Low Power Consumption InAlAs–InGaAs-InP HBT SPDT PIN Diode X-band Switch

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Abstract— **The results of the first monolithic SPDT X-band PIN diode switch fabricated with InAlAs–InGaAs HBT's lattice matched to InP is reported. The InP-based HBT PIN diode switch achieves similar performance to a GaAs implementation but with half the power consumption. The insertion loss is 0.89 dB and the off-isolation is > 35 dB at 10 GHz. The IP3 is 29.6 dBm while the total power consumption is 10.2 mW. Monolithic integration of PIN diodes with an InP-based HBT process provides monolithic switch functions for use in microwave and millimeter-wave communication systems.**

I. Introduction

The fabrication of PIN's and HBT's on the same wafer can lead to monolithic T/R modules which integrate efficient HBT power amplifiers with high power handling switches. Integrated PIN/HBT circuits can also be used to realize variable gain amplifiers, attenuators, phase shifters, and detection type circuits. A previous demonstration has shown successful integration of PIN diodes using AlGaAs–GaAs HBT process to fabricate a 1–10 GHz PIN attenuator and an X-band SPDT switch, while maintaining an HBT f_T and $f_{\max}$ of 23 GHz and 50 GHz, respectively [1].

Both the PIN diode and HBT performance has been shown to be strongly dependent on the vertical MBE material structure. PIN diode device design trade-offs are reported in [2]. The high p+ type base doping and the n+ type subcollector doping reduces the contact resistances of the PIN diode device while also producing low lateral base resistance and collector contact resistance for the HBT device. A compromised performance between a PIN diode with low off-capacitance and an HBT with high cut-off frequency is achieved by choosing the collector layer thickness and doping. While a thick collector layer lowers the off-capacitance of the diode, it also lowers the f_T of the HBT. This is the fundamental performance trade-off of the common HBT/PIN process.

In this letter, we report on the integration of the PIN diodes and HBT's using InAlAs–InGaAs HBT MBE technology. In this technology, the HBT/PIN integration can be achieved with improved HBT device frequency characteristics due to the higher carrier velocity in InGaAs material. Our InAlAs–InGaAs HBT's typically realize an f_T and $f_{\max}$ of 60 and 100 GHz, respectively, and have reported circuit performance up to 40 GHz [3]. This opens up integrated HBT/PIN IC applications in the millimeter-wave frequencies.

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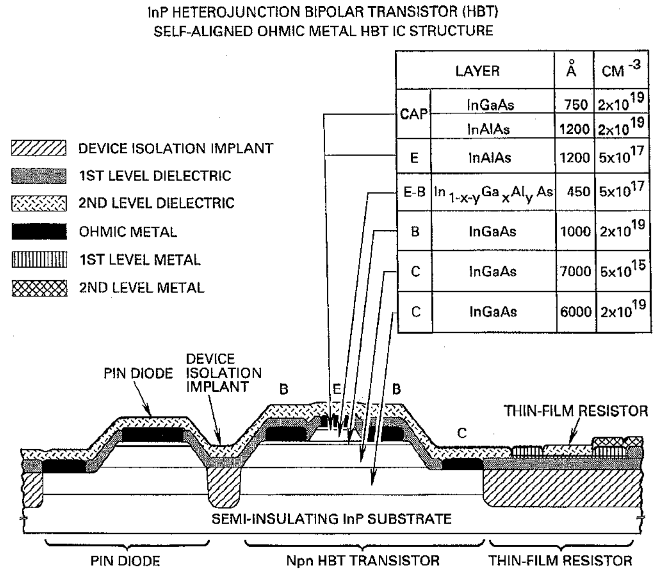

Fig. 1. HBT-PIN diode MBE profile.

The following sections will describe the performance of an X-band SPDT switch fabricated using InAlAs–InGaAs HBT's and how these results compare with the same switch circuit fabricated using AlGaAs–GaAs HBT technology.

II. InAlAs–InGaAs HBT Process

The MBE profile of InAlAs–InGaAs HBT and PIN process is shown in Fig. 1. These structures were grown by MBE on both 2-in and 3-in semi-insulating InP substrates. Be and Si were used as p- and n-type dopants, respectively. This profile incorporates a base thickness of 1000-Å uniformly doped to 2×10^{19} cm^{-3}, an n- collector 7000-Å thick and lightly doped to 5×10^{15} cm-3, and an n+ subcollector doped to 2×10^{19} cm^{-3}. The base-emitter junction is compositionally graded by using a quarternary layer of $\mathrm{In}_{1-x-y}\,\mathrm{Ga}_x\,\mathrm{Al}_y$ As between the base and the emitter. Compositional grading gives the HBT higher current gain, lower $V_{ce}(sat)$, and a lower and more uniform V_{be}. A 1-μm fully self-aligned HBT process was used to fabricate the transistors.

The fabrication involves a mesa etch process to access the base and collector, and a self-alignment scheme to minimize the distance from the base ohmic metal to the emitter mesa. Nonalloyed contacts (Ti–Pt–Au) were used for the emitter and collector. Isolation was achieved by mesa etch. An f_T and $f_{\max}$ of 60 GHz and 100 GHz, respectively, were achieved

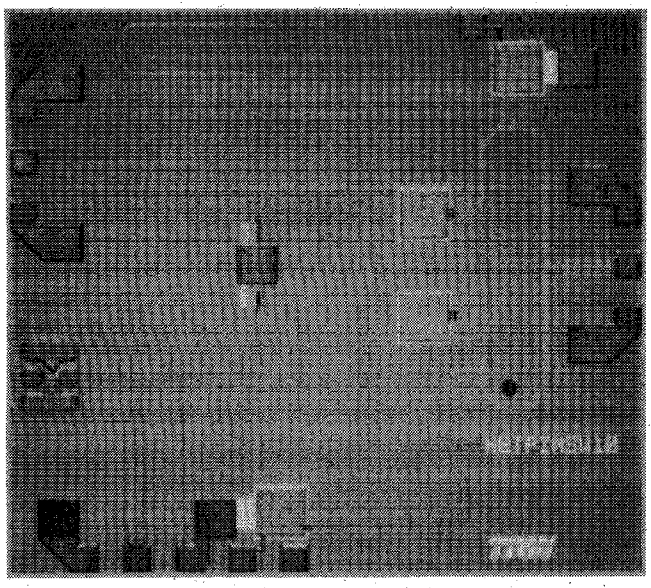

Fig. 2. Photograph of the SPDT X-band PIN diode switch. Chip size is 2.4 × 2.4 mm^2.

for a 1 × 10-μm^2 single-emitter HBT device at $J_c \approx 40 - 50$ kA/cm^2.

The lightly doped collector is used to construct the intrinsic layer of the PIN diode. The heavily doped base and sub-collector constructs the P+ and N+ type layers of the PIN. The reverse breakdown voltage is on the order of 10 V which is about half of that produced with AlGaAs–GaAs HBT technology. The ideality factor of the PIN diode is approximately 2.0 while the forward bias turn-on voltage is 0.66 V at $I_d = 8$ mA. The turn-on voltage is 1.26 for the AlGaAs–GaAs HBT PIN diodes, respectively. The lower turn-on voltage of the InAlAs–InGaAs HBT PIN's translates to half the power consumption for similar rf performance.

III. X-Band SPDT Switch Performance

A photograph of a single-pole double-throw X-band PIN diode switch fabricated using InAlAs–InGaAs HBT technology is shown in Fig. 2. Similar switch topologies have been reported [4]–[7]. The circuit described here is identical to one previously demonstrated in AlGaAs–GaAs HBT technology [1]. Each arm of the switch consists of two 5 × 15-μm^2 dual base shunt pin diodes in parallel. The shunt configuration is used for reliable thermal grounding. Quarter-wavelength lines transform the low impedance "on"-diode to an open at the output port for good isolation. Quarter-wave transformers are also used as rf chokes in the bias network of each pin diode arm. MIM capacitors were used to terminate the quarter-wave lines instead of radial stubs in order to suppress coupling which could degrade the off-isolation. The chip area is 2.4 × 2.4 mm^2.

A plot of the insertion-loss and isolation is shown in Fig. 3. The insertion loss is 0.89 dB at 10 GHz. The 1-dB bandwidth of the insertion loss is around 35% and is limited by the bandwidth of the quarter-wave transformers. The "off" isolation is >37 dB. The isolation is determined mainly by the impedance of the short path to ground of the forward biased shunt diode. The impedance path to ground through the diode is comprised mainly of the total contact resistance of the shunt diode in series with the inductive backside via. At X-band, the contact resistance of the diode, $\approx 2 - 4$ ohms, dominates this impedance path. The input and output return-losses at 10 GHz are better than 15 dB.

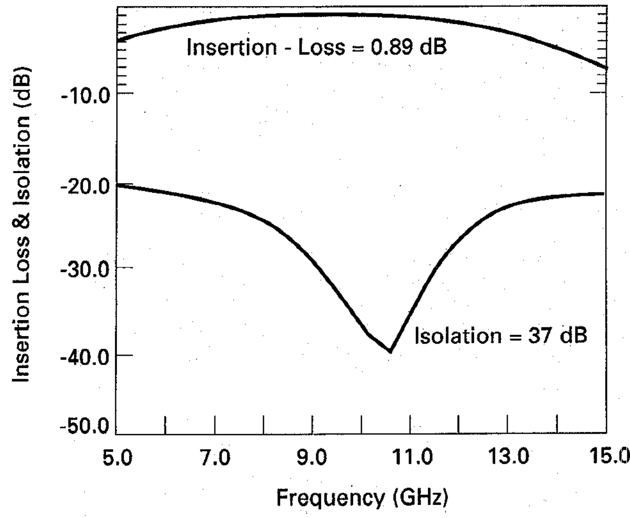

Fig. 3. Insertion-loss and isolation performance of the X-band switch.

TABLE I
Comparison of InAlAs–InGaAs and AlGaAs–GaAs HBT-PIN X-Band SPDT Switch Performance.

Parameter	InAlAs–InGaAs HBT	AlGaAs–GaAs HBT
Insertion Loss	0.89 dB	0.82 dB
Isolation	37.7 dB	25 dB
IP3	29.6 dB	32.7 dBm
Input Return Loss	34 dB	27 dB
Output Return Loss	25 dB	24 dB
Reverse Breakdown Voltage	10 V	20V
Power Dissipation	10.6 mW	20.2 mW

Table I compares the performance of X-band SPDT switches fabricated using InAlAs–InGaAs and AlGaAs–GaAs HBT process technologies. The insertion loss is within 0.1 dB while the isolation for the InAlAs–InGaAs switch is better by more than 10 dB. This improvement in isolation may be due to a lower PIN series contact resistance as a result of the higher p+ base and n+ sub-collector doping levels of the InAlAs–InGaAs HBT/PIN structure. The IP3 of the InAlAs–InGaAs switch is $\approx$ 30 dBm, slightly lower than the AlGaAs–GaAs switch performance of $\approx$ 33 dBm at a reverse bias of 7 volts. The input and output return-losses are comparable, all of which are better than 20 dB. The total power dissipation of the InAlAs–InGaAs switch is 10.6 mW, about half that of the AlGaAs–GaAs switch, due to the lower turn-on voltage of the InAlAs/InGaAs PIN diode.

IV. Conclusion

The performance of an X-band SPDT switch fabricated in InAlAs–InGaAs-InP HBT technology has been reported. This circuit demonstrates the monolithic integration of PIN diode switch functions with an InP-based HBT technology which yields transistor f_t and $f_{\max}$ of 60 and 100 GHz, respectively. Improved PIN diode switch performance was achieved with the InAlAs–InGaAs HBT technology compared to the AlGaAs–GaAs HBT technology.

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