APPLICATION NOTE 35

Thermal Analysis of Gallium Arsenide MESFETs

Introduction

Temperature calculations are of extreme importance to the designers of semiconductor devices and systems. The reason for this is that the useful life of a semiconductor is directly related to the temperature of the active region. In Gallium Arsenide MESFETS, heat is generated near the surface under the gate. This application note deals with the analysis of heat flow under these conditions.

Background

Heat Flow Equation

The parameters which will be used in the equations and other calculations in this note will be defined as follows:

T = Temperature, in degrees Centrigrade (Celsius)
P = Power, in watts
A = Area, in square centimeters
Q = Heat Flux, which is the same as power per unit area or Q=P/A, in watts/sq.cm.
F = Distance that heat flows in the material (thickness) in centimeters
Kth = Thermal Conductivity, in watts/cm-deg C
Rth = Thermal Resistance, in degrees C/watt

While the units are somewhat mixed, they are those in most general use among engineers performing thermal analysis.

The temperature in a homogeneous solid of thermal conductivity Kth satisfies Poisson's equation as follows:

$$\nabla^2 T = -(Q/Kth)$$

There are many forms of the above heat flow equation depending on the physical boundaries that are set. For semiconductors, the x, y, and z dimensions are fixed, the heat source is on the upper surface, and heat spreads in all directions. Radiation and convection are usually excluded. However, although the heat flow is three dimensional, the boundary conditions in the semiconductor impose limits on the spreading.

Poisson's heat flow equation is not easy to solve without use of a computer. The first modern attempt at doing so was made by Dietzel, Hein and Lenzi in the late sixties [1]. The software that they developed (TASIC) was capable of solving the three dimensional heat flow equation including any combination of heat sources and sinks located on the top surface of a rectangular slab of arbitrary dimensions.

MESFET Analytical Solutions

Fortunately the heat flow problem is simplified somewhat for MESFETs. In this case the heat is dissipated between the gate and the drain, but very close to the gate. Thus the gates themselves form discrete heat sources. If the FET has more than one gate, the gates are thermally coupled due to spreading in the x and y directions. Cooke [2] has noted that an analytical solution to this thermal problem can be extracted directly from the microwave stripline literature, since the thermal and electrical problems obey the same differential equation. [3]

The solution technique evaluates the thermal resistance of MESFETs with any number of gate segments. It uses two approximations:

(1) heat flow off the gate end is assumed negligible,
and
(2) spreading off the outer gates is assumed not to be limited by chip size.

Both of these approximations are valid for modern MESFET designs.

The inputs needed are:

(1)	The gate to gate spacing	**(S)**
(2)	The gate length	**(L)**
(3)	The unit gate width	**(Z)**
(4)	The number of gates	**(n)**
(5)	The die thickness	**(F)**

The solution was derived by treating the heat flow in a MESFET as analogous to the capacitances of multiple, coupled transmission lines.[4] The derivation uses Getsinger's model which resolves transmission lines capacitance into three components:[5]

- A parallel plate capacitance
- An internal fringing capacitance
- An external fringing capacitance

These capacitance and the equation for the characteristic impedance Zo for both single and multiple pairs of transmission lines can be used to derive an expression for the even mode capacitance, which is analogous to thermal resistance. The final expression for C_{even} involves a ratio of elliptic integrals, but fortunately Hillberg's algorithm provides a simplified analytical solution.[6]

After all the manipulating is done, the final equation for the thermal resistance (Rth) can be evaluated as follows:

$$Rth = \frac{n}{\pi Z Kth\left[\frac{2(n-1)}{\ln(M)} - \frac{(n-2)}{\ln(P)}\right]}$$

where

$$M = 2\frac{\left[\cosh(\pi\frac{S+L}{4F})/\cosh(\pi\frac{S-L}{4F})\right]^{1/2}+1}{\left[\cosh(\pi\frac{S+L}{4F})/\cosh(\pi\frac{S-L}{4F})\right]^{1/2}-1}$$

$$P = 2\sqrt{\frac{1+sech(\frac{\pi L}{4F})}{1-sech(\frac{\pi L}{4F})}}$$

Over the practical temperature range for MESFETs the thermal conductivity for GaAs is:[2]

$$Kth = 1.08T^{-0.26} W/cm\text{-}°C$$

Once the thermal resistance, Rth, has been found the temperature can be evaluated. For a static case (power is CW) the temperature of the MESFET channel is evaluated as:

$$T = (P*Rth) + Ta$$

where **Ta** is the ambient or heat sink temperature.

However, as noted above, the thermal conductivity (**Kth**) of GaAs is temperature dependent, leading to errors in the evaluation of T. This apparent difficulty is easily circumvented using the Kirchoff transformation technique described by Joyce.[7] This leads to the following expression for the true channel temperature:

$$Ttrue = [0.74(\Delta T)Ta^{-0.26}+Ta^{+0.74}]^{1.35}\ °C$$

where

ΔT = T-Ta = The calculated temperature rise

MMICAD Implementation

The equation described in the previous section have been implemented into the PROC block of MMICAD as shown in Figure 1.

```
!FILE NAME:    THERMAL.CKT

!Description:  Precise Interdigitated GaAs FET Thermal
               parameters calculation

!Input Data:   L    = gate length [length unit in DIM
statement]
               S  = spacing between Gates [length unit in
               DIM        statement]
               Z  = total gate width [length unit in DIM
                      statement]
               n  = number of gates ( >1 )
               F  = thickness of substrate [unit in DIM
                     statement]
               To = ambient temperature [°C]
               PW = total power dissipation [ Watts ]
!Output Data:  Kth  = temperature dependent thermal
                    conductivity [W/length unit in DIM
                       statement-°C ]
               RTH = thermal resistance [ °C/Watts ]
               DT = temperature increase in channel [ °C ]
               Tc = channel temperature for temperature
                      independent Kth
               Tt = true channel temperature [°C ]

!Reference:    H.F.Cooke, "Precise technique finds FET
               thermal resistance", Microwaves & RF,
               August 1986. pp. 85-87
-------------------------------------------------------------------------------------------
--------
mode param

GLOBAL
 DIM LNG=1e-6  ! dimensions in microns

PROC
 L=2
 S=30
 Z=13680 ! total gate width = 72*190
 n=72
 F=param
 To=30
 PW=10.0 ! total power
 COSP=  COSH(PI*(S-L)/4/F)
 COSM=  COSH(PI*(S+L)/4/F)
 SECH=  1/COSH(PI*L/4/F)
 M=  (2*SQRT(COSM/COSP)+1)/( SQRT(COSM/COSP)-1)

 P=  2*SQRT( (1+SECH)/(1-SECH) )
 TZK=  N/PI/( (2*(N-1)/LN(M))-((N-2)/LN(P)) )
 KTH=  DIMLNG*108*(To^(-0.26))
 RTH=  TZK/Z/KTH
 DT=  RTH*PW
 Tc=  To+DT
 Tt=  ( 0.74*DT*To^(-0.26)+To^(0.74) )^(1.35)

param
STEP 100
!sweep 100 600 10

OUT
 OUTVAR RE[L] DATA T
 OUTVAR RE[S] DATA
 OUTVAR RE[Z] DATA
 OUTVAR RE[F] DATA
 OUTVAR RE[n] DATA
 OUTVAR RE[To] DATA
 OUTVAR RE[PW] DATA
 OUTVAR RE[KTH]  RESULTS t
 OUTVAR RE[RTH] RESULTS
 OUTVAR RE[DT] RESULTS
 OUTVAR RE[TC] RESULTS
 OUTVAR RE[Tt] RESULTS
 OUTVAR RE[Tt] PLOT

GRID
 PLOT 100 600 50 150
```

Figure 1 MMICAD Circit File

A Mitsubishi power MESFET was analyzed with the following inputs:

# of gates **(n)** =	72
Length of gates **(L)** =	2
Width of gate **(Z/n)** =	190
Spacing of gates **(S)** =	30
Heat sink temperature **(Ta)** =	30
Thickness of substrate **(F)** =	100
Total power **(P)** =	10

The inputs to MMICAD are shown in Figure 2, with the results of the analysis in Figure 3. The temperature in the channel of the MESFET is calculated as 80.8 Celsius.

```
!  File: C:\MMICAD\THERMAL\RECOVER.CKT


! MMICAD -- Thu Aug 13 12:14:52 1992
! MESFET Thermal data calculations
!  FREQ  OUTVAR  OUTVAR  OUTVAR  OUTVAR  OUTVAR
```

Figure 2 Input Data

```
!  File: C:\MMICAD\THERMAL\RECOVER.CKT

! MMICAD -- Thu Aug 13 12:14:29 1992
! MESFET Thermal data calculations
! FREQ   OUTVAR  OUTVAR  OUTVAR  OUTVAR  OUTVAR
!          RE[KTH]  RE[RTH]   RE[DT]    RE[TC]    RE[TT]
  1.000    4.46E-5    4.416       44.158     74.158     80.840
```

Figure 3 Calculated Data

To determine the influence of substrate thickness on this MESFET's thermal behaviour, the substrate thickness was swept from 100 to 600 microns using parameter mode. The results are shown in Figure 4. As can be noted from the graph the temperature of the channel with a substrate thickness of 600 microns has increased to 142 Celsius.

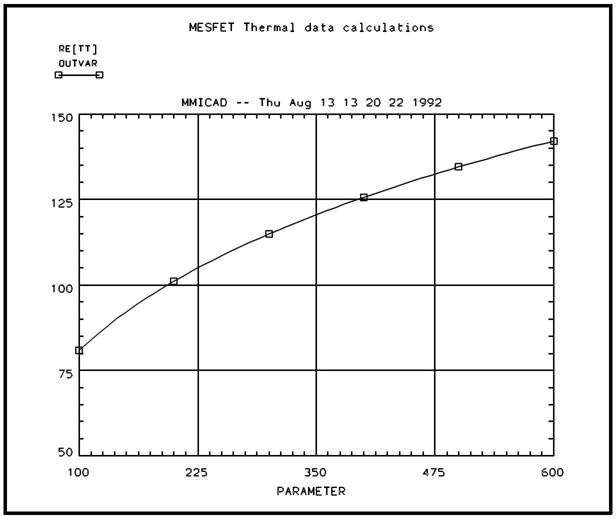

Figure 4 A plot of true temperature versus substrate thickness

Conclusion

This application note demonstrates the use of MMICAD for rapid estimation of the thermal behaviour of MESFETs as a function of the physical properties of the transistor.

References

[1]Dietzel, K.R., Hein, V.L., and Lenzi, V.D. TASIC (Thermal Analysis of Substrates and Integrated Circuits) Unpublished Bell Telephone Laboratories Program.

[2]Cooke, H.F., "Precise Technique Finds FET Thermal Resistance", Microwaves: Vol. 25, No. 8, Aug. 1986.

[3]Cohn, S.B., "Shielded Coupled Strip Transmission Line", IRE Trans. Microwave Theory and Techniques, MTT-3, 1955, pp 134.

[4]DeLorenzo, et al, "GaAs FET Principles and Technology", Artech House, 1982, pp 313-347.

[5]Getsinger, W.J., "Coupled Rectangular Bars between Parallel Plates, IRE Trans. Microwave Theory and Techniques, Vol. MTT-10, No. 1, 1982.

[6]Hilberg, W., "From Approximations to Exact Relations for Characteristic Impedances", IEEE Trans. on MTT, Vol. MTT-17, No. 5, 1969.

[7]Joyce, W.D., Solid State Electronics, V18, p 321, 1975.