State-of-the-Art Performance Millimetre Wave Gallium Arsenide Gunn Diodes Using Ballistically Hot Electron Injectors

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ABSTRACT

Ballistically hot electron injectors have been designed using a graded gap GaAs/AlGaAs structure and incorporated into the cathode side of a GaAs Gunn diode drift region. Epitaxial material has been grown using MBE techniques and diodes fabricated. RF assessment at 94GHz has resulted in efficiencies over 2.3%, above 50mW output power, combined with low sideband noise performance and much improved temperature stability.

INTRODUCTION

The design of microwave Gunn diodes has been traditionally based upon epitaxially grown n^+-n-n^+ structures with an n-type drift region sandwiched between two n^+ contact regions to which ohmic contacts are made [1], Fig. 1(a). The operating frequency and efficiency are primarily dictated by the thickness and doping of the drift region.

As the systems requirements have become more stringent with higher frequencies and output powers demanded, these basic designs have reached the limits of their performance.

These are firstly that there is a rapid fall-off in power at frequencies above 60GHz in Gallium Arsenide (GaAs) Gunn diodes requiring the less efficient second harmonic component of the power to be utilised. There has been an alternative provided by the development of indium phosphide (InP) [2]. However, this technology is relatively immature and has questionable reliability, partially reflected in its limited commercial availability.

Secondly, and more importantly, the operation of these GaAs devices over the full military specification temperature range (-45°C to +25°C) is severely restricted by the turn-on characteristics of the devices, Fig. 2(a). As the temperature is reduced, the "turn-on" voltage, V_{on}, the point above threshold voltage at which coherent RF power is obtained, increases on the point where it equals the peak-power voltage, V_{pk}. This forces the diode to be operated at a higher voltage, with corresponding loss of power, reduced efficiency, poor fm sideband noide performance and the increased possibility of device failure at the excessive voltage.

A third consideration focusses on the method of accelerating the electrons at the cathode to enable transfer to the low mobility state. In n^+ -n-n^+ structures this accelerations is provided by the field in the drift region, resulting in a portion of this region which does not support domain formation. This "dead zone" may be as much as 0.25μm in a drift region of approximately 1.5μm in millimetric diodes and, since it acts as a parasitic resistance, results in reduced efficiency.

HOT ELECTRON INJECTION

Our solution to the above problems has been to tailor the electric field at the cathode. We have chosen to use a hot electron injection technique, whereby very large electric fields are created inside the semiconductor by using built-in potentials. The advantages of this type of engineered structure are that the metal-semiconductor interface can be removed from the region of the high fields at the cathode, making the ohmic contact process less critical, and that the nucleation point for the accumulation layer can be fixed as a function of bias.

There are a variety of possible structures which canbe used for hot electron injection, including a Schottky barrier, a planar-doped barrier and a graded-gap AlGaAs injector. The Schottky barrier, while feasible in principle, returns us to the problems of metal-semiconductor interfaces and their associated processing difficulties. Modern growth techniques, such as molecular beam epitaxy, allow the design of bothpdbs and graded AlGaAs injections with a large degree of freedom. Figs. 1(b),(c).

To produce mmW power with as little bias dependence as possible the optimum injector shape has a slowly increasing potential with an abrupt drop back to the potential of GaAs. The statement of the ideal barrier shape for voltage independent electric field after the injection can be seen if a general triangular potential barrier at height Φ and arms l and m under a bias v is considered. The electric field at the end of arm L is approximately given by $\Phi/l + v/(l + m)$. Thus for the barrier to set the electric field rather than the voltage we require $\Phi/l >> v\ (l + m)$. The simplest solution is to let l tend to zero - the graded gap injector.

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The active region of a Gunn diode, including the injector, has been modelled using a Monte-Carlo calculation [3]. The simulation has shown that a thin n^+ layer between the injector and the drift region is critical for controlling the electric field, while retaining the hot electron properties. A number of iterations of the simulation were performed until an acceptable design was derived. The simulations were quite sensitive to the lattice temperature in a non-trivial manner due to the interacting nature of the various parts.

An initial, and knowingly unrealistic temperature of 300K was used in the simulation which was refined after measurements of both CW and pulsed RF operation of the initial design indicated a more realistic value of lattice temperature of 450K. Subsequent designs, and structures grown to those designs, took this temperature difference into account leading to a rapid convergence towards an optimum design of the whole structure. The latest results are from devices manufactured to this design.

An additional benefit from using hot electron injection is the much improved temperature stability. This is due to the temperature of the electrons being set by the injection energy, typically equivalent to 2000K. Changes in the substrate temperature in the 130 degree range required for military specifications are relatively small in comparison.

EXPERIMENTAL RESULTS

Most of the effort in developing the graded-gap devices has been concentrated on the demonstration of performance capability in the second harmonic mode of operation in a full-height WG27 radial mode cavity around 94GHz. The structures were produced at GEC Hirst Research Centre using MBE with Si doping throughout and fabricated into integral heat sink (IHS) devices with AuGeNi ohmic contacts. The chips were then mounted in ODS138 packages and bonded with low inductance Maltese Cross gold pretoms prior to hermetic sealing.

The first parameters by which the injector performance may be assessed are the DC I-V traces. For a standard n^+-n-n^+ structure the curve exhibits a peak followed by a region of negative gradient; for a graded gap structure under forward bias the I-V trace has no peak, and the maximum current is reduced, Fig. 3 (a),(b). Injection at too high an energy will produce a curve with no peak but a region of positive gradient following the low-field characteristic, Fig. 3(c).

RF performance to date has been most encouraging with powers at room temperature of up to 80mW at 90GHz and 2.4% efficiency; the best results achieved for mm-wave GaAs devices at this frequency. 50-60mW at 94GHz with efficiencies of 1.6% is achieved reproducibly (See Table 1). FM sideband noise is better than -80dBc/Hz 100kHz from carrier, equal to that obtained from the best standard devices. Significantly, these devices exhibit a turn-on voltage very close to threshold, Fig. 2(b), which allows coherent oscillations around peak power over the full military specification temperature range with none of the disadvantages detailed previously. Further evidence of the improved temperature stability can be seen from the power, frequency and peak-power voltage variation across this temperature range, generally a factor of two or more below that typically exhibited by devices without hot electron injection. This is an added bonus for VCO designers who can then utilise a larger bandwidth since there is no longer need for compensation for frequency drift with temperature.

All devices tested have undergone initial screening, being run CW continuously for 168 hours at 80°C ambient temperature. No significant change in operating parameters has been noted. Lifetest measurements on these devices is continuing.

DISCUSSION AND CONCLUSION

The Monte-Carlo simulation has been used extensively to define the optimum structure for graded-gap Gunn diodes operating at 94GHz. Further refinements are still possible, however, including the grading of the drift region length [4] and increasing the average doping in the drift region so that the electric field will be engineered throughout the device. Placement of the injector structure at the cathode should improve the efficiency by siting the source of heat closer to the heat-sink. Together, these refinements are expected to give powers of 100mW with greater than 3% efficiency at 94GHz with no deterioration in the temperature performance.

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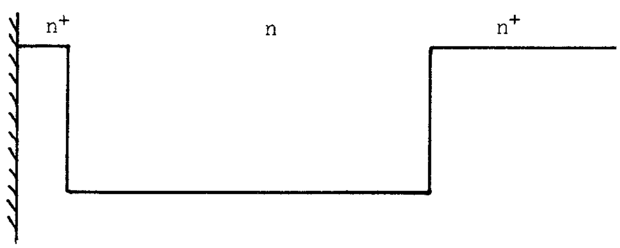
TABLE 1

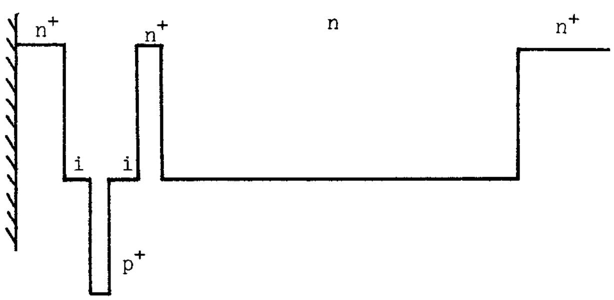
PERFORMANCE OF GRADED-GAP GaAs GUNN DIODES

Temperature (°C)	V_{on} (V)	V_{op} (V)	I_{op} (mA)	Freq. (GHz)	Power (mW)	eff(%)
-40	3.9	4.9	680	90	58	1.75
+25	3.2	4.7	660	90	50	1.6
+80	3.1	4.8	640	90	42	1.4

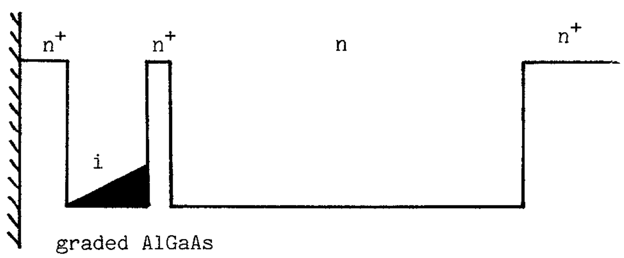
FIGURE 1



a) Standard n+ -n-n+ structure



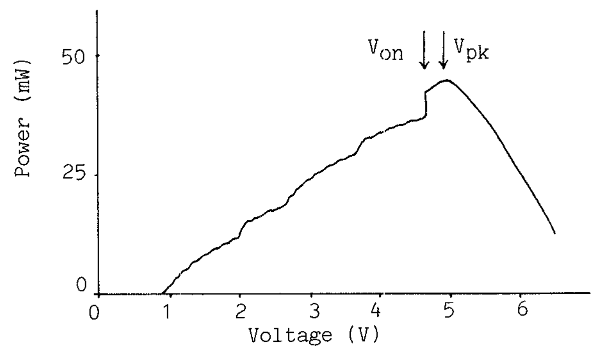
b) pdb structure



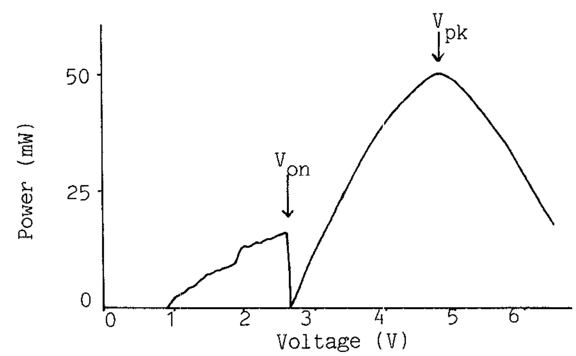
c) graded-gap structure

FIGURE 2. Turn-On Characteristics for

a) a standard structure
b) a graded-gap structure



a)



b)

FIGURE 3 DC I-V traces for

a) a standard structure

b) a graded-gap structure

c) a structure with a high barrier