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GaAs MMIC Research and Development in Australia

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Abstract - Rapid growth in the demand for millimetre-wave components in telecommunications and defence-related applications has resulted in an increasing need for monolithic microwave integrated circuits (MMICs). In partnership with the Australian Department of Defence and commercial clients, CSIRO Telecommunications and Industrial Physics is putting a substantial research effort into developing MMIC-based telecommunication systems. MMICs, fabricated using pseudomorphic HEMTs and Schottky diodes as active devices, cover a frequency range of 1-100 GHz. Diode-based mixers, multipliers, up and down converters, HEMT-based amplifiers (both for low-noise and power applications) and composite diode and HEMT-based circuits such as voltage control oscillators have been designed and successfully fabricated. These circuits have been used in applications such as wireless backhaul links and high-data-rate wireless communication and local-area networks. This paper presents an overview of CSIRO's MMIC development program.

I. Introduction

Research in developing radar systems started at the CSIRO Radiophysics Laboratory (now part of CSIRO Telecommunications and Industrial Physics) during the second world war. Over the years, CSIRO has developed expertise in the design and development of microwave components and antennas for radio astronomy receivers. This led to major commercial projects in aviation, telecommunications, defence electronics and computer networking. Today, CSIRO Telecommunications and Industrial Physics is recognised as a world leader in millimetre-wave technology.

Increasing demand on existing telecommunication services will inevitably result in crowding the limited spectrum available at lower microwave frequencies. This, along with the need to transfer data with increasing speed, has resulted in telecommunication service providers developing wide-band systems that operate at millimetre-wave frequencies (30 to 300 GHz). Systems based on MMICs would not only be cost effective but also be reliable than their counterparts constructed from discrete components. In 1984, with the expectation that the key components of such wideband millimetre-wave systems would be integrated circuits, CSIRO initiated a program of research and development in GaAs MMIC technology. In 1990, a GaAs MMIC Design and Prototyping Service was established for the communication and defence industries. The aim was to provide these industries with a convenient low-cost and low-risk entry point to the new technology. This provided an alternative to the high initial cost of commercial foundry runs required to develop custom-designed GaAs MMIC prototypes.

Over the years CSIRO's GaAs MMIC Design and Prototyping Service has successfully designed, fabricated, tested and packaged a number of GaAs microwave and millimetre-wave integrated circuits with applications in defence, millimetre-wave trunks for personal communications, and wireless distribution of wide-band information services [1]. A number of performance-verified MMIC designs are now available as part of an ever-expanding library, developed through a parallel program of generic research. To assist clients who require large quantities, CSIRO has established a relationship with a major US foundry. This provides a convenient path to large-scale manufacturing of circuits prototyped at CSIRO.

This paper briefly describes the design and fabrication processes used and presents performance data of typical MMICs produced using CSIRO's pseudomorphic HEMT and planar diode technologies.

II. mm-Wave Circuits and Systems Design

Considerable time has been spent in constructing accurate models for both active and passive devices which are used in the design of MMICs fabricated in CSIRO. Active elements used are: HEMTs (power and low-noise) and diodes (Schottky and varactor). Passive elements used are: capacitors, resistors, inductors, directional couplers, air-bridge cross-overs and via-holes for contacts to the ground plane. These models can accurately predict the performance of MMICs such as small signal amplifiers, mixers, frequency doublers and oscillators operating up to 100 GHz. Large signal device models are also available for a number of active device topologies. These are based on the Curtice-cubic, non-linear FET model implemented in the Libra circuit simulator. The modelling work has established the basis for first-pass design success in MMICs fabricated recently. In addition to this, an accurate, custom-designed, physics-based, non-linear model for HEMTs [2] has also been developed.

Figures 1-4 show some of the circuit layout of MMICs designed using Libra as design tools. Figure 4 is an MMIC design with a high level of complexity. It contains a combination of amplifiers, VCOs and mixers, which, by using an innovative switch, allows a wide range of possible user-selectable sub-system configurations. Other novel circuits designed are bi-directional amplifiers and high-speed switching circuits.

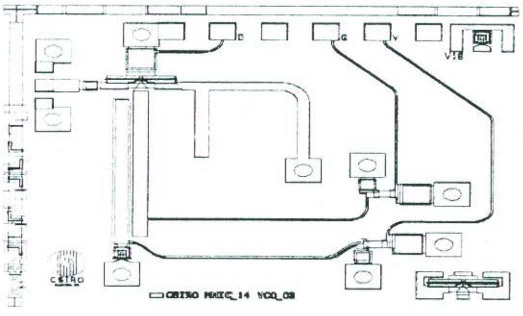

Fig. 1 29 GHz voltage control oscillator

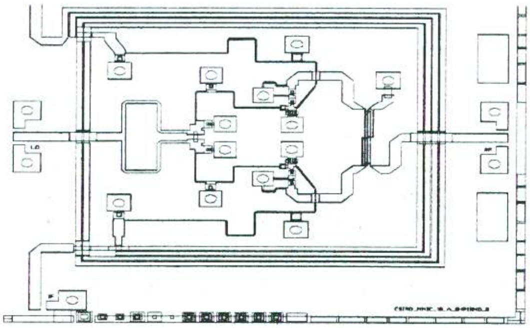

Fig. 2 60 GHz sub-harmonically pumped mixer

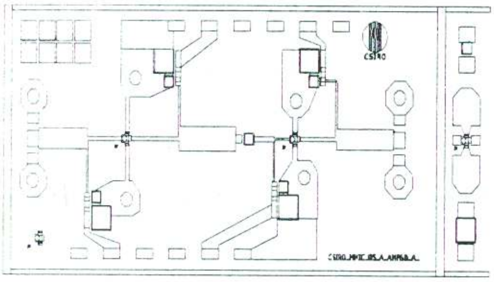

Fig. 3 2-Stage LNA

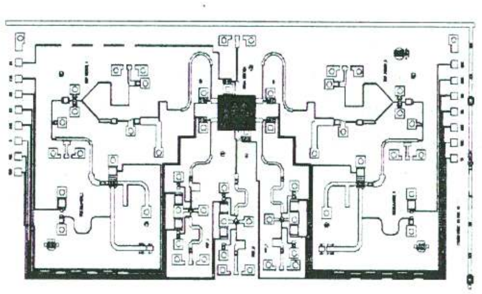

Fig. 4 Multifunction chip.

III. GaAs IC Prototyping and Testing

CSIRO operates a well-equipped GaAs IC Prototyping Facility which includes molecular-beam-epitaxy (MBE), submicron electron-beam-lithography (EBL), reactive-ion-etching (RIE) and e-beam evaporated/sputtered metal/dielectric deposition. These form the basis of MMIC processing. In-house, physics-based models have been developed [3] to optimize wafer layer structures for MMICs with different requirements such as high gain, high power, low noise, etc. These models have been used in the development a unique pseudomorphic layer structure which provides low-noise and high-gain pseudomorphic HEMTs (pHEMTs). pHEMTs fabricated in the Facility on this material, with 0.2μm e-beam written gate stripes, demonstrated 7 dB maximum stable gain at 100 GHz and a maximum oscillation frequency of 200 GHz [4]. The room-temperature noise figure of this device was measured to be 0.55 dB at 13 GHz and estimated to be 3.9 dB at 94 GHz. Epitaxial structures have also been developed with increased linearity and power-handling capability. HEMTs fabricated on this material exhibit a saturation current of 1 A mm^{-1} with a predicted RF output power capability of 600 mW mm^{-1} at frequencies near 10 GHz. Composite layer structures developed, such as HEMT-Schottky diode and HEMT-varactor diode, enable more than one function, such as amplifiers, mixers and oscillators, to be incorporated in a single MMIC. Other material structures under investigation are HEMT-photodetector and HEMT-optical modulators.

Using classical theory, considerable effort is being made to understand current conduction and noise mechanism in the quantum well of a HEMT. By using Boltzmann's Equation in a generalised form to include high electron density, such as would occur in a two-dimensional electron gas in a HEMT, a theory has been developed which predicts the noise performance of quantum-confined highly conductive bands [5]. Figure 5, based on this theory, shows the difference in the predicted minimum noise figure between a classical MESFET and HEMTs using GaAs and InGaAs quantum wells. The theory is now being used to optimize the material structure to further improve in the minimum noise figure of devices. Hall measurements provide carrier-concentration profiling as well as quantitative information on trap and DX centre density while PL and PR spectroscopy are used to investigate the bandgap energies for layers grown in the pHEMT structure.

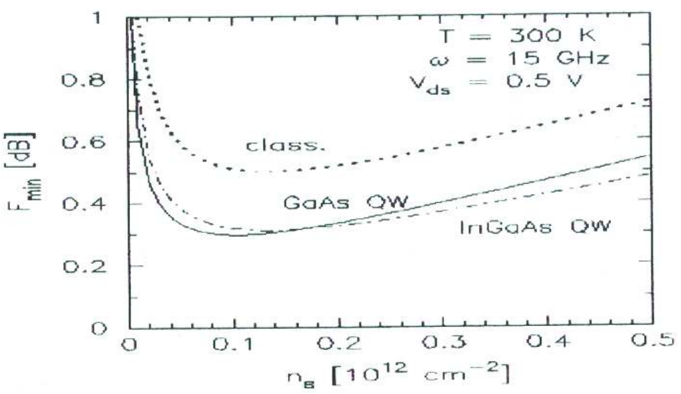

Fig. 5 Theoretical estimate of the minimum noise figure in the case of a classical MESFET and HEMTs with a GaAs 2-DEG well and an InGaAs 2-DEG well.

The EBL system provides gate electrodes with a footprint as narrow as 0.15 μm and a "mushroom" cross-section. The "mushroom" shape provides a short footprint, necessary to keep the transit time of the electrons travelling under the gate small, which is essential for high-frequency operation as well as providing a small gate electrode capacitance. The large metallic head assists in reducing the gate parasitic resistance and, as a consequence, keeps the CR time-constant small, which is also a requirement for high-frequency operation. Figure 6 shows a scanning electron micrograph of a gate cross section.

The use of RIE to selectively dry etch the n+ cap of the HEMT structure has resulted in uniform device performance across the wafer. Figure 7 is a scanning electron micrograph showing the recess in the cap of the pHEMT material in the vicinity of the gate. For MMICs of moderate complexity incorporating such HEMTs, typical circuit yields of 40-50% on a 50 mm-square wafer are being achieved.

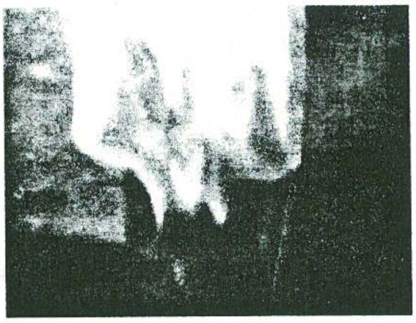

Fig. 6 0.15 μm mushroom gate metallisation.

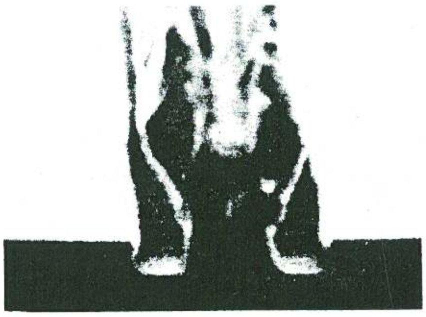

Fig. 7 Dry etched recess in the n+ cap using an RIE.

A standardised process-control module, for DC-IV measurements at various stages of processing an MMIC wafer, is incorporated to monitor the fabrication processes. Device physics-based models use DC-IV data on HEMTs and diodes to estimate device parameters such as gate length and parasitic resistances which are not easily measurable [6]. These data are stored in a database and used to optimize the process line. Automated, on-wafer, RF probing is also carried out. Figure 8 shows the performance of the two-stage, low noise amplifier shown in Fig. 3. The dark line is the simulated performance, as predicted by the design, while the light lines show the performance repeatability of a number of MMICs measured on the same wafer. Similarly Fig. 9 shows the performance of the 60 GHz image reject mixer shown in Fig. 2 [7]. In the past five years, 40 different MMICs have been designed and tested. These include amplifiers covering a frequency range of 0.5 to 110 GHz, diode-based mixers for 40, 60 and 100 GHz, varactor-based voltage control oscillators for 12, 20 and 30 GHz, pHEMT switches operating at 60GHz and bi-directional amplifiers.

Optoelectronics is becoming an integral part of telecommunication. CSIRO Telecommunications and Industrial Physics is developing capabilities for fabricating optoelectronics integrated circuits (OEICs). The present goal is to produce optical detectors, capable of operating at microwave frequencies of 20 GHz and beyond. The detector structure is designed to be planar to fairly easily integrate them into the Facility's MMIC technology. The goal is to produce a fully matched, low-noise, integrated optical receiver.

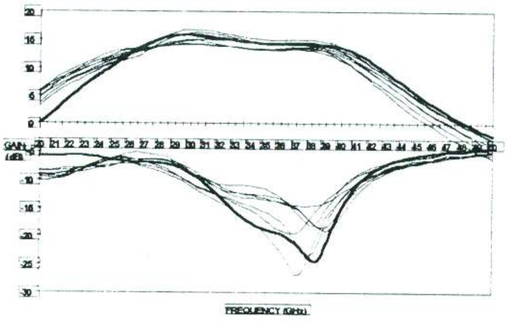

Fig. 8 Comparison between simulated and measured performance of a number of low noise amplifier.

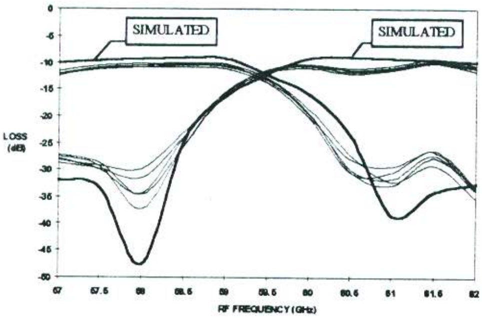

Fig. 9 Comparison between simulated and measured performance of a number of mixers.

IV. Conclusions

Using novel MBE-grown material structures and unique device models, high-performance MMICs have been designed and fabricated at the CSIRO Telecommunications and Industrial Physics. MMICs fabricated perform close to the design expectations after only a single design/fabrication cycle, thus providing a low-risk entry point for those wishing to develop such circuits. CSIRO's success in MMIC technology is raising industry awareness of the potential benefits of using GaAs MMICs in microwave systems. Optoelectronic devices and integrated circuits are also being investigated with a view to combining mm-wave circuits and optical devices on the same wafer.

Acknowledgements

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