InP-BASED MONOLITHIC INTEGRATED PIN DIODE SWITCHES FOR MM-WAVE APPLICATIONS

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ABSTRACT:
We report on the measured performance of monolithic integrated mm-wave switching circuits which operate at Ka-Band, V-Band and W-Band as well as on a technology for multi-functional MMICs. The coplanar switches are using high-performance InGaAs PIN diodes as active switching elements. The focus of the illustrated measurement results is on the characteristics of the W-Band switches. The SPST (single-pole single-throw) switches exhibit a low minimum insertion loss of 0.66 dB (1.17 dB) at 85 GHz (84 GHz) with an extremely high corresponding isolation of 29.2 dB (24.5 dB). Even under extremely low DC-power consumption conditions of 0.95 mW (0.8 mW), the switches demonstrated impressive isolations of 23.7 dB (20.7 dB). Excellent mm-wave performance is also achieved with the 94 GHz SPDT (single-pole double-throw) switch. An insertion loss as low as 1.4 dB in transmit mode and 1.8 dB at 96 GHz in receive mode is obtained. A very high isolation value greater than 40 dB is observed. Furthermore, we are developing a heterointegration technology for multi-functional MMICs and present a first comparison between heterointegrated SPST switches (PIN + HFET layer structure) and the normal SPST switches (only PIN structure).

I.) INTRODUCTION:

The rapid developments in terms of communication and sensor systems lead to a growing demand for T/R-modules which operate at millimeter-wave frequencies. Future broadband point to multi- point transmissions will use Ka-Band frequencies in rural environments and V-Band frequencies for urban transmission links, which allow a high local density of base stations. High-resolution sensor systems are aiming on even higher frequencies in W-Band to realize the desired performance. Essential for the use of these systems in commercial applications are the costs of the entire fabrication process of the modules. Today, the T/R-modules are fabricated as MCMs (multi-chip-modules) consisting of various discrete chips like switches, amplifiers, oscillators and mixers. Some of these different functionalities could be implemented on one wafer as shown by Kobayashi et al. (1) for a HFET/HBT/PIN diode multi-functional chip. With this approach, the overall size of the chips is smaller and thus the cost of the module is reduced. Additionally, by reducing the number of the implemented chips less interconnections between the chips are needed which would also reduce the module costs. In this paper we describe the technology for the heterointegration of a PIN/HFET combination using only one MBE growth step and we illustrate a comparison between heterointegrated switches and single PIN diode switches.
So far, we focussed our research activities on the switching circuits as one part of the T/R-module and therefore we also report on the performance of our W-Band coplanar switching circuits (SPSTs, SPDT) which will complete our mm-wave switching circuit family. Very good mm-wave performance has already been demonstrated by the authors (2), (3) at Ka-Band and V-Band frequencies. All switches are using InGaAs PIN diodes as active switching elements. The PIN diode itself offers, due to the high cut-off frequency and the high power-handling capability, a very good mm-wave performance as shown by Putnam et al. (4) using GaAs PIN diodes. The superior material properties of InGaAs make this material very attractive for fabricating PIN diodes and offer substantial advantages over GaAs. The high mobility

combined with the low turn-on voltage leads to a low ON-state impedance of the diode at very low forward bias levels. Consequently, the DC-power consumption of these switches is extremely low while the excellent mm-wave performance (e.g. high isolation) is maintained. This is an important argument for applications where many T/R-modules are needed, e.g. phased array radar. Moreover, the InGaAs PIN diode is compatible with other high-speed devices like InGaAs HFETs demonstrated by Berg et al. (5). The following sections will illustrate the performance of the InGaAs PIN diode switches.

II.) InGaAs PIN DIODE

The PIN diodes were modeled with a small signal equivalent circuit based on discrete device characterization as described in (2). The OFF-state capacitance was determined to be C_{off} = 11.7 fF and the ON-state resistance was R_{on} = 2.5 Ω at 0.8 V forward bias. According to these values, the cut-off frequency is 5.4 THz for the InGaAs PIN diode with a diameter of 10 μm. The characterized diodes showed a turn-on voltage of 0.4 V and a breakdown voltage of –16 V. The intrinsic layer is fully depleted at a reverse bias level of –3 V according to C-V-measurements.

Naturally, the low turn-on voltage and the breakdown voltage affect the power-handling capability of the diodes. Therefore we investigated the switching capability of the InGaAs PIN diode under different input power levels at a frequency of 1.9 GHz and 5 GHz. The measurements indicated that the PIN diode can handle 22.5 dBm of input power at a reverse bias of –3 V without any degeneration of the switching behaviour. The power-handling capability can be further increased if the diode is biased to –5 V. At this bias level, the diode can handle about 26.5 dBm of input power.

A lower forward current which is needed to drive an InGaAs PIN diode into a low-impedance ON-state should lead to a reduced switching time of the diode. This is due to the fact that less charge is stored in the intrinsic zone under forward bias conditions and when the diode is switched to reverse conditions, less charge has to be removed to deplete the i-region in order to drive the diode into the high-impedance OFF-state.

III.) Ka-BAND AND V-BAND SWITCHES:

All coplanar circuits described in this paper were modeled and designed as previously explained in (2). The InGaAs PIN diode was placed directly under the centre signal line of the coplanar waveguide in order to prevent a series resonance of the airbridge inductance and OFF-state capacitance of the diode which would invert the switching behaviour at higher mm-wave frequencies.

Several switching circuits were designed and fabricated to cover the different frequency bands in the mm-wave range. Every SPST switch includes one diode in shunt configuration. The SPDT switches are using one shunt diode in each branch to guide the mm-wave signal.

For the Ka-Band, we implemented a simple SPST switch without on-chip biasing and DC-blocking capacitors, a SPST switch with on-chip biasing and two DC-blocking capacitors (SPST-DC) and a SPDT switch with on-chip biasing and four DC-blocking capacitors. For the operation in V-Band we have only measured the performance of a SPST and a SPST-DC switch so far due to the fact that we were not able to do any three port measurements at this frequency band.

The electrical performances of these switches are very impressive and are listed at the end of the text in Tab. 1 together with the measurement results of the W-Band switches.

IV.) W-BAND SWITCHES:

The S-parameter measurements at the SPST switches were performed up to 110 GHz. The measured mm-wave characteristics of the simple SPST are depicted in Fig. 1. At a centre frequency of 85.5 GHz, this switch exhibits an insertion loss (S21 OFF) as low as 0.66 dB and a record high corresponding isolation value (S21 ON) of 29.2 dB. If the DC bias is lowered to 0.6 V and thus the DC-power consumption reduced to 0.95 mW, the isolation is still at a very high level of 23.7 dB. As can be seen in Fig. 1, the switch could be operated over a wide frequency range without a remarkable degeneration of the switching characteristics.

From 70 GHz up to 94 GHz, the measured insertion loss is smaller than 1 dB and an isolation higher than 25 dB is maintained.

Furthermore, we investigated the performance of the W-Band SPST-DC switch (Fig. 2). The measured S-parameters are illustrated in Fig. 3. The minimum insertion loss (S21 OFF) is measured to be only 1.17 dB at a centre frequency of 84 GHz. The isolation (S21 ON) was determined under two different forward bias conditions and therefore under two different DC-power consumption levels. For a power consumption of 28 mW, the corresponding isolation value is 24.5 dB. Again, we decreased the forward bias and even under an extremely low DC-power level of 0.8 mW (forward bias 0.6 V, forward current 1.34 mA), a high isolation of 20.7 dB is achieved. This verifies the assumption that the low turn-on voltage and the high carrier mobility of InGaAs leads to low-power consumption switching MMICs. Like the SPST switch mentioned before, this SPST-DC design could operate over a wide frequency range. The insertion loss is lower than 1.3 dB from 70 GHz up to 91 GHz and the isolation is higher than 24 dB over the entire measurement range.

The layout of the 94 GHz SPDT switch is illustrated in Fig. 4. The insertion loss in transmit mode was found to be as low as 1.4 dB and in receive mode it was measured to be 1.8 dB at 96 GHz. For this SPDT switch, an excellent isolation value over 40 dB was achieved. Further details on the design and the measured S-parameters will be published in Alekseev et al. (6).

V.) HETEROINTEGRATION TECHNOLOGY :

For multi-functional MMICs, it is possible to use the layer structure of one device e.g. HBT and use it also for the PIN diode structure on the same wafer. But with this approach, trade-offs between the performance of both devices have to be taken into account. In order to maximize the performance of a mm-wave T/R-module, several different layer structures may be integrated on one wafer. For applications in the V- and W-Band, InP-based devices exhibit excellent performance. InGaAs PIN diodes demonstrated impressive switching capabilities and InGaAs HFETs showed the best results for LNAs. The HFET itself could additionally be used as a high-power amplifier and as a mixer.

On the way to the multi-functional MMICs, it is necessary to develop a new technology which enables us to implement different devices on one wafer. On principle, there are two ways to do this. With selective growth, which means growing the first layer structure, etch it selectively and overgrow the whole wafer with the second layers. But this approach, however, needs at least two growth steps. The other method is to stack the layers of the devices, e.g. the PIN diode over the HFET layers. We decided to use the second method. In Fig. 5 the stacked layer configuration for the heterointegration of an InGaAs PIN diode and an InGaAs HFET are shown. The PIN layers are those described in (2) and the HFET layers are listed in (5). This configuration (PIN over HFET) is the only possibility to integrate these two devices with one MBE growth step because the HFET needs a semi-insulating material underneath it to operate properly.

One critical point during the technology process is the selective mesa etching down to the thin cap layer of the HFET. This has to be done very precisely because the cap layer of the HFET should not be damaged due to some overetching. Unfortunately, the n-layer of the PIN diode and the cap layer of the HFET consist both of the same material n^+-InGaAs. Therefore a 11 nm thick InP etch stop layer was implemented which allows a selective etching down to the InGaAs cap layer of the HFET.

The first investigation on the way to the multi-functional chip was the performance evaluation of a PIN diode grown on HFET layers. Therefore the PIN mesa was etched down to the InP etch stop layer using a H_2SO_4-based acid. After removing the InP layer with a HCl solution the remaining layers were etched down to the substrate with the first acid. With this layer configuration, discrete PIN diodes and switches were fabricated to check the performance and to compare it with a single PIN diode wafer.

A comparison between two heterointegrated and two single SPST-DC switches is depicted in Fig. 6. No difference in all four measured S-parameters could be observed. Measurements, which were done on the discrete PIN diode devices and on the simple SPSTs yielded the same result. Consequently, the first step towards the heterointegration of an InGaAs PIN diode and an InGaAs HFET has been made. The next step will be the integration of PIN diode-based and HFET-based circuits on one wafer.

VI.) CONCLUSION

High-performance InGaAs PIN diodes were used to fabricate monolithic integrated coplanar switching circuits for operation frequencies in Ka-Band, V-Band and W-Band. For the SPSTs, insertion losses as low as 0.66 dB and record high isolation values up to 29 dB were achieved. The SPDTs showed minimum insertion losses of 1.4 dB and excellent isolation performances over 40 dB. Furthermore, a technology for the heterointegration of a PIN/HFET multi-functional MMIC is illustrated and measurement results revealed that the electrical performance of the InGaAs PIN diode switches is not degenerated by the presence of the HFET layers underneath the PIN diode.

Figures and tables:

	SPST IL (dB) / IS (dB)	SPST-DC IL (dB) / IS (dB)	SPDT IL (dB) / IS (dB)
Ka-Band	**0.41 / 24.4**	**1.13 / 24.2**	**1.33 / 30.6**
V-Band	**0.52 / 28.6**	**0.84 / 28.0**	**--- / ---**
W-Band	**0.66 / 29.2**	**1.17 / 24.5**	**1.40 / 40**

Tab. 1: Summary of the measured mm-wave performance of the fabricated coplanar InGaAs PIN diode switches

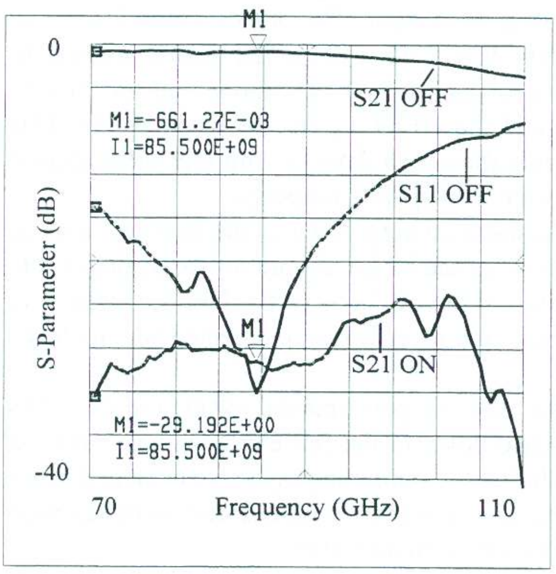

Fig. 1: Measured S-parameters of the W-Band SPST switch.

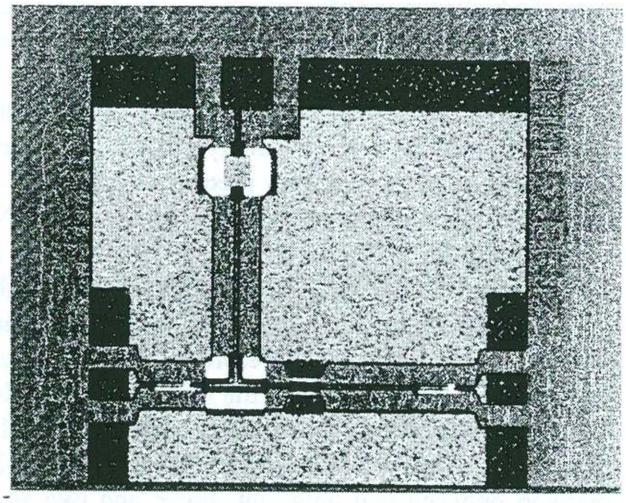

Fig. 2: Photograph of the W-Band SPST-DC switch. Chipsize is 0.81 x 0.84 mm^2

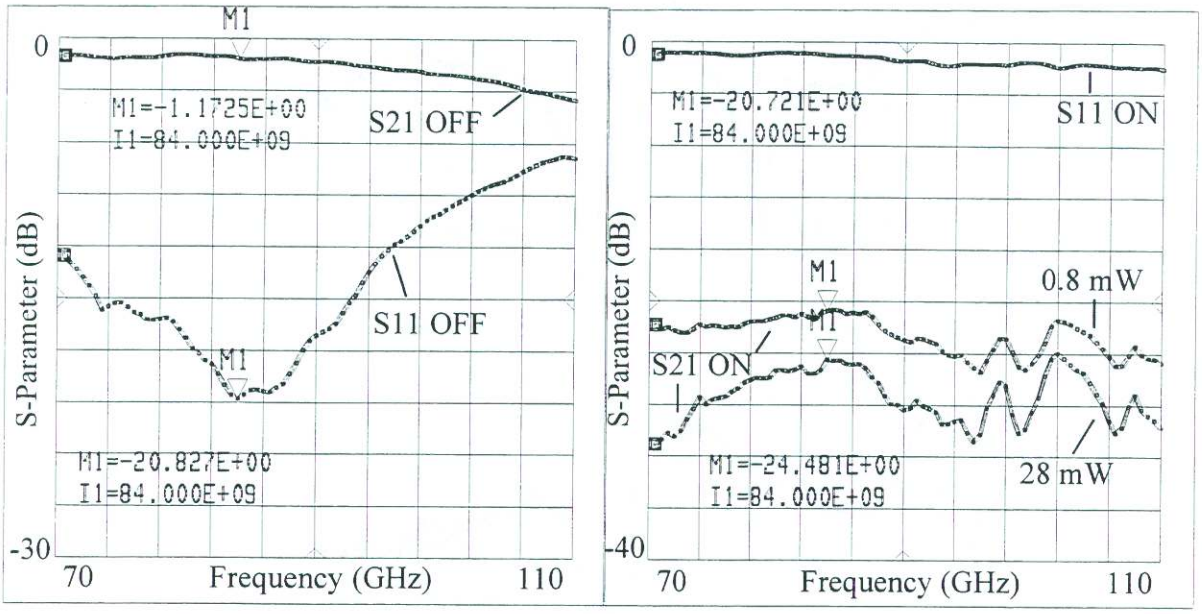

Fig. 3: Measured S-parameters of the W-Band SPST-DC switch shown in Fig. 2. The isolation performance (S21 ON) is illustrated for two different DC-power consumption levels.

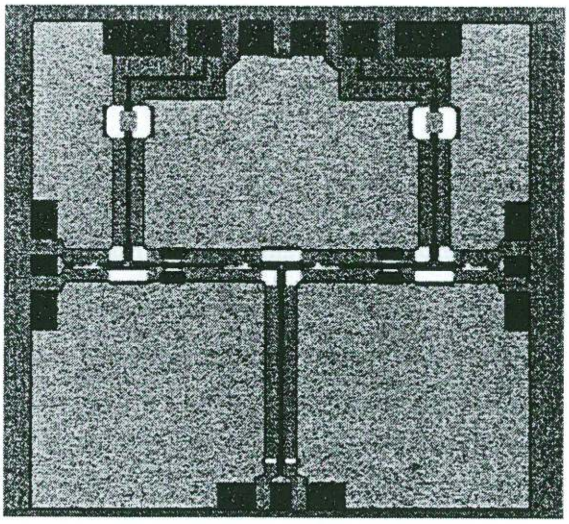

Fig. 4: Layout of the W-Band SPDT Switch. Chipsize is 1.45 x 1.38 mm^2

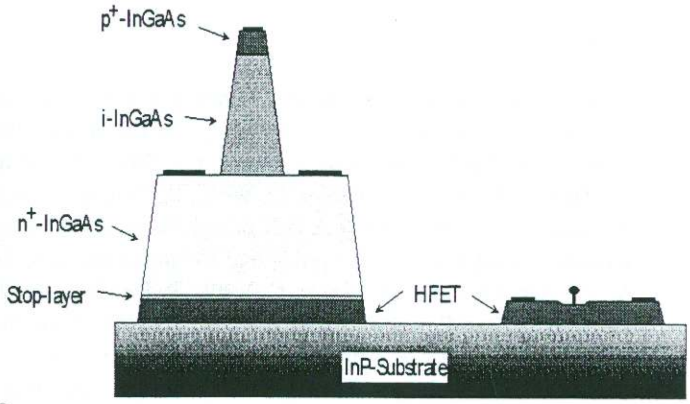

Fig. 5: Layer structure for the heterointegration of an InGaAs PIN/HFET combination

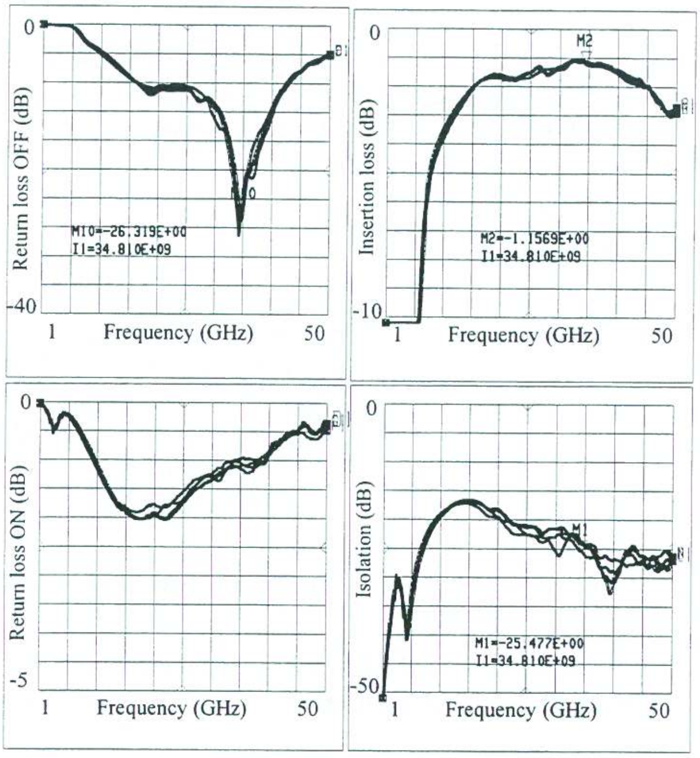

Fig. 6: Comparison of the measured S-parameters of two heterointegrated (PIN on HFET layers) and two normal (only PIN layers) SPST-DC switches

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