EMBEDDED TRANSMISSION LINE (ETL) MMIC FOR LOW-COST, HIGH-DENSITY WIRELESS COMMUNICATION APPLICATIONS

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ABSTRACT

A new embedded transmission line (ETL) MMIC approach which allows flexibility in mixing different transmission line types (i.e., coplanar and striplines) for maximum MMIC (Monolithic Microwave Integrated Circuits) design flexibility and permits the elimination of back-side processing for low production cost is described. This ETL MMIC approach is an enabling technology allowing for low-cost, batch fabrication, and high-density integration of microwave and RF components (including silicon mixed signal products) for emerging wireless communication applications.

INTRODUCTION

Advanced microwave multi-chip assemblies combine MMIC chips and other components using low-cost, batch fabrication and assembly processes. To lower the cost with higher yield, new design concepts, other than conventional microstrip-based GaAs MMICs with chip-and-wire assembly techniques, must be used. Greater demand in module packing density requires multichip integration in the vertical dimension, necessitating the use of vertically integratable MMIC components. This is especially true for handheld communication equipment. We have conceived and demonstrated an embedded transmission line (ETL) MMIC approach which allows flexibility in mixing different transmission line types (i.e., coplanar and striplines) for maximum MMIC design flexibility and, in one configuration, permits the elimination of back-side processing for low production cost. The ETL MMIC concept, circuit designs, microwave performance, and system applications are described in this paper.

EMBEDDED TRANSMISSION LINE (ETL) MMIC TECHNOLOGY

The new Embedded Transmission Line (ETL) MMIC approach utilizes matching circuits with transmission lines and lumped passive components embedded in a low-K dielectric (such as polyimide) medium. Figure 1 shows the sketch of an ETL MMIC cross section with an unthinned GaAs substrate. The new MMIC can be used either upright (with the GaAs substrate down) or in inverted configuration for flexibility of vertical integration in modules. This approach differs from traditional MMIC design in that transistor

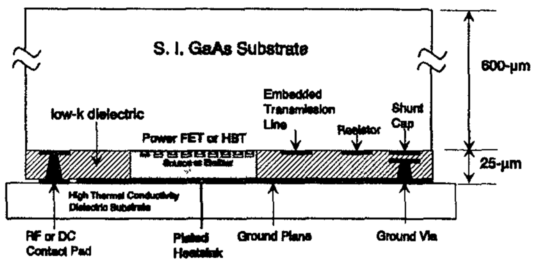

Figure 1: ETL Power MMIC with Flipped Transistor

sources or emitters are individually grounded to the top-side ground plane (through plated heatsink over source or emitter interconnect bridges) to provide excellent heat transfer (in inverted configuration) and low-inductance ground connections. Other passive components such as transmission lines, resistors, and capacitors are fabricated on the GaAs as before; they are redesigned taking into account the new circuit configuration. Shunt components such as MIM capacitors are readily grounded through gold plugs in the thin dielectric rather than the GaAs substrate as in the conventional MMIC approach. The thickness of the dielectric layer can be on the same order as the plated source/emitter (25 to 50 µm). For RF I/O and biases, connecting pads are isolated from the top-side ground plane, allowing for on-wafer testing and flexible interconnections to other module components. No through-GaAs substrate vias (as in the conventional MMIC case) are required for the shunt components, which greatly simplify the process and reduce the costs. If desired, the substrate can be thinned (Figure 2, showing I/O's through GaAs substrate) and extra ground plane provided to allow desirable I/O pads for vertical integration with other ETL MMIC chips or multi-layer distribution board. The I/O and bias pads can be provided either through the GaAs layer or the polyimide layer, depending on applications.

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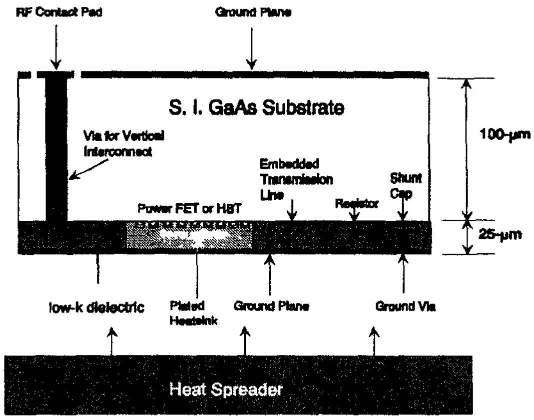

Figure 2: ETL MMIC with I/O Taken From GaAs Side

The characteristics of embedded transmission lines were obtained using a 3-D electromagnetic simulator software. Figure 3 shows the characteristic impedance and effective dielectric constant of standard microstrip lines (with 4-mil thick GaAs substrate) and embedded transmission lines with a 1-mil thick polyimide layer (dielectric constant = 3) for two GaAs substrate thickness (4 and 25 mils). As expected, the effect of the thin polyimide layer with its associated ground plane is to lower the characteristic impedance and effective dielectric constant for a given conductor width.

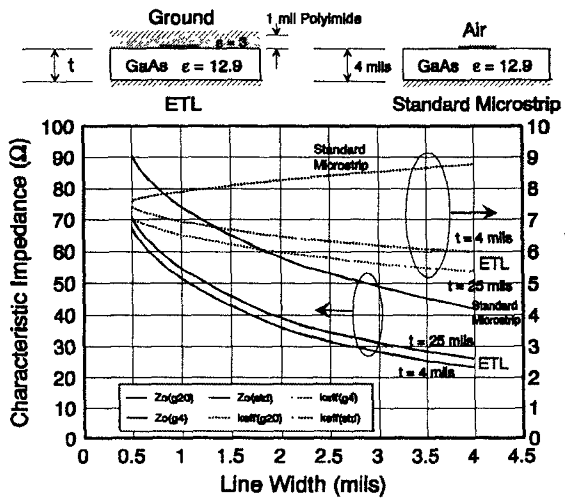

Figure 3: Transmission Line Characteristics

ETL MMIC DESIGN, FABRICATION, AND PERFORMANCE

Using the above described ETL MMIC concept, we have demonstrated power amplifiers at 44 GHz, low-noise amplifiers at 20-, 28, and 38 GHz, and 4-bit phase shifters at 20- and 44 GHz. The 20 and 44 GHz components will be integrated in 20 GHz receive module and 44 GHz transmit module for EHF airborne phased array antenna applications.

AlGaAs/InGaAs on GaAs pseudomorphic high electron mobility transistor (pHEMT) technology was used for demonstrating our ETL MMIC approach. As in conventional MMICs, the devices are used for power, low-noise amplifications, and switches (for phase shifters). The circuit design technique is similar to that of conventional MMICs by using S-parameters, large-signal load-pull and noise parameter data, and switching characteristics (on resistance and off capacitance). Only slight modification of conventional MMIC fabrication technique is required for ETL MMIC fabrication. The process steps are identical to conventional MMIC process up to the source interconnect level. Then, a thin layer of polyimide is applied and the first thick metal interconnect formed. Plated 25-μm height gold via "plugs" are then formed to connect the device source and capacitor (shunt) to the ground plane. Necessary I/O's and bias vias are also formed at this point. A thick polyimide is than spun coated and cured to a thickness of 25 μm. Planarization and dielectric thickness control is achieved through mechanical lapping of the polyimide. Coplanar pads suitable for on-wafer rf charactrization are provided on either the GaAs or polyimide ground plane.

Figure 4 shows an ETL Q-band four-stage MMIC amplifier using 50 μm/100 μm/200 μm/400 μm gate width pHEMTs. The gate length is 0.25 μm. Figure 4(a) shows the front or active side (through 1 mil thick polyimide) of the MMIC chip. Figure 4(b) shows the backside of the GaAs with input/output vias and bias pads. The GaAs substrate thickness is 4 mils. The chip size is 60 by 160 mils. The MMIC was mounted with the polyimide-side ground plane down to the heatsink. Stable amplifier operation has been obtained at 44.5 GHz (the design center frequency) with up to 27 dB small-signal gain (1 dB bandwidth = 1.5 GHz). With increased input drive, an output power of 100 mW with 20 dB gain was achieved. This ETL MMIC will be vertically integrated with the ETL phase shifter MMIC on the backside (stacked) for Q-band transmitter array applications.

ETL low-noise amplifiers at K-, Ka-, and Q-band were also demonstrated. Figure 5 shows the K-band three-stage ETL MMIC low-noise amplifier with 150 μm gate width pHEMT in each stage. The ETL chip

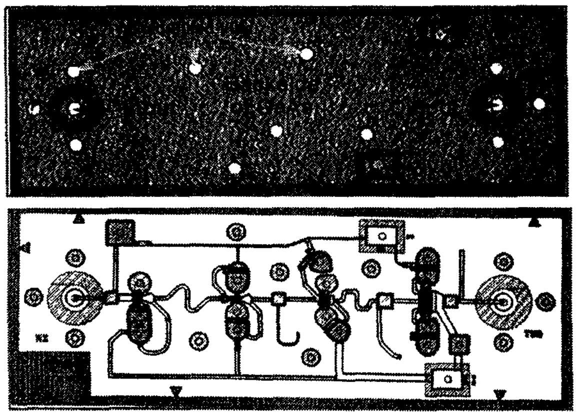

Figure 4: 44 GHz Four-Stage ETL MMIC Amplifier

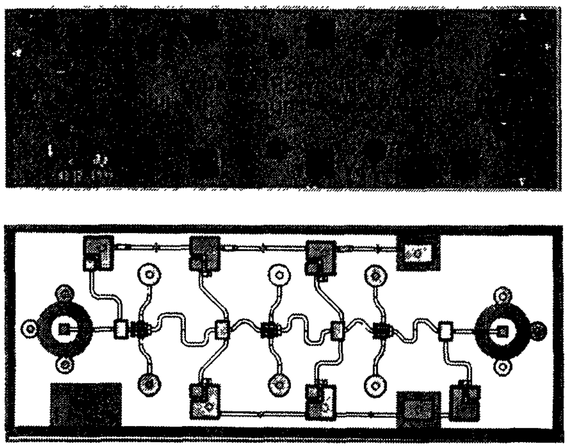

Figure 5: A Three-Stage K-Band ETL MMIC Low-Noise Amplifier

achieved a gain of ~ 30 dB over the 19 to 28 GHz frequency band (Figure 6). Figure 7 shows the noise performance. A noise figure of 1.3 dB with 25 dB gain was obtained at 22 GHz. The noise figure remains below 2 dB up to 25 GHz. Other amplifiers on the same mask achieved gains of up to 25 dB over a very broadband centered at 28 GHz and 36 GHz. In addition to power and low-noise amplifiers, we also demonstrated ETL MMIC phase shifters at K- and Q-band frequencies. Figure 8 shows chip layout and photograph of the top side (polyimide) configuration of a K-band phase shifter. Switched lines with pHEMT switches were used. Since the pHEMT is operated at zero bias, no dc power is consumed. The chip measures 86 mils x 176 mils, including RF transitions for vertical integration with other multilevel circuit board. Figure 9 shows the relative insertion phase of the four major phase states. Excellent performance is achieved at the design center frequency of 21 GHz. The circuit layout of the Q-band four-bit phase shifter is shown in Figure 10. The chip measures 61 mils by 138 mils.

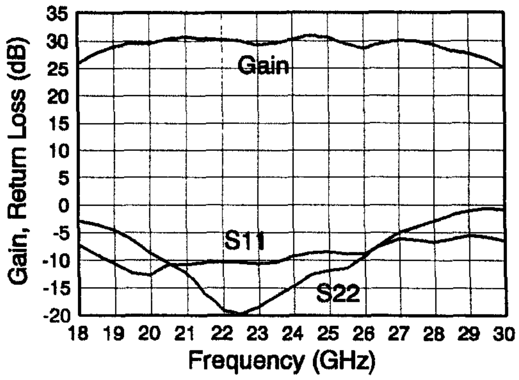

Figure 6: Gain-Frequency Response of a K-Band Three-Stage pHEMT ETL MMIC Amplifier

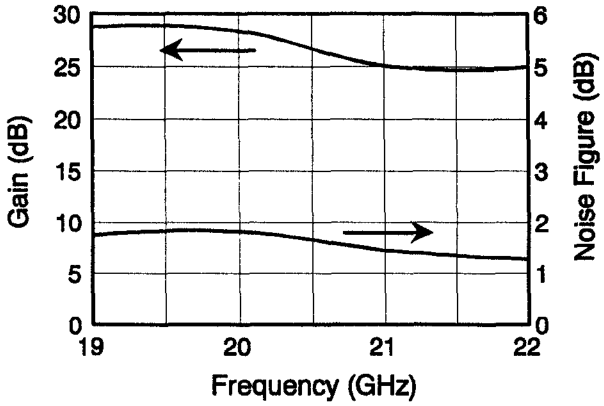

Figure 7: Noise Performance of a K-Band Three-Stage pHEMT ETL MMIC Amplifier (Vd = 2 V; Id = 37 mA)

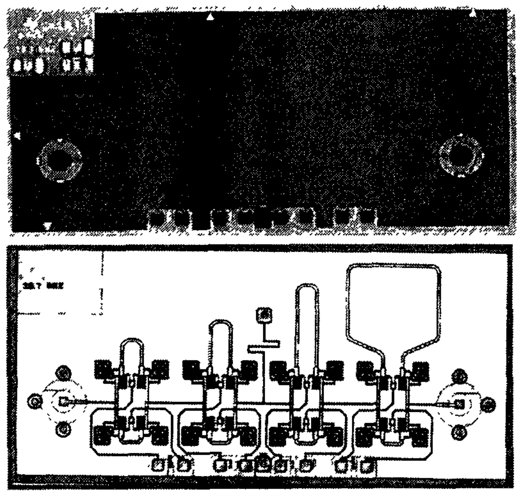

Figure 8: K-Band Four-Bit ETL MMIC Phase Shifter

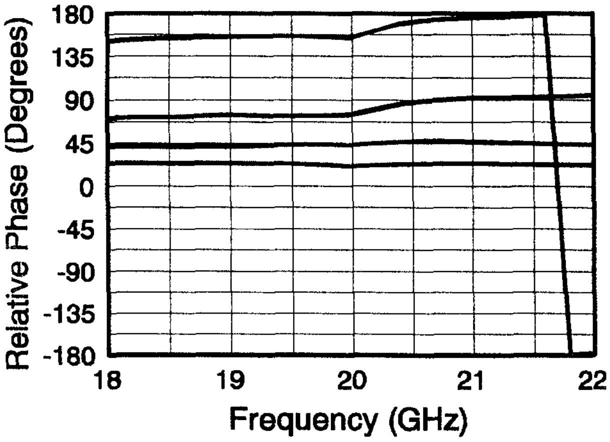

Figure 9: Insertion Phase of K-Band Four-Bit ETL MMIC Phase Shifter

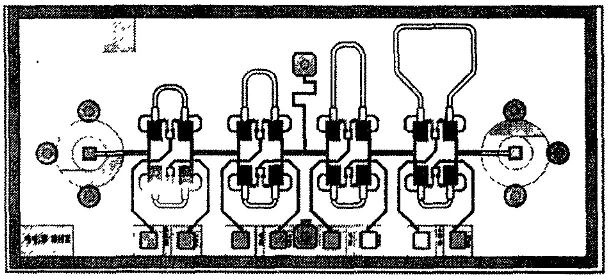

Figure 10:Q-Band Four-Bit ETL MMIC Phase Shifter

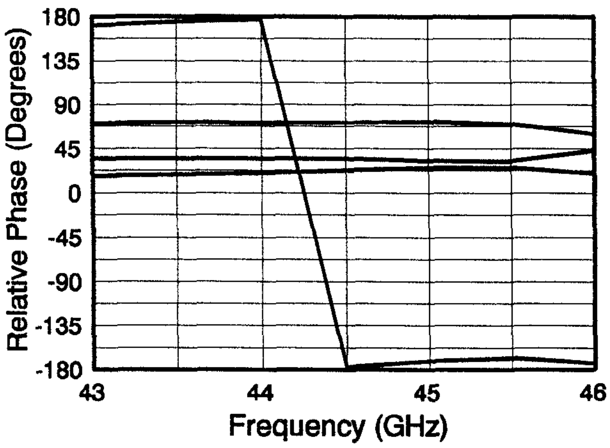

Figure 11: Insertion Phase of Q-Band Four-Bit ETL MMIC Phase Shifter

The insertion phase of the Q-band four-bit phase shifter is shown in Figure 11. Deviations of the 45-degree and 90-degree bits are caused by proximity coupling from a dc return pass as the measured individual phase bits are very close to the design value. Rerouting of the dc return pass is expected to improve the phase responses.

SYSTEM APPLICATIONS OF ETL MMICS

The ETL MMICs described above have been developed to demonstrate low-cost, ultra-compact solid-state transmit and receive phased-array modules for advanced airborne phased-array communication applications. Since only coplanar I/O's and bias pads are used for the ETL MMIC, it is very suitable for low-cost, batch fabrication, and integration with multilayer board (for RF and DC distribution and control signals) by using surface mounting technique for chip-to-board or chip-to-chip (stacked MMIC) interconnection without using bonding wires. For single-function applications, we also demonstrated the performance of low-noise and power ETL MMIC amplifiers with 25-mil thick, unthinned GaAs substrate. Thus, we have shown that it is feasible to design a MMIC without backside processing (wafer thinning, via etch, and plating), resulting in significant cost savings in production.

CONCLUSIONS

Our newly developed Embedded Transmission Line (ETL) MMIC approach is an enabling technology allowing for low-cost, batch fabrication, and high-density integration of microwave/millimeter-wave and RF components (including silicon mixed signal products) for military radar, EW, and emerging commercial wireless communication applications. The same concept can also be used for high-speed clock distributions of silicon ICs. Because of the quasi-hermetic nature of the ETL MMIC, it also simplifies the packaging requirement with resulting lower cost. Application areas include: wireless cable systems (such as 28 GHz LMDS), wireless local area network (WLAN), mobile satellite communications, and automotive radar @77 GHz.

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