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PERFORMANCE CAPABILITIES OF INDIUM PHOSPHIDE n^+-n-n^+ TRANSFERRED ELECTRON DEVICES AT MILLIMETRE WAVE FREQUENCIES

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ABSTRACT

This paper describes the development of indium phosphide n^+-n-n^+ devices which exhibit good output power and conversion efficiency capabilities in the mm wave frequency range. A brief review of the material growth and device fabrication technologies is given before the resultant device performances are discussed. It is shown that above 50 GHz indium phosphide exhibits clear power and efficiency advantages over existing gallium arsenide TEOs. Details are also given of the second order stability parameters shown by practical indium phosphide devices together with their likely importance to the system designer.

INTRODUCTION

Throughout the mm wave frequency range there is a growing demand for low-noise, solid-state oscillators. At frequencies below 100 GHz this demand has to date been partially satisfied by the gallium arsenide TEO. However this device's low output power capability and more importantly its poor conversion efficiency (<0.5%) have limited its applications. Thus, there is a clear need for higher efficiency and higher frequency TEOs, particularly for systems requiring multi-mixer drive levels and operating frequencies above 100 GHz.

Theoretical studies of the transferred electron effect in III-V semiconductors have shown that indium phosphide could provide the sought after improvements to mm wave TEO performances[1]. An examination of the internal dynamics of electron transfer reveals that indium phosphide should exhibit the transferred electron effect at frequencies a factor of two higher than those seen from gallium arsenide. Further, a comparison of the velocity field characteristics of the two materials shows that indium phosphide has a higher electron peak-to-valley velocity ratio with a less temperature dependent electron velocity behaviour. Together, these factors suggest that indium phosphide TEOs should exhibit better d.c. to r.f. conversion efficiencies at greater output power levels with the added advantage of improved temperature stability.

This paper describes the development of indium phosphide devices whose r.f. performances support the above predictions. In addition the r.f. performances exhibited by typical indium phosphide oscillators are presented which show that the device second-order parameters are comparable to existing gallium arsenide TEO performances.

MATERIAL GROWTH

It has already been demonstrated that high d.c. to r.f. conversion efficiencies can be achieved at mm wave frequencies using n-n^+ indium phosphide material on which an injecting cathode contact is utilised.[2] However, our work with this device structure has shown that although excellent pulsed mm wave devices can be produced,[3] there are difficulties in producing a usable CW device. Unfortunately, the injecting cathode contact has a strongly positive current with temperature behaviour (dI/dT) which makes manufacture of reliable CW devices for system use problematical. Therefore, the likely system requirements of low-noise, good reliability and thermal stability have led us to initially concentrate on the inherently less efficient three layer n^+-n-n^+ material structure. This material is grown by vapour phase epitaxy using the phosphorus trichloride process, with the active (n) region normally being specified at a carrier density of 5.10^{15} to $1.5.10^{16}$ atoms cm^{-3} and an active length (L) of 0.7 to 2.5μm (see Figure 1). The actual values used are dependent upon the operating frequency, efficiency and impedance level required of the finished oscillator device.

DEVICE FABRICATION

To realise the low thermal and parasitic electrical resistances which are essential to efficient mm wave operation, the devices are fabricated as integral heat sink (IHS) devices with a total semiconductor thickness of 10-12μm,[4] (see Figure 2). An optimised Ni/Ge/Au metal scheme is used to provide an ohmic, metal/semiconductor contact exhibiting low contact resistivities within the range 1 to 3.10^{-6} ohm cm^2. Device area definition is performed using a photo-etching technique[5] to produce vertical sided device geometries.

Finally, owing to the thermal constraints imposed by indium phosphide's high threshold field (3 x GaAs), the IHS devices are ultrasonically bonded to the device encapsulations to achieve the lowest thermal impedance possible.

RF PERFORMANCE

(i) Primary Characteristics

Using the above technology allied to a knowledge of the important material related RF operating characteristics[7] devices have been fabricated for TEO operation from 30 to 140 GHz. An investigation into the operating modes of TEOs throughout this frequency range has established that fundamental frequency operation is possible from indium phosphide up to at least 120 GHz but only up to 60-70 GHz from gallium arsenide. At higher frequencies than these, both materials operate in a harmonic extraction/enhancement mode, with gallium arsenide ceasing to generate significant power above 110 GHz whilst indium phosphide is already capable of 10 mW power levels at 120 GHz and 1 mW at 140 GHz. Thus, the theoretically predicted higher operating frequency potential of indium phosphide has been practically verified.

Conventional resonant-cap and post-coupled waveguide circuits were used in the assessment of the indium phosphide device performances. Operating in the fundamental frequency mode, these devices have to date generated highest powers of 210 mW at 50 GHz (4%), 160 mW 70 GHz (3%), 120 mW 80 GHz (3%) and 50 mW 90 GHz (2%). Also at a lower power level the best efficiencies have been 4.75% 140 mW at 57 GHz, 3.25% 70 mW 75 GHz, 2% 30 mW 98 GHz and 1.3% 19 mW 106 GHz. A comparison of current device performances from both Plessey indium phosphide and gallium arsenide TEOs is presented in Figure 3. From these results it can be seen that the theoretically expected advantages of indium phosphide in terms of output power and efficiency are also borne out by the real device perfor-

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mances. Additionally, as material optimization is carried out for operation in the 90 to 140 GHz range we expect that the performance capabilities predicted in Figure 3 will be approached.

(ii) Secondary Characteristics

The figures quoted above probably represent some of the highest powers and efficiencies generated from n^+-n-n^+ TEO structures. However, in themselves they are not sufficient to ensure the successful application of these devices, since often the oscillator second order parameters are the system designer's prime concern. For this reason we have started to study the noise performance, voltage stability and temperature stability of our devices.

Preliminary noise measurements in W-band have shown that indium phosphide devices can exhibit a close-to-carrier FM noise performance similar to that seen from gallium arsenide TEOs. Interestingly we have found that indium phosphide shows a strong 1/f noise dependence at least out to 10 MHz from carrier indicating a lower thermal noise level than that of gallium arsenide. This observation does correlate with the lower diffusion coefficient:low field mobility ratio (D/μ) inherent in indium phosphide.

With regard to the device voltage and temperature stability these characteristics are perhaps more clearly illustrated by considering the behaviour of a practical TEO. Figure 4 shows the output power and frequency variations with bias voltage (dP/dV and dF/dV) of a typical indium phosphide oscillator. It can be seen that, unlike gallium arsenide, this device exhibits an output power which monotonically increases with bias voltage. In fact this feature is a direct consequence of indium phosphide's more temperature stable velocity-field characteristics which results in the device output power and conversion efficiency being relatively insensitive to active layer temperature and hence input power. Further, this more stable velocity-field characteristic is evidenced in the device performance with temperature which shows a power and frequency variation (dP/dT and dF/dT) of -0.013 dB $^oC^{-1}$ and -8 MHz $^oC^{-1}$ respectively.

Although all these second order parameters are perfectly compatible with existing gallium arsenide TEO performances the linear voltage pushing behaviour of indium phosphide could prove a real benefit to the system designer. Since there are no difficulties associated with frequency and power maxima, linear electronic bias voltage control can be simply implemented with indium phosphide TEOs. Thus for example frequency temperature compensation to track a known transmitter temperature drift becomes possible using basic electronic bias voltage control techniques.

Finally Table 1 presents comparison of the performance data for a harmonic mode gallium arsenide and a fundamental frequency indium phosphide device operating in the popular 94 GHz window. This data clearly demonstrates that indium phosphide can provide a higher power, more efficient alternative to the existing gallium arsenide TEO with similar stability parameters.

CONCLUSIONS

The results presented clearly support the theoretically expected advantages of indium phosphide over gallium arsenide as a TEO material. In addition to the greater output powers, better efficiencies and higher frequency capability, it has been shown that indium phosphide TEOs exhibit stability parameters compatible with system design needs. We therefore conclude that it should be possible to develop stable high power, efficient mm wave oscillators with good bias tuning behaviour using indium phosphide n^+-n-n^+ devices.

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TABLE 1

Parameter	Gallium Arsenide (TEO273)	Indium Phosphide
Frequency GHz	94	94
Output power mW	15	30
Input power W	5.2	1.8
dF/dV ($\pm$ 0.2V) MHz V^{-1}	$\pm$ 300*	-640
dP/dV ($\pm$ 0.2V) dB V^{-1}	$\pm$ 0.6*	+2.0
dF/dT (25-50^{o}C) MHz $^oC^{-1}$	-6	-8.0
dP/dT (25-50^{o}C) dB $^oC^{-1}$	-0.03	-0.012
Q_e	300**	100

*Device operating at frequency and power maxima.

**Harmonic mode can give anomalously high Q_e values.

Figure 1
PROFILE OF TYPICAL InP mm WAVE EPITAXIAL LAYER

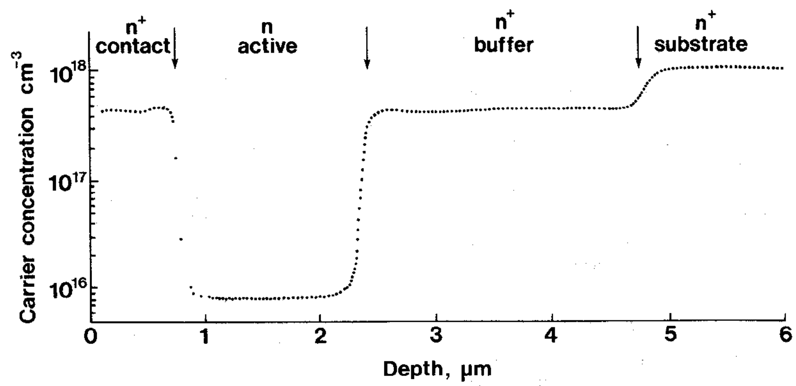

Figure 2
INTEGRAL HEATSINK DEVICE STRUCTURE

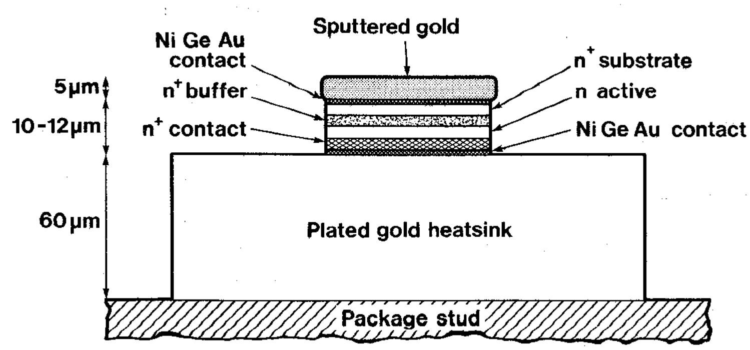

Figure 3
OUTPUT POWER AND CONVERSION EFFICIENCY CAPABILITIES OF PLESSEY n^+-n-n^+ TEO's

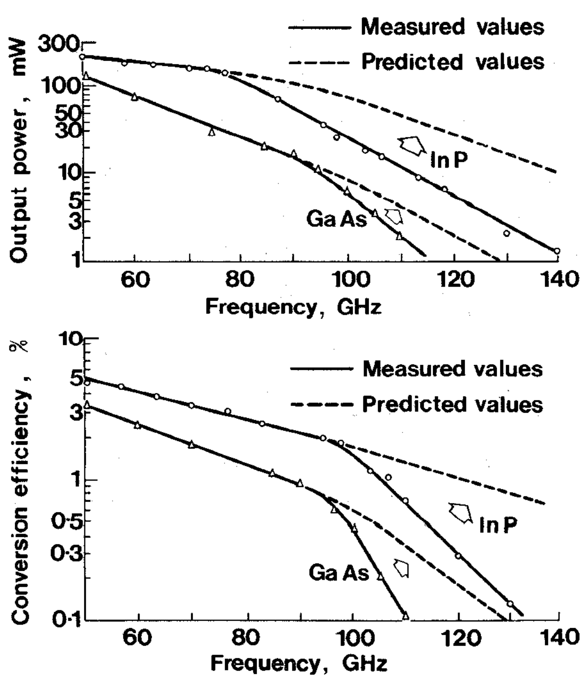

Figure 4
TYPICAL VOLTAGE CHARACTERISTICS OF InP TEO