CIRCUIT SIMULATION PROGRAM ORIENTED PHYSICAL MODELLING OF INTEGRATED CIRCUIT ELEMENTS

By

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1. Introduction

Investigation of various semiconductor devices and structures requires the solution of a system of partial differential equations, which consists of

— equations describing the charge transport,

— relationships expressing the charge continuity,

— Maxwell equations determining the general properties of the electric field.

The solution must refer to the medium depending on the doping conditions and with the initial and boundary conditions depending on the geometry of the semiconductor device and the external (electrical, optical, thermal etc.) excitations. An analytical solution for the practically used structures is only possible with extreme simplifications because of electric field and charge concentration etc. depending on material characteristics to be taken into account. First of all, numerical solution methods have reasons for existence but even so, simplifying methods must be used, because the complete solution of the above mentioned problem goes beyond the capacity of the modern heavy-duty computers. The number of space points to be allocated by transforming the differential equations into finite-element equations is in the range of ten thousands to one million depending on the method chosen and the degree of fineness of discretization, and the solution of the system brings up a whole series of theoretical and practical problems starting from the question of the existence and uniqueness of the solution to the needed extreme computing capacity related to the nonlinearity of the individual medium characteristics. There are two ways of solving this problem:

1. Reduction by decreasing the number of dimensions

Good results can be reached on one-dimensional models without extremely tedious computations. On the other hand, several practically important problems become inaccessible.

2. Applying regional approximation

In this case lumps of the examined structure are modelled by different, but simpler relationships describing only the main properties of the given lump. These lumps are interfaced to each other at their junctions by internal boundary conditions.

2. Regional approximation

The basic problem of the lumped models is partitioning to lumps and properly determining the internal boundary conditions. Although this problem can also be solved as a pure mathematical one considering it as independent of the semiconductor device, partitioning and determining the internal boundary conditions can be done much easier based upon the knowledge of the physical processes in the semiconductor and the operation of the device. These facts were discovered already in 1958, "primitive age" of semiconductors, when Linvill published his model named after him [1]. The basic philosophy of his conception was to focus discretization on the conclusions which can be drawn from the processes of semiconductor physics. For this sake he created new circuit elements (storance, driftance, diffusance, combinance, Fig. 1).

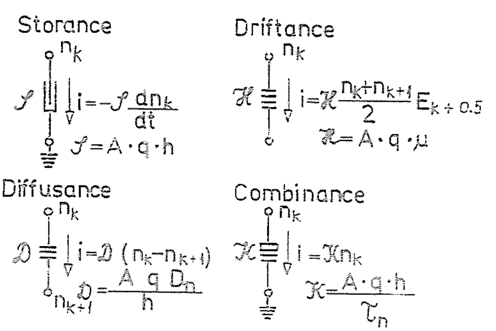

Fig. 1. Linvill's set of models

The introduction of these special circuit elements—inaccessible to the conventional circuit solution methods based on Kirchhoff's equations—although crossed the practical spreading of Linvill's idea but has had an extremely good influence in the field of semiconductor device modelling. It was recognized early in the 70's that a certain modification of Linvill's idea to use conventional circuit elements in discretization had extraordinarily good possibilities in modelling semiconductor devices and integrated circuit elements.

3. Medium models

The TRANZ-TRAN nonlinear circuit analysis program developed at the Department of Electronic Devices by the late 60's was primarily designed for analyzing circuits with integrated circuit elements. In developing the set of models for this program much stress was laid on models describing the operation of each semiconductor device in the following way:

a) The terminal parameters are related by equations based on the physical theory of semiconductor devices. No relationships based on the empirical approximation of certain measured characteristics by mathematically convenient but physically insupported functions were applied.

b) The various secondary effects were analysed and taken into account from two points of view: effects which in full vigour practically inhibit the normal operation of the tested circuit were taken into consideration by error signals, while model equations contained those important for the design engineer, but with a limited accuracy permitting economic running times even in case of rather big circuits (e.g. operational amplifiers).

These previously introduced viewpoints permitted to complete the TRANZ-TRAN program system with the exact calculation of thermoelectric effects, very important in integrated circuits. This method based on the general transport theory of thermodynamics (Onsager theory) could be inherently integrated to the improved version of the program with no algorithmic difficulty [2, 3]. This method is the first—to our knowledge even internationally—to permit computer modelling of combined electrical-thermal transport phenomena such as the medium-model-based examination of heat distribution in cooling effect, and the switching heat transient of the Bi_2Te_3 Peltier cooling element. Earlier reports detailed the structure of the medium model used by the TRANZ-TRAN circuit analysis program based on Linvill's mentioned idea and our results [4, 5]. These analyses resulted in elaborating the theory and realization of a basically new thermal functional element [6].

4. Modelling of bipolar devices

The operation of a bipolar transistor has been examined by the modified Linvill method [7, 8]. The diffusance and combinance were replaced by resistances, the storance by capacitance, and the driftance by controlled current sources in the base region (Fig. 2). The $p-n$ junctions around the base were modelled by a circuit of diodes and current sources instead of the exponential voltage-carrier concentration transformer of the original Linvill model (Fig. 3). As a representative result of the application of this method, in Fig. 4 the distribution of the injected minority carrier concentration in the inhomogeneous base of a transistor is seen versus space and time.

This method was completed—almost simultaneously with other authors—by applying, beyond the classical basic elements of network theory (resistor, capacitor, current and voltage sources), also its complex semiconductor elements (e.g. bipolar transistor) available in a circuit analysis program.

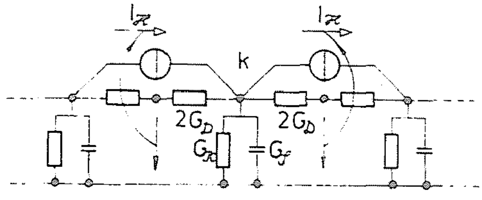

Fig. 2. Lumped model of the base region

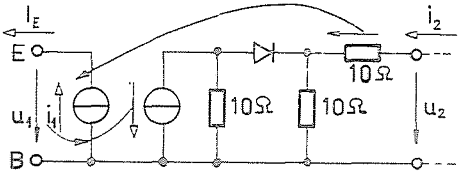

Fig. 3. Models of the junctions around the base region

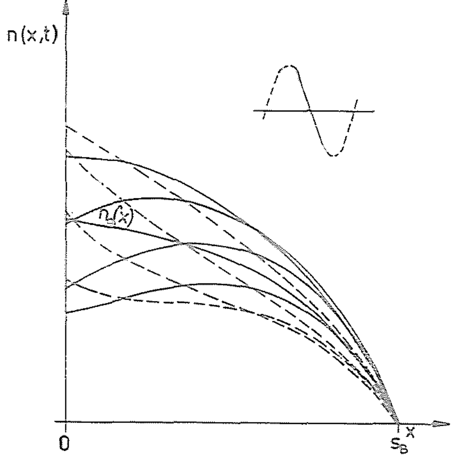

Fig. 4. Minority carrier distribution calculated using the regional approximation method based on Linvill's idea, with a sinusoidal excitation at different time instants

The phenomenon of current crowding is an important disturbance in the integrated circuit transistors: The recombination current of the base majority carriers flowing in the direction of the base contact hence perpendicular to the useful minority carrier flow from emitter to collector, causes a voltage drop in the base. Thereby the opening voltage between emitter and base is reduced, controlling, in turn, exponentially, the injected minority charge carrier flow. Now, much of the total transistor current flows through a section of the emitter which is close to the base contact. The farther sections conducting only a small amount of current take part in effects adverse to the operation of the transistor.

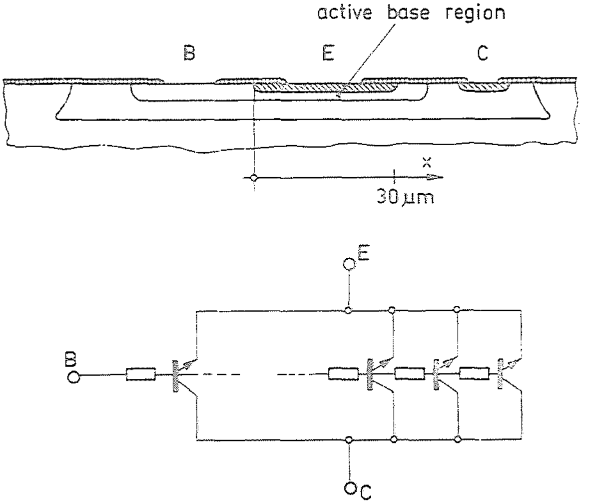

Fig. 5. Model of a bipolar transistor for examining the current crowding phenomenon

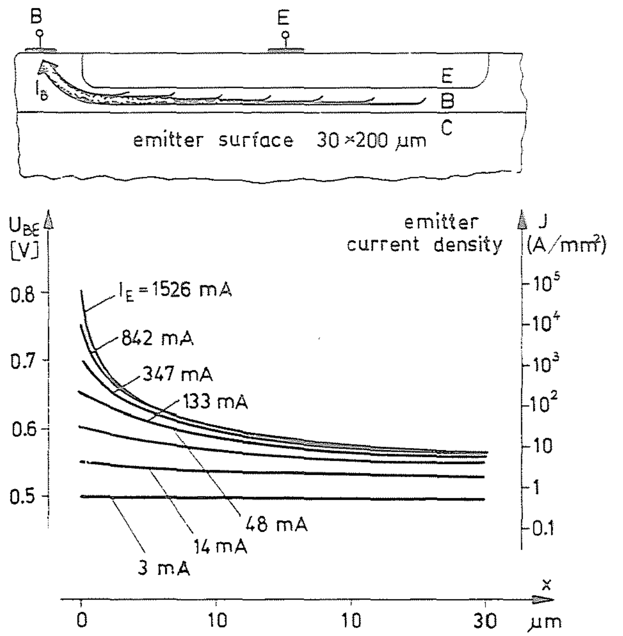

Fig. 6. Distribution of emitter-base voltage and emitter current density in a high-power planar transistor calculated with circuit analysis program

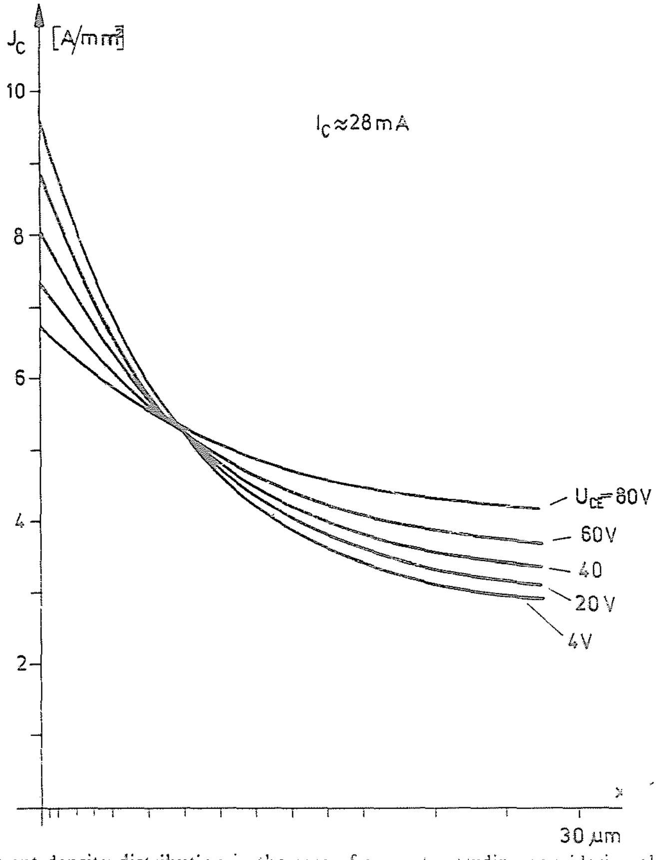

Fig. 7. Emitter current density distribution in the case of current crowding considering also the thermal coupling of the base lumps

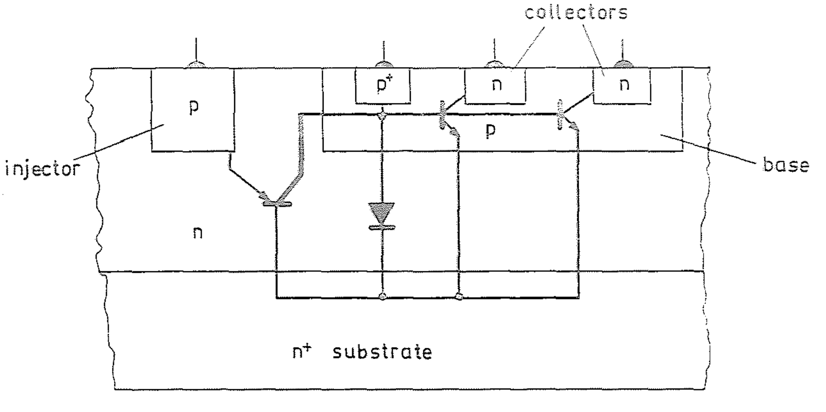

Fig. 8. Simple model of an I^2L element

The discretization is seen in Fig. 5, the emitter current distribution versus space in Fig. 6. The original result of the examination is shown in Fig. 7. Utilizing the fitness of the TRANZ-TRAN program to analyzing thermal-electrical phenomena, it has been proved that the inequality in the current density distribution because of thermal coupling of the base lumps decreases with increasing collector voltage. This finding may be useful first of all in constructing high-power transistors.

The I^2L circuit is a new and promising element of the *LSI* integrated circuit technique. Based on the previously mentioned method, several models

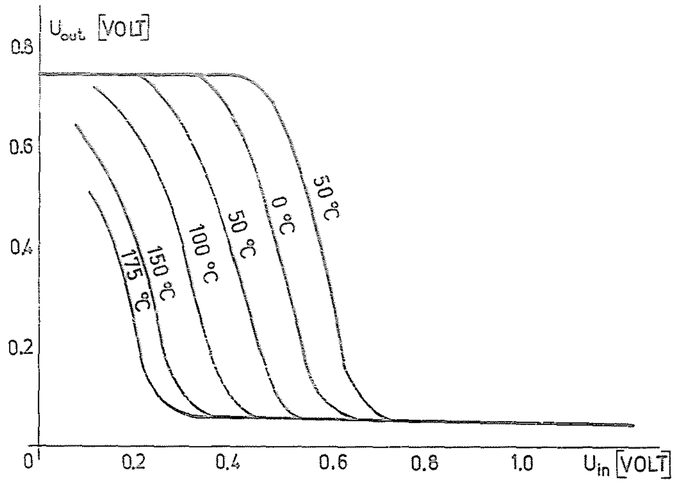

Fig. 9. Transfer characteristics of the I^2L element at different temperatures

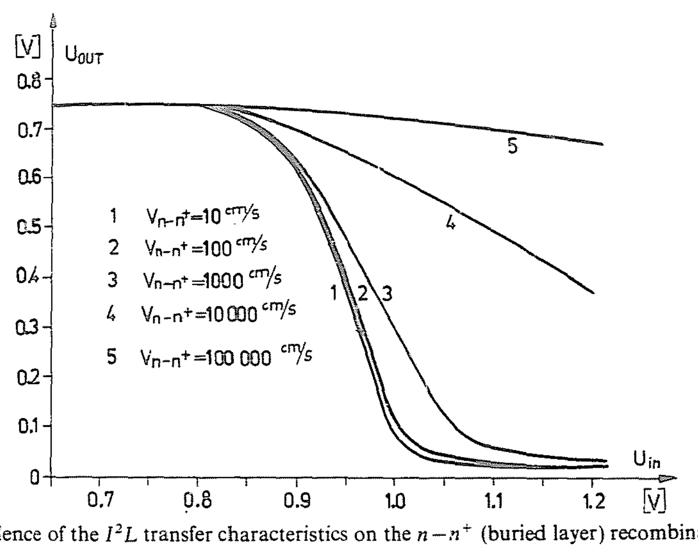

Fig. 10. Dependence of the I^2L transfer characteristics on the $n-n^+$ (buried layer) recombination velocity

of different complexities have been worked out for I^2L elements [9]. The simplest one is shown in Fig. 8. This model, although very simple, describes the operation of the I^2L element with an adequate accuracy, at a simple determination of its main parameters. The transfer characteristics of this model at different temperatures are seen in Fig. 9, while Fig. 10 demonstrates the dependence of the transfer characteristics on the recombination velocity of the $n-n^+$ (buried layer) junction.

5. Modelling of MOS devices

A new physically supported circuit-oriented model of MOS transistors with a topology similar to the Ebers-Moll model of bipolar transistors [10, 11, 12] has been developed and built into the TRANZ-TRAN circuit analysis program. Afterwards this model was completed with relationships considering thermal and substrate effects [13]. Besides—using the relevant experiences—a functional model has been worked out for relatively complex digital circuit-parts (gates, $J-K$ flip-flops etc.) so as to permit modelling of some critical circuit-parts to physical standards. Our results are illustrated in Fig. 11 on the transient waveforms of the dynamic RAM type 1103 (Fig. 12) [14].

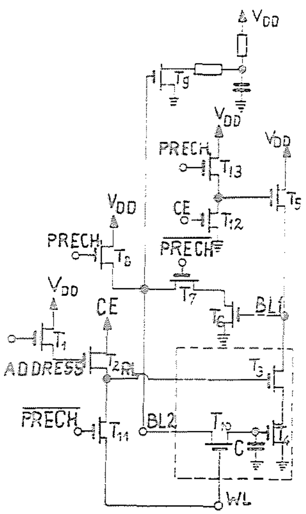

Fig. 11. Layout of the SIGNETICS 1103 dynamic MOS RAM memory cell

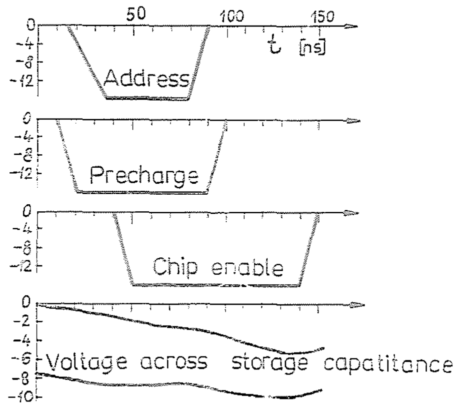

Fig. 12. Voltage drop on the capacitance of the 1103 dynamic storage cell at logical "0" and "1" level. The voltage level is evaluated at the 100 nsec time instant

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Summary

The paper gives an account of the research on physical modelling of various integrated circuit elements by using the TRANZ-TRAN circuit analysis program. The application of the circuit analysis program in this field affords a very efficient method for examining the characteristics of the individual devices with appropriate accuracy. Methods have been developed for:

— exact investigation of the base region of transistors,
— examining the current crowding phenomena in bipolar transistors,
— physical and circuit-oriented modelling of I^2L elements,
— simulation of various MOS structures.

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