EQUIVALENT CIRCUITS FOR IMPATT AND OTHER MICROWAVE DIODES

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SUMMARY

Equivalent circuits for active semiconductor devices are useful for designing oscillators and amplifiers. However, the parameters are unlikely to represent physical elements of the device. Parameters of passive devices are more easily related to specific portions of the device, although it is not necessary that this equivalence hold true. Package and mount impedances further complicate this problem.

INTRODUCTION

Equivalent circuits for passive diodes have been deduced from the physical characteristics of the device. Approximate values of the parameters were obtained from dc measurements and refined by microwave measurements.

Package equivalent circuits may have from two to five elements. Although each element represents a specific portion of the package, it is not necessary to use all five elements unless the equivalent circuit must be valid over a broad frequency band including frequencies above X-band.

Although the effects of the mounting circuit may be included in the package circuit elements, it is often useful to separate the packaged diode circuit from the mount. When the diode terminates a coaxial line, the calculated values of mount parasitics agree quite well with measured values. Frequency independent equivalent circuits of waveguide, stripline, and microstrip mounts have not been studied in such detail.

Equivalent circuits for active diodes such as IMPATTS have been derived, but the elements do not identify so well with the physical parts of the diode. In fact, one successful model uses lengths of transmission lines. Measured impedances of four double drift IMPATT types were measured at both high and low power levels. Equivalent circuits with calculated impedances close to these measured values were derived.

Beam Lead Mixer Diode

Mixer diodes may be represented by a junction resistance shunted by a capacitance. This combination is in series with a resistance representing contact and substrate resistances. Beam lead diodes are more easily modelled than are packaged chips because the parasitic elements are small. In fact, the parasitic inductance of the beam lead itself is less than that of a wire connecting a chip to a microstrip circuit or to a package. These parasitics may be represented by a small shunt capacitance and a series inductance as shown in Figure 1. The element values were obtained by measuring the impedance of an HP 5082-2709 diode from 2 GHz to 12 GHz and using the Compact optimization program to help find element values that give the same impedance.

Figure 2 shows the measured and calculated admittance at several frequencies. The maximum difference in phase and magnitude of the reflection coefficient is 1.8° and 0.01 respectively.

Figure 1. Beam Lead Mixer Diode Equivalent Circuit

For these measurements the diode was mounted on a 10 mil thick alumina substrate. No attempt was made to separate the mounting circuit parasitics from the diode so slightly different element values may be expected for a microstrip circuit of different thickness or dielectric properties.

It is possible that a different set of five element values would give similar calculated admittance values. However, this set is reasonably consistent with 1 MHz and dc measurements.
Ceramic Packages

Ceramic packages have been modelled\(^2\) as a three element T network (Figure 3) with element values determined by reactance measurements of open and shorted packages. The lead inductance, \(L_R\), varied from .09 nH for crossed mesh leads in a Ceramics International Minipak (12 mil ceramic ring height) to more than 1 nH for a single wire lead in a pill-prong package (66 mil ceramic ring height). Figure 3 shows the element values for crossed mesh leads in the pill-prong package.

An earlier analysis\(^3\) using similar techniques showed the need for a 5 element package model for frequencies above X-band. Figure 4 shows this model with the elements identified on a sketch of a typical diode package. The element values refer to a Metceram 54 package, similar to Hewlett-Packard outline 31, mounted in a 7 mm 50 ohm coaxial line. Notice that the lead inductance, \(L_2\), is less than the post inductance \(L_1\). In some packages the opposite may be true, depending on past height and diameter and the type of lead connection. Since this model includes the mount parasitics, the element values would change for different mounting circuits.

**Equivalent Circuit of the Mount**

The packaged diode model would have more general use if the mount parasitics were treated separately so that the diode model would be valid in any mount. This problem was analyzed by Getsinger\(^8\) for several types of transmission lines. Other authors have expanded the analysis for waveguide\(^9\) and coaxial lines.\(^6^7\) For example, when the mount circuit is separated, the model in Figure 4 becomes the more complicated model in Figure 5. That portion of the model labelled "package" is valid in a different mount if the rest of the model is properly adjusted.

**A Ceramic Packaged Mixer Diode**

Diode and package manufacturers usually simplify the package equivalent circuit to a shunt capacitance followed by a series inductance to the semiconductor chip. Since the parasitics of the mount will vary for different types of mounts, these published package parasitics can only be considered as approximate values.

The impedance of a ceramic packaged mixer diode, HP 5032-2701, was measured in a 7 mm 50 ohm line and 3 different models were derived. Input power level was adjusted to provide 1.5 mA of rectified current at each frequency.
The simplest model, with a 2 element package circuit, is shown in Figure 6. Figure 7 shows a more complicated package circuit from reference 3 with the same semiconductor model. Figure 8 shows the Monroe T network package also using the same semiconductor model.

Figure 6. Simple Model for 5082-2701 Mixer Diode

C p = .09 pF  
L p = .36 nH  
R s = 4 Ω

Figure 7. Owens-Cawsey Model for 5082-2701 Mixer Diode

C 1 = .012 pF  
C 2 = .058 pF  
L 1 = .12 nH  
L 2 = .22 nH  
C j = .357 pF  
R s = 4 Ω  
R j = 266 Ω

Figure 8. Monroe Model for 5082-2701 Mixer Diode

C p = .058 pF  
L 2 = .222 nH  
C j = .357 pF  
L p = .122 nH

Figure 9 shows the impedance of these three models compared to the measured impedance from 4 GHz to 12 GHz. In this frequency range, there is little improvement gained by using the more complicated model. Table I shows the maximum error in angle and magnitude of the reflection coefficient for each of the three models.

**TABLE I**

<table>
<thead>
<tr>
<th>Model</th>
<th>Magnitude</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td>0.04</td>
<td>3°</td>
</tr>
<tr>
<td>Monroe</td>
<td>0.03</td>
<td>3°</td>
</tr>
<tr>
<td>Owens-Cawsey</td>
<td>0.03</td>
<td>2°</td>
</tr>
</tbody>
</table>

Maximum error in reflection coefficient using the above models for the HP 5082-2701 mixer diode.
An extreme example of an equivalent circuit that bears no relation to the physical elements is shown in Figure 10. This model was derived by Walter Ku at Cornell University. It matches the measured impedance of the HP 5082-0610 diode quite well.

![Z1 = 2.8 Ω, r = 75.9 Ω, Z2 = 14.9 Ω, R = 2.1 Ω, Stub length = \( \frac{1}{6} \) at 10 GHz]

A more conventional equivalent circuit using 9 lumped elements has been developed for small* and large† signal IMPATT models. A technique‡ for measuring large signal impedance on a low level network analyzer requires the determination of the current for starting oscillation at each frequency of interest. Since the cavity impedance is fixed, the low level impedance at that current is also the large signal impedance at the operating bias current.

With these techniques for measurement and for semiconductor modelling combined with a four element equivalent circuit for the package and mount§, four double drift CW IMPATT diode types were measured and modelled.‖ The four diodes are 5082-0607, 5082-0608, 5082-0610, and 5082-0611.

The equivalent circuit for these diodes is shown in Figure 11. The element values are given in Table II. The optimization program matched the measured and calculated impedance values at intervals of one gigahertz over the frequency range indicated in the table. Maximum differences in magnitude and angle of reflection coefficient over these frequency intervals are also shown.

![Figure 11. Impatt Diode Equivalent Circuit]

**TABLE II**

<table>
<thead>
<tr>
<th>Diode</th>
<th>5082-</th>
<th>5082-</th>
<th>5082-</th>
<th>5082-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0607</td>
<td>0608</td>
<td>0610</td>
<td>0611</td>
</tr>
<tr>
<td>( L_1 ) nH</td>
<td>.36</td>
<td>.26</td>
<td>.26</td>
<td>.26</td>
</tr>
<tr>
<td>( C_p ) pF</td>
<td>.34</td>
<td>.55</td>
<td>.55</td>
<td>.55</td>
</tr>
<tr>
<td>( L_2 ) nH</td>
<td>.15</td>
<td>.15</td>
<td>.15</td>
<td>.15</td>
</tr>
<tr>
<td>( C_M ) pF</td>
<td>.05</td>
<td>.05</td>
<td>.05</td>
<td>.05</td>
</tr>
<tr>
<td>Sm. sig. ( R_3 ) Ω</td>
<td>24.4</td>
<td>11.2</td>
<td>19.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Lg. sig. ( R_3 ) Ω</td>
<td>10.7</td>
<td>7.9</td>
<td>10.1</td>
<td>4.9</td>
</tr>
<tr>
<td>( L ) nH</td>
<td>4.1</td>
<td>1.94</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>( R_1 ) Ω</td>
<td>4.7</td>
<td>10.0</td>
<td>9.9</td>
<td>4.5</td>
</tr>
<tr>
<td>( C ) pF</td>
<td>.35</td>
<td>1.0</td>
<td>.4</td>
<td>.8</td>
</tr>
<tr>
<td>Sm. sig. ( R_2 ) Ω</td>
<td>21.1</td>
<td>9.1</td>
<td>15.6</td>
<td>8.14</td>
</tr>
<tr>
<td>Lg. sig. ( R_2 ) Ω</td>
<td>8.1</td>
<td>6.1</td>
<td>8.4</td>
<td>3.92</td>
</tr>
<tr>
<td>( F_{\text{min GHz}} )</td>
<td>6.0</td>
<td>6.0*</td>
<td>9.0*</td>
<td>10.0</td>
</tr>
<tr>
<td>( F_{\text{max GHz}} )</td>
<td>10.0</td>
<td>9.0*</td>
<td>14.0</td>
<td>14.0**</td>
</tr>
<tr>
<td>Max ( \Delta</td>
<td>r</td>
<td>) sm.</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Max ( \Delta</td>
<td>r</td>
<td>) lg.</td>
<td>2°</td>
<td>2°</td>
</tr>
<tr>
<td>Max ( \Delta</td>
<td>r</td>
<td>) lg.</td>
<td>3°</td>
<td>3°</td>
</tr>
</tbody>
</table>

* Large signal model is valid from 5 GHz to 10 GHz
** Small signal model is valid to 15 GHz

Although Gupta§ showed that only \( R_1 \) and \( L \) need be related to power level, this work was unsuccessful in showing this relationship. Instead \( R_2 \) and \( R_3 \) were the only elements which differed from small signal to large signal models.

The four element "package" model in Figure 11 includes the test circuit diode mount. An equivalent circuit for the mount (APC-7 coaxial line) was calculated and the model was modified to separate the mount, package, and chip. The chip elements were unchanged. A two element package as in Figure 6 was not successful in duplicating the measured small signal impedance of the HP 5082-0610 diode at the highest frequency. However, when a T-section (Figure 3) is used, this model is just as successful as the model in Figure 11. Maximum difference between measured and calculated reflection coefficient is less than 0.01 in magnitude and less than one degree in angle.

The two models are compared in Figure 12. The calculated impedance is compared to the measured impedance in Figure 13.
CONCLUSION

Computer aided techniques which have proven useful for passive semiconductor devices may also be applied to IMPATT diodes. Although the model elements bear no relation to physical parts of the semiconductor, the calculated model impedance closely matches the measured impedance over a broad frequency range.

REFERENCES

1. Compact Engineering, Inc. 1088 Valley View Ct. Los Altos, CA


