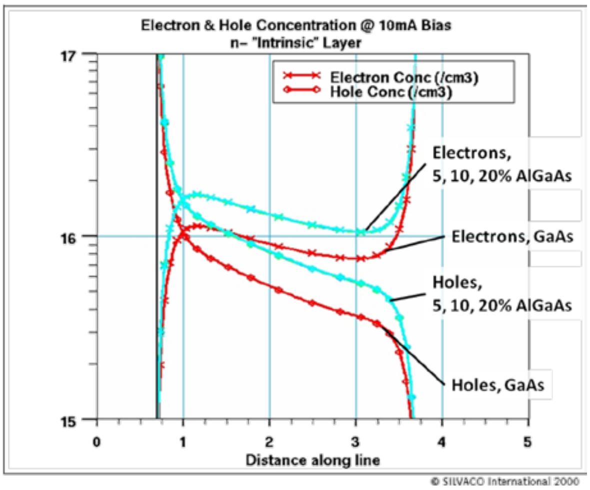

Figure 4 - Simulation of the electron and hole concentration distributed within the four basic PIN structures

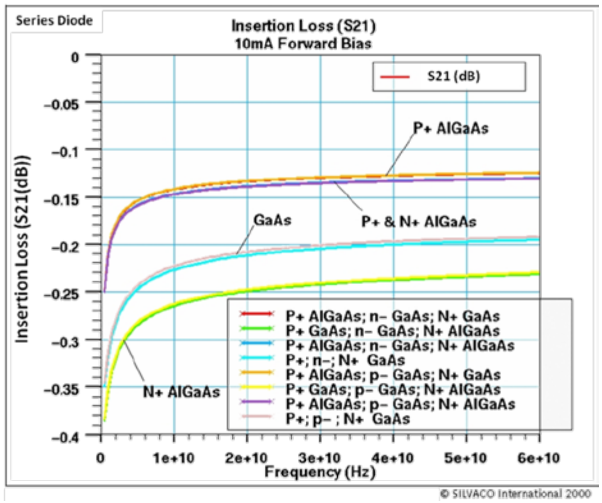

Figure 5 -Frequency response plots of Insertion Loss show the best performance obtained by the single heterojunction P+ AlGaAs – I – N+ structure

Insertion loss simulations, displayed in Figure 5, of a double heterojuction 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.

The simulation presented in Figure 5 with regard to the predicted performance of the double heterostructure P+ – I – N+ AlGaAs PIN diode is completely at odds with the expectations of the authors. It was anticipated that the P+ – I – N+ AlGaAs diode should have had the lowest insertion loss of all of the PIN heterostructure variants. In the worst case it is even more difficult to understand why the performance is poorer that the homojunction control structure. It is believed that the abnormal predicted RF behavior shown in Figure 5 is due to errant values for the hole parametric data resident in the simulation program but this was not able to be verified. Also, unfortunately, this P+ – I – N+ double heterostructure was unable to be fabricated, due to the inability to grow the required N+ AlGaAs layer at the cathode/“I” region interface, to empirically test the accuracy of the simulated predictions.

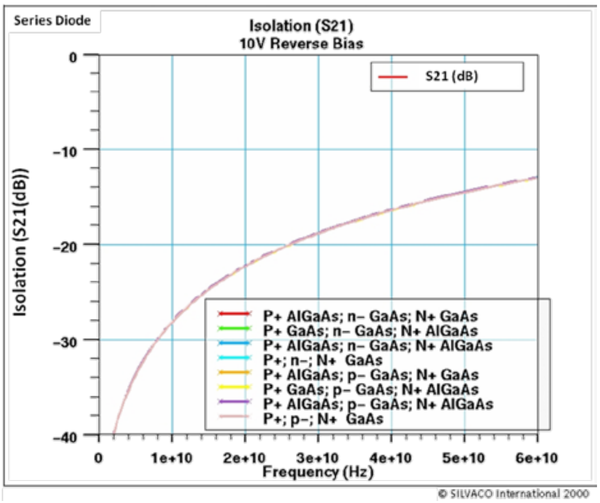

Figure 6 - Frequency response plots of the reverse biased Isolation for every PIN hetero-structure layer combination

Lastly, Figure 6 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 to the aluminum fraction in the AlGaAs heterojunction for all PIN diode structures.

III. Results

Presented in Figure 7 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 all the variants, 5%, 10%, & 20% AlGaAs fractions, of the AlGaAs heterojunction PIN. The measurements of the all the heterojunction-PIN structures yielded a 27% reduction in IL when compared to a GaAs homostructure PIN diode. This measured data can be contrasted with the simulations in Figure 5 which predicted a 37% reduction in the overall device insertion loss. This difference is felt to

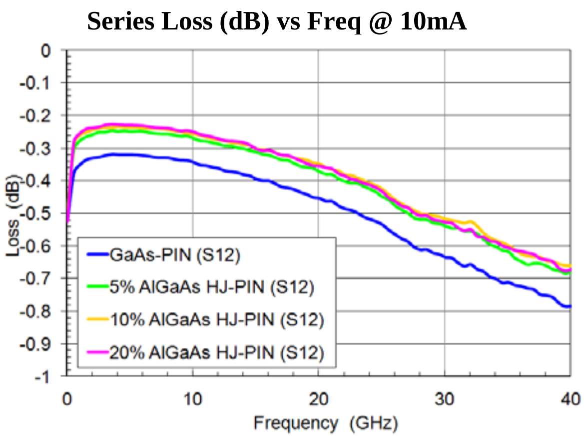

Figure 7 - Measured Insertion Loss for Series Configured Heterojuction AlGaAs vs GaAs PIN Diode

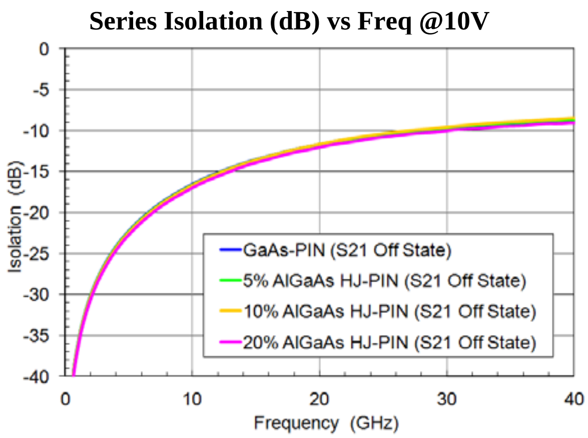

Figure 8 - Measured Isolation for Series Configured Heterojuction AlGaAs vs GaAs PIN Diode

Heterojuction AlGaAs vs GaAs PIN Diode

be to the inability to de-embed all of the external parasitics associated with the loss measurements.

In Figure 8 is the measured isolation of the series diode in the “Off State” displaying two sets of curves 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.

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 structure of various switches, as given below in Figure 9, 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 or the effect of adding multiple arms to the switch but are certainly adequate to judge the effect of the bandgap changes in the semiconductor structure.

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.

It can also be shown that in series and series-shunt switches, power handling is limited by the series diode 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. Since thermal resistance of the AlGaAs/GaAs diode is identical to the GaAs diode, effectively the switch can handle higher input power. The measured 27% decrease in insertion loss that was observed in the heterojuction PIN diode equates to approximately 50% increase in maximum input power.

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

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

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

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

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

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

Figure 9 – Insertion Loss and Isolation Equations for Various PIN Switch Structures

IV. Conclusion

Simulations of AlGaAs/GaAs PIN diode structures 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 these simulations for both a single and dual heterojunction PIN diodes was presented in contrast to a comparable homojunction GaAs PIN structure. Further, it has been shown that mmW integrated GaAs PIN diode switches should exhibit dramatic improvements in terms of reduced insertion loss with no penalty to pay in terms of isolation.

While space constraints prevent a detailed presentation of measured high frequency performance, PIN based switch circuits and RF probable test structures fabricated from this material have been produced, tested, and have demonstrated excellent broadband RF performance from 50 MHz through 50 GHz.

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