A Monolithic HEMT Passive Switch with Integrated HBT Standard Logic Compatible Driver for Phased-Array Applications

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***Abstract*—We have achieved the first demonstration of a monolithically integrated high electron mobility transistor (HEMT) passive switch with a heterojunction bipolar transistor (HBT) switch-driver circuit that represents key integrated mixed-signal functions. The HEMT-HBT monolithic microwave integrated circuit (MMIC) is fabricated using selective molecular beam epitaxy (MBE). The single HEMT series switch is driven by an HBT circuit that provides both level shifting and wide voltage drive swing to adequately turn the passive HEMT switch device on and off. The MMIC can be made compatible for operation from either standard TTL or CMOS control signals. The series $0.2 \times 200\,\mu m^2$ passive HEMT switch achieves 1.6–2.9 dB insertion loss over a 50 MHz to 12 GHz band when the HEMT is turned on. The corresponding return-losses are >10 dB across the band. When the switch is turned off, the isolation ranges from >40 dB at 1 GHz and decreases to 15 dB at 12 GHz. This integrated HEMT switch and HBT switch driver MMIC represents a basic building block that can be applied to programmable phase shifters used in phased-array antenna applications and can result in a dramatic reduction in size and improvement in performance of these systems.**

I. INTRODUCTION

IN PHASED-ARRAY systems, the antenna is comprised of a multitude of receiver elements in a geometrically configured array. Each element has its own receiver and/or transmitter, both of which require programmable phase shifters. These phase shifters often consist of a bank of several discrete passive phase shifters with corresponding electronic switches for selecting the appropriate phase shift path when the beam is being steered. These switches are controlled by a digital word and require a decoder and level shifter/driver circuit between the programmable word and the switches. Usually, these functions are not monolithically integrated with the phase shifter monolithic microwave integrated circuits (MMIC's). In large arrays with several antenna elements, much of the peripheral circuitry such as the decoder, level shifter/driver, and control lines can substantially contribute to the size and weight of the phased array, but moreover, they can limit the minimum spacing between the elements due to the excessive hardware. For example, the optimum element spacing that maximizes scanning angle or beam steering coverage while minimizing grating lobe interference is a half-wavelength. At millimeter-wave frequencies, this optimum element spacing is roughly on the order of the size of a typical phase-shifter (MMIC). By integrating the driver and level-shift circuitry with the high electron mobility transistor (HEMT) switch, much of the overhead in size and weight of the peripheral digital control circuitry can be eliminated and a much smaller element spacing can be achieved, improving the beam-scanning coverage.

In this work we demonstrate the monolithic integration of these basic building blocks, namely, a series passive HEMT switch with an HBT standard logic compatible driver circuit using selective molecular beam epitaxy (MBE). While the radio-frequency (rf) performance of the HEMT-HBT switch-driver MMIC is limited to the lower microwave spectrum, it represents the first MMIC that integrates these mixed-signal circuit functions required for the programmable phase-shifter MMIC's used in phased array applications. The selective HEMT-HBT MBE technology and RF results of the mixed-signal circuit are discussed in this letter.

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II. SELECTIVE MBE AND MERGED HEMT-HBT PROCESS

The HEMT-HBT monolithic integration was realized using selective MBE and a merged HEMT-HBT process, which has been documented in detail elsewhere [1], along with some of its first MMIC circuit demonstrations [2], [3]. This technology integrates 0.2-μm gate-length pseudomorphic InGaAs-GaAs HEMT's with 2-μm emitter-width GaAs-AlGaAs HBT's. The HEMT devices achieve $g_m > 500$ mS/mm with $f_T \sim 60$ GHz. The HBT devices achieve $\beta = 60$, with f_T and $f_{\max}$ of 23 and 50 GHz, respectively, at a current density $J_c = 20\,\mathrm{kA/cm}^2$. The monolithically integrated HEMT and HBT devices have demonstrated dc and microwave performance equivalent to that of baseline single-technology devices.

III. HEMT SWITCH WITH INTEGRATED HBT DRIVER

For switch applications requiring low insertion loss at millimeter-wave frequencies, the passive HEMT switch is often used because of its low noise, millimeter-wave frequency, and low dc power performance. Such HEMT switches are commonly used in programmable phase shifters and attenuators. Because of their enhancement mode bias and negative voltage pinch-off requirements, however, a standard logic (CMOS/TTL) compatible switch-driver/level-shifter circuit must be employed. Logic compatible driver circuitry is preferably designed using bipolar technology like HBT's, because they offer good drive capability and switching speeds

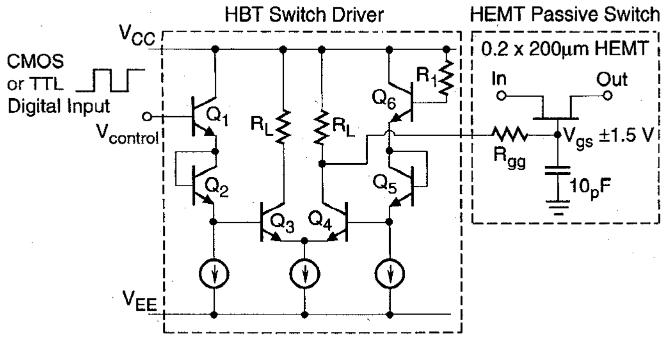

Fig. 1. Circuit schematic of CMOS/TTL-compatible HBT switch-driver integrated with a series passive HEMT switch.

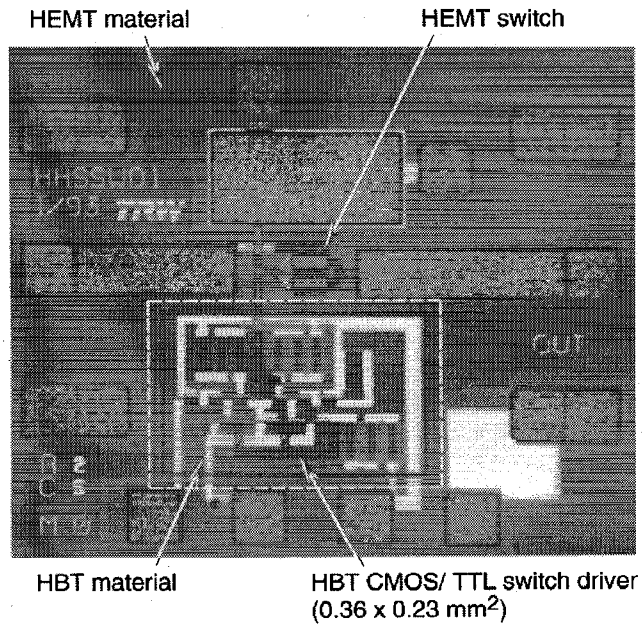

Fig. 2. Microphotograph of the HEMT-HBT switch MMIC. The total MMIC is $0.88 \times 0.75\,\text{mm}^2$ in area.

under low dc power operation. In many cases where there is >4 bits of control resolution (>16 states) in a digitally controlled passive HEMT phase shifter or attenuator, the dc power and size will be determined by these peripheral control/driver circuits. The monolithic integration of HBT switch driver circuitry would eliminate the need for several off-chip silicon driver IC's, discrete wire-bonds, and interconnect substrates, which limit the minimum size of the phased array.

Both passive HEMT switch and logic compatible driver/level-shifter circuit functions have been integrated as a single bit switch/driver MMIC building block. The schematic of this TTL/CMOS logic controlled HEMT MMIC switch is shown in Fig. 1. A $0.2 \times 200\,\mu\text{m}^2$ HEMT device is used as a series passive FET switch that has an on-resistance of ≈5–6 Ω and an off-capacitance of ≈0.037 pF. The HBT driver circuitry can be biased to accept either standard CMOS or TTL control logic signals by adjusting the Vcc and Vee supplies as well as the current drawn through the current sources. The driver circuit converts the logic input, V_{control}, to a ±1.5 voltage swing centered about the HEMT gate threshold range, which is directly applied to the gate of the passive HEMT switch. For a typical HEMT device, the V_{gs} turn-on voltage is ≈0.5 V and the V_{gs} pinch-off is ≈−3 V. The ±1.5 voltage swing at the output of the HBT driver circuit is just enough to adequately bias the HEMT switch on and off, given that the nominal gate bias, V_{gs}, is centered at ≈−1.3 V.

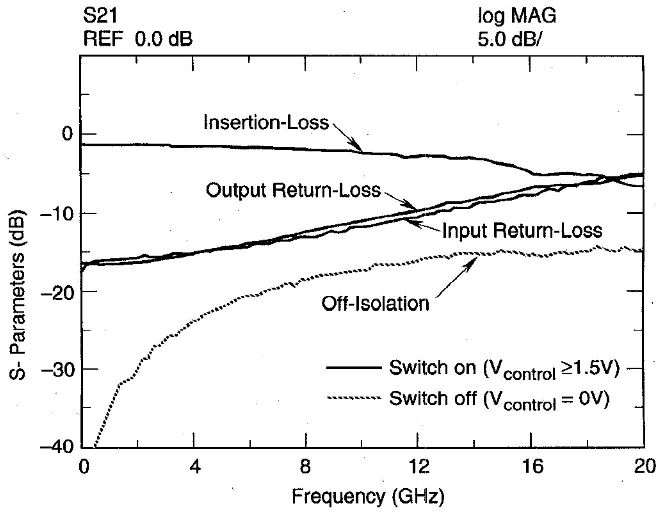

Fig. 3. Broadband insertion-loss, input and output return-loss, and off-state isolation of the HEMT-HBT MMIC switch.

Fig. 2 shows a microphotograph of the HEMT-HBT switch MMIC. The total MMIC is $0.88 \times 0.75\,\text{mm}^2$ while the HBT driver circuit is only $0.36 \times 0.23\,\text{mm}^2$, or 12.5% of the total chip size. This overhead in size of the HBT switch driver circuitry is expected to be well under 2–3% of a fully microwave matched passive HEMT switch integrated with a microstrip phase shift element.

Fig. 3 gives broadband insertion-loss, return-loss, and off-state isolation of the HEMT-HBT MMIC switch. At a control voltage level of ≥1.5 V (a threshold centered for 3-V CMOS logic), the HEMT switch is turned fully on ($V_{gs} = 0.5$ V) and achieves an insertion loss of 1.6 dB at 50 MHz, which reduces to 2.9 dB at 12 GHz. The insertion-loss is slightly higher than that predicted from the typical passive HEMT on-resistance. Atypically high source/drain contact resistances could explain the performance degradation. The corresponding input and output return-losses are >10 dB across this frequency range. At a control voltage of 0–1.4 V, the HEMT switch is turned off ($V_{gs} \approx -3$ V) and achieves an off-isolation of >40 dB at 1 GHz, which reduces to about 15 dB at 12 GHz. The total power consumption of the HBT switch driver is 30 mW using a $V_{cc} = 1.5$ V and a $V_{ee} = -3.5$ V. It should be noted that the measured switch performance is reflective of the performance of a large series passive $0.2 \times 200\,\mu\text{m}^2$ HEMT device that has no matching circuitry. Thus, in this demonstration, the performance of the switch is limited by the passive HEMT characteristics, which is dependent on device size. The performance could be enhanced at higher frequencies by employing matching circuitry and choosing an optimal device size.

IV. Conclusion

A single-bit passive HEMT switch with integrated HBT logic compatible switch driver was demonstrated. The monolithic HEMT-HBT integration was achieved using selective

MBE technology. Potential size and performance benefits were suggested for phased array applications by way of monolithic integration of HEMT switch and HBT switch control functions onto the same chip. This work illustrates just one of the potential application advantages that the HEMT-HBT selective MBE IC technology offers. Further development of the HEMT-HBT MMIC technology will reveal the true potential of this new revolutionary MMIC integration capability.

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