Reprinted from SPIE Vol 259—Millimeter Optics

# New indium phosphide sources

**L. Wandinger**
**Electronics Technology and Devices Laboratory**
**Electronics Research and Development Command, Fort Monmouth, New Jersey 07703**

## Abstract

The Indium Phosphide (InP) Gunn device is fast becoming a key component in the millimeter wave region. The device has superior performance as wideband low noise amplifier, low noise local oscillator, self-oscillating mixer, and low to medium power source. Its development and advances are primarily fueled by military systems requirements and developments covering missile and projectile guidance, high resolution radar systems, intercept secure communications and EW and ECM functions.

In this paper an overview of the current status of indium phosphide Gunn device development and future trends is presented. Covered will be in particular key parameters leading to indium phosphide's advantage at millimeter-wave frequencies, recent material and device developments, oscillators, amplifiers and systems applications with emphasis on current capabilities. Other devices such as InP FET and InP IMPATT devices are not considered in this paper because of their current limitations to microwave frequencies.

## Introduction

Since its introduction a decade ago, the InP Gunn device has rivaled the GaAs Gunn in performance and system application. The potential of InP Gunn devices as high power pulsed sources for microwave applications has been demonstrated at 16 GHz with a peak power of 15W at 10% duty cycle.[1] In recent years significant advances have been made in extending the frequency range of InP Gunn devices into the 94 GHz range, increasing CW power output and conversion efficiency steadily Today 94 GHz InP Gunn diode oscillators surpass similar GaAs Gunn diode oscillators by a factor of 2:1 in output power and by a factor of almost 3:1 in conversion efficiency. Similarly, 40 GHz to 60 GHz InP Gunn amplifiers have a 3 to 6 dB lower noise measure than GaAs counterparts. However, these highlights are not signaling maturity in this field and significant advances can be expected within the next five years. This paper traces the advantages of InP for millimeter-wave components, recent progress in InP Gunn device development and initial applications in military systems.

## Advantages of InP

Let's look at the key scattering and transport properties which are the cause for the superior performance of InP versus GaAs Gunn devices. These properties are tabulated in Table 1.

As is well known, the Gunn effect is based on the existence of a many valley conduction band structure and on the transfer mechanism of electrons from low effective mass, high mobility states of the central valley to high effective mass, low mobility states of the satellite valley under the influence of high electric fields leading to a negative differential mobility region. It was shown,[2] that the dominant speed limitation of hot-electron effects in GaAs is not determined by the intervalley scattering rate, which is much faster, but by the rate with which electrons can gain or lose energy in the central valley of the energy band structure. The same conclusion applies to InP since evidence suggests that the $\Gamma$-L scattering is even faster than the $\Gamma$-X scattering.[3] It is shown from photo emission data[4] that the intervalley relaxation time $\tau_{L\Gamma}$ which is the average time for an electron to be scattered from the L-valley to the central ($\Gamma$) valley is $\approx 2.5 \times 10^{-13}$s.

Two time constants govern the central valley dynamics: The energy relaxation time $\tau_e$ due to collisions[5] and the acceleration-deceleration time $\tau_{ad}$ required for an electron to gain or lose the energy $E_s$[6] separating central valley from satellite valley.

Table 1 shows that the values of these time constants for InP are both smaller by a factor of 2 than those for GaAs. This leads to the conclusion that InP should be approximately twice as fast as GaAs or the ultimate frequency limit for InP should be twice as high as for GaAs.[7] Since $\tau_{ad}$ decreases with increasing field strength, the speed of hot electron devices increases with increasing field. The 3-times higher threshold field of InP is clearly a decisive factor in this category. The frequency limit of GaAs Gunn devices is placed at about 100 GHz.

Table 1. Advantages of InP

| | Reason | GaAs | InP |
|---|---|---|---|
| Higher Frequency Limit | Central Valley Dynamics: | f≈100 GHz | 2f |
| | Energy Relaxation time due to collisions | $6\times10^{-12}$s | $3\times10^{-12}$s |
| | Acceleration-deceleration time for electron to gain or lose $E_s$ | $1.48\times10^{-12}$s | $0.75\times10^{-12}$s |
| | Intervalley Relaxation time | | $2.50\times10^{-13}$s |
| Higher Efficiency η | Higher $v_p:v_v$ ratio | 2.4 | 4.0 |
| Transfer Mechanism and η less T dependent | $E_{\Gamma\text{-}L}$ 0.31eV in GaAs<br>$E_{\Gamma\text{-}L}$ 0.6 eV in InP | Efficiency degrades by<br>0.2% per °C | 0.05% per °C |
| Lower Noise | Noise proportional to $D(E)/\mu(E)$<br>Low D in InP at fields above threshold | at $E/E_{th}=2$<br>142 cm$^2$/s | 72 cm$^2$/s |
| Thermal Conductivity | | 0.54 W/cm°C | 0.68 W/cm°C |
| Threshold Field | At f<20 GHz, $L_a \geq 10\mu m$<br>Increased Power dissipation precludes CW operation | 3.5 KV/cm | 10.5 KV/cm |
| Active Region Length | Experimental Evidence | $L_a$ | $\approx 2L_a$ |

The peak-to-valley velocity ratio[8,9] is an important parameter for the efficiency of Gunn oscillators. The efficiency is proportional to $v_p - v_v / v_p + v_v$[10], and a high peak-to-valley ratio is clearly desirable. As Table 1 shows, InP has a clear advantage over GaAs in this category. With increased temperature, the peak-to-valley ratio and consequently the device efficiency are reduced in general. However, the electron transfer in InP is much less temperature sensitive, due to the large Γ-L energy separation. A detailed analysis[11] shows that in InP the efficiency degrades less rapidly with T, a valuable property with operating device temperatures as high as 225°C.

Noise in Gunn devices is proportional to D/μ where D is the electron diffusion coefficient and μ is the negative differential mobility. It was shown[12] that above threshold the noise decreases with increasing electric field. In addition, it was shown that the characteristics of polar scattering and intervalley scattering at fields above threshold lead to a low diffusion coefficient in InP. Consequently, lower noise is an inherent property of InP because of its higher threshold field.

The high threshold in InP (3 times GaAs) which proved so advantageous for low noise and upper frequency limit is the biggest drawback of InP for low frequency devices due to greatly increased power dissipation in thicker active layers (10μm for X-band device) preventing CW operation. At higher frequencies, the active region length in InP is twice that of GaAs[13] which is a technological advantage in fabricating millimeter-wave devices. Finally, the thermal conductivity of InP at room temperature is 0.68 W/cm°C versus 0.54 W/cm°C for GaAs, a 25% advantage.

## Material preparation

Vapor phase epitaxy (VPE) provides excellent control in growing suitable Gunn device structures. The preferred growth technique for InP is the $PCl_3$-In-$H_2$ system, using the chloride transport process.[14] It yields low background impurities, precise control over layer doping, uniformity, thickness, surface morphology, extremely flat active layers, complex multilayer doping profiles and abrupt high-to-low doped transition layers (several orders of magnitude) of less than 0.5 μm.

The epitaxial structure is grown on tin doped substrates oriented 2° off (100) towards (110) using high purity $H_2S/H_2$ mixtures to achieve the required doping profile. Typical growth rate of this technique is 0.07 μm/min. producing device quality material with mirror surfaces. Typical values for high quality low $10^{15}$cm$^{-3}$ doped layers range from 4500-5200/40,000-60,000cm$^2$/V-sec at 300°K/77°K. Low numbers of deep level traps as indicated by low carrier concentration freeze-out between 300°K and 77°K attest to the quality of the material.

## Device design and technology

The fabrication of high efficiency low noise millimeter-wave InP Gunn devices requires optimization of active layer doping profile, device geometry, and above all, cathode contacts while striving for good thermal design, metallurgical stability and device reliability. The electrical characteristics of the cathode contact play a dominant role in the proper operation of an InP Gunn device, its efficiency and output power. Three basic types of cathode contacts have been discussed:[15] (1) ohmic cathode; (2) constant current cathode; and (3) two-zone cathode. Each type differs in terms of the number and energy distribution of electrons which are injected into the active region of a Gunn device and the electric field boundary conditions at the cathode interface.

The efficiency of the ohmic cathode is limited due to the low cathode field, the injection of low energy electrons, the concentration of the high field near the anode and a current well above the valley current. The predicted efficiency is in the 5% range.

The ideal constant current cathode is a controlled height Schottky barrier contact with a reverse saturation current density limited to that corresponding to the valley velocity in the bulk semiconductor. Computer simulations have indicated efficiencies in excess of 20% at bias voltages well above those for ohmic cathode contacts. This cathode has the disadvantage of a strong temperature dependence which is tied to the thermal activation of the barrier injection process.

The two-zone cathode is characterized by injecting highly energetic electrons into the active region of the device without pinning the electric field at the boundary, thereby yielding high efficiency operation comparable to the constant current cathode.

A typical InP Gunn device structure is shown in Figure 1. It consists of the various epitaxial layers, metal contacts and a plated gold heat sink to reduce thermal resistance and facilitate chip bonding and packaging. The mesa structure is formed by chemical etching. Thermal resistance of 94 GHz devices ranges between 35-40°C/W of which less than one-third is contributed by the InP mesa itself.

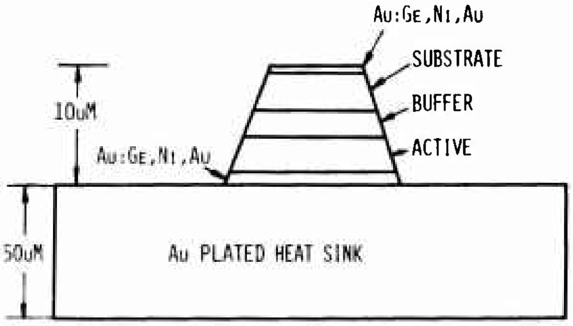


Figure 1. InP Gunn Device Structure

Figure 2. InP Mesa, Thickness 10μm (1600X)

Series resistance due to a thick substrate degrades device efficiency. At millimeter-wave frequencies skin effect loss is added due to the confinement of RF currents. The skin depth at 94 GHz is about 10 μm. Substrate thinning to skin depth level has improved device performance drastically. A SEM photograph of a super thin InP Gunn mesa is shown in Figure 2.

The device is mounted in a N-34 package with cross ribbon bonded top contact as shown in Figure 3.

## Oscillators

InP Gunn oscillators for 60 GHz and 94 GHz have been developed. Two-layer, three-layer and two-zone cathode device structures whose detailed doping profiles are shown in Figure 4 have been used. Alloyed Au:Ge,Ni,Au contacts for both sides have been used on all structures.

The two-layer devices showed slight current limiting with direct metal contact as cathode and yielded the highest efficiencies at 60 GHz. It resembles the previously discussed constant current cathode. As expected, the three-layer ohmic cathode devices had significantly lower efficiency.

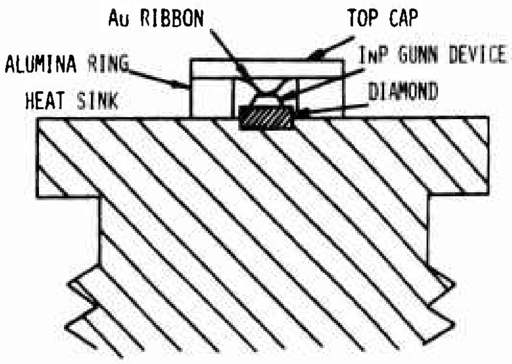


Figure 3. Packaged InP Gunn Device

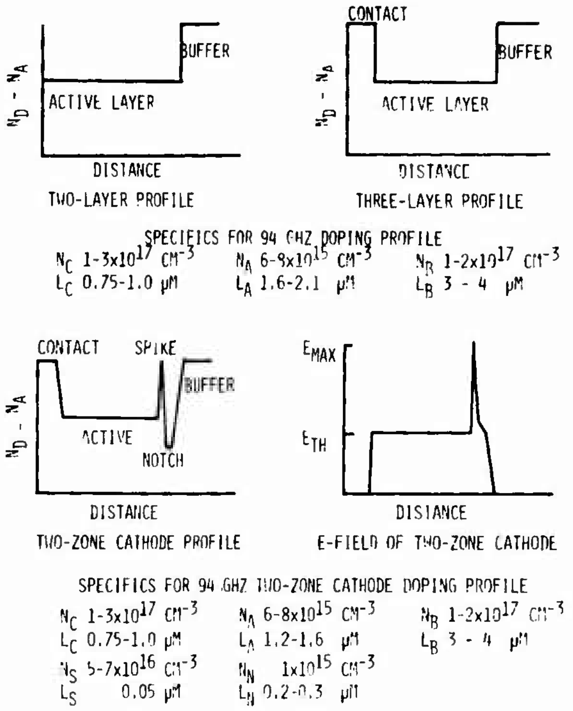


Figure 4. Three Different Doping Profiles with Specifics for 94 GHz InP Gunn Devices

The two-zone cathode structure is a complex profile consisting of buffer-notch-spike-active-contact layers. Doping levels and length of the various layers as well as static electric field profile across the device can be taken from Figure 4. The notch doping and length are designed to assure a rapid rise of the electric field across this zone, thereby accelerating the electrons to high energies. Since the highly doped narrow spike reduces the electric field rapidly, the energetic electrons retain much of their energy during transit of the spike. Thus, hot electrons are injected into the active region effectively reducing the cathode dead space.

At 60 GHz, a coaxial-waveguide circuit[16] as shown in Figure 5 produced the best power levels and efficiencies. In this circuit, a coaxial line is terminated on one end by the InP Gunn device and on the other end by a multi-section low pass filter DC biasing network. A reduced height opening provides both coax-to-waveguide coupling and impedance transformation to full height waveguide. Center conductor length and diameter are varied for circuit optimization. A dielectric tuning rod allows limited tuning of about 1 GHz.

At 94 GHz, the familiar "hat" or radial line circuit as shown in Figure 6 was used exclusively. The oscillator frequency is primarily determined by the diameter of the hat, its distance from the waveguide wall and to a lesser extent by the thickness of the hat and the post diameter and length above it. The diode is mounted in the waveguide wall and a similar bias feed-through as described above is used. A sliding short provides impedance matching

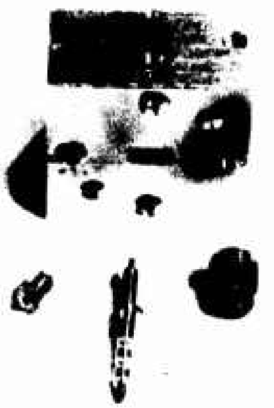


Figure 5. 60 GHz Coax-Waveguide Circuit

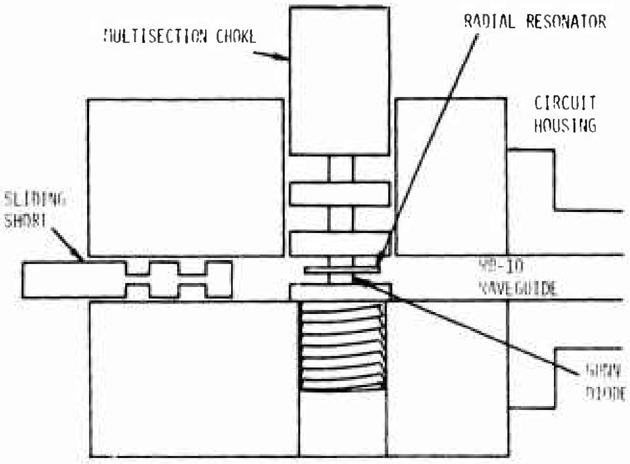


Figure 6. 94 GHz Radial Line Resonator

and optimum coupling location, $(2n+1/4)\lambda_g$ behind the diode, resulting in maximum power output. The performance of the various InP Gunn structures is summarized in Table 2.

Table 2. RF Performance of Millimeter-Wave InP Oscillators

| | CW | | | | PULSED | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | f (GHz) | Po (mW) | η (%) | t* (μm) | Pulse Width (μs) | Duty Cycle | f (GHz) | Po (mW) | η (%) | t* (μm) |
| Two-layer Devices | 56.5 | 194 | 4.7 | 50 | 0.25 | 0.10 | 54.5 | 860 | 4.8 | 50 |
| | 61.1 | 123 | 3.0 | 40 | 0.25 | 0.10 | 67.8 | 135 | 7.0 | 20 |
| | 83.8 | 49 | 5.7 | 20 | 0.25 | 0.10 | 89.9 | 68 | 5.1 | 20 |
| | 89.5 | 125 | 3.3 | 10 | 0.25 | 0.10 | 99.0 | 24 | 6.0 | 20 |
| | 96.4 | 73 | 2.1 | 10 | 0.50 | 0.01 | 90.3 | 236 | 4.3 | 10 |
| | 105.8 | 35 | 1.5 | 20 | 0.25 | 0.10 | 71.5 | 99 | 8.4 | 20 |
| Three-layer Devices | 57.2 | 120 | 1.9 | 50 | 0.25 | 0.10 | 57.1 | 220 | 3.7 | 30 |
| | 94.1 | 63 | 1.3 | 20 | 0.25 | 0.10 | 66.7 | 175 | 3.3 | 40 |
| | 100.2 | 36 | 0.8 | 20 | 0.15 | 0.06 | 63.0 | 100 | 0.8 | 50 |
| | | | | | 0.50 | 0.01 | 93.3 | 52 | 0.8 | 40 |
| | | | | | 0.25 | 0.10 | 100.3 | 14 | 0.2 | 40 |
| Two-zone Cathode Devices | 57.5 | 32 | 0.9 | 40 | 0.50 | 0.10 | 57.0 | 130 | 1.6 | 20 |
| | 94.5 | 20 | 0.5 | 40 | 0.50 | 0.10 | 88.2 | 34 | 0.6 | 40 |
| Combiner<br>2 diodes 40mW; 39mW<br>Dual Radial Line | | 75 | 95.0 | Initial results to demonstrate feasibility, not optimized. | | | | | | |

t* = total device thickness

Both CW and peak power results are reported. Overall the best CW power levels and efficiencies have been obtained with two-layer direct metal contact devices. In the 94 GHz region, the best device produced a power output of 125 mW with 3.3% efficiency at 89.5 GHz. This dramatic improvement in performance at this frequency resulted from minimizing skin effect losses and series resistance losses by thinning the device to 10 μm. As expected, the three layer ohmic contact devices show lower performance levels. The results for the two-zone cathode devices are preliminary since only non-optimum doping profiles have been available.

Devices under pulsed conditions show marked increases in performance due to the lower operating temperature. The best results are 860mW at 54.5 GHz and 236mW at 90.3 GHz. In the pulsed mode, the highest efficiency was 8.4%. Regular CW rather than specially designed devices were used for these measurements.

InP Gunn devices are inherently broadband devices. A reduced height waveguide resonator was used to demonstrate the mechanical and electronic tuning capabilities of InP Gunn oscillators at 60 GHz. This oscillator was tuned mechanically from 52 GHz to 64 GHz with power variations less than 2.5 dB. Varactor tuning covered a range of 2.3 GHz.

## Amplifiers

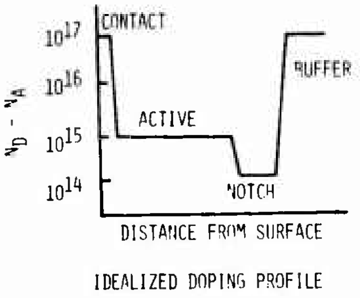
The broadband negative resistance characteristics of an InP Gunn device together with its low noise properties are ideal for the development of low noise InP Gunn reflection amplifiers for either narrow or broadband applications in the millimeter-wave region. It has been shown[17] that the noise measure M approaches a limit

$$M_{Min} \longrightarrow \frac{q\,D(E)}{kT\,\mu(E)} \qquad (1)$$

where q is the electronic charge, k is Boltzmann's constant, T is the absolute temperature, D(E) is the electron diffusion coefficient and μ(E) is the differential negative mobility, both field dependent quantities. At approximately twice threshold field, D(E) of InP is only one-half that of GaAs.[18]

A low noise measure requires a low nL product and a uniform DC electric field over most of the device which can be achieved with a cathode notch structure[19] as shown in Figure 7. This structure has been used to fabricate InP Gunn amplifiers. It consists of a sequence of buffer-notch-active-contact layers with doping profile specifications indicated in the same figure to cover the frequency band 40-60 GHz. Device fabrication and packaging have already been covered in the oscillator section.

Coaxial-waveguide circuits as discussed previously were predominantly used for the amplifiers. The noise measure decreased steadily with decreasing nL products and reached a minimum of 7.8dB for nL between $1\text{-}2\times10^{11}$ $cm^{-2}$. This might be an inherent limit of the n-type notch contact structure. When the notch width becomes comparable or greater than the active layer width as is the case for low doped active layers needed to achieve uniform fields, a series resistance is added to the device due to the appreciable voltage drop across the notch region. Improvements in the noise measure can be achieved with the use of a p-type notch profile. A noise measure of 4-6dB for Gunn amplifiers in the 40-60 GHz region is projected.



SPECIFICS FOR 40-60 GHZ NOTCH PROFILE

| | |
|---|---|
| $N_C$ 1-3x$10^{17}$ $CM^{-3}$ | $N_A$ 0.8-1.0x$10^{15}$ $CM^{-3}$ |
| $L_C$ 0.75-1.0 uM | $L_A$ 2.0-3.5 uM |
| $N_N$ 3-5x$10^{13}$ $CM^{-3}$ | $N_B$ 1.0-2.0x$10^{17}$ $CM^{-3}$ |
| $L_N$ 1.4-1.8 uM | $L_B$ 3 - 4 uM |

Figure 7. InP Cathode Notch Device For Amplifier

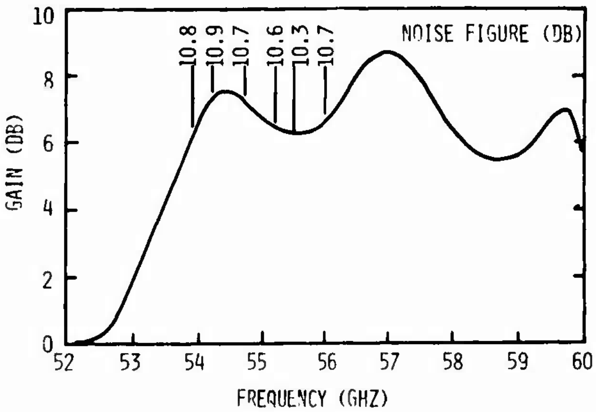


Figure 8. Gain and Noise Figures of 56.5 GHz Amplifier

A typical gain response and noise figure of a single stage InP Gunn reflection amplifier for the upper end of this band is shown in Figure 8. As the results show, a gain of 6-8dB with noise figures between 10-11dB is typical. Between 40-60 GHz, full band operation of the amplifier is presently not possible because of the lack of full band circulators. As is seen, amplifiers with 5 to 6 GHz bandwidth can be fabricated with present day circulators. Both diodes and circuits are not limiting full band operation. A plot of power out versus power in is shown in Figure 9 with the diode operated for best noise figure. An amplifier with 20dB gain and 100mW saturated power output at 60 GHz tunable over 4 GHz is feasible with existing technology.

## Systems Applications

Military systems requirements in communications, radar, guided weapons and electronic warfare provide a strong impetus in the millimeter-wave field. The frequencies of interest range from 35 GHz to 220 GHz. Advantages to be gained range from high resolution all-weather capability to anti-jam, low probability of intercept potential with the added benefits of small size and weight for portable operation. A principal thrust is to combine low cost designs with advanced millimeter-wave technology for practical hardware and systems. In the device area, the Gunn device is emerging as a key component and in the circuit technology area, the dielectric image guide integrated circuit is gaining stature for these applications.

Recently,[20] the development of a binocular radio at 70 GHz and a 94 GHz radar has demonstrated the feasibility of this approach in military systems. The basic component for the transceiver front end is the millimeter-wave Gunn oscillator in dielectric image guide. It can be used as a low noise local oscillator, a self-oscillating mixer and a low noise transmitter. The principal construction of such a device is shown schematically in Figure 10. It consists of a Gunn oscillator mounted in a metal plane serving as heat sink and support. Boron nitride with a dielectric constant of 4 is used as dielectric image guide. The diameter of the hole which houses the packaged Gunn device determines the operating frequency. The top metallization provides the ground path, DC bias is applied through the bottom with an anodized aluminum insert separating device from metal support. A modified top connector is needed to extract the IF signal if this structure is used as a self-oscillating mixer. In the binocular radio, a single integrated Gunn oscillator performed both transmitter and receiver function. In the 94 GHz radar, these functions are performed by a self-oscillating mixer and a low power transmitter both using dielectric image guide Gunn oscillators. A range of 1-2km for the binocular radio has been achieved with good voice communication. These developmental systems represent important steps in the development of affordable systems. As improved InP Gunn oscillators with more power and higher efficiency become available, systems performance will improve significantly, such as range and power drain.

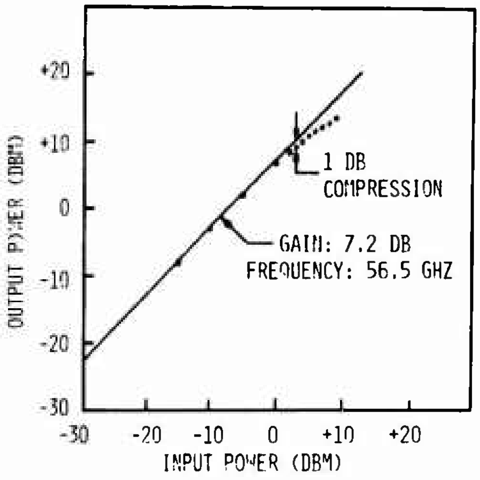


Figure 9. Gain Compression Data of 56.5 GHz Amplifier

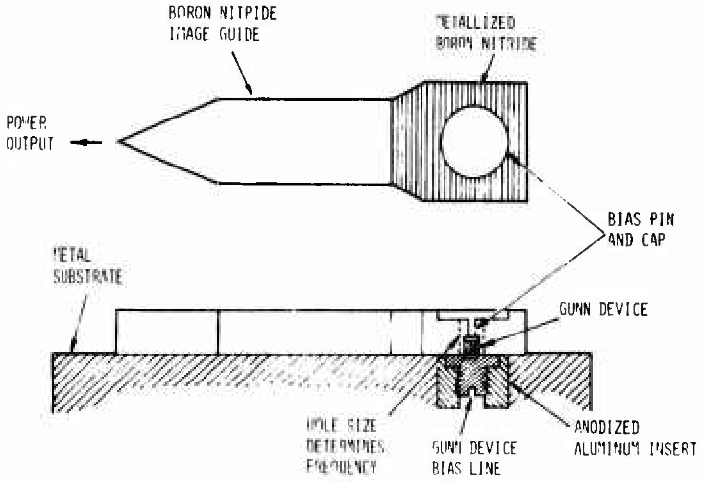


Figure 10. Dielectric Image Guide Gunn Oscillator

## Future Trends

### Two-zone cathode

Due to its complexity, the two-zone cathode structure received only a limited amount of effort in the past. VPE produced sections and non-optimum complete profiles. Efforts have recently been concentrated to achieve this structure by VPE and latest results are highly promising as Figure 11 shows. Molecular beam epitaxy is an alternate technique to grow a two-zone doping profile. However, experimental results to grow InP layers and composite profiles by MBE are only sporadic and the technique cannot be immediately applied to this area. Ion implantation may be useful to achieve one section of a modified structure.

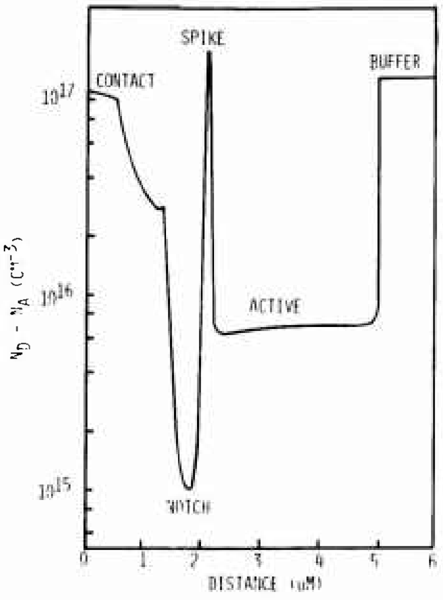


Figure 11. Two-zone Cathode Doping Profile Grown by Vapor Phase Epitaxy

Thermal resistance. Currently, the thinned integral heat sink technology with Au as heat sink has been developed. Replacement of Au with Ag heat sink capitalizing on its higher thermal conductivity can yield a maximum improvement of 30%. The biggest reduction in thermal resistance of millimeter-wave InP Gunn devices can be expected from developing diamond heat sink technology. For super thin devices (10µm) the contribution of the plated heat sink and the copper package to the total thermal resistance is no longer negligible. At 500°K, type IIa diamond has a thermal conductivity which is by a factor of 4 higher than that of Au or Cu. As a result, a significant reduction in the thermal resistance of the device and an increase in its power output and efficiency can be obtained by applying a diamond heat sink. An optimum efficiency of 10% at 100 GHz is predicted for InP Gunn devices.

Pulsed sources. The potential of InP Gunn devices as high power pulsed sources has been demonstrated. Efforts are now in progress to develop InP Gunn oscillators with a peak power goal of 1.5W at 94 GHz. To achieve this goal, higher current, higher voltage devices with larger cross-sectional area, or higher active layer doping levels together with most efficient cathode contacts will be developed. Low loss matching circuits are needed to match the lower impedance devices for high performance.

Combiners. To increase power output, in particular under pulsed operation, multiple diode combining techniques using both hybrid-coupled and resonator combiners have been developed for IMPATTS. Most of the results to date have been achieved by circuit combining techniques. Initial results with a dual CW InP Gunn diode combiner in the 94 GHz region are very promising, as shown earlier in this paper. A power output of 500mW at 94 GHz from an InP Gunn device combiner as a near term goal appears attainable.

140 GHz InP Gunn oscillator. As shown earlier in this paper, the prospects of achieving a high performance InP oscillator at 140 GHz and higher frequencies are very favorable. Efforts will be initiated near term to investigate this area.

Millimeter-wave integrated circuits. The potential of millimeter-wave integrated circuits incorporating InP Gunn devices for new and low cost receiver and transmitter functions appears quite promising. Initial circuits, as discussed in the section of systems applications are the first step in this direction.

## Conclusion

The state-of-the-art, recent advances and future trends of millimeter-wave InP Gunn oscillators and amplifiers have been described. Most significant are the results which show that InP has surpassed GaAs in this area by a factor of 2:1 in output power and a factor of about 3:1 in efficiency, at 94 GHz. The real benefit of low noise, high performance InP Gunn devices will become even more obvious as operating frequencies are pushed to 140 GHz and higher where no other semiconductor device with similar performance characteristics for low noise application is available. The potential of InP Gunn devices for pulsed operation through the millimeter-wave frequency range and increased power output through combining is just beginning to be tapped. The benefits of millimeter-wave IC's are just beginning to emerge.

## Acknowledgments

The author would like to thank J. Crowley, from Varian, and Y. Chang, from TRW, for material provided for this paper. Experimental data for this paper was obtained from work performed at Varian under Contract No. DAAB07-78-C-2940 and N00123-77-C-0459.

## References

1. Irving, L. D., Pattison, J. E. and Braddock, W., Electron. Lett. 14, 116-117 (1978)
2. Rees, H. D., IBM J. Res. Develop. 13, 537-542 (1969)
3. Fawcett, W. and Herbert, D. C., Electron. Lett. 9, 308-309.
4. James, L. W., J. Appl. Phys. 44, 2746-2749 (1973)
5. Glover, G. H., J. Appl. Physics 44, 1295-1301 (1973)
6. Kroemer, H., Solid State Electronics 21, 61-67 (1978)
7. Ridley, B. K., J. Appl. Phys. 48, 754-764 (1977)
8. Fawcett, W. and Hill, G., Elec. Lett. 11, 80-81 (1975)
9. Fawcett, W., Boardman, A.D. and Swain, S., J. Phys. Chem. Sol. 31, 1963-1990 (1970)
10. Hilsum, C., Electron. Lett. 6, 448-449 (1970)
11. Hilsum, C., Proc., Proc. 3rd Cornell Electr. Engr. Conf. 1-9 (1971)
12. Hammar, C. and Vinter, B., Electron. Lett. 9, 9-10 (1973)
13. Paxman, D. Acta Electronica 15, 245-252 (1972)
14. Fairman, R. D., Omori, M., and Fank, F. B., Proc. 6th Intl Symp. on GaAs and Related Compounds, p. 45-54 (1976)
15. Gray, K. W., Pattison, J. E., Rees, H. D., Prew, B.A., Clarke, R. C., and Irving, L. P., Proc. 5th Cornell Electr. Engr. Conf. 215-224 (1975)
16. Hamilton, R. J., Fairman, R. D., Long, S. I., Omori, M., and Fank, F. B., IEEE Trans. MTT-24, 775-780 (1976)
17. Thim, H., Electron. Lett. 7, 106-107 (1971)
18. Bauhahn, P. E., Haddad, G. I., and Masnari, N. A., Electron Lett. 9, 460-461 (1973)
19. Sitch, J. E., and Robson, P. N., IEEE Trans. ED-23, 1086-1094 (1976)
20. Chang, Y., and Yuan, L. T., ERADCOM Contract DAAB07-78-C-3003; also Microwave Journal 23, 31-36 (1980)