SINGLE-PULSE RF DAMAGE OF GaAs FET AMPLIFIERS*

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ABSTRACT

Several GaAs MMIC (microwave monolithic integrated circuits) amplifiers have been tested for damage from single pulses of microwave power applied to the circuit input terminals. Damage characteristics are described and modeled.

INTRODUCTION

For nearly a decade, researchers have been evaluating the response of GaAs microwave integrated circuits (MICs) to stressful levels of microwave input signals. The question asked has always centered on how much incident energy is needed to damage the device. Early experimenters [1,2] exposed their devices to pulse trains consisting of 2- to 100-ns pulses at a repetition rate of a few kilohertz lasting for several minutes. These investigators observed a rather low threshold for damage–in the range of 10 to 100 nJ per pulse. The damage was described as "metal migration" and "massive channel damage." Later, investigators placed more emphasis on damage from single shots, but their particular mission still demanded the use of procedures that allowed the damage to accumulate over a number of shots [3,4]. The results of these experiments were essentially the same as those of experiments using pulse trains.

Our goal was somewhat different from the goals of previous investigators. We wanted to know how much incident energy in a single shot was needed to damage a device with a minimum history of exposure. Like the others, we started with low power levels, but in contrast to them, we increased the power after each shot by 6 dB. Usually the devices could be damaged in just eight shots starting, for example, from 16 mW. The results were markedly different from those obtained with pulse trains. The incident energy for failure was two to three orders of magnitude higher (microjoules), and the type and location of damage were different. Metal migration was never observed, but microexplosions from rapid bulk heating of the GaAs were seen under the gate necks. Also, on the higher power shots, arcing between gate and source contacts was evidence at the gate necks over the surface. These results are exciting because they suggest a natural survival mechanism, which, if properly understood could be artfully enhanced to result in devices able to withstand much higher incident pulse energies.

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EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup shown in figure 1, was similar to that used by others [1,2]. The signal from a CW oscillator was modulated with a PIN diode switch which could generate rectangular pulses from 5 to 100 ns with 2-ns rise times. This video pulse was amplified by a 1-kW TWT amplifier run at saturation, providing a flat output pulse. A variable attenuator at the amplifier output was used to control the power incident on the amplifier under test. Three oscilloscopes monitored the input pulse, the output pulse, and the pulse reflected from the GaAs amplifier under test.

Immediately after each shot, the amplifier noise figure and small signal gain were measured to test for damage. The noise figure did not change by more than ± 0.3 dB until the damaging shot occurred, at which point the noise figure increased by 2 dB or more and the small-signal gain decreased about the same amount.

Although the reflection diagnostic did not measure the reflected energy accurately because of interference from extraneous reflections in the passive circuitry, it nevertheless provided a way to measure the time to failure during the damaging pulse. Figure 2 shows failure events recorded in the reflected signal. Failure is observed at 80 ns on the figure. The incident energy for failure can be estimated by integrating the incident power over the time to failure.

RESULTS

Four different brands of low-noise GaAs MESFET amplifiers were tested at 9 GHz. The test data are listed in Table I, and the physical and geometric properties of the tested amplifiers, as measured from electron micrographs or obtained from the manufacturer, are listed in Table II.

In Table II, the finger widths (gate lengths) as measured with a scanning electron microscope occasionally differed from the values reported by the manufacturers. The discrepancy was caused by a passivation layer of a thickness roughly proportional to the discrepancy. The volume of semiconductor heated by the microwave pulse was estimated from the depth, width, and length data and may be in error by an order of magnitude because of the uncertainty in estimating the spatial distribution of current density in a MESFET under stress. The energy density listed in the table is calculated by dividing the average energy for failure for each brand of amplifier by the heated volume (also listed). Note that the device with the highest failure energy density had the largest number of input stage gate fingers, the thickest passivation layer, and the largest gate-to-source separation distance.

Several points of interest concerning the test results are listed in Table I. First, as mentioned in the introduction, the energy for failure was one to two orders of magnitude higher than that observed by others. Second, during the damaging shot, both the reflected and output signals frequently exhibited step changes in signal strength (fig. 2), and sometimes spikes were observed at the beginning and end of the reflected pulse. Third, the energy needed for damage appears to be independent of pulse power. And fourth, the output power during the damaging shot was a small fraction of the input power, both before and after damage.

An autopsy was performed on each damaged device with the use of a scanning electron microscope. In every case but one, the damage took place at the gate necks of the first stage MESFET. A typical example is shown in figure 3. This contrasts with the pulse train experiments of others in which the damage frequently occurred at random locations along the gate fingers. However, as observed by others [5], the damaged area was mostly confined to the region between the gate and source, rather than between gate and drain. It may also be relevant to note that, when several gate fingers were connected in parallel, as was the case for the device shown in figure 3, the gate nearest the input end of the input bus was the most susceptible to damage.

MATHEMATICAL MODEL

A simple mathematical model has been developed to describe the damage sequence. We view the MESFET as a diode in which the current flow is one dimensional and the pulse length is sufficiently short to insure that heat transfer can be ignored (adiabatic). The resistivity and the dimensions of the gate finger metal and semiconductor are found to be important for determining the distribution of energy in the device. Here we outline the main assumptions and report the key results.

MESFET biasing has been ignored for two reasons. First, at the power levels applied during our experiments, the voltages generated by the rf signal far exceed the bias voltages. Second, other investigators, having made careful measurements of the effects of bias on the rf damage threshold, have found the effects to be minimal [5,6].

For breakdown studies, the MESFET is conveniently viewed as a pair of diodes–one formed by the gate and source and the other by the gate and drain. Because the current through the gate-drain diode is limited by the amplifier's output impedance, we can ignore this diode when accounting for the energy absorbed in the MESFET. Figure 4 shows the current density modeled in the gate-source diode by a pair of one-dimensional currents. The current in the finger metal is horizontal, and that in the GaAs under the metal is vertical. The current versus voltage curve (I-V curve) is modeled as shown in figure 5. We have modeled the avalanching portions of the curve with exponentials and have ignored the low-voltage characteristics since a negligible amount of energy is absorbed in the low-voltage regions of the curve. We have also ignored space charge effects, which would tend to reduce the current below that given by the exponentials in the I-V curve. In a future study, we plan to include these effects because we expect they will be important in determining whether the damage occurs by arcing between contacts or by bulk heating of the semiconductor.

The reflectivity is the ratio of the effective resistance of the semiconductor to the transmission line characteristic impedance. The effective resistance of the GaAs is calculated by taking the derivative of the idealized I-V dependence and, consequently, it varies during the rf cycle. On the average the resistance of the semiconductor drops as the incident power increases. This contributes to a basic mechanism that causes the current density to increase at the gate neck above that along the rest of the finger. At high enough input power, the diode is nearly short-circuited during most of the cycle. The energy represented by the matched power in figure 5 indicates that 1.4 uJ is being absorbed during the microexplosion, while the energy needed to raise an equivalent volume of material by 1000 C accounts for 0.7 uJ which is within experimental tolerance of the precision for measuring the volume of the exploded material.

The drop in impedance of the MESFET as damage occurs is not well understood, but our preliminary model suggests some reasonable explanations for the differences between our observations and those of others using pulse trains. First, at high incident power the damage is most likely to occur at the gate necks because the current drain through the gate finger by the avalanching semiconductor is enough to cause a significant voltage drop along the finger. In this case the highest voltage drop, and therefore the highest power dissipation, is at the gate neck. At lower input power, the voltage drop along the finger is small compared to the voltage drop in the vicinity of random flaws. For this reason one is more likely to observe failure at random locations along the gate finger when the power is low.

Second, the threshold for failure (either voltage or temperature) at a gate neck is sharp, and the resistance of the superheated material is low enough to shunt all the current from all the gate fingers through the failing neck. The result is a microexplosion which blows the superheated material away, opening the circuit at the one gate neck and allowing the process to repeat itself at another neck. As the microexplosions occur in one finger after another, a series of reflected pulses is generated. This explains the appearance of steps often seen in the diagnostics.

Third, the burnouts occur between the gate and the source, not the gate and drain, because the source is connected directly to ground and, contrasted to this, the drain is connected to some output impedance which is significantly larger than the impedance of the failing neck.

FUTURE WORK

Over the next year we expect to improve the reflection diagnostic by increasing its resolution and adding a phase measuring capability. In addition, we will incorporate an instrument for measuring the harmonic content of the reflected radiation. An optical spectrometer will be used to observe the light emitted during the destruction sequence. This should enable us to distinguish arcing from bulk heating with greater certainty.

REFERENCES

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TABLE I
TEST DATA

BRAND	SERIAL #	PULSE LENGTH ns	POWER AT FAILURE (Watts)	ENERGY TO 1st EVENT (μJ)
A	8	100	27	0.7
A	6	100	40	0.8
A	9	100	40	0.8
A	15	10	490	2.2
B	46	100	87	2.0
B	48	100	200	4.8
B	49	10	600	4.0
C	928	100	56	4.5
C	982	100	83	5.3
C	39	10	430	4.3
D	108	100	70	5.6
D	105	100	87	4.4
D	104	100	210	2.5
D	103	10	360	3.0

TABLE II
PHYSICAL & GEOMETRIC PROPERTIES

Brand		A	B	C	D
Depth of channel	μ	0.6	0.2	0.6	0.6
Finger width reported by maker	μ	0.8	0.3	0.5	0.5
Finger width measured by SEM	μ	0.8	1.2	0.6	1.5
Finger length	μ	175	67	213	101
Number of gate fingers		4	8	4	5
Heated volume	μ^3	336	32	213	126
Gate-source separation	μ	1.0	4.5	0.9	2.6
Failure energy density	nJ/μ^3	3.3	1100	42	100

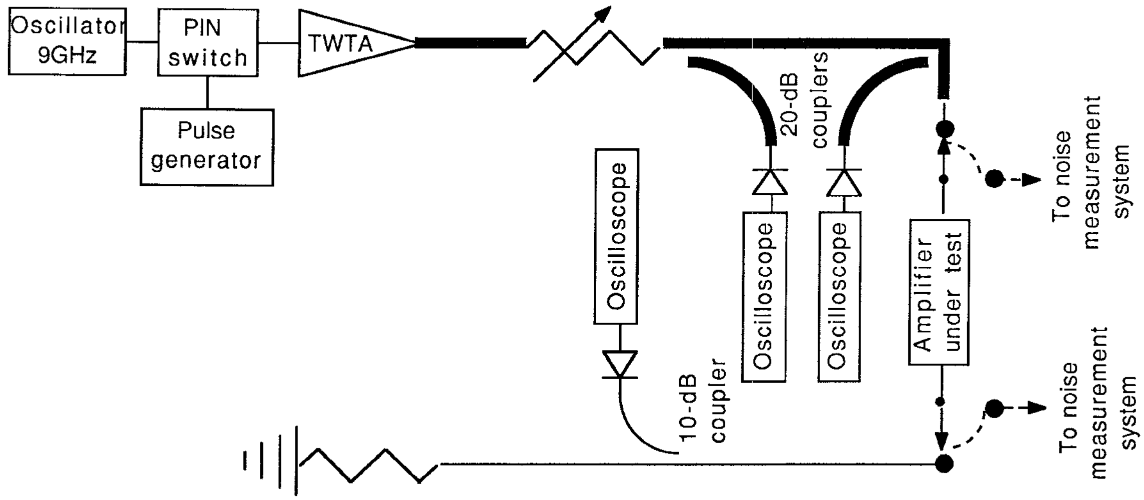

Figure 1
The experimental setup.

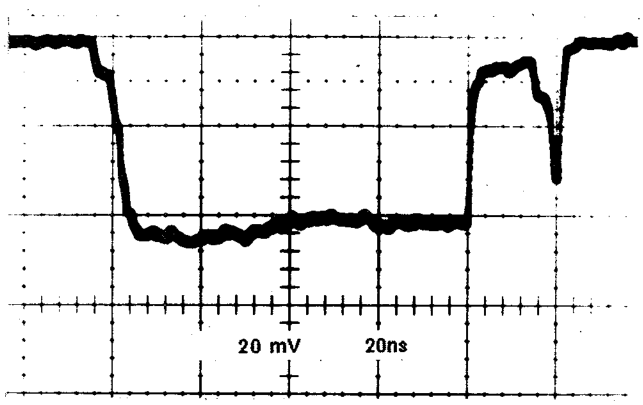

Figure 2
Typical step-like failure event seen in pulse reflected from amplifier under test.

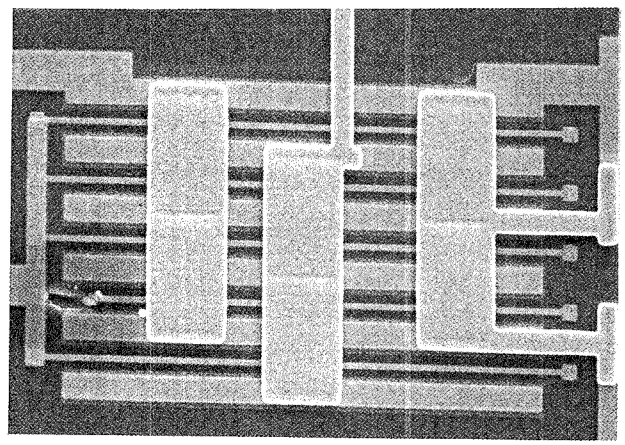

Figure 3
Microexplosion at gate neck on device whose reflection signature is shown in figure 2.

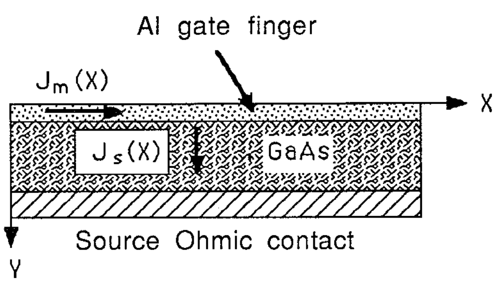

Figure 4
MESFET is modeled by a single diode with 1-D current densities.

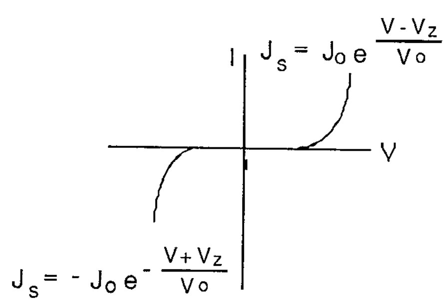

Figure 5
Idealized I-V curve