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HIGH EFFICIENCY MILLIMETER WAVE MONOLITHIC IMPATT OSCILLATORS

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ABSTRACT

This paper describes methods of integrating GaAs IMPATT diodes and impedance matching circuits on the same chip. Lumped element as well as distributed element matching circuits were used in two separate approaches. The common technology to both approaches is the use of thick layers of polyimide that form the dielectric medium for passive circuit elements. MBE grown double-drift GaAs IMPATT structures with AlGaAs etch stop layers were used to fabricate monolithic oscillators for the 30-90 GHz applications. The best overall performance was achieved at 32.5 GHz with 1.25 W cw output power and 27% efficiency.

INTRODUCTION

Due to very large power densities ($> 10^5$ W/cm^2) involved in their operation, the IMPATT diodes are always fabricated adjacent to a good heat sink made of a high thermal conductivity material. Commonly used semiconductors in the fabrication of IMPATT diodes e.g. GaAs, Si, InP, are notoriously low thermal conductivity materials which makes them unsuitable as heat sinks. Furthermore, in conventional IMPATT diode processing, it is desirable to remove all or most of the semiconductor substrate to reduce the series resistance. Monolithic integration of the IMPATT diodes and the matching circuits therefore can not be achieved in the same sense as the GaAs FETs where the semi-insulating properties of undoped GaAs is utilized to facilitate the fabrication of passive circuit elements.

In conventional IMPATT technology, discrete diodes are produced with high quality heat sinks (plated metal or metallized diamonds) and are hermetically sealed in microwave packages. Individual contacts are made to devices using thermocompression bonded or electroformed gold ribbons .Packaged devices are then placed in microwave circuits which are often in the form of waveguide cavities, to extract power. The devices described in this paper deviate from the conventional in the sense that the impedance matching circuits are produced on the same chip as the IMPATT diode; connected to it directly without requiring individual device packaging.

DESIGN AND FABRICATION

Design

Two different design approaches were used to realize monolithic IMPATT diode oscillators. These are illustrated in the schematic drawings of Figures 1 and 2. In the first approach, impedance matching circuits are in the form of lumped elements fabricated using two levels of polyimide. In the second approach, only one thick layer of polyimide is used to fabricate distributed element circuits. Common to both technologies is the manner in which IMPATT diodes are produced which will be described below in detail.

In the design of both types of circuits, the IMPATT diode susceptance, B, was assumed to be equal to ωC_d , where $\omega = 2\pi f$ and C_d is the depletion layer capacitance as measured at 1 MHz. The external circuit impedance was transformed to 0.5 ohm at the device terminals, implying that the device series negative resistance is allowed to drop to -0.5 ohm. The output port of the oscillator is matched to 50 ohms.

In the first design [Figure 1(a)], a six-element impedance matching circuitry was used. Capacitors were in the form of MIM capacitors using a thin layer of polyimide as the insulator. Inductors were in the form of high impedance transmission lines produced on a thicker layer of polyimide. Electrical contacts were made between circuit elements and the IMPATT diode by the use of via holes produced in the polyimide. In the second approach, a two-stage Chebbycheff impedance transformer was used to match the real part of the device impedance. Also, a short high impedance transmission line was included between the impedance transformer and the device as shown in Figure 2 to resonate the reactive part of the device impedance. Physical dimensions of the circuit elements were determined by a computer optimization scheme.

Fabrication

The fabrication techniques used in both approaches are identical with the exception of the extra polyimide layer used in the lumped element approach. Processing steps of this approach are shown in Figure 3. IMPATT structures were grown in a Riber 2300 system[1] on semi-insulating substrates.

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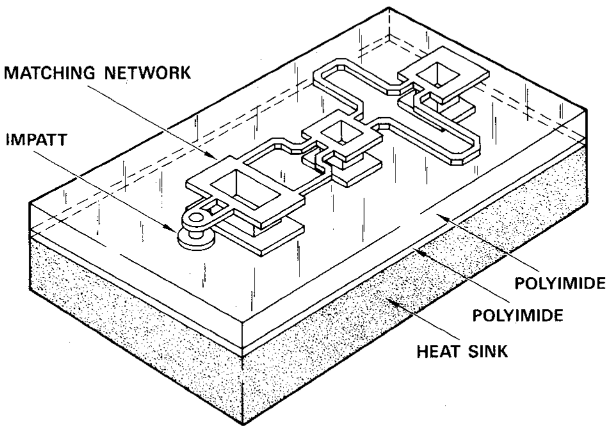

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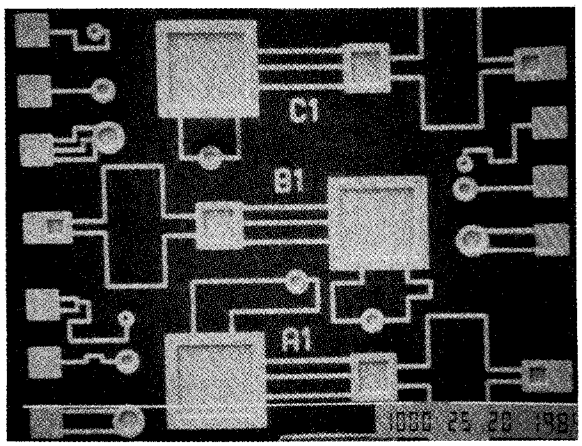

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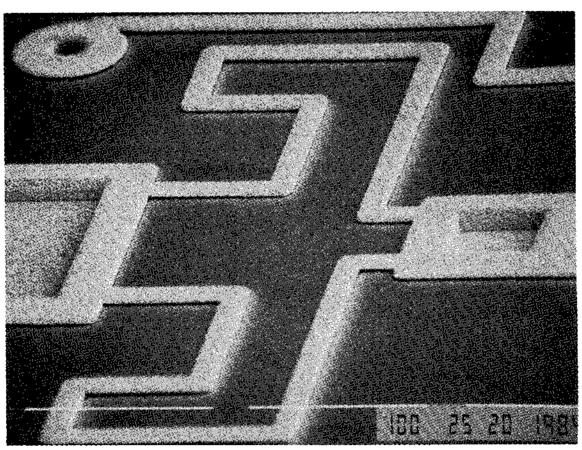

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Figure 1(a) *Schematic drawing of monolithic IMPATT oscillator with lumped element impedance matching circuits.*

(b) *SEM picture of completed devices*

(c) *Details of the impedance matching circuits*

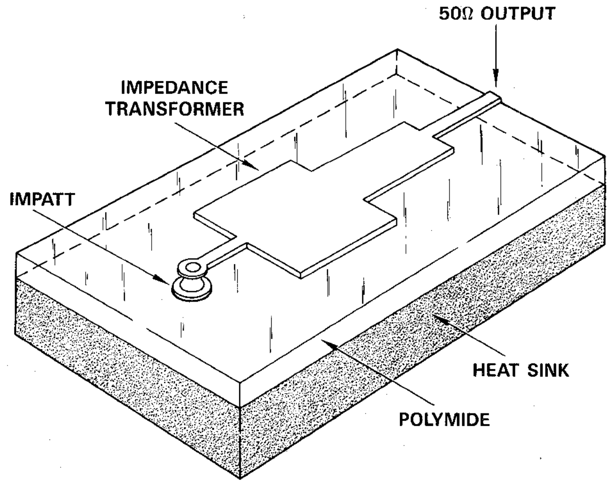
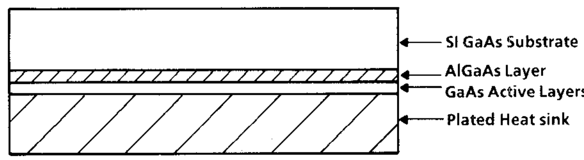


Figure 2 *Schematic drawing of monolithic IMPATT oscillator with distributed element impedance matching circuits*



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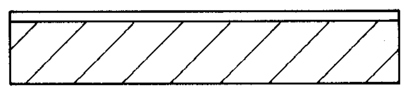

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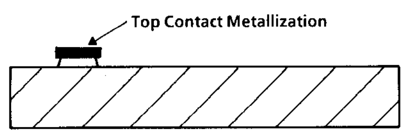

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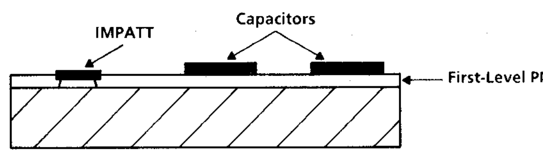

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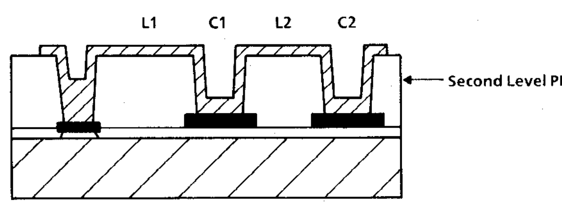

(e)

Figure 3 *Processing sequence of monolithic IMPATT oscillator*

Since the starting substrate is completely removed in the process that follow, its conductivity type is unimportant. Some of the IMPATT diodes designed for 30-35 GHz operation were hybrid-Read type with doping profiles nearly the same as that described in Reference 2. All other devices were flat-profile type. Also included in each structure was a 0.5 µm thick AlGaAs layer located between the substrate and the active IMPATT structure. The function of this layer is to act as etch-stop during the removal of the substrate.[3]

As shown in Figure 3(a), the front side of the wafer was metallized and then electroplated with Au to form a 150 µm thick heatsink. The GaAs substrateand the AlGaAs etch-stop layer were removed sequentially in selective etchants, to reveal the epitaxially grown IMPATT structures [Figure 3(b)]. The top contact metal of the diode was used as the etch mask to define device areas. Since the total thickness of the remaining semiconductor is less than 1 µm, the undercut produced during mesa etching is negligible compared to device diameter which was kept constant at 50 µm. In order to produce the capacitors, a thin layer of polyimide was spun over the wafer and completely cured. The top surface of this polyimide layer was metallized and capacitors were formed by selective area electroplating. Excess metallization was subsequently removed [Figure 3(d)]. A thicker layer of polyimide (~ 10 µm) was established over the first layer and again fully cured. Using silicon nitride as the etch mask and oxygen as the reactive ion, via holes were produced in the polyimide in a reactive ion etching system to reveal the top contacts of IMPATT diode and the capacitors. Once again selective area electroplating was used to fabricate inductive circuit elements and connections between the diode and the circuit [Figure 3(e)]. As seen in this last figure, the IMPATT diode is completely encapsulated inside a durable dielectric and is directly connected to the impedance matching circuitry. A drastic reduction in the device-to-circuit transition parasitics is obvious. A SEM photograph of the the completed test bar is shown in Figure 1(b). The details of the circuit elements are shown in Figure 1(c). Finally, devices were sectioned and placed in test fixtures that included an antipodal fin-line circuitry made on duroid to function as microstrip-to-waveguide transitions.[4]

RESULTS AND DISCUSSION

Millimeter wave testing was carried out in the frequency range of 30-90 GHz in various test set-ups. Typically, device output powers have shown monotonic increases with the bias current while the oscillation frequency remained relatively constant (± 100 MHz). It was found that the device performance was not improved with the use of external tuners. The oscillation frequency was also not influenced by tuning to any appreciable degree. These results point out that the monolithic IMPATT diode is operating in a high Q circuitry. Frequency spectrum of a typical device is shown in Figure 4.

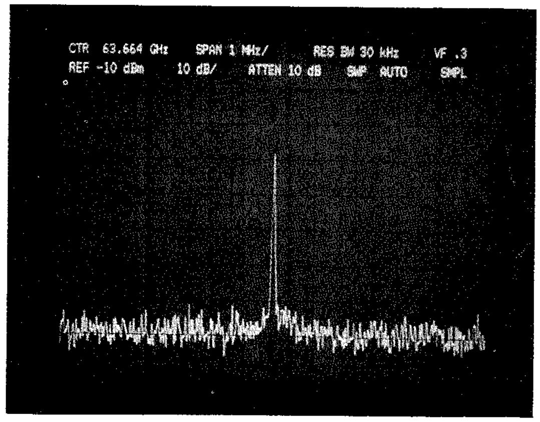

Figure 4 Typical frequency spectrum of a V-band IMPATT oscillator

The output power performances of devices with either type matching circuits were comparable. Since it is easier to fabricate, most results were obtained with the distributed element matching circuits. Best cw results were obtained in the 30-33 GHz range with hybrid-Read structures as shown in Figure 5. Efficiencies as high as 27% were obtained in this frequency range with 1.25 W cw output power. Device operating temperatures were about 300°C. Flat profile devices consistently gave lower efficiencies but could be operated over a large frequency range. Best efficiencies obtained from flat profile devices are about 20% and 9% for double drift and single drift devices.

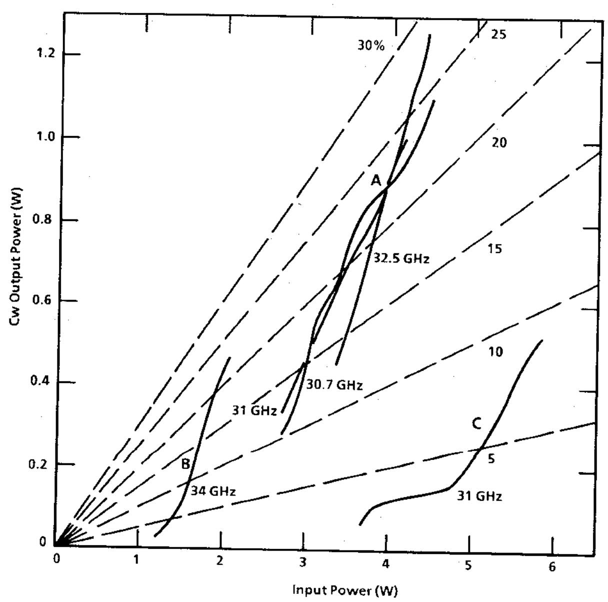

Figure 5 Output powers and efficiencies of Ka-band devices A: Hybrid-Read structure, B: Double-drift, flat-profile, C: Single-drift, flat-profile structure

Another important feature of the monolithic devices is the oscillation frequency and performance uniformity of the devices from the same wafer. For example, a frequency variation of ± 300 MHz was measured with 60 GHz devices sampled over a 6 cm^2 area. Device yields were high; typically over 90% (dc yield) with a best result of 98% of 1000 devices tested.

CONCLUSION

Processing techniques were developed to fabricate GaAs IMPATT diodes and impedance matching circuits on the same chip. Thick layers of polyimide were used as the dielectric material to fabricate passive circuit elements. IMPATT diodes were connected to the impedance matching circuits directly thus reducing the detrimental effects of device-to-circuit transition parasitics. The oscillation frequency and the load impedance levels were determined by the on-chip circuitry. Good oscillation frequency and performance uniformity was achieved with devices from the same wafer. 1.25 W cw output power was achieved at 32.5 GHz with hybrid-Read structures with 27% efficiency.

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