Short Papers

Characterization of Resonant Tunneling Diodes for Microwave and Millimeter-Wave Detection

I. Mehdi, J. R. East, and G. I. Haddad

***Abstract*—The purpose of this short paper is to report on the direct detection capabilities of resonant tunneling diodes in the 10–100 GHz range. An open circuit voltage sensitivity of 1750 mV/mW (in Ka-Band) is measured which is higher than the sensitivity of comparatively biased commercially available solid state detectors. However, the detector properties are a strong function of diode bias and the measured tangential signal sensitivity (−32 dBm at Ka-Band with 1 MHz bandwidth) and the dynamic range (25 dB) of the diode are smaller compared to other solid state detectors.**

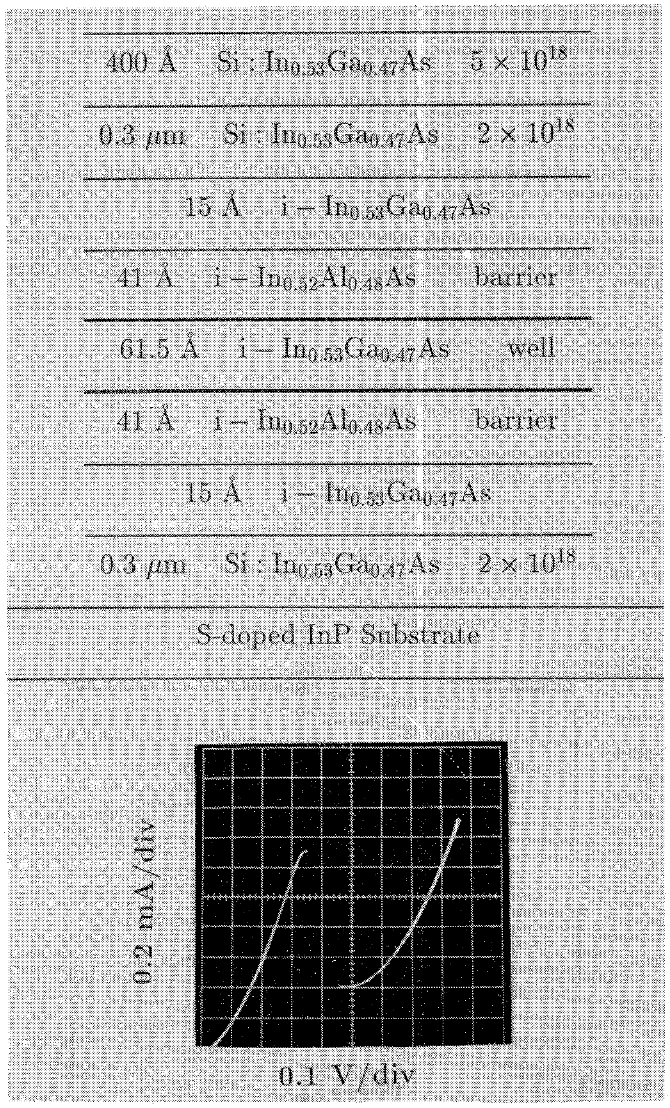
I. Introduction

In microwave detection, solid-state devices are used as nonlinear elements to accomplish direct rectification of an applied RF signal. Tunnel diodes, back diodes, point-contact diodes, and Schottky barrier diodes are some of the devices that have been used as video detectors. Qualitative and quantitative reviews of various devices as detectors can be found in literature [1]–[3]. The Schottky barrier diodes are the most commonly used detectors at present. This paper will present information on the video detector performance of resonant tunneling diodes (RTD's). A brief summary of considerations for resonant tunneling diode video detectors is given in the next section. Detector performance between 10 and 100 GHz is summarized in the following section.

II. Considerations for Device and Circuit Design

Two groups of RTD's were evaluated for video detector performance. The devices are InGaAs based structures grown on InP substrates. The devices are fabricated by depositing ohmic contacts and heat sinks on the epitaxial side of the wafer, removing the InP substrate by selective etching, depositing a second ohmic contact on the exposed substrate side and forming mesa diodes by reactive ion etching. The final structure is a honeycomb configuration with diodes 4 μm in diameter. The diodes are contacted via a whisker in a waveguide mount and in order to improve the whisker contact the diode chip is coated with polyimide and reactive ion etching is used to etch holes in the polyimide. The doping and material information for the two structures and the corresponding experimental current versus voltage characteristics are shown in Fig. 1. A potential problem in devices with dc negative resistance is that the device and circuit combination can be unstable. An approximate equivalent circuit for a RTD inside the waveguide test cavity is shown in Fig. 2. The equivalent circuit consists of the barrier region negative resistance (R_d) and capacitance (C_d), a series parasitic resistance (R_s) and an inductance (L_s) to couple energy into and out of the waveguide. This inductance is approximately the post inductance in the waveguide. The stability conditions of various combination of circuit elements have been studied previously [4] and it has been shown that the device will be stable if

$$\frac{L_s}{C_d R_d^2} < \frac{R_s}{R_d} < 1. \tag{1}$$



(a)

Fig. 1. Measured current-voltage characteristics and device structures of (a) diode A, (b) diode B.

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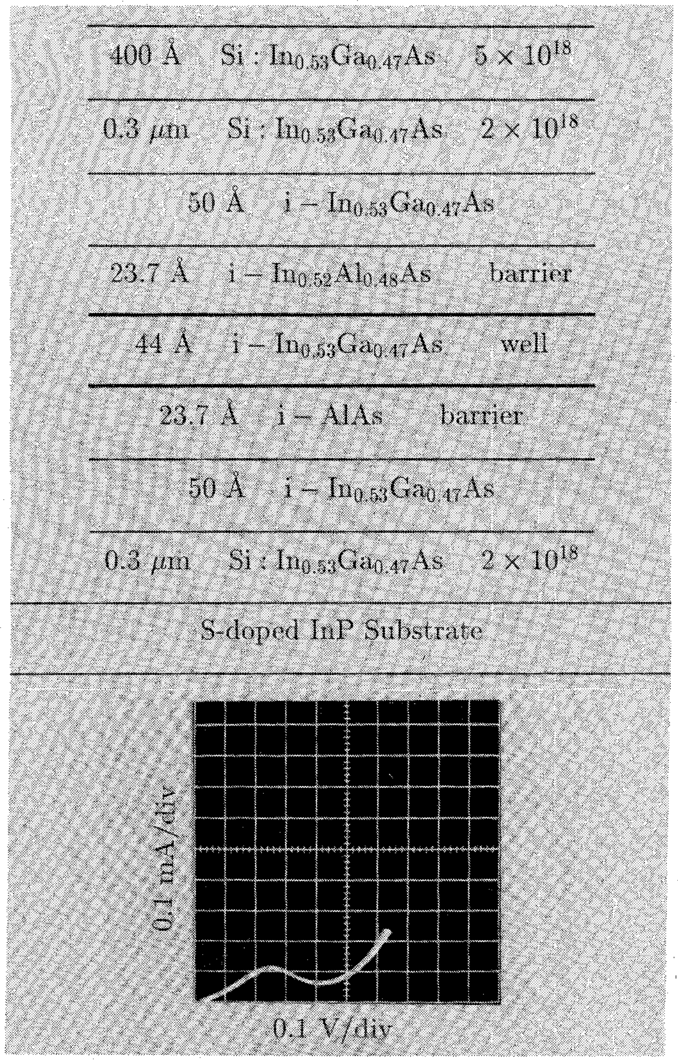


(b)

Fig. 1. Continued

Two devices, diode A Fig. 1(a) and diode B Fig. 1(b), are studied. The inductance associated with the whisker contact is 0.2 nH and since the two diodes were processed with the same technology their R_s is similar. Assuming that R_d and C_d of the devices are designable the stability criteria becomes

$$L_s < R_d^2 C_d \tag{2}$$

which further reduces to

$$L_s < \frac{(\Delta V)^2}{(\Delta I)^2} C_d \tag{3}$$

if one assumes that the NDR region is linear. If one further assumes that the device capacitance can be approximated with a parallel plate model both devices have approximately 0.8 fF of capacitance. Thus, one can see that in order to design a device that does not oscillate with the bias circuit either the separation between the peak and valley voltages has to be increased or the device current has to be reduced. The latter design criteria was used to design diode B and as can be seen from Fig. 1(b) the device is not oscillating. A complete discussion of device stability along with the effect of various device parameters on device stability has been presented elsewhere [4], [5]. The effect of parasitic elements on the detection properties of a nonlinear device is detrimental and has been established previously [3]. The detrimental effect becomes stronger as the operating frequency increases and thus the device and microwave circuit that are used must have low series resistance, low series inductance and low device capacitance.

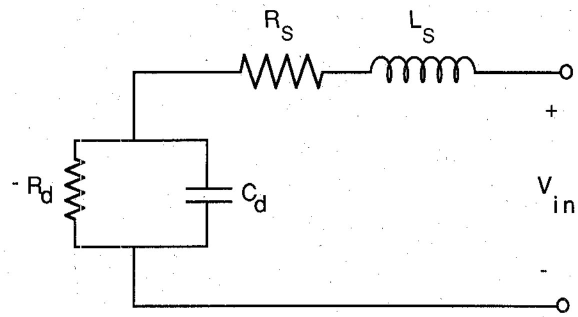


Fig. 2. Equivalent circuit for a resonant tunneling diode.

III. Experimental Results

In this study we have characterized the RTD by measuring open circuit voltage sensitivity, tangential signal sensitivity, dynamic range, and video resistance which are all commonly used criteria to determine the performance of a detector diode [1].

A. Open Circuit Voltage Sensitivity

The video output voltage for an available microwave input power P_{av} can be written as

$$V_o = \beta_v (R_L / R_V + R_L) P_{av}, \tag{4}$$

where R_L, R_V is the load and video resistance and

$$\beta_v = (1/2) \frac{f''(v_o)}{[f'(v_o)]^2} \tag{5}$$

is defined as the open circuit voltage sensitivity in mV/mW. $f'(v_o), f''(v_o)$ refer to the first and second derivative of the I-V at the bias voltage v_o. β_v for diode A as a function of frequency in the Ka band is shown in Fig. 3(a) for different bias points using an available power level of -20 dBm. The sensitivity reaches a maximum value of 1750 mV/mW when the diode is biased at 0.37 V which corresponds to the diode peak-current voltage. This is because at this point the diode presents the maximum curvature in it's I-V characteristic. Increasing the diode voltage beyond this causes the diode to switch and it is found that at the valley point (0.55 V) the value of β_v is greatly reduced. The diode open circuit voltage sensitivity as a function of bias is shown in Fig. 3(b) for an operating frequency of 33 GHz. With an available power level of -10 dBm it is found that diode A switches when biased at 0.23 V.

The open circuit voltage sensitivity of diode B was measured with an input power level of -5 dBm, Fig. 3(b). Measurements at lower input power levels were not successful because of the low detection capabilities of diode B. It should be noted that the I-V characteristic of this device shows two NDR regions and thus the increase in the open circuit voltage sensitivity at higher voltages is due to the fact that the diode is approaching the second NDR region. However, it was not possible to stably bias this diode in its second NDR region. β_v is related to both the curvature and the slope of the I-V characteristic and since the double barrier structure allows for the flexibility of designing the I-V characteristic the measurements presented here are not

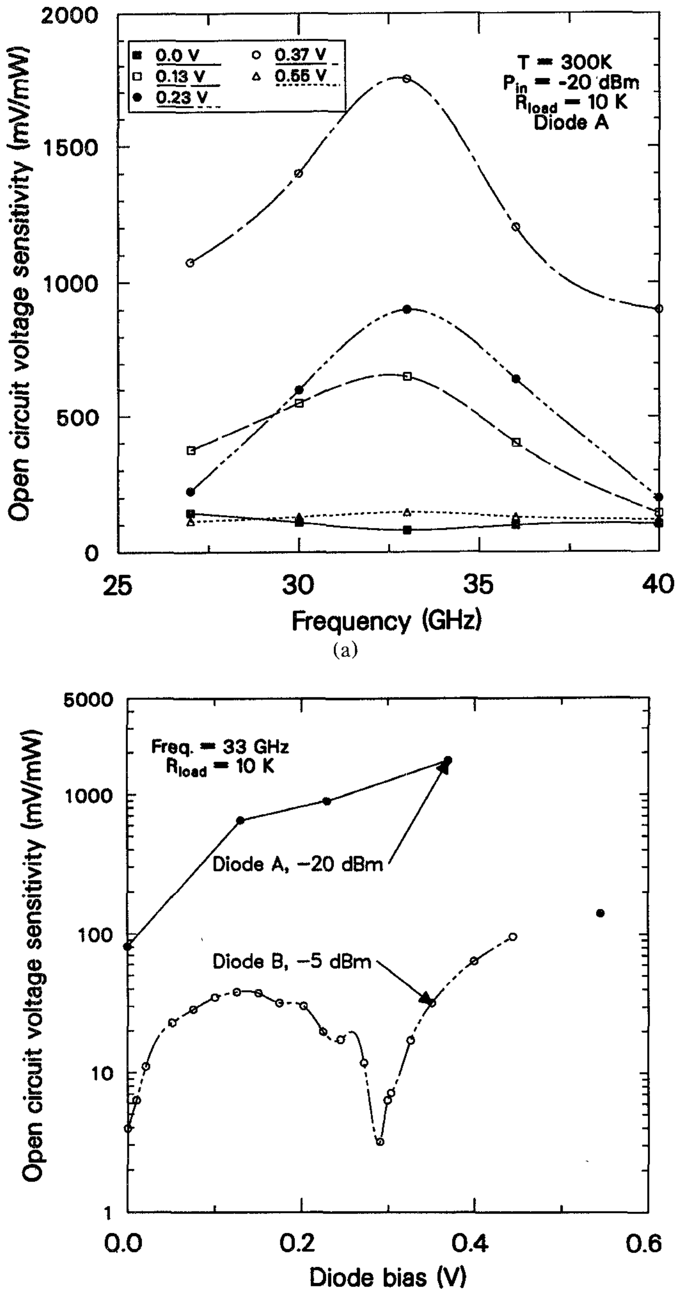


Fig. 3. (a) Open circuit voltage sensitivity of diode A as a function of frequency for various bias points. (b) Open circuit voltage sensitivity of diode A and diode B at 33 GHz.

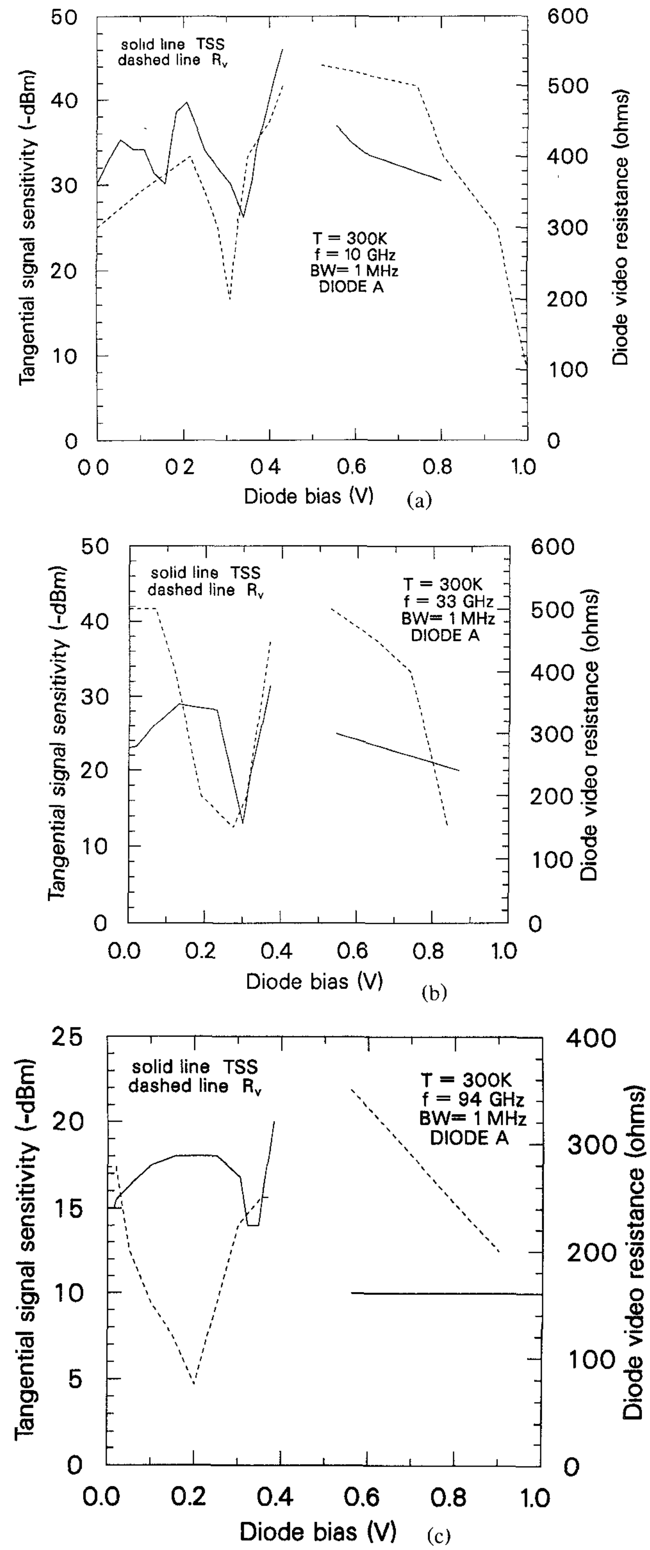
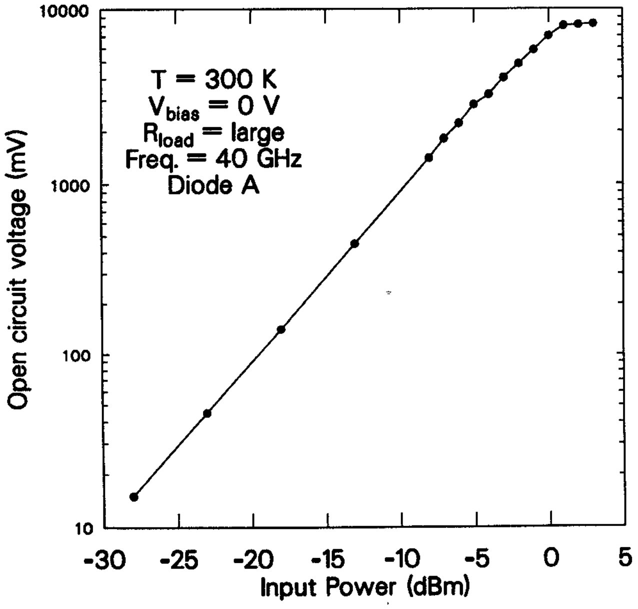


Fig. 4. TSS and video resistance of diode A as a function of bias (a) at 10 GHz; (b) at 33 GHz; and (c) at 94 GHz. Note the scale change in (c).

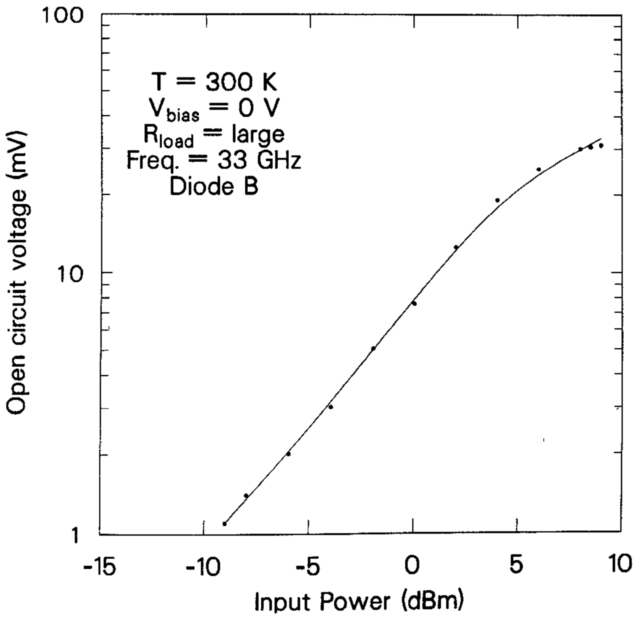
indicative of all RTD's. By designing the device so that the ground quasi-bound state is fairly close to the cathode layer Fermi level a large nonlinearity in the I-V characteristic around zero bias can be produced.

B. Tangential Signal Sensitivity and Video Resistance

The tangential signal sensitivity (TSS) measurement is carried out with a 1 kHz square wave modulated signal whose level is adjusted such that the highest noise peaks observed on an oscilloscope in the absence of signal are at the same level as the lowest noise peaks in the presence of a signal. The measured data for Diode A at 10 GHz, 33 GHz, and 94 GHz is shown in Fig. 4(a)–(c) respectively. The amplifier video bandwidth for all measurements was 1 MHz. At each frequency the E-H tuner was adjusted to provide the best matching between the source and the diode. The effect of bias on TSS and R_v is quite dramatic. The TSS increases at small bias levels, due to the nonlinearity of the I-V, but decreases rapidly in the region where the I-V is basically linear. The TSS becomes a maximum just before the NDR region. Just before reaching the peak



(a)



(b)

Fig. 5. (a) Diode A output voltage as a function of input signal power at 40 GHz. (b) Diode B output voltage as a function of input signal power at 33 GHz.

current value the output signal switches polarity, and thus the maximum measured TSS is measured for a signal that is opposite in phase to the signal obtained at zero bias or at bias voltages away from the negative differential resistance region. This can be understood from the fact that as the sign of $f''(v_o)$ changes the output video signal will also change polarities. It was also observed that the TSS is worse at the valley of the I-V curve compared to at the peak. Since the origin or nature of excess current in RTD's is not well understood at this time it is not clear why the valley point is noisier than the peak current point.

Assuming that TSS falls off as the square root of the bandwidth it is seen that our results in Ka-band are significantly better than the results reported in [6] at X-band. This improvement can be attributed to our device performance and experimental setup. The TSS of the stable diode (diode B) was also measured at 33 GHz. The diode did not switch in the NDR region. The trend observed however is similar to the measurement in the unstable diode. The maximum TSS occurs when the diode is biased at the peak current point.

TABLE 1
PERFORMANCE COMPARISON OF RESONANT TUNNELING DIODES WITH SOME COMMERCIALLY AVAILABLE DIODES FOR VIDEO DETECTION APPLICATIONS

Performance Criteria	β_v (mV/mW)	TSS (−dBm)	R_v (Ω)	Dynamic Range (dB)
Point Contact				
1–100 GHz	400	35	3 K–15 K	50
Schottky				
1–18 GHz	1000	55	200–400	60
18–40 GHz	1000+	50	200–400	55
zero bias				
1–40 GHz		56	2 K–15 K	
Backward				
1–18 GHz	700	50	50–150	45
RTD				
X-Band	1900	46	500	39
Ka-Band	1750	32	450	25
W-Band		20	250	
zero bias				
X-Band		30	300	34
Ka-Band	100	27	500	28
W-Band		15	300	

C. Dynamic Range

Dynamic range is defined as the range in dB of the microwave power level from the TSS power point to the level at which the detector output is reduced by 1 dBm from square-law performance. The output voltage as a function of input power at 40 GHz is shown in Fig. 5(a) for diode A. At 40 GHz and no bias the dynamic range is found to be 28 dB. When the diode is biased at the peak voltage point the dynamic range decreases to 25 dB. For diode B at 33 GHz with no bias the dynamic range is 17 dB, Fig. 5(b). With zero bias the diode can handle more input power as compared to when the diode is biased at the peak current point because at the peak current point the diode can switch. However, the loss in the dynamic range is not considerable because the diode is more sensitive when biased at the peak current position.

Table I presents a comparison between the RTD and some other commercially available detector diodes. The performance data for the other devices have been obtained from [7, p. 347]. The data for the zero biased Schottky diode was obtained from M/A COM, Inc. It can be noted that the RTD is not found to be superior to other devices in all respects but it does offer improved performance in some areas.

IV. CONCLUSION

The potential of the resonant tunneling diode as a detector for the microwave and millimeter-wave region has been demonstrated. A fabrication scheme which removes the substrate from the device was used to fabricate diodes which were characterized up to 100 GHz. Even though the responsivity of the diode is superior to other commercially available solid state devices the resonant tunneling diodes that were tested did not have a superior TSS compared to Schottky diodes. Moreover, the diode detection mechanism is strongly dependent on diode bias and in order to use the diode in a regenerative mode the diode will have to be biased stably in the negative resistance region. The application of the diode in doppler systems is also limited because of the noise associated with the device. The origin or characteristics of this noise are not understood presently but may be related to low frequency bias circuit oscillations.

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A Technique for Correction of Parasitic Capacitance on Microwave f_t Measurements of MESFET and HEMT Devices

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***Abstract*—The current gain cutoff frequency, f_t, has become a critical figure-of-merit for evaluating performance of MESFET and HEMT devices. The f_t is related to a capacitance parameter, C_{tot}, through the equation $f_t = \mathrm{Gm}/(2\pi C_{tot})$. This capacitance, however, includes a parasitic component primarily due to contact pad and device geometry as well as a parasitic component due to Rd, Rs and Rds. This paper describes a technique which determines this parasitic capacitance for FET-type devices. Consistently accurate corrections can then be made to reported f_t values. Ion implanted InGaAs MESFET's with 0.25 μ gate lengths have achieved 120 GHz f_t before correction and 151 GHz f_t after correction.**

I. Introduction

The accuracy of microwave f_t measurements has become an important issue since this parameter is widely used as a figure-of-merit for speed and frequency evaluation of MESFET and HEMT devices. Currently, microwave devices are characterized on-wafer from 45 MHz to 26.5 GHz using Cascade RF probes and Cascade calibration standards on quartz substrates. The current gain, $|H_{21}|$, of the device is calculated from measured S-parameters and f_t is determined by extrapolating $|H_{21}|$ using a slope of -6 dB/octave down to the unity current gain point. Fundamentally after calibration, f_t should be independent of device gate width and only scale with gate length.

However, in a recent work [1], the $|H_{21}|$ vs. frequency plot shows a dependence on gate width. In addition, the ratio of f_t for 0.1 micron gate device to that of a 0.2 μ gate device should approach 2 rather than 1.1 as the work indicates. These discrepancies can be attributed to inaccurate calibration and parasitic capacitance corrections.

In this work, we show that the f_t dependence on gate width is mainly due to the parasitic capacitance associated with the pad layout of the device. An accurate technique is then presented for determination of the parasitic capacitance of MESFET and HEMT devices.

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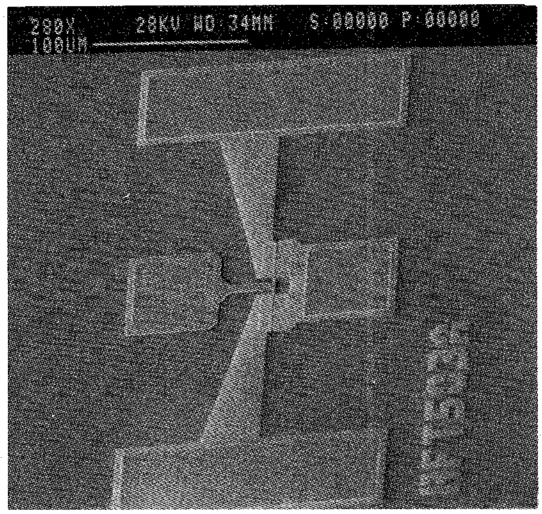

Fig. 1. A typical 0.25 × 50 micron cascade probed MESFET.

TABLE I
AVERAGE VALUE AND STANDARD DEVIATION OF f_t AND C_{total} AT $V_{ds} = 3$ V

Gate Width	Gm (mS/mm)		ft (GHz)		C_{total}(pf)	
	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.
50 μ	458	21	82.9	1.9	0.044	0.001
100 μ	440	14	97.2	4.2	0.072	0.002
150 μ	437	14	104.2	4.6	0.100	0.003
200 μ	428	16	107.8	1.8	0.126	0.003

II. Experimental Cascade f_t Data

The ion implanted InGaAs MESFET's used in this work have 0.25 μ long "T" shaped gates with total gate widths of 200, 150, 100, and 50 μ. The device pad layout is the same for all gate width variations and a typical device (50 μ gate width) is shown in Fig. 1. Over 15 devices of each gate width are used to determine the average f_t value at $V_{ds} = 3.0$ V and its standard deviation as listed in Table I.

