Development of a High Voltage mmW GaAs PIN Diode Switch

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ABSTRACT

The initial development of a three pole three throw, (3P3T), switch for 35 to 40 GHz applications on the surface was thought to be a straightforward frequency scaled adaptation of a previously completed 6 port, 77 GHz switch for automotive collision avoidance radar systems. This misimpression was clearly demonstrated during the customer funded development and reliability qualification of this switch.

This paper will cover the difficulties involved in transforming a relatively low voltage, system qualified and validated PIN switch product into a much higher voltage, 100% on wafer tested and characterized for all port characteristics at frequency with full reliability qualification. Topics covered will include the techniques needed to increase the PIN switch breakdown voltage by modifying the PIN structure and incorporating nitride under the transmission lines. A description of the voltage limitations of this underlying nitride film and the use of test structures to validate the DC characteristics of the physical changes to the circuit dielectric structure along with the results of the final device high temperature qualification is provided. In addition, design and process changes to effect higher yields through reduced circuit element breakage, increased bond pad strength and improved metallization definition capability will be discussed.

INTRODUCTION

GaAs PIN diodes used in microwave systems as switches, phase shifters, and attenuators have found their way into an assortment of commercial and military applications. A variety of PIN switch designs operating at mmW frequencies are now made possible with the integration of the PIN diode and passive elements onto a common substrate. Multi port switch designs used in automotive applications are well suited to handle small signal RF power while operating at relatively low potentials as used in 12 volt systems. However, in a large signal design, the need to handle larger voltage excursions has placed additional constraints on the layout and construction of the high voltage PIN switch.

DISCUSSION

Observations made during the development of the automotive switch showed a limitation of placing transmission lines and capacitors in direct contact with the exposed semiconductor surface. Whenever a metal feature, such as M1 shown in figure 1, is placed in intimate contact with the semiconductor, a junction is formed by the exchange of charge between the metal and the semiconductor. In the case of GaAs, the work function of the metal and the density of states along the GaAs surface influence the electrical characteristic of this junction. Even the bulk properties of the semi-insulating GaAs substrate and the processing steps leading up to the evaporation of the Metal 1 features will have an effect on the characteristics of the junction. At relatively low operating voltages, the amount of leakage current flowing from M1 to ground is negligible. However, as the voltage applied begins to exceed the potential barrier of the junction, a sizable leakage current will flow rendering the circuit useless for normal operation. The importance of providing adequate electrical isolation became apparent during the development and qualification of the next generation mmW GaAs PIN Diode Switch intended for high voltage operation. The circuit

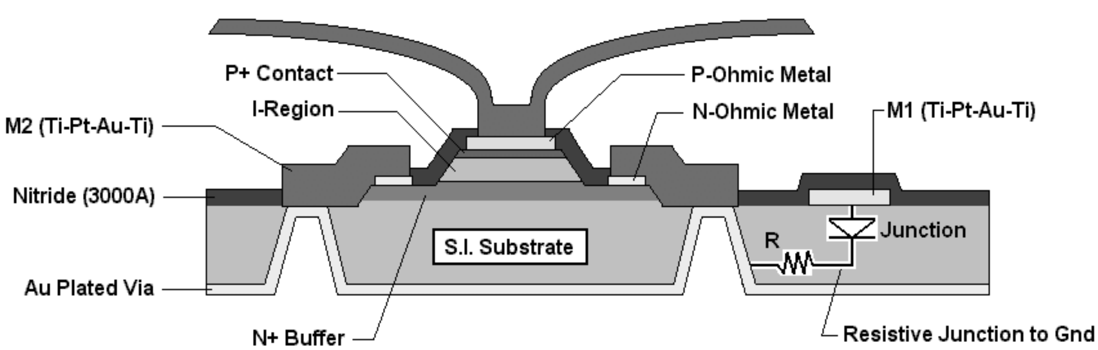

Figure 1. Cross sectional view of a PIN switch with M1 in contact to the GaAs surface

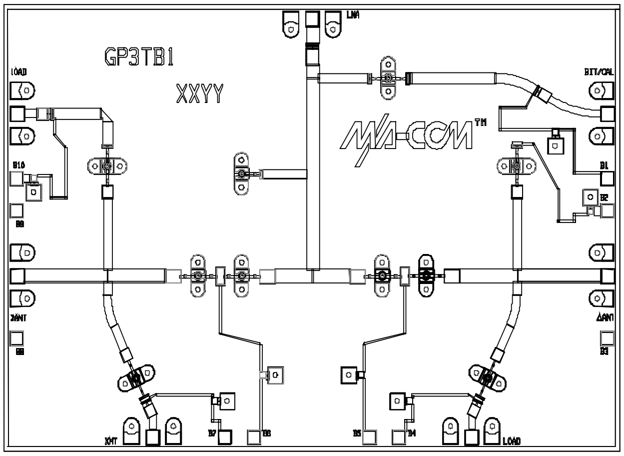

Figure 2 – Ka-Band GaAs 3P3T SWITCH

layout of the high voltage switch, as shown in figure 2, was optimized for 35 to 40 GHz applications. It was based on a frequency scaled adaptation of a previously completed 6 port, 77 GHz switch used for automotive collision avoidance radar systems. The design rules for the lateral dimensions of the required high voltage PIN diode as well as the process specifications for producing the mmW GaAs integrated circuit were identical to that used in the automotive switch. The only apparent difference between the two designs was the operating voltage requirement. The high voltage switch needed to handle peak RF voltages approaching 70 volts whereas the automotive switch typically saw voltages of less than 15 volts. As a result, the I-region thickness of the PIN diode was increased to accommodate the higher voltage and a silicon nitride film was added underneath the transmission line to reduce leakage current from the transmission line to ground. Silicon nitride was chosen specifically for its dielectric strength and mechanical properties. Shown in figure 3 is a cross sectional view of the high voltage PIN switch containing two layers of silicon nitride sandwiched between the M1 feature and the GaAs surface. The present design of using a composite nitride film was reached through experimentation with 1000 angstrom and 4000 angstrom thick films. Our first attempt in using a 1000-angstrom tensile film proved to be inadequate to support the 56-volt bias required as part of the HTRB burn-in reliability test. This limitation was easily remedied by depositing a second layer of compressive nitride 3000 angstroms thick to the first for a total of 4000 angstroms. Our decision to use a composite nitride film permitted us to combine two nitride layers of sufficient thickness to support large potentials while affording us the ability to tailor the mechanical properties of the composite film. The thickness of each nitride layer was chosen to balance the opposing tensile and compressive forces in order to reduce the overall film stress. The mechanical attachment of the composite film to the GaAs surface was improved significantly as the film stress was reduced. With the insertion of the nitride stack beneath the M1 feature, the previously formed junction, shown in figure 1, is now transformed into a capacitor in the equivalent circuit shown in figure 2. The layers of M1 and nitride stacked on top of the semi-insulating surface form the resulting MIS capacitor. Reliability testing of devices patterned with transmission lines and capacitor structures was performed on samples containing 1000 angstrom and 4000 angstrom nitride films. Samples of each type were assembled, thermally stressed and then tested for breakdown voltage. The test results confirmed the 1000-angstrom nitride layer thickness was insufficient to support a potential of 56 volts. Identical tests performed on the 4000-angstrom nitride samples confirmed these devices could support potentials in excess of 250 volts without any signs of degradation.

A set of high voltage switches containing 4000 angstrom of composite nitride was submitted for accelerated life test. These devices were burned in at 125’C with a bias of 56 volts over an incremental period of 168, 340, 500 and 1000 hours. At each time interval, the devices were evaluated at 56 and 70 volts and the reverse leakage current was measured at room temperature. Test conditions in excess of the customer’s specification were used to assess the robustness of the design and to offer the customer an added margin of safety. All devices under test had survived the1000 hour burn-in with no signs of degradation in the leakage current. The state of the art PIN process was then deemed qualified to manufacture

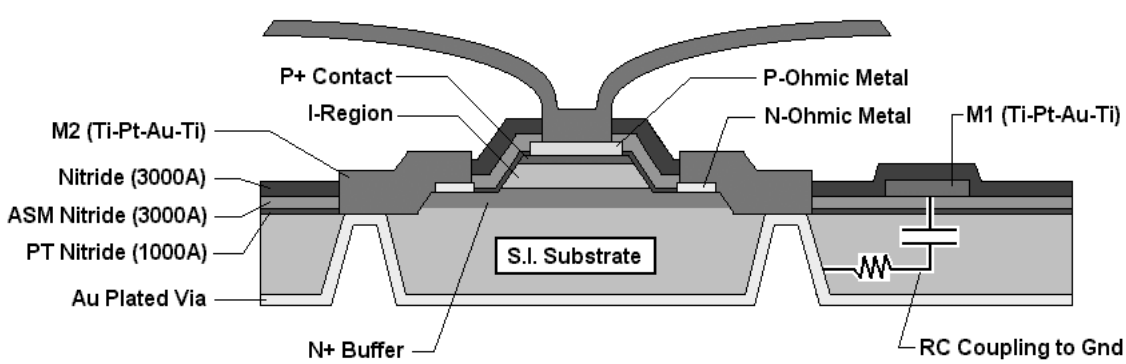

Figure 3. Cross sectional view of the new state of the art

the high voltage switch based upon the favorable completion of the life test.

The apparent success in qualifying the high voltage switch through accelerated life test was unfortunately limited to the pre-production runs. Subsequent attempts to manufacture this part were often plagued with an assortment of process related problems the most significant of which was mechanical damage to the diode element. Our decision to fabricate the High voltage switch by using the identical process as used for the automotive switch and changing only the epi parameters and mask dimensions eventually proved to be unwise. Unfortunately, very little consideration was given to understanding the hazards of increasing the diode height needed to accommodate the thicker I-region.

The impact of this one seemingly simple change of increasing

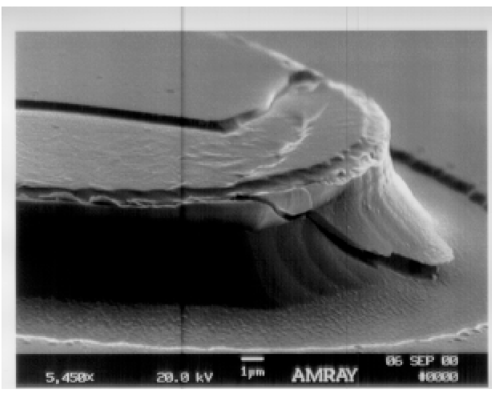

Figure 4. Sheared Mesa

the I-region thickness to support higher RF voltages would cascade through the process creating two major unforeseen defects. The first of these was the sporadic occurrence of mechanical damage to the diode mesa. Shown in Figure 4 is an example of sheared mesas revealed after the METAL 1 liftoff step. Several factors, such as the design rules for dimensioning the diode and specific processing steps leading up to the METAL 1 liftoff, were identified as the cause for

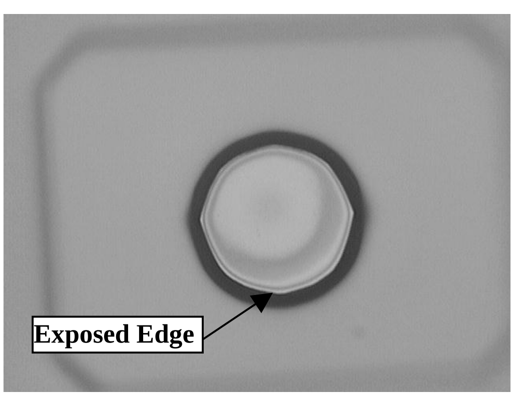

Figure 5 – Inadequate Resist

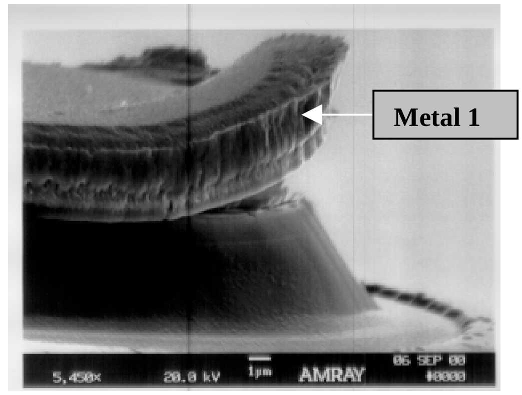

Figure 6 - Metal Encapsulated

the mesa shearing. The design rules used in the automotive switch routinely produce a mesa structure with no overhang of the P-ohmic metal. However, when applied to the high voltage diode, undercutting of the P-ohmic metal would often occur. The undercut, resulting from the additional 2µm etch depth, would form a brim of P-ohmic metal extending beyond the mesa. The exposed edges were difficult to cover using a 4µm thick resist for the METAL 1 photo. Figure 5 shows evidence of inadequate resist coverage indicated by the variegated patterns on top of the mesa. These edges were susceptible to having METAL 1 anchor to them. In some instances, an entire mesa, as shown in figure 6**,** was encapsulated in METAL 1 providing a solid attachment to the mesa. The process of lifting off the METAL 1 film would

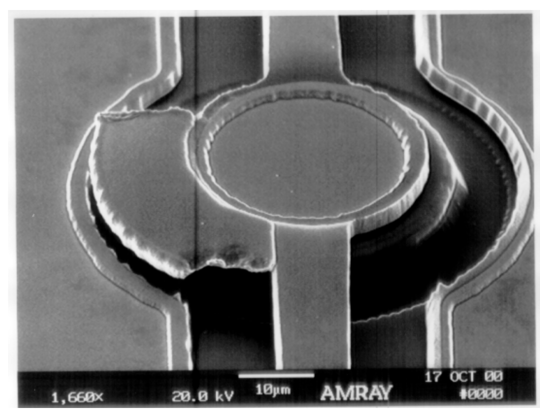

Figure 7. Metal 2 flagging

tear at the P-ohmic metal and often pull sections of GaAs off with it. Other instances of inadequate resist coverage provided by the subsequent Isolation and N-ohmic photo steps would further exasperate the symptoms attributing to the mesa shear. The isolation photo would leave the top edge of the mesa exposed during the isolation etch step further increasing the risk of undercutting the P-ohmic metal. Then the following N-ohmic photo and metal liftoff process would generate metal flags extending beyond the mesa perimeter thus increasing the probability of Metal 1 attachment. Each of these difficulties was identified and eventually solved by simply increasing the resist thickness used in the Isolation, N-ohmic and Metal 1 photo processes. The second major difficulty in manufacturing this part would occur during the Metal 2 liftoff step. Flags of the electrically isolated Metal 2, shown figure 7, trapped between the anode and cathode would remain producing a visual reject at final inspection. Here again the diode topology was such that Metal 2 thickness was greater than the resist thickness. By increasing the resist thickness used in the Metal 2 photo from 4µm to 6µm we were able to achieve a clean metal liftoff.

While the above changes to the structure and the related process were required to insure the DC survivability of the high voltage mmW GaAs switch, the effect of these modifications on the high frequency characteristics and overall performance of the switch was a major concern. In

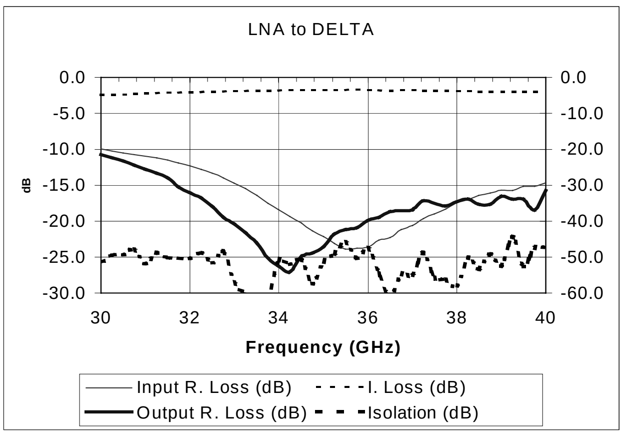

Figure 8 – LNA to DELTA vs Frequency

Figure 8 and Figure 9 are presented plots of the on wafer measured RF performance of the switch fabricated with the modified dielectric structure under the transmission lines from 30 GHz to 40 GHz. As can be seen in these measurements, the Input Return Loss, the Output Return Loss, the Insertion Loss, and the Isolation are plotted versus frequency for the LNA to DELTA, LNA to SUM, and XMT

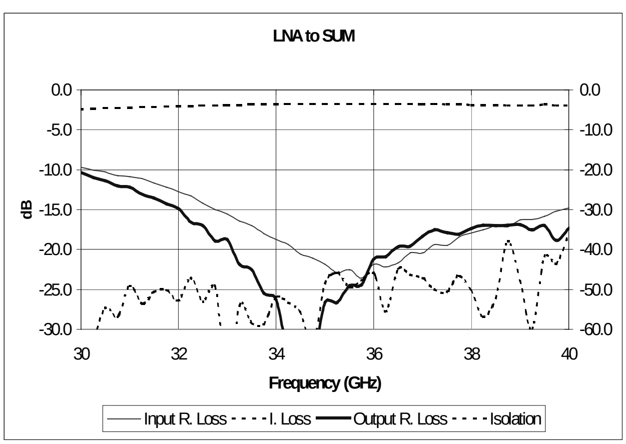

Figure 9 – LNA to SUM vs Frequency

to SUM port configurations.

Not only are all of the measurements well within the high voltage switch specifications, but based upon measurements taken from several wafer lots, the thicker nitride modification to the transmission line structure actually improved the overall high frequency, switch performance by several tenths of a dB (out of a 1.0 dB spec) when compared with the previous nominal 1kÅ PECVD nitride film. This is felt to be due to the fact that the thicker nitride layer acts as a much better dielectric relative to the high frequency transmission characteristics of the integrated circuit as compared to the underlying semi-insulating GaAs substrate.

Summary

The development efforts to produce a high voltage, mmW GaAs PIN diode switch revealed a number of interesting observations concerning the design and use of semi-insulating GaAs as a high frequency substrate material. While the typical bulk resistivity of semi-insulating GaAs of $\rho > 10^7$ Ω-cm is adequate to insure both DC and RF isolation between the shunt connected PIN diodes which form the active elements of the high voltage switch, it has proved to be an inadequate insulator for the isolation of passive elements from an underlying ground plane, i.e. transmission lines, and parallel plate capacitors. This is due to the fact that “semi-insulating GaAs” is in actuality a semi-conducting material and behaves as a large value resistor rather than as a true insulator. This semi-conducting nature of the semi-insulating GaAs substrate was also seen in the high frequency performance of the high voltage switch. The incorporation of much thicker silicon nitride film which has a bulk resistivity of $\rho > 10^{14}$ Ω-cm was seen to significantly improve the switch performance over the 30 GHz to 40 GHz frequency range.

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