High Power GaAs IMPATT Amplifier

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Abstract—**10-W p–n junction GaAs IMPATT diodes with MTTF more than 10^6 h, have been developed. Using these diodes, amplifiers of 5-W output power, 10-dB gain, 17-percent efficiency, 150-MHz bandwidth, and 80-dB signal-to-noise ratio (S/N ratio) have been constructed.**

I. Introduction

At PRESENT, the greatest concern in microwave equipment development, especially in high-power microwave equipment, is to replace TWT's by high-power solid-state microwave sources. For high-power and high-efficiency solid-state microwave sources, IMPATT diodes and FET's [1], [2] are promising, and efforts until now have been mainly concentrated on the GaAs IMPATT diode with a Pt Schottky barrier [3]–[6]. Experimentally, excellent results of output power of 12 W at J band [5] and efficiency of 37 percent at S band [6] have been obtained by the Pt Schottky barrier type GaAs IMPATT diodes. However, these Schottky barrier type diodes have not been used for practical devices. This is because they are less reliable at elevated temperatures [7] due to the rapid interdiffusion of Pt with GaAs [8], [9].

On the other hand, p–n junction type GaAs IMPATT diodes are expected to be reliable because a homogeneous and stable junction is available and failure of the p–n junction due to the interdiffusion of contact metals with GaAs is prevented by the P^+-GaAs region. In spite of the expected high reliability of the p–n junction type GaAs IMPATT diodes, only a few developments and applications of them have apparently been made. Reported results [10] regarding the efficiency and the output power were not satisfactory compared to those of the Pt Schottky barrier types.

For practical purposes, reliability is the most important factor. From the point of view of reliability, we chose the p–n junction type for the basic IMPATT structure and have made efforts to improve the efficiency and the output power. In order to obtain a high efficiency, optimization of the structure parameters and the fabrication processes have been investigated. For a high output power, power combination by parallel connection of multichips has been examined. Reliability of these diodes are evaluated by accelerated life test and the mean time to failure (MTTF) at 200°C is deduced. Using these diodes, high-power solid-state amplifiers have been constructed for high-power multichannel microwave radio equipment.

In this paper, we describe the design criteria for the high-power and high-efficiency J-band p–n junction type GaAs IMPATT diodes, their microwave characteristics, and their reliability. Application of these diodes to high-power solid-state amplifiers for J-band multichannel microwave radio equipment is also discussed.

II. GaAs IMPATT Diode

The GaAs IMPATT diodes have the p–n junction hi-lo structure. Principles of the diodes design are as follows.

1) In order to obtain a high efficiency, avalanche region is narrowed by narrowing the hi region and increasing its carrier concentration (N_H) to such an extent so as not to introduce tunneling injection. Moreover, the carrier concentration of the lo region (N_L) is lowered to give a large N_H/N_L ratio [11], [12].

2) The low carrier concentration of the lo region enables the diodes to operate at a low current density, therefore at a low bias current.

3) In order to obtain a high output power, the junction area is increased by parallel connection of multichips. The multichip structure is also employed for reducing skin effect, thermal resistance, and thermal inhomogeneity.

4) In order to prevent tuning burnout [13], the diodes are designed so as not to punch through at the breakdown and to only slightly punch through under operation. The optimum punch through factor is experimentally determined by changing the width of the hi region.

p–n junction type GaAs IMPATT diodes are fabricated from epitaxial P^+-N-N^--N^+ on N^{++} GaAs wafers successively grown by liquid phase epitaxy. The p–n junction thus formed by the successive growth is clean and homogeneous, which is more reliable than the Pt Schottky barrier formed by separate processes. The thickness of each epitaxial layer is controlled by changing the growth time. The surface of the epitaxial layer is mirrorlike, and the interface between the neighboring two layers is sufficiently uniform. The typical carrier profile of the active region of the diodes is shown in Fig. 1. The carrier profile is measured by the conventional differential capacitance method. The P^+ region is Ge doped with a net carrier concentration of 1×10^{18} cm^{-3} and 1-μm thickness. The hi region is Sn doped with a net carrier concentration of 1×10^{17} cm^{-3} and 0.3-μm thickness. In the lo region, the carrier concentration is notably lowered to 6×10^{14} cm^{-3}. In this figure, it should be noted that the hi region has a higher carrier concentration and a narrower thickness and the lo region has a lower carrier concentration than the so far reported GaAs hi-lo IMPATT diodes' structure [4], [14].

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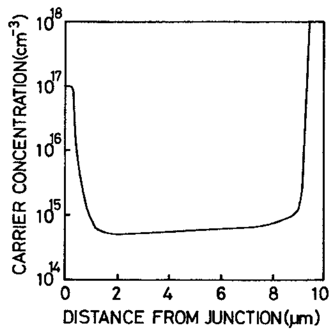

Fig. 1. Typical carrier profile of the p–n junction type GaAs IMPATT diode.

TABLE I
CHARACTERISTICS OF THE p–n JUNCTION TYPE GaAs hi-lo IMPATT DIODES

Diode	Number of chips	Output (W)	Efficiency (%)	Frequency (GHz)	J^* (A/cm^2)
A-1	1	2.9	23.3	6.5	354
A-2	2	8.0	21.6	6.4	340
A-3	2	6.1	20.3	6.3	320
A-4	2	5.7	19.8	6.7	308
A-5	4	10.7	18.0	6.0	333
B-1	2	6.5	20.0	6.4	320
B-2	2	5.0	20.3	7.0	320
B-3	3	9.8	19.4	5.8	300
B-4	4	10.0	20.6	5.9	255
B-5	4	11.0	21.6	5.7	310
C-1	1	2.6	26.6	7.3	265
C-2	2	6.0	20.0	7.7	340
C-3	2	5.2	18.8	7.6	340

J^*: current density at maximum efficiency

The p–n junction type GaAs IMPATT diodes are mounted in a *J*-band waveguide test cavity with a hat structure for frequency determination. Their characteristics are measured using a WRJ-7 waveguide test circuit under the optimum tuning for obtaining the maximum output power.

In Table I typical characteristics of fabricated diodes are summarized. The highest efficiency is obtained by a one-chip diode and is 26.6 percent at 7.3 GHz. The highest output power is obtained by a four-chip diode and is 11 W at 5.7 GHz. These diodes show maximum efficiencies at current densities as low as about 300 A/cm^2. This value is almost half of the one obtained by the conventional hi-lo structure [4], [14], and it is mainly attributed to the low carrier concentration in the lo region.

Fig. 2 shows an example of power combination by multichips in parallel. The output power increases as the number of diode chips is increased without decreasing efficiency. The output power of each chip is understood to be well combined. This is attributed to the low negative Q of the hi-lo type GaAs IMPATT diodes [15].

An example of typical input-output power characteristics of four-chip diodes is shown in Fig. 3. The junction tempera-

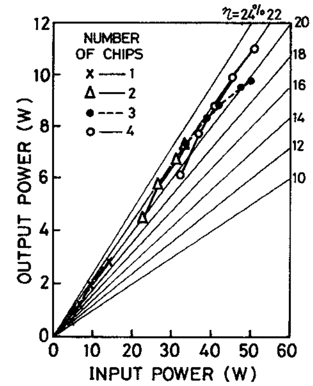

Fig. 2. An example of power combination by multichips in parallel, where chips are increased from one to four.

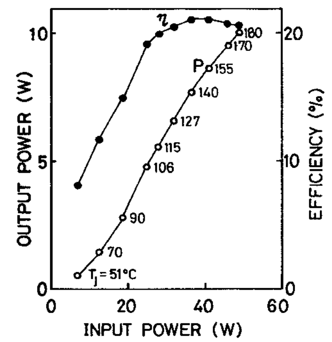

Fig. 3. Typical input-output power characteristics of four-chip diode with junction temperatures.

tures at the operating points are also shown. An output power of 10 W is obtained with an efficiency of 20.6 percent at a junction temperature of 180°C. Four-chip diodes in Table I all deliver 10 W at junction temperatures less than 200°C. Similarly, by two-chip diodes, output power over 5 W is reproducibly obtained with efficiency more than 20 percent at a junction temperature less than 200°C. Because of the reduced thermal resistance and the improved thermal homogeneity due to the multichip structure, the temperature rise and the thermal inhomogeneity of the diodes are believed to be kept minimum.

Thus the p–n junction type GaAs IMPATT diodes, having an optimized hi-lo structure, deliver high output powers with high efficiencies at low junction temperatures and are expected to be highly reliable. To evaluate the reliability of these diodes, accelerated life test and dc bias tests were performed. Groups of diodes were placed in furnaces having a N_2 atmosphere and thermally aged at four different temperatures of 275, 300, 320, and 340°C. Diode characteristics were checked at appropriate intervals to judge the failure. The failure criterion used in the tests was 20-percent shift in breakdown voltage at 1 mA.

Fig. 4 shows the mean time to failure (MTTF) of the diodes as a function of temperature. The logarithmic MTTF at four different temperatures are linearly related to the reciprocal of the absolute temperature. At a junction temperature of 200°C, MTTF's more than 10^6 h were deduced from the extrapolation of the Arrhenius plots to lower temperatures with an activation energy of 1.8 eV.

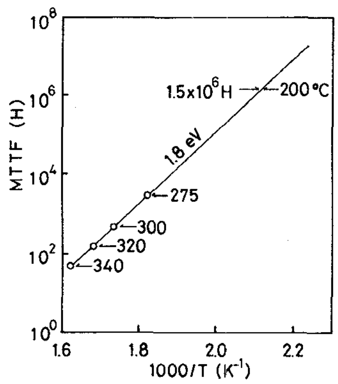

Fig. 4. MTTF-temperature relation. Activation energy is 1.8 eV and MTTF of 10^6 h is deduced at 200°C.

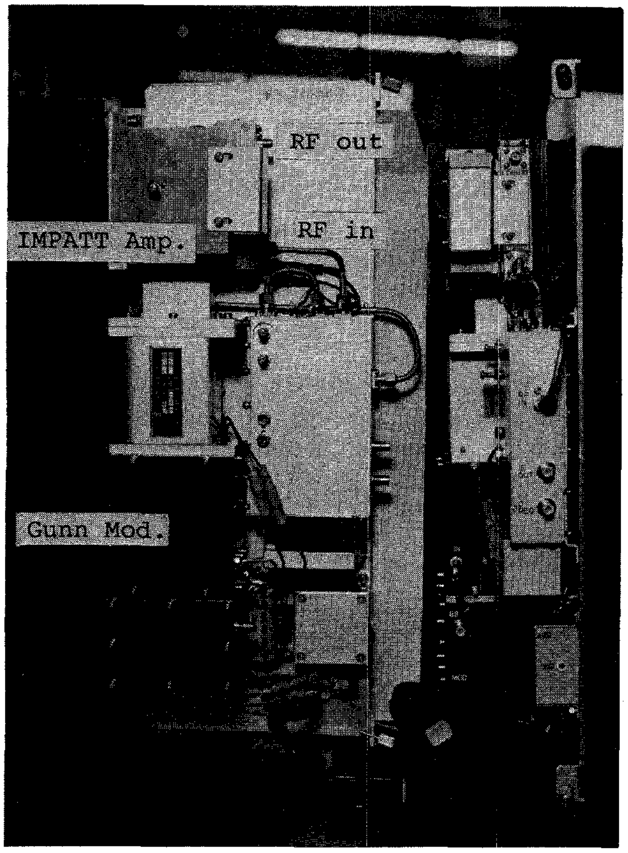

Fig. 5. Photograph of the transmitter using the GaAs IMPATT amplifier.

The MTTF of 10^6 h is well satisfied compared with the life of the Pt Schottky barrier type GaAs IMPATT diodes or TWT's. It is one order of magnitude longer than the Pt Schottky barrier type diodes and is 50 times longer than the TWT's.

III. GaAs IMPATT Amplifier

Using the high-power and high-reliability p–n junction type GaAs IMPATT diodes, high-power one-stage solid-state amplifiers have been developed for *J*-band multichannel microwave radio equipment. In this investigation, 5-W class two-chip diodes have been used aiming for 5-W class IMPATT amplifiers.

Fig. 5 shows the transmitter using the GaAs IMPATT amplifier and in Fig. 6 the block diagram of the amplifier is shown. Output power from a 0.5-W Gunn modulator is amplified by the GaAs IMPATT amplifier. A five-port circulator is used to separate the input and output power.

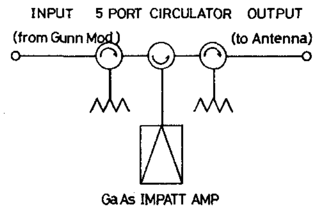

Fig. 6. Block diagram of the GaAs IMPATT amplifier.

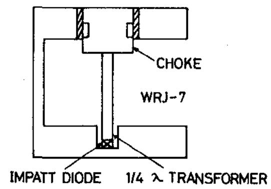

Fig. 7. Structure of the diode cavity used for the GaAs IMPATT amplifier.

TABLE II
CHARACTERISTICS OF THE GaAs IMPATT AMPLIFIER

Amp. No.	Output Power (W)	Gain (dB)	Eff. (%)	Thermal Noise S/N(dB)	Locking Bandwidth (MHz)	Freq. (GHz)	ΔT_j (°C)
A-1	6.5	11.1	17.1	> 80	> 150	7.47	170
A-2	5.1	10.1	16.0	> 80	> 150	7.73	145
A-3	6.0	10.8	17.7	> 80	> 150	7.59	152
A-4	5.5	10.4	15.7	> 80	> 150	7.57	162
A-5	5.8	10.6	17.5	> 80	> 150	7.57	148

The diode cavity is a waveguide-coaxial type as shown in Fig. 7. The waveguide-coaxial type is preferable for reducing the load impedance and for better tunability. Impedance matching between the diode and the load is accomplished by a quarter wavelength transformer. The center frequency is varied by changing the length of the choke. As output power generally decreases with increasing the locking bandwidth, the operation point is settled so as to obtain the highest output power with the bandwidth being enough to transmit 1800 telephone channels.

Characteristics of the amplifiers are summarized in Table II. Output power over 5 W are reproducibly obtained with gains more than 10 dB and junction temperatures less than 200°C. Efficiencies are more than 15 percent, the locking bandwidths over 150 MHz and the S/N ratio more than 80 dB. The highest output power is 6.5 W, which is obtained with an efficiency of 17 percent at a junction temperature of 195°C (corrected by the ambient temperature). This temperature rise under operation is satisfactory for guaranteeing the reliability of the diode.

Characteristics of the amplifier versus the dc input power of the IMPATT diode are shown in Fig. 8. With increasing dc input power, the locking bandwidth decreases, which is thought to be due to the increase of the negative Q of the

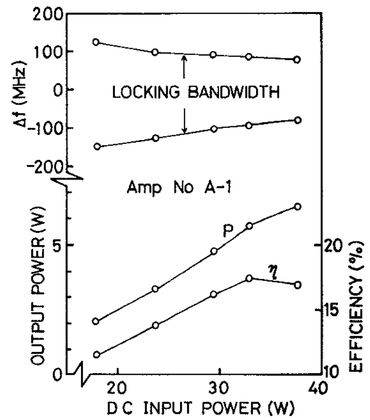

Fig. 8. Characteristics of the GaAs IMPATT amplifier versus dc input power of the diode.

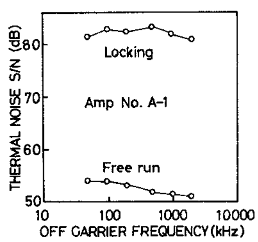

Fig. 9. Thermal noise characteristics of the GaAs IMPATT amplifier. Deviation is 200 kHz rms and the bandwidth is 3.1 kHz.

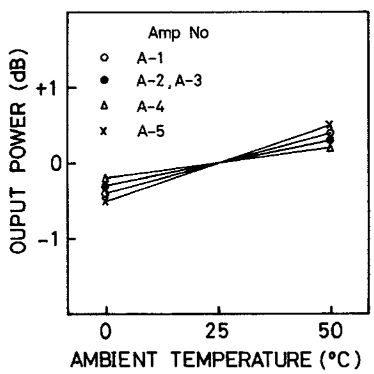

Fig. 10. Temperature dependence of the output power of the GaAs IMPATT amplifier.

diode. However, it is still more than 150 MHz at output power of 6.5 W, which is large enough for transmitting 1800 telephone channels.

Fig. 9 shows the thermal noise characteristics of the amplifier under free running and locking operations, respectively. The S/N ratio is measured at a deviation of 200-kHz rms and a bandwidth of 3.1 kHz. Under the free running operation, the S/N ratio is less than 60 dB, but under the locking operation the S/N ratio of the amplifier is more than 80 dB. This S/N ratio is satisfactory for practical microwave radio equipment.

The temperature dependence of the output power is shown in Fig. 10. In every case, for the temperature range between 0 and 50°C, the change of the output power is less than 1 dB. The thermal stability of the amplifier is excellent and is acceptable for practical use.

As described above, the 5-W GaAs IMPATT amplifiers have excellent characteristics regarding gain, efficiency, bandwidth, noise, and thermal stability and are expected to be promising for a high-power solid-state microwave amplifier.

IV. Conclusion

From this work, the following can be concluded.

1) By optimizing the diode structure and combining the output power of multichips, 10-W p-n junction type GaAs hi-lo IMPATT diodes with efficiencies more than 20 percent and MTTF's more than 10^6 h have been developed in *J* band. The highest efficiency is 26.6 percent at 7.3 GHz and the highest output power is 11 W at 5.7 GHz.

2) Using the 5-W class two-chip diodes, amplifiers delivering output power of over 5 W with 10-dB gain have been constructed. Efficiency, locking bandwidth, and S/N ratio are more than 15 percent, 150 MHz, and 80 dB. Change of the output power is less than 1 dB for the temperature range between 0 and 50°C.

3) Because of the excellent thermal stability and the high reliability, the 5-W GaAs IMPATT amplifiers can be used for practical high-power solid-state multichannel microwave radio equipment.

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A New Look at Noise in Transferred Electron Oscillators

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***Abstract*—Low-frequency current and voltage fluctuations have been measured, and it has been confirmed that noise in packaged transferred electron devices (TED's) is due to three distinct noise mechanisms: flicker, generation–recombination, and thermal noise. For transferred electron oscillators (TEO's), this low-frequency noise is upconverted into the microwave frequency range and adds to the intrinsic RF noise. We have found that between 1 kHz and 1 MHz off the carrier, temperature-dependent generation–recombination noise is the main contributor to the total noise. A model of a noisy TEO is presented. This model permits the calculation of AM and FM noise spectra from device and circuit parameters for measured low-frequency noise or the derivation of device characteristics from noise and circuit parameter measurements.**

I. INTRODUCTION

ACKET [1], Copeland [2], DeCacqueray *et al.* [3], and many others have shown that generation–recombination noise is a major contributor to the low-frequency noise of bulk n-GaAs. Sweet [4] found that AM and FM noise is due to intrinsic RF noise, thermal in origin, and "excess noise," a low-frequency noise that is upconverted into the microwave range and has a $1/f$ characteristic. What happened to the generation–recombination noise? The purpose of this investigation is to study the AM and FM noise characteristic of TEO's and identify the physical causes of noise from the measured data. To verify the experimental findings, a simplified model of a nonlinear oscillator is discussed, describing the noise behavior of the TEO in steady-state oscillations.

More than 100 TEO's obtained from various manufacturers have been measured. The data presented are representative of all devices tested.

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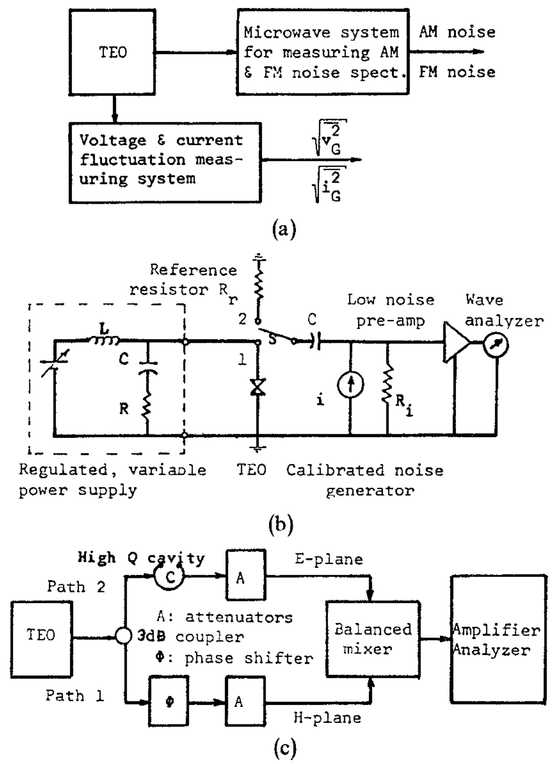

Fig. 1. Noise measuring system. (a) Principle of measurement. (b) Low frequency. (c) Microwave set-up.

II. MEASURING SYSTEM

The experimental work has been performed on n-type GaAs TED's mounted in waveguide cavities. All TED's and cavities are commercially available. At a manufacturer recommended operating voltage, the oscillator is tuned to test frequency 9.28 GHz and matched for optimum power output ranging from 15 to 800 mW.

The noise measuring system (cf. Fig. 1(a)) is used to measure low-frequency TEO noise below and above threshold (cf. Fig. 1(b)). The semiconductor is replaced by an equiv-