Detection of Avalanching in Submicrometer Field-Effect Devices

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Abstract—**In submicrometer field-effect devices, where large electric fields are produced in the channel region under normal biasing conditions, the presence and the onset of avalanching can be detected by the measurement of the noise power spectrum of the drain current at a frequency in the UHF range. This technique is illustrated by measurements on GaAs MESFET's.**

I. Introduction

GaAs MESFET's have continued to reach successively higher levels of performance over the past 16 years through numerous improvements in device design. Along with better buffer layers and reduced parasitics, these devices have been designed with smaller and smaller gate lengths, and simultaneously higher doping levels in the channel region, in an attempt to reach higher cutoff frequencies and lower noise figures. Devices at the presently reached state of the art are usable in the millimeter-wave range at frequencies above 100 GHz [1], and have gate lengths in the range 0.1–0.2 μm.

With such small gate lengths, and when the normal drain-to-source dc bias voltage in the range of 1–3 V is applied, the electric field reached in the channel of these devices becomes very large, with a distinct possibility of significant avalanche ionization taking place in the channel. The device designer therefore requires a method of determining if a significant amount of avalanching is indeed occurring in a given device at a given dc bias, and what is the dc bias required for the onset of avalanching in the device. The need to establish the presence of avalanching may also arise in other contexts, e.g., in the study of device reliability and failure modes.

The two usual methods of establishing the existence of avalanching—by dc current-voltage characteristic and by estimating electric field strength reached—are not definitive for submicrometer field-effect devices. The dc drain-source (I_D-V_{DS}) characteristic of the device does not provide a clear indication of whether or when avalanching is indeed taking place, because the dc drain current does not quite saturate but continues to increase with increasing V_{DS} even in the absence of avalanching. The positive slope of the I_D-V_{DS} characteristic results from the widening of the channel in the velocity saturation region with increasing drain voltage [2]. The calculated value of electric field reached in the device is also not a clear indicator of avalanching, because the static ionization rate-electric field (α-E) relationship is not applicable to these devices. Monte-Carlo simulations have shown that it is the electron energy, and not the strength of electric field, that governs the likelihood of ionization [3].

This letter describes a simple and rapid experimental method for detecting avalanching in MESFET channels and other similar semiconductor regions. The method is based on the measurement of the noise power spectrum of the drain current at some frequency typically in the UHF or low microwave frequency range. The variation of this noise spectral density with dc bias provides an indication of avalanching. Since the measurements can be carried out at a low frequency (below the microwave frequency range) the method can be employed even before the device has been diced, bonded, and packaged, e.g., at the wafer stage during the device fabrication process. The theoretical basis of this method is explained in Section II, and an experimental test of the method is presented in Section III.

II. Noise Spectrum of Drain Current

There are several potential noise sources in a MESFET that can influence the power spectrum $S_{id}(f)$ of the short-circuit noise current i_d accompanying the dc drain current I_D. Experimental measurements [4], [5] as well as theoretical considerations [6] show that the noise spectrum is best understood by dividing the frequency domain into three regions. At the low-frequency end [4], [5], the noise spectrum is dominated by $1/f$ noise and generation-recombination noise, and is therefore large and frequency dependent. In the mid-frequency interval, extending typically from 10^7 or 10^8 (depending on the device) to a frequency of the order of 10^{11} Hz, the noise spectrum is frequency independent. At still higher frequencies [6], the noise spectral density decreases due to effects of finite carrier relaxation time and transit time. In all of the subsequent discussions in this paper, attention is confined to this mid-frequency range where the noise spectrum is white.

In the absence of avalanching, the noise in the drain current of a MESFET is the diffusion (or velocity fluctuation) noise due to the hot carriers drifting through the channel. The power spectral density of this diffusion noise can be expressed [7]–[9] as a modified thermal noise:

$$S_{id}(f) = 4kT_0 g_m P \qquad (1)$$

where

k Boltzmann's constant,
T_0 lattice temperature in Kelvin,

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g_m transconductance of the MESFET, and
P a factor dependent on the device material, structure, geometry, and operating conditions.

The factor P can be either experimentally measured [10] or theoretically calculated [7]–[9]; several different expressions for this factor are available in the literature [7]–[9], based on different models constructed to represent the device, and valid under different conditions. For present purposes, the significant result is that P is of the order of unity, and it does not change appreciably with dc bias in the "saturation" region (above the so-called "knee") of the I_D–V_{DS} characteristic of the MESFET. The transconductance g_m also does not change very significantly in this region [10].

When avalanche ionization does take place, both the dc drain current I_D and the power spectrum $S_{id}(f)$ will contain a component due to the avalanche-generated carriers. In GaAs at room temperature, the ionization rates of electrons and holes are not vastly different [11]. Under such circumstances, the power spectral density S_{ia} of the avalanche-generated current can be calculated analytically under some simplifying assumptions [12], [13]. It is found that at low frequencies defined by

$$\omega \ll M\tau \tag{2}$$

the spectral density S_{ia} can be expressed as a modified shot noise:

$$S_{ia}(f) = 2qI_P M^3 \tag{3}$$

where

q magnitude of the electronic charge,
I_P primary current causing avalanching,
M current multiplication factor, defined as the ratio of the total current I_D to the primary current I_P, and
τ transit time of carriers through the avalanche region.

At higher frequencies, the power spectrum shows a decline due to finite transit-time effects. This result, and in particular the cubic dependence of the noise power spectral density on the multiplication factor, has been experimentally verified [14], and is a characteristic feature of avalanche noise.

A comparison of (1) and (3) shows that, for a MESFET biased in the saturation region, the drain noise current has a power spectral density whose dependence on the dc bias current is different in the presence and in the absence of avalanching. In the absence of avalanching, the entire noise is essentially diffusion noise, and it varies very little with I_D. In the presence of avalanching, the noise will consist of two parts: diffusion noise associated with the primary current I_P, and avalanche noise associated with the avalanche-generated current $I_D - I_P$. If I_P is approximately constant (i.e., the increase of I_D is mostly due to avalanching rather than due to the nonsaturation mechanism mentioned in Section I), the diffusion noise will again be essentially independent of I_D, while the spectral density of avalanche noise will be a cubic function of I_D. As a result, the total noise spectral density will also have the same cubic functional dependence on the drain current. This distinction is used as an indicator of the onset of avalanching in the following.

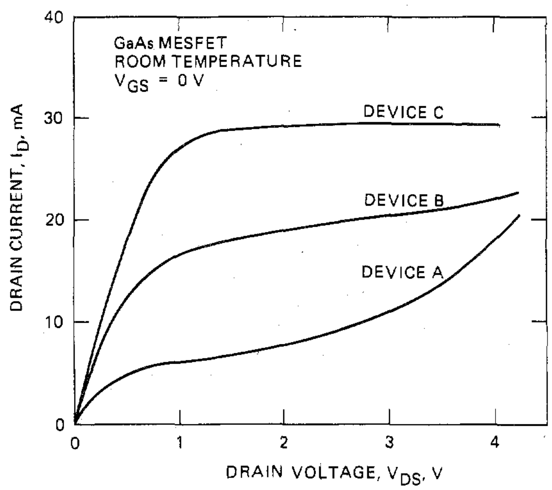

Fig. 1. DC channel characteristics at $V_{GS} = 0$ for three different GaAs MESFET's.

III. Experimental Results

The above test of avalanching was tried on some experimental GaAs MESFET's under development. For the sake of comparison, the results reported here refer to three different kinds of devices whose dc I_D–V_{DS} characteristics are shown in Fig. 1 for a gate bias $V_{GS} = 0$.

1) Device A has a gate length of approximately 0.1 μm and a channel region doping density $N_D = 6 \times 10^{18}$ cm^{-3}. It is a state-of-the-art millimeter-wave device with a high gain and good noise performance at frequencies well above 50 GHz.

2) Device B has a gate length of 0.25 μm and a channel region doping density $N_D = 10^{18}$ cm^{-3}. It is also a state-of-the-art device with a good gain and a very low noise figure at microwave frequencies (10–20 GHz).

3) Device C has a gate length of 0.25 μm and a channel region doping density $N_D = 8 \times 10^{17}$ cm^{-3}. It is a microwave device with a very high gain (over 10–20 GHz) but poor noise performance.

The noise current spectrum at the drain–source port, with the gate–source port short circuited, was measured for each device using the system shown in Fig. 2. The measuring equipment is essentially a tuned receiver, having a known (i.e., separately measured) noise equivalent bandwidth, and a known input impedance. The spectral density of the short-circuit drain noise current is calculated from the noise power measured by the receiver. The exact frequency of measurement is not critical. It is only necessary that the frequency be sufficiently high that the measured noise power is not influenced by the low-frequency noise sources such as $1/f$ noise and generation-recombination noise, and sufficiently low that the noise power spectrum of the diffusion noise as well as the avalanche noise is white. That these conditions are met is easily verified by varying the frequency of measurement to ascertain that the measured noise spectrum is indeed white.

The measured spectra at 1.15 GHz are shown in Fig. 3 for the three devices as a function of dc bias current. A line of slope 3 is also drawn in the figure to help identify the bias range for which the noise power spectrum has a cubic dependence on bias current. It is clear from the spectra that the dependence is cubic only for device A at drain currents

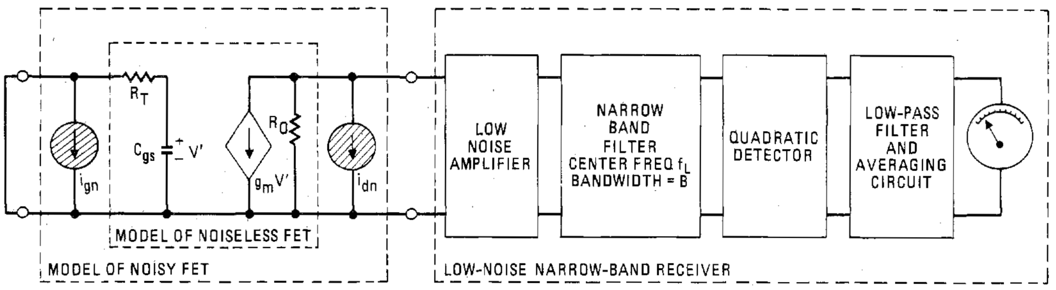

Fig. 2. Noise power measurement setup.

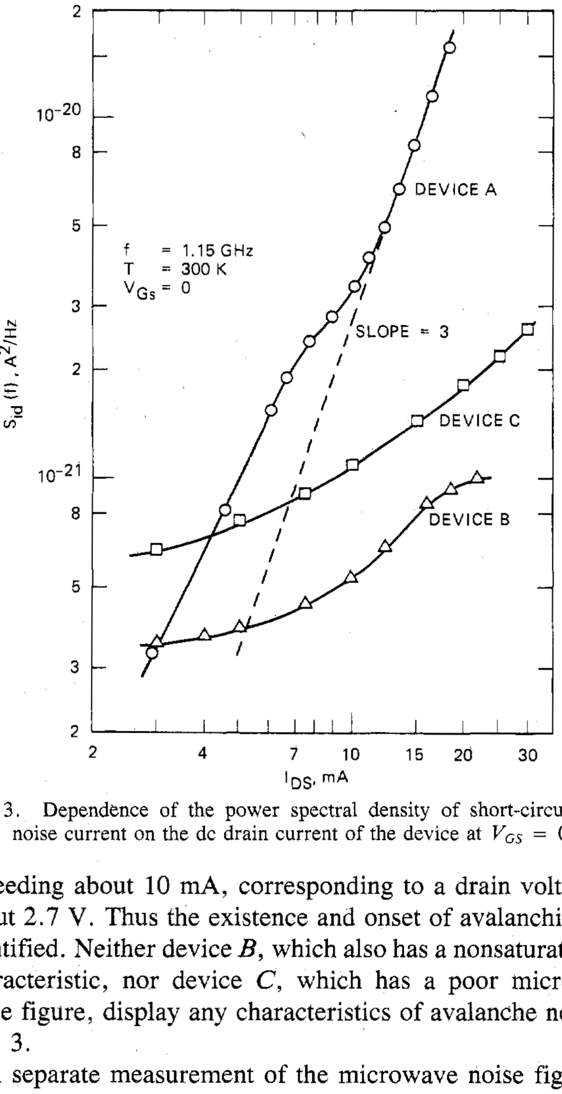

Fig. 3. Dependence of the power spectral density of short-circuit drain noise current on the dc drain current of the device at $V_{GS} = 0$.

exceeding about 10 mA, corresponding to a drain voltage of about 2.7 V. Thus the existence and onset of avalanching are identified. Neither device *B*, which also has a nonsaturating dc characteristic, nor device *C*, which has a poor microwave noise figure, display any characteristics of avalanche noise in Fig. 3.

A separate measurement of the microwave noise figure of device *A* at 18 GHz as a function of V_{DS}, shown in Fig. 4, further verifies the onset of a new noise source starting around $V_{DS} = 2.7$ V in this device. The noise figure of the other two devices did not show any increase with V_{DS} up to $V_{DS} = 4$ V.

IV. Conclusion

A technique has been presented for identifying the onset of avalanching in submicrometer field-effect devices, where other methods of determining the presence of avalanching are not useful. The technique is simple since it requires only the measurement of the noise power output between the drain and source terminals, with the gate shorted to the source, and it can be used even at the wafer stage of device processing.

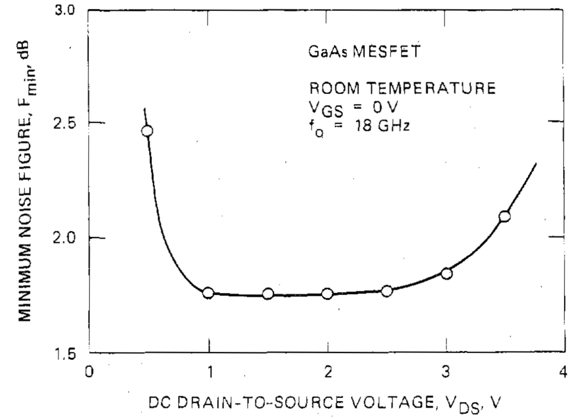

Fig. 4. Dependence of the measured microwave noise figure of device *A* on the dc drain-to-source voltage V_{DS}.

References

[1] H. Q. Tserng, "A 115 GHz monolithic GaAs FET oscillator," in *1985 GaAs IC Symp. Tech. Dig.*, Oct. 1985, pp. 11-12.

[2] K. Lehovec and R. Miller, "Field distribution in junction field-effect transistors at large drain voltages," *IEEE Trans. Electron Devices,* vol. ED-22, no. 5, pp. 273-281, May 1975.

[3] C. Moglestue, "Hot, tepid and temperate electrons in bulk GaAs," *Proc. Inst. Elec. Eng. Pt. I—Solid State and Electron Dev.*, vol. 133, no. 2, pp. 35-46, Apr. 1986.

[4] P. A. Folkes, "Thermal noise measurements in GaAs MESFETs," *IEEE Electron Device Lett.*, vol. EDL-6, no. 12, pp. 620-622, Dec. 1985.

[5] J. Graffeuil, J. F. Sautereau, G. Blasquez, and P. Rossel, "Noise temperature in GaAs epi-layer for FETs," *IEEE Trans. Electron Devices,* vol. ED-25, no. 6, pp. 596-599, June 1978.

[6] R. Brunetti and C. Jacoboni, "Analysis of the stationary and transient autocorrelation function in semiconductors," *Phys. Rev. B,* vol. B29, no. 10, pp. 5739-5748, May 15, 1984.

[7] A. van der Ziel, "Thermal noise in field-effect transistors," *Proc. IRE,* vol. 50, no. 8, pp. 1808-1812, Aug. 1962.

[8] W. Baechtold, "Noise behavior of GaAs field-effect transistors with short gate lengths," *IEEE Trans. Electron Devices,* vol. ED-19, no. 5, pp. 674-680, May 1972.

[9] H. Statz, H. A. Haus, and R. A. Pucel, "Noise characteristics of gallium arsenide field-effect transistors," *IEEE Trans. Electron Devices,* vol. ED-21, no. 9, pp. 549-562, Sept. 1974.

[10] M. S. Gupta, "Bias dependence of diffusion noise in GaAs MESFETs with submicron gate lengths," in *Proc. 9th Int. Conf. Noise in Physical Systems* (Montreal, Canada). Singapore: World Scientific Pub., 1987, to be published.

[11] G. E. Stillman, C. M. Wolfe, J. A. Rossi, and A. G. Foyt, "Unequal electron and hole impact ionization coefficients in GaAs," *Appl. Phys. Lett.*, vol. 24, no. 10, pp. 471-474, May 15, 1974.

[12] A. S. Tager, "Current fluctuation in a semiconductor (dielectric) under the conditions of impact ionization and avalanche breakdown," *Sov. Phys.—Solid State,* vol. 6, no. 8, pp. 1919-1925, Feb. 1965.

[13] R. J. McIntyre, "Multiplication noise in uniform avalanche diodes," *IEEE Trans. Electron Devices,* vol. ED-13, no. 1, pp. 164-168, Jan. 1966.

[14] I. M. Naqvi, C. A. Lee, and G. C. Dalman, "Measurements of multiplication effects on noise in silicon avalanche diodes," *Proc. IEEE,* vol. 56, no. 11, pp. 2051-2052, Nov. 1968.