wave monolithic integrated circuit techniques involving field-effect transistors and related devices.

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X-Band Burnout Characteristics of GaAs MESFET's

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Abstract **— *X*-band μs pulse, ms pulse, and CW-burnout data have been measured for two commercially available 1-μm gate GaAs MESFET's. Values of incident pulse power required to cause burnout indicate a threshold level for pulse durations 0.2 μs or longer and for CW. The incident power threshold level for burnout is in the range 3 to 6 W for the MESFET type with a Ti/Pt/Au gate metallization and in the range 1.5 to 3 W for the MESFET type with an Al gate metallization. Many MESFET's were observed to fail during a single pulse.**

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I. Introduction

LOW-NOISE gallium-arsenide (GaAs) metal-semiconductor field-effect transistors (MESFET's) have been developed for use as RF amplifier stages in microwave receivers. One important application for these RF amplifier stages will be in transmit–receive radar systems which share a common antenna. Transmit–receive radar systems usually have protection devices to limit the micro-

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wave power incident upon the GaAs MESFET. Since the protection devices cannot respond instantaneously, there is a short duration of time (1–10 ns) during which the protection device cannot limit the microwave power incident upon the GaAs MESFET. During this short duration of time, the MESFET may be burned out [1]–[4]. When limiting occurs (e.g., after 10 ns), there is still leakage of the order of 100 mW through the limiter which can cause GaAs MESFET degradation or burnout [3]. There are also some applications in which it may be desired to omit a limiter in order to reduce weight, cost, or the degradation in system noise figure caused by the limiter insertion loss which may be in the range 0.2 to 0.8 dB. The reliability of such radar systems will depend upon the burnout properties of the GaAs MESFET. Information on this subject is still rather sparse [1]–[4]. For this reason an experimental investigation has been carried out to obtain X-band μs pulse, ms pulse, and CW-burnout data for GaAs MESFET's. The investigation being reported upon is a continuation of an investigation initiated to obtain nanosecond pulse burnout data [2].

The paper is organized as follows. The GaAs MESFET's selected for the investigation are described in Section II. The X-band system used to overstress the MESFET's and the test procedures are described in Section III. The X-band pulse and CW-burnout results are given in Section IV. Typical SEM photographs of overstressed MESFET's are discussed in Section V. Section VI is the conclusion.

II. MESFET Selection

Two commercially available GaAs MESFET's with 1-μm gate lengths were tested. One has an Al gate metallization, and the other has a Ti/Pt/Au gate metallization. The GaAs MESFET dice were bonded using silver epoxy to 50-Ω microstrip circuits, and 0.7-mil gold bond wires were attached using thermocompression bonding techniques. Next, the dc characteristics and X-band S-parameters were measured. Then microwave matching networks which consisted of sections of low impedance line located close to the MESFET were used for input and output matching. Single-stage noise figures were in the 2.5–4.0-dB range with associated power gains in the 5–10-dB range at 9.35 GHz. Detailed information on the MESFET's tested is given in Table I.

III. Experimental Procedures

The X-band pulses used to overstress the GaAs MESFET's were generated using the system shown in Fig. 1. The CW source frequency was 9.3 GHz. The diode modulator was a low-power switch that was turned on by a pulse from the pulse generator. When the pulse generator output voltage returned to zero, the diode switch returned to its normal off position. The diode switch output was a pulse-amplitude-modulated X-band signal the envelope of which had a risetime and falltime of 2.0 ns. The diode switch output was amplified by a wide-band low-power solid-state X-band preamplifier and by a wide-band high-power TWT amplifier. The X-band pulse power P_I incident

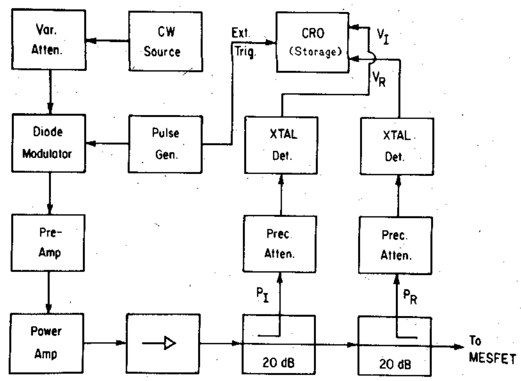

Fig. 1. X-band high-power pulse system. The pulse generator could be triggered for a single pulse or for a pulsetrain with duty factors up to 0.33. For CW experiments the diode modulator was removed and power meters were inserted to measure P_I and P_R.

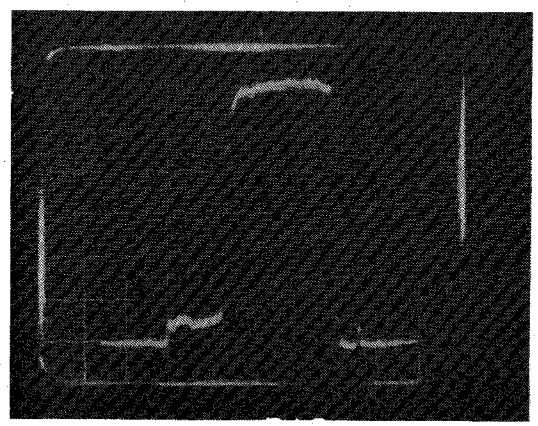

Fig. 2. Photograph of CRO trace corresponding to the rectified waveform of microwave pulse reflected from MESFET. The abrupt increase in amplitude of the reflected pulse indicates the time of failure. The pulse duration was 0.2 μs. The time of failure was 0.07 μs.

TABLE I
MESFET Physical Characteristics

Parameter		Type-A	Type-B	Type-C
Gate Metal		Ti/Cr/Pt/Au	Al	Al
Gate Pad		Ti/Cr/Pt/Au	Al	Ti/Pt/Au
Source-Drain (Ohmic Contact)		Au-Ge/Ni/Au	In/Ge/Au	Au-Ge/Pt
Source-Drain (Pad Overlay)		Ti/Cr/Pt/Au	None	Ti/Pt/Au
Gate Length		1 micron	1 micron	1 micron
Number of Gates		1	2	2
Total Gate Width		500 μm	300 μm	300 μm
Channel Length		3.5 μm	5 μm	3 μm
Glassivation (Over Channel)		Yes	No	Yes
Pinch-off Volt. (Nominal)		-3 V	-5 V	-4 V
I_{DSS}(Nominal)		80 mA	100 mA(max)	60 mA
Bias Conditions	I_D	15 mA	10 mA	10 mA
	V_{DS}	3.5 V	5 V	3 V

upon a MESFET and power P_R reflected by a MESFET were measured using directional couplers and wide-band crystal detectors as shown in Fig. 1. The waveforms of the rectified voltage pulses at the crystal detector output were displayed on storage oscilloscope(s). Shown in Fig. 2 is a photograph of a CRO trace corresponding to the crystal-detector rectified waveform of a single microwave pulse

TABLE II
TYPES OF X-BAND SIGNAL USED TO OVERSTRESS GaAs MESFET'S

Pulse Duration	Pulse Duty Factor (Duration ÷ Period)	Exposure: Number or time
0.2 μsec	Single Pulse - Repeated	10
	.000031, 00036, 0032 .036, 33	5 to 10 min.
5.0 μsec	Single Pulse - Repeated	10
	00028, .0031, 030, .30	5 to 10 min.
5 msec	Single Pulse - Repeated	10
	.077, .33	5 to 10 min.
CW		10 to 15 min.

TABLE III
TYPICAL SEQUENCE OF X-BAND INCIDENT POWER LEVELS USED TO OVERSTRESS GaAs MESFET'S

Incident Power			
dBm	W	dBm	W
20	0.10	33	2 0
23	0.20	34	2 5
26	0.40	35	3.2
28	0 63	36	4.0
30	1.00	37	5.0
32	1.58	38	6.3

reflected by a MESFET. The rectified voltage observed on the CRO was related to the microwave power incident upon the crystal detector via a calibration curve. The calibration curve was established by measuring for each crystal detector the dc-rectified voltage produced by a CW (sinusoidal) microwave signal. The information contained in the rectified voltage pulse waveforms was processed to obtain values for the pulse power P_I incident upon the MESFET, the pulse power P_R reflected by the MESFET, and the pulse energy E_A absorbed by the MESFET. For the CW experiments, power meters were also used to measure values for P_I and P_R. The values for P_I and P_R measured using power meters agreed within 0.5 dB with the values for P_I and P_R determined from the crystal detector rectified voltage waveforms.

After the GaAs MESFET noise figure and power gain were measured, it was exposed to one of the four types of X-band signal described in Table II. Initially, the incident pulse peak power was set at 0.1 W. (Occasionally, an initial level as low as 0.01 W was used.) If the GaAs MESFET was exposed to a pulse signal, it was first exposed to a single pulse. If the MESFET did not burnout, the single pulse was repeated. If 10 single pulses did not cause burnout, the GaAs MESFET was exposed to a pulsetrain with the lowest duty factor listed in Table II for several minutes. If burnout did not occur, the duty factor was increased to the next higher value given in Table II; then the GaAs MESFET was exposed to a pulsetrain with the higher duty factor for several minutes. If burnout did not occur, the procedure was continued until the highest duty factor listed in Table II was used. If the GaAs MESFET was exposed to a CW signal, the exposure time was typically 10 to 15 min. After exposure to an X-band signal with a 0.1-W power level, the GaAs MESFET noise figure and power gain at 9.35 GHz were measured again. If no significant change in noise figure occurred, the incident pulse power was increased and the test procedure was repeated. A typical sequence of incident power levels used in the experiment is given in Table III. The test procedure was repeated at increasing incident power levels until a significant reduction in MESFET noise figure was observed.

IV. X-BAND PULSE AND CW-BURNOUT RESULTS

The most significant observations will now be presented and discussed. One observation was that a gradual degradation in noise figure did not occur. Instead, the GaAs MESFET's failed catastrophically. A second observation was that for the types of signals listed in Table II, the only failure mode observed was a gate-to-source short-circuit which causes an abrupt increase in the dc gate and drain bias currents and an abrupt increase in the power reflected by the GaAs MESFET. Another observation is that the pulse duty factor did not affect the incident power level at which a GaAs MESFET failed. Several GaAs MESFET's that did not fail at an incident power level P_I when overstressed with an X-band pulsetrain with a high duty factor failed on a single pulse when the incident power P_I was increased to the next level listed in Table III (usually 1 or 2 dB higher). Many cases were observed in which failure was caused by a single pulse. Shown in Fig. 2 is a photograph which illustrates a single pulse failure in which failure occurred during the pulse. Failure during a microwave pulse was most clearly indicated by an abrupt increase in the power reflected by the MESFET [5]. The incident power levels at which GaAs MESFET failure occurred are plotted versus pulse duration in Fig. 3. The data plotted are for GaAs MESFET's that failed for all the types of signals listed in Table II. Also shown are nanosecond pulse burnout data reported previously [2]. The data in Fig. 3 suggest the existence of an incident power threshold level at pulse durations longer than 0.2 μs. The incident power threshold level is in the range 3 to 6 W for Type-A MESFET's which have a Ti/Pt/Au gate metallization, and in the range 1.5 to 3 W for Type-C MESFET's which have an Al gate metallization. Shown in Fig. 4 are values for the absorbed pulse energy E_A required to cause burnout versus pulse duration. Values for E_A were calculated using

$$E_A = (P_I - P_R) \times T_F \tag{1}$$

where T_F is the time to failure. If the MESFET failed during a single pulse, the value for T_F was determined from a photograph similar to that shown in Fig. 2. If the MESFET did not fail during a single pulse, the value used for T_F was the pulse duration. The data plotted in Fig. 4 correspond quite well to a relationship

$$E_A(J) = 2T_F(s) \tag{2}$$

for $1\ \mu\text{s} < T_F < 10$ ms.

As stated previously, pulse duty factor appears not to be a significant variable. Shown in Fig. 5 are values of the absorbed power ratio $(1 - P_R \div P_I)$ versus incident power P_I as a function of pulse duration and pulse duty factor for Type-A MESFET's. The data for Type-C MESFET's are

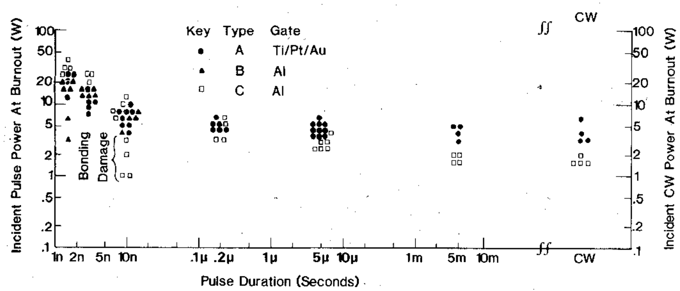

Fig. 3. Values of microwave incident power P_I required to cause burnout versus pulse duration T. Note that CW values are given at far right. The P_I values are believed to be accurate ± 0.5 dB.

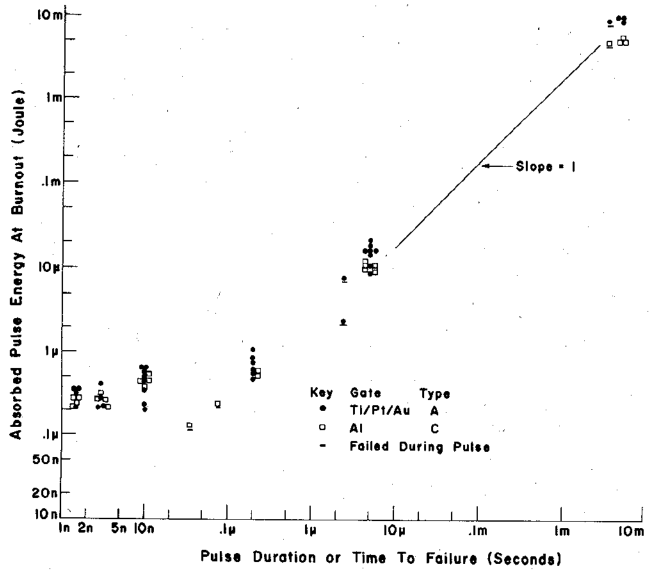

Fig. 4. Values of microwave absorbed pulse energy E_A required to cause burnout versus pulse duration T. Note that single pulse failures are indicated by underlining (_). The E_A values are believed to be accurate ± 1.0 dB.

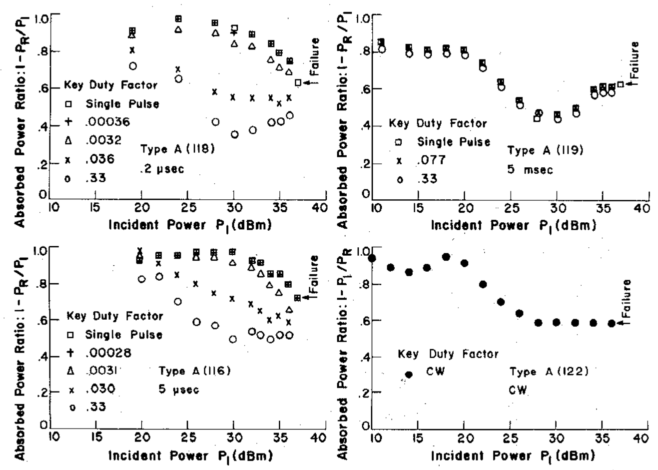

Fig. 5. Values of absorbed power ratio $(1 - P_R \div P_I)$ versus incident power P_I for different values of pulse duration and duty factor. The values shown are for Type-A MESFET's. The values for Type-C MESFET's have a similar pattern.

similar. Initially, the MESFET's were matched to the 50-Ω microstrip transmission line at a low power level (-20 dBm), and the absorbed power ratio was near 1. As the incident power level P_I is increased, rectification effects occur in the MESFET causing the dc gate current and dc drain current to change. At a constant P_I value, increasing the duty factor causes an increase in the rectified dc gate and drain current which can alter the fraction of the incident power absorbed. What is interesting is that the absorbed power ratio $(1 - P_R \div P_I)$ usually remains above 0.5. At P_I values above 35 dBm, the values for the absorbed power ratio seem to converge to a value of 0.6 ± 0.1 independent of pulse duty factor at pulse durations of 0.2 μs, 5 μs, and 5 ms and for CW signals. The results for Type-C MESFET's are similar. Thus it can be stated that both types of MESFET's absorb more than half the microwave incident power at P_I values near the burnout level for all the types of signals listed in Table II.

V. Characteristics of Overstressed MESFET's

Following burnout, each MESFET was examined with an optical microscope (OM) and many were examined with a scanning electron microscope (SEM). For the types of signals listed in Table II, the only type of failure observed was a metallic gate-to-source short-circuit. Type-C SEM photomicrographs will be discussed first. For a 0.2-μs pulse duration, the failure site was located either in the channel at a point close to the connection between the gate stripe and the metallization path that comes from the gate pad or at that connection point as shown in Fig. 6. For a 5-μs pulse duration, the failure site was always located at the connection between the gate stripe and the metallization path that comes from the gate pad. As shown in Fig. 7, the damage does extend a short distance along the gate stripe in the channel. However, the most severe damage is along the metallization path in the direction toward the gate pad. For 5-ms pulse durations and CW signals, this trend continued with the most severe damage being located along the gate metallization path crossing the edge of the GaAs epi-layer mesa as shown in Fig. 8. Shown in Figs. 9–11 are SEM photomicrographs for Type-A MESFET's overstressed with 0.2-μs, 5-μs, and 5-ms pulses. The size of the failure site and its location show a pattern similar to that shown in Figs. 6–8 for Type-C MESFET's. For both Type-A and Type-C MESFET's the size of the failure site increased as the pulse duration increased and was largest for CW overstressing. The explanation appears straightforward. The data shown in Fig. 4 indicate that the absorbed pulse energy increases linearly with pulse duration for pulse duration greater than 1.0 μs. Assuming that most of the absorbed pulse energy is confined to the failure site, then the size of the failure site should increase as the pulse duration increases because of the accompanying increase in absorbed pulse energy.

The existence of an incident power threshold level required to cause failure may indicate that avalanche breakdown is at the origin of the failure. The microwave signal applied to the gate electrode creates high potential gradients between the gate and source electrodes. At the incident power threshold level, the electric field may have been high enough to cause avalanche breakdown at some location between gate and source. The initial failure probably

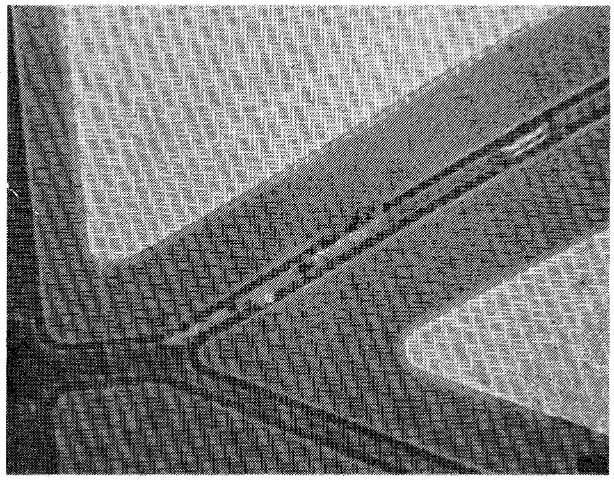

Fig. 6. SEM photomicrograph (2000×) of Type-C MESFET (#212) overstressed with a 3.2-W, 0.2-μs pulsetrain with a 0.001 duty factor. The damage area begins at the connection between the gate stripe and the metallization path that comes from the gate pad. The damage extends a short distance along the gate stripe in the channel.

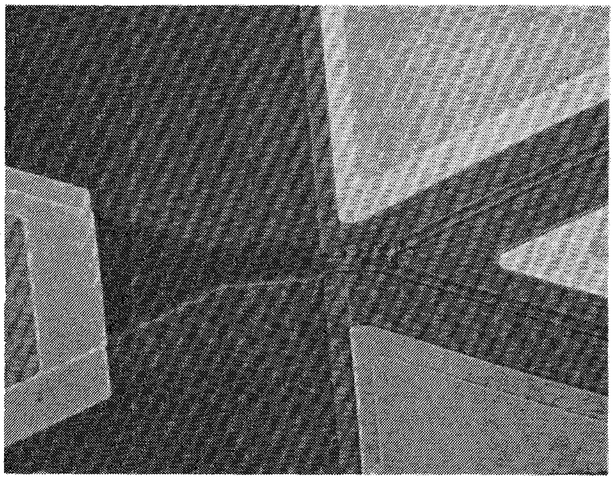

Fig. 7. SEM photomicrograph (1000×) of Type-C MESFET (#210) overstressed with a 3.2-W, 5-μs pulsetrain with a 0.0025 duty factor. The damage area occurs at the connection between gate stripe and the metallization that comes from the gate pad. The damage extends a short distance toward the edge of mesa where GaAs epi-layer has been removed and also a short distance along the gate stripe in the channel.

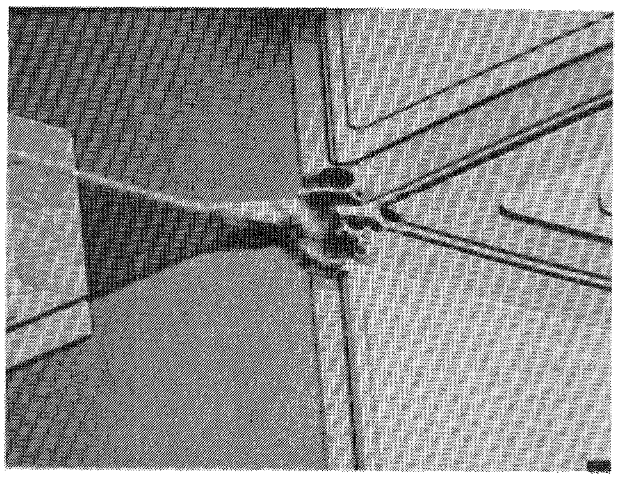

Fig. 8. SEM photomicrograph (1000×) of a Type-C MESFET (#231) overstressed with a 2.0-W, 5-ms pulsetrain with a 0.077 duty factor. The damage area seems centered at the point where the gate metallization crosses the edge of GaAs epi-layer mesa.

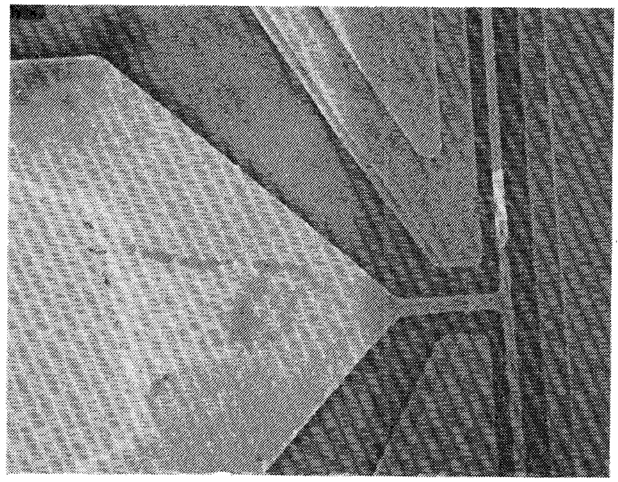

Fig. 9. SEM photomicrograph (1500×) of Type-A MESFET (#118) overstressed with a 5-W, 0.2-μs single pulse. The damage area is located in the channel at a point close to the connection between the gate stripe and the metallization path that comes from the gate pad.

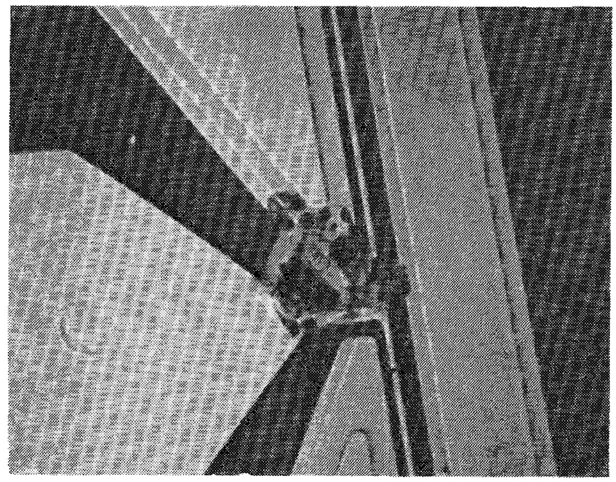

Fig. 10. SEM photomicrograph (1000×) of Type-A MESFET (#102) overstressed with a 5-W, 5-μs pulsetrain with a 0.0025 duty factor. The damage area extends over a large area that includes the entire metallization path from the gate pad to the gate stripe, the gate pad metallization, the source metallization, and the gate stripe.

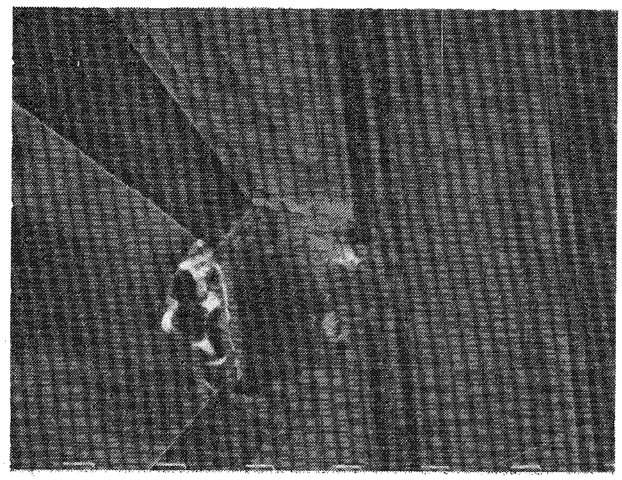

Fig. 11. SEM photomicrograph (1500×) of Type-A MESFET (#121) overstressed with a 3.2-W, 5-ms pulsetrain with a 0.077 duty factor. The damage location is similar to that described in Fig. 10, but the amount of damage is greater.

created a low resistance path in the GaAs material [6]. The resulting high current flowing along this path raised the local temperature high enough to cause melting of the adjacent metal contacts which probably further reduced the resistance of the current path. The metallic short-circuits observed could be the result of metal flowing along the path caused initially by avalanche breakdown. An electro-thermal analysis is being carried out with a goal of increasing our understanding of the failure process.

VI. Conclusion

Microwave μs pulse, ms pulse, and CW-burnout data have been measured for two commercially available 1-μm gate MESFET's. Gradual degradation in noise figure and power gain were not observed. All failures were catastrophic and were associated with a metallic gate-source short-circuit. The data indicate the existence of an incident power threshold level for pulse durations 0.2 μs or longer and for CW. The incident power threshold level for burnout is in the range 3–6 W for Type-A MESFET's which have a Ti/Pt/Au gate metallization and in the range 1.5–3 W for Type-C MESFET's which have an Al gate metallization.

Acknowledgment

The comments of the reviewers on failure mechanism description were quite helpful and are appreciated.

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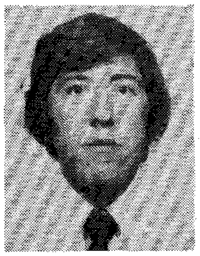

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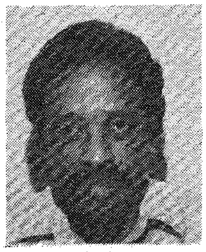

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