MICROWAVE TRANSISTORS, BIPOLAR AND FIELD EFFECT - TODAY AND TOMMORROW

Sanehiko Kakihana
Hewlett Packard Company
Palo Alto, California

Abstract

The state-of-the-art low noise and high power microwave transistors of both bipolar and field effect types are reviewed. The analyses are made to determine the future potentials of bipolar and field effect transistors in microwave applications. It appears that the bipolar transistor is approaching old age both as low noise and high power devices, but field effect transistors show increasing promise in both applications. The trend for monolithic integration of maturing bipolar devices is also discussed

Introduction

While Impatt and Gunn devices were attracting most of the attention ever since their introduction in the early 60's, microwave transistor technology has been quietly making steady progress. The mainstay of microwave transistors thus far has been the silicon npn bipolar transistor, but with the entry of GaAs MESFET in 1969, we are entering a new era where field effect transistors may supersede the bipolar transistor both as low noise and as power devices.

In this paper state-of-the-art silicon bipolar devices and MESFET will be reviewed. An attempt will then be made to forecast the futures of bipolar transistors and MESFET which use either silicon or GaAs. The trend for monolithic integration of maturing bipolar devices is also discussed.

Review of State-of-the-Art Devices

Bipolar Transistor

Low Noise Transistor.
FIG. 1 shows the performance of low noise silicon bipolar transistors commercially available today. Assuming that with good low noise circuit design 0.5 to 1.0 dB noise is added to the device noise, the data presented in FIG. 1 shows that low noise amplifiers with noise figures of 3.0 dB at 2 GHz, 4.5 dB at 4 GHz and 6.0 dB at 6 GHz can be built.

Practically all of the ECM applications can be served by these transistors. These improved low noise transistors also affect the basic approach of terrestial microwave communication link. In straight-through repeater the signal is received, amplified and retransmitted all at the RF frequency. The low noise transistors are used in the front-end amplifiers

In comparison with the base-band and IF type repeater this direct approach is much cheaper, mostly because of the savings from the omission of multiplexer and terminal equipment. Phased array radar is another area in which a large number of low noise transistors is expected to be used. Today's low noise transistors can fulfill the needs at L, S and low C-band.

High Power Transistor. In 1965 Herold[1] prepared a market survey of electron tube devices which he saw were being threatened by agressively expanding solid state devices. FIG. 2 shows the high frequency portion of his curves to which were added data points of state-of-the-art solid state devices as of 1972. Herold had already conceded the pf (power-frequency) domain below curve A to solid state devices. He felt that the area between curves B and C was still contested between tube devices and solid state devices, while the high power frequency domain above curve C was quite safe for tube devices for the next two decades.

However, in less than a decade not only have the solid state devices taken over the contested area but have made a deep penetration into what was expected to be a safe haven for the microwave tube devices.

Transistor development is behind that of Impatt and Gunn devices in the push toward higher pf products, but even transistors have already broken into the tube territory above curve C at frequencies below 4 GHz.

A complete 5 watt power transistor chain at 4 GHz is now available. Table I shows such a chain at 4 GHz with ratings of power output, power gain, efficiency and the junction temperature.

The most significant implications of the advent of L and S-band power transistors is that it is now possible to build straight-through repeaters over these bands without going through complex processes of down-conversion, up-conversion and multiplication through a long chain of varactor multipliers. In addition to the clear advantage of transistors with respect to the over all DC to RF conversion efficiency, the power transistor chain should lead to a considerable cost saving arising from a reduced number of components and the basic simplicity of the system.

Today's high power devices are ruggedized against short-term failure modes such as "current hogging" problem or the infinite VSWR problem. The solution for the former is provided by an emitter-ballasting technique while the latter problem is solved by including a thick undepleted layer of collector material.

The most serious long term failure mode of power transistors is due to migration of metal. When the current density is 10^5 amp/cm^2 and the junction temperature is 150°C MTBF for a transistor with 2.0 micron wide and 1.0 micron thick aluminum stripe is approximately 40,000 hours. A similar device with Mo-Au metallization will have a MTBF of 300,000 hours under identical conditions. To insure MTBF of 50,000 hours for a radio repeater, devices with aluminum stripes operating under the above conditions will obviously not be adequate, while devices with Mo-Au metallization may meet the requirement.

Field Effect Transistor. In 1967 Hooper[2] and Lehrer demonstrated the feasibility of fabricating a Schottky barrier gate GaAs FET which is usable in microwave frequencies. In 1970 a group at IBM Zurich Laboratory announced a GaAs MESFET with f_{MAX} around 30 GHz. Their lastest result shows f_{MAX} in excess of 40 GHz and NF of 5.0 dB at 10 GHz[3]. Using these devices the same group has built an amplifier with 15 dB gain and NF of 10 dB over 15-18 GHz.

Hewlett Packard this year entered this new exciting field of microwave devices with a device with f_{MAX} = 40 GHz and a device noise figure of 3.3 dB at 12 GHz.

Where Are We Headed?

Low Noise Transistor

Bipolar Transistor. The bipolar transistor has served us long and has come a long way as a low noise device, but with the introduction of GaAs MESFET with a noise figure of 3.3 dB at 12.4 GHz, its usefulness as a low noise device at high frequencies is already seriously undermined.

In the hope of determining the future usefulness of bipolar devices in a low noise front end amplifier at very high frequencies, the noise figure was analysed on the basis of a realistic equivalent circuit.

In FIG. 3 a plot is made of noise figures for devices with emitter line widths equal to 2.0, 1.0 and 0.5 microns. The f_T at minimum noise bias is assumed to be 4 GHz. FIG. 3 shows that in a device with 0.5 micron emitter a noise figure less than 4 dB can be attainable at 8.0 GHz and less than 3.0 dB at 6.0 GHz.

Field Effect Transistor. In order to investigate the optimum design of the gate channel and predict future capabilities of MESFET the transconductance and gate to source capacitance were calculated for a wide range of carrier concentrations in the channel for two sets of mobility data. The first set represents typical GaAs material obtained by a liquid epitaxial technique of Hewlett Packard Company, and the other set of data was obtained from the published curve of resistivity vs concentration.

The noise figure was then calculated from an equivalent circuit proposed by van der Ziel. By including the extrinsic resistance R_S and R_g the following expression for the minimum noise figure has been derived.

$$F_{MIN} = 1 + 2\frac{\omega C_{gs}}{g_{mo}}\left\{ C\sqrt{RP} + \sqrt{\left[P + g_{mo}(R_g + R_S)\right]\left[1 - C^2\right]R} \right\} + \frac{2P}{g_{mo}R_I}(1 + K)\frac{(\omega R_I C_{gs})^2}{1 + (\omega R_I C_{gs})^2} \qquad \text{EQN (1)}$$

In EQN (1) R, C and P are the multiplying factors introduced by Baechtold . The noise figures calculated for GaAs MESFET with 1.0 micron gate is plotted in FIG. 4 .

High Power Transistor

The maximum power of a transistor is limited by the base stretching or Kirk effect which sets limit on the current and by the base-collector junction voltage breakdown. The expression for the power output of an npn transistor can be arranged in the following manner to show the frequency dependence of $P_M X_C$.

$$(P_M X_C)\, f_T^2 = \frac{q v_{DS}^2 N_O V_{BO}}{40\pi^2 \epsilon \gamma \beta_O}\left(2.05 \frac{X_{BO}}{W_{BC}}\right)^{1.18} \qquad \text{EQN (2)}$$

The $P_M X_C$ products calculated from EQN 2 for 100% efficiency and 25% efficiency have been plotted in FIG. 5 along with the curve prepared by DeLoach. The $P_M X_C$ products obtained from state-of-the-art power transistors are also plotted in FIG. 5 . The dot-dash curve in FIG. 5 was obtained by introducing more realistic f_T in EQN .

Assuming the output impedance level of 5 ohms is desirable, the powers which may be obtained from bipolar power transistors are:

Frequency	Predicted Power Output
4 GHz	10 watts
6 GHz	7 watts
8 GHz	6 watts
10 GHz	4.6 watts
12 GHz	4 watts

Trend Toward Monolithic IC

The conventional junction-isolated monolithic IC may be usable up to 2 GHz range but because of the large lateral coupling through the isolation junction, it is not expected to be usable beyond 2 GHz. Three good potential candidates for higher frequency monolithic IC are (1) dielectric isolation, (2) air isolated beam-lead and (3) silicon on sapphire techniques. The use of either one of these techniques should enable us to fabricate monolithic IC usable up to 4 GHz or even as high as 6 GHz by 1975.

Conclusion

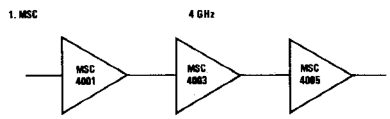
Today's bipolar npn low noise transistor has a noise figure as low as 4.5 dB at 4 GHz and can be utilized in almost all of the military applications in the L,S and low C-bands. Bipolar power devices which put out 5 watts at 4 GHz are now available and 5 watts at 6 GHz may be achievable in a year or two.

However, as a low noise device at frequencies beyond 6 GHz, the bipolar microwave transistor using either silicon or GaAs will be fighting a loosing battle against MESFET's. Likewise, the bipolar power transistor is nearing its limit above 21 GHz, although a power output of more than 4 watts may be attainable up to 12 GHz. Field effect transistors shown great promise both as low noise devices and high power devices.

As bipolar microwave transistor technology matures, there will be a trend toward monolithically integrating such devices. 4 GHz monolithic linear amplifiers using silicon bipolar devices should appear in the market by 1975. GaAs devices will be monolithically integrated in the near future.

References

1. E.W. Herold, IEEE Spectrum, Jan. 1965, p.50
2. W.W. Hooper and W.I. Lehrer, Proc. IEEE 55, July 1967, p.1237
3. W.Baechtold,W.Walter,P.Wolf, Electronics Letters, Vol 8, No.2, Jan.1972, p.35
4. W.Baechtold, IEEE Trans. of Electron Devices, Vol. ED-18, No.2, Feb. 1971,p.97



POWER	1.4W	3.0W	5.0W
GAIN	8.2 dB	5.8 dB	4 dB
EFFICIENCY	30%	30%	30%
Tj	183°C	190°C	162°C

TABLE 1 MICROWAVE POWER TRANSISTOR CHAIN AT 4 GHz

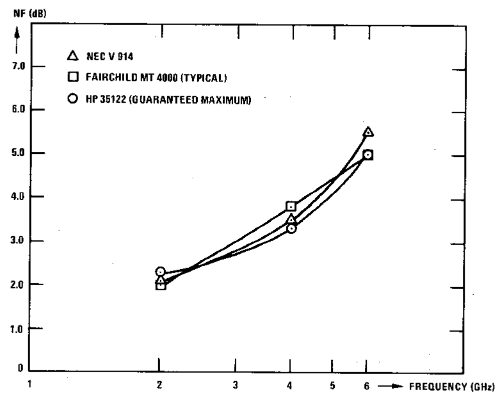


FIG. 1 NOISE FIGURE vs FREQUENCY OF COMMERCIALLY AVAILABLE LOW NOISE TRANSISTORS

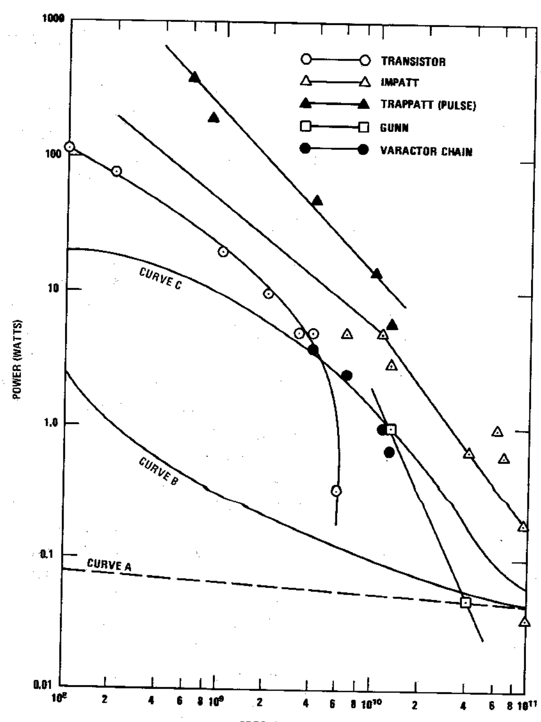


FIG. 2 STATE-OF-THE ART MICROWAVE SOLID STATE DEVICES PLOTTED ON HEROLD'S PF PLOT

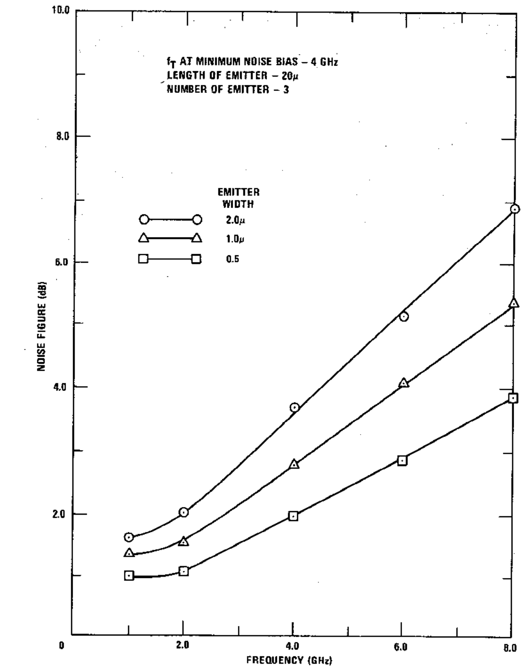


FIG. 3 NOISE FIGURE OF SILICON NPN BIPOLAR TRANSISTOR AS FUNCTION OF EMITTER WIDTH

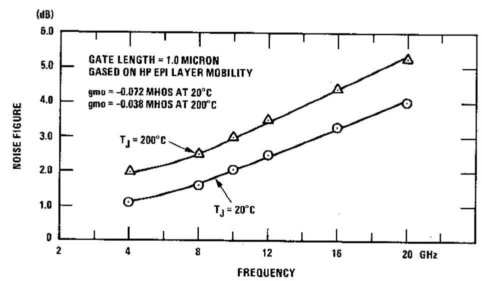


FIG. 4 VARIATION OF MINIMUM NOISE FIGURE OF GaAs MESFET WITH FREQUENCY (CALCULATED)

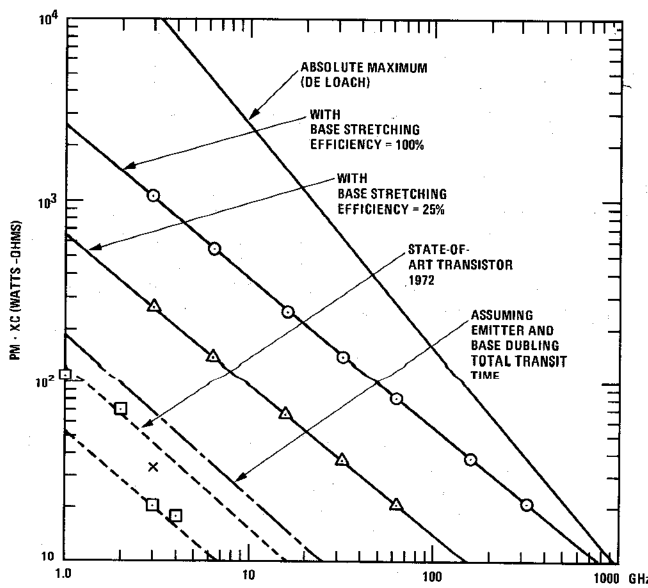


FIG. 5 FREQUENCY DEPENDENCE OF ABSOLUTE MAXIMUM POWER AVAILABLE FROM SILICON NPN TRANSISTOR