Monte Carlo Simulation of Microwave Noise Temperature in Cooled GaAs and InP

Jose Miguel Miranda Pantoja, *Member, IEEE*, Chih-I. Lin, Mohamed Shaalan, Jose Luis Sebastian, and Hans L. Hartnagel, *Fellow, IEEE*

***Abstract*—A simulation at microscopic level of the intrinsic microwave noise temperature associated to GaAs and InP semiconductors under far from equilibrium conditions has been performed. The dependence of the noise temperature on the electric field, doping level, and physical temperature has been investigated, and the results show the existence of threshold fields above which electron heating and partition noise due to intervalley scattering can make the cooling inefficient in terms of noise improvements. A comparison with available experimental data has also been made to verify the accuracy of the models used in the simulation.**

***Index Terms*—Microwave noise, Monte Carlo.**

I. Introduction

SEMIEMPIRICAL modeling of the noise temperature based on circuital techniques has demonstrated to be the best way to simulate the noise performance of different microwave devices, such as Schottky diodes [1]–[4] and low-noise transistors [5]–[7]. Monte Carlo techniques have also been applied to calculate the noise temperature in these devices at microscopic level [8]–[11], but strong requirements of computing power and memory storage are demanded by these calculations. Therefore, the integration of the Monte Carlo method in circuital computer-aided design (CAD) tools is still impractical. In addition, strong assumptions need to be made when setting the boundary conditions and degeneracy effects, and these assumptions usually limit the simulation at a microscopic level to a qualitative description of the device performance. Despite these limitations, recent work has shown that it is possible to predict noise measurements of real-world ungated transistors with Monte Carlo simulations [12]. Furthermore, the fast developments in microprocessor technology have made possible the simulation of noise at the microscopic level with affordable computers [13].

The most important feature of Monte Carlo techniques is that they enable us to investigate the physical origins of the noise sources in a semiconductor device. In addition, with a Monte Carlo simulation, it is possible to differentiate between noise and electron temperatures. These two temperatures may have quite different values [14], although it is a common practice to make them equal in the simulation of noise at the circuital level.

The subject of this paper is to investigate how the high-frequency noise temperature varies in GaAs and InP as a function of the physical temperature and under far from equilibrium conditions. This paper illustrates how the dynamics of the carriers in the material may play a major role in the calculation of the noise temperature. We have made extensive calculations of this temperature under different conditions of doping concentration, physical temperature, and applied field by using a Monte Carlo simulator that enables us to follow the fluctuations of charge carriers in the time domain. From these simulations, it has been possible to investigate under which conditions the cooling of the material may lead to an efficient reduction of the noise temperature.

We believe that this paper may be helpful for the investigation of an accurate physical model of noise in cooled Schottky diodes for mixing applications, where GaAs plays a major role, and also for low-noise transistors based on InP technology. In addition, an accurate modeling of the noise mechanisms in bulk semiconductors is essential to establish microwave noise measurements as a valuable tool for the qualification of semiconductor fabrication technologies.

Section II is devoted to the techniques used in our calculations. In this section, we describe how the noise temperature may be calculated in a simulation at microscopic level, as well as different hints to achieve a fairly high degree of efficiency. The calculations presented in this paper were performed with a personal computer in reasonable computing times. In Section III, we describe the results of our simulations and discuss the physical origins of the complex dependence presented by the microwave noise temperature in the hot electron regime. Different examples are presented in which the calculations are made from 10 to 300 K, and the doping concentration is swept from 10^{15} cm^{-3} to 10^{17} cm^{-3}. Finally, Section IV is devoted to the comparison between the results of the simulations and available experimental data.

II. Monte Carlo Simulation of Noise

The intrinsic noise temperature $T_N(f)$ can be calculated at microscopic level in a homogeneous semiconductor from the spectral density of current fluctuations $S_I(f)$ and the differential admittance $Y_D(f)$ [15] as

$$T_N(f) = \frac{S_I(f)}{4k\,\mathrm{Re}\{Y_D(f)\}} \tag{1}$$

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J. M. M. Pantoja and J. L. Sebastian are with the Departamento de Fisica Aplicada III, Universidad Complutense de Madrid, 28040 Madrid, Spain.

C.-I. Lin and H. L. Hartnagel are with the Institut für Hochfrequenztechnik, Technische Hochschule Darmstadt, D-64283 Darmstadt, Germany.

M. Shaalan is with Siemens AG, D-81359 Munich, Germany.

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where k is the Boltzmann constant. In the simulation of noise in homogeneous semiconductors at high frequencies, the fluctuations of velocity play the major role in the noise performance since the scattering mechanisms able to produce fluctuations in the number of carriers are usually slow and relax at microwave frequencies and beyond. This is the case for the generation recombination processes and also for the most important trapping centers due to crystalline defects and undesired impurities. If the fluctuation of the number of carriers is neglected, (1) leads directly to

$$T_N(f) = \frac{qS_V(f)}{4k\mu_D(f)} \tag{2}$$

where S_V is the spectral density of velocity fluctuations and μ_D is the differential mobility.

The Monte Carlo scheme for the noise simulation is essentially divided into the calculation of the following parameters.

1) *The instantaneous carrier velocities and energies at regular time intervals.* This part is developed as in any conventional Monte Carlo simulator of carrier transport in semiconductors [16].
2) *The mean velocity and mean energy, both obtained by averaging the instantaneous values.* The mean energy directly gives the mean electron temperature via the equipartition law (see below). In addition, by calculating the mean velocities at different applied fields, the differential mobility for (2) can be obtained numerically.
3) *The instantaneous velocity fluctuations at the time intervals used in 1).* This is obtained by simply calculating the modulus of the difference between the mean and instantaneous velocity for each time interval.
4) *The spectral density of velocity fluctuations.* This calculation is usually performed by means of the Wiener–Khintchine theorem.

In a Monte Carlo simulation of noise, it is necessary to achieve a good compromise between accuracy and efficiency since one needs to reach the convergence not only in the velocity, but also in its fluctuations. In the estimation of the instantaneous velocities and energies, it is possible to achieve dramatic improvements of the efficiency if the time between consecutive collisions is obtained with the algorithm of San Giorgi *et al.* [17]. In our simulator, the discretization of the total scattering rate has been made with a step function of six intervals. The width of each interval has been optimized with a scheme based on the algorithm of Powell [18], which is the goal for this optimization to minimize the difference between the step function and total scattering rate. With this simple procedure, it is possible to reduce the self scattering events below 30% of the total collisions, thus obtaining a noticeable improvement of the efficiency without any degradation of the accuracy [19].

The physical models used in the simulator are well known, and have been taken from [16] for the simulations at 300 K. However, in order to avoid inaccuracies in the calculations at low temperatures, it is necessary to take into account the dependence of the GAP energy (energy difference between conduction and valence band), effective mass, dielectric permittivity, and phonon energies with temperature. This dependence has been considered in our simulation by using the analytical models suggested in [20] and [21]. Three types of valleys (main, L, and X valleys) were considered in both GaAs and InP, and nonparabolicity effects were also taken into account. Neutral impurity scattering has been neglected since it is not an electrostatic mechanism and, therefore, deviates very weakly the trajectories of the carriers. The results of our simulations will be presented as a function of the ionized impurity concentration, which can be considered equal to the free carrier concentration for the doping ranges investigated in this paper.

The electron temperature T_{EL} is obtained by assuming the validity of the equipartition principle

$$T_{\mathrm{EL}} = \frac{2}{3k}E \tag{3}$$

where E is the mean energy. This energy is calculated by promediating the energies in all the valleys of the conduction band with weighting factors equal to the total times spent by the carriers in each valley. The equipartition principle can be considered accurate up to electron concentrations of around $4 \cdot 10^{17}$ cm^{-3}. At higher doping levels, degeneracy effects such as those imposed by the Pauli Exclusion Principle and also the electron–electron scattering must be taken into account [22], [23].

Although the well-known Wiener–Khintchine theorem can be used in the calculation of the noise spectrum, we have performed most of the spectral estimations presented in this paper with a novel procedure based on the maximum entropy method (MEM). This procedure enables us to estimate the spectrum with a fairly high degree of efficiency, especially when the carrier population at the satellite valleys is negligible. Under these conditions, the resulting spectrum is nearly Lorentzian [13] and the autoregressive transfer function obtained from the prediction coefficients of MEM provides us the spectrum with less than 150 poles and a fairly high degree of accuracy. In addition, the analytical approach provided by MEM is convenient in Monte Carlo simulations of noise since it provides a spectrum nearly free of statistical fluctuations. Nevertheless, it has been found that the Wiener–Khintchine theorem is more efficient for the calculation of non-Lorentzian spectra, such as those obtained in GaAs at very high fields. The autocorrelation function was estimated in this case with a double fast Fourier transform. The computing times needed to achieve the convergence of the spectra can further be minimized with windowing techniques. A Hann-type window effectively reduces the statistical noise of the spectra, but it is necessary to apply it to the tail of the autocorrelation function instead of to the full function, otherwise strong inaccuracies in the spectral estimations at the lowest frequencies are obtained. The total simulation time spent in the calculations of the noise temperature was 10 h per curve with a first-generation 200-MHz personal computer.

III. Results of the Simulation

We have performed different simulations of the noise temperature at microwave frequencies in n-type samples of GaAs

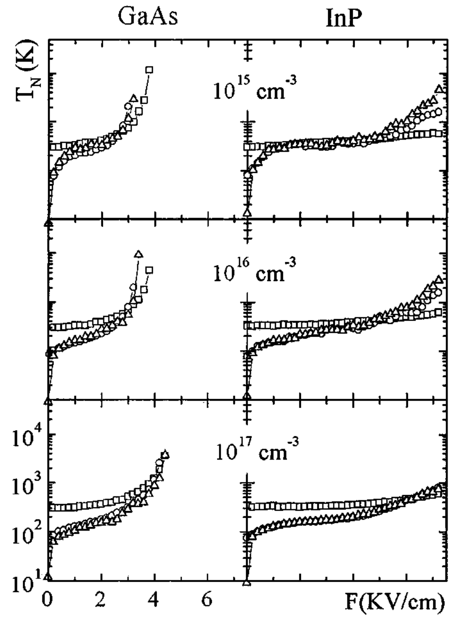


Fig. 1. Calculated noise temperature as a function of the electric field. Squares: 300 K. Circles: 77 K. Triangles: 10 K.

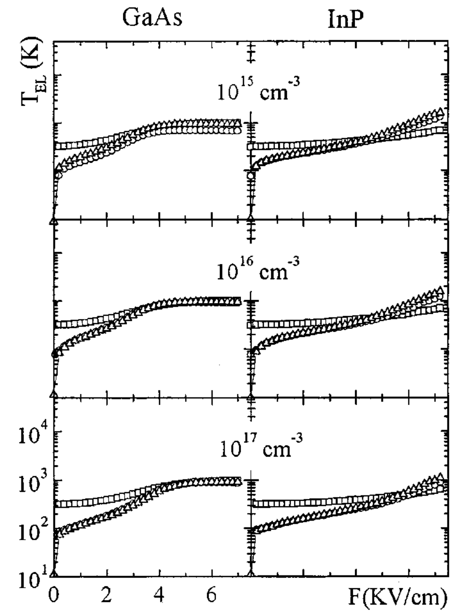


Fig. 2. Electron temperature calculated from the equipartition law and the mean energy. Squares: 300 K. Circles: 77 K. Triangles: 10 K.

and InP with levels of ionized impurities, which are typical of a number of microwave devices, from 10^{15} to 10^{17} cm^{-3}. The noise temperature is depicted in Fig. 1, where it can be seen that it is possible to reach threshold electric fields above which the cooling of both GaAs and InP makes the material noticeably noisier. This increase of the noise temperature is particularly remarkable at the lowest doping levels. The cooling of GaAs from 300 to 10 K at 3 kV/cm can make the noise temperature to increase as much as an order of magnitude. Similar results may be observed in InP excited with electric fields around 7 kV/cm. Only under near-equilibrium conditions it is possible to effectively reduce the noise temperature by cooling the material. This fact becomes critical when the physical temperature is lowered from 77 to 10 K since the noise temperature in these two cases is nearly the same from 0.4 kV/cm to the threshold fields above which the partition noise generated by the transfers to satellite valleys becomes important.

The performance of the noise temperature at 300 K is qualitatively different from that at low temperatures. In fact, a sophisticated dependence of this temperature on the physical temperature, electric field, and doping level is obtained in both InP and GaAs. At 300 K, the carriers have enough energy to emit phonons even under equilibrium conditions, and also the phonon population in the material is high enough to make phonon absorption probable. Under these conditions, the phonons operate as an efficient thermal regulator for the carriers, and this results into a smooth noise temperature increase as a function of the field. However, at 77 and 10 K, the carriers need to be heated by an external field in order to reach energies that enable them to emit phonons with a nonnegligible probability. If the doping level is low, there are nearly no scattering mechanisms at these temperatures and the carriers suffer a strong heating, even at very low fields. This heating noticeably increases the noise temperature under these conditions, but a saturation is obtained when phonon emission becomes probable. If the doping level is moderate or high, impurity scattering can reduce the electron heating. However, this scattering mechanism is effective only at very weak fields and, therefore, it can only make the electron heating to appear at slightly higher fields in doped materials. As a result, an abrupt increase of the noise temperature due to electron heating will always appear at low temperatures, no matter which material or which doping concentration we choose.

The phonon emission is not able to keep the noise temperature in saturation at very high fields since the transitions between the main and satellite valleys become important and generate strong partition noise. The high energy difference between the main and satellite valleys in InP makes the noise temperature saturation to appear in this material at fields as high as 5 kV/cm. In fact, a negligible population of InP satellite valleys was registered at all the applied fields and ionized impurity concentrations investigated in this paper.

Fig. 2 shows the electron temperature, which converges faster than the noise temperature due to the fact that the first one is free from the statistical fluctuations of the noise spectra. In addition, it is not necessary to obtain the differential mobility to calculate the electron temperature. The calculation of this mobility needs a strong amount of computing time, especially under near-equilibrium conditions. It can be seen from Fig. 2 that when GaAs is cooled and a high field is applied, the electron temperature noticeably differs from that of the noise temperature. Under these conditions, the intervalley scattering makes the noise temperature to suffer a strong increase due to partition noise, whereas the electron temperature suffers a saturation as a consequence of the electron cooling. Therefore, strong inaccuracies may result when the electron temperature is used to model hot electron noise sources in GaAs-based devices. However, the electron temperature remains close to the noise temperature in InP at all the doping levels and temperatures investigated in this paper.

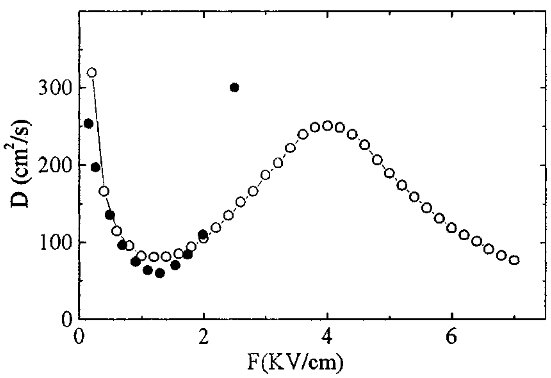


Fig. 3. Comparison between theoretical and experimental hot electron diffusion coefficient in GaAs with a doping concentration of 10^{15} cm^{-3} at 77 K.

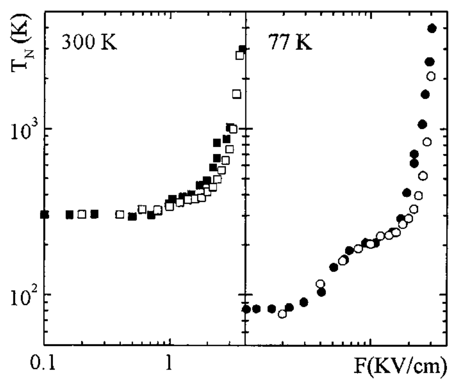


Fig. 4. Comparison between pulsed noise temperature measurements at 10 GHz and simulation. The doping concentration is 10^{15} cm^{-3}.

IV. Comparison with Available Experimental Data

Despite the lack of available experimental results on both mobility and microwave noise below 77 K, the direct relationship between the diffusion coefficient and the noise spectrum enables us to test the physical models used in the simulations. The diffusion coefficient can be obtained from the spectral density of velocity fluctuations at zero frequency [15]

$$D = \frac{S_V(0)}{4}. \quad (4)$$

Our calculations at 300 K give a diffusion coefficient of 230 cm^2/s for GaAs and 130 cm^2/s for InP. Both values are in excellent agreement with previous work [24]. Fig. 3 shows a comparison between the calculated diffusion coefficients in GaAs at 77 K and those measured by Bareikis *et al.* [25]. The agreement is considered excellent at all the fields with the exception of the last experimental point, which strongly deviates from the simulated curve. However, this measured point may be conciliated with the theoretical curve if one takes into account that the autocorrelation function of velocity fluctuations did not reach a negligible value in the sample measured at 77 K and 2.5 kV/cm. The Monte Carlo calculations show that the autocorrelation function needs around 10 ps to reach a negligible value, and the mean velocity obtained for this field reveals that the carriers cross a total length of 3 μm in this time, which is comparable to the size of the sample used by Bareikis *et al.* in their measurements—7.5 μm [25]. Therefore, it is reasonable to assume that the measurements under these conditions cannot directly be compared to the simulation, in which full thermalization is implicitly assumed. The assumption that the spectral density of velocity fluctuations experiments an overshoot when the thermalization is not complete is consistent with previous work [26], [27]. This overshoot partially compensates the well-known velocity overshoot effects and, under the conditions of this experiment, the measured noise temperature may accurately be reproduced even at the largest fields. This can be seen in Fig. 4, which shows the pulsed noise temperature measured at 10 GHz with the same sample used to obtain the experimental diffusion coefficient shown in Fig. 3.

V. Concluding Remarks

The cooling of GaAs and InP may lead to an efficient reduction of the microwave noise temperature only when the applied electric fields are close to thermal equilibrium conditions. In fact, it has been shown that it is possible to reach threshold fields above which the cooling can degrade the noise performance of the semiconductor, due to the enhancement of the electron heating and intervalley scattering. In addition, the relevance of this last mechanism at low temperatures can lead to strong inaccuracies in the noise calculations of cryogenically cooled GaAs devices if the electron temperature is utilized to model the noise sources of the device. Therefore, the simulation of these devices at circuital level needs the use of a hybrid approach in which Monte Carlo schemes are used to calculate the noise sources.

References

[1] M. Trippe, G. Bosman, and A. Van Der Ziel, "Transit time effects in the noise of Schottky barrier diodes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1183–1192, Nov. 1986.

[2] A. Jelenski, E. Kollberg, and H. Zirath, "Broad band noise mechanisms and noise measurements of metal-semiconductor junctions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1193–1201, Nov. 1986.

[3] H. G. Zirath, S. M. Nielsen, H. Hjelmgren, L. P. Ramberg, and E. L. Kollberg, "Temperature variable noise characteristics of Au-GaAs Schottky barrier millimeter-wave mixer diodes," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1469–1476, Nov. 1988.

[4] A. Jelenski, A. Grüb, V. Krozer, and H. L. Hartnagel, "New approach to the design and the fabrication of THz Schottky barrier diodes," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 549–557, Apr. 1993.

[5] M. W. Pospieszalski, "Modeling of noise parameters of MESFET's and MODFET's and their frequency and temperature dependence," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1340–1350, Sept. 1989.

[6] A. Cappy, "Noise modeling and measurement techniques," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1–10, Jan. 1988.

[7] A. Cappy, A. Vanoverschelde, M. Schortgen, C. Versnaeyen, and G. Salmer, "Noise modeling in submicrometer-gate two dimensional electron gas field effect transistor," *IEEE Trans. Electron Devices*, vol. ED-32, pp. 2787–2795, Dec. 1985.

[8] T. González, D. Pardo, L. Varani, and L. Reggiani, "A microscopic interpretation of hot-electron noise in Schottky barrier diodes," *Semiconduct. Sci. Technol.*, vol. 9, pp. 580–583, 1994.

[9] ——, "Monte Carlo analysis of noise spectra in Schottky-barrier diodes," *Appl. Phys. Lett.*, vol. 63, no. 22, pp. 3040–3042, 1993.

[10] E. Starikov, P. Shiktorov, V. Gruzinskis, L. Varani, J. C. Vaissiere, J. P. Nougier, and L. Reggiani, "Monte Carlo calculation of noise and small-signal impedance spectra in submicrometer GaAs n^+nn^+ diodes," *J. Appl. Phys.*, vol. 79, no. 1, pp. 242–252, 1996.

[11] T. González, D. Pardo, L. Varani, and L. Reggiani, "Monte Carlo analysis of the behavior and spatial origin of electronic noise in GaAs MESFET's," *IEEE Trans. Electron Devices*, vol. 42, pp. 991–998, May 1995.

[12] J. Mateos, T. González, D. Pardo, P. Tadyszak, F. Danneville, and A. Cappy, "Numerical and experimental analysis of the static characteristics and noise in ungated recessed MESFET structures," *Solid State Electron.*, vol. 39, no. 11, pp. 1629–1636, 1996.

[13] J. M. M. Pantoja, J. L. Sebastián, and S. Muñoz, "Coupled maximum entropy—Monte Carlo estimation of microwave, mm-wave and sub mm-wave spectrum of velocity fluctuations in GaAs," *Appl. Phys. Lett.*, vol. 72, no. 2, pp. 238–240, 1998.

[14] L. Varani, P. Houlet, J. C. Vaissiere, J. P. Nougier, E. Starikov, V. Gruzinskis, P. Shiktorov, L. Reggiani, and L. Hlou, "A model noise temperature for non linear transport in semiconductors," *J. Appl. Phys.*, vol. 80, no. 9, pp. 5067–5075, 1996.

[15] A. van der Ziel, *Noise in Solid State Devices and Circuits*. New York: Wiley, 1986.

[16] C. Jacoboni and P. Lugli, *The Monte Carlo Method for Semiconductor Device Simulation*. Berlin, Germany: Springer-Verlag, 1989.

[17] E. Sangiorgi, B. Ricco, and F. Venturi, "MOS2: An efficient Monte Carlo simulator for MOS devices," *IEEE Trans. Computer-Aided Design*, pp. 259–271, July 1988.

[18] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes in C: The Art of Scientific Computing*, 2nd ed. Cambridge, U.K.: Cambridge Univ. Press, 1995.

[19] J. M. Miranda, C. Lin, M. Shaalan, H. L. Hartnagel, and J. L. Sebastian, "Influence of the minimization of self-scattering events on the Monte Carlo simulation of carrier transport in III–V semiconductors," *Semiconduct. Sci. Technol.*, vol. 14, pp. 804–808, 1999.

[20] J. S. Blakemore, "Semiconducting and other major properties of gallium arsenide," *J. Appl. Phys.*, vol. 53, no. 10, pp. R123–R179, 1982.

[21] M. V. Fischetti, "Monte Carlo simulation of transport in technologically significant semiconductors of the diamond and zin–blende structures—Part I: Homogeneous transport," *IEEE Trans. Electron Devices*, vol. 38, pp. 634–649, Mar. 1991.

[22] T. Gonzalez, J. E. Velazquez, P. M. Gutierrez, and D. Pardo, "Electron transport in InP under high electric field conditions," *Semiconduct. Sci. Technol.*, vol. 7, pp. 31–36, 1992.

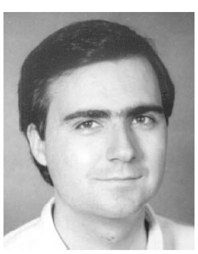
[23] J. M. M. Pantoja and J. L. Sebastián, "Monte Carlo simulation of electron velocity in degenerate GaAs," *IEEE Trans. Electron Device Lett.*, vol. 18, pp. 258–260, June 1997.

[24] M. Shur, *Physics of Semiconductor Devices*, ser. Solid-State Physical Electronics. Englewood Cliffs, NJ: Prentice-Hall, 1990.

[25] V. Bareikis, J. Liberis, I. Matulionienè, A. Matulionis, and P. Sakalas, "Experiments on hot electron noise in semiconductor materials for high-speed devices," *IEEE Trans. Electron Devices*, vol. 41, pp. 2050–2060, Nov. 1994.

[26] T. Gonzalez, J. E. Velazquez, P. M. Gutierrez, and D. Pardo, "Analysis of the transient spectral density of velocity fluctuations in GaAs and InP," *J. Appl. Phys.*, vol. 72, no. 6, pp. 2322–2330, 1992.

[27] P. Shiktorov, V. Gruzhinskis, E. Starikov, L. Reggiani, and L. Varani, "Transient-time effect on electronic noise in submicron $n^{+}nn^{+}$ structures," *Appl. Phys. Lett.*, vol. 68, no. 11, pp. 1516–1518, 1996.



Jose Miguel Miranda Pantoja (M'92) was born in Madrid, Spain, in 1965. He received the degree of Licenciado in physics and the Ph.D. degree from the University Complutense de Madrid, Madrid, Spain, in 1989 and 1998, respectively.

In 1990, he was the recipient of a fellowship funded by IBM, under which he was involved in the development of CAD tools for low-noise amplifier design for three years. Since 1991, he has been Associate Lecturer, Faculty of Physics, University Complutense. He has been a Visiting Researcher at the Technical University of Darmstadt, Darmstadt, Germany, and at the University of Chalmers, Göteborg, Sweden. His current research interests are in the area of noise modeling and measurement of semiconductor devices.

Dr. Pantoja was awarded the "Premio Extraordinario de Doctorado" for his doctoral dissertation.

Chih-I. Lin was born in Taipei, Taiwan, R.O.C., in 1966. He received the B.Sc. degree from the Tsing-Hua University, Hsing-Chu, Taiwan, R.O.C., in 1988, the Dipl.-Ing. degree in electrical engineering from the Darmstadt University of Technology, Darmstadt, Germany, in 1995, and is currently working toward the Ph.D. degree at the Darmstadt University of Technology.

In 1996, he joined the Terahertz Group, Darmstadt University of Technology. His current research interest is focused on terahertz electronics, including the development of Schottky diodes and integrated diode arrays and circuits for mixing and frequency-multiplying applications in the submillimeter-wave region.

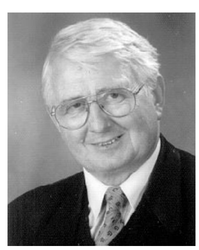
Mohamed Shaalan was born in Cairo, Egypt, in 1967. He received the B.Sc. degree from Ain-Shams University, Cairo, Egypt, in 1989, and the M.Sc. (Diplom-Ingenieur) and Ph.D. (Doktor-Ingenieur) degrees from the Darmstadt University of Technology, Darmstadt, Germany, in 1994 and 1998, respectively.

His research was focused on the use of nonlinear devices integrated with planar antennas for the generation of submillimeter-wave signals by means of quasi-optical techniques. He is currently with SIEMENS AG, Munich, Germany, mainly in the field of cellular base-station technology, in particular, the analog radio-frequency part.

Jose Luis Sebastian was born in Zaragoza, Spain, in 1950. He received the Licenciatura and Licenciado degrees from the University Complutense de Madrid, Madrid, Spain, in 1973 and 1974, respectively, and the Ph.D. degree from the University of Surrey, Surrey, U.K., in 1977, all in physics.

In 1977, he joined the University Complutense de Madrid, as a Reader, and in 1983, he became a Full Professor of electricity and magnetism. He has authored numerous scientific papers on topics related to microwave low-noise and high-power amplifiers, as well as topics related to electromagnetic-field calculations on biological tissues. He also authored a book on electromagnetic compatibility for undergraduate students.

Prof. Sebastian is currently chairman of the Spanish URSI Committee.



Hans L. Hartnagel (SM'72–F'92) received the Dipl.-Ing. degree from the Technical University of Aachen, Aachen, Germany, in 1960, the Ph.D. and Dr.Eng. degrees from the University of Sheffield, Sheffield, U.K., in 1964 and 1971, respectively.

After having been with Telefunken, Ulm, Germany, for a short period, he joined the Institute National des Sciences Appliquées, Villeurbanne, Rhône, France, and then the Department of Electronic and Electrical Engineering, University of Sheffield, as a Member of staff. In January 1971, he became a Professor of electronic engineering at the University of Newcastle upon Tyne, Newcastle upon Tyne, U.K.. Since October 1978, he has been the Professor of high-frequency electronics at the Technical University of Darmstadt, Darmstadt, Germany. He has authored several books and numerous scientific papers on microwave semiconductors, devices, and their technology and circuits. He has held many consulting positions, partly while on a temporary leave of absence from his university positions.

Dr. Hartnagel was awarded the Dr.h.c. degree from the University of Rome "Tor Vergata," Rome, Italy, in 1994, and the Dr.h.c. degree from the Technical University of Moldova, Kishinev, Romania, in 1999.