POWER RF MOSFET TRANSISTORS

POLYFET RF DEVICES

1. Basic Considerations
    1.1. Use a Printed Circuit Board - In most cases superior and more repeatable performance can be obtained using a printed circuit board with stripline inductors. It is also easier to maintain a good ground plane around the transistor.
    1.2. Fixed Tuned Matching Networks - A well designed amplifier with a fixed tuned matching network eliminates the factory or field tune up and even more important, eliminates lossy variable capacitors. Today's more consistent transistors can be easily purchased to drop into a wideband circuit with no tuning.
    1.3. Low Q Matching Networks - The use of low loaded Q matching Networks minimizes the loss due to high RF circulating currents. Any component variation in production is less likely to cause a problem in a low Q matching network. Use an external filter for any desired additional frequency selectivity.
    1.4. Ruggedness - Always use a transistor that will withstand ∞ VSWR if possible. This will prevent a lot of unexplained failures. If a device that will withstand ∞ VSWR is not available, use the most rugged available.
    1.5. Power Dissipation - Select a transistor that has a dissipation capability at least twice the RF power out rating. This will help ensure maximum reliability.
    1.6. Power Output - Operate the transistor at a power level that is 65 - 80% of the rated power output. This will provided less power slump with temperature and more efficient operation. The rated power output of a transistor is defined as the data sheet power specification.
    1.7. Largest Available Transistor - Select a large transistor over combining two or more small ones. Not only is this more economical; but, the circuit design is simpler and more reliable.
    1.8. Mounting Flange Packages - Flange packages must be mounted on flat (± 1 Mil/inch) surface if the proper heat transfer is expected. It is also important that the flange not be twisted or bent before or during installation and there are no tooling marks in the area where the transistor is mounted.
    1.9. Surface Mount Packages - Surface mount packages may be installed using epoxy or solder. When soldered properly, thermal resistances equivalent to the flanged packages can be expected. Some degradation in thermal resistance will be experienced when epoxy is used; the extent depends on the conductivity of the epoxy used.
    1.10. Silicone Grease - A high quality silicone grease like Dow Corning 340 or equivalent should always be used on flange devices. The use of silicone grease will improve the interface thermal resistance by at least 0.2^{0}C/Watt and as much as several ^{0}C/Watt if the heatsink surface has a poor flatness.
    1.11. Relationship of Leads to Circuit - This is one of the most important aspects of transistor mounting! The transistor should fit in the circuit without stressing the leads when torqued to the heatsink. Never solder a transistor into a circuit before torqueing to the heatsink! The two most important points to remember when mounting a transistor are:-
    - Don't Stress the leads excessively.
    - Keep the source lead inductance at a minimum.

2. Recommendations for mounting Polyfet transistors
   2.1. Tapped holes in heatsinks should be free of burrs and have a minimum depth of 0.25 inches.
   2.2. Suitable length screws should be used with a 4-40 UNC/2A thread. A washer should be used to spread the joint pressure.
   2.3. For transistors up to 80 Watts Pout, the heatsink should be a minimum of 0.120 copper or 0.200 Al. For transistors of greater levels of Pout, thickness should be increased proportionally.
   2.4. Flatness and finish of mounting surfaces is critical. Flatness should be 0.0008 inch or better and finish should be minimum of 16.
   2.5. A sparing use of evenly distributed heatsink compound on the transistor flange is recommended. Suitable brands of heatsink compound are: Dow Corning 340, Eccotherm TC-5 (E&C) and Wakefield 120.
   2.6. The screws through the flange holes should first be finger tight then tightened to 0,6 to 0,75 Nm to achieve the published thermal resistance between the device and the heatsink.
   2.7. When a transistor is removed from a heatsink, the joint pressure will almost certainly have distorted the flange. Grinding or lapping of the flange according to the information above is necessary to restore proper conditions for mounting.

3. RF Components
   3.1. It is important to realize RF Mosfets are low impedance devices at high frequencies. Designing with low impedance devices require special considerations:
   - With a low impedance circuit you have to be more concerned with current flow as opposed to high voltage in a high impedance circuit. This means that ground current paths and the current handling capability of components have to be watched carefully.
   - Stray inductances are extremely important. Of particular importance is the transistor lead inductance and any series inductance in a shunt component in a matching network. Don't forget that the inductance associated with the ground path is also very important.

   3.2. The key point to remember when designing at low impedance is that when you need a matching component, like a 1 Ω capacitor, make sure you do not forget about series lead impedance and possibly the ground return impedance. It does not take much stray inductance to equal the 1 Ω capacitive impedance you are seeking, only about 1 nh and 150 Mhz! That is about 1/16" of a stripline transistor's lead.
   3.3. Since the impedances levels are so low, components used in the circuits must be selected carefully. Of particular importance is the selection of capacitors. Again the main concern is current handling capability and lead inductance. Any capacitors used at low impedance points in VHF or UHF circuits at the 40W level or higher should have ribbon leads or no leads at all (chips). The best capacitors for use at low impedance points are the uncased mica and porcelain ceramic types. These capacitors have low series resistance components for very low loss and are therefore capable of operating at high RF currents. At higher impedance or lower frequencies, NPO chips or NPO leaded capacitors with very short leads will work.

4. Notes on Capacitors
   4.1. Many different dielectrics, such as paper, plastic, ceramic, mica, polystyrene, polycarbonate, teflon, oil, glass and air, are used in the manufacture of capacitors.

4.2. Ceramic dielectric capacitors vary widely in both dielectric constant (K=5 to 10,000) and temperature characteristics. Generally, the higher the K the worse the temperature coefficient. Low K ceramic manufactured using magnesium titanate, has a positive TC whereas those manufactured using calcium titanate have a negative TC(Temperature Coefficient). By combining these two materials in varying proportions, a range of controlled TC can be generated. These capacitors are sometimes called temperature compensating capacitors, or NPO (negative positive zero) ceramics. NPO ceramics are well suited for oscillator, resonant circuit or filter applications.

4.3. High K ceramic capacitors are typically termed general purpose capacitors Their temperature characteristics are very poor and their capacitance may vary as much as 80% over various temperature ranges. They are commonly used only in bypass applications at RF.

4.4. Ceramic capacitors specifically for RF applications are typically high Q. They may have ribbon leads or no lead at all to reduce inductance. The lead material is usually solid silver or silver plated and, thus, contains very low resistive losses. Chip capacitors, with no ribbon leads, are generally used for frequencies above 500 Mhz.

4.5. Mica Capacitors typically have a dielectric constant of about 6, thus they are physically large for any given capacitor value. They have very good temperature characteristics and are used in applications where PCB area is not of concern. Silver mica capacitors have tolerances of +20ppm/^{o}C over a range of -60^{o}C to +89^{o}C. Micas are becoming increasingly less cost effective than ceramic types.

4.6. Metallized film capacitors represent a broad range of dielectrics used, such as teflon, polystyrene, polycarbonate and paper. These capacitors have tight tolerances over the temperature range. Polystyrene, however, typically cannot be used over +85^{o}C as it is very temperature sensitive above this point. Most of these capacitors are large in comparison to ceramics and are used only where space is not a constraint.

5. Notes on Inductors

5.1. At RF frequencies, inductors have a series resistance and is paralleled by distributed capacitance. At very high frequencies the inductor can look more capacitive than inductive.

5.2. Recent advances in inductor technology have led to development of microminiature fixed-chip inductors. These inductors feature a ceramic substrate with gold plated solderable wrap-around bottom connections. They come in values from 0.01 µH to 1.0 mH, with typical Qs that range from 40 to 60 at 200 Mhz.

5.3. When winding your own inductors, some methods of increasing Q to extend its useful frequency range are:-

- Use a large diameter wire. This decreases the ac and dc resistance of the windings.
- Spread the windings apart to decrease the distributed capacitance.
- Increase the permeability of the flux linkage path by winding the inductor around a magnetic-core material such as iron or ferrite.

5.4. Considerations to take when using magnetic core materials:-

- Adding a magnetic core material to a air-core inductor can reduce the Q of the inductor due to the losses in the core.
- The permeability of all magnetic cores changes with frequency and usually decreases to a very small value at the upper end of their operating range.
- The higher the permeability of the core, the more sensitive it is to temperature variation.

- The permeability of the core changes with applied signal. If too large an excitation is applied, saturation of the core will result.
- Powdered-iron cores can typically handle more RF power without saturation or damage than the same size ferrite core.
- Powdered-iron core tend to yield higher Q inductors, at high frequencies, than an equivalent size ferrite core. This is due to the characteristic of powdered iron core which produce much less internal loss. The higher Q makes it very useful in narrow band or tuned circuit applications.
- At very low frequencies, or in broad-band circuits which spans the spectrum from VLF up through VHF, ferrite seems to be the general choice. This is true because ferrites have a higher permeability. The higher permeability is needed at the low end of the frequency range where for a given inductance, fewer windings would be needed.

6. Notes on Resistors
    6.1. Carbon composition resistors are poor high frequency performers. Between each pair of densely packed carbon granules is a very small parasitic capacitor. These parasitics add up to be a significant component of the resistor's equivalent circuit.
    6.2. Wire wound resistors have problems at radio frequencies too, exhibiting varying impedances over various frequencies. This is particularly true of the low resistance values in the frequency range of 10-200 Mhz.
    6.3. A metal film resistor has the best characteristics over frequency. Thin film chip resistors, produced on alumina or beryllia substrates, exhibit very low parasitics and are now popularly used from dc to 2 Ghz.

Component Types	Applications	Manufacturer or Equivalents
Capacitors		
Electrolytic	Low Freq. bypass	Distributor Item
Hi-K Ceramic	HF bypass	Distributor Item
Mylar	HF bypass	Distributor Item
NPO Ceramic	VHF Byapss and Matching	Distributor Item
Dipped Mica	VHF Coupling	Distributor Item
Uncase Mica	VHF & UHF Matching and Bypass	F.W. Capacitors
NPO Chips	VHF bypass & Matching	ATC - 700 Series
Porcelian Chips	UHF & Microwave Matching	ATC - 100 Series
Piston trimmers	UHF & Microwave Matching	Johanson Man. Corp.
Compression Mica	UHF & UHF Matching	Arco
Cores		
Ferrites Cores/Beads	Matching Transformers/Chokes	Amidon
Powdered Iron	RF Chokes	Amidon
Other		
Wire Wound Res.	Low Value Resistor	Distributor Item
Simi-Rigid Coax	Matching transformer	Micro-Coax
Heatsink Material	Heatsink, Copper, Brass, Alum.	Wakefield
Carbon Resistors	Oscillation Supression	Distributor Item
Board Material	Teflon Glass P.C.B.	3M
Board Material	Epoxy Glass P.C.B.	Distributor Item
Copper Tape	Adhesive Backed conductor	3M
Power Combiners	Broadband Output Combiner	RF Power

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The following is a list of suggested suppliers. Polyfet is neither recommending nor endorsing any of them for use.

Amidon - POB 25867, Santa Ana, Ca. 92799. Ph:(714)850-4660; Fax:(714)850-11163
Micro Coax- POB 993, Collegeville, PA. 19426 Ph:(610)489-3700; Fax:(610)489-1103
Arco - 5310-J Derry Ave., Agoura Hills, Ca. 91301. Ph:(818)707-6465
F.W. Capacitors - POB 12636, Florence, SC. 290504 Ph:(803)662-4728
Johanson - 301, Rockaway Valley Rd, Boonton NJ 07005 Ph:(201)334-2676 ; Fax:(201)334-2954
ATC - 1 Norden Ln, Huntington Stn, NY. 11746 Ph:(516)547-5700; Fax:(516)547-5748
RF Power - 125 Wilbur Pl, Bohemia NY. 11716 Ph:(516-563-5050; Fax:(516)563-4747

1. RF Measurements, Power and Impedance
    1.1. Power Measurements - Given an RF power amplifier circuit in input and load matched to 50 ohms, the measurement of power gain as well as absolute output power deserves some comment. The reason is that no one has yet developed an ideal wattmeter which combines all the properties of high accuracy, fast response, insensitivity to harmonics, and insensitivity to radiated RF power. The table below is a summary of the present state of the art for wattmeters:-

Wattmeter Type	Accuracy	Harmonic Insensitivity	Response	Insensitivity to Radiated Power
Thermo-electric	< 1%	Excellent	Good	Sensitive
Thermistor	<1%	Excellent	Good	Moderate
Termination type with diode detection reading RF peaks	< 1%	Poor	Fast	Good

1.1. For accurate measurements of input and output power, Polyfet uses a pair of electronic wattmeters of the thermoelectric type. These wattmeters and associated heads are mounted in a shielded enclosure along with the associated switches, bi-directional couplers, attenuators and loads. A typical measurement set-up is illustrated, Fig. 1. below.

2. Description of Figure 1
    2.1. The source is isolated from the test amplifier with 3 or 6 dB attenuator. If more isolation is required, a circulator may be used.
    2.2. The output attenuator is adjusted to be exactly 30.0 dB over the frequency range of interest.
    2.3. The input is calibrated over the frequency range to agree with the reading of the output meter.

3. Precautions for RF Power Transistors
    3.1. Some precautions are necessary when designing with RF power transistors in order to assure optimum reliability. A review of the important ones may save you some costly burnouts.
    - Initial Amplifier Turn-on - The life or death of your transistor in a newly completed amplifier design may depend on how it is first tested. Always begin at a low Drain voltage and minimum drive. Watch the drain current, power output and the spectrum analyzer carefully. Both Id and Pout should come up smoothly. Tune the amplifier while watching the spectrum analyzer for spurious response. Spurious responses below 1 or 2 Mhz are the most lethal. Any spurious response that will occur in an amplifier can be seen at a very low drain voltage. Good starting voltages are 9 volts for 12 volt amplifiers and 15 volts for 24 to 28 volt amplifiers.
    3.2. Operate the transistor within Specifications - Do not sacrifice reliability to achieve a little extra power output or gain by excluding specifications. Voltage breakdowns, maximum drive, and power dissipation are very important; but, three other specifications are most often abused.

- Load VSWR - Although MOSFETS are not as sensitive to VSWR as bipolar transistors, some caution should be applied. In general, the higher frequency of operation, the higher VSWR tolerance of the device. Most manufacturers specify a maximum load VSWR for safe operation. The maximum permissible VSWR is less at lower frequencies. Example: a transistor which is safe with and ∞ VSWR load at 1 Ghz maybe capable of withstanding only a 10:1 VSWR at 100 Mhz. Also the maximum VSWR specifications on a data sheet is usually for a transistor-circuit combination. Some circuits present higher VSWR's to the transistor than others.
- Frequency Range - A transistor should be used within its intended frequency range if possible. If a transistor is used at a lower frequency it will be more fragile and more susceptible to oscillations. If operated at higher frequencies, lower gain and poorer efficiencies can be expected.
- Safe Operating Area - Unlike Bipolar transistors, MOSs do not have secondary breakdowns and similar SOA curves are not available. The transistor should be operated within 75% of the maximum power dissipation specified.

3.3. Spikes and Power Supplies - The source of DC power for an RF amplifier is very important. Spikes and high voltage kill transistors! For example, an automotive electrical system which supplies a nominal 12 volts usually runs at 13.6 volts and can go to 16 volts or have spikes even higher. Watch your supply voltage carefully, get rid of the spikes and make sure the transistor you use can handle what is left.

3.4. An often overlooked supply voltage problem occurs in the electronically regulated power supply. Many of the finest laboratory power supplies are sensitive to radiated RF. While the RF amplifier is being tuned or being subjected to a load mismatch, the power supply may suddenly add several volts on its own. Always watch your voltmeter to make sure this does not happen to you.

4. General Circuit Techniques

The emphasis here is on VHF and UHF circuit design at relatively high power levels of 40 to 150 Watts. Solid State power amplifier designs at lower frequencies or lower power levels do not require near the care of many precautions prescribed here.

4.1. Which Class of Operation - The "normal" operating mode for a MOS RF power transistor is Class AB, for which most data sheets are presented. This is the best compromise mode for linearity and efficiency. Class A operation would be used for ultra-linear amplifiers requiring -40 to -50 dB intermodulation. Operating the transistor power output backed off from the saturated power output will also improve linearity.

4.2. The Concept of Low Impedance - A transistor is usually a low impedance device. (MOS devices are higher impedance than Bipolars) Designing with low impedance active components requires that the designers have the proper concept. He must think in a way that is opposite in many cases from previous design work.

- Current is critical, not voltage. Components must be capable of carrying high RF currents at low loss.
- Lead inductance is important. - Any lead inductance associated with the transistor or capacitors may severely degrade the amplifier performance.
- Ground paths must also be considered - In high impedance circuits the ground path is carried from component to component on a printed circuit run. This cannot be done with low impedance circuit design! A continuous groundplane on the back side of a PC board

is an ideal arrangement. Remember parasitic inductance in the ground path is of equal importance to the signal path.

- The important thing to remember when working with low impedances is to keep all parasitic and loss terms an order of magnitude below the element being used.

4.3. Grounds - When designing with RF power amplifiers, the technique used to ground the various components is so important that it deserves additional attention. Several tips listed below will help optimize our amplifiers. REMEMBER GROUNDING BECOMES MUCH MORE CRITICAL AT EITHER THE HIGHER POWER LEVELS OR HIGHER FREQUENCIES!

- Ground the transistor source leads at the body of the transistor. Not at ends of the leads! Not 1/8” away from the body!
- The back side of the PCB should be nearly a continuous ground plane. The top side ground should be connected to the bottom side ground using straps under each source lead. Plated through holes could also work.
- Components in the matching networks have critical ground paths too. The ground on the shunt capacitors on the gate of the transistor is often the most critical. Remember the shunt capacitor required here is often 1 or 2 ohms and therefore the total inductive impedance in the ground return to the source must be extremely small. For this reason, 2 capacitors in parallel, one back to each source lead, (as in AM and AT packages) are usually needed.
- Capacitors elsewhere in the matching networks even at slightly higher impedance points, still require a good ground. A direct connection to the continuous back side ground using a strap through a hole in the board is the best technique.
- Grounds for components and connectors at higher impedances near 50 ohms are not so important and do not require as much care.

5. Thermal Consideration

5.1. With today’s high power transistors, a design engineer must have a good understanding on thermal resistance properties of a transistor and its applications. To have a high degree of reliability, thermal considerations of the design must be studied in detail. A low overall thermal resistance is essential for a high power transistor in order to keep the junction temperature at a minimum. If the junction temperature is kept low enough, it is possible to design a transistor power amplifier that will last in excess of 500,000 hours.

5.2. Polyfet Mosfet VDMOS transistors have the drain on the bottom side of the die. To provide electrical isolation to the flange, the die is mounted on a Beryllium (BeO) insulator which is then attached to the flange. BeO is chosen for its good thermal conductivity property and close thermal expansion match to silicon. BeO does add a measurable thermal resistance to the make up of the transistor thermal equivalent circuit.

5.3. Polyfet transistors are gold metallized. There is less concern with electromigration due to heat than with transistors built with aluminum metal. Nevertheless, it is recommended to keep junction temperatures at 150 ^{o}C or less even though the data sheet calls for a maximum of 200^{o}C. There is nothing magical about the 200^{o}C value. Lower temperature will only tend to enhance reliability. Most military designs limit this number to 125^{o}C. Junction Temperature can be calculated from the formula:-

$$T_j(\text{Ave.}) = P_d\, \theta\, jc + T_C$$

where: T_j = junction temperature, θ jc = thermal resistance (from data sheet), P_d = power dissipation, T_C = device case temperature.

1.1. We must remember that the thermal resistance of all materials increases with increasing temperature. In a transistor, the die itself and the BeO insulator are the weakest links. The θ jc numbers given in data sheets are for 25°C case temperature, but in actual use of a device we are talking about case temperatures around 75°C typically, where the θ jc would be some 25% higher. See Fig 1. below.

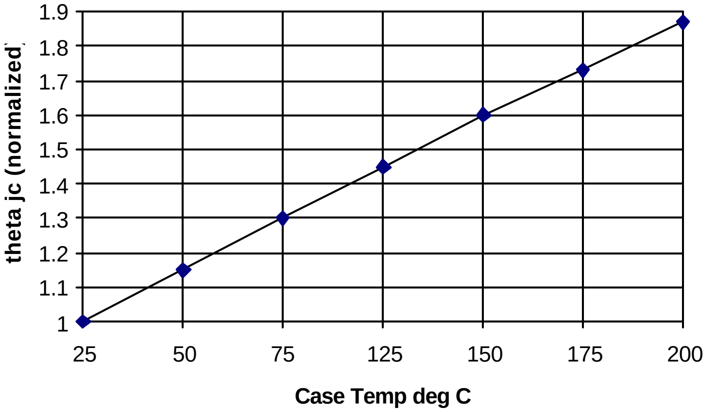

Figure 1 Approx. theta jc for combined resistance of Si and BeO

1.2. For a given package the θ jc is in direct relation to the die area or more exactly the active area. In other words, the larger the die, the lower θ jc. Transistors designed for higher power levels have larger dice in general than low power transistors, but UHF and microwave devices with their denser geometries have smaller active areas than lower frequency units for a given power level. As an example, an 80 watt VHF transistor has typically 20-22 K mils^2 of die area. From Fig 2. we can find the die θ jc as 0.3 °C/W (plot B). When a 60 mil (1.5mm) thick BeO insulator is added to the thermal chain (plot A), the total θ jc becomes 0.7-0.8 °C/W. 4

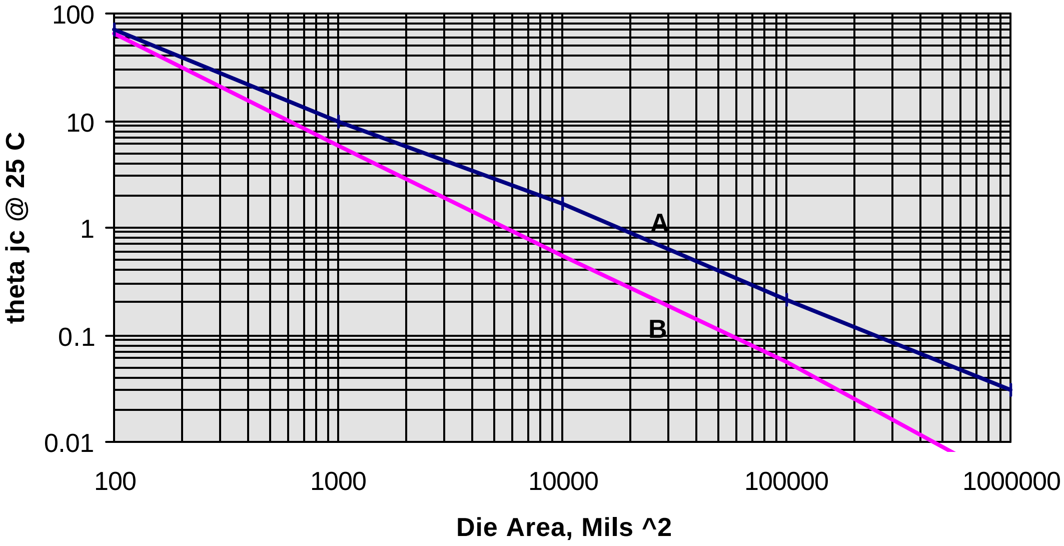

Figure 2 theta jc for various die sizes (plot B) and combined die and 60 mil BeO (plot A)

1.3. Of equal importance to the transistor junction to case thermal resistance is the thermal resistance between the transistor and the environment. Each of the interfaces and layers of material in the heat flow path must be carefully investigated to insure the proper thermal design. Fig 3 is a thermal flow chart of a transistor - heat sink combination. The thermal resistance in the heat flow part are θ jc(transistor to case), θcs (transistor case to heatsink), and θsa heatsink. All are very important. The thermal resistance numbers for case to heat sink θcs vary for different package configurations as shown below:-

Large Gemini:	0.07 - 0.1 ^{o}C/W.
0.5” flange:	0.1^{o}C/W.
Standard push pull	0.15^{o}C/W.
0.38” flange:	0.2^{o}C/W.
Small Gemini	0.2-0.3^{o}C/W.

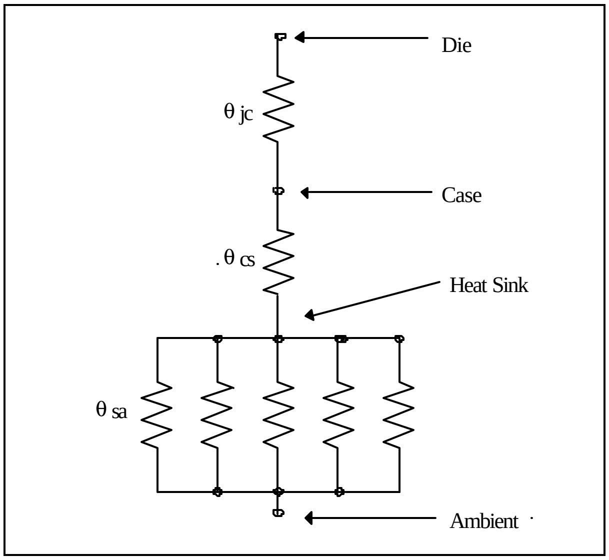

Figure 3 Thermal flow path of a transistor to heat sink

1.4. The heat sink is responsible for getting rid of the heat to the environment by convection and radiation. Because of all the many heat transfer modes occurring in a finned heat sink, the accurate way to obtain the exact thermal resistance of the heat sink would be to measure it. However, most heat sink manufacturers today provide information about their extrusions concerning the thermal resistance θ sa per unit length. This information can be used to calculate the size and types of heat sink required without having to start from scratch.

1.5. When the power dissipation and the thermal resistances of all interfaces are known, the requirement for the type and size of the heat sink required can be figured as :

$$\theta\ sa = \{(T_j - T_A)/P_d\} - (\theta\ jc + \theta\ cs)$$

Assume θcs is 0.1^{o}C/W and T_j = 150^{o}C, T_A = 50^{o}C, θ jc = 0.6^{o}C/W and the P_d=100W.

Then, the θsa is 0.3 °C/W. This means that a sufficient length of suitable extrusion is required to obtain this θsa value, which does not include forced air cooling. The θsa of a typical extrusion 4.5” (11.5cm) wide and 6”(15cm) long with 1”(25mm) high finds can be lowered by approximately a factor of three with an air flow of 10ft (300cm)/second. The forced air cooling is most efficient if turbulence can be created within the fins. This can be approached by directing the air flow against the cooling fins instead of along them longitudinally. The heat sink material must have good thermal conductivity. Aluminum is the most common material for heat sinks because of its good conductivity and light weight. Copper would, of course, be better because its thermal conductivity is about twice that of aluminum, but it is heavier and more expensive. Fortunately there is a happy medium. An aluminum heat sink can be equipped with a copper heat spreader, which is a copper plate of around 0.25” to 0.5” in thickness fastened to the top of the aluminum heat sink, and against which the transistor is mounted. The heat spreader should extend at least one inch beyond the transistor package in each direction. Although an additional thermal interface is created, the area is relatively large and there will still be a considerable improvement in the total θsa of the structure.

Appendix A

VSWR & dBm Chart

VSWR versus RETURN LOSS

VSWR	Return Loss (dB)	Volt Refl Coeff
1.00	66.02	0.00
1.01	46.06	0.00
1.02	40.09	0.01
1.03	36.61	0.01
1.04	34.15	0.02
1.05	32.26	0.02
1.06	30.71	0.03
1.07	29.42	0.03
1.08	28.30	0.04
1.09	27.32	0.04
1.10	26.44	0.05
1.11	25.66	0.05
1.12	24.94	0.06
1.13	24.29	0.06
1.14	23.69	0.07
1.15	23.13	0.07
1.16	22.61	0.07
1.17	22.12	0.08
1.18	21.66	0.08
1.19	21.23	0.09
1.20	20.83	0.09
1.25	19.08	0.11
1.30	17.69	0.13
1.35	16.54	0.15
1.40	15.56	0.17
1.45	14.72	0.18
1.50	13.98	0.20
1.60	12.74	0.23
1.70	11.73	0.26
1.80	10.88	0.29
1.90	10.16	0.31
2.00	9.54	0.33
3.00	6.02	0.50
4.00	4.44	0.60
5.00	3.52	0.67
10.00	1.74	0.82
20.00	0.87	0.90

POWER-CONVERSION CHART

dBm	(mW)	dBm	(mW)	dBm	(mW)
-20	0.010	-7	0.200	6	3.98
-19	0.013	-6	0.251	7	5.01
-18	0.016	-5	0.316	8	6.31
-17	0.020	-4	0.398	9	7.94
-16	0.025	-3	0.501	10	10.00
-15	0.032	-2	0.631	11	12.59
-14	0.040	-1	0.794	12	15.85
-13	0.050	0	1.00	13	19.95
-12	0.063	1	1.26	14	25.12
-11	0.079	2	1.58	15	31.62
-10	0.100	3	2.00	16	39.81
-9	0.126	4	2.51	17	50.12
-8	0.158	5	3.16	18	63.10
				19	79.43
dBm	**(W)**	**dBm**	**(W)**	**dBm**	**(W)**
20	0.100	34	2.51	48	63.1
21	0.126	35	3.16	49	79.4
22	0.158	36	3.98	50	100
23	0.200	37	5.01	51	126
24	0.251	38	6.31	52	158
25	0.316	39	7.94	53	200
26	0.398	40	10.0	54	251
27	0.501	41	12.6	55	316
28	0.631	42	15.8	56	398
29	0.794	43	20.0	57	501
30	1.000	44	25.1	58	631
31	1.259	45	31.6	59	794
32	1.585	46	39.8	60	1000
33	1.995	47	50.1		

GLOSSARY OF TERMS

Ampere:	A unit of electrical current or rate of flow of electrons (abbreviated: Amp).
Amplifier:	A device which draws power from a source other than the input signal and which produces as an output an enlarged reproduction of the essential features of its input. The amplifying element may be an electron tube. transistor, magnetic circuit. or any various device.
Attenuation:	The decrease in amplitude of a signal during its transmission from one point to another. It may be expressed as a ratio, or by extension of the term, in decibels.
Attenuator: (pad)	1. An adjustable resistive network for reducing the amplitude of an electrical signal without introducing appreciable phase or frequency distortion. 2. A distributed network that absorbs part of a signal and transmits the remainder with a minimum of distortion or delay.
Avalanche Breakdown:	The application of excessive voltage to a semiconductor material creates an excess of high energy (or hot) electrons. These electrons can excite additional carriers into a high-energy state, which makes the semiconductor more conductive. With the same voltage applied, it can result in a high current flow with destructive breakdown in a FET in an avalanche effect.
Band:	1. Any range of frequencies which lies between two defined limits. 2. A group of radio channels assigned by the FCC to a particular type of radio service.
Bandwidth:	The range within the limits of a frequency band.
Bipolar:	Refers to a transistor in which both majority and minority carriers (electrons and holes) carry current, and which is formed with PN junctions.
Breakdown Voltage:	The reverse bias voltage at which a rectifying junction begins to conduct a large reverse current (higher than normal reverse leakage). Reverse breakdown can be caused by avalanche breakdown or by other electrical or thermal effects. Gate-to-source and gate-to-drain breakdown in a FET avalanche effects, but may take place without damage to the device so long as the reverse current is limited to a safe value.
BVGss:	Breakdown voltage. gate-to-source. The voltage at which gate-source capacitor ruptures.
Ciss:	Capacitance gate-to-source. The capacitance that exists between the gate and source electrodes of a Mosfet.
Crss:	Reverse feedback capacitance as exist between drain and gate of a Mosfet.

Coss:	The output capacitance between drain and source of a Mosfet.
CW:	Abbreviation for continuous wave.
Calibrate:	To ascertain, by measurement or by comparison with a standard, and variations in the readings of another instrument. or to correct the readings.
Capacitance:	Also called capacity. In a capacitor or a system of conductors and dielectrics. That property which permits the storage of electrically separated charges when potential differences exist between the conductors. The capacitance of a capacitor is defined as the ratio between the electric charge that has been transferred from one electrode to the other and the resultant difference In potential between the electrodes. The value of this ratio is dependent on the magnitude of the transferred charge. Abbreviation: C).
Circuit:	The interconnection of number of devices in one or more closed paths to perform a desired electrical or electronic function.
Class A, AB, C:	Bias classes that are used by engineers when designing a circuit. The use of the circuit dictates which class is to be used. They range from Linear (Class A) to raw power (Class C).
Drain Efficiency:	The ratio, usually expressed in percentage, of useful power output to final stage power-supply power input of a transistor.
Conductor:	1. A bare or insulated wire or combination of wires not insulated from one another, s suitable for carrying an electric current. 2. A body of conductive material so constructed that it will serve as a carrier of electric current.
Conjugate Match:	A transistor input or output port is conjugately matched when connected to an impedance which has the same resistance as the transistor port and a reactance of the same magnitude but opposite sign. This means that the reactances cancel, and that maximum power transmission takes place and that there is no mismatch loss.
Continuous Waves: CW	Electromagnetic waves generated as a continuous train of identical oscillations.
Correlation:	1. The relationship, expressed as a number between minus one and plus one, between two sets of data, etc. 2. A relationship between two variables; the strength of the linear relationship is indicated by the coefficient of correlation.
Current:	The movement of electrons through a conductor. Measured in amperes. and its symbol is I.
Decibel (dB):	The standard unit for expressing transmission gain or loss and relative power levels. Power Gain is expressed by:-

$$Gain(db) = 20\log\frac{Pout(Watts)}{Pin(Watts)}$$

dBm	The term "dBm" is used, when a power of one milliwatt is the reference level. Not to be confused with “dB”, which indicates the ratio of power output to power input: 0 dBm = 1 milliwatt 10 dBm = 10 milliwatt 30 dBm = 1 Watt 40 dBm = 10 Watt
Depletion Layer:	The portion of the epitaxial layer that lies directly beneath the gate of a PET and becomes depleted of carriers (electrons) when a negative bias is applied to the gate.
Dopant:	A substance added to silicon (or other transistor base material) to make it more conductive.
Drain:	1. The current taken from a voltage source. 2. In a field-effect transistor, the terminal connected to DC supply and load.
Duty Cycle:	The amount of time a device operates, as opposed to its idle time. Applied to a device that normally runs intermittently rather than continuously. Ratio of time on to time-off expressed as a percentage.
F_t	Unity current or voltage gain frequency, or cut-off frequency. $Ft \cong \frac{Gm}{2\pi(Ggs + Cgd)}$
F_{max}	Unity Power Gain Frequency. Also maximum frequency of oscillation. $F\max \cong \sqrt{\frac{Ft}{8\pi RgCgd}}$
FET:	Field Effect Transistor. A unipolar device in which the number of carriers available to carry current in the conducting region is controlled by the application of an electric field to the surface (in the form of a capacitor or reverse-biased diode junction) of the semiconductor. As a unipolar device, the current in a FET is carried only by the free majority carriers (in an N-channel FET, electrons) in the conducting channel and there is little or no current carried by the minority carriers (holes - in an N-Channel FET). Compare this to the bipolar transistor in which both positive and negative free carriers carry approximately equal currents
Frequency:	The number of recurrences of a periodic phenomenon in a unit of time. Unit of measurement for electrical frequency is “hertz”. Radio frequencies are normally expressed in kilohertz at and below 30.000 kilohertz, and in megahertz above this frequency.

Frequency Range:	1. In a transmission system, those frequencies at which the system is able to transmit power without attenuating it more than an arbitrary amount. 2. In a receiver, the frequency band over which the receiver is designed to operate, covering those frequencies the receiver will readily accept and amplify. 3. A designated portion of the frequency spectrum.
GaAs:	Gallium Arsenide. A type 111-V (from the periodic table) compound of gallium and arsenic which has a resistivity sufficiently high to fabricate field-effect transistors. Compared to silicon, the free carriers can reach about twice the limiting velocity with one-third the applied voltage, thus a higher frequency of operation.
GaAs FET:	A field-effect transistor made of gallium arsenide.
Gain:	Also called transmission gain. 1. Any Increase in power when a signal is transmitted from one point to another. Usually expressed in decibels. Widely used for denoting transducer gain. 2. The ratios of voltage, power, or current with respect to a standard or previous reading.
Gain Compression:	Gain is a measure of amplification. It reaches some maximum value at a specific output power level. As Pin is increased from this point, Gain decreases.
Gate:	1. A circuit having two or more inputs and one output, the output depending upon the combination of logic signal at the inputs. 2. Controls the flow of current from the drain to the source.
Gate Length:	The distance along which the electrons must travel when moving from source to drain. That is, length is the shorter of the two gate dimensions (gate width is the longer dimension). The frequency response of a FET, with all other things equal. is inversely proportional to its gate length. Gate length is also known as channel length.
Gate Width:	The size of the FET channel that carries current, That is, width is the longer of the two gate dimensions (gate length is the shorter dimension). The power handling capacity of a FET, with all other things equal, is directly proportional to its gate width. Increasing gate widths increases gM, transconductance, and Coss, output capacitance as well.
gM:	DC transconductance, which is the ratio of the change in the drain current to changes in gate voltage: $gm = \frac{\Delta Ids}{\Delta Vgs}$ for given Vds and Ids
GNF:	Small signal gain. resulting from tuning for optimum noise figure. Also designated GA..
Gp:	Small-signal gain resulting from tuning for optimum output power.

GT: Transducer power gain. The insertion power gain of a transistor with no assumptions made concerning S12, S11, S22 or the source of load impedances. The maximum value of GT for an unconditionally stable transistor is MAG (Maximum Available Gain).

$$G_T = \frac{4 G_S G_L \left| y_f \right|^2}{\left| (y_i + Y_S)(y_o + Y_L) - y_f y_r \right|^2}$$

Where G_S= Source Conductance
G_L= Load Conductance
Y_S =Source Admittance
Y_L= Load Admittance

Maximum Available Gain occurs when y_r=0 and when Y_L and Y_s are the complex conjugates of y_o and y_i, respectively.

$$MAG = \frac{\left| y_f \right|^2}{4 g_i g_0}$$

Where $y_{f\,rio}$= y parameters
g_i= input conductance
g_0=output conductance

Gumax: Maximum unilateral transducer power gain. Transducer power gain with S12. assumed equal to zero, and input and output conjugately matched for maximum power transfer.

Hertz: A unit of frequency equal to one cycle per second. Abbreviated Hz.

IC: Abbreviation for internal connection or Integrated circuit.

Id(max.}: Maximum allowable drain current that can be maintained under steady state condition without damage to the transistor.

Idq: Quiescent current. Drain current with no RF applied to the circuit (Vdd and gate bias only).

Idss: Drain-to-source leakage current. The current that results from a given drain to source voltage applied to the FET with the gate voltage held at zero.

Igss: Gate-to-source leakage current at a stated reverse gate-to-drain voltage.

Implanted Layer: An active layer formed by the implantation of dopants directly into the substrate crystal.

Insulators:

1. A material of such extremely low conductivity that, in effect, no current flow through it.
2. A high-resistance device that supports or separates conductors to prevent a flow of current between them or to other objects.

Ion Implantation:	A method of semiconductor doping in which selected dopants are ionized and accelerated at high velocities to penetrate the semiconductor substrate and become deposited below a surface. The high precision system is used to form active layers.
MAG:	Maximum available gain, at a frequency where the transistor is unconditionally stable and the input and output ports are simultaneously conjugately matched. Also designated GA(max.), Gmax.
Maximum Operating Voltage:	The maximum bias voltage that can be continuously applied to a particular transistor without damage occurring.
MESFET:	Metal Semiconductor Field Effect Transistor. MESFET is one form of GaAs FETs.
NFopt:	A measure of the noise generated by a transistor when tuned for minimum noise figure at a given frequency. Also designated NFmin.
NF50:	Noise figure of a transistor at a given frequency, when inserted in an untuned 50-Ohm circuit. This figure is most often used for the calculation of noise resistance.
Ohm:	Symbolized by the Greek letter omega (Ω). The unit of resistance. It is defined as the resistance, at 0 ^{0}C, of a uniform column of mercury l06.3OO cm long and weighing 14.4521 grams. One ohm is the value of resistance through which a potential difference of one volt will maintain a current of one ampere.
Operating Temperature:	The temperature or range of temperature over which a device is expected to operate within specified limits of error.
Operating Temperature Range:	The interval of temperatures in which a component device or system is intended to be used, specified by the limits of this interval.
Oscillations:	1. A state of instability in an amplifier where excessively large amounts of current may be drawn to damage the transistor. 2. The state of a physical quantity when, in the time interval under consideration, the value of the quantity is continually changing in such a manner that it passes through maxima and minima (e.g., oscillating pendulum, oscillating electric current, and oscillating electromotive force). 3. Fluctuations in a system or circuit, especially those consisting of the flow of electric currents alternately in opposite direction; also, the corresponding changes in voltages.
P1dB:	1. Power output at the -1dB gain compression point; essentially the maximum output power available from the transistor while providing linear amplification. 2. The point a which the gain of the amplifier is no longer linear and is reduced by 1 dB.
Passivation:	The formulation of an insulating layer directly over a circuit or circuit element to protect the surface from contaminants, moisture, or particles.

Pin:	Power Input.
Planar:	The process, and result, of the semiconductor or IC fabrication process in which the lateral diffusion of the base, and the dopant is restricted to the extent required by the device, thus eliminating the need for etching.
Pmax:	Maximum continuous power dissipation at or below a stated reference temperature (usually 25 ^{0}C) or linearly derated at a higher ambient temperature.
Pout:	Power output.
Power Added Efficiency:	The ratio of RF power output minus RF power input to the DC input power. Expressed in percentage.: $h = \frac{(Pout - Pin)}{(Vdd \times Id)} * 100\,\%$
Power Gain:	Ratio between power In and power out expressed as dB.
Pref:	The power flowing back to the generator from the load.
PRT:	Pulse repetition time. The time elapsed from the beginning of one pulse to the beginning of the next.
Psat:	Saturated power output. Usually specified at some level of small-signal gain compression, such as 2dB or (most usually) 3 dB.
PT(max.):	Maximum continuous power dissipation that can be sustained without device damage.
Pulse:	1. The variation of a quantity having a normally constant value. This variation is characterized by a rise and a decay of a finite duration. 2. An abrupt change in voltage, either positive or negative, which conveys information to a circuit.
Pulse Duration:	Also called pulse length or pulse width. The time interval between the points at which the instantaneous value on the leading and trailing edges bears a specified relationship to the peak pulse amplitude.
Rdson:	Low field drain-to-source resistance. The slope of the drain I-V characteristic near the origin of the curve, and an indicator of the active channel resistivity and the drain and source contact quality.
RN:	Equivalent noise resistance, used in the FET model to predict noise figure performance.
Rth:	The internal junction-to-case thermal resistance which is the rated increase in junction temperature with respect to the case temperature per unit of dissipated power.

Return Loss:	Same as S11. Ratio of reelected power to forward input power. Measured in dB.
Schottky Diode:	A rectifying junction formed by depositing a layer of metal onto the surface of a barrier which gives the metal-semiconductor interface rectifying properties, with semiconductor. This creates an electrostatic the metal acting as the anode and the N-type semiconductor as the cathode. Since the Schottky diode is a surface device, and since its metal layer can be fabricated at the same time as ohmic (drain and source) contacts, it is used to provide the gate structure of GaAs fets. Also designated: Schottky-barrier diode, metal-semiconductor diode, hot-carrier diode.
Source:	1. The device which supplies signal power to a transducer. 2. In field-effect transistor, the electrode that corresponds to the cathode of a vacuum tube. In N channel Mosfets, this terminal is connected to ground.
Sparameters:	Scattering parameters -- a group of measurements taken at different frequencies which represent the forward and reverse gain and the input and output reflection coefficients of a transistor (or other device) when the input and output ports are terminated in equal impedances, usually 50 + J0 ohms. Specifically, they are:
S11:	Input reflection coefficient expressing magnitude and phase of the input match.
S12:	Reverse transfer coefficient expressing the magnitude and phase of the reverse isolation.
S21:	Forward transfer coefficient expressing the forward gain magnitude and phase.
S22:	Output reflection coefficient expressing the magnitude and phase of the output match.
StriplIne:	On a circuit board, a printed conductor between two ground planes having properties similar to coaxial transmission lines.
td:	Delay time -- the time interval during pulse turn on of a transistor which is the time from which the input reaches 10% of its full amplitude to the time at which the output reaches 10% of its amplitude.
tf:	Fall time -- the time interval during pulse turn-off of a transistor during which the drain pulse goes from 90% to 10% of its amplitude.
tr:	Rise time-the time interval during pulse turn on of a transistor during which the drain pulse goes from 10% to 90% of its maximum amplitude.
T_A:	Ambient temperature; the air temperature surrounding a particular device.
T_C:	Also Tcase; the surface temperature of a transistor case under operating condition.
Tj:	Junction temperature. Strictly, the measured or estimated temperature of the junction of a transistor. Also known as die temperature.

Vds:	Drain-to-source voltage. For a FET, the normal operating bias between the drain and the source are 24V, 28V and 50V for base stations; 12.5V for mobile platforms and 7V for handheld portable units.
Vgs:	Gate-to-source voltage. In normal linear operation of a Mosfet, the operating bias between the gate and the source is in the 3 volt range
(VSWR) Voltage Standing-wave Ratio	Ratio between the sum and difference of the incident and reflected voltage waves.
θjc	Junction-to-case thermal resistance, specified in terms of temperature rise vs. power dissipation in the junction of a transistor (^{0}C/W).