V-BAND MONOLITHIC IMPATT VCO

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ABSTRACT

Integration of a GaAs IMPATT oscillator and a varactor diode was achieved on a single chip. The IMPATT oscillator was in the form of a half-wavelength microstrip resonator exited on both ends symmetrically by a pair of diodes. A third diode was placed close to one end of the resonator and used to control the oscillation frequency of the oscillator through a coupling capacitor. Depending on the value of the coupling capacitor, tuning ranges of up to 1.5 GHz could be obtained at a center frequency of 55 GHz. Typical output powers were in the 100 to 400 mW range.

INTRODUCTION

IMPATT diodes are commonly used as the power sources in many millimeter-wave systems. In this role IMPATTs bridge the gap between much bulkier klystons and low power three-terminal solid-state devices. The integration level of IMPATTs also lie between these two types of devices. They can be integrated at a low level with other millimeter wave devices, but this integration is achieved in hybrid circuits. The cost and the performance of such circuits often depend on the control of parasitics due interconnections. There is therefore a need for a technology to fabricate IMPATT diodes and as much of the other active and passive circuit elements as possible on a single chip.

A monolithic IMPATT fabrication technique was developed recently for millimeter wave applications[1,2]. This technique allowed the fabrication of high power IMPATT diodes and all necessary impedance matching and biasing circuits on the same chip. In this technology the IMPATT diode is placed adjacent to a good heat sink metal whereas all passive circuit elements are fabricated on a thick layer of polyimide placed over the IMPATT. Although this technology is not directly compatible with the standard MMIC technology as applied to GaAs FET circuits, it enables the fabrication of entire IMPATT circuits on a single chip. Free running oscillators fabricated in this way produced as much as 1.1 W CW output power with 10% efficiency at 58.5 GHz[2]. This technology was extended in this paper to the fabrication of Voltage Controlled Oscillators (VCO) operating in the V-band frequencies. This integration included the fabrication of IMPATT and varactor diodes, resonators, and bias filter circuits in a monolithic form. The output from the chip was in microstrip form, prematched to 50-ohm line impedance

DESIGN AND FABRICATION

The IMPATT structure used for this investigation was of flat-profile, double-drift type grown by MBE on a semi-insulating (SI) GaAs substrate. The IMPATT structure is shown in Table 1. The active IMPATT layers were separated from the substrate by a thin layer of undoped $Al_{0.5}Ga_{0.5}As$. The function of this layer was to aid in device fabrication by allowing selective etch of the substrate as will be discussed below. It is completely removed during processing, therefore it does not influence the device operation. Si and Be were used as the dopants for n- and p-type layers, respectively. Doping levels in the n^+ and p^+ contact layers were kept as high as possible to minimize series resistances. Since both the substrate and the AlGaAs "etch-stop" layers are completely removed during device fabrication, their conductivity types are not important to the device operation.

Layer	Thickness (μm)	Doping (cm^{-3})
p^+	0.2	1E19
p	0.2	2.5E17
n	0.2	2E17
n^+	0.5	5E18
$Al_{0.5}Ga_{0.5}As$	0.5	--
SI SUBSTRATE	500	--

Table 1. The IMPATT structure

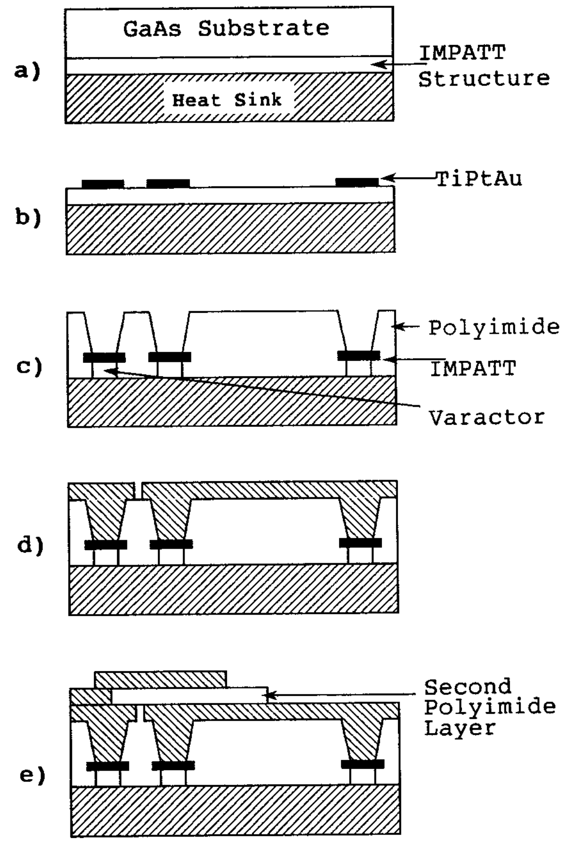

Figure 1. Fabrication steps of monolithic IMPATT VCO.

Figure 1 shows the fabrication steps. As a first step the wafer was coated with TiPtAu to make reliable contact to the p^+-layer and a thick layer (175 - 200 μm) of Au was electroplated on this metallization. The substrate was then chemically removed in a selective etch[3]. The AlGaAs layer prevented the etching of the IMPATT structure during substrate removal. This layer was subsequently removed in HF acid which does not attack GaAs. The chemical method of substrate removal was preferred over the mechanical lapping techniques since less damage was introduced and greater precision was obtained in the thickness of the remaining layers.

The IMPATT and varactor diode areas were defined by a second TiPtAu metallization and mesa etching. Since the total thickness of the GaAs is only about 1.1 μm at this stage, the device active areas were defined with greater accuracy. A 10 μm thick layer of polyimide was then spun over the wafer and fully cured. Via holes were produced in the polyimide by oxygen reactive ion etching (RIE) over the top contacts of the IMPATT and varactor diodes. The resonator and bias circuits were produced on the polyimide surface by selective area electroplating. A second but thinner (1 μm) layer of polyimide was produced over these circuits to form the dielectric layer of the coupling capacitor. A second electroplating step was applied to extend the varactor top contact over one edge of the resonator as shown in Figure 1e. The chip size was 2.25 mm X 1.5 mm.

In the design of the V-band circuits, a half-wavelength resonator loaded on both ends symmetrically by 50 μm diameter IMPATT diodes was used. The size of the resonator was 0.95 mm X 0.7 mm. The IMPATT diodes were placed 125 μm from either end of the resonator. The varactor diode also consisted of a 50 μm diameter IMPATT diode placed close to one end of the resonator as shown in Figure 2. IMPATT and varactor bias filters consisted of 1/4 wavelength long transmission lines terminated by 120° radial stubs. During the normal operation of the VCO IMPATT diodes were driven above their breakdown

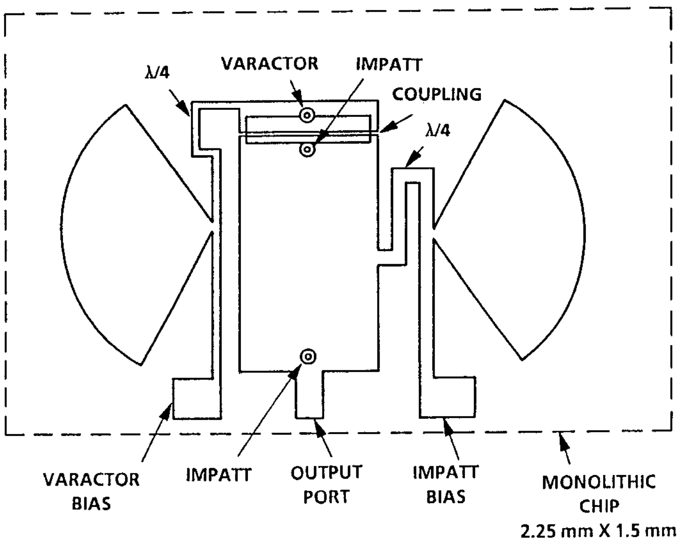

Figure 2. *A schematic Drawing of the Monolithic IMPATT VCO Circuit.*

voltages whereas the varactor diode was operated below its breakdown voltage therefore it served as a variable capacitor. The value of the coupling capacitor could be adjusted by the thickness of the second polyimide layer. Figure 3 is a SEM picture of the completed circuit.

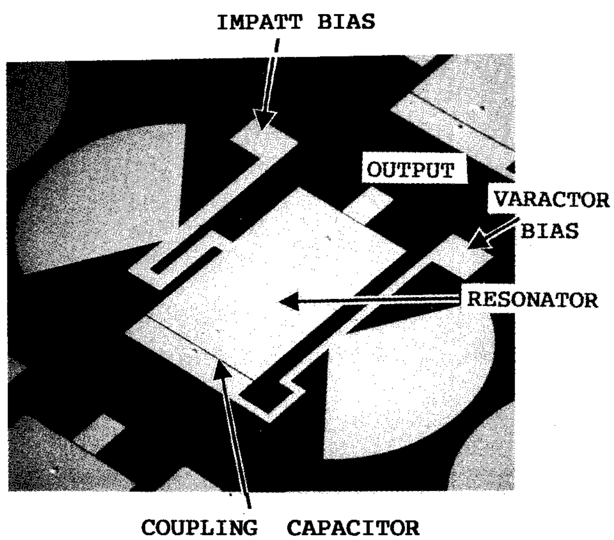

Figure 3. *A SEM Picture of the VCO Circuit.*

RESULTS AND DISCUSSION

The device operation principle can be more clearly described by examining the cross sectional drawing and the equivalent circuit of the device, as shown in Figure 4. G and C_d are the conductance and the depletion layer capacitance of each IMPATT diode, C is the varactor diode capacitance as a function of voltage, C_o is the coupling capacitor, l_1, l_2, and l_3 are the lengths of transmission lines that make up the resonator. In the simple equivalent circuit shown in Figure 4b, the series resistance of the IMPATT diodes and the inductance of the via hole interconnections were not included, since these do not introduce significant error in the oscillation frequency predictions. Under resonance conditions, the microstrip resonator supports a standing wave with an electric field profile approximately as shown in Figure 4c. Because of the loading effects of the depletion layer capacitances of the IMPATT diodes, the length of the resonator is shorter than an equivalent resonator operating at the same frequency but without active devices. The function of the varactor diode in this circuit is to modify the loading of the resonator through a coupling capacitor. If the varactor capacitor is very low then the circuit becomes a simple oscillator. This case is represented by the C=0 curve in Figure 4c. On the other hand, if the varactor capacitance is very high, $C=\infty$, then one side of the resonator is short circuited. The oscillation frequency in this case is half that of C=0 case. For more realistic values of the varactor capacitances, the oscillation frequency varies within a narrower range of frequencies close to C=0 case. As the varactor voltage is varied between V_o and V_1, where $V_1 > V_o$, the resonator length is effectively modified by a distance Δl. This correspond to a tuning range of Δf.

The oscillation frequency of the VCO was calculated using the equivalent circuit of Figure 4b. Since the device admittance at the output port is purely real in resonance, the oscillation frequency corresponds to to the frequency where the device susceptance becomes equal to zero. The actual value of the IMPATT negative conductance, -G, is not essential for these estimations, but will be required for large signal analysis. The oscillation frequency estimated in this fashion agreed within 5% of the measured values.

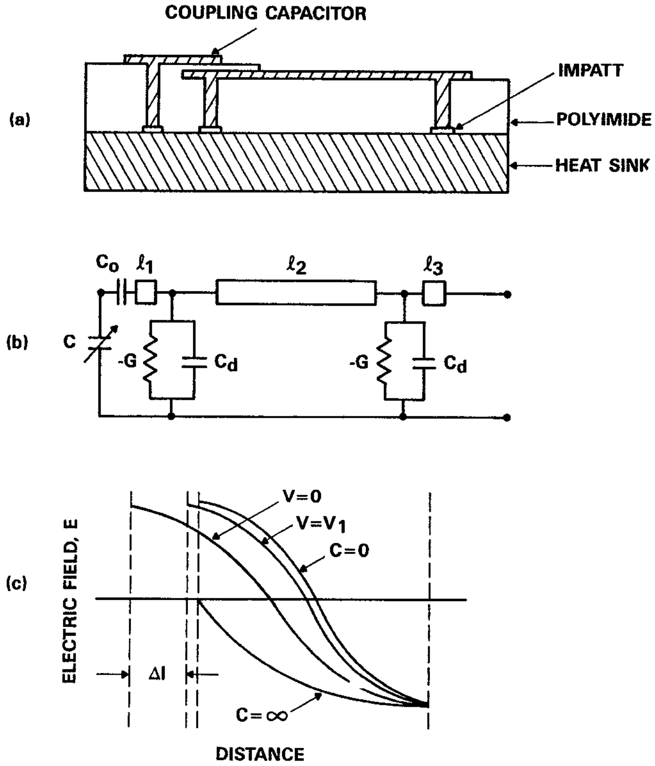

Figure 4. Cross-sectional Drawing and the Equivalent Circuit of the Monolithic IMPATT VCO.

For testing purposes, a transition was made from the monolithic chip to a 50-ohm microstrip line produced on alumina, which was in turn connected to an antipodal finline microstrip-to-waveguide transition[4]. All devices were tested under CW conditions without the use of tuners. The oscillation frequencies of circuits from several wafers were found to be reproducibly within 53 to 59 GHz range. The output power levels were typically within the range of 100 to 400 mW. The highest output powers corresponded to devices having the smallest coupling capacitors, and hence the smallest tuning ranges. Figure 5 shows a typical tuning range for a coupling capacitor of 3.5 pF. A tuning range of over 1.5 GHz was obtained with this device at a center frequency of 55.2 GHz. The output power was on the average 140 mW and showed a variation of less than 2 dB. Note that the oscillation frequency increases with increasing varactor voltage in agreement with varactor capacitance decrease. For a coupling capacitor of 0.5 pF, the same circuit produced a tuning range of 220 MHz at a center frequency of 56.4 GHz. The output power in this case was 300 mW and showed a variation of less than 0.5 dB.

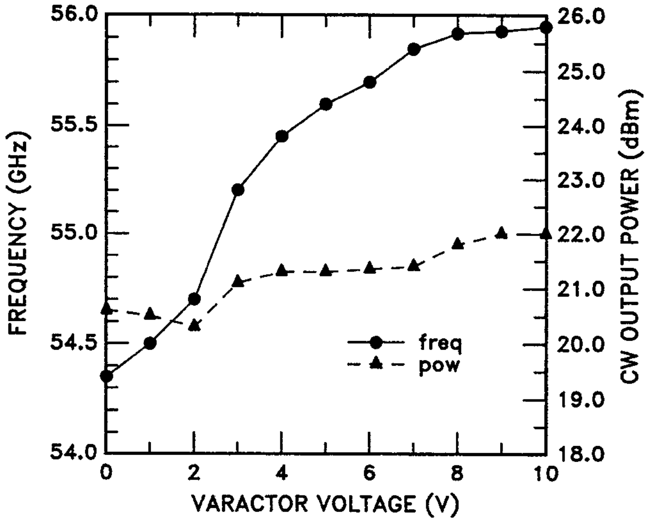

Figure 5. Tuning Characteristics of V-band VCO.

CONCLUSIONS

Design and fabrication techniques were developed to realize V-band monolithic GaAs IMPATT VCO circuits. Under CW operation, up to 400 mW output power was realized. The tuning range, at a center frequency of 55 GHz was over 1.5 GHz with with an output power variation of 2 dB.

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