MILLIMETRE-WAVE GUNN DIODE TECHNOLOGY AND APPLICATIONS

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Abstract

Gunn diode oscillators have been used in military, commercial and industrial applications for the past forty years. In the case of millimetre wave operation, the Gunn diode continues to offer at least equal and often superior levels of performance to MMIC technology. This paper will discuss the hot electron injection structures that have been developed over the past twenty years and more recent work that enables the tailoring of device characteristics to match specific applications and operating environments. The importance of well controlled device packaging and heat-sinking design will be shown, with some results of the consequential reliability of Gunn diodes in production. The design of the Gunn diode oscillator itself is crucial to gain optimum performance and long term reliability; some mechanically tunable oscillator designs will be described before going on to present a patented novel 'planar' substrate oscillator developed for use at 77 and 94 GHz. Work undertaken to successfully manufacture commercial 125GHz Gunn oscillators for millimetre-wave radar and imaging applications will also be presented.

1. Introduction

The Gunn diode has long been the favoured solid-state device for coherent power generation at mm-wave frequencies. Its low phase-noise and moderate output power levels make it ideal for many RADAR and imaging applications. Although it is known that InP devices offer higher RF powers at millimeter-wave frequencies than GaAs [1], the InP material system does not support the use of graded-gap hot electron injection. This means the higher output powers and frequencies offered by InP devices are achieved at the cost of temperature stability: a factor that is essential for many applications.

State-of-the-art output powers and frequencies obtained using Gunn diode technology are illustrated in Figure 1, along with the packaging and heatsinking materials used. The majority of these results were achieved in the research laboratory and rely on the use of diamond heatsinking (which has demonstrated output power increases of up to 200% in comparison to gold [2]), and quartz ring or 'open' packages [3]. The use of these techniques in a manufacturing environment would be extremely difficult to implement while simultaneously maintaining overall yield, quality assurance, and allowing integration of the devices into practical real-world rugged systems. All of the devices manufactured commercially at e2v are based on the use of an integral gold heatsink and are ruggedly packaged using an alumina ring. This proven technology has undergone stringent lifetime and reliability testing, including that required by the automotive industry's quality standard, ISO/TS 16949:2002. Although, from an electrical viewpoint, fused quartz rings offer superior performance due to a lower effective permittivity (and therefore package parasitic capacitance), quartz suffers from its fragility and high thermal expansion mismatch with the gold plated copper base (essential for heatsinking purposes) potentially leading to mechanical failure and reducing operational lifespan.

In recent years alternative technologies offering higher levels of functionality have gradually become available for power generation at millimeter-wave frequencies. Examples of this include SiGe MMICs with operating frequencies now extending to above 77GHz [4], a wide range of commercially available GaAs MMICs up to around 100GHz, W-band GaN MMICs demonstrated in the laboratory [5], and commercially available InP devices up to 325GHz [6]. However, in terms of cost, power and simplicity, the GaAs Gunn diode remains an attractive alternative. Making the technology even more attractive is the recent development at e2v of the 125GHz diodes and oscillators shown in Figure 1 which, to the knowledge of the authors, demonstrate the highest ever reported power at D-band for a GaAs Gunn device [7]. The output power from this device is currently far in excess of that available using an off-the-shelf MMIC, while also exhibiting superior phase noise characteristics.

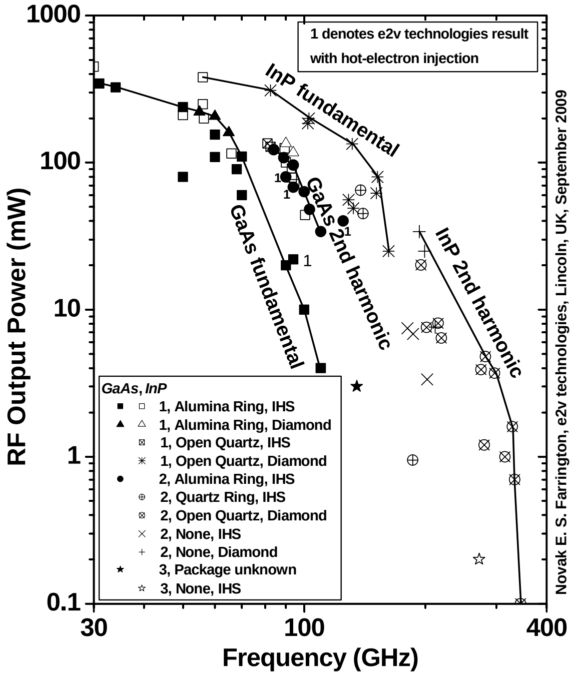


Figure 1. Compilation of published state-of-the-art results between 30 and 400 GHz for GaAs and InP Gunn diodes under CW operation. Legend format: ‘mode of operation (‘1’ denotes fundamental, ‘2’ second-harmonic, etc.), package type, heatsink technology’. Solid lines outline the highest powers and frequencies achieved experimentally to-date from each material in fundamental and second-harmonic mode.

2. Applications and operating environments

Although only power, frequency and phase noise have been considered so far, many applications place stringent requirements on other performance characteristics such as turn-on voltage, temperature drift (both RF power and frequency), and oscillator tuning characteristics. Some typical applications for a Gunn diode oscillator will now be examined with relation to the performance required of the diode itself. It is noted at this point that the following discussion does not aim to represent an exhaustive list, but rather a selection taken to represent the extremes placed on device performance.

Of particular interest at the present time is the use of Gunn diode oscillators as high-power, high-frequency, and low phase noise sources for use in passive millimeter-wave imaging systems. Here a Gunn diode oscillator is often used to provide local oscillator (LO) power to the mixer when heterodyne detection is employed. The diode’s RF output may be applied directly to the mixer LO port, or will sometimes be used as the pump for a frequency multiplication stage. Here the requirements placed on the Gunn diode itself are relatively simple and are in effect similar to those of the simple Doppler frequency velocity measuring devices used by law enforcement agencies for measuring a motorist’s speed. Here, only sufficient RF output power at a fixed frequency, temperature stability and satisfactory phase noise are required for correct operation of the system.

A conceptually more complicated class of system is that of millimetre-wave FMCW radar. This is currently one of the main applications for the GaAs Gunn diodes manufactured by e2v which are used in a wide variety of FMCW radar systems for applications such as automotive radar, missile guidance, smart munitions, security radar, and runway foreign object and debris (FOD) detection radar. Depending on the FMCW system architecture, the Gunn diode can be employed in a number of ways. Placing the simplest performance requirements on a Gunn diode oscillator would be its use for the generation of a carrier signal onto which a modulated signal is upconverted: an example of such a system is shown in Figure 2. In this instance, as with fixed-frequency LO generation and Doppler systems, the Gunn diode is required only to provide a constant power at a fixed frequency.

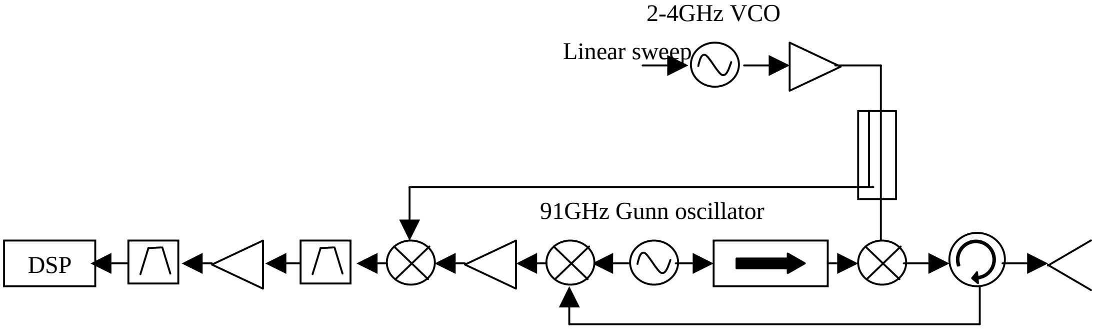
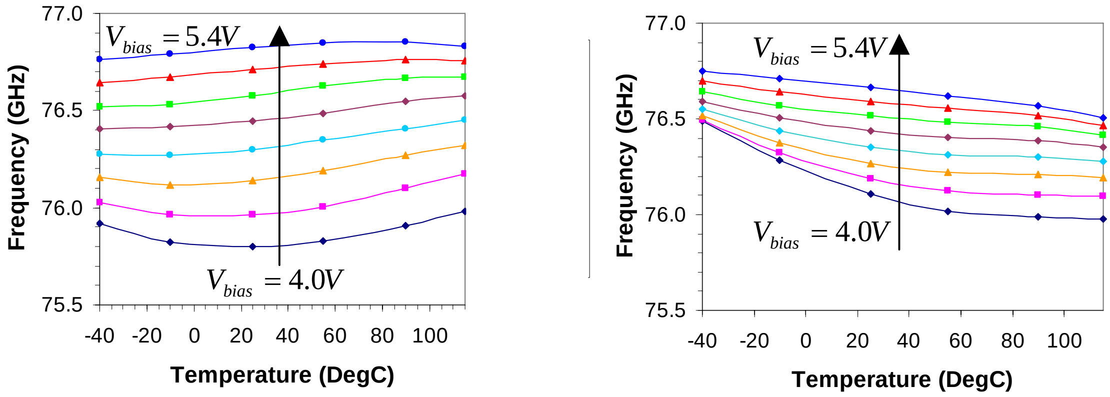


Figure 2. 94GHz FMCW radar imaging sensor using upconversion of the modulated signal to a 91GHz carrier. (after [20]).

More commonly in an FMCM system, the Gunn oscillator will act as a voltage controlled oscillator (VCO) with it's output directly modulated either through the use of bias voltage pushing (direct tuning) or through the use of varactor tuning. Direct tuning can typically achieve modulation bandwidths of around 600MHz at V- and W-bands, while varactor tuning can achieve larger bandwidths of over 1000MHz at the expense of output power (typically 50% less than direct tuning). At this point it is worth noting that although Gunn diodes are considered to be inherently broadband devices [8], the resonant circuits on which the oscillator modules are generally based, restrict the overall bandwidth.



(a) (b)

Figure 3. Measured frequency tuning characteristics over temperature of (a) an optimised GaAs Gunn diode with graded AlGaAs hot electron injector, and (b) a similar diode with un-optimised epitaxial structure.

In the case of a Gunn diode oscillator acting as a directly modulated VCO, not only does the oscillator need to provide sufficient power across a specified frequency and ambient temperature range but its voltage tuning characteristics must remain constant with temperature to avoid the introduction of non-linearity into the FMCW chirp and subsequent degradation of the radar range resolution. An example of this is shown in Figure 3 where the typical responses of optimised and un-optimised Gunn diode epitaxial structures with hot electron injectors are shown. In the optimised case, the spacing between the individual curves (which represent constant bias voltage) remains constant with temperature and so the device shows minimal change in tuning characteristic ($\delta f/\delta V$) with temperature. The variation of oscillation frequency with temperature in GaAs Gunn devices utilising hot electron injection has been shown to be around $1/10^{th}$ of a comparable InP device with no hot electron injection [7].

In all of the above applications, performance over temperature, phase-noise and turn-on voltage have been shown to be key performance characteristics for the Gunn diode oscillator. In order to improve on the performance characteristics of conventional Gunn diodes, the use of hot electron injection was researched and developed in the late 1980's at GEC [9]-[13]. The basic operation of a Gunn diode will be discussed later, along with the theory of operation, and device structure for a Gunn diode with a graded bandgap hot electron injector.

3. Reliability

Besides meeting the operational requirements of a given system, the Gunn diode must also often meet stringent automotive or military reliability requirements. In general the distribution of any semiconductor device lifetime usually follows a lognormal pattern where initially the failure rate rises rapidly due to infant failures arising from defects in the semiconductor material itself or packaging issues. Once these infant failures have been accounted for, the failure rate drops and any further performance degradation or device failure is generally due to intermetallic effects in the ohmic contacts, diffusion of the dopant in the semiconductor itself, or package failure. All of these failure mechanisms are to varying extents, related to thermal effects within the semiconductor device itself.

All devices manufactured at e2v go through an extensive screening process to identify infant failures. This includes a hot-store, extended burn-in at elevated temperatures, automated optical inspection, and multiple DC and RF electrical testing stages. Once the infant failures have been rooted out, thermal management of the device is paramount to the long term reliability as the majority of the long term device failure and degradation mechanisms will be accelerated with elevated temperatures. Besides good heatsinking, the operational temperature of and self-heating effects in the device can be controlled by the hot-electron injector structure; therefore providing long term reliability which can be engineered into a device at the semiconductor level.

4. Device operation, epitaxial structure and material growth

Only a very brief description of Gunn diode operation is included here as it will be assumed that the reader is familiar with the transferred electron (or Gunn) effect. A more comprehensive review is beyond the scope of this paper and can be found in a number of texts and published articles [14], [15]. The Gunn diode can, at its most basic, be thought of as a DC-to-RF converter: when an applied bias voltage exceeds a certain threshold, oscillation will occur, the frequency of which will depend on the material properties and the geometry of the device itself. This is due to the transferred electron effect exhibited by certain binary and ternary compound semiconductors.

A brief, one paragraph explanation of the transferred electron effect could be that as an electron is accelerated through the material by an electric field, it accumulates energy and so the probability of it being scattered from the central conduction band valley to the nearest (in terms of energy and momentum) satellite valley increases. This probability increases dramatically when the electric field reaches a certain threshold value related to the distance, in energy and momentum, between the conduction band's central valley and the nearest satellite valley. The scattering mechanism is columbic in nature and involves a change in both momentum and energy and so the transfer process is extremely inefficient with large amounts of energy being lost to phonon excitation (and elevation of the lattice temperature).

A description of how the transferred electron effect results in oscillation (again in one paragraph) could then be that the effective electron mass (related to the parabolicity of the conduction band profile) is greater in the satellite valley than in the central valley. This means electron velocity in the satellite valley due to an applied electric field is lower than that in the central valley. The effect of this is a 'bunching' of electrons as they travel along the length of the device, with those in the satellite valley moving at a slower rate than those in the central valley. This leads to a depleted region followed by a region of accumulation (known collectively as a high-field domain), which sets up an internal electric field opposing that applied externally. The effect of this is a continuing reduction in the net electric field across the device which continues until the threshold electric field is crossed (preventing the nucleation of any further high-field domains). At this point the high-field domain stops expanding and propagates at a constant velocity through the device until it reaches the cathode contact layer at which point it collapses and the electric field through the device increases again. Oscillation is observed in the current and voltage at the device terminals as the domain forms at the anode, expands, propagates and collapses at the cathode, before another domain nucleates at the anode.

The fundamental physics behind conventional Gunn device operation are very much centred on electron energy, lattice temperature, and random scattering processes. These give rise to the following inherent limitations of conventional Gunn devices:

- The onset of oscillation (turn-on voltage) in a Gunn device varies greatly with ambient temperature.
- The oscillation frequency is highly dependant on temperature as it is defined (in part) by the length of the region in which the domain propagates (transit region). A small portion (referred to as the 'dead zone') of this region is required to accelerate electrons to the point at which they have sufficient energy to transfer to the satellite valley. The length of the dead zone, and therefore the effective transit region length and oscillating frequency are also dependant on temperature.
- The random nature of the scattering mechanisms which facilitate domain nucleation, lead to small variations in the point at which domain nucleation occurs. This effectively varies the length of the transit region from cycle-to-cycle leading to phase noise at the output.

In order to address these issues the use of a hot electron injection structure was proposed and demonstrated in the 1980's by GEC engineers [9]-[13]. The reasoning behind this was to raise the electron energy sufficiently to greatly increase the probability of their direct entry to the conduction band satellite valley upon delivery to the transit region. The injected electrons have greater energy than those at equilibrium with the transit region lattice, and so are referred to as 'hot'. With the majority of the injected electrons directly entering the satellite valley, the dead-zone is effectively eliminated along with the temperature dependency of the oscillation frequency and turn-on voltage. In addition the overall conversion efficiency is increased (due to the reduced parasitic positive resistance) and because the random factors of domain nucleation are reduced, the phase noise is decreased.

The epitaxial structure of a conventional GaAs Gunn device is generally a lightly doped n- transit layer, sandwiched between two heavily doped n+ contact layers (upon which the ohmic contacts are formed). The epitaxial structure of a device with hot electron injection, optimised to have a free-running fundamental oscillation frequency of around 45GHz is shown in Figure 4. It has the same n+n-n+ structure as a conventional Gunn device but with the inclusion of a hot electron injector between the n+ GaAs cathode contact layer and the n- GaAs transit region.

		Cathode
0.5 *µm*	GaAs $n=5\times10^{18}$	Contact layer
10*nm*	GaAs undoped	Spacer
50*nm*	$Al_{0.017}Ga_{0.983}As$ to $Al_{0.32}Ga_{0.68}As$	Step-graded launcher
10*nm*	GaAs undoped	Spacer
<50*nm*	GaAs $n=1\times10^{18}$	Doping spike
<2 *µm*	GaAs $n=2\times10^{16}$	Transit region
0.5 *µm*	GaAs $n=5\times10^{18}$	Buffer
10 *µm*	n^+ GaAs	Substrate
		Anode

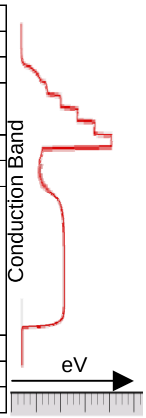


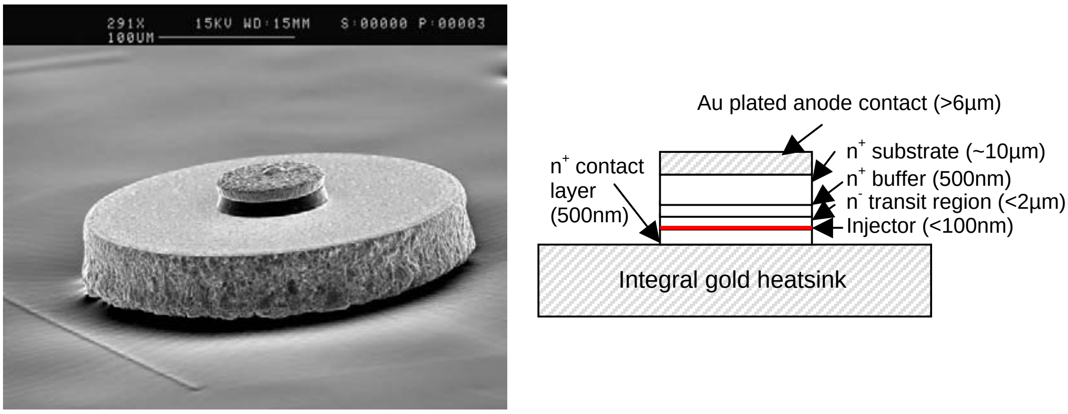
Figure 4. Epitaxial structure and conduction band diagram for a 45GHz fundamental frequency GaAs Gunn diode with step-graded AlxGa1-xAs launcher. (Note: not to scale).

The injector itself consists of two components: a graded-gap launcher and thin (<50nm) n+ doping 'spike'. The doping spike situated between the launcher and the transit region is required to control the electric field at the start of the transit region while retaining the hot electron properties. Its thickness is therefore restricted to make probable the ballistic transport of the injected electrons through it. In its absence a depletion region is formed behind the launcher in forward bias that inhibits high-field domain nucleation and acts as a 'dead zone' [10], [11]. The graded-gap launcher itself can have a continuous or discreet profile. The device structure illustrated in Figure 4 contains five layers with a discrete increase in aluminium content in each towards the anode. Originally the stepped injector structure was introduced to improve repeatability in the growth of the epitaxial structure compared with the linear variant

A 10nm nominally undoped GaAs spacer layer is included at each side of the launcher to prevent dopant diffusion into, and thus degradation of, the launcher [16]. The extremely tight control required over the thickness and composition of each epitaxial layer requires the growth be performed using molecular beam epitaxy (MBE). For this type of Gunn device, growth is carried out on n+ GaAs substrates, around 10µm of which will remain as part of the device structure after the fabrication process. This is to prevent damage or strain in the epitaxial layers during the bonding and packaging process. However, the amount of substrate material included in the device will generally be kept to a minimum to reduce the parasitic positive resistance it introduces.

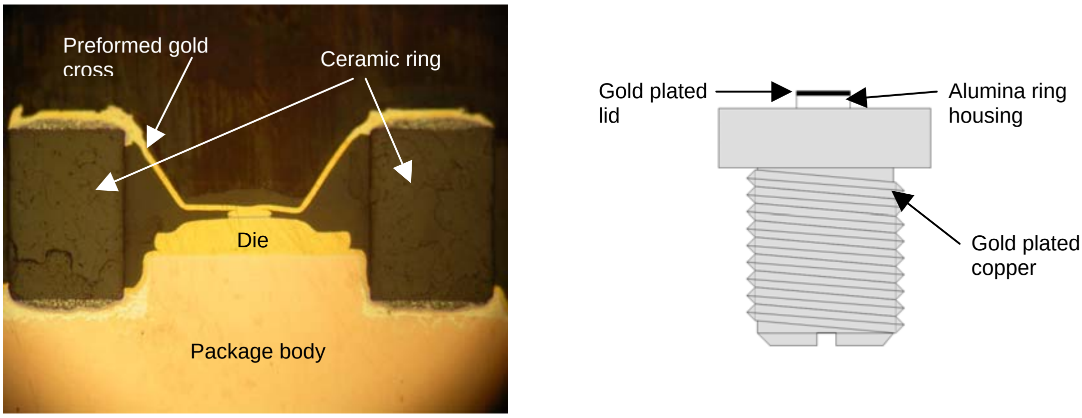
5. Fabrication and packaging for device reliability

As mentioned in earlier, the inter-valley scattering process which is the basis of the transferred electron effect is extremely inefficient, and the majority of the applied energy is dissipated as heat. It has been calculated that the power density in a GaAs Gunn diode is ~ 120kW.cm^{-2} [16] and so for reliable long term operation, good heatsinking is essential. In order to achieve this, a fabrication process which supports the formation of an electroplated gold integral heatsink is used, the results of which are shown in Figure 5.



(a) **(b)**

Figure 5. (a) SEM of a fabricated GaAs Gunn diode with integral gold heatsink, and (b) schematic representation of a GaAs device with electroplated HIS (not to scale).



(a) **(b)**

Figure 6. GaAs Gunn diode package: (a) micrograph of alumina ring package cross-section (without lid) for a 77GHz ACC device.) and (b) schematic of whole package.

Once fabricated, the devices are thermosonically bonded to a commercially available package consisting of a partially metallised alumina ring (>250µm thick) brazed onto a threaded gold-plated copper stud (Figure 6b). The thickness of the alumina ring is kept to a minimum to reduce as far as possible the standoff distance between the oscillator circuit resonant disk and the metal plane of the package top surface. Connection between the top of the alumina ring and the device's top contact is achieved by thermocompression bonding the centre of a pre-fabricated gold cross to the electroplated gold on the device anode, and then bonding the four arms of the cross to the metallised region on the top of the alumina ring (Figure 6). The package is then hermetically sealed by soldering a circular metallised lid onto the alumina ring.

It is noted here that the fabrication and packaging processes are optimised for yield and device reliability. For example bonding equipment which provides a calibrated, reproducible force in the *z*-axis is used to minimize risk of damage to the semiconductor itself during the bonding process. The thickness and profile of the pre-fabricated gold cross are also optimised for longevity, particularly if pulsed operation (and high repetition of the heating and cooling cycle) will be required by the customer.

6. Oscillator design and performance

In the discussions so far, the oscillation frequency of a Gunn diode has been assumed to be the free running value, solely due to the dynamics of domain formation and propagation in the transit region, and free from the effects of an external circuit. In practice, a device needs to be attached to a circuit that provides DC power, and couples out RF power: the circuit will have reactive elements and a resonant frequency associated with it. The circuit can therefore be designed to resonate with the Gunn diode in order to optimise output power and efficiency at a given frequency. At millimeter-wave frequencies the most common circuit configuration used to do this is the waveguide-based second-harmonic resonant disk oscillator. A schematic diagram of the cross-section of a second harmonic resonant disk oscillator is shown in Figure 7.

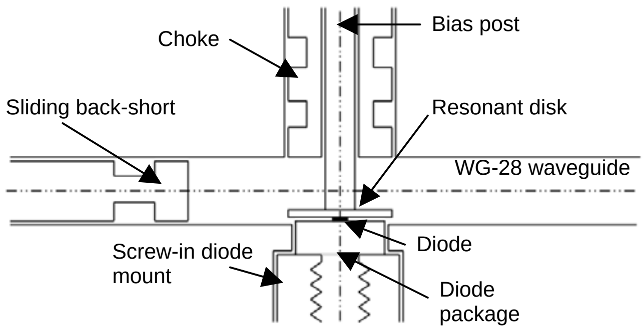
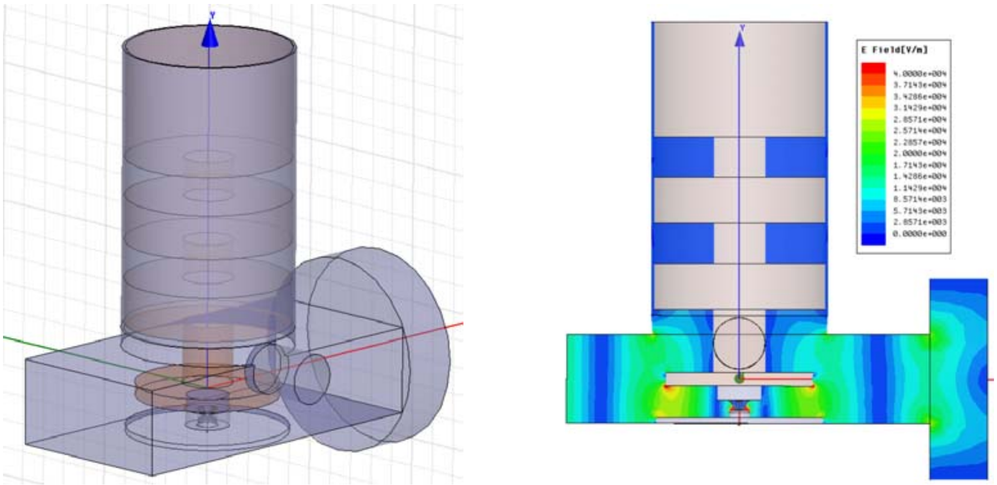


Figure 7. Simplified schematic cross-section of a generic waveguide-based second harmonic resonant disk oscillator circuit showing all mechanically tunable components.

In a resonant disk oscillator the packaged diode will typically be positioned in the waveguide floor and the DC power for the diode is supplied through the bias post and choke assembly (often a single piece of machined metal), which is insulated from the waveguide block. The frequency of oscillation is coarsely determined by a combination of the resonant disk diameter, post width, and the length of the section of post between the resonant disk and the bottom of the lowest choke section. The operational principle is such that three distinct electromagnetic modes of propagation exist [17]: a TE_{01} rectangular waveguide mode (in the rectangular waveguide section), a radial mode (between the resonant disk and the waveguide floor), and a quasi-coaxial (TEM) mode (between the resonant disk and the bottom of the choke). Two separate resonances are therefore supported: a fundamental frequency resonance in the TEM mode along the quasi-coaxial line (which is inductive) between the choke and the disk (a capacitor), and a resonance at the second harmonic between the disk and the waveguide floor. In order to obtain maximum power at the output, the two resonances must be synchronized (through optimisation of the disk diameter and post/choke geometry), and the coupling between the radial mode and the magnetic field of the TE_{01} waveguide mode maximized (through optimisation of the disk diameter, distance between the disk and waveguide floor, and backshort distance).

Figure 8 shows an Ansoft High Frequency Structure Simulator (HFSS) model of a second harmonic resonant disk oscillator configuration using a circular waveguide back short and frequency tuning pin. Although not showing the quasi-coaxial TEM mode and its resonance (the plot illustrates the electric field at second harmonic frequencies, not fundamental), Figure 8 shows power being coupled between the diode and the waveguide output (left), and a degree of interaction between the resonant disk and the waveguide floor.



(a) (b)

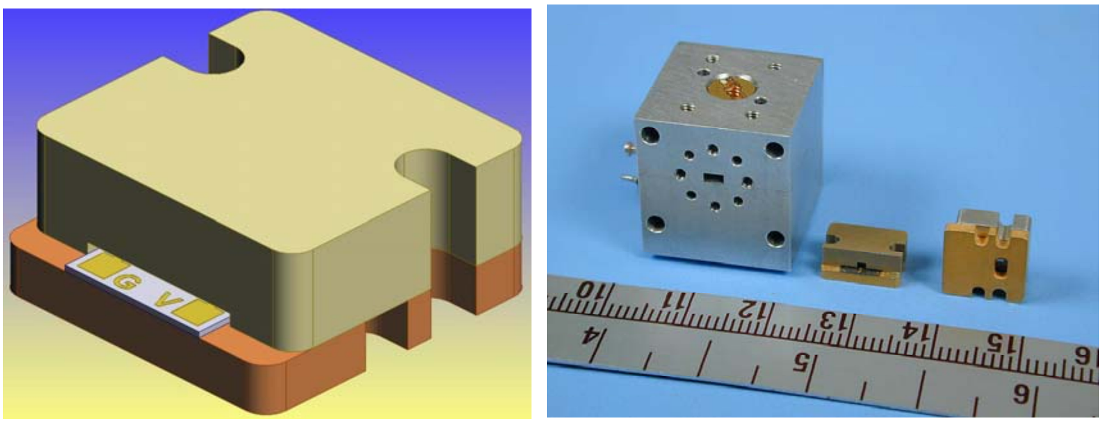
Figure 8. Ansoft HFSS model of a second harmonic resonant disk millimetre-wave oscillator with tuning pin and circular waveguide sliding backshort, (b) simulated field electric field plot for the oscillator at second harmonic frequencies.

Although this type of oscillator is relatively narrowband, it is noted that wideband mechanically tunable (‘Carlstrom’) oscillators [8], [18] can be achieved through the use of a choke section which contacts with and slides up the bias post. This can be used to increase the resonant disk-choke distance and therefore adjust the oscillation frequency. However, because the resonant disk diameter is not adjustable, the resonances are only truly synchronised for one post length at which a peak in power is obtained: before and after this the power tails off.

Although the Carlstrom oscillator can provide relatively wideband tuning, the tuning is performed mechanically which makes it unsuitable for many applications outside of the laboratory. If practical wideband tuning is required then a varactor-tuned design can be used: this again is typically implemented in waveguide. Here, instead of the resonant frequency being determined by the geometry of the circuit elements, the tuning of a varactor mounted in the waveguide along with the Gunn diode can be used to alter the frequency. This however comes at the price of output power and overall efficiency.

One of the main perceived limitations of millimeter-wave Gunn diode technology is often thought to be the requirement for waveguide technology, particularly if high output powers are required. However, waveguide-based Gunn oscillators can be mechanically designed for mounting on planar microstrip circuits with either a stepped impedance transformer, or a microstrip probe coupled transition between the planar circuit and the waveguide (depending on the required connection angle between the waveguide and the planar line). Such arrangements have shown insertion losses as low as 0.5dB at 94GHz.

To achieve a true planar Gunn diode VCO, a novel, patented concept has been developed and successfully demonstrated at e2v [19]. Suitable for high-volume production the design features relatively wideband varactor tuning and offers a solution where the key drivers of size, cost, performance and versatility may be satisfied simultaneously. This solution was shown to give ~ 30mW at 77GHz, which is about half the power produced by an equivalent rectangular waveguide cavity oscillator. Figure 9(a) shows a solid model of a hermetically packaged planar substrate VCO, while Figure 9(b) gives an idea of the module size, compared to a regular rectangular waveguide cavity VCO.

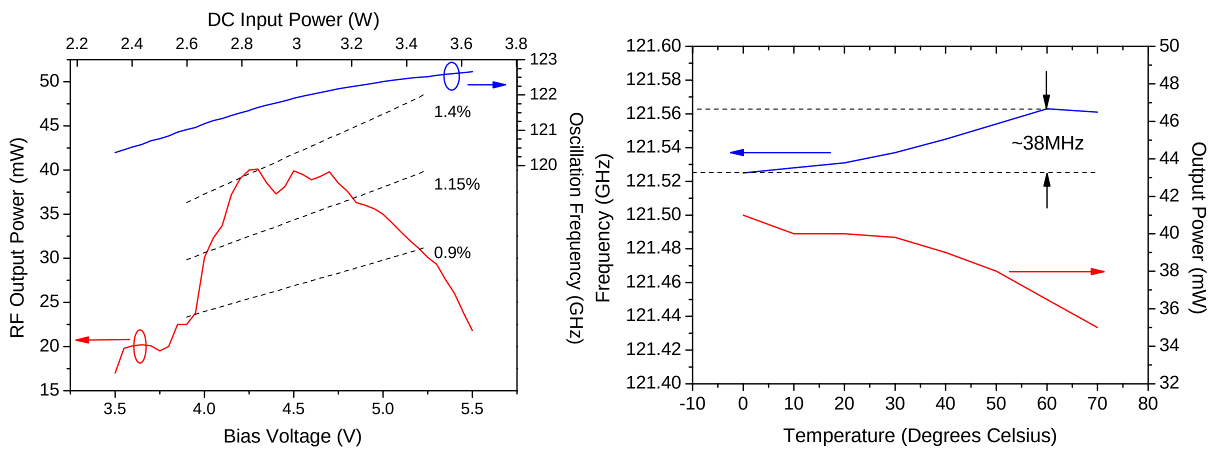


(a) (b)

Figure 9. (a) Solid model illustration of VCO package. (WG output on lower surface), and (b) Relative sizes, mm/inch, of VCO's. a) Cavity type, b) new VCO with microstrip output, c) new VCO with waveguide output.

7. Development of D-band GaAs Gunn diode technology

The benefits of GaAs technology over InP have already been discussed and were the driving force for the development of 125GHz GaAs Gunn devices and oscillators at e2v. These devices were developed to meet an increasing demand for solid-state sources at higher frequencies. The MBE growth of several wafers was performed along with device fabrication test and oscillator refinement. The result of the work, shown in Figure 1, was the demonstration of a record RF output power for a GaAs device when 40mW was measured at 122GHz [7].



(a) (b)

Figure 10. Performance characteristics of the D-band Gunn diodes reported in [7]: (a) RF output power and frequency variation with bias voltage (dashed lines represent lines of constant efficiency), and (b) variation with temperature.

It is seen in Figure 10 that although overall efficiency is low (as was expected from a second harmonic device), impressive power levels were achieved, especially considering the use of gold as a heatsinking material, and alumina as the packaging material. The average RF power from a batch of 10 diodes was around 32mW [7] which is sufficient for many applications. As such these devices represent the first ruggedly packaged, commercially viable GaAs source of D-band power.

8. Conclusions

This paper has reviewed the state-of-the-art in Gunn diode technology before going on to review a variety of applications into which e2v commercially supply devices. The demands such applications place upon the oscillator and diode itself have been discussed in detail, along with the fundamental physical mechanisms behind device operation. This framed the argument for the use of devices employing hot electron injection, the epitaxial semiconductor structure for which was presented.

The operation of, and performance trade-offs, between a number of different implementations of Gunn VCOs developed at e2v technologies, has been discussed. The paper has also outlined and presented results from an ongoing programme in the optimisation of packaged, high-performance D-band hot electron injected GaAs Gunn diodes, suited for volume manufacture.

Acknowledgments

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