# MONOLITHIC 60 GHz GaAs CW IMPATT OSCILLATOR

Burhan Bayraktaroglu

Texas Instruments Incorporated
POB 655936, MS 134
Dallas, TX 75265

## ABSTRACT

A monolithic circuit design was developed for GaAs IMPATT diodes to enable their operation under CW conditions at V-band ferquencies. All impedance matching circuits were fabricated on the top surface of the GaAs substrate. At 61.5 GHz 100 mW CW output power was obtained with 13.5% conversion efficiency. In an alternative design, varactor diodes were integrated with the IMPATT circuits to produce the first monolithic VCOs operating under CW conditions. Over 3.5 GHz tuning bandwidth was obtained at a center frequency of 70 GHz with a CW output power of 15 mW.

## INTRODUCTION

IMPATT diodes are well known for their high power performances at frequencies extending into the mm-wave range. Many radar systems have a need for high power microwave souces in their transmitters that can only be addressed by the use of IMPATT diodes. At present all IMPATT diodes are produced in discrete form and operated in external circuits. This technology is a major limitation to the wide spread use of IMPATTs in compact, light-weight, low-cost systems that require higher degree of integration. The application of the modern MMIC technology to the fabrication of monolithic IMPATTs has so far been unsuccessful. Alternative methods of fabricating active and passive circuit components on a single chip have been tried in the past[1-3]. Although these methods were not directly compatible with the mainstream MMIC technology, the results obtained showed promise for improving processing yields and uniformity, lowering unit costs, and enhancing device performances. More recently monolithic integration of IMPATT oscillators with radiating elements was achieved[4] using a MMIC compatible technology.

The prime difficulty in the integration of IMPATTs on the top surface of GaAs is the removal of excess heat. Since IMPATT diodes are particularly high power devices and the GaAs substrate has notoriously low thermal conductivity (0.46 W/cm°C at 300°K), direct placement of the diodes on the GaAs surface results in unacceptably high thermal resistance. The second difficulty is in the fabrication of impedance matching circuits to extract power efficiently. The impedance levels of millimeter wave IMPATTs under large signal operating conditions are low (typically 1-4 Ω range), therefore parasitic circuit elements between the diode and the matching circuits play an important role in device performance.

We have developed design and fabrication techniques that overcome these difficulties. To reduce the thermal resistance, the device was spread over a large surface area by the use of a matrix of small mesas. A self-aligned contact fabrication technique was used to minimize series resistances. All mesas were connected together and to the impedance matching circuitry by the use of air bridges. As a demonstration of this technology, V-band CW oscillators and VCOs were fabricated. This paper describes the fabrication techniques and test results obtained with circuits operating in the 60-70 GHz range.

## DESIGN AND FABRICATION

All epitaxial layers used in this study were grown by MOCVD on a semi-insulating (SI) GaAs substrate. Si and Zn were used as the n- and p-type dopants. A typical device structure was as shown in Figure 1. A thick $n^+$ layer was used as the contact to the n-layer.



CH2591-6/88/0000-0063$01.00 © 1988 IEEE    IEEE 1988 Microwave and Millimeter-Wave Monolithic Circuits Symposium

| Layer | Doping (cm$^{-3}$) | Thickness (μm) |
|---|---|---|
| $p^+$ | $5 \times 10^{18}$ | 0.3 |
| p | $2 \times 10^{17}$ | 0.25 |
| n | $1.6 \times 10^{17}$ | 0.30 |
| $n^+$ | $3 \times 10^{18}$ | 1.0 |
| Substrate | Undoped | 500 |

*Figure 1. The 60 GHz IMPATT structure.*

The diode active area was divided into small sections and spread over a larger surface area to provide an effective heat sink. In such a design there are several trade-offs to be made. The total area over which the device is spread must be kept as small as possible to maintain lumped operation. This is also essential for minimizing the parasitic capacitive elements. The size of each diode section is chosen by considering the fabrication tolerances and thermal resistance of each section. We have analyzed a large number of possible section sizes and seperations between sections. A design that produces the maximum output power under CW conditions was achieved by maximizing the total device size for a given spread area. The results discussed in this paper were obtained using 5 μm diameter IMPATT mesas placed on 25 μm centers. A matrix of 2 X 5 mesas were used for a total device area of $2 \times 10^{-7}$ cm$^2$ .

A cross-sectional drawing of the monolithic IMPATT circuit is shown in Figure 2. Individual IMPATT sections were defined by TiPtAu metallization. These sections were then mesa isolated by the use of $BCl_3$ reactive ion etching. This type of isolation produces less than 100 nm undercuts so that the device area is precisely defined. A self-aligned technique was then used to produce contacts to the n+ layer[5]. Another mesa isolation was used to seperate $n^+$ layers. Passive circuit elements such as transmission lines, MIM capacitors, and inductors were produced on the surface of SI GaAs substrate. A 3.5 μm tall air bridge was used to connect individual IMPATT mesas to the impedance matching circuitry. A close-up of the air bridge connection is shown in Figure 3. Via holes were used to ground one terminal of the device. Figure 4 shows the completed 60 GHz oscillator circuit. As seen in this figure, the diode impedance was

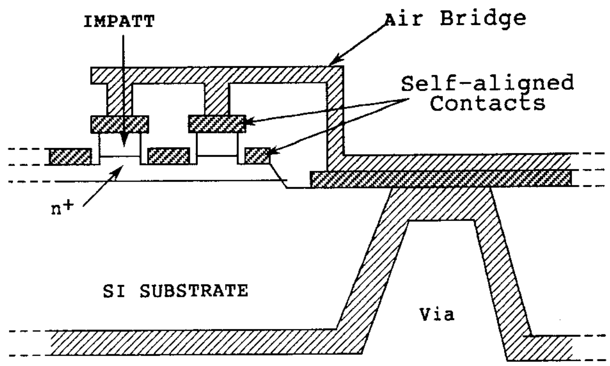


*Figure 2. A Cross-Sectional Drawing of the Monolithic Circuit.*

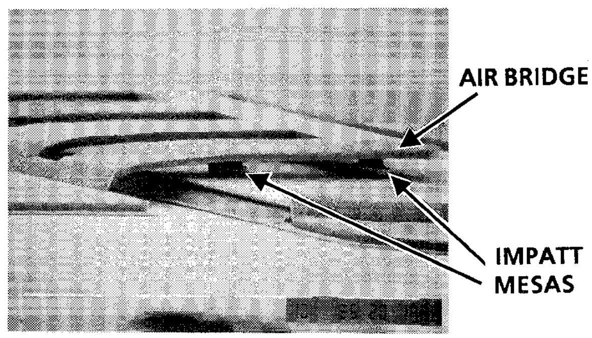


*Figure 3. SEM Picture of the Air Bridge Connections to IMPATT Mesas.*

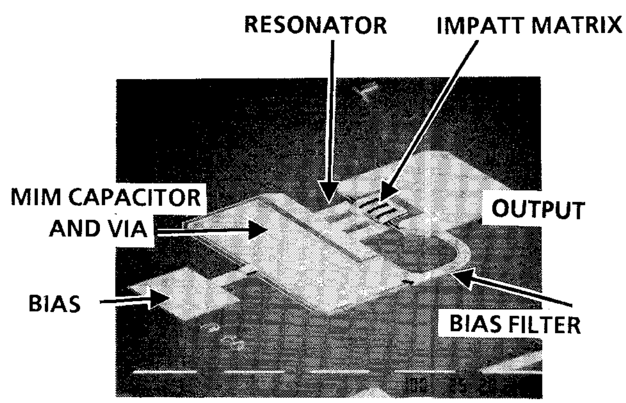


*Figure 4. SEM Picture of the Monolithic IMPATT Oscillator.*

matched to the line impedance of 50 Ω by the use of short sections of high impedance transmission lines in series with a quarter-wave impedance transformer. A bias filter was provided by the use of a large MIM capacitor and a quarter-wave high impedance transmission line. Typical dc yields from 2" wafers were 80%.

## RESULTS AND DISCUSSION

The mm-wave testing was carried out in V-band waveguide test set-ups. A microstrip-to-waveguide transition was used to couple the power from the monolithic chip to the waveguide. Less than 2 GHz variation was found in the free running oscillation frequency of monolithic oscillators from a 2" wafer at a center frequency of 60 GHz. Most devices were operated without the need for external tuning.

Best results were obtained from flat-profile, double-drift IMPATT structures such as the one shown in Figure 1. The output characteristics of a device operating at 61.5 GHz is shown in Figure 5. A maximum of 100 mW CW output power was obtained at 13.5% conversion efficiency. This is the highest efficiency reported for GaAs IMPATTs at this frequency. It is seen in this figure that both the output power and the efficiency of the device is still increasing at the highest dc bias point (junction temperature 275°C). This indicates that devices are operating under thermally limited conditions. Increased output powers should therefore be possible under pulsed bias conditions.

In an alternative design, monolithic VCO circuits were fabricated. This circuit included an oscillator circuit similar to the one described above and a varactor circuit on the same chip. The varactor diodes were fabricated by removing the p-type portion of the IMPATT structure and producing Schottky contacts to the n-type drift layer. The fabrication of the varactor diodes were similar to the fabrication of IMPATTs. In this design, two 5 µm diameter varactors and a 2 X 4 matrix of IMPATT mesas were employed. The varactor was biased with respect to the IMPATT diodes through a low-pass biasing circuit. Figure 6 shows an equivalent circuit of the VCO. In this figure $C_d$, $C_a$, and $C_v$ are the capacitances of the IMPATT diode, the parasitic capacitance due to the air bridge, and the varactor diode capacitance, respectively.

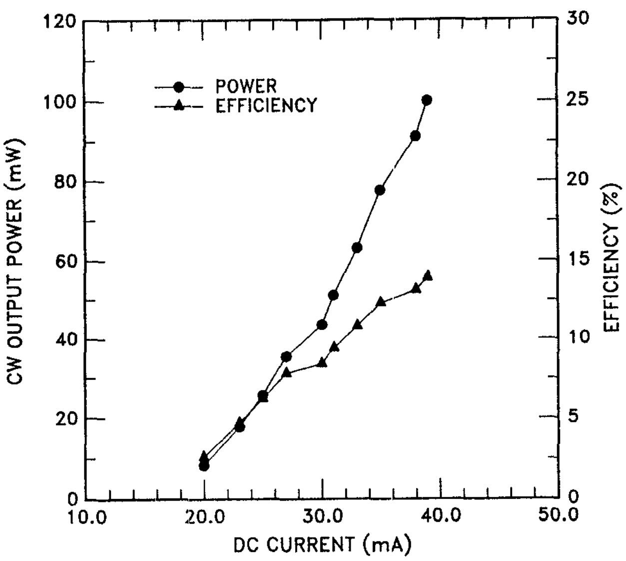


*Figure 5. The Oscillator Output Characteristics.*

Typically $C_a/C_d$ ratio is 0.15. $C_1$ and $C_2$ are MIM capacitors with values of 20 and 11 pF, respectively. Figure 7 is a SEM picture of the complete circuit and a close-up of the air-bridge connections to the varactors. The tuning behavior is shown in Figure 8. A tuning range of more than 3.5 GHz was achived at a center frequency of 70 GHz. The VCO circuit produced a CW output power of 15 mW at 70 GHz with an estimated junction temperature of 175°C. This result, to best of our knowledge, represents the first monolithic CW IMPATT VCO.

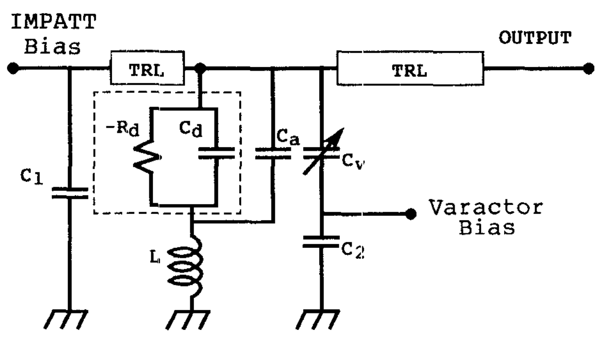


*Figure 6. The Equivalent Circuit of Monolithic IMPATT VCOs.*

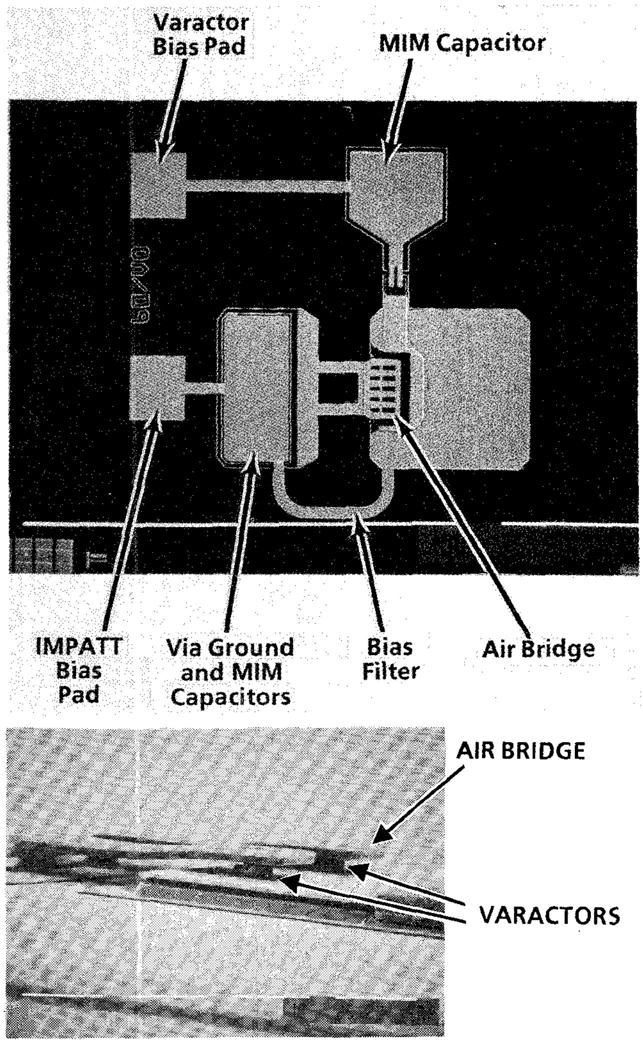


*Figure 7.* *SEM picture of the Monolithic IMPATT VCO and Air Bridge Connections to Varactors.*

## CONCLUSIONS

A monolithic fabrication technique was developed for GaAs IMPATT diodes. This technique is entirely compatible with the standard MMIC technology. As a demonstration, V-band CW oscillators and VCOs were fabricated and tested. The monolithic circuits produced excellent efficiencies, tuning bandwidths, and yields.

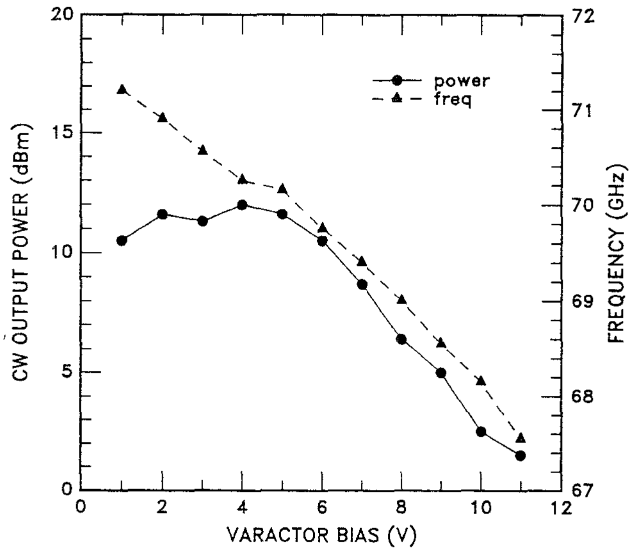


*Figure 8.* *Tuning Characteristics of Monolithic VCO.*


## ACKNOWLEDGEMENTS

The author would like to thank A. Elliot for technical assistance, S.A. Lambert for providing the MOCVD wafers, J. Fuller for editing assistance, and J. Armata of U.S. Army ET&D Labs for his guidance and constant support. This work was sponsored by U.S. Army LABCOM Contract No. DAA1001-86-C-0002.


## REFERENCES


1. B. Bayraktaroglu and H.D. Shih, "High Efficiency Monolithic GaAs IMPATT Diodes," Electronics Lett., p.259, Vol.21, 1985

2. B. Bayraktaroglu and H.D. Shih, "High-Power 60 GHz Monolithic GaAs IMPATT Diodes," Electronics Lett., p.562, Vol.22, 1986

3. N.L. Wang, M.G. Adlerstein, R. Brooks, G. Chu, W. Hoke, D. Masse, and W. Stacy, "Q-Band Monolithic GaAs IMPATT Oscillator," GaAs IC Symposium Dig., p.143, 1987

4. B.Bayraktaroglu, N. Camilleri, and S.A. Lambert, "Monolithic Millimeter Wave IMPATT Transmitter," IEEE/ Cornell Conf. on Adv. Concepts in High Speed Semicond. Dev. and Circuits Dig., p.381,1987

5. B. Bayraktaroglu, N. Camilleri, H.D. Shih, and H.Q. Tserng, "AlGaAs/GaAs Heterojunction Bipolar Transistors with 4 W/mm Power Density at X-band," IEEE MTT-S Inter. Microwave Symposium Dig., p.969, 1987