I-1. GaAs POST-THRESHOLD MICROWAVE AMPLIFIER, MIXER, AND OSCILLATOR

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Bulk GaAs was operated simultaneously as a microwave amplifier, mixer, and oscillator under cw conditions. This was achieved by biasing the sample at post-threshold conditions, i.e., beyond the bias at which the sample broke into Gunn-type oscillations.[1,2] It was found that even under these post-threshold conditions, wherein the device was oscillating at a certain frequency, the device simultaneously had the properties of a linear active element capable of mixing and amplification at other frequencies. The frequencies at which the device exhibited simultaneous amplification, mixing, and oscillation were not harmonically related. These frequencies were determined jointly by semiconductor and microwave circuits.

The n-GaAs had a carrier concentration of $(1 - 3) \times 10^{13}$ per cc at 300° K. The wafers were 45 - 65 microns thick with either indium-gold or indium-nickel ohmic contacts. The samples were operated as oscillators and/or amplifiers in a coaxial microwave cavity.[3] The current-voltage characteristic is shown in Figure 1, where the various regimes of operation are indicated.

Subthreshold Amplification. As bias voltage on the sample was increased above 22 volts (4900 V/cm) the sample began to show linear gain at a frequency of 3.622 GHz. The gain increased as a function of bias as shown in Figure 2. At a bias voltage of 23.6 volts (5300 V/cm) a maximum gain of 36 dB was measured. As the bias was further increased, the sample oscillated at 3.622 GHz. Amplification as a function of incident signal level is shown in Figure 3. Microwave gain was linear as long as the amplifier output was below -20 dBm. Furthermore, the noise figure for amplification at 3.622 GHz was 20 dB.[4] As gain was increased, by applying higher bias, the noise figure remained invariant.

Post-Threshold Amplification. As bias voltage exceeded 23.6 volts, the sample broke into oscillations and the current dropped,[1,2] as shown in Fig. 1. For bias voltages in excess of 23.6 volts the device maintained its operation as an oscillator at 3.622 GHz. The power output was 0 dBm and -40 dBm at the fundamental and second harmonic, respectively.

At a voltage of 27.2 volts the device once again began to amplify, but now at a frequency of 2.492 GHz. This took place while the device was simultaneously oscillating at 3.622 GHz. The post-threshold amplification at 2.492 GHz increased up to 38 dB at higher bias levels. Plots of post-threshold gain and sample current as functions of bias voltage are shown in Fig.2. When the voltage exceeded 30.2 volts the sample oscillated at 2.492 GHz and the 3.622 GHz oscillations disappeared. The oscillator power output at 2.492 GHz was about +13 dBm.

Post-threshold amplification at 2.492 GHz was linear with respect to input signal level as is evident from Figure 4. However, gain began to saturate when the amplifier output exceeded about 0 dBm. The amplifier noise figure was about 23 dB.[4] Interestingly, the noise figure showed a tendency to decrease as a function of gain at higher bias levels.

Heterodyne Amplification. In its post-threshold condition the device was oscillating at 3.622 GHz and amplifying at 2.492 GHz, simultaneously. These properties were utilized in a heterodyne amplifier circuit shown schematically in Figure 5. The 3.622 GHz signal generated by the bulk GaAs sample was used as a local oscillator. An external signal at 6.114 GHz was injected into the cavity. This injected signal mixed with the L.O. to produce a difference frequency at 2.492 GHz, which was then amplified as the bias was increased from 27.2 to 30.2 volts, and removed from the cavity as shown in Fig. 5. A maximum net conversion gain of 10 dB from 6.114 GHz to 2.492 GHz was measured.

Aside from the practical significance of the results, several interesting aspects about the modes of operation are immediately obvious. From Figs. 1 and 2 it is seen that the sub- and post-threshold amplification occurred when the dc current-voltage curve had a positive slope. Although over a limited voltage range the I-V curve did exhibit a negative dc slope, no microwave gain was observed over that portion.

It was shown elsewhere[3] that microwave gain in bulk GaAs is associated with the excitation of growing space charge waves. It was further shown that beyond a certain maximum bias the space charge wave may transform into a travelling domain. From Fig. 1 it seems likely that at a voltage of 23.6 volts the space charge wave at 3.622 GHz transformed into a travelling domain, and this brought about a sudden drop in current. The postulated travelling domain, which is not fully grown, would lower the field intensity in the GaAs medium outside the domain. This will make the external medium inactive. However, as larger bias is applied the semiconductor medium outside the domain is once again made active. It will be noted from Fig. 2 that both sub- and post-threshold gain commence at the same sample current, namely 11 ma. Hence, it seems plausible that post-threshold amplification takes place in the GaAs medium "external" to the travelling domain.

It will also be noted from the above example that the post-threshold oscillating and amplifying frequencies bear no harmonic relation to each other. Although both frequencies could be varied by circuit tuning over a reasonably wide range, it was found that the post-threshold amplifying frequency was invariably lower than the oscillating frequency existing simultaneously in the structure.

References.

1. J. B. Gunn, "Microwave Oscillations of Current in III-V Semiconductors", Solid State Comm., Vol. 1 pp 88-91, September 1963.
2. J. B. Gunn, "Instabilities of Current in III-V Semiconductors," IBM J. Res. & Dev., Vol. 8, pp 141-159, April 1964.
3. B. W. Hakki, & S. Knight, "Microwave Phenomena in Bulk GaAs," IEEE Trans. ED-13, pp 94-105, January 1966.

4. B. W. Hakki, "GaAs Post-Threshold Microwave Amplifier, Mixer, and Oscillator," IEEE Proc. Vol. 54, pp 299-300, February 1966.

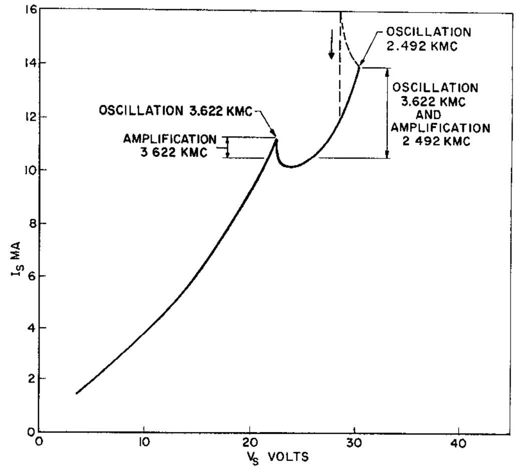

Figure 1. Current-Voltage Characteristics of a Bulk GaAs Wafer. Sample thickness = 45 microns; carrier concentration 1.5 x 10^{13}/cc.

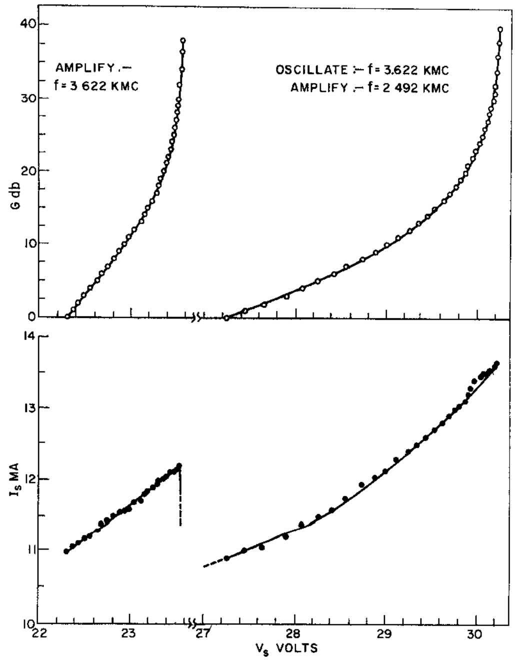

Figure 2. Microwave Gain and Sample Current vs. Bias Voltage

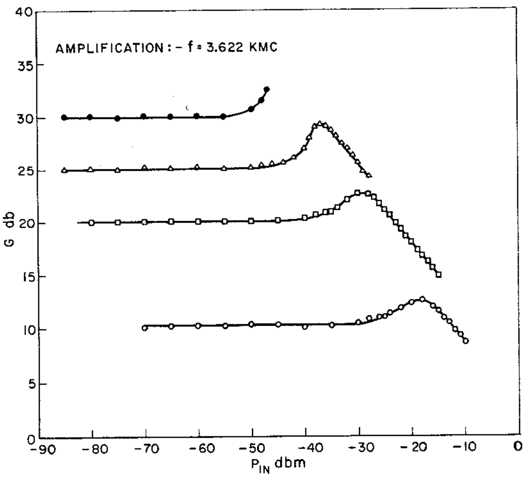

Figure 3. Sub-Threshold Gain at 3.622 GHz vs. Incident Signal Level. Gain was varied by adjusting bias on semiconductor.

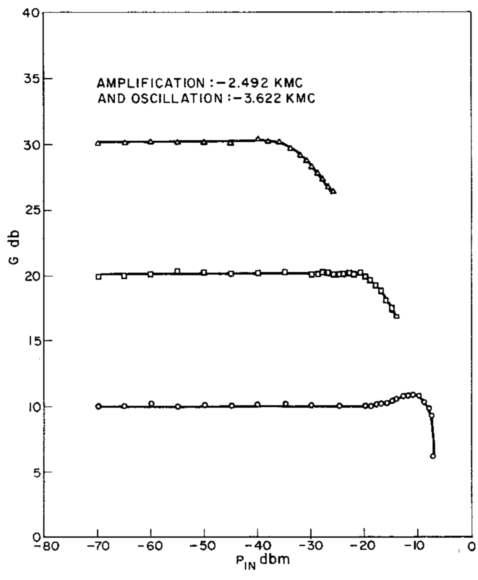

Figure 4. Post-Threshold Gain at 2.492 GHz vs. Incident Signal Level. Gain was varied by adjusting bias on semiconductor.

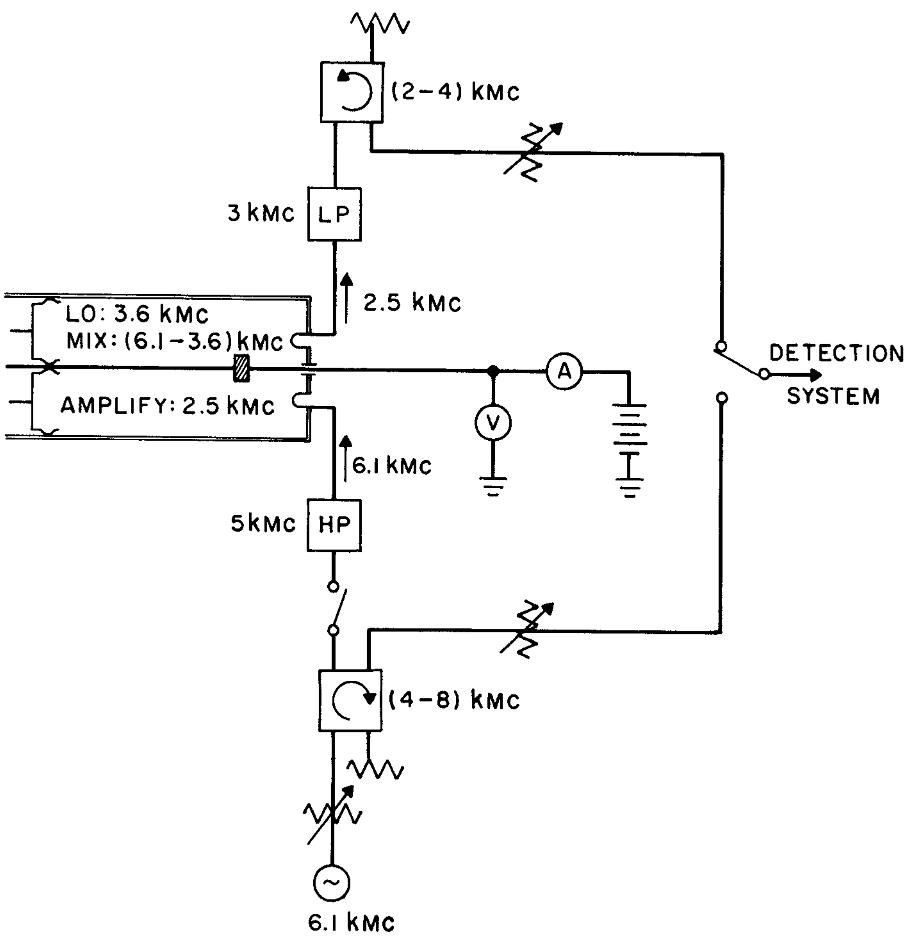

Figure 5. Schematic Circuit of Bulk GaAs Heterodyne Amplifier