Velocity-Fluctuation Noise in Semiconductor Layers and in MESFET Channels Under Hot-Electron Conditions

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***Abstract*—The power spectral density of velocity-fluctuation noise in a semiconductor layer, or in the channel of a MESFET device, in the presence of a biasing electric field creating hot-electron conditions, is calculated from the nonlinear dc current–voltage characteristic of the semiconductor existing under those conditions, by the use of Gupta's nonlinear thermal noise theorem. The calculated results are shown to agree with measured noise temperatures for a variety of devices, at microwave frequencies and at moderately high electric fields. An empirical result relating the excess noise temperature in GaAs to the electric field is proposed.**

I. INTRODUCTION

A. Motivation

THE VELOCITY-FLUCTUATION noise in a layer of a bulk semiconductor, or in the channel of a MESFET device, under hot-electron conditions created by large applied electric fields, has been studied both theoretically [1]–[3] and experimentally [4]–[6] by numerous authors. There are several reasons for such strong interest in this subject:

1) It has been established [7] that the velocity-fluctuation noise due to carriers in the active channel region is the dominant source of noise in a GaAs MESFET device at microwave frequencies. In comparison to the contribution from this noise source, all other sources of noise in the device, including the shot noise in the gate leakage current, the generation-recombination noise in the space-charge regions of the channel, and the avalanche noise due to carrier multiplication in the channel, are nonessential (i.e., they either are very small, or can be made small by judicious design), as confirmed by the existence of GaAs MESFET devices in which the entire observed microwave noise can be accounted for by velocity-fluctuation noise alone.

2) The limiting sensitivity of optical receivers employing GaAs MESFET's is determined by intrinsic noise generated in the channel, which is dominated by velocity-fluctuation noise [8].

3) The study of velocity-fluctuation noise in semiconductor channels is a convenient vehicle for studying the hot-electron transport phenomena [9].

Given this interest in the subject, it would be desirable to have a simple method of calculating the power spectral density of the noise current due to velocity fluctuations in bulk semiconductors and in MESFET channels. The purpose of this paper is to present such a method.

B. Objective

In the limiting case of a linear two-terminal device in thermal equilibrium, velocity-fluctuation noise reduces to thermal noise and its power spectral density can be easily calculated by applying Nyquist's theorem. This is because Nyquist's theorem, which is applicable only to a linear resistor in thermal equilibrium, expresses the noise spectrum solely in terms of the terminal resistance and temperature of the device, and does not require a knowledge of the structural and microscopic details of the resistor, such as its geometry, conduction mechanism, material nonuniformity, etc.; the effect of these details on the noise is accounted for via the value of the terminal resistance.

By contrast, the channel region of a MESFET device is nonlinear, and under normal operating conditions, the charge carriers in it are not at equilibrium. As a result, Nyquist's theorem is not directly applicable to the channel, and all published calculations [1], [7], [10], [11] of velocity-fluctuation noise in the channel region of a MESFET device require that a detailed model of the channel be constructed based on postulates concerning the geometry of the nonuniform channel region, the variation of electric field or carrier temperature along the channel, the relationship between electric field and carrier velocity, and other relevant variables. Such calculations of velocity-fluctuation noise in the channel of a MESFET device "from first principles" therefore are involved, their validity is subject to the numerous assumptions made in model construction, and their results are expressed in terms of a number of parameters some of which can only be approximately estimated.

The objective of this paper is to show that the power spectral density of the velocity-fluctuation noise at low frequencies (including the microwave frequency range), where the noise is white, can be calculated by the use of the author's nonlinear thermal noise theorem [12], [13]. This theorem relates the noise spectral density to the ter-

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minal current–voltage characteristic of the two-terminal sample under consideration, and expresses it in terms of 1) the nonlinearity of the terminal characteristic, 2) the current flow present under non-equilibrium conditions, and 3) the carrier temperature. The first two of these quantities can be measured directly and the third can often be estimated or approximated. This paper will show that the noise power spectrum calculated in this manner agrees well with experimentally measured values of power spectral densities for a variety of devices and over a range of dc bias and temperature.

II. Noise Calculation

A. Definition of Temperatures

In a two-terminal semiconductor device, such as a bulk sample of semiconductor or the channel of a field-effect transistor, four different temperatures can be defined as follows, and must be distinguished from each other for proper interpretation of results later on:

1) Ambient temperature T_0, which is the temperature of the surroundings with which the device is maintained in thermal contact. In practice, this temperature will be measured as the temperature of the heat-sink on which a device is mounted. As a result, the temperature will typically be the room temperature, oven temperature, or the coolant (such as liquid nitrogen) temperature.

2) Lattice temperature T_l, which is the temperature of the semiconductor lattice itself, and can be defined in terms of the thermal energy in the lattice. For inhomogeneous samples, the lattice temperature may be defined locally, and it can be spatially varying; for example, it may be higher near potential barriers or regions with large electric fields, and lower near ohmic contacts where the electric field drops to zero or heat-sinking occurs.

3) Electron (or carrier) temperature T_e, which is a measure of the average thermal (i.e., random) kinetic energy among the set of carriers of interest. When there are several distinct classes of carriers within a device, more than one T_e may be defined, and obviously T_e can also be spatially varying. Furthermore, an electron temperature may be defined for a particular direction within the lattice, by taking the average kinetic energy of carriers due to the random velocities only in that direction, and the effective mass appropriate for that direction; thus, one may have "longitudinal" and "transverse" electron temperatures, respectively parallel and perpendicular to an applied electric field.

4) Noise temperature T_n, which is a measure of the spectral density of noise voltage v_n (or current i_n) appearing (or flowing) between two specified terminals or reference planes under open-circuit (or short-circuit) conditions

$$T_n \equiv S_{v_n}(f)/4k \operatorname{Re}[Z_{ss}] \equiv S_{i_n}(f)/4k \operatorname{Re}[Y_{ss}] \quad (1)$$

where S_{v_n} and S_{i_n} are the one-sided power-spectral densities (defined for positive frequencies only) of v_n and i_n, respectively, k is Boltzmann's constant, Z_{ss} and Y_{ss} are the small-signal (i.e., linearized) impedance and admittance of the device, respectively, and Re $[\cdot]$ denotes the real part. As a result, T_n is in general a function of frequency. Furthermore, different noise temperatures may be defined and measured by a suitable choice of terminals, such as "longitudinal" and "transverse" noise temperatures when the terminals are separated along, or perpendicular to, an applied electric field.

In thermal equilibrium, the temperatures T_0, T_l, T_e, and T_n become identical in accordance with the second-law of thermodynamics and Nyquist's theorem. But in the presence of an applied dc or RF voltage resulting in large electric fields, the identity will usually be replaced by the inequality $T_0 \leq T_l \leq T_e$ as there is a flow of energy from carriers to the lattice, and from lattice to the surroundings. The noise temperature T_n may fall below or rise above T_e depending on the type of device characteristics. (For near-equilibrium operation, T_n rises for sublinear and falls for supralinear current–voltage characteristic [13], so that $T_n > T_e$ for the channel of a field-effect transistor and $T_n < T_e$ for p-n junction diodes).

The ambient temperature T_0 can always be measured directly, and the noise temperature T_n can also be measured directly by a narrow-band sensitive receiver measuring the noise power output, provided T_n is defined at terminals that are externally accessible. The lattice temperature T_l in the presence of bias can also be estimated from measurements; for example, if T_l is uniform throughout the device, the measurement of terminal voltage and current under low-duty-cycle pulsed conditions and with the device at an elevated temperature can be used for estimating T_l. The electron temperature T_e, however, is not directly measured. It is primarily a theoretical parameter, and has usually been determined indirectly, for example, by noise measurements, or has been calculated, for example, in Monte Carlo simulations of carrier transport.

B. Noise Mechanisms

At equilibrium, the noise is entirely thermal in origin arising from the random fluctuations in the velocities of charge carriers, associated with the maintenance of thermal equilibrium between the semiconductor device and its surroundings. In the presence of a current flow through the sample, not only do other noise sources like g-r, avalanche, and $1/f$ noise become operative, the noise due to fluctuations in carrier velocities may itself be quantitatively modified. It is then referred to as "diffusion noise" or "velocity fluctuation noise," and may be viewed as a generalization of thermal noise. All subsequent discussions in this paper are addressed to this noise mechanism alone. The term "hot-electron noise" is avoided here, since it has sometimes been used in the literature as a collective term referring to all noise mechanisms under conditions of T_e being significantly larger than T_l and its meaning has become obscured by such usage.

The spectral density of the velocity fluctuation noise, in the presence of a biasing electric field, cannot be calculated from Nyquist's theorem, even if the temperature T_0 is replaced by an elevated temperature such as T_l or T_e corresponding to the applied field. The difference between velocity fluctuation noise at equilibrium (which is just the thermal noise) at T_e, and velocity fluctuation noise under nonequilibrium conditions, arises in the following manner. In the presence of an electric field, the carriers gain energy from the field, and the carrier temperature T_e increases. The carrier scattering rate is a function of the lattice temperature T_l as well as the carrier temperature T_e, and therefore is influenced; for example, the intervalley scattering rate sharply increases with increasing electric field of a few kilovolts per centimeter in GaAs at room temperature. A variation of scattering rate with electric field will, in turn, cause a variation in carrier mobility and diffusivity in the presence of bias. The change of carrier mobility in the presence of an electric field will manifest itself as a nonlinearity in the terminal current–voltage (I–V) characteristic of the semiconductor sample, while a change of carrier diffusivity will manifest itself through a change in diffusion noise. This also explains microscopically why the changes in diffusion noise can be deduced from the nonlinearity of the I–V characteristic.

C. *Statement of Theorem*

The theorem that relates the spectral density of short-circuit noise current to the nonlinear I–V characteristic has been proved through thermodynamic, rather than microscopic, arguments in [14], and its interpretation in terms of electrical current and voltage is presented in [13]. Reference should be made to these papers for a careful and complete statement of the assumed postulates and of the theorem deduced from them. The final result is stated here briefly in a form that is directly useful for the problem at hand. The validity of this theorem has previously been demonstrated [13] by applying it to Schottky-barrier, p-n, and tunnel junctions for low bias levels. Here the theorem will be applied to bulk semiconductors, including the channel region of MESFET devices, under hot-electron conditions and in the presence of hot-electron effects such as intervalley-scattering in semiconductors with multivalley band structure.

For a class of nonlinear resistors defined in [13], which are maintained in a steady driven state (i.e., dc biased) not too far from equilibrium, this theorem expresses the terminal noise voltage and current in terms of 1) the nonlinear current–voltage characteristic of the resistor, 2) the magnitude of the dc bias current, and 3) the temperature. In common with the Nyquist theorem and other fluctuation-dissipation theorems, the microscopic details of the electrical conduction process are not explicitly required, and are implicitly included in the theorem via their effect on the terminal current–voltage characteristic of the resistor. For resistors with nonlinearity of the second order, the theorem expresses the power spectral density of the short-circuit noise current i_n at the terminals of the resistor as

$$S_{i_n}(f) = \frac{\overline{i_n^2}}{\Delta f} = 4kT_e\left[\frac{dI}{dV} - \frac{1}{2}I\left(\frac{d^2I/dV^2}{dI/dV}\right)\right] \quad (2)$$

where Δf is the bandwidth over which the mean square value $\overline{i_n^2}$ is determined, k is Boltzmann's constant, T_e is the absolute temperature of carriers participating in conduction, and V, I are the terminal voltage and current variables for the resistor, respectively. All derivatives are evaluated at the bias point at which the noise spectrum is to be calculated.

The above theorem can be directly applied to a bulk sample of semiconductor, or to the channel of a MESFET device treated as a two-terminal resistor between the source and the drain terminals. Examples of its application to Si, GaAs, and InP samples are presented in the next section. In carrying out a comparison with experimental results, it will be convenient to express the noise power spectrum in terms of the noise temperature. The noise temperature T_n for the two-terminal device can be determined with the help of (1), Y_{ss} being the linearized conductance (dI/dV) of the device. This is the "longitudinal" noise temperature, since the noise current in (2) is defined at the same pair of terminals at which the biasing voltage V is applied. The noise temperatures appearing in all subsequent discussions in this paper are also longitudinal. The excess noise temperature $T_n - T_0$, above the ambient temperature T_0, and normalized to T_0, is therefore

$$\frac{T_n - T_0}{T_0} = \frac{T_e}{T_0}\left[1 - \frac{1}{2}I\left(\frac{d^2I/dV^2}{(dI/dV)^2}\right)\right] - 1. \quad (3)$$

D. *Applicability of Results*

The following are the significant limitations to the use of the theorem:

1) High-Field Limitation: The theorem assumes that the noise generating carriers in the device under consideration can be described by a single carrier temperature. This requirement imposes some restrictions, and requires some precautions, in the use of the theorem. First, the electric field must be uniform everywhere in the device, so that the local carrier heating is the same everywhere. This implies that in devices with nonuniform structures, or when the applied field is so large that the field distribution inside the device becomes nonuniform [15], the theorem should not be applied at the terminals of the entire device treated as a whole. Second, when the electric field becomes so large that the distribution function of the carriers in the phase space cannot be adequately described by the Maxwell–Boltzmann distribution at an effective temperature T_e, the thermodynamic arguments on which the theorem is based are no longer valid. As a result, the noise calculated from the theorem can be expected to increasingly deviate from measured values at larger electric field strengths.

2) Upper-Frequency Limitation: The theorem predicts a flat (i.e., frequency-independent) noise power spectral density. Calculations of the autocorrelation function of velocity fluctuations show [3] that the correlation times are of the order of the relaxation time of the carriers, and are typically no more than 1 ps. The velocity fluctuation noise therefore can be expected to behave essentially as white noise for frequencies upto approximately 100 GHz. The theorem in (2) is limited to this frequency range only.

3) Low-Frequency Limitation: It should be remembered that the theorem accounts only for the velocity fluctuation noise. (However, unlike some other theoretical models [16], the intervalley-scattering noise does not have to be separately accounted for; it is subsumed in the total velocity fluctuation noise predicted by the theorem, since the nonlinearity of the terminal I–V characteristics includes the effect of intervalley scattering). The measured noise power spectra show [4] that several other noise mechanisms including g-r and $1/f$ noise, may be simultaneously present at lower frequencies, and in some devices up to frequencies approaching 1 GHz. Consequently, the noise calculated from the theorem can provide only a lower bound to the total noise at these lower frequencies. Experimental measurements have also shown that at frequencies in and above the gigahertz range the noise mechanism is entirely velocity fluctuations, and the noise power spectra become flat (i.e., frequency independent); it is here that the results of the theorem should be compared with experimental data. The theorem therefore is useful for determining the intrinsic (as contrasted, for example, with upconverted) microwave noise in MESFET channels and other bulk regions of semiconductor under nonequilibrium conditions.

III. Experimental Verification

The validity of the theorem is verified by comparing the predicted noise power spectral density with experimentally measured values for bulk semiconductor samples, as well as MESFET channels, under hot-electron conditions. Application of the theorem requires only a knowledge of the dc current–voltage characteristic at the terminals of a two-terminal device. Numerous authors have reported in the literature the results of simultaneous measurements of dc I–V characteristic as well as the noise power spectral density on the same sample. From these, four example are chosen to illustrate the applicability of the theorem under different carrier heating situations. In the first three of these examples, the carrier temperature T_e is approximated by the ambient temperature T_0.

A. Bulk Silicon

Baechtold [17] reported the measured dc characteristic and noise temperature for an epitaxially grown n-type silicon layer of 3-μm length, having a donor density $N_D = 1.3 \times 10^{17}$ cm^{-3}, maintained at room temperature. His I–V characteristic is reproduced in Fig. 1(a), and the normalized excess noise temperature calculated from that characteristic, with the help of (3), is shown as a curve in Fig. 1(b). The measured values of normalized excess noise temperature at 4 GHz, obtained by Baechtold [17] as a function of dc bias, are shown by circles in Fig. 1(b). It is clear that the theorem is useful for noise prediction up to approximately 8 V bias, which corresponds to a field strength of 25 kV/cm.

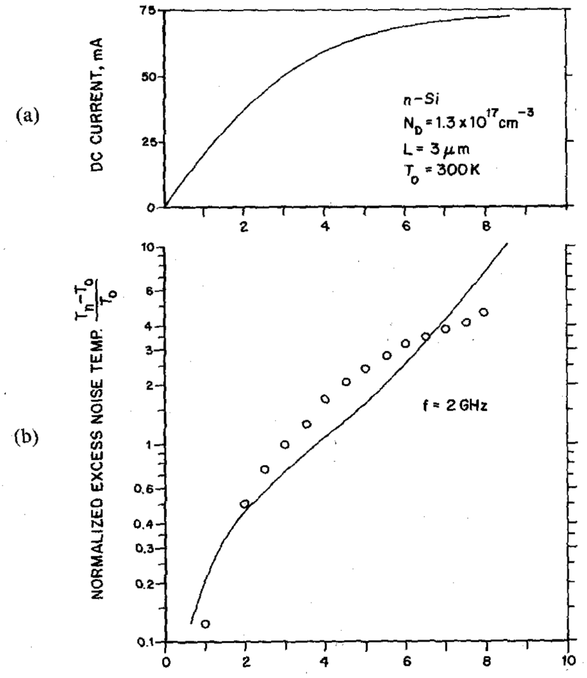

Fig. 1. (a) Measured dc current–voltage characteristic of a silicon epitaxial layer [17]. (b) Calculated (solid curve) and measured (circles) values of the normalized excess noise temperature of the sample.

B. Bulk InP

The second example is that of a semiconductor sample in which intervally scattering is present. Fig. 2(a) shows the dc I–V characteristic of an epitaxially grown n$^+$-n-n$^+$ InP mesa diode with an active region of length 5 μm and doping density $N_D = 2.7 \times 10^{15}$ cm^{-3}, maintained at room temperature, as reported by Gasquet *et al.* [15]. The normalized excess noise temperature for this sample, as calculated from (3), is drawn as a curve in Fig. 2(b) and the measured values [15] at 10.5 GHz are shown by circles in Fig. 2(b). The agreement with calculated values is satisfactory for voltages up to 3 V, which corresponds to a field of approximately 6 kV/cm. Theoretical calculations by Gasquet *et al.* [15] show that for bias voltages up to this magnitude, the electric field in the sample can be treated as being uniform everywhere except near the ends, so that a single carrier temperature can be ascribed to the entire sample without significant error. Their measurements also showed [15] that the noise power spectral densities were larger at frequencies below 1 GHz, and increased with decreasing frequency, indicating the presence of other noise mechanisms at lower frequencies.

C. GaAs MESFET Channel

The dc current–voltage characteristic of the channel of a commercial n-channel GaAs MESFET (Plessey-GAT1)

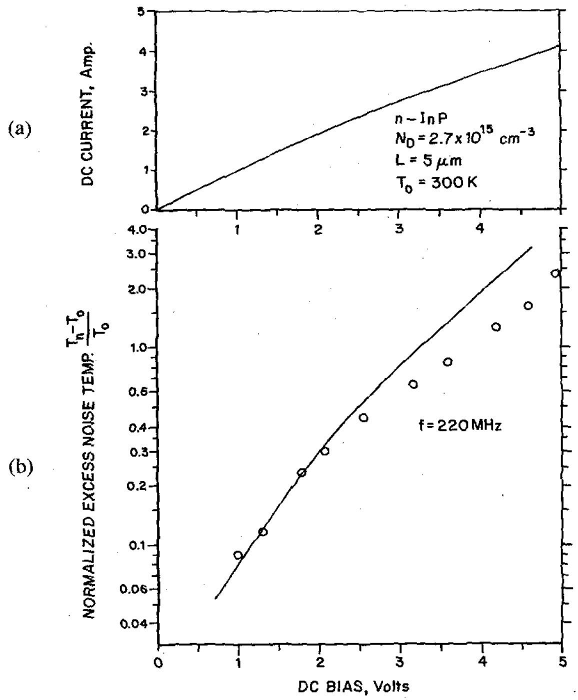

Fig. 2. (a) Measured dc current-voltage characteristic of an indium phosphide epitaxial layer [15]. (b) Calculated (solid curve) and measured (circles) values of the normalized excess noise temperature of the sample.

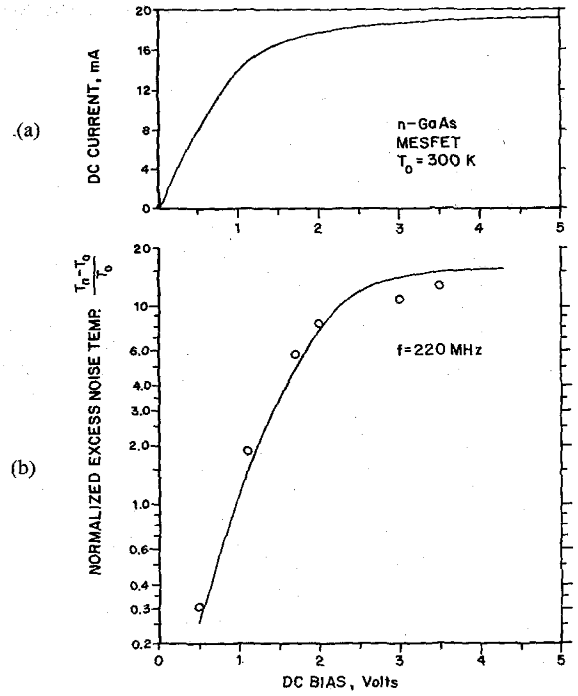

Fig. 3. (a) Measured dc current-voltage characteristic of the channel of an n-channel GaAs MESFET [18]. (b) Calculated (solid curve) and measured (circles) values of the normalized excess noise temperature of the sample.

at a temperature of 300 K, taken from the work of Sodini *et al.* [18], is shown in Fig. 3(a) for a zero gate voltage. The authors estimated that under dc bias conditions, the channel temperature increased by about 30 and 60 K for drain-to-source dc voltages of 2 and 4 V, respectively, and therefore the characteristic shown in Fig. 3(a) was measured under isothermal conditions at 300 K by carrying out low-duty-cycle pulsed measurements. The normalized excess noise temperature for the MESFET channel, calculated by applying (3) to the characteristic of Fig. 3(a), is shown by the curve in Fig. 3(b). Experimentally measured values of this noise temperature were found to be essentially independent of frequency over the frequency range explored (220 to 800 MHz), and are also plotted in Fig. 3(b) as circles for various bias voltages. From the agreement between calculated and measured noise temperatures, it may be concluded that the presence of the depletion-region under the gate, defining the lateral extent of the channel, has not invalidated the use of the theorem in (2).

D. GaAs at 77 K

The final example is of a 10-μm-long n-type GaAs sample with doping density 1-3 × 10^{15} cm^{-3}, maintained at 77 K. The measured dc *I-V* characteristic taken from the work of Maslov and Rzhevkin [19] is shown in Fig. 4(a). When this sample is kept at liquid-nitrogen temperature, where carrier energies are small, a large amount of carrier heating must take place on applying an electric field before any significant intervally transfer can occur. As a re-

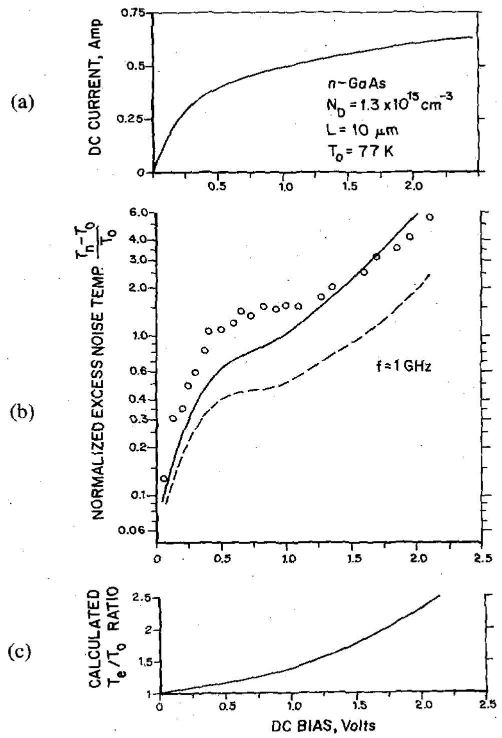

Fig. 4. (a) Measured dc current-voltage characteristic of a GaAs sample at 77 K [19]. (b) Calculated values of the normalized excess noise temperature of the sample, ignoring (dotted curve) and including (solid curve) the rise of electron temperature T_e above the lattice temperature T_l. Measured values shown by circles. (c) Calculated T_e/T_l ratio as a function of dc bias voltage for the sample under test.

sult, there should be a marked difference between the nature of noise temperature versus dc biasing field relationship for GaAs at liquid-nitrogen and at room temperatures. Such a difference is indeed observed experimentally. The normalized excess noise temperature for this sample, experimentally measured at 1 GHz as a function of dc bias and taken from [19], is shown as circles in Fig. 4(b). It shows a range of bias voltages in which the noise temperature of the sample increases very little with increasing bias, in contrast with the steep variation on either side of this voltage range. A detailed theoretical modeling of this phenomenon, involving the temperature sensitivity of conductivity and power dissipation, has been carried out by Maslov and Rzhevkin [20] in order to explain the plateau in the noise temperature versus bias plot.

As an alternative to such modeling, (3) can be used for predicting the behavior of noise temperature. In this case, however, since the carrier heating is large, the rise of T_e above T_l cannot be ignored. Since it is the electron temperature T_e that is required in (3), the variation of T_e with bias must be known before the bias dependence of T_n can be found. Maslov and Rzhevkin carried out [19] a numerical calculation of T_e for their sample, and their result is shown in Fig. 4(c). The information contained in Fig. 4(a) and (c) together is sufficient to evaluate the noise temperature from (3). The normalized excess noise temperature calculated in this manner is shown by the solid curve in Fig. 4(b). For comparison, a calculation of the same quantity from Fig. 4(a) and (3), and ignoring the carrier heating by assuming $T_e = T_0 = 77$ K, results in the dashed curve of Fig. 4(b) and shows a much poorer agreement with measured data. It is apparent that proper accounting for T_e is essential.

IV. ANALYTICAL APPROXIMATION FOR NOISE TEMPERATURE

The experimentally measured dc current–voltage characteristic of a semiconductor layer, or of the channel in a MESFET device, can often be fitted to an empirical algebraic relationship. A commonly used analytical approximation to the I–V characteristic of bulk GaAs layers at room temperature is the following [21]:

$$I = A \tanh (BV) \tag{4}$$

where A and B are empirically determined fitting constants that depend on numerous device parameter (as well as the gate-to-source voltage in the case of a MESFET channel). The empirical relationship (4) holds only for the range of low bias voltages, extending well above the "knee" where the current saturates but where carrier heating is not very large. For a sample obeying this relationship, the noise temperature can be determined directly by substituting (4) into (3). Then the noise temperature of the sample in the presence of a voltage V across it, is given by

$$\frac{T_n(V)}{T_0} = 1 + \sinh^2 (BV) \tag{5}$$

where the electron temperature has been approximated by the ambient temperature, since (4) itself is restricted to this condition. The spectral density of noise current for this sample, under the same conditions, is found from (2) to be bias-independent.

For low values of bias voltage, the field everywhere in the sample is uniform [15], except near ohmic contacts at the ends. In this case V can be expressed in terms of the electric field E and the sample length l, thus leading to an empirical relationship between excess noise temperature and electric field

$$\frac{T_n - T_0}{T_0} = \sinh^2 \left(\frac{B}{l} E\right). \tag{6}$$

This may be a better approximation than such empirical expressions as Baechtold's [16] cubic relationship

$$\frac{T_n - T_0}{T_0} = \delta \left(\frac{E}{E_{\text{sat}}}\right)^3 \tag{7}$$

which are often used in device modeling.

V. CONCLUSIONS

It has been shown that the author's nonlinear thermal noise theorem, stated in (2), is useful for calculating the noise temperature of two-terminal bulk semiconductor samples and channel region of MESFET devices, in the microwave frequency range and under nonequilibrium hot-electron conditions created by applied electric fields. This noise temperature can be calculated directly from a knowledge of the dc current–voltage characteristic of the two-terminal sample. In those cases where a large carrier heating occurs (as, for example, in GaAs at liquid-nitrogen temperatures), an estimate of the carrier temperature under the same high-field conditions is also required.

The applicability of the theorem has been demonstrated by applying it to various semiconductors, both with and without a multivalley band structure giving rise to intervalley scattering, at room as well as cryogenic temperatures, and to epitaxial layers as well as the channel region of a MESFET device. This theorem accounts only for the velocity fluctuation noise (including intervalley scattering noise), and yields the noise power spectral density at frequencies where the noise is white, i.e., at frequencies small compared to the inverse of the relaxation time in which the carrier velocity randomizes. While the theorem remains valid at all lower frequencies, the noise temperature it yields is not the total noise temperature at those low frequencies where other noise generating mechanisms, such as $1/f$ or g-r noise, are significant. In practice, therefore, the theorem would be useful for determining the total intrinsic noise in the microwave frequency range.

With the help of a typical analytical approximation to the dc I–V characteristic, it is shown that the excess noise temperature in a GaAs layer of MESFET channel can be expressed as an algebraic function of electric field. Such a relationship may be used to determine a "local" noise temperature in the modeling of nonuniform devices.

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