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Generation-recombination noise analysis in heavily doped *p*-type GaAs transmission line models

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Low-frequency noise measurements are performed on heavily doped p-type GaAs transmission line models. Excess noise exhibits $1/f$ noise and generation-recombination (GR) noise components. A study of the GR components vs device geometry shows the spectral densities due to contact resistances to be negligible. Thus the noise sources due to the volume resistances are predominant, and have to be located in the bulk layer or in the space-charge region of the devices. These two possibilities concerning the location of the GR noise sources are investigated. For both cases, expressions for the variance and the relaxation time associated to fluctuations in the charge carriers are given. The comparison between the experimental data with the theoretical results shows that the GR noise sources are located in all probability in the space-charge region. © *1996 American Institute of Physics.* [S0021-8979(96)02406-9]

I. INTRODUCTION

Heterojunction bipolar transistors (HBTs) are of great interest for many microwave applications,[1] due in part to their supposed feeble low-frequency noise level. However, it turns out that low-frequency noise measurements in AlGaAs/GaAs HBTs exhibit excess noise composed of $1/f$ noise and generation-recombination (GR) noise.[2–5] This excess noise is often assumed to come from the base layer. This article is a contribution to the study of GR noise in the base by performing low-frequency noise measurements on base-related transmission line models TLMs. Conduction takes place in the heavily doped p-type base and is analogous to that of the base current.

In Sec. II, the structure of devices studied is given. In Sec. III, measurements are presented. The spectral densities show $1/f$ and GR phenomena. Their decomposition into several components is explained. In Sec. IV, a study of noise vs length between contacts will permit one to distinguish between contact and volume noise. In Sec. V, theoretical expressions of the variance of the spectral densities and of the GR time constants are established. Experimental results are then discussed. In Sec. VI, noise measurements vs temperature are presented.

II. DEVICE STRUCTURE

Transmission line model (TLM) test structures consist of various resistances. The values of these resistances are determined by the distance between the contacts. In this study, the devices are constituted of all the layers from subcollector to base of the associated AlGaAs/GaAs HBTs.

A schematic cross section of the device is given in Fig. 1. Devices are issued from a metal-organic chemical vapor deposition (MOCVD) process. A layer of AlGaAs of a few nm thick only is left between contacts. This layer is completely depleted and acts as an electrical passivation ledge.[6] The p^{++} GaAs base layer is very heavily C-doped, with a doping equal to $p^{++}=4\times10^{19}$ cm^{-3}. The thickness of this layer is 90 nm.

Devices with different lengths between contacts are available: $L_1=5$ μm. $L_2=15$ μm, $L_3=30$ μm, and sometimes $L_4=130$ μm. The width of these devices is 80 μm.

The measured resistance R of these devices comprises a volume resistance R_V and two contact resistances R_c. These resistances are related by

$$R=R_V+2R_c. \tag{1}$$

For all samples, $2R_c$ measured was always about 3 Ω.

III. EXPERIMENT

Low-frequency voltage noise measurements were performed in the range 1 Hz–100 kHz using a FFT analyzer. Care was taken that whatever the bias current, devices always exhibited an ohmic behavior. Thus we can write for the spectral densities:

$$\frac{S_V}{V^2}=\frac{S_I}{I^2}=\frac{S_P}{P^2}=\frac{S_R}{R^2} \tag{2}$$

with S_V, S_I, S_P, S_R the spectral densities associated to fluctuations of voltage, current, charge carriers, and resistance; V, I, P, and R being the voltage, current, number of free charge carriers, and measured resistance, respectively.

All spectra showed excess noise composed of a $1/f$ component, several generation-recombination components, and white noise.[7] For all TLMs, spectral densities were decomposed using a least square fit method with the help of the following relation:

$$S_R=\frac{b}{f}+\sum_{i=1}^{z}\frac{C_i}{1+\omega^2\tau_i^2}+S_{R\text{white}} \tag{3}$$

with b the value at 1 Hz of the $1/f$ noise, C_i the value of the plateau of the GR component with τ_i the GR time constant.

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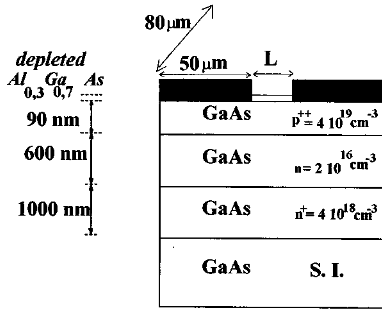

FIG. 1. Structure of a TLM.

τ_i is associated to the cut-off frequency by

$$\tau_i = \frac{1}{2\pi f_i}. \tag{4}$$

The white noise is defined by

$$S_{R\text{white}} = \frac{S_{V\text{white}}}{I^2}. \tag{5}$$

The voltage white noise $S_{V\text{white}}$ in the case of TLMs is thermal noise $4kTR$ calculated with the value of the measured resistance R. An example of a spectrum decomposed into its different components is presented in Fig. 2.

All the spectral densities exhibited a quadratic evolution with bias current I. In this article we will be interested only in the GR noise.

IV. EVOLUTION OF SPECTRAL DENSITIES WITH LENGTH

In order to distinguish between noise due to the access resistances and noise due to the volume resistances, a study of the GR phenomena vs length L between contacts must be performed.

A. Theoretical expressions

As fluctuations in volume resistances and contact resistances [cf. relation (1)] are uncorrelated, the measured spectral density of the GR noise is such as

$$S_R = S_{R_v} + S_{2R_c} \tag{6}$$

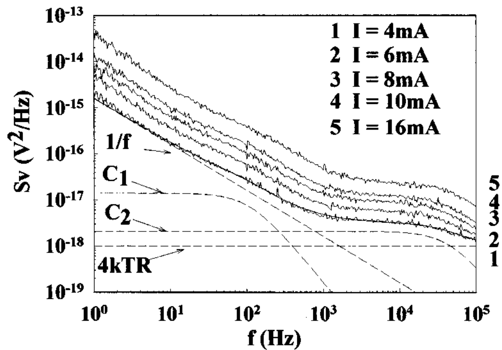

FIG. 2. Noise spectra for various base currents of TLM with length between contacts $L = 30$ μm. Decomposition of a spectral density into its different components.

with S_{R_V} and S_{2R_c} the GR spectral densities associated to the volume resistance R_V and to the contact resistances R_c, respectively.

Generation-recombination spectral densities due to the volume resistance obey the following law:

$$\frac{S_{R_V}}{R_V^2} = \frac{S_p}{P^2} = \frac{1}{P^2} \sum_{i=1}^{z} \frac{4\tau_i A_i}{1+\omega^2\tau_i^2} \tag{7}$$

with P the number of carriers in the p-type layer, τ_i the time constant, and A_i a parameter related to the plateau of the GR component.

The variance $\overline{\Delta P^2}$ associated with the fluctuations of the charge carriers is given by

$$\overline{\Delta P^2} = \int_0^\infty S_p \, df = \sum_{i=1}^{z} \int_0^\infty \frac{4\tau_i A_i \, df}{1+(2\pi\tau_i)^2 f^2} = \sum_{i=1}^{z} A_i. \tag{8}$$

For the GR spectral density due to contact resistances we have

$$S_{2R_c} \propto \sum_{j=1}^{y} \frac{K_j \tau_j}{1+\omega^2\tau_j^2} \tag{9}$$

with K_j a coefficient independent of length L.

As P, R_V, and $\overline{\Delta P^2}$ should be proportional to length between contacts L, relation (6) becomes with the help of relations (7) and (9):

$$S_R \propto \left[\sum_{i=1}^{z} K_i \frac{\tau_i}{1+\omega^2\tau_i^2} L + \sum_{j=1}^{y} K_j \frac{\tau_j}{1+\omega^2\tau_j^2} \right] \tag{10}$$

with K_i and K_j coefficients independent of length L.

Hence, if noise due to access resistances is predominant, no evolution with length L is to be seen.

B. Experimental results

It is possible to estimate values of $\overline{\Delta P^2}/P^2$ from experimental results. In the ohmic regime, the quantity $\overline{\Delta P^2}/P^2$ is defined by

$$\frac{\overline{\Delta P^2}}{P^2} = \int_0^\infty \frac{S_p}{P^2} \, df = \int_0^\infty \frac{S_{R_v}}{R_v^2} \, df = \frac{\Sigma_{i=1}^{z} A_i}{P^2} \tag{11}$$

with S_P and S_{R_v} the GR spectral densities associated with fluctuations of carriers and fluctuations of resistance, respectively.

By integrating the expression for the GR noise given in relation (3), relation (11) becomes

$$\frac{\overline{\Delta P^2}}{P^2} = \frac{1}{4R_v^2} \sum_{i=1}^{z} \frac{C_i}{\tau_i}. \tag{12}$$

We estimated the ratio $\overline{\Delta P^2}/P^2$ for different TLMs using values of the GR plateaus and time constants issued from the decomposition of the Lorentzians. An example of values with an accuracy of 10% of $\overline{\Delta P^2}/P$ calculated using relation (12) and values of P is given in Table I.

The evolution of $\overline{\Delta P^2}/P^2$ with length L is studied. We have reported values of $\overline{\Delta P^2}/P^2$ vs $1/L$ in Fig. 3.

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TABLE I. Values of the measured resistance R_v, of $\overline{\Delta P^2}/P$, and of $1/P$ for different TLMs of length between contacts $L_3=30$ μm and for a bias current $I=8$ mA.

TLM	R_v (Ω)	$\frac{\overline{\Delta P^2}}{P}$	$\frac{1}{P}$
1	121	9.2×10^{-3}	1.2×10^{-10}
2	113	6.3×10^{-3}	1.2×10^{-10}
3	109	5.2×10^{-3}	1.2×10^{-10}

By considering the fact that the number of carriers P is proportional to L, the experimental evolution is

$$\overline{\Delta P^2} \propto L^s \quad \text{with} \quad 0.8 \leqslant s \leqslant 1.$$

According to relation (10), each GR component must be analyzed separately. We then can study S_R vs length L when $f \rightarrow 0$. The evolution with L of the plateau extracted by fit has been plotted in Fig. 4 for a GR component with a cut-off frequency of about 45 kHz at room temperature.

In Fig. 4 we observe a linear evolution of the GR plateaus with L. Thus the noise due to the access resistances is not predominant at larger values of L. The same results were obtained on analogous nonpassivated devices. This leads to the assumption of GR sources located in the volume or at the p^{++}-GaAs/n-GaAs interface.

C. Simulation

The electrical isolation of the p-n junction should be sufficient for limiting conduction in the p^{++}-GaAs layer. However, leakage currents in the space-charge region on the n-GaAs side must be considered. The percentage of leakage currents may not be negligible due to the low thickness ($\leqslant 90$ nm) of the p^{++}-GaAs layer. Another interest of the simulation of the current in this TLM is that the conduction is the same as that of the base current in a HBT.

Hence, a bi-dimensional simulation has been performed on the structure centered around the p^{++}-GaAs/n-GaAs junction. Results of the current density distribution in the device is given in Fig. 5.

The peak of the current density seen in Fig. 5 should be due to the passage of carriers into a zone of higher mobility. The major part of the conduction is located in the 90 nm of the bulk layer, but the interesting part of the result obtained is that conduction also takes place on about 10 nm in the SCR on the n-GaAs side. Even if this leakage current is small, it can contribute to a GR process revealed by noise measurements. In view of these simulation results, the GR noise sources can indeed be located in the bulk or in the SCR.

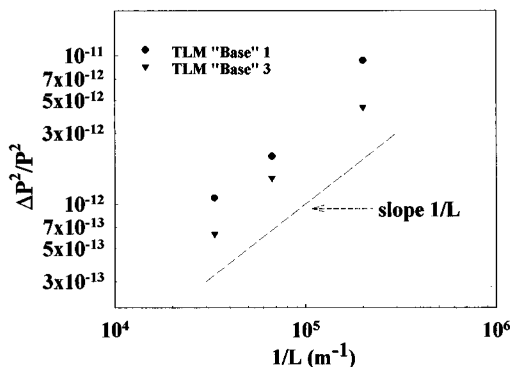

FIG. 3. $\overline{\Delta P^2}/P^2$ vs length between contacts L.

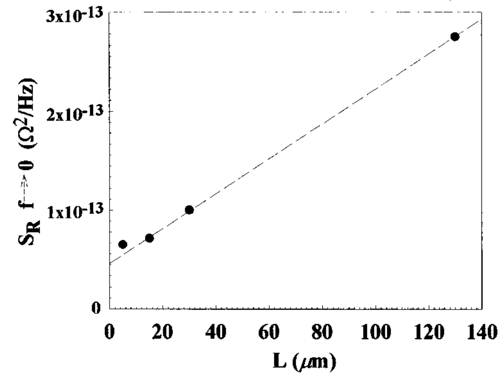

FIG. 4. Plateau vs length between contacts L for TLM 2 at $I=8$ mA.

V. GR NOISE FEATURES IN THE BULK AND IN THE JUNCTION

Expressions for the variance and the relaxation time associated to GR phenomena are given hereafter. We consider two cases: first GR noise in the p^{++}-GaAs bulk, and then GR noise in the space-charge region between the p^{++}-GaAs and the n-GaAs.

A. Noise due to traps located in the p^{++}-GaAs bulk

The material studied here is a heavily doped p-type GaAs layer. Regarding its high doping of 4×10^{19} cm^{-3}, the material is considered to be degenerate. The variance $\overline{\Delta P^2}$ characterizes generation-recombination noise. In any case it holds that $\overline{\Delta P^2}$ has to be equal or smaller than P. From the values of $\overline{\Delta P^2}/P$ presented in Table I, we get $\overline{\Delta P^2} \ll P$.

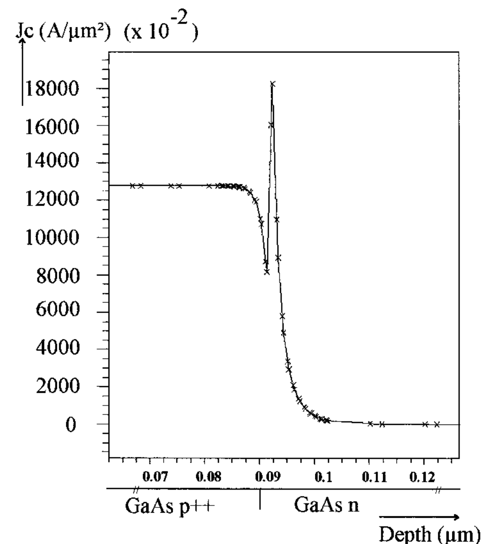

FIG. 5. Simulation of conduction in the TLM.

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1. Theoretical expressions

Theoretically, the variance $\overline{\Delta P^2}$ for semiconductors is given by[8]

$$\overline{\Delta P^2}=\frac{1}{1/P+1/P_T+1/(Z_T-P_T)} \tag{13}$$

with P the number of free charge carriers in the valence band, P_T the number of traps occupied by holes, Z_T the number of traps.

P_T and Z_T are related by

$$\frac{P_T}{Z_T}=(1-f_T)=\frac{e^{(E_T-E_F)/kT}}{1+e^{(E_T-E_F)/kT}}=\frac{e^y}{1+e^y} \tag{14}$$

with f_T the density of probability of traps filled with electrons, E_T the trap energy, and E_F the Fermi level.

In this material, the Fermi level is located at about 3.5 kT below the top of the valence band at room temperature. As traps lie in the gap, y must be such that $y>3.5$. In this case, the expression of $\overline{\Delta P^2}$ is simplified and becomes

$$\overline{\Delta P^2}\approx\frac{1}{1/P+e^y/Z_T}. \tag{15}$$

The theoretical expression of the GR time constant is given by

$$\tau^{-1}=\frac{\sigma v_{\text{th}}}{\Omega}\left(P\ \frac{Z_T}{Z_T-P_T}+P_T\right) \tag{16}$$

with v_{th} the thermal velocity, Ω the volume of sample considered, and σ the capture cross section of the trap.

As $y\geqslant 3.5\ kT$, the expression for the time constant τ can also be simplified and becomes

$$\tau^{-1}=\frac{\sigma v_{\text{th}}}{\Omega}\ (P\ e^y+Z_T). \tag{17}$$

2. Experimental results

Experimentally, for devices with $L=30\ \mu$m, the number of free carriers in the bulk P is $P=8.6\times10^9$. This result combined to the values of $\overline{\Delta P^2}/P$ given in Table I leads to a value of the variance of $\overline{\Delta P^2}\approx 8.2\times10^7$, e.g., for TLM 1. Since $\overline{\Delta P^2}\ll P$, according to relation (15), the approximation $\overline{\Delta P^2}=Z_Te^{-y}$ has to prevail. Phenomena are observable when $E_T-E_F\leqslant 4kT$.[9] Using $y\approx3.5$, we obtain $Z_T\approx2.7\times10^9$. This leads to a density of traps of at least $z_T\approx1.3\times10^{19}\ \text{cm}^{-3}$.

With a mean value of τ of 3×10^{-6} s at room temperature for the GR component considered, this gives a capture cross section σ of about $4\times10^{-23}\ \text{cm}^2$ with relation (17). This value is much lower than those usually published for known hole traps in bulk GaAs[10] as well as the cross section of a single electron ($10^{-22}\ \text{cm}^2$). Therefore, it is possible that the cross section might be thermally activated, as can be observed by Levinshtein *et al.*[11] Then σ can be written as $\sigma=\sigma_0\exp(-E_a/kT)$ with σ_0 a prefactor independent on temperature[12,13] and E_a the carrier barrier height energy. Levinshtein *et al.*[11] finds values of σ of the same order of magnitude as those measured here; but for nondegenerate GaAs.

B. Noise due to traps located in the space-charge region

Let us consider recombinations in the space-charge region (SCR) between p^{++}-GaAs and n-GaAs.[14] Since the conduction is determined by the p^{++} bulk layer, we have

$$P=P_v+P_1\approx P_v\,, \tag{18}$$

$$\Delta P=\Delta P_1\,, \tag{19}$$

$$G=G_v+G_1=(q\mu_vP_v+q\mu_1P_1)/L^2, \tag{20}$$

$$\frac{\overline{\Delta R^2}}{R^2}=\frac{\overline{\Delta G^2}}{G^2}\approx\frac{\overline{\Delta G_1^2}}{G^2}\approx\left(\frac{\mu_1}{\mu_v}\right)^2\frac{\overline{\Delta P_1^2}}{P^2} \tag{21}$$

with P_v the number of holes in the p^{++}-GaAs layer, μ_v their mobility, P_1 the number of holes in the SCR, μ_1 their mobility, G_v the conductance of the p^{++}-GaAs layer, and G_1 the conductance of the SCR. Due to the high dope we have $\mu_v\approx50\ \text{cm}^2/\text{V s}$. The value of μ_1 is determined by the dope and the electric field in the SCR, it amounts to $\mu_1\approx150\ \text{cm}^2/\text{V s}$. The ratio $\mu_1/\mu_v\approx3$ is in accordance with the peak in Fig. 5. Consequently, we have

$$\frac{\overline{\Delta R^2}}{R^2}=\frac{\overline{\Delta G^2}}{G^2}\approx9\,\frac{\overline{\Delta P_1^2}}{P^2}\leqslant9\,\frac{P_1}{P^2}\ll\frac{1}{P}. \tag{22}$$

Note that the experimental values in Table I confirms this inequality.

A theoretical analysis of the variance and of the GR time constant is performed. The expressions used are established in the Appendix. Two cases must be considered. Relations obtained are summarized below:

For a low trap density, the variance is expressed by

$$\overline{\Delta P_1^2}\approx z_TWL/\gamma. \tag{23}$$

In our case, $\gamma\approx0.37\ (\text{nm})^{-1}$.

The GR time constant is given by

$$\tau^{-1}\approx2\sigma v_{\text{th}}N_v\ e^{-E_T/kT} \tag{24}$$

with N_v the density of states in the valence band.

For a high trap density, the variance is expressed by

$$\overline{\Delta P_1^2}\approx\frac{\pi(z_TN_v)^{1/2}WL}{2\gamma}\ e^{-E_T/2kT} \tag{25}$$

and the GR time constant by

$$\tau^{-1}\approx2\sigma v_{\text{th}}(z_TN_v)^{1/2}e^{-E_T/kT}. \tag{26}$$

VI. TEMPERATURE DEPENDENCE OF THE VARIANCE AND RELAXATION TIME

A. Study of the variance

Experimentally, the variance $\overline{\Delta P^2}$ is found to be much lower than P_v. The temperature dependence of the variance was experimentally found to be slight.[15]

According to Eq. (15), for bulk phenomena, the temperature dependence is approximately given by

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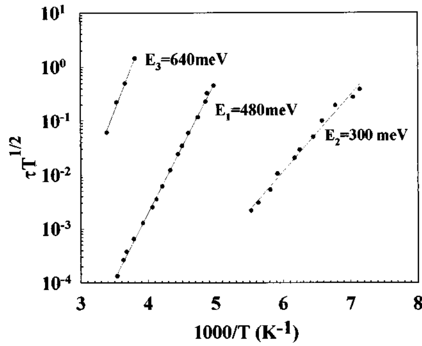

FIG. 6. Arrhenius plots of $\ln(\tau T^{1/2})$ vs $1000/T$ for TLM 2 with $L=30$ μm at $I=8$ mA. Slopes of lines are proportional to an energy representing the signature of traps.

$$\overline{\Delta P^2} \approx Z_T\ e^{-y} \propto \exp(-E_T/kT).$$

For SCR phenomena, Eq. (25) predicts $\overline{\Delta P^2} \propto \exp(-E_T/2kT)$ and Eq. (23) gives $\overline{\Delta P^2} \propto \gamma^{-1} \propto T$, thus $\overline{\Delta P^2}$ should be weakly dependent on temperature.

In view of these results we can conclude that the GR noise most probably stems from the SCR with a rather low trap density. Experimentally we obtain, according to Eq. (21):

$$\overline{\Delta P^2} = (\overline{\Delta R^2}/R^2) P^2 9 \approx 7 \times 10^6.$$

With the help of Eq. (23) the trap density is then found to be $z_T \approx 10^{18}$ cm^{-3}.

B. Study of the time constant

In the bulk region, if Eq. (16) prevails, this energy has to be ascribed to a thermally activated capture cross section, thus $\sigma(T) = \sigma_0 \exp(-E_a/kT)$ with σ_0 a prefactor.[12,13] Since the p^{++}-GaAs layer is degenerated, the number of free holes is nearly independent of the temperature.[16] The thermal velocity is proportional to $T^{1/2}$. We then get

$$\tau^{-1} \propto T^{1/2} \exp(E_T - E_F - E_a).$$

Therefore we have made an Arrhenius plot of $\ln(\tau T^{1/2})$ vs $1000/T$ (see Fig. 6). Three energies and prefactors were extracted from the slopes of the lines. The results are given in Table II.

The signature of traps estimated here cannot be compared to those reported in the literature for p-type GaAs.[10,17] Published results are given for nondegenerated materials and the capture cross section is not thermally activated.

When GR phenomena originate in the space charge region, then Eq. (24) or Eq. (26) applies. In view of the experimental results of the variance and the strong temperature dependence of the relaxation time, it seems to be most obvious that Eq. (24) prevails. The temperature dependence of τ is determined by the temperature dependence of σ, v_{th}, $N_v \propto T^{3/2}$, and the exponential factor $\exp(-E_T/kT)$, thus

$$\tau^{-1} \propto T^2 \exp(-E_a - E_T)/kT.$$

It is here not possible to establish which part of the activation energy can be ascribed to the traps and which part to the cross section. Values of $E = E_a + E_T$ are extracted from an Arrhenius plot of $\ln(\tau T^2)$ vs $1000/T$. Results are given in Table III.

TABLE II. Signature of traps: energy and capture cross sections extracted from an Arrhenius plot of $\ln(\tau T^{1/2})$ vs $1000/T$.

E (meV)	σ_0 (cm^2)
480	6.7×10^{-14}
300	2.2×10^{-15}
640	1.7×10^{-14}

TABLE III. Signature of traps: energy extracted from an Arrhenius plot of $\ln(\tau T^2)$ vs $1000/T$.

E (meV)
420
280
820

Recent measurements performed on CBE-grown TLM with the same structure as those studied here showed no GR components. Traps observed on devices analyzed in this article may thus be induced by the epitaxy technique.

By considering the evolution of the variance and of the GR time constant with temperature, traps must be probably located in the SCR.

VII. CONCLUSION

Low-frequency noise measurements on p-type GaAs very heavily doped exhibit generation-recombination components. The noise due to contact resistances was shown to be negligible. The generation-recombination noise sources were found to be located in the bulk region or in a space-charge region of the device. Expressions for the variance associated to charge carrier fluctuations and expressions of the GR time constants are given for each case. For bulk noise sources, noise vs temperature measurements were performed. Signature of traps, that is the energy and capture cross sections were extracted. Capture cross sections of traps were shown to be probably thermally activated. However, to our knowledge, no thermally activated cross sections have been reported for p-type GaAs in the literature. We can therefore assume the GR components observed to originate from the space-charge region or at the p-n junction interface.

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APPENDIX: THEORETICAL ANALYSIS OF GR PHENOMENA IN THE SPACE-CHARGE REGION

In order to derive expressions for the variance $\overline{\Delta P_1^2}$ and the relaxation time of the GR process, we consider the energy band diagram as sketched in Fig. 7. The space-charge region has traps that produce GR noise. The band bending of the valence band for $0 < x < \lambda$ is given by

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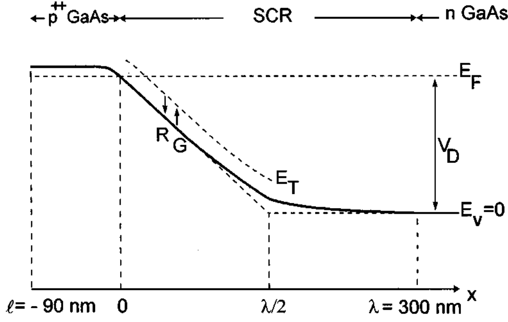

FIG. 7. Energy band diagram of the TLM.

$$V(x)=-V_D(2x\lambda-x^2)/\lambda^2$$

with

$$\lambda=(2\epsilon V_D/qN_D)^{1/2}\approx 300 \text{ nm}. \tag{A1}$$

Here ϵ is the dielectric constant, V_D is almost equal to the band gap (1.4 V), N_D the donor density in n-GaAs, and λ the junction width. The relevant part of the SCR is given by $0\leqslant x\ll\lambda$, here we can make the approximation

$$V(x)=-2V_D x/\lambda. \tag{A2}$$

Using Eq. (A2), the number of free holes in the SCR is calculated to be

$$P_1=WL\int_0^\lambda p(0)e^{qV(x)/kT}\,dx\approx WLp(0)\lambda kT/2qV_D. \tag{A3}$$

Since $P_v\approx WLlp(0)$ we obtain $P_1/P_v\approx\lambda kT(2qV_Dl)\approx 0.03$. Here W is the width, L the length, and $l=90$ nm the thickness of the TLM structure. With the help of $\mu_1/\mu_v\approx 3$ we find $G_1/G_v\approx 0.09$.

The spatial cross-correlation spectral density of the hole density for unit length $p^*_{(x)}$ is given by[18]

$$S_p^*(x,x',\omega)=\frac{4\tau(x)p^*_{(x)}z^*_{T,\text{eff}}(x)}{[p^*_{(x)}+z^*_{T,\text{eff}}(x)][1+\omega^2\tau^2(x)]}\,\delta(x-x') \tag{A4}$$

with

$$z^*_{T,\text{eff}}=z^*_T f_T(x)[1-f_T(x)], \tag{A5}$$

$$f_T^{-1}(x)=1+\exp[(E_F-E_T)(x)/kT]=1+\exp(\gamma x-b), \tag{A6}$$

$$\tau^{-1}(x)=\frac{\sigma v_{\text{th}}}{WL}[p^*_{(x)}+z^*_{T,\text{eff}}(x)]/f_T(x), \tag{A7}$$

$$p^*_{(x)}=p^*_{(0)}\exp[qV(x)/kT]=p^*_{(0)}\exp(-\gamma x), \tag{A8}$$

$$\gamma=2qV_D/\lambda kT\approx 0.37(\text{nm})^{-1}\quad\text{and}\quad b=|E_T|/kT. \tag{A9}$$

Here, $z^*_T = z_T WL$ is the hole trap density for unit length, δ the Dirac delta function, and f_T the Fermi–Dirac distribution function.

The variance $\overline{\Delta P_1^2}$ is

$$\overline{\Delta P_1^2}=\int_0^\lambda\int_0^\lambda\int_0^\infty S_p^*(x,x',\omega)dx\,dx'\,df$$

$$=\int_0^\lambda\frac{p^*_{(x)}z^*_{T,\text{eff}}}{p^*_{(x)}+z^*_{T,\text{eff}}}\,dx. \tag{A10}$$

With the help of Eqs. (A5), (A6), and (A8) the variance can be written as

$$\overline{\Delta P_1^2}\approx\int_0^\infty\frac{z^*_T\,dx}{2+e^{\gamma x-b}+e^{b-\gamma x}+[z^*_T/p^*_{(0)}\,e^{\gamma x}]}$$

$$=\frac{z^*_T/\gamma}{\sqrt{\beta-1}}\left[\frac{\pi}{2}-\arctan\left(\frac{\beta\,e^{-b}+1}{\sqrt{\beta-1}}\right)\right] \tag{A11}$$

with

$$\beta=1+z^*_T\,e^b/p(0). \tag{A12}$$

In Eq. (A11) the integral is taken from 0 to ∞, since for $x=\lambda/2$ it yields $\gamma x\gg 1$. The spectral noise density of the fluctuations ΔP_1 is given by

$$S_{p_1}(\omega)=\int_0^\lambda\int_0^\lambda S_p^*(x,x',\omega)dx\,dx'. \tag{A13}$$

Since the relaxation time is a function of x, the spectrum can deviate from the ideal Lorentzian spectrum. The region where the denominator in the integral given by Eq. (A11) is minimum determines the corner frequency of the spectrum. This minimum is obtained at

$$x=x_1=\left(b-\frac{\ln\beta}{2}\right)\Big/\gamma<b/\gamma=(E_T/2E_g)\lambda$$

with E_g the band gap. According to Eq. (A7), the relaxation time is then found to be

$$\tau^{-1}(x_1)=\frac{\sigma v_{\text{th}}}{WL}2p^*_{(0)}e^{-b}\beta^{1/2}. \tag{A14}$$

We can consider several situations.

(1) Low-trap density: $z^*_T<p^*_{(0)}\,e^{-b}\quad(\beta\approx 1)$.
In this case we obtain

$$\overline{\Delta P_1^2}=z^*_T/\gamma(1+e^{-b})\approx z_T WL/\gamma \tag{A15}$$

and

$$\tau^{-1}=\frac{2\sigma v_{\text{th}}p^*_{(0)}\,e^{-b}}{WL}\approx 2\sigma v_{\text{th}}N_v\,e^{-E_T/kT} \tag{A16}$$

with $N_v\approx p^*_{(0)}/WL$ the density of states in the valence band.

(2) High-trap density:

$$p^*_{(0)}\,e^{-b}\ll z^*_T\ll p^*_{(0)}\,e^b\quad(1\ll\beta\ll e^b).$$

Here we obtain

$$\overline{\Delta P_1^2}=\frac{\pi z_T^{*1/2}p_{(0)}^{*1/2}}{2\gamma}\,e^{-b/2}\approx\frac{\pi(z_T N_v)^{1/2}WL}{2\gamma}\,e^{-E_T/2kT} \tag{A17}$$

and

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$$\tau^{-1}=\frac{2\sigma v_{\rm th}z_T^{*1/2}p_{(0)}^{*1/2}e^{-b/2}}{WL}\approx 2\sigma v_{\rm th}(z_TN_v)^{1/2}\ e^{-E_T/kT}. \tag{A18}$$

At very high (unrealistic) trap densities $z_T^* \gg p_{(0)}^*\ e^b$; the variance becomes equal to $\overline{\Delta P_1^2} = p_{(0)}^* WL/\gamma$.

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