THE CAPABILITIES AND STATE OF THE ART OF GUNN AND LSA DEVICES

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1. Introduction

Ridley and Watkins [1] conceived of the idea that electrons in solids could be forced to undergo a change in energy and mass that would lead to bulk negative resistance. Hilsum [2] later developed the idea as it applied to Gallium Arsenide with high electric fields applied. Ridley [3] subsequently pointed out the natural tendency of such bulk negative resistance devices to form high-field, traveling domains.

Quite independently from the development of these analytical concepts, Gunn [4] experimentally discovered microwave transit-time oscillations in Gallium Arsenide subjected to high electric fields.

In a series of computer studies, Copeland [5] discovered that the original, truly bulk effects anticipated analytically by Ridley and Watkins, and by Hilsum, could be brought about by forcing only limited space charge accumulation (LSA). He experimentally verified these non-transit-time oscillations resulting from $1 \times 10^4 < N_e/f < 2 \times 10^5$ sec/cm^3 where N_e is the electron concentration and f the operating frequency enforced by a cavity resonance.

Independently, Kennedy [6] had discovered high power microwave oscillations in this non-transit-time mode that required the above mentioned N_e/f ratio.

The remainder of this presentation will deal with the ultimate capabilities of these Gunn and LSA devices, along with the present state of the art of these devices and a few of the related GaAs materials problems.

2. Fundamental Concepts

Electrons in the conduction band of GaAs can have two widely different effective masses associated with a lower and a higher energy condition. Normally the electrons are predominantly in the lower energy, lighter effective mass condition where they exhibit high mobility. When applied electric fields exceed 3 kV/cm, electrons in the lighter mass condition can gain energy from the field faster than they can lose energy by colliding with the atoms in the crystal. The electrons gain up to .35 Volts of energy and then some of them transfer to the heavier mass condition. A larger and larger fraction of the electrons are in the heavier mass, lower mobility condition as the applied electric field is increased. Thus the average electron drift velocity

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depends on electric field as is shown in Fig. 1. The low-field positive slope is 7,500 cm^2/V-s and the magnitude of the maximum negative slope is 2,500 cm^2/V-s. If the electrons remain uniformly distributed in a sample, the current density is everywhere proportional to the drift velocity shown and the sample voltage is its thickness L times the electric field shown. Thus an I vs V plot for LSA conditions is the same as the v vs E plot except for multiplying constants. The full amplitude sinusoidal and non sinusoidal LSA signals are shown superimposed upon an average bias for typical LSA operation. For bias fields above 3 kV/cm, if one fails to keep N_e/f in the range mentioned above, electron relative motions cause space charge build up to form the high field domains found by Gunn, with an associated transit-time oscillation at about $f = 1 \times 10^7$ cm/s/L.

It is possible to operate GaAs bulk devices over a very wide range of operating parameters. Fig. 2 shows a mode chart of $f \times L$ vs $N_e \times L$ in a log-log plot. The Gunn domain oscillation at or near a transit-time frequency associated with $f \times L = 1 \times 10^7$ occurs over a limited range of $N_e \times L$ as shown. Above $N_eL = 2 \times 10^{13}/cm^2$ domain fields are excessive and avalanche breakdown occurs. Space charge disturbances, less pronounced than domains, yield transit-time oscillations at the transit-time frequency and twice that frequency for $.5 \times 10^{12} < N_e \times L < 2 \times 10^{12}/cm^2$. Below $N_e \times L = .5 \times 10^{12}$, stable negative resistance amplification is exhibited at the transit-time and twice the transit-time frequency.

The optimum LSA operation occurs between $.5 \times 10^5 < N_e/f < 2 \times 10^5$ sec/cm^3 as shown for $f \times L$ values ranging from 1×10^7 cm/s to 1×10^{10} cm/s. It should be noted that for LSA oscillations L can exceed a transit-time thickness L_{TT} for Gunn operation at a given frequency, by a large number. A value of $f \times L = 1 \times 10^{10}$ cm/s corresponds to $L/L_{TT}=1000$, or $L/L_{TT} = f \times L/1 \times 10^7$cm/s. If $N_e/f < .5 \times 10^5$ sec/cm^3, it is experimentally difficult to start LSA oscillations in samples with $L/L_{TT} > 1$. If $N_e/f > 2 \times 10^5$sec/cm^3, only nonsinusoidal LSA voltage signals, as shown in one case in Fig. 1, with fast rise and fall times in the region of maximum magnitude of negative slope of v vs E, will properly limit the space charge accumulation.

The equivalent circuit of a bulk GaAs device, optimally loaded, and with limited space charge accumulation is a capacitor of reactance $(N_e/f)(R_o) \times 14 \times 10^{-5}$ ohms in parallel with a negative resistance equivalent to 20 R_o, where R_o is the low-field positive resistance of the device.

3. The Capabilities of Bulk GaAs Devices

The important parameters of bulk GaAs devices are N_e/f,

L/L_{TT}, R_o and the applied bias electric field E, along with the maximum temperature rise, at the hot plane of the device, compared to a room temperature ambient heat sink. At low duty cycle, where no self-heating exists, Gunn and LSA diodes with sinusoidal voltage waveforms can operate with about 20% efficiency with ideal material. If the nonsinusoidal voltage of Fig. 1 is present, the diodes can operate with 40% efficiency.

When duty cycle is raised, self heating occurs, lowering the efficiency. The heating is minimized by lowering (N_e/f) to $.5 \times 10^5$ sec/cm^3, the lowest value in the optimum range for LSA. A compromise of conditions yielding high average power results in a predicted efficiency of about 15%. Fig. 3 shows how predicted peak power varies with frequency for various values of L/L_{TT} and with other parameters set at values found to be experimentally tractable. The length of the pulses, to reasonably limit transient heating during the pulse, is about 5 microseconds at 10 GHz and scales as 1/f. The equation for the output peak power plot is:

$$P_{pk} = 2 \times 10^{16}\ E/R_o\ (L/L_{TT})^2\ (1/f)^2,$$

where L is limited to a maximum value of about half a free space wave length ($L/L_{TT} = 1000$) where the minimum value of R_o is 15 Ω due to skin depth considerations. This minimum allowable value of R_o scales as L/L_{TT} directly, but $R_o = 5$ Ω is convenient for most microwave resonators used. Experimentally, devices with L/L_{TT} between 50 and 100 have yielded 2 kW of peak power at 7 GHz with 5% efficiency and these same devices at 1.8 GHz, where L/L_{TT} is between 12.5 and 25 have yielded 6 kW of peak power with 15% efficiency.

Within the limits of pulse length given above, pulse repetition rate can be increased until the hottest plane, in the device properly bonded on one side to a good copper heat sink, is 200°C above the room temperature heat sink ambient. Fig. 4 shows the maximum duty cycle as a function of frequency for various values of L/L_{TT} for this 200°C temperature rise. The relatively poor heat conductivity of GaAs and the high power density make it necessary to drastically reduce the duty cycle to prevent overheating, with sharp efficiency reduction and even device failure. In the regions where "duty cycle" above 1.0 are indicated, CW operation at even higher (N_e/f) or E could be tolerated without increasing the temperature rise beyond 200°C. The equation for scaling this maximum duty cycle for a maximum allowed temperature rise (ΔT), as plotted is:

$$\text{Maximum duty cycle} = \frac{4.88(\Delta T)f}{(\frac{N_e}{f})(\frac{L}{L_{TT}})^2 E[(\frac{8.33 \times 10^7}{R_o(N_e/f)(L/L_{TT})})^{1/2} + 15.6]}$$

Fig. 5 shows the product of the peak power and the maximum duty cycle which yields the maximum average power as a function of frequency for various (L/L_{TT}) values and the other fixed parameters shown. The highest average power at 10 GHz is 5.5 W for $L/L_{TT} = 100$. This is not an absolute limit. The value of R_o can be lowered to 1.5 Ω at $L/L_{TT} = 100$, which raises the average power to 18 W under these conditions. Two such devices in series with heat sinks on the top of one and on the bottom of the other would double the average power to 36 Watts. Further increases in average power, due to efficiency improvement and more stacking of devices, are also possible. It should be noted that the maximum average power varies as 1/f, whereas the peak power varies as $(1/f)^2$, with all other parameters fixed.

For any given duty cycle and operating frequency, a maximum value of L/L_{TT} can also be predicted as shown in Fig. 6. Any greater L/L_{TT} would cause overheating, while any lower L/L_{TT} would lower the peak and average power achievable.

These Figs. 3-6 clearly show the wide range of capabilities of bulk GaAs devices that are not at all limited by the simple Gunn domain transit-time condition where $L/L_{TT} = 1$.

4. Present State of the Art of Gunn and LSA Devices

Pulsed Gunn and LSA diodes operated at low duty cycle with sinusoidal voltage waveforms have yielded 5 - 15% efficiency. 15 - 30% efficiency has been obtained under nonsinusoidal voltage operating conditions. CW Gunn devices with efficiencies from 4 - 12% have been tested, while CW LSA devices with efficiencies of 2 - 5% have been tested.

Low power CW Gunn diodes have shown operating lifetimes of over 15,000 hours and high peak power LSA diodes have shown operating lifetimes of over 5,000 hours.

Pulsed Gunn and LSA diodes in proper cavities have shown remarkably short pulse rise times and have yielded pulses 3 nsec long. Pulse bursts of just one or a few cycles can be predicted.

Phase locking of Gunn and LSA oscillators has been shown to be comparable to that of other oscillators with similar values of circuit Q.

Noise performance of Gunn and LSA diodes has been shown to be at least comparable with klystron oscillators although no extensive device research has as yet been undertaken to minimize the noise.

GaAs material of sufficient uniformity and mobility is becoming more available commercially and ten or more laboratories have developed means of epitaxially growing GaAs of a quality sufficient for microwave devices.

Fig. 7 is a plot of peak powers, plotted against frequency, for Gunn and LSA diodes, with some CW Gunn and LSA diode results and some pulsed and CW Avalanche diode results also shown for comparison.

One remarkable result is the CW Gunn results at Bell Telephone Laboratories of over 350 MW near 16 GHz with over 11% efficiency. Two high efficiency results during pulsed operation have been achieved at RCA including over 600 W peak at over 60% efficiency at just under 1 GHz in an Avalanche diode and including over 140 W peak at about 30% efficiency at just over 2 GHz in a Gunn diode. The high peak power pulsed LSA devices at Cayuga Associates have yielded 6 kW with 15% efficiency at 1.8 GHz, 2 kW with 5% efficiency at 7 GHz and 20 W with 7.5% efficiency at 31 GHz.

The LSA pulse power prediction limit shown is that shown in Fig. 3 for L/L_{TT} = 1000.

5. Conclusions

Many of the predicted peak and average power capabilities of Gunn and LSA devices are beginning to be partially achieved. It can be concluded that the next few years, with the improvement of GaAs material properties, will bring about the full achievement of these capabilities. The resulting usefulness of these bulk GaAs devices in microwave communications and radar equipment as well as in ordinary laboratory equipment will be great. Almost complete use of these and related devices can be expected in new, compact, light-weight microwave systems, bringing about a microwave electronics revolution of a scope that should equal that brought about at low frequencies by the introduction of the transistor.

6. Acknowledgment

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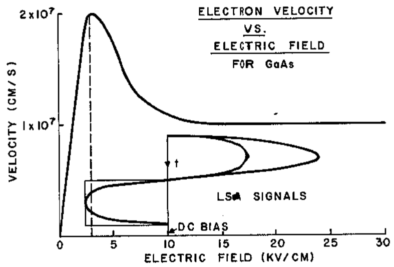

Fig. 1. Electron velocity vs electric field for GaAs.

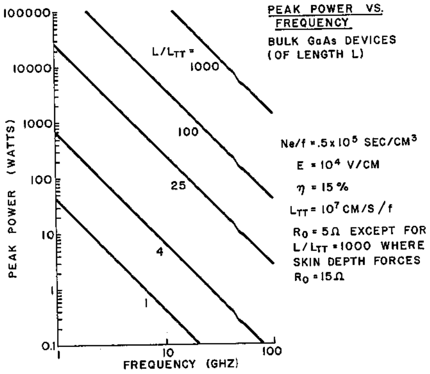

Fig. 3 Peak Power vs frequency. Bulk GaAs devices.

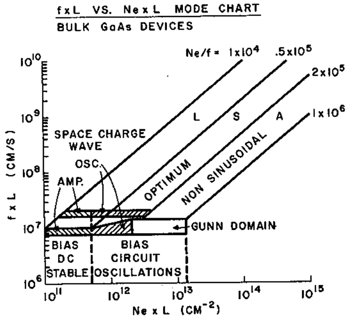

Fig. 2. f x L vs N_e x L mode chart. Bulk GaAs devices.

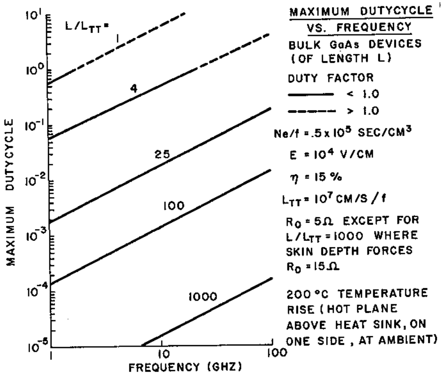

Fig. 4 Maximum duty cycle vs frequency. Bulk GaAs devices

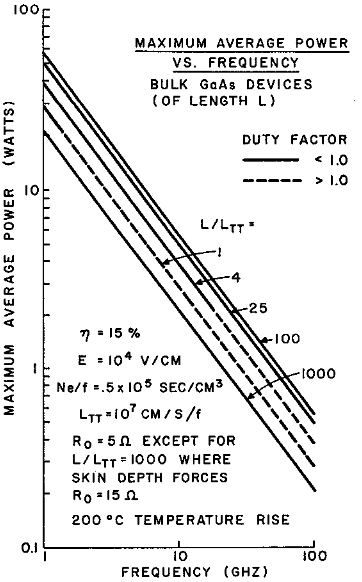

Fig. 5. Maximum average power vs frequency. Bulk GaAs devices.

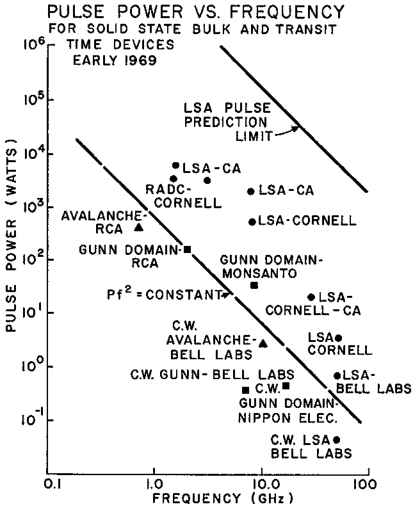

Fig. 7. Pulse power vs frequency for solid state bulk and transit time devices - early 1969.

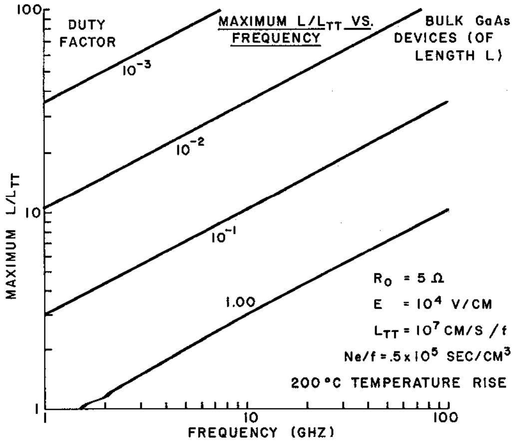

Fig. 6. Maximum L/L_{TT} vs frequency. Bulk GaAs devices.