IMPEDANCE MEASUREMENT OF MILLIMETER-WAVE IMPATT DIODES

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ABSTRACT

Impedance measurement for characterizing a millimeter-wave IMPATT diode mounted in a waveguide is described. Passive parameters and active impedances of Si SDR IMPATT diodes, measured under various conditions, are presented.

Introduction

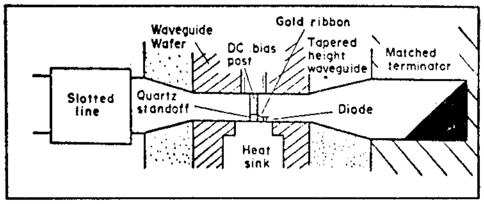
In order to evaluate the quality of a diode and to design a suitable circuit for it, the diode must be characterized in terms of an equivalent circuit.
In this paper, impedance measurement for characterizing millimeter-wave (mm-wave) IMPATT diodes is described. Many techniques for characterizing a diode mounted in a waveguide have been published. They fall into two broad categories of basic techniques : the transmission loss measurement technique[1] and the relative impedance measurement technique.[2,3] A kind of relative impedance measurement technique, i.e., the matched terminator method, was adopted for the present measurement. The main difference in the matched terminator method from the usual relative impedance measurement techniques is in the waveguide termination of the diode mount. In the former, a matched terminator is used as the waveguide terminator behind the diode, while a movable short is used in the latter. The matched terminator method was thought very suitable for measurement of mm-wave IMPATT diodes, for the following reasons.

1) Impedance measurements can be made at any frequency and any input power level.
   In the transmission loss measurement technique, measurements can be made only at the series-resonant frequency of the diode, and at small input power.
2) The effect of the lossy movable short on measured values can be eliminated.
   The movable short, which is used in the usual relative impedance measurement techniques, has considerable circuit loss in mm-wave frequency range. In order to cancel out the effect of a such lossy network, fairly complex techniques, such as methods with additional low-frequency measurement,[4] and a computer-aided curve-fitting method,[5] must be used.
3) Measurements can be made stably in fairly wider frequency and input power ranges.
   The IMPATT diode under the measurement is heavily loaded by the matched terminator. Therefore, the diode can scarcely oscillate, and the negative conductance of the diode can be measured stably.

In the following sections, first, the measurement method, and then its application to impedance measurements of mm-wave Si SDR IMPATT diodes, are described.

Measurement Method

Depicted in Fig.1 is the waveguide-mounted diode circuit used for the measurement and its equivalent circuit. The diode is embedded in a reduced height waveguide wafer. Matching to a regular height waveguide is accomplished by a pair of tapered height waveguide sections. A matched terminator is also provided in the regular height waveguide section behind the diode. The electrical distance from the diode plane to the probe in the slotted-line section is represented by θ, and the characteristic impedance of the reduced



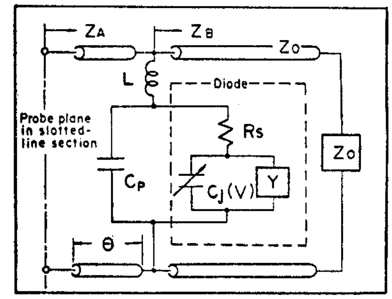


Fig.1. Experimental test circuit and its equivalent circuit.

height waveguide section is denoted by Z_o. The IMPATT diode structure may be characterized by an equivalent circuit consisting of an active admittance of avalanche and drift regions ($Y = G + jB$), and passive parameters, i.e., a series resistance (R_s), a junction capacitance (C_j), an inductance of the bias post (L), and a parasitic capacitance (C_p), as shown in Fig.1.

First, in order to measure the passive parameters, the diode is reversely biased below breakdown voltage. In this condition, active admittance Y is zero, and impedance at the diode plane (Z_B) is then given by

$$Z_B = \frac{Z_o Z_d}{Z_o + Z_d} \tag{1}$$

$$Z_d = j\omega L + \frac{1}{j\omega C_p + 1 / (R_s + 1 / j\omega C_j)} \tag{2}$$

$$C_j = C_{jo} (1 + V / \phi)^{1/2} \tag{3}$$

where V is the reverse bias voltage, C_{jo} is the zero-bias capacitance, and ϕ is the built-in voltage (assumed to be 1 V in this measurement).
As the bias voltage V is varied, it is shown from equations (1) - (3) that the locus of Z_B lies on a circle on the Smith Chart, if R_s is constant. When $R_s \omega C_p \ll 1$, then the circle center is on the real axis of the chart, and the circle passes through the chart center. Consequently, when impedances Z_A (see Fig. 1), measured by the slotted-line, are plotted on a Smith Chart, impedances Z_B can be obtained by rotating the circle of the Z_A locus around the chart center so as to place the circle center on the chart real axis, as shown in Fig. 2. Therefore, by measuring impedances Z_A at each of three bias voltages or more, we can obtain the passive parameters : R_s, C_j, L, and C_p, with the aid of equations (1) - (3).

Next, impedances for the IMPATT diode biased into

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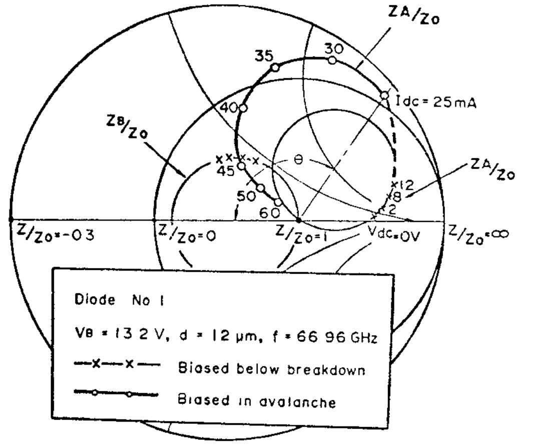

Fig.2. Typical example of measured impedance loci.

avalanche are measured. By the below-breakdown measurement, electrical length θ and passive parameters has been evaluated. Therefore, from impedance Z_A measured in avalanche condition, an active admittance Y = G + jB can be calculated by using equations (1) - (3). It is evident that admittance Y can be measured at any bias, input power and frequency conditions by using this measurement method. Examples of measured impedances Z_A in avalanche, as a function of bias current, are shown in Fig.2 with a heavy solid line curve.

MM-Wave IMPATT Diode Measurement

Passive parameters and active admittances of three Si SDR IMPATT diodes were measured. Two of them (diode No.1 and No.2) were made from the same diode wafer. They had a breakdown voltage (V_B) of 13.2 V, and their junction diameters (d) were 12 μm (diode No.1) and 9 μm (diode No.2). The other diode (diode No.3) had a breakdown voltage of 9.6 V, and a junction diameter of 9 μm. Impedance measurements were made at 64.96 GHz, 78.97 GHz and 86.05 GHz.

In Table 1, measured passive parameters of the diodes obtained by the below-breakdown measurements are summarized. Theoretical values calculated from diode sizes and electrical properties are also described in the table. They show fairly good agreement with the measured values at any frequencies.

Table 1. Measured and calculated passive parameters.

Diode	Parameter	Measurement Frequency (GHz)			Calculated Value
		86.05 *	78.97	64.96 **	
No.1 d=12μm VB=13.2 V	Lp (nH)	0.2	0.2	0.2	0.1
	Rs (Ω)	5	7	7	9
	Cp (pF)	0.01	0.01	0.01	0.01
	Cj (VB)(pF)	0.04	0.04	0.04	0.03
No.2 d=9μm VB=13.2 V	Lp (nH)	0.2	0.2	0.2	0.1
	Rs (Ω)	35	12.5	18	16
	Cp (pF)	0.01	0.015	0.01	0.01
	Cj (VB)(pF)	0.03	0.03	0.03	0.02
No.3 d=9μm VB=9.6 V	Lp (nH)	0.2	0.2	0.2	0.1
	Rs (Ω)	18	18	16	16
	Cp (pF)	0.02	0.01	0.01	0.01
	Cj (VB)(pF)	0.04	0.03	0.03	0.02

* Diode No.3 was measured at 84.65 GHz

** Diode No.1 was measured at 66.96 GHz

Active admittances of the diode, i.e., diode admittances exclusive of R_S and C_j, as shown in Fig.1 with the symbol Y, were measured as a function of frequency, bias current and input mm-wave power level, as follows.

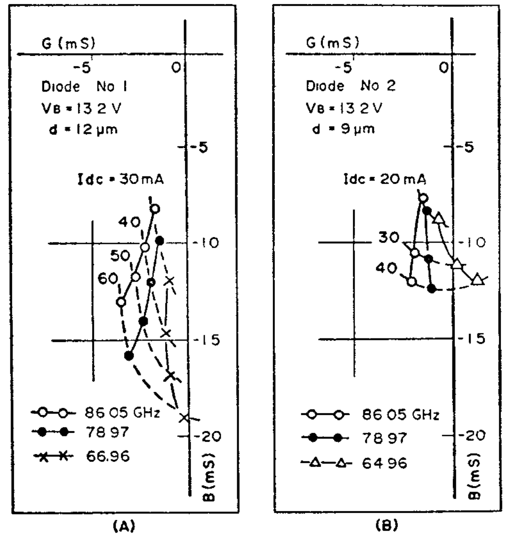

Fig.3. Active admittances measured at a small mm-wave input power. (An active admittance Y is the diode admittance exclusive of R_S and C_j, as shown in Fig.1.)

Fig.3 shows the measured active admittances when the input mm-wave power is very low. They are marked on admittance planes as a function of frequency and DC bias current. It is shown that the negative conductances of these diodes increase with frequency. In order to clarify the active admittance variation, the active admittances of diode No.2 are rewritten as a function of bias current in Fig.4.

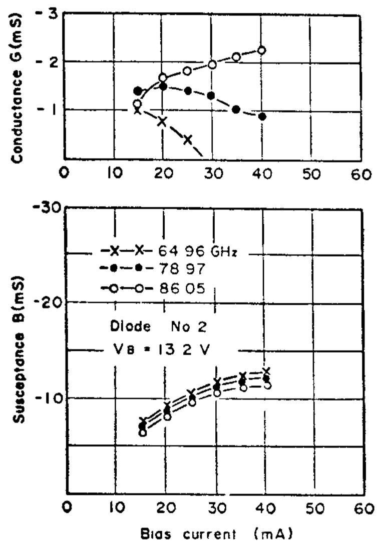

Fig.4. Active admittance Y = G + jB as a function of bias current. (Diode No.2)

Measured active admittances of diode No.3 are shown in Fig.5. They are also shown in Fig.6 as a function of bias current. Diodes No.2 and No.3 had about the same parameters, except for breakdown voltage, as shown in Table 1. Therefore, by comparing Fig.4 with Fig.6, it is made clear that the active susceptance and its dependence on bias current are strongly affected by breakdown voltage. This is consistent with the fact that the tuning range of a bias-current-tuned IMPATT oscillator is severely affected by diode breakdown voltage.[6]

Fig.7 shows measured active admittances of diode No.1 as a function of mm-wave voltage applied to the

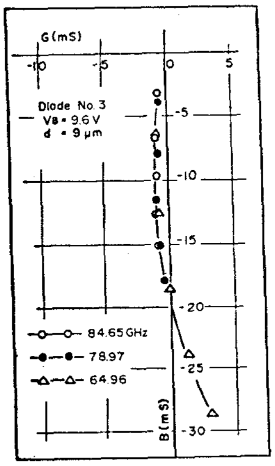

Fig.5. Active admittance of diode No.3 measured at a small mm-wave input power.

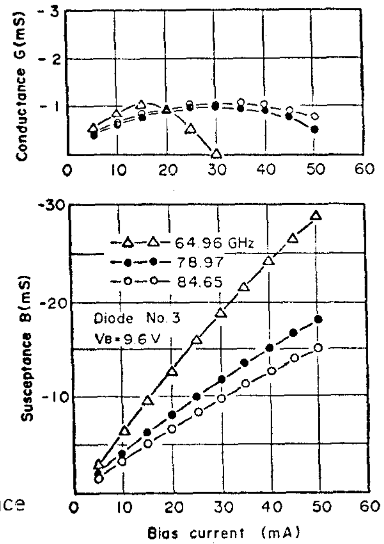

Fig.6. Active admittance Y = G + jB as a function of bias current. (Diode No.3)

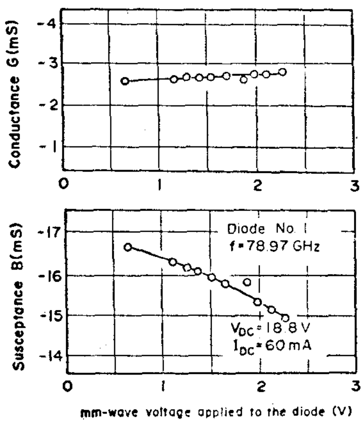

Fig.7. Active admittance Y = G + jB as a function of mm-wave voltage applied to the diode.

diode (V_{mm}), which was calculated from measured mm-wave input power (P_{in}) by using the following equation :

$$|V_{mm}|^2 = \frac{|Z_d - j\omega L|^2}{|Z_d|^2 + \mathcal{Re}(Z_d)\cdot Z_0}(1 - |\Gamma_B|^2)\, Z_0 \cdot P_{in} \quad (4)$$

where

$$\Gamma_B = \frac{Z_B - Z_0}{Z_B + Z_0} . \quad (5)$$

As shown in Fig.7, in so far as the measurement was made, no decrease in active conductance, caused by an increase in mm-wave voltage, could be observed.

Fig.8 shows the effect of the junction diameter on the active admittance. In this measurement, first, the admittance of a diode with 15 μm diameter was measured, and then, after the diameter was converged to 9 μm by chemical etching, the admittance was measured again. From Fig.8, it is found that the active admittance is almost in proportion to the square of junction diameter.

Conclusion

Impedance measurement of mm-wave IMPATT diodes by means of the matched terminator method has been described. By using this measurement result, improvements can be achieved in the evaluation of IMPATT diodes and the design of diode circuits in the mm-wave frequency range. The matched terminator method can also be applied readily to the measurement of other types of mm-wave semiconductor devices, such as varactors and mixer diodes.

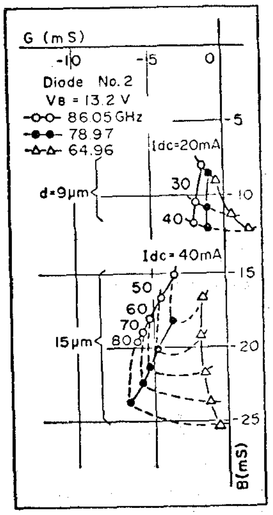

Fig.8. Dependence of active admittance on junction diameter.

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