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NUMERICAL SIMULATION OF THE INFLUENCE OF ELECTRON BEAM INDUCED EXCESS CHARGE CARRIERS ON POTENTIAL AND CHARGE CARRIER DENSITY DISTRIBUTIONS IN GaAs MESFET

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Abstract

Such scanning electron microscopy modes as electron beam induced current (EBIC), cathodoluminescence (CL) and scanning electron acoustic microscopy (SEAM) are widely used for the characterization of semiconductor specimens and devices. These methods are based on the generation of excess charge carriers by an electron beam inside of the investigated specimen. Usually, theoretical models used to explain the physics of these methods presuppose the low injection case.

However, in experimental investigations, the low injection condition cannot always be observed. Thus, for the interpretation of such measurement results more complicated simulation models have to be used. Such simulations can be carried out by means of numerical simulation programs. Important results of such simulations are how the charge carrier density distributions as well as the potential distributions are influenced by the electron beam induced excess charge carriers inside of investigated semiconductor devices, as for example Gallium Arsenide (GaAs) Metal Semiconductor Field Effect Transistors (MESFET). Additionally, processes such as the recharging of deep levels by the excess charge carriers and the effects of the recharging on the electrical potential distribution can be investigated.

Key Words: Simulation, electron beam induced excess charge carriers, potential distribution, charge carrier distribution, deep levels, GaAs MESFET.

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Introduction

Microscopic electrical properties of semiconductor materials and devices can be effectively investigated by such scanning electron microscopy modes as electron beam induced current (EBIC), cathodoluminscence (CL) and scanning electron acoustic microscopy (SEAM). By these methods, dislocations, point defect distributions, striations, Schottky diodes, pn-junctions, bipolar transistors etc. have been investigated (Balk *et al.*, 1975; Leamy, 1982; Holt and Lesniak, 1985; Kaufmann *et al.*, 1987). For the investigation of semiconductor devices the measurement of electron beam induced currents (EBIC) is the most powerful method (Kaufmann and Balk, 1993).

Besides experimental investigations, all these methods often demand simulations in order to make possible an unequivocal interpretation of the measurement results and to determine material parameters. For many cases, simple models dealing only with the minority charge carriers can be used (Donolato, 1978). For these models it is assumed that only the minority charge carrier distribution is changed and the majority charge carrier distribution, as well as the potential distribution, remains unchanged. This is the low injection case (Sze, 1981) which requires that for experimental investigations only very low electron beam currents in the picoampere range are used. The lower the specimen under investigation is doped, the lower the beam currents have to be. But such low beam currents cannot always be used, as often the signal to noise ratio of the measured signal is too bad or the sensitivity of the experimental equipment is not suitable for such measurements. Then the results obtained by the simulations presupposing the low injection case cannot be used without a critical review and a knowledge of the processes which occur inside of the semiconductor specimen or device.

In order to obtain an understanding of the effect of high electron beam currents on the electrical state of semiconductor devices we have investigated the influence of electron beam induced excess charge carriers on the charge carrier density distributions and on the potential distributions inside a GaAs MESFET (galliumarsenide metal semiconductor field effect transistor). GaAs MES-

FETs are relatively simple semiconductor devices which are used as very fast amplifiers in both microwave and very fast digital circuits (Shur, 1987). The changes of the mentioned distributions for different electron beam currents are demonstrated. For the simulations, the semiconductor equation system consisting of the continuity equations for electrons and holes and the Poisson equation has been solved numerically. Additionally, the influence of deep level recharging has been considered and is demonstrated by an example.

Structure of GaAs MESFET

GaAs MESFETs are unipolar transistors which usually have three contacts; two of these are ohmic contacts (source and drain), and one is a rectifying metal semiconductor contact (Schottky diode; gate). The contacts are on a conducting semiconductor layer whose thickness is around 100 nm and whose lateral extension is restricted by the device area. Below this conducting layer is either a semi-insulating GaAs substrate or a very weakly n^-- or p^--.doped buffer layer depending on the manufacturing process used. The conducting layer can be produced by either ion implantation into the semi-insulating substrate or buffer layers or by epitaxial methods (molecular beam epitaxy (MBE); metal organic vapour phase epitaxy (MOVPE)). The conducting layer is typically n-doped (in the order of $n = 3 \cdot 10^{17}\,\mathrm{cm}^{-3}$) with silicon in order to obtain good conductivity. The density of free charge carriers in the buffer layer is very low at thermal equilibrium. Both an n^- or p^- charge density is possible.

Theory and Simulation Model

Basic semiconductor equations

For simulating the effect of electron beam induced excess charge carriers on the charge carrier and potential distributions, the equation system consisting of the continuity equation and the Poisson equation has to be solved. Poisson's equation is:

$$div\ grad\,\varphi = -\frac{e}{\varepsilon}\cdot\left(p - n + N_D^+ - N_A^- - N_t^-\right) \qquad (1)$$

with potential φ, elementary charge e, dielectric constant ε, hole density $p(r,t)$ and electron density $n(r,t)$. The density distribution of charges fixed at donors and acceptors is represented by N_D^+ and N_A^-, respectively. The meaning of N_t^- is explained subsequently. Continuity equations for electrons and holes are:

$$\frac{\partial n}{\partial t} = \frac{1}{e}\cdot div\ J_n - R_{SRH} + G_{eh} \qquad (2a)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{e}\cdot div\ J_p - R_{RSH} + G_{eh} \qquad (2b)$$

In these equations are J_n the electron current density, J_p the hole current density, R_{SRH} the recombination rate of electrons and holes given by the Shockley, Read, Hall theory and G_{eh} the electron beam induced electron and hole generation rate. The current densities depend on the hole density $p(r,t)$ or electron density $n(r,t)$, the hole mobility μ_p or electron mobility μ_n, the hole diffusion constant D_p or the electron diffusion constant D_n and the electric field distribution $E = -grad\ \varphi$ within the specimen. Current equations for electrons and holes are:

$$J_n = e\cdot n\cdot \mu_n \cdot E + e\cdot D_n \cdot grad\ n \qquad (3a)$$

$$J_p = e\cdot p\cdot \mu_p \cdot E - e\cdot D_p \cdot grad\ p \qquad (3b)$$

A formal simplification of these equations is possible if the Einstein relations valid for nondegenerate semiconductors are used:

$$D_p = \mu_p \cdot \frac{k\cdot T}{e} \qquad (4a)$$

$$D_p = \mu_p \cdot \frac{k\cdot T}{e} \qquad (4b)$$

Deep levels have a two-fold effect on the state of semiconductors. On the one hand, they serve as recombination centres for free charge carriers, and on the other hand, they are rechargeable traps. The recombination rate based on the Shockley-Read-Hall model for a single level recombination centre is

$$RG_{SRH} = \frac{n\cdot p - n_i^2}{C_{cn}\cdot(n+n_1) + C_{cp}\cdot(p+p_1)}\cdot C_{cn}\cdot C_{cp}\cdot N_t. \qquad (5)$$

The parameters C_{cn} and C_{cp} can be expressed as $C_{cn} = \sigma_n \cdot v_{n,th}$ and $C_{cp} = \sigma_p \cdot v_{p,th}$, where σ_n and σ_p are the electron and hole capture cross sections of the deep level, respectively, and v_{nth} and v_{pth} are the electron and hole thermal velocities, respectively. N_t is the density of deep levels. The square of the intrinsic charge carrier density is:

$$n_i^2 = n_1 \cdot p_1 = N_C \cdot N_V \cdot exp\left[-(W_C - W_V)/k\cdot T\right].$$

Other parameters are: the electron density at the bottom of the conduction band if it is assumed that the Fermi level equals the deep level,

$$n_1 = N_C \cdot exp\left[(W_t - W_C)/k\cdot T\right],$$

the hole density at the top of the valence band if it is assumed that the Fermi level equals the deep level,

$$p_1 = N_V \cdot exp\left[(W_V - W_t)/k \cdot T\right],$$

the effective density of states in the conduction band,

$$N_C = 2(2\pi m_n kT / h^2)^{3/2},$$

and the effective density of states in the valence band

$$N_V = 2(2\pi m_p kT / h^2)^{3/2}.$$

W_t, W_C and W_V are the energy levels of the deep level, the conduction band bottom and the valence band top, respectively.

The steady state trap filling in dependence on the free charge carrier densities is given by:

$$f_t = \frac{n \cdot C_{cn} + p_1 \cdot C_{cp}}{C_{cn} \cdot (n + n_1) + C_{cp} \cdot (p + p_1)} \qquad (6)$$

If the filling state of traps is changed, the traps are recharged. Thus, if there are traps which are negatively charged if occupied by an electron and uncharged if unoccupied, a charge density fixed at the traps is present. The density of the charged traps is:

$$N_t^- = N_t \cdot f_t \qquad (7)$$

This distribution is considered by Poisson's equation (1).

Electron beam induced excess charge carrier generation

The generation of excess charge carriers by an electron beam has been discussed by several authors (e.g. Wu and Wittry, 1978; Leamy, 1982; Donolato *et al.*,1982). Here only the description used in this paper is presented. For describing the electron hole pair generation in homogeneous semiconductors an equation consisting of two terms has been used:

$$G_{eh}(\mathrm{r},t) = \frac{W_{PE} \cdot I_{PE}(t)}{W_{eh} \cdot e} \cdot \langle g(\mathrm{r}) \rangle. \qquad (8)$$

The number of generated electron hole pairs depends on the electron beam energy W_{PE}, the electron beam current $I_{PE}(t)$, and the electron hole pair generation energy W_{eh}. W_{eh} is material specific and depends strongly on the band gap of the investigated material; for GaAs, a value of W_{eh} = 4.6 eV has been used according to Wu and Wittry (Wu and Wittry, 1978).

The term for describing the spatial distribution of the electron hole pair generation can be separated into a term for describing the lateral distribution and one term for describing the depth distribution (Kaufmann and Balk, 1995):

$$\langle g(\mathrm{r}) \rangle = \langle g_{xy}(x,y) \rangle \cdot \langle g_z(z) \rangle. \qquad (9)$$

Both terms depend on the scattering of the primary electrons within the specimen. Finally, the primary electrons are stopped in the specimen; the depth which the primary electrons reach can be calculated by a formula given by Kanaya and Okayama (Kanaya and Okayama, 1972):

$$R_{PE} = \frac{2.76 \cdot 10^{-10} \cdot A \cdot W_{PE}^{5/3}}{\rho_s \cdot Z^{8/9}}. \qquad (10)$$

In this equation A is the atomic weight, ρ_s the density of the semiconductor and Z the atomic number (values for GaAs are: $A_{GaAs} = 72.32$, $\rho_{GaAs} = 5316\,kgm^{-3}$, $Z_{GaAs} = 32$ and R_{PE} in µm).

For the description of the lateral distribution of the electron hole pair generation, a normal function has been assumed:

$$\langle g_{xy}(x,y) \rangle = \frac{1}{2\pi\sigma_{PE}{}^2} \cdot exp\left(-\frac{x^2 + y^2}{2\sigma_{PE}{}^2}\right). \qquad (11)$$

By σ_{PE} the extension of the energy dissipation volume which depends on the material investigated is considered; we have used a value of $\sigma_{PE} = 0.17 \cdot R_{PE}$ (Kaufmann and Balk, 1995).

For the depth distribution, a formula given by Wu and Wittry (Wu and Wittry, 1978) has been used:

$$g_{z,GaAs}(z) = exp\left\{-\left[\frac{\left[\frac{z}{R_{PE}}\right] - 0.125}{0.35}\right]^2\right\} - 0.4 \cdot exp\left\{-32 \cdot \frac{z}{R_{PE}}\right\} \qquad (12)$$

with $z \le R_{PE}$.

The expression $\langle g_z(z) \rangle$ is normalized, thus a normalization constant is necessary for equation (12):

$$\langle g_z(z) \rangle = A \cdot g_z(z). \qquad (13)$$

The normalization constant is:

$$A = \left(\int_0^{R_{PE}} g_{z,GaAs}(z)\, dz \right)^{-1}_{z_m = 0}. \qquad (14)$$

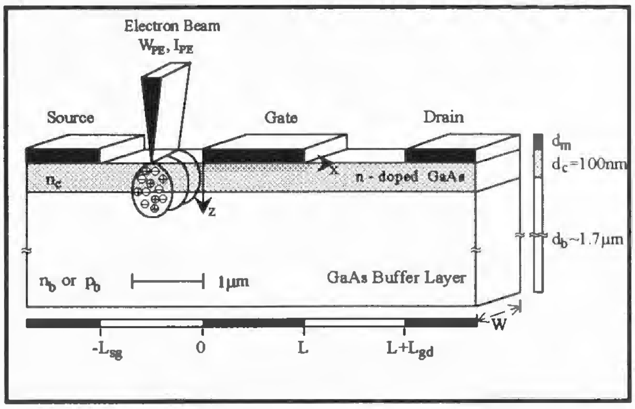

Figure 1. Two-dimensional simulation region with normalization width W drawn in.

The distribution of generated electron hole pairs in GaAs is shown for a primary electron energy of W_{PE} = 4keV in Figure 2b.

Numerical simulation

For the solution of the equation system we have used a modified version of the device simulation program MINIMOS 5 of TU Vienna which is capable of the simulation of metal oxide semiconductor field effect transistors (MOSFET) and MESFET on silicon and GaAs. We have modified the program to deal with electron beam induced excess charge carrier generation and recharging of deep levels. Additionally, the recombination model has been changed.

Due to the restricted computer resources we carried out only two-dimensional simulations. The simulation region used for simulations is shown in Figure 1. The donor density in the active layer is $n_c = 3 \cdot 10^{17} cm^{-3}$ and the thickness of this layer is $d_c = 100$ nm. The buffer layer has been assumed to be slightly n-doped with a donor density $n_b = 1 \cdot 10^{14} cm^{-3}$. The dimensions of the simulation region are given in Figure 1. The primary electron energy was chosen to be W_{PE}=4 keV. For the results given in the section dealing with deep levels, it has been assumed that there is a hole trap density of $N_t = 10^{14} cm^{-3}$ in the whole simulation region. The simulation region defined can be used for GaAs MESFET with ion implanted and epitaxial grown layers since the different properties of these layers can be represented by different material parameters.

Of course, two-dimensional simulations cannot result in quantitatively correct results because such effects as diffusion of the charge carriers in the third dimension and the three-dimensionality of the electron hole pair generation volume cannot be considered correctly. Roughly, these effects can be dealt with by normalizing the two-dimensional electron hole pair generation volume. The main difference between two- and three-dimensional simulations is that the density of free charge carriers is lower in three dimensions than in two dimensions. In two-dimensional simulations, the three-dimensional charge carrier density distribution is projected on the two-dimensional simulation plane. Thus, in this plane, the density of excess charge carriers is much higher than in three-dimensional simulations. For that reason, the simulated changes of the potential distribution are too high. In two-dimensional simulations, the correct charge carrier density in the center plane of the three-dimensional generation volume can be approached if the two-dimensional generation rate is normalized by a suitable length factor. This length should be in the order of the expected diameter of the area in which the charge carrier distribution is changed in the third dimension. This diameter can be estimated from two-dimensional simulations. We have used a length of W=1 µm. An inaccuracy of this length has the same effect as an inaccurate electron beam current.

Results

Influence of excess charge carriers on the charge carrier and potential distributions

The electrical state of a semiconductor device without deep levels can be described completely by the distributions of the electrical potential and the charge carriers. These distributions are shown in Figure 2 for an undisturbed GaAs MESFET, i.e. for a GaAs MESFET without electron beam induced excess charge carrier generation. The potential φ is highest inside the conducting layer. Junctions exist under the gate contact and between the conducting layer and the buffer layer. In these regions, the potential decreases. Furthermore, the potential decreases slightly in the buffer layer. The electron density is, of course, highest in the highly doped conducting layer. Under the ohmic contacts a higher doping concentration has been assumed in order to consider the doping effects during ohmic contact fabrication. Below the gate, the conducting layer is depleted. The hole density is very low in the whole device because the intrinsic charge density n_i of GaAs is very low and both the conducting and the buffer layer are n-doped. In Figures 3, 4 and 5 the changes of these distributions, i.e. the differences $\Delta\varphi = \varphi(I_{PE}) - \varphi(I_{PE} = 0)$, $\Delta p = p(I_{PE}) - p(I_{PE} = 0)$, $\Delta n = n(I_{PE}) - n(I_{PE} = 0)$, are shown for different electron beam currents (I_{PE} = 1 pA, 100 pA, 10 nA, and 1 µA). The electron beam position is in the middle between gate and source contact. The unnormalized two-dimensional electron hole pair generation rate distribution for a primary electron energy of W_{PE} = 4 keV and a beam current of I_{PE} = 1 pA is shown in Figure 2b. The generation volume is very small, and electron hole pair generation occurs mainly in the conducting layer.

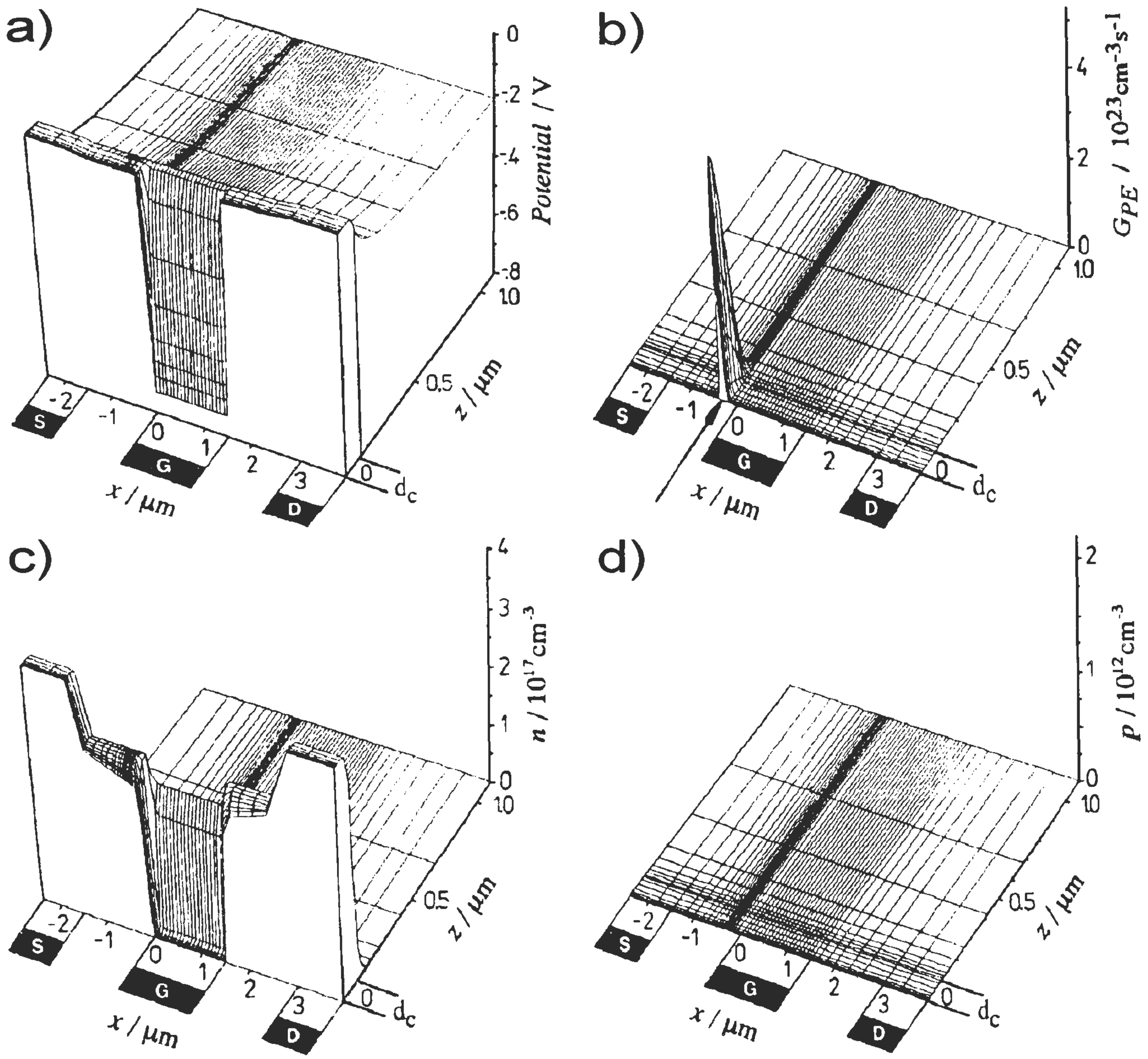

Figure 2. Undisturbed potential φ (**a**), electron density n (**c**), and hole density p (**d**) distributions in an GaAs-MESFET with dimensions and parameters as given in the explanation to Figure 1. A two-dimensional electron hole pair generation rate distribution for a primary electron energy of W_{PE} = 4 keV and a beam current of I_{PE} = 1 pA is shown in (**b**).

The hole distribution is strongly disturbed by the excess charge carriers because the hole density is in both the conducting layer and the buffer layer very low in a GaAs MESFET without electron beam induced electron hole pair generation. The disturbance of the hole density distribution occurs symmetrically about the electron beam axis as is shown in Figure 3. Higher hole densities are present in both the conducting and the buffer layer. The reason for the high hole density in the buffer layer is that the holes drift into the buffer layer due to the junction between the conducting layer and the buffer layer. As can be seen in Figure 2a, a potential gradient is present even in the deeper regions of the buffer layer. Thus, the holes drift into these regions. Due to the potential distribution in the undisturbed GaAs MESFET, the excess electrons remain mainly in the conducting layer. Changes of the electron distribution in the buffer layer are mainly caused by the excess holes which are shielded by the electrons. The differences in electron distribution are illustrated in Figure 4. The changed charge distributions cause a change of the potential distribution as is shown in Figure 5.

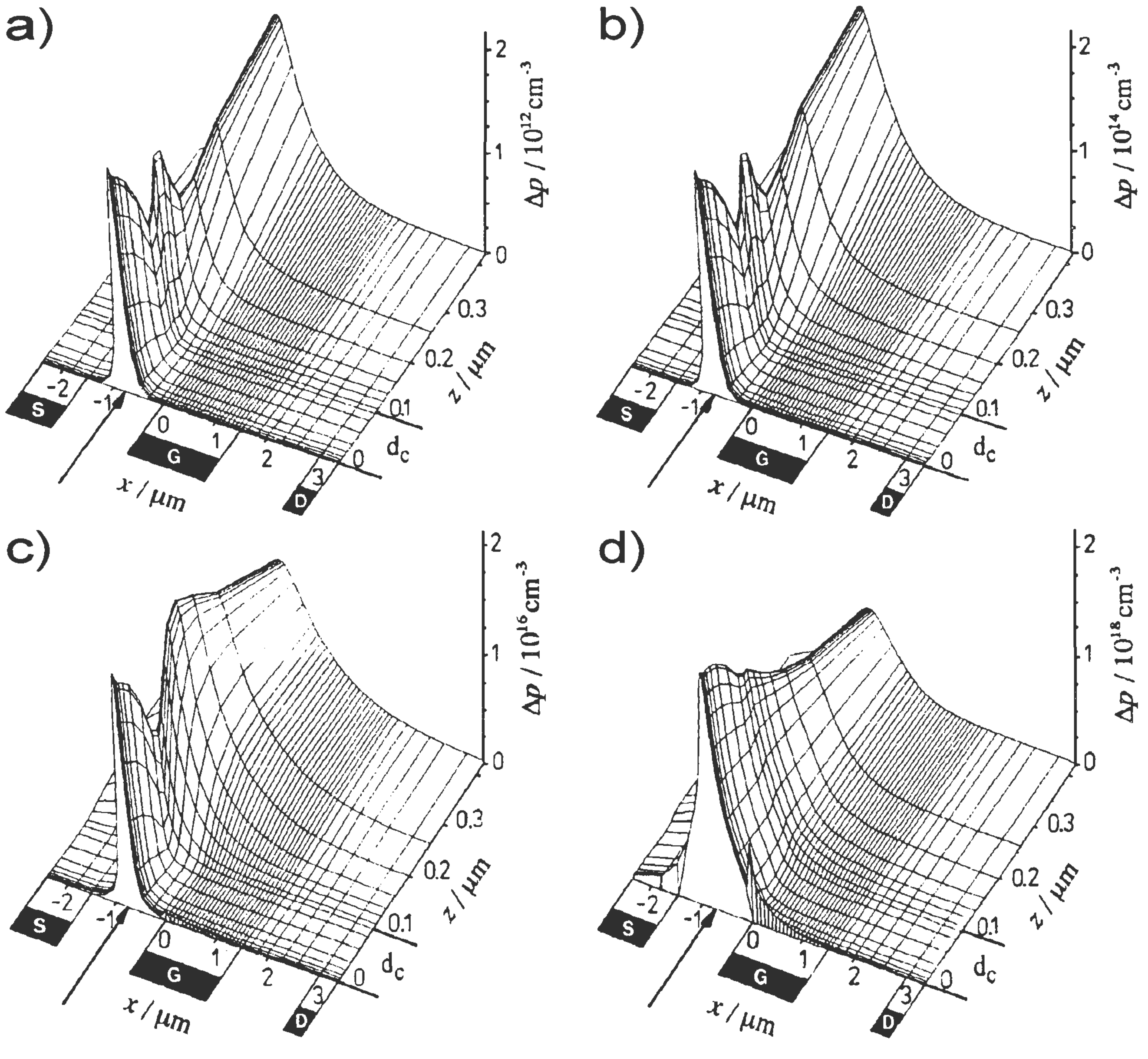

Figure 3. Differences in hole density distributions ($\Delta p = p(I_{PE}) - p(I_{PE} = 0)$) for electron beam currents of (**a**) I_{PE} = 1 pA, (**b**) I_{PE} = 100 pA, (**c**) I_{PE} = 10 nA, and (**d**) I_{PE} = 1 µA.

At low electron beam currents around I_{PE}=1 pA only the hole density distribution is significantly changed. The changes of the electron density ($\Delta n \cong 1 \cdot 10^{12}\,cm^{-3}$) and of the potential ($\Delta\varphi \cong 10\mu V$) are small in comparison to the electron density and the potential differences in the undisturbed GaAs MESFET. In the highly doped conducting layer, the excess holes can be effectively shielded by the free electrons. Thus the potential change in the conducting layer is very small in contrast to the one in the buffer layer. The electron density difference distribution at the border between the conducting and the buffer layer has an interesting shape. Due to the potential increase in the buffer layer, a voltage in forward direction is applied to the junction. Thus the electron density is increased in this area and a peak in the distribution is present.

At I_{PE}=100 pA, the shapes of the difference distributions are very similar to the shapes at I_{PE}=1 pA. But the differences are all higher by a factor 100. The electron density difference ($\Delta n \cong 1 \cdot 10^{14}\,cm^{-3}$) reaches new values as high as the electron density in the undisturbed GaAs MESFET. Thus the conditions of the often used low injection case are no longer fulfilled. The potential differences reach values up to $\Delta\varphi \cong 10mV$.

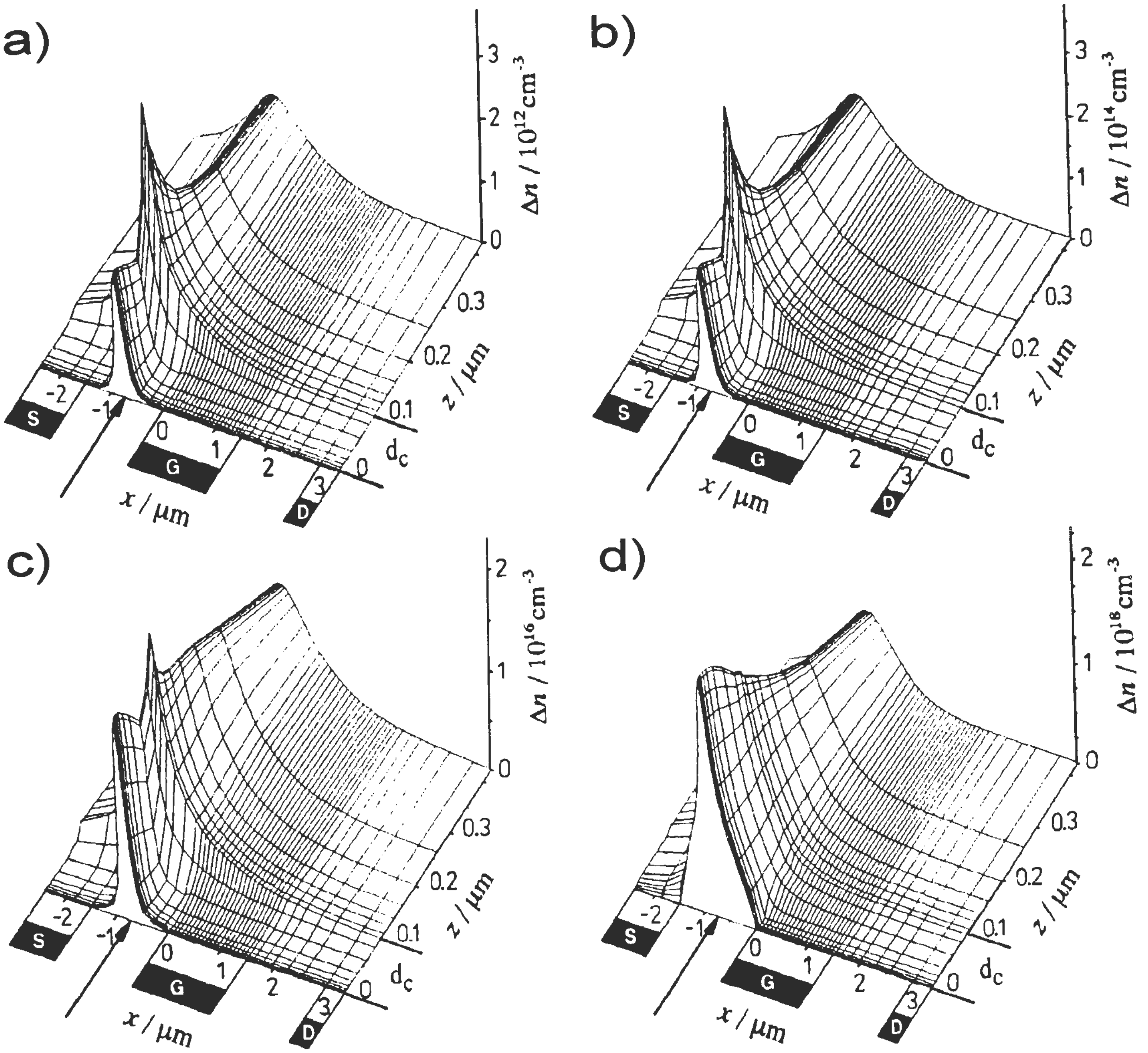

Figure 4. Differences in electron density distributions ($\Delta n = n(I_{PE}) - n(I_{PE} = 0)$) for electron beam currents of **(a)** I_{PE} = 1 pA, **(b)** I_{PE} = 100 pA, **(c)** I_{PE} = 10 nA, and **(d)** I_{PE} = 1 µA.

The shapes of the distributions are changed if the beam current is further increased to a value of I_{PE}=10 nA. The values of the electron density changes ($\Delta n \cong 2 \cdot 10^{16}\,cm^{-3}$) approach the value of the electron density ($n \cong 3 \cdot 10^{17}\,cm^{-3}$) in the undisturbed conducting layer. The potential is partially decreased in the conducting layer. Furthermore, the influenced area is strongly enlarged.

At a beam current of I_{PE}=1µA, the changes of the charge carrier densities and the potential are greater than the charge carrier densities and potential differences in the undisturbed GaAs MESFET. The influence of the electrical potential of the undisturbed GaAs MESFET on the excess charge carrier distributions is scarcely observable. The potential is increased in a great area in the buffer layer and the conducting layer; the increase is no longer restricted on the area around the electron beam axis. The potential barrier of the gate contact is partially decreased.

Influence of the recharging of deep levels on the potential distribution

Deep levels in semiconductors may serve as traps for the free excess charge carriers which may be stored in

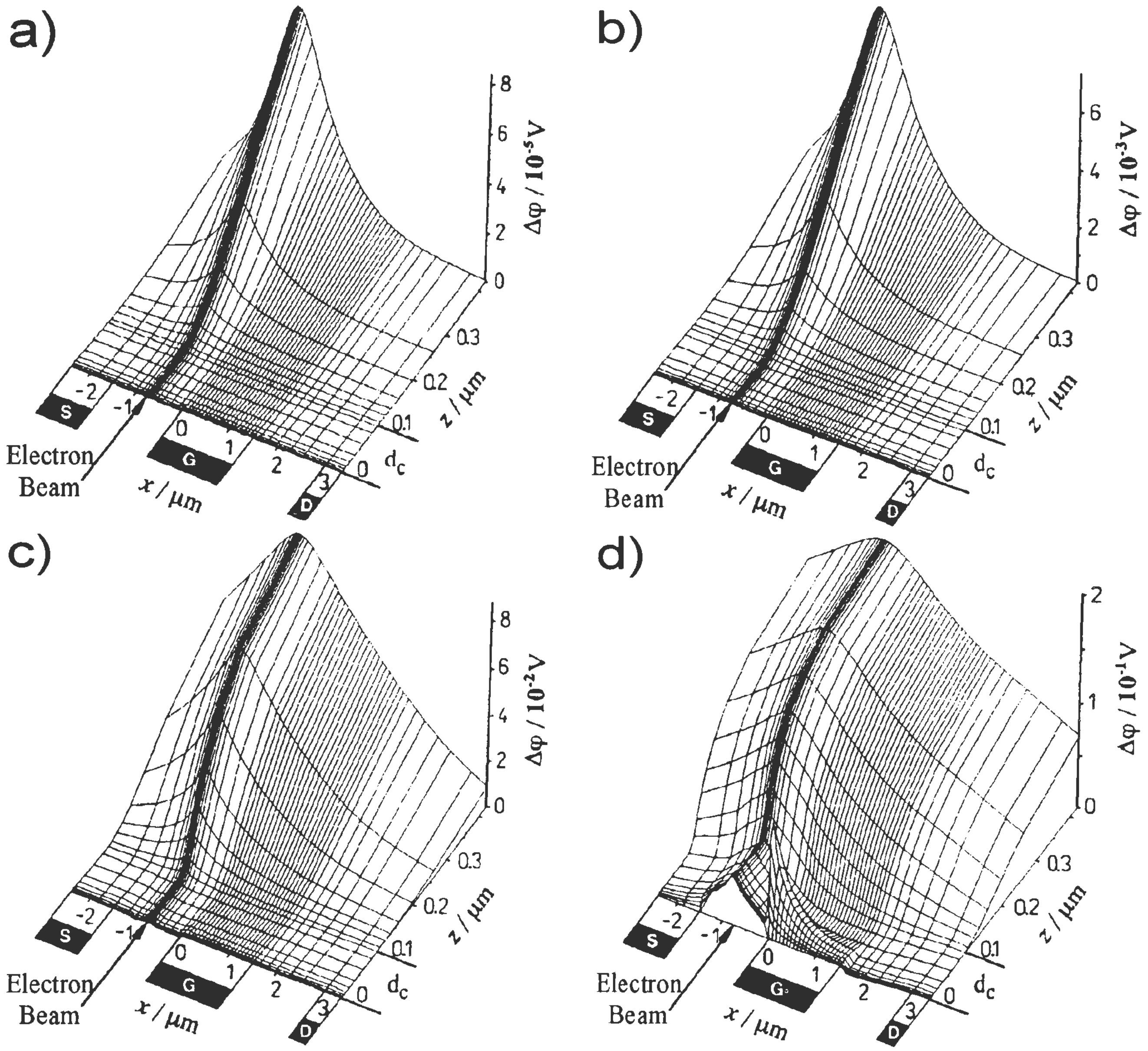

Figure 5. Differences in the potential distributions ($\Delta\varphi = \varphi(I_{PE}) - \varphi(I_{PE} = 0)$) for electron beam currents of (**a**) I_{PE} = 1 pA, (**b**) I_{PE} = 100 pA, (**c**) I_{PE} = 10 nA, and (**d**) I_{PE} = 1 μA.

these traps. The traps are recharged if the occupation state is changed. So, if hole traps which have a greater capture cross-section for holes than for electrons are present in the GaAs MESFET, the electrical potential is strongly disturbed even at low electron beam currents since a great number of traps becomes more positively charged.

Distributions of recharged hole traps in a GaAs MESFET are shown for electron beam currents I_{PE}=1 pA and I_{PE}=10 nA in Figure 6. The density of hole traps has been assumed to be $N_t = 1\cdot10^{14}cm^{-3}$. At I_{PE}=1 pA, the traps are recharged only in the buffer layer and in a small part of the gate depletion layer. In the buffer layer, the recharging occurs symmetrically around the electron beam axis. At an electron beam current of I_{PE}=10 nA, far more traps in a larger area are recharged because the density of excess holes is much higher. In some parts of the buffer layer, all hole traps are occupied. Even in the conducting layer the hole density is high enough so that a high number of traps are recharged. The effect of the recharged traps is the same as the effect caused by an equivalent number of holes. The potential is changed by the recharged traps. As a measure for the influence of the recharged traps, the maximum of the potential change:

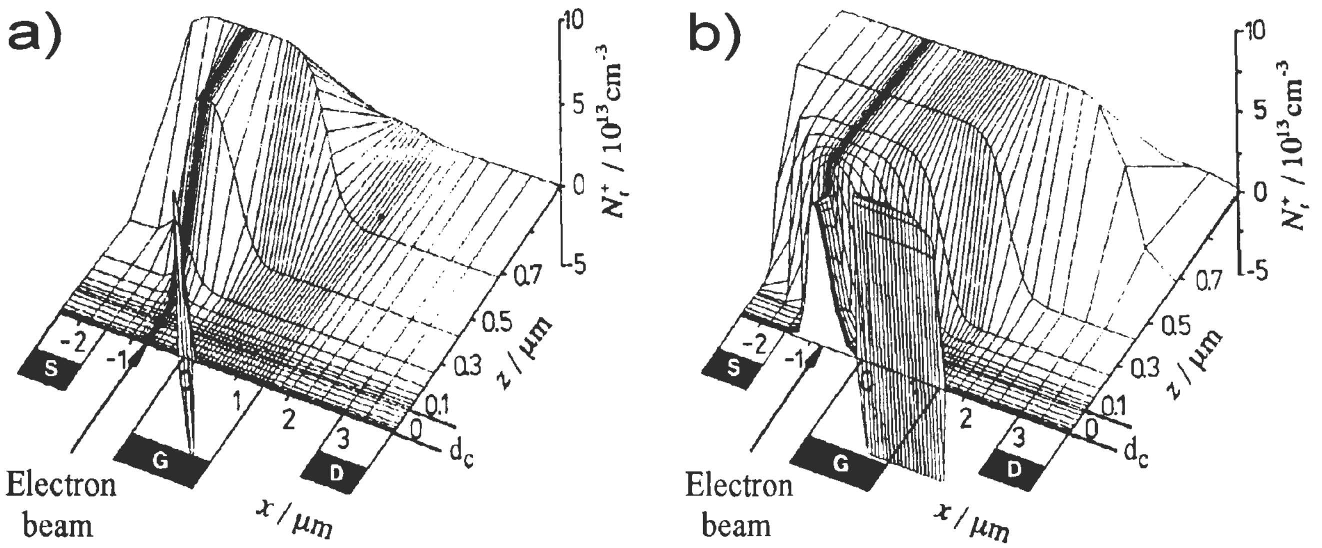

Figure 6. Distribution of recharged deep levels for electron beam currents of **(a)** I_{PE} = 1 pA and **(b)** I_{PE} = 10 nA. Trap parameters are $N_t = 1 \cdot 10^{14} cm^{-3}$, $\sigma_n = 2 \cdot 10^{-19} cm^2$, $\sigma_p = 5 \cdot 10^{-17} cm^2$ and $W_t - W_V = 0.69eV$. Other parameters are as in Figure 1.

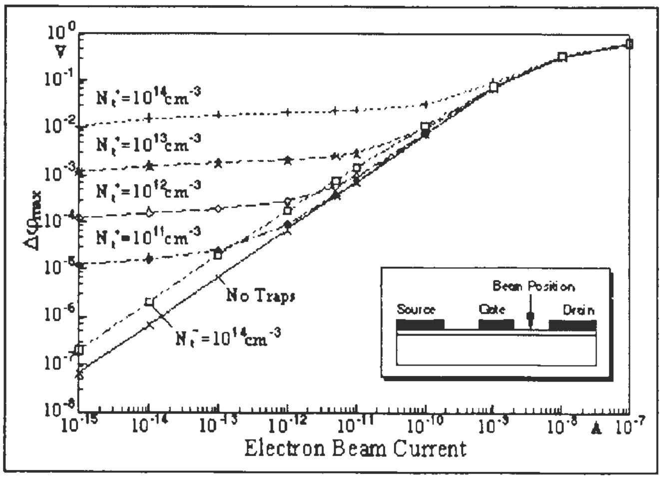

Figure 7. Maximum values of potential changes for different deep level densities. Electron beam position is the middle between gate and source. Parameters and electron beam position are as in Figure 6.

$$\Delta\varphi_{max} = \left[\varphi(I_{PE}) - \varphi(I_{PE} = 0)\right]_{max}$$

in the GaAs MESFET can be used. The values of $\Delta\varphi_{max}$ in dependence on the electron beam current are shown for different hole trap densities in Figure 7.

Without deep levels, the maximum potential difference increases linearly with increasing electron beam current up to beam currents of I_{PE}=1 nA. At higher beam currents the maximum value of potential change increases more slowly. If hole traps are present, the potential is changed significantly even at very low electron beam currents whereas the height of the potential change depends on the trap density. With increasing beam current, $\Delta\varphi_{max}$ increases only slightly at low beam currents and converges at higher beam currents to the curve for the maximum potential change for a GaAs MESFET without traps. Electron traps have only a small influence as is demonstrated in Figure 7.

Discussion and Conclusions

The simulations have shown how the potential, the charge carrier and the trap distributions are changed in a GaAs MESFET by electron beam induced excess electron hole pairs. By the simulation results, it is confirmed that at low electron beam currents in the picoampere range, the changes are small in comparison to the potential differences and majority charge carrier densities in the undisturbed device. Only the minority charge carrier density is strongly changed. At high electron beam currents, the changes are much higher than the initial potential differences and charge carrier densities. A state similar to an electron hole pair plasma is reached. The information yielded by electron beam induced current or cathodoluminescence measurements is no longer strongly correlated to the properties of the investigated GaAs MESFET. Meaningful results can only be obtained using very low electron beam currents. Although the results are obtained for a special semiconductor device, the information of how the distributions are changed can be used as a basis for the interpretation of similar problems.

Additionally, the special influence of traps is shown. As has been shown, the effect of recharged traps on the potential is very strong in lightly doped semiconductors. Hence, in GaAs MESFET based on semi-insulating GaAs substrates, the potential in the substrate is easily disturbed. The effect of disturbances on electron beam induced current measurements is very weak if no bias voltages are applied to the investigated device; however, if a source drain voltage is applied, the recharging of the traps has a great effect on the source drain current because the junction between the conducting and the buffer layer is changed. In this paper, it has been shown that the potential change depends strongly on the trap density and the electron beam current.

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Discussion with Reviewers

D.B. Holt: How easy will it be to generalize your results to other devices or materials? I am unfamiliar with the MINIMOS 5 simulation program you used. Is it freely available? What sort of computer is required to run it?
Authors: MINIMOS is a device simulation program written by the group of Prof. Selberherr at the TU Vienna (Prof. Dr. S. Selberherr, Institute for Microelectronics, Gusshausstrasse 25-29, 1040 Vienna, Austria). The program is suitable for simulations of MOSFET and MESFET based on Si or GaAs. Other similar device structures may be investigated if the program is modified accordingly.

The source code of the program is available against accepting the licence conditions either by mail or via internet (FTP-host: iue-sw-tuwien.ac.at (128.130.68.59) under account anonymous. As a password, use your E-mail address). The program is written in FORTRAN. As a computer, at least a workstation is required. We used both a DEC-Station 5000 and a Convex 220.

D.B. Holt: I am an advocate of the free publication of software as part of the literature, as this will continue the long tradition of scientific communication. It enables the reader to check results for themselves and to build on the work already done rather than reinvent the (software) wheel for themselves. Would it be possible and useful for you to make your calculations available as software?
Authors: On principle, we are willing to hand over the software with our modifications if the licence agreement of MINIMOS has been accepted before (see above). But, as we did not intend to publish the program, our modifications are not documented and no operating instructions are available.

D.B. Holt: Since you use numerical methods to carry out your simulations, why do you use semi-empirical analytical expressions for the spatial distribution of the electron hole pairs generated by the beam? Monte Carlo simulations can give numerical expressions of such distributions rapidly and relatively accurately even for complex structures such as device heterostructures.
Authors: The distributions calculated by the used semi-empirical expression are similar to the results obtainable

by Monte Carlo simulations. Furthermore, the distribution of the electron hole pairs is strongly determined by their diffusion and drift (compare the size of the assumed generation volume with the simulated distributions of the charge carriers). So, small inaccuracies in the assumed electron hole pair generation volume have only a small influence on the results. The resulting small deviations can be neglected in first principle investigations. Thus, we preferred the more practical way and implemented the semi-empirical expression.

D.B. Holt: Have you related, or how would you relate, your results to and test them against experimental data? Does your treatment predict that EBIC image of MESFETs will be modified or wash out (gradually lose contrast) at high injection levels? Could the approach to such modification disappearance of contrast be measured as the electron beam current increases, to determine the magnitude of build-in potentials?

A. Jakubowicz: Do the authors have any experimental data verifying their computational findings?

Authors: We have calculated electron beam induced gate currents linescans and compared them with measured linescans for low electron beam currents (I_{PE}=1 pA). A good conformity has been found. Due to the spatial structure of the MESFET, the electron beam induced gate current is affected by the shown changes of the potential, etc., only at very high electron beam currents (I_{PE}=10 nA). Thus, an unequivocal experimental verification was not possible with our means (due to the increase of the beam diameter with increasing electron beam currents). Simulations have shown that the contrasts wash out at higher beam currents. At low beam currents at both sides of the gate, sharp peaks are present in Gate-EBIC linescans. The peaks become broader at higher beam currents, and a significant Gate-EBIC is measurable between the gate and the ohmic contacts.

We do not think that in such small devices as GaAs MESFET the magnitude of built-in potentials could be determined by measurements of EBIC since at the high currents necessary for the disappearance of contrasts the electrical state of the device is disturbed in a very large area. The identification of a single junction is not possible under such conditions.

A. Jakubowicz: In **Discussion and Conclusions**, the authors say: "Meaningful results can only be obtained using very low electron beam currents." What kind of results do the authors have in mind? I feel that the right strategy is to choose a current level or current levels (sometimes more than one may be needed) that will allow a specific device-related problem to be understood.

Authors: Our statement may be misleading. What we mean is that if the aim of an investigation is to investigate the properties (for example, the extension of junctions) of an undisturbed device, it is necessary to choose low electron beam currents in order to not change the device properties by the probe. Otherwise, the measurement results reflect the properties of a disturbed device.

Of course, if the investigations have a special aim and if the results can only be obtained with special electron beam currents, these currents should be used. But the selection of the correct electron beam requires a lot of experience and knowledge of the special problem. We think simulations will be a powerful aid for such investigation.

A. Cavallini: It is of major interest to investigate the recharging of deep traps by the electron beam generated carriers and the effects on the potential. The trap recharging could significantly shift the quasi-Fermi level, especially in lightly doped material. How would this affect the simulation results?

Authors: As the band gap does not change in the investigated semiconductor specimen, the Fermi level is constant in the whole specimen. The main effect of the recharging of the deep levels is a change of the potential distribution. As the quasi-Fermi levels depend on the electrical potential and the charge carrier densities, they are charged accordingly. A spatial variation of the quasi-Fermi levels means that the charge carrier distributions are not in an equilibrium. If a deep level is positively charged, the electrons are attracted by the deep level and the holes are repelled. This occurs until a new steady state equilibrium is reached. In lightly doped semiconductors, the effect of the recharging of the traps is greater than in highly doped semiconductors since the recharged deep levels cannot be effectively shielded.