DESIGN AND REALIZATION OF GaAs D-BAND IMPATT OSCILLATORS

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Abstract

GaAs IMPATT oscillators for cw operation at D-band frequencies are designed and fabricated. The active devices are encapsulated using the novel module technique on diamond heat sinks. For the design of the module a CAD-software package is applied which considers the complete outer waveguide resonator structure as well as the module encapsulation structure. As active devices GaAs single-drift flat-profile IMPATT diodes and Read-type IMPATT diodes are investigated. The Read-type diode structure is designed by the help of a numerical program for calculation of the device impedance. The main design feature is low dc input voltage yielding high dc current density. Experimental results for rf output power and noise behaviour are given for both types of diodes in the frequency range from 110-150 GHz.

1 Introduction

Avalanche transit-time devices are keyelements for power generation at mm-wave frequencies and can be applied in various systems, for example as low-noise local oscillator or self-oscillating mixer. For the realization of mm-wave oscillators the most critical parameter that determines rf-performance is the impedance matching of the active diode to the resonant circuit. In particular at elevated mm-wave frequencies the rf-behaviour predominantly is determined by the diode encapsulation structure. Up to now, the encapsulation structure mainly is realized with the help of quartz stand-offs and gold bond ribbons. Because of the intricated encapsulation process high failure rates occur and the reproducibility of the rf-behaviour is a critical task. A decisive improvement is achieved from MMIC-technique for the fabrication of mm-wave oscillators which yields excellent reproducibility due to the applied photoresist technology (see for example [1][2]). In order to bring forward the advantage of photoresist technology for encapsulation of two-terminal devices also on diamond heat-sinks an encapsulation module representing a monolithic integration of active diode and sourrounding standoff structure has been developed [3]. Good rf-performance achieved by the help of this technique is demonstrated at W-band frequencies, yielding a conversion efficiency of more than 10 % at 90 GHz with a GaAs IMPATT diode [4].

This work is concerned with the design and fabrication of modules and resonator structures for D-band frequencies. Resonator and module are optimized using a finite element CAD software package for calculation of the entire impedance. As active devices conventional applied single-drift flat-profile GaAs IMPATT-diodes as well as Read-type diodes are investigated. Experimental values for rf-output power and noise measure for the frequency range from 110-150 GHz are reported.

2 The encapsulation module

The principal cross-section of the module can be seen in Fig. 1. Initial material for the fabrication is semiinsulating GaAs on which a GaAlAs etch-stop layer followed by the desired layer sequence for the active diode is grown. For the epitaxial growth standard molecular beam epitaxy is used. The semiinsulating GaAs material is used for electrical isolation of the diode from the stand-off structure and replaces seperately mounted quartz stand-offs. The diode top contact structure is realized by selective etching technology for GaAs substituting the gold bond ribbons (see Fig. 1). The REM-photograph in Fig. 2 shows a module seen from the epitaxial layer side, i.e. the side which has to be bonded onto the heat-sink. The stand-off structure guarantees the mechanical fixing of the module on the diamond heat-sink. Photoresist technology applied for the realization of all critical dimensions of the module results in high reproducibility. Instead of thermocompression bonding of a tiny single diode (diameter $\simeq$ 15-20 μm) on a diamond heat sink and contacting this device with gold bond ribbons the whole module is bonded in one step on the diamond heat sink.

3 The resonator structure

The modules are incorporated into a D-band waveguide resonator terminated at one end with a sliding short for tuning. A disk-type radial resonator structure is mounted directly on the module top-metallization. This leads to a height of the resonant disk above the waveguide bottom which is equal to the module height (module dimensions: see Fig. 1). This distance is much lower as compared to conventionally encapsulated devices with quartz stand-offs. Therefore, the resonant structure was investigated in order to ensure that impedance matching between active device and resonator is possible. For the computer simulation a finite element CAD sofware package is used ('HFSS', Hewlett Packard). The program considers the complete outer resonator structure as well as the module encapsulation structure. The result shows that a typical negative resistance from -0.2 up to -2.0 Ω can be matched in the frequency range from 110-150 GHz if the cap diameters are between 0.6-1.4 mm.

4 Diode structures

The GaAs single-drift flat-profile IMPATT diodes are realized with an doping concentration in the active region between $3.0 \cdot 10^{17} cm^{-3}$ and $3.4 \cdot 10^{17} cm^{-3}$ [5]. Generally, the maximum dc input power of the devices is thermally limited due to the relatively poor thermal conductivity of GaAs. This limits the maximum dc current density which, however, is necessary for efficient operation at elevated frequencies. The current density can be increased only if the operation voltage is reduced. This demand results in a Read-type diode structure [6]. For the design of this structure a numerical program for calculation of the device impedance has been applied. Drift,- diffusion,- impact ionization- and space charge effects as well as tunnel induced current are taken into account. The resulting diode structure together with the principal electric field distribution is shown in Fig. 3. The design of the high field region is suggested from Monte-Carlo simulation of Read-type structures [9] pointing out that supression of tunneling is achieved from this design for ensuring operation predominantly in IMPATT-mode. The calculated negative resistance for the Read-type structure in comparison to a flat-profile structure optimized for 140 GHz is shown in Fig. 4 as function of the operation frequency (small-signal operation). A constant dc input power density of 500 kW/cm^2 is assumed leading to a device temperature of 450 K. It can be seen that the Read-type diode offers almost twice the negative resistance as compared to the flat-profile structure.

For ensuring low-ohmic contacts a well established contact system for GaAs has been applied for all diodes investigated: TiPdAu for the p^+-ohmic contact and AuGeNi/Au for the n^+-ohmic contact.

5 Experimental results

The measured breakdown voltage for the flat-profile diodes is between 7.8-8.2 V. The value of 6.2 V for the Read-type diode demonstrates the achieved reduction of operation voltage. Thus, the maximum dc current density for long-time stable operation is about 65 kA/cm^2 for a flat-profile diode and 80 kA/cm^2 for a Read-type diode (diode diameter: 20 μm). For the rf measurements, all modules are fabricated with identical dimensions but active diodes having different diameters. The best results for rf output power are depicted in Fig. 5. Flat-profile diodes lead to 80 mW at 111 GHz and 63 mW at 118 GHz (diode diameter: 18-23 μm). The highest oscillation frequency observed from a flat-profile diode is 131 GHz (diode diameter 18 μm). As expected, the Read-type diodes lead to essentially better rf-performance. At 122 GHz 75 mW are realized, the highest oscillation frequency for cw-operation is 150 GHz (1mW output power). The diode diameters applied for 120-150 GHz are in the range from 17 to 27 μm.

The noise measure represents a characteristic quantity for the principal noise behaviour of a device as it is independent from the resonator behaviour and the diode area. Evaluation of the noise measure requires measurement of the external Q-factor and the rms-frequency deviation. Several oscillators fabricated are used for investigation of the noise behaviour. The noise-to-carrier ratio for evaluation of the rms-frequency deviation has been measured with the help of a spectrum analyzer. For determination of the external Q-factor a self-injection method has been applied [10]. The measured values are in the range from 30-500 for various resonator configurations tested. In Fig. 6 the experimental as well as theoretical values for the noise measure are presented. The measurements are performed at relatively low rf output power levels ($P_{rf} \simeq$ 2-5 mW) allowing the quantitative comparison with theoretical small-signal results [11]. For the calculations a dc current density of 50 kA/cm^2 and a device temperature of 450 K are assumed. which are in correspondence to the experimental values. For a flat-profile diode at 131 GHz a minimum noise measure of 27 dB is observed. The noise measure for a Read-type diode leads to a value of 26 dB at 144 GHz.

6 Conclusion

In this paper the investigation of GaAs IMPATT diodes for the frequency range from 110 up to 150 GHz is presented. The achieved results for the rf-output power point out that the module technique is a practical tool for the encapsulation of GaAs transit-time devices for D-band frequencies. The advantage resulting from this technique is high reproducibility and easy device handling. The measured power levels for the Read-type diodes, compared to flat-profile diodes, demonstrate that the reduction of dc input voltage leads to superior rf-performance at elevated frequencies. The good noise behaviour of the GaAs IMPATT devices is demonstrated by noise measurements performed up to 144 GHz.

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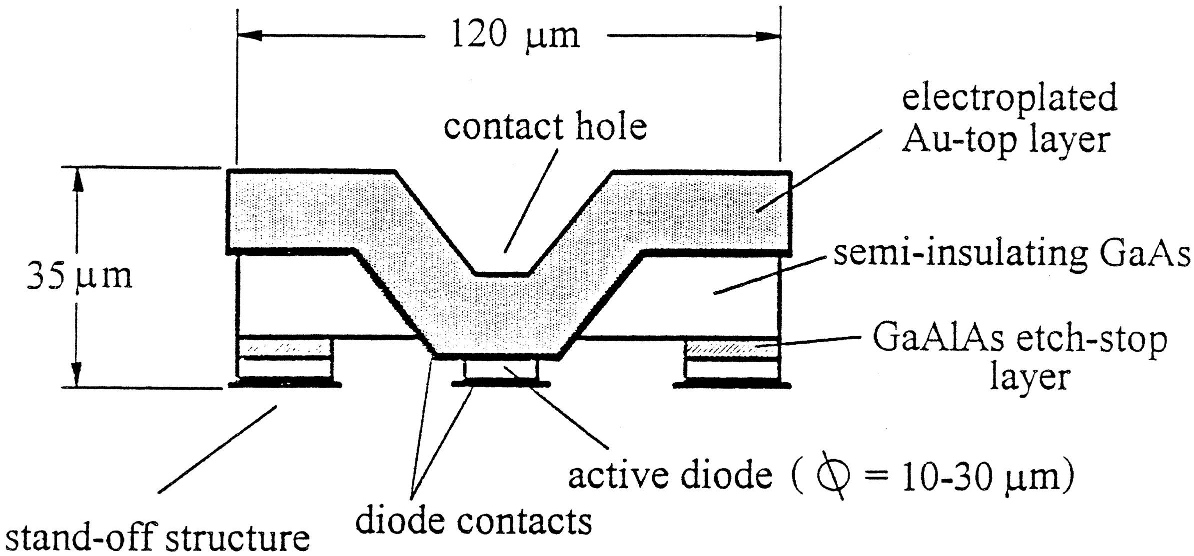


Figure 1: Principal cross-section of an encapsulation module (dimensions are for D-band frequencies)

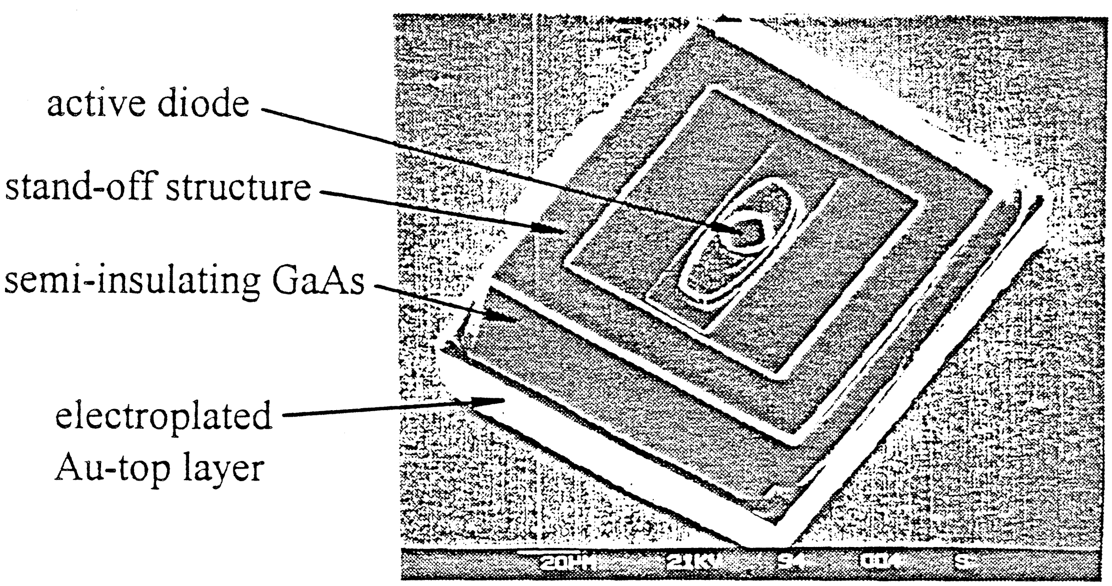
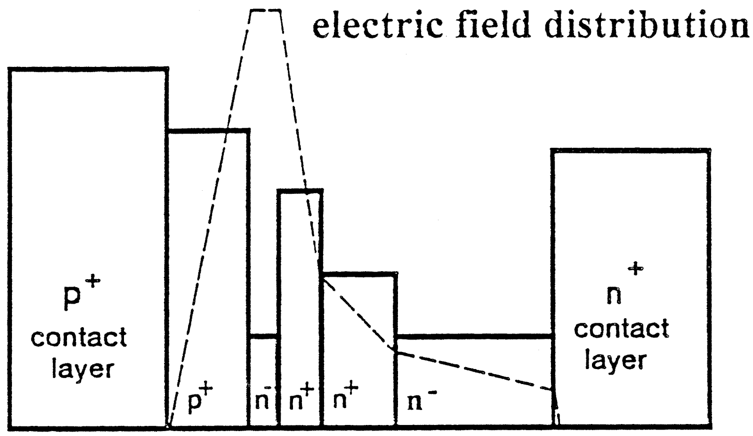


Figure 2: REM-Photograph of an encapsulation seen from the epitaxial layer side



layer	p^+	n^-	n^+	n^+	n^-
N_D (cm^{-3})	$2*10^{18}$	$1*10^{17}$	$2*10^{18}$	$5*10^{17}$	$1*10^{17}$
width (nm)	50	16	25	44	124

Figure 3: Read-type IMPATT diode structure for D-band frequencies with the electric field distribution

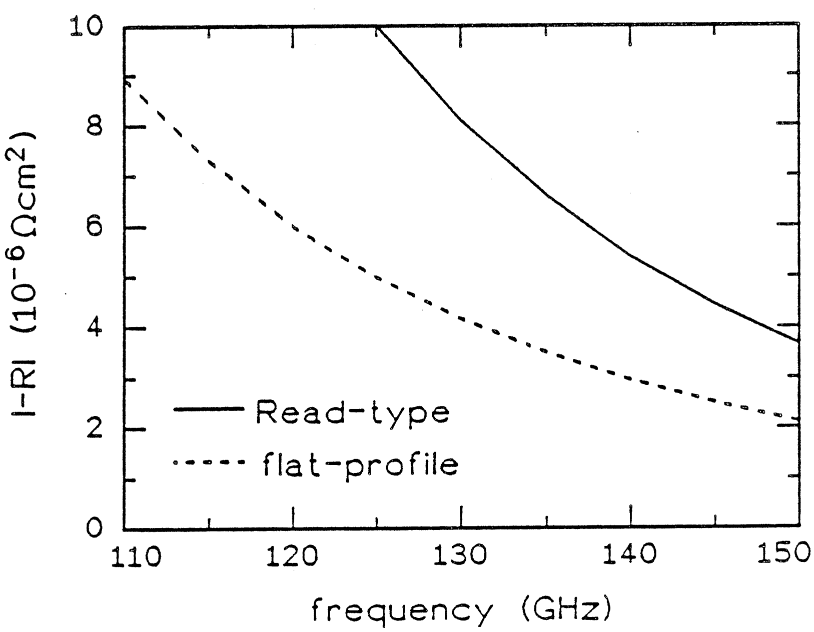


Figure 4: Negative resistance of the Read-type diode structure and a flat-profile diode structure optimized for 140 GHz (dc input power density = 500 kW/cm^2)

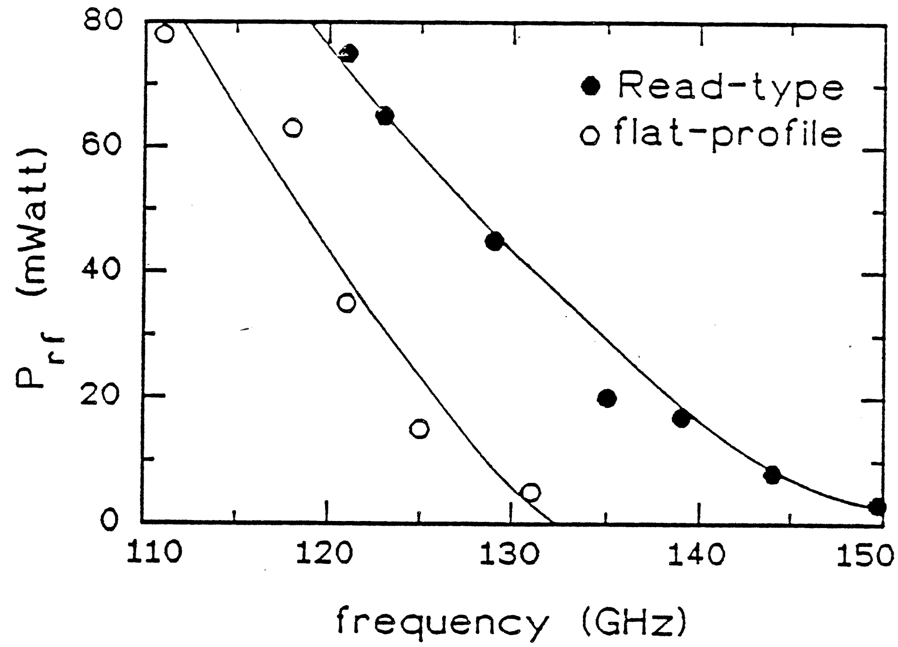


Figure 5: Rf-output power for flat-profile and Read-type diodes

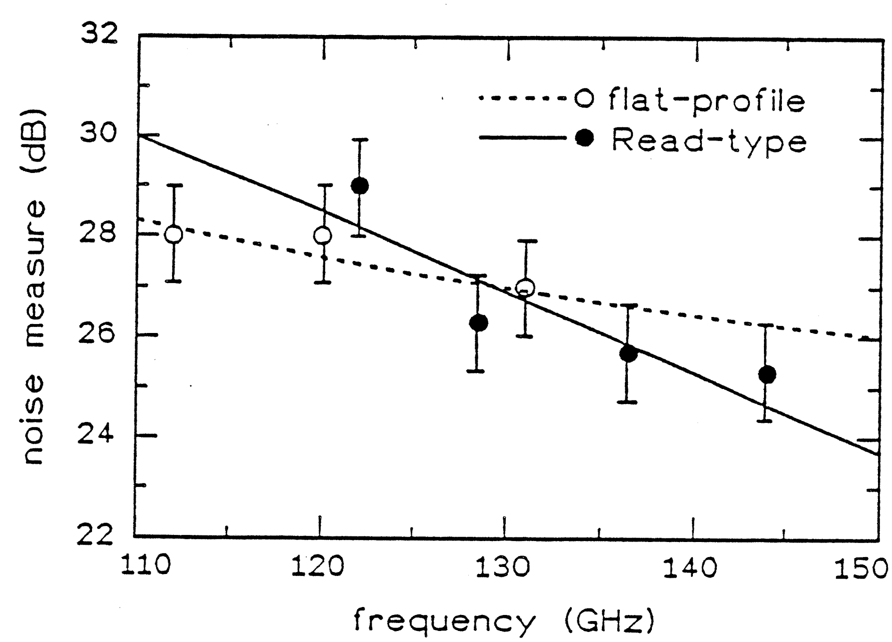


Figure 6: Experimental and theoretical values for the noise measure (small-signal operation)