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W-band InGaAs/InP PIN Diode Monolithic Integrated Switches

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Abstract — The design, fabrication, and experimental characteristics of InGaAs PIN diodes are presented for InP-based W-band monolithic integrated switches. The diodes with 10μm-diameter were used and showed a breakdown voltage of 17 V, a turn-on voltage of 0.36 V, and a switching cutoff frequency of 6.3 THz. The monolithic integrated switches employed microstrip transmission lines and backside via holes for low-inductance signal grounding. A radial stub-based design was used for on-chip biasing, and the high-frequency characteristics of the switches were verified by on-wafer W-band testing. The SPST PIN monolithic switch demonstrated 25 dB isolation, 1.3 dB insertion loss, and 0.8 dB reflection loss at 83 GHz.

I. INTRODUCTION

Millimeter-wave switches compatible with GaAs- or InP-based high-frequency electronics are key elements in developing front-end transmitter-receiver modules at the millimeter-wave frequencies [1]. PIN diodes are ideally suited for such applications due to their superior power handling capabilities and high switching cutoff frequencies. An important application for such transmitter-receiver modules is the emerging high-frequency collision-avoidance technology for the automotive industry.

GaAs PIN diodes have been employed in state-of-the-art monolithic millimeter-wave switches, demonstrating 1dB insertion loss and 30dB isolation at 94GHz with an estimated switching cutoff frequency of 4THz [2]. However, PIN diodes fabricated using InGaAs on InP substrates offer the advantage of lower turn-on voltage, higher electron mobility, and compatibility with InP-based high frequency electronics. X-band single-pole double-throw (SPDT) switches fabricated using the *base-collector-subcollector* layers of InAlAs-InGaAs-InP HBTs [3] confirmed this expectation and demonstrated similar performance to GaAs-based PIN diode designs at only half the power consumption, as a result of their lower turn-on voltage. The compatibility of InGaAs PIN diodes with high-frequency InP-based electronics offers several additional advantages for the realization of millimeter-wave functions, such as the possible integration of switching and current-limiting PIN diodes with InGaAs/InP HBT- and HEMT-based circuits. The higher operation frequencies achievable with the use of InP-based HEMT technology opens the road to building new imaging-radar systems as well as to minimizing the size and therefore the cost of collision avoidance systems.

First results on the basic characteristics of InGaAs/InP PIN diodes for millimeter-wave analog applications have been recently reported by the authors [4]. By optimizing the PIN layers for millimeter-wave frequencies, that work demonstrated that the switching cutoff frequency was improved from 7THz to 17THz using 1μm-thick *i*-InGaAs layer and 5μm-diameter InGaAs/InP diode. This paper presents a further extension of the characteristics and use of PIN diodes by applying the InGaAs/InP-based technology to monolithic integrated PIN switches for W-band operation and demonstrating, for the first time, results from such circuits. A single-pole single-throw (SPST) monolithic InGaAs/InP switch was designed, fabricated, and tested by on-wafer probing at W-band. 10 μm-diameter PIN diodes were used in the switch design, which also included on-chip integrated biasing networks and backside via holes.

II. CIRCUIT DESIGN

The SPST monolithic switch design was based on InGaAs PIN diode equivalent circuits extracted from discrete device characterization. The intrinsic diode resistance and capacitance values were also verified by drift-diffusion modeling. The switches were designed using the HP EEsof microwave simulator Libra, and their characteristics were verified by three-dimensional electromagnetic simulations.

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The ON- and OFF-state PIN diode equivalent circuits used in the microwave simulation are shown in Fig.1. The equivalent circuit of the diode in the ON-state includes the intrinsic resistance of the diode (*Rd*), the parasitic access resistance (*Rs*), the airbridge parasitic inductance (*Lab*), and parasitic fringing capacitance (*Cpar*), as shown in Fig.1(a). The diode equivalent circuit in the OFF-state is shown in Fig.1(b) and includes the OFF-state depletion and displacement capacitance (*Coff*) in addition to the parasitic elements *Lab*, *Cpar*, and *Rs*. The values of the intrinsic diode resistance (*Rd*) and capacitance (*Coff*) were estimated by discrete-device microwave characterization in conjunction with drift-diffusion device modeling. Parasitic capacitance and inductance were evaluated from separate characterizations of the same MMIC technology.

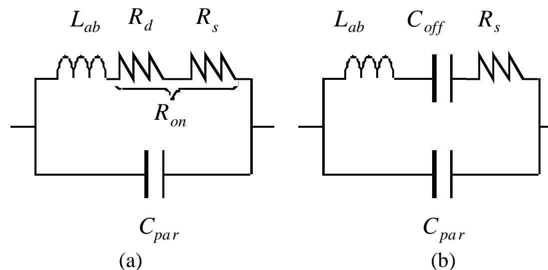

Fig.1. Equivalent circuit of InGaAs PIN diode in ON- and OFF-states

The SPST switch employs a section of high-impedance (Z_o= 85Ohm) microstrip transmission line, which was connected to two 50-W coplanar microwave probe pads and shunted in the middle by a InGaAs/InP PIN diode. When the diode is in the OFF-state, the total diode capacitance ($C_{tot} = C_{off} + C_{par}$), the airbridge/via-hole inductance, and the sections of microstrip line form a bandpass filter at the design frequency. The switch uses a single shunt stub filter. By employing the InP-based PINs in conjunction with double stub design, one should be able to increase the bandwidth of operation at the expense, however, of increased transmission losses. Given the fact that pass frequency of the ON-state filter is sufficiently higher than the design frequency, the incoming signal is reflected back at the diode and only small portion of it, proportional to the voltage across the turned-on diode, propagates to the output port. The isolation of the SPST switch is therefore 6 dB less than it would be in a SPDT configuration, since the latter presents half the available signal voltage across the diode.

The MMIC switch design parameters were optimized using the linear microwave simulator HP EEsof/Libra. Optimized parameters included the length and the characteristic impedance of the microstrip transmission line section for a given a choice of diode parameters and design frequency. Once the circuit schematic was finalized, the layout of the switches was generated using the automatic synchronization function of Libra and a device library developed in-house. The generated layout data were then imported into the three-dimensional electromagnetic HP EEsof Momentum simulator, and the circuit performance was analyzed at a higher degree of accuracy, as necessary for millimeter-wave designs. Momentum simulations allowed us, for example, to account for distributed airbridge and via hole effects, as well as to calculate the high-impedance transmission line characteristic at W-band frequencies with better precision.

III. InGaAs PIN Monolithic Switch Technology

The monolithic PIN W-band SPST switches were fabricated using a technology specially developed for this purpose. Fig. 2 shows a photograph of the monolithic chip, which is 1.5 x 0.6 mm^2. The switches employed InGaAs PIN diodes fabricated on InP substrates. A bias network in distributed form is also shown in the photograph. It was integrated on-chip and does not require the use of bypass capacitors. The bias network consisted of a microstrip open radial stub with a quarter-wave impedance transformer and allowed decoupling of the DC biasing pad from the high frequency signal path. The size of the radial stub was optimized for maximum bandwidth. The SPST switches used one backside via hole for shunting the diode and four via holes to form coplanar-to-microstrip mode transitions at the microwave probe pads.

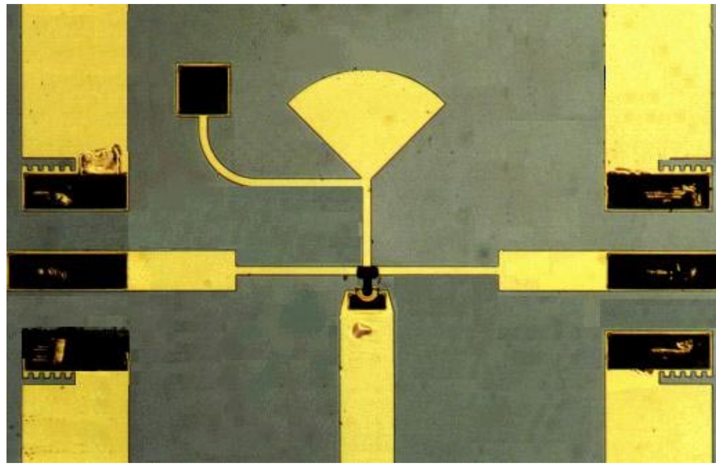

Fig. 2. Photograph of fabricated W-band single-pole single-throw InGaAs PIN switch.

The InGaAs PIN diodes were made from the following layers starting from the SI InP substrate: n^+ (1 µm, 1.4x10^{19} cm^{-3}), i (1 µm, ~10^{14} cm^{-3}) and p^+ (0.15 µm, 1.4x10^{19} cm^{-3}). The layers were grown using solid-source MBE. The growth rate was 0.7 µm/hr, and a 380-Å undoped AlInAs buffer was used between the substrate and the diode layers. In order to obtain an abrupt doping profile from the n^+ to i-region and to assure a low background doping in the i-InGaAs layer, the growth temperature was kept at a low value of about 450ºC. The diodes were fabricated by employing wet etching to form 10µm-diameter mesas. Airbridges were used to connect the top p-ohmic metal contacts to the interconnect lines of the circuit. A scanning electron microscope photograph of a fabricated PIN diode is shown in Fig.3.

The wafers were thinned down to 100 µm, and backside via holes were etched using an in-house technique which employs a Ti mask to control via hole dimensions and concentrated HCl to produce an anisotropic etch profile. Backside Au electroplating completed the fabrication process.

IV. DC and High-Frequency Experimental Characteristics of PIN Diodes

DC characterization of the PIN diodes showed a high reverse breakdown voltage of 17 V and a low turn-on voltage of 0.36 V (@ I = 10 µA), as demonstrated in Fig.4. Discrete PIN diodes were characterized initially from DC to 26 GHz and later directly at W-band to verify their characteristics with higher precision. The measurement setup used for this purpose consisted of an HP 8510B network analyzer and a millimeter-wave waveguide test set with WR-10 waveguides and W-band coplanar probes for on-wafer characterization of the devices up to 110 GHz.

Analytical expressions for the insertion and return loss of a shunt PIN diode on a 65-Ω coplanar waveguide were used to analyze the measured performance and to calculate the total diode impedance in the ON- and OFF- states.

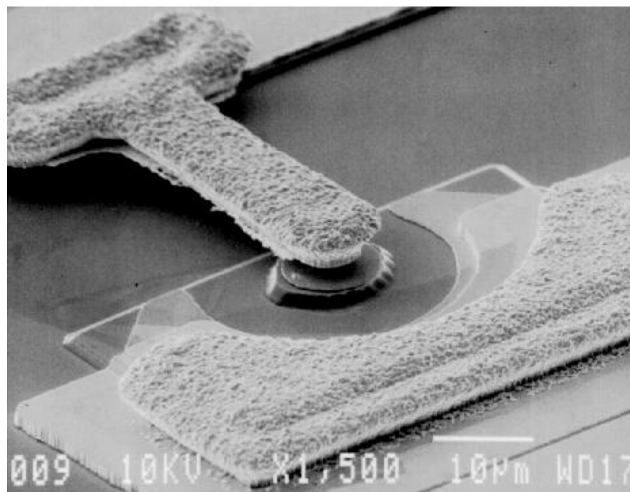

Fig. 3. SEM of a fabricated InGaAs PIN diode

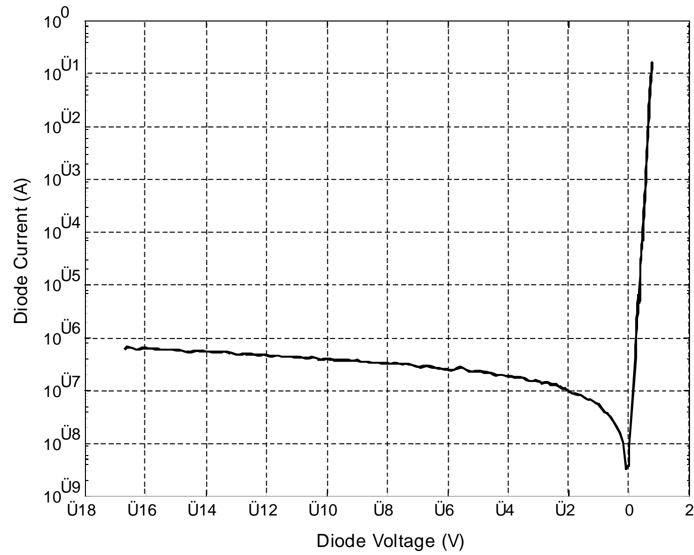

Fig. 4. IV-characteristics of a InGaAs PIN diode

The bias dependence of the insertion loss of the InGaAs PIN diode in the OFF-state measured at 78 GHz is shown in Fig.5 and was used to calculated the OFF-state capacitance $C_{off,}$

where IL(dB) is the measured insertion loss in the OFF-state, Z_o is characteristic impedance of the transmission line, C_{par} is the parasitic pad capacitance, and f is the operating frequency.

The bias dependence of the return loss of InGaAs PIN diode in ON-state measured at the same frequency (see Fig.6) was used to calculate its total ON-state resistance R_{on} (see Fig.1), where RL(dB) is the measured return loss in the ON-state and L_{ab} is the inductance of the airbridge.

The analytically-extracted diode parameters were: R_{on} (V = 0.65 V) = 2.4 $_{\Omega}$, C_{off} (V = -5 V) = 11 fF. The parasitic capacitance C_{par} was found to be 14 fF. The switching cutoff frequency, was estimated for these diodes at *6.3 THz*, indicating the high potential of this technology for very high frequency applications. The high electron mobility of InGaAs allowed the development of diodes with reduced OFF-state capacitance C_{off} without sacrificing their low ON-state resistance R_{on}. Moreover, this permitted an improvement in the figure of merit fcs while using less than half of the biasing power normally employed in GaAs switches, thus resulting in power consumption savings combined with very high frequency operation capability and InP-based technology compatibility.

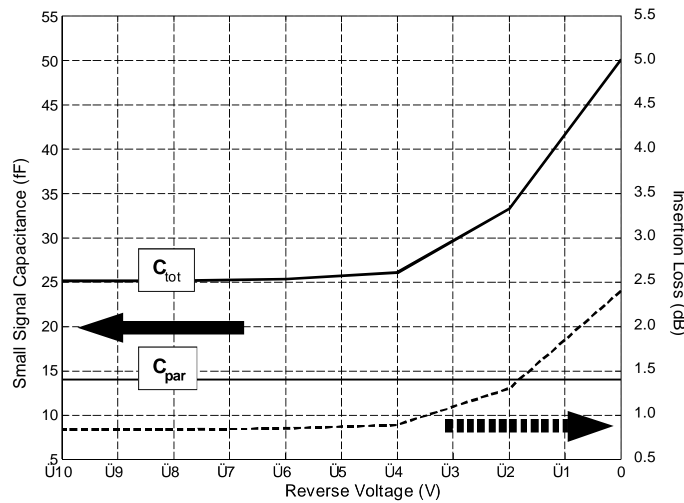

Fig.5. Bias dependence of PIN diode insertion loss and equivalent small-signal capacitance in the OFF-state

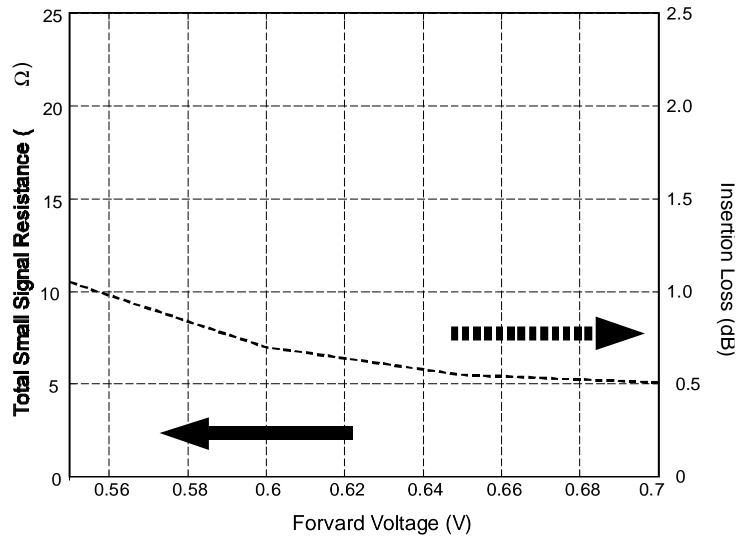

Fig.6. Bias dependence of PIN diode return loss and equivalent small signal resistance in the ON-state

V. InGaAs PIN SPST Switch Performance

On-wafer characterization of the integrated InP-based monolithic PIN switch was conducted from 75 to 100 GHz using the setup described earlier. The switches demonstrated state-of-the art performance. Typical response characteristics in the ON and OFF states are shown in Fig.7.

For design and analysis purposes, the switches can be considered as a high-impedance microstrip line (Z_o = 85 W) shunted by an InGaAs PIN diode. When a diode is OFF, its impedance can be approximately modeled by a small depletion capacitance. In the OFF-state, its impedance is much higher than *Zo*, and the injected signal passes through the switch with only a small insertion loss. The latter was measured to be only 1.3 dB at 83 GHz for the switch presented in this work. When the diode is turned ON, its impedance may be modeled as a small resistance plus the inductance of the airbridge and the via hole providing the ground connection. If the total diode ON-state impedance is much smaller than *Zo*, the signal is shunted to ground and reflected back with a small reflection loss. This was measured to be as low as 0.8 dB in case of the SPST switches described in this paper. A small portion of the signal also leaks to the isolated port and was measured to correspond to an isolation of 25 dB. The minimum VSWR was 1.1, and its value was less than 2 over a 5.4-GHz bandwidth, demonstrating good matching in the OFF-state. Tests of the integrated radial stub bias network confirmed that its parasitics does not interfere with the switch performance.

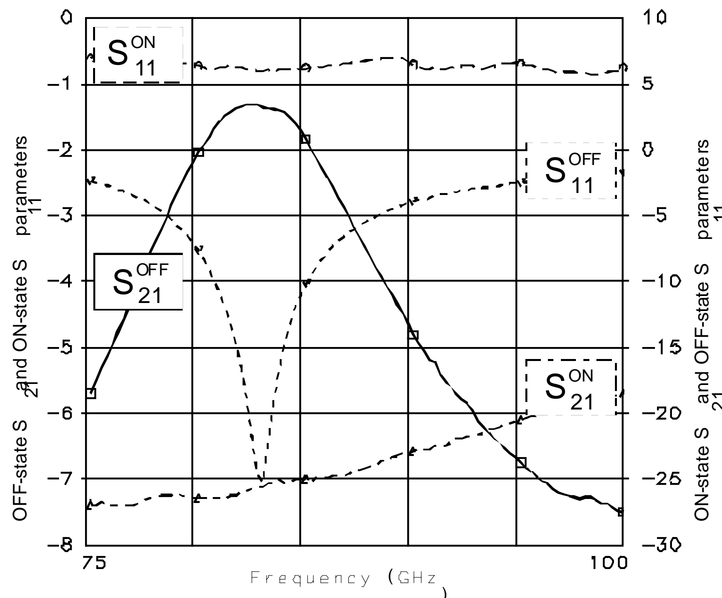

Fig.7. Performance of W-band SPST switch obtained by on-wafer probing and on-chip biasing

Good agreement was obtained between the frequency response of measured and simulated S-parameters. The use of Momentum-based simulations in addition to Libra design optimization permitted enhancement in the agreement between simulated and experimentally obtained InP-based PIN SPST switch characteristics.

VI. CONCLUSIONS

InGaAs/InP PIN diodes were used for the development of W-band monolithic switches for the first time and showed state-of-the-art performance at very high frequencies of operation, low power consumption, and compatibility with InP-based millimeter-wave electronics. The PIN diodes had a 10μm-diameter, breakdown voltage of 17 V, turn-on voltage of 0.36 V, and a switching cutoff frequency of 6.3 THz. Radial stubs were used for on-chip biasing. The millimeter-wave performance of the switches were verified by on-wafer W-band testing and showed 25 dB isolation, 1.3 dB insertion loss, and 0.8 dB reflection loss at 83 GHz.

ACKNOWLEDGMENTS

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