Broad-Band Electromagnetic Radiation Damage in GaAs MESFETs

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Abstract

A failure mechanism is observed for SiN_2-passivated metal semiconductor field-effect transistor (MESFET) devices exposed to fast risetime DC video pulses. The intensity of the pulses is about 33% of the value required to cause single-pulse failure. The failure mechanism, which degrades performance by surface flashover and erosion of the passivation layer, eventually leads to sputtering of the gate-source metallization. The results are observed using a combination of optical, electron, and X-ray micrographs, plus MESFET terminal parameters.

Introduction

Gallium arsenide metal-semiconductor field-effect transistors (GaAs MESFETs) will be required to operate in adverse intense electromagnetic environments — for example, close to radar or jammer transmitters. With limiters [1] the MESFET devices can be protected from levels associated with single-pulse burnout [2,3], but still experience levels far beyond their normal operating level. This paper addresses energy levels below the burnout level associated with single-pulse failure, where a MESFET may be subjected to numerous pulses, each of which modifies (degrades) the MESFET's physical properties. The mechanism that we are studying gradually reduces the gate-to-source resistance in the MESFET.

New failure mechanism

We report here a failure mechanism having a higher power threshold for single-pulse damage than does rectification failure [3]. This new mechanism damages the surface of the passivation layer by coating it with a thin conductive film. We believe this mechanism will allow damage to accumulate over repeated applications of a test pulse insufficiently intense to cause damage on a single shot. For the present we are calling the mechanism plasma erosion. It was identified through damage tests performed by injecting a square DC pulse directly into the input port of a low-noise GaAs MESFET amplifier. The gate-to-source voltage, V_{gs}, arising from an incident pulse of given voltage and risetime depends on the gate-to-source resistance, R_{gs}, of the avalanching MESFET. The exact threshold voltage for damage from a DC pulse depends upon the pulse risetime and the value of the DC blocking capacitor typically found in series with the gate of the first-stage MESFET. In this case, R_{gs} was inferred from the experimental damage voltage dependence on pulse risetime. The space-charge-limiting phenomenon causes R_{gs} to increase with increasing electric field and ensures that, at sufficiently high incident power, the gate-to-source field will grow large enough to initiate plasma erosion.

Experimental setup

Figure 1 shows the experimental setup. A charge-line pulser launches a square pulse into a coaxial line. The risetime of the pulse immediately downstream from the switch is about 1 ns, and the pulse length is either 15 or 86 ns as determined by the charge-line length. For testing the risetime dependence of the damage threshold, the risetime is purposely degraded by passing the pulse through various lengths of RG-58 coaxial transmission line.

A DC square pulse was used in these tests instead of a microwave pulse, because the DC, in conjunction with the blocking capacitor, gave us pulses sufficiently short to prevent damage by bulk heating. With the equipment available at the time we could not generate sufficiently short microwave pulses to reach this regime.

Single pulse results

The circled area in Figure 2 shows typical damage from a single square DC pulse. This damage appears as a discoloration when viewed through an optical microscope. It is not visible to a scanning electron microscope, which suggests that the discoloration is a thin film transparent to the lowest energy electron beam capable of micrometer resolution (≈ 2 kV). Since the bias current changed a few percentage points, we presume that the film is conductive. In contrast, Figure 3 is a cross-sectioned MESFET damaged from a single microwave pulse. The damage extends well below the surface, indicating that the bulk of the semiconductor was heated. When the incident power slightly exceeds the threshold for damage, the result is always catastrophic. This unstable behavior, which may result from a GaAs phase change, contrasts strongly with the DC pulse case in which the amount of damage depends smoothly on the energy reaching the gate.

Multiple pulse results

To test the hypothesis that pulses at voltages below the threshold for damage by single pulses gradually modify

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the physical properties of the device, we subjected an amplifier to a series of tests, commencing with a 100 Hz repetition rate. The tests started with –30-V pulses applied to the rf input. After about one hour, if no damage was observed, the voltage was decreased by –5 V and the test repeated. Damage was ascertained by observing the amplifier gain just prior to each pulse. This was accomplished in real time by recording the oscilloscope display of the amplifier output using a video camera connected to a videotape recorder. The device failed during the –40-V test after 85 min. at the 100 Hz repetition rate. No change in the gain was observed until a fraction of a second before failure. The failure process took 40 to 50 pulses. During this period the rf signal from the amplifier changed appreciably after each pulse. The optical photomicrograph of the damage was similar to that shown in Figure 2 for single-pulse damage except that the discoloration spread over a larger area. Figures 4 and 5 are electron microscope photographs taken using 25- and 40-kV electrons. Backscattered electrons are imaged, which increases the contrast between materials having different atomic numbers. Each photograph shows an identical region of the device under test (DUT). The region labeled “undamaged” is a gate-to-source gap shown for comparison

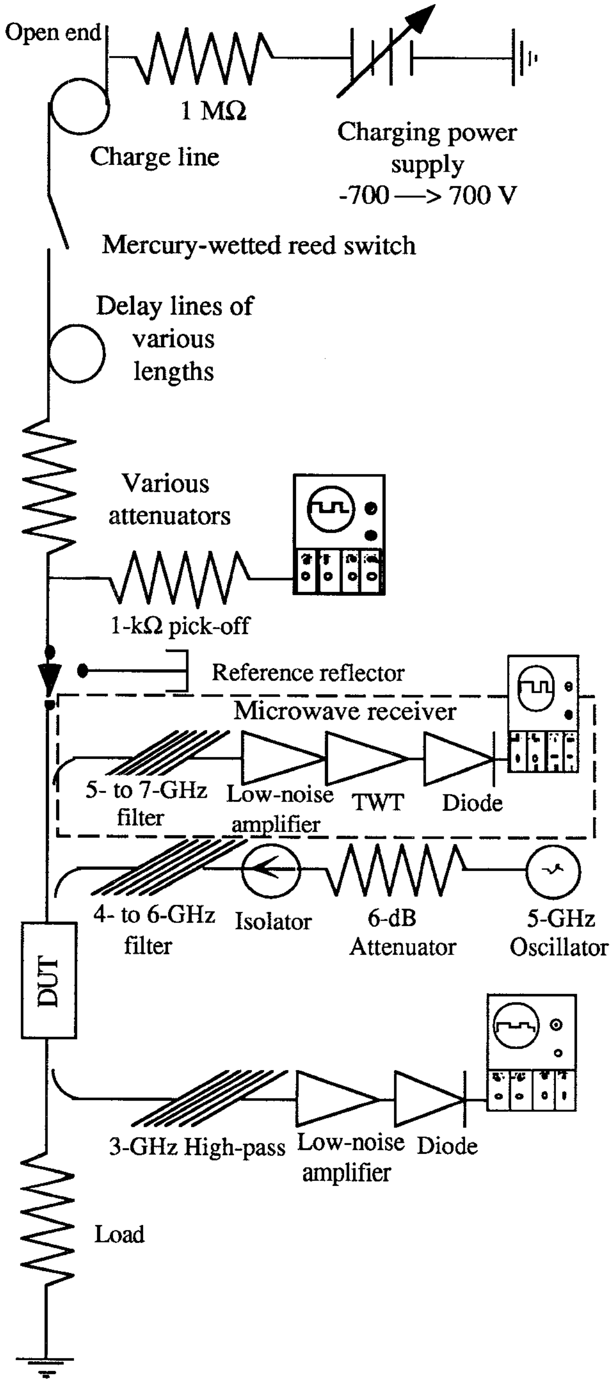

Figure 1. Experimental setup for determining GaAs MESFET damage thresholds from wide-band pulses.

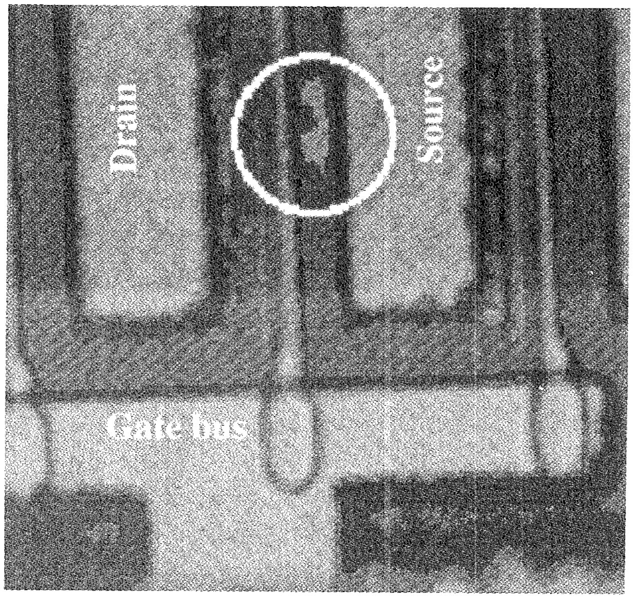

Figure 2. Surface flashover damage to a GaAs MESFET from a 140-volt DC pulse.

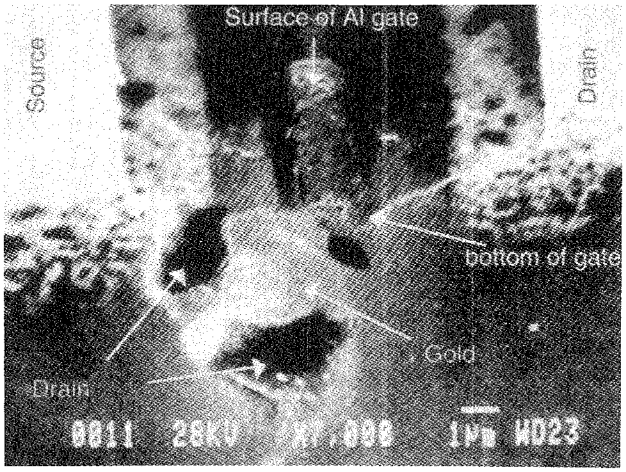

Figure 3. High-power microwave damage to an unbiased GaAs MESFET. The damaged region has been sectioned to show that morphological changes extend at least 1 μm below the surface.

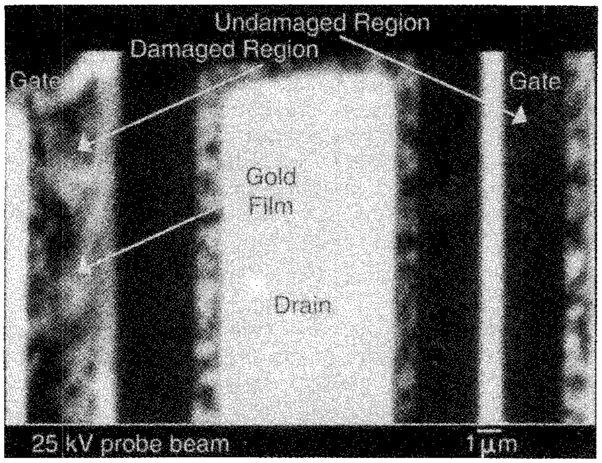

Figure 4. Electron microscope photograph of plasma erosion damage on the surface of a GaAs MESFET.

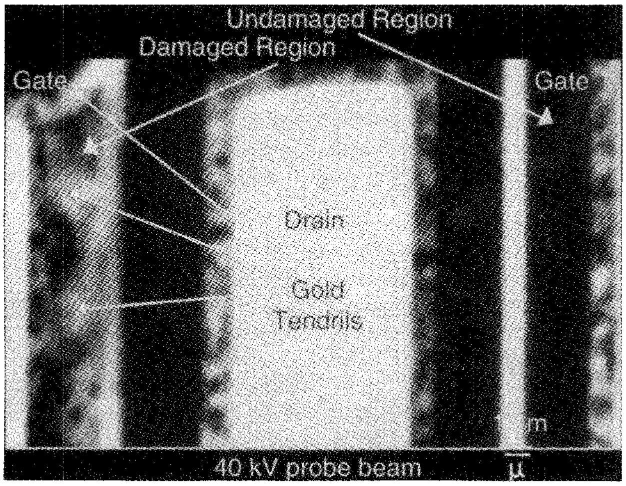

Figure 5. Plasma erosion damage imaged with a 40-kV electron beam indicates that the deposited material is thin compared to an electron penetration depth.

with the damaged gate-to-source gap labeled "damaged." An electron microprobe analysis of the plumes seen in the damaged region indicates a gold concentration 160% higher than in the corresponding undamaged region. The gold in the undamaged region is a result of coating for specimen preparation. The 40-kV image shows fainter plumes and a more eroded gate than the 25-kV image. Since the 40-kV electrons penetrate deeper into the surface, this indicates that the plumes are a thin surface phenomenon and that material has been removed from the gate metal. Images made from the secondary electrons show much less contrast than those made from the backscattered electrons, and this also suggests that the plumes are thin since secondary electrons enhance the contrast of topographic features such as humps and rills.

Data analysis

Figure 6 is a plot of the experimental data showing the threshold voltage for single-pulse damage versus DC pulse risetime. Figure 7 shows a model circuit for the DUT. The gate-to-source resistance, R_{gs}, is normally several megohms due to reverse biasing of the gate Schottky junction but may be significantly lower during avalanche breakdown. The DC blocking capacitor, C_b, only transmits energy over time periods comparable to the time, $C_b R_{gs}$ (Fig. 8). If this is short compared to the pulse length, the pulse length has no

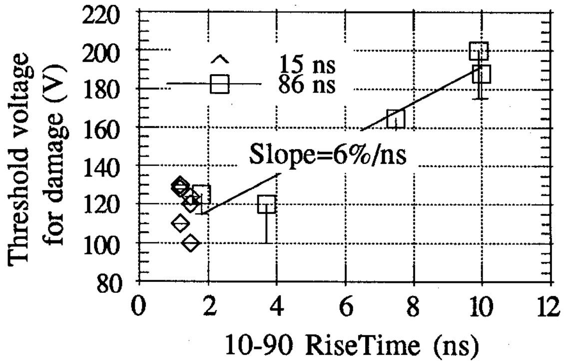

Figure 6. The DC pulse amplitude required for damage depends on the pulse rise-time.

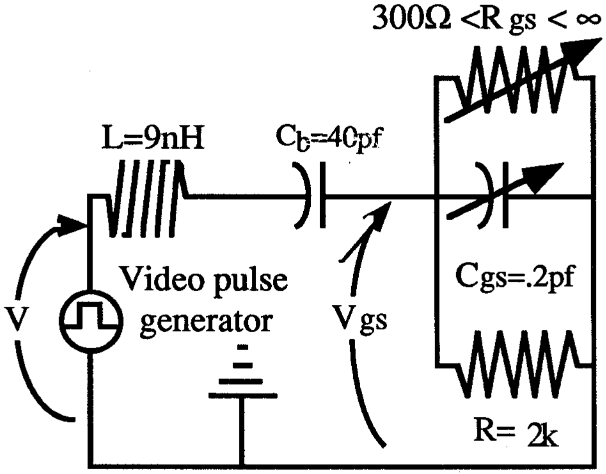

Figure 7. The circuit model used to infer the gate-to-source flashover voltage.

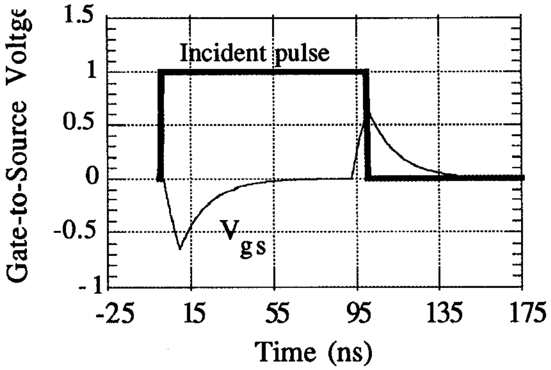

Figure 8. The gate-to-source voltage calculated using the model circuit of Figure 5 with $R_{gs} = 300\ \Omega$.

bearing on the damage threshold. On the other hand, if C_bR_{gs} is comparable to or shorter than the pulse risetime, the peak value of V_{gs} will be sensitive to the risetime, and the sensitivity will depend on C_bR_{gs}. This was the case for these experiments. The risetime dependence of the incident pulse voltage required for damage is consistent with $R_{gs} = 250 \pm 25\ \Omega$, which agrees with the 222 Ω calculated from the Mott-Guerny law for space-charge-limiting current flow [4]. With the use of 250 Ω for R_{gs}, the value of V_{gs} obtained when the incident voltage is high enough to cause single-pulse plasma erosion is 140 V, which corresponds to a field of nearly 50 MV/m. This electric field is remarkably high considering that DC fields as low as 3 MV/m between macroscopic electrodes are sufficient to cause air breakdown. Plasma erosion occurs at voltages much lower than 140 V but, at such low voltages, there is insufficient energy in a single pulse to deposit enough material to observe. This explanation would still be consistent with the observed increase in threshold voltage with risetime, since the energy available for damaging the MESFET depends on the energy in the high-frequency Fourier components of the square test pulse, which is sensitive to both risetime and amplitude. The multiple pulse tests were performed to test this interpretation. In these tests no degradation of amplifier performance was observed for a remarkably long period preceding the damage events. This is consistent with the notion that a plasma is formed in the gate-to-source gap between the electrodes insulated with SiN_2. Plasma ions accelerated by the high fields bombard the SiN_2 where the field lines terminate and thus sputter the material away. Eventually the sputtering action digs a hole through to the gold conductor and the sputtering of gold commences. Through a plasma transport mechanism, the gold vapor is then deposited in plumes that tend to follow the electric field lines. The resulting contact between the gate and source electrodes then alters the electrical performance of the amplifier.

Conclusions

The results on DC pulse damage thresholds can be used to predict the microwave power level that would cause single-pulse plasma erosion. The microwave power threshold should be

$$P = \frac{V_{gsf}^2}{Z_o},$$

where V_{gsf} is the threshold voltage found from the DC experiment, and Z_o the characteristic transmission-line impedance. If V_{gs} is 140 V, then we should expect to see single-pulse erosion effects starting at about 400 W. Of course, if the incident energy is larger than the threshold for damage by microwave bulk heating (rectification failure [1]) then the appearance of the damage will be dominated by bulk heating. Single shot damage from erosion will be apparent only if the incident energy which causes rectification failure is limited by using sufficiently short pulses (< 10 ns). Multiple microwave pulses below the threshold for rectification failure may result in plasma erosion, but this hypothesis has not yet been tested.

Future work

To confirm the plasma erosion hypothesis, we are setting up an experiment to observe the optical emission from the hypothesized plasma. Relating the brightness of this emission to the test voltage and the failure time should provide enough information for a quantitative model.

The notion that microwave pulses also cause erosion will be tested using 3- to 4-ns microwave pulses with sublethal energy content.

If the plasma erosion hypothesis is correct, then increasing the thickness of the passivation layer should improve hardness to this type of damage. Once the mechanism is confirmed, devices will be coated to various thicknesses to test for hardness.

Circuits not containing blocking capacitors are expected to fail by bulk heating when subjected to DC pulses, and from the few tests already performed, this appears to be the case.

References

1. J. H. McAdoo, W. M. Bollen, W. Catoe, and E. Stoneham, "Hardening Gallium Arsenide Microwave Integrated Circuits Against Directly Injected High-Power Microwave Radiation," HDL Contractor Report No. HDL-CR-91-060-02, February 1992.
2. J. H. McAdoo, W. M. Bollen and R. Garver, "Single-Pulse Rf Damage of GaAs FET Amplifiers," 1988 IEEE MTT-S Digest, p. 289.
3. J. H. McAdoo, W. M. Bollen, R. Seeley, W. Catoe, and J. Frey, "Rectification Failure in GaAs MESFETs Subjected to Single Pulses of Intense Microwave Radiation," IEEE 1990 Microwave and Millimeter-Wave Monolithics Circuits Symposium Digest of Papers, pp. 47-49.
4. G. Sh. Gildenblat, A. R. Rao, and S. S. Cohen, "Space-charged-limited currents in materials with nonlinear velocity-field relationships," IEEE Trans. Electron Devices, V. **ED-34**, pp. 2165-2172, 1987