The results of a numerical experiment, using two-step vector relaxation, on transport of mobile charge carriers in an integrated circuit element with injection are presented.

There are currently only a few papers [1, 2] concerning the two-dimensional numerical analysis of transport of charge carriers in a single-collector I^2L elements, which form the basis for large integrated circuits with injection feeding [3]. This is explained by the complexities that arise in solving the system of nonlinear partial differential transport equations [4], which in its turn greatly complicates the design and development of such circuits.

The difficulties of such an analysis are related to the fundamental two-dimensional nature of the processes occurring in these structures, which are a result of the internal interaction of two types of transistors with vertical (n--p--n) and horizontal (p--n--p) structures with common collector--base and base--emitter regions. This essentially involves mutual compensation and unbalance of charge-carrier flows in the most diverse directions.

In this paper, we demonstrate the efficiency of the techniques developed in [4] for the example of a numerical analysis of charge transport processes in the single-collector I^2L element with a submerged n^+ layer shown in Fig. 1 (the geometric dimensions of the structure analyzed are given in µm).

The analysis was performed for two operational states of the inverter based on such an element [1], arising when 1) a rectilinear bias voltage is applied to the resistive contact of the injector, while the bias in the remaining contacts equals zero and 2) rectilinear bias voltages are applied to the injector and base contacts, i.e., the horizontal p--n--p transistor is saturated.

The fundamental system of equations (see (1)-(5) in [4]) was solved assuming that the Boltzmann statistics are valid as in [1, 2]. In so doing, the effect of the high level of doping, whose main effect is to narrow the width of the forbidden band [5], was not included in the analysis for the following reasons:

a) its magnitude is uncertain [6, 7], and it is difficult to ascertain which of the theoretical formulations is correct from the experimental results [8];

b) the experimental results on narrowing of the forbidden band also include other effects (deionization of the impurity, degeneracy, etc.) [9] and therefore they depend on the specific structure of the device on which the measurements were performed;

c) the mechanism of two-step recombination--generation (following the Shockley--Reed--Hall model [2, 8]) has a dominant effect on the results of modeling.

But, since the effect of the high level of doping is manifested only with impurity concentrations in the active regions of the device exceeding \(2 \times 10^{22} - 10^{24} \) 1/m³ [10, 11], the results presented in this paper were obtained for low levels of these concentrations.

The surface concentrations for different regions of the device are presented in Table 1.

The distribution of donors \(N_d\) and acceptors \(N_a\) in the I^2L element analyzed was approximated, according to [3], by exponentials. The structure consists of a common epitaxial p substrate with impurity concentration \(N_a = 0.3 \times 10^{22} \) 1/m³.
The numerical experiments were performed using a program for two-dimensional numerical analysis of \( I^2L \) elements "PNAIIL" [12] (for Boltzmann statistics), written in the FORTRAN IV language for the ES computer using the technique proposed in the first part of this work [4]. We should point out here that the development of the program for solving this problem, which is still largely an art and requires from 1 to 5 man years [13] and more for one type of device only, can be greatly accelerated using the procedure described in the first part of this work. The PNAIIL program is based on the following:

1) Sharfetter–Hummel formulation of the continuity equation;

2) a method for choosing the initial approximation [14] modified as indicated in the first part of this work [4];

3) a universal method, the Hummel and Siedman–Chu methods, from [15] and the two-step VRS method from part 1 of this work;

4) Chebyshev's cyclical method [16] and the Buleev–Stone method [17, 18] (for continuity equations only) for solving the system of linear algebraic equations.

All quantities were determined at nodes by a quasiuniform, over the regions of the device, grid of spatial discretization. The total number of basic unknowns in the approximate algebraic problem was \( 5 \times 10^5 \) and higher.

Figure 2a shows the behavior of \( |\delta y|_{\text{max}} \) (curve 1 shows the number of Newton iterations) for the Siedman–Chu method (S–C) (curve 1) single-step [15] (curve 2) and two-step VRS (curve 3), methods in which, to increase the rate of convergence as well as to decrease the machine time used, two iterations of sections 2 and 3 of the method in [4] are performed. Thus a single iteration of the two-step method requires no greater computational time than two iterations of the Siedman–Chu method. In the present numerical experimental the voltages of the resistive contacts have the following values: \( V_1 = 0.7 \text{ V}; V_e = V_b = V_c = 0.5 \text{ V}. \) It is evident from the graphs that the rate of convergence of the two-stepped VRS method (TS) is much higher than that of S–C method and higher than that of the single-step method (SS) proposed in [15]. Comparing the amounts of machine time used, we note that for the SS method \( \approx 20 \) equivalent S–C iterations are required, while for the TS method approximately 18 iterations are required (i.e., the TS method is approximately 1.1 times more efficient than the SS method).

A numerical experiment taking into account the effect of Auger recombination, using the generalized two-step VRS method, was performed for the same bias voltages. The maximum deviation was approximately 0.7% for the collector current. This indicates the negligibly small effect of this recombination mechanism for the device examined and for the bias voltages given, agreeing with the results in [8], which were obtained for a bipolar transistor.