CHARACTERIZATION OF SEMICONDUCTOR DEVICES USING TECHNOLOGICAL AND GEOMETRIC PARAMETERS

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ABSTRACT

In many cases the characterization of semiconductor devices in terms of their technological and geometric parameters is more important for process analysis and device design optimization than that in terms of electrical parameters. This paper presents and extension to the FIT-3 parameter extraction program which allows to use any combination of technological, geometric and electrical parameters in characterization of semiconductor devices. The approach is flexible enough to be used for a variety of technologies and for all basic analyses (DC, AC and time-domain).

1. INTRODUCTION

Accurate and reliable simulation of electronic circuits cannot be obtained without accurate models of circuit elements, and in particular semiconductor devices. This is especially relevant to analog designs and IC technologies where post-fabrication tuning is extremely difficult if possible at all. Therefore parameter extraction tools, which determine such values of device model parameters that provide the best fit of device characteristics against the measurement data, are essential components of computer-aided design software systems.

Although several approaches to extraction of device parameters have been proposed in the literature [Ban88], [Dav90], [Gar88], [Vai89], [Con85], [Dog83], [Yan83], the proposed methods are based on electrical parameters of device models. The electrical parameters are very useful from the circuit design perspective, however, they are rather inconvenient from manufacturing point of view as they cannot provide the required feedback for process analysis and device design optimization. A set of technological and geometric parameters is much more relevant to manufacturing processes than a set of electrical parameters. Technological and geometric parameters are also much more convenient to impose technology constraints and analyse parameter deviations and correlations, for example due to variations of fabrication processes. Quite often a "mixed" set of parameters is used which includes electrical as well as technological and geometric parameters.

It should be noted that technological parameters and dependencies between technological and electrical parameters are closely related to manufacturing technology, and as this technology evolves, both the set of parameters and dependencies change. Therefore, a capability of (flexible) parameter conversions is an important aspect of parameter extraction programs.

The possibility to extract the technological and geometric parameters is an extension of FIT program [ZK91], [KZD91].

2. PARAMETER CONVERSION

The extraction approach used in FIT-2 and FIT-3 programs is the iterative, simulation-based and data-driven one. It uses general optimization methods and an "open" circuit simulator [Zub84, Zub89] rather than traditional set of equations. Basic advantages of the proposed approach include:

(1) explicit model equations need not to be known as they are provided by the circuit simulator,
(2) fitting can be performed not only for single devices but for functional blocks or whole circuits as well,
(3) the same extractor can be used for a variety of devices and/or device models.

Several optimization methods are built into the program to provide reliable and efficient fitting of device characteristics.
The modularity of the realization enables an easy evolution of the program as for example addition of new functionalities or new optimization methods.

FIT-3 allows to fit all measurements of a device (DC, AC, transient, ...) with the same model which gives a consistent characterization of modeled devices.

In order to support different sets of parameters, an interface has been built into the FIT-3 program that accepts a user-defined conversion of technological and geometric parameters (used as optimization variables) into electrical parameters (used as circuit variables).

FIT-3 requires a specification of the set of optimization variables (together with their contraints). In simple applications, when only electrical parameters are extracted, the set of electrical parameters is used as the set of optimization variables, so the relationship between the parameters of the (simulated) circuit and the optimization variables is straightforward. However, in the case of extraction of technological and/or geometric parameters (used as optimization variables), a conversion to electrical parameters is needed for obtaining the corresponding responses from the simulated circuit. In order to support such conversions, an interface has been built into the FIT-3 extractor for accepting user-defined transformations of (arbitrary) optimization variables into equivalent parameters of the simulated circuit.

This interface is composed of two routines, VARDEF and VARMAP; VARDEF performs a mapping of the set of names of optimization variable names into a corresponding set of names of circuit variables (names of circuit variables must be correct with respect to the circuit description file, as required by SPICE-PAC), while VARMAP performs a mapping of values of optimization variables into the corresponding set of values of circuit variables assuming that the ordering of variables is the same as for VARDEF.

3. IMPLEMENTATION IN FIT-3 PROGRAM

For "nonstandard" applications, two routines VARDEF and VARMAP must be user-defined and linked with the FIT-3 program. The routines must conform to the following FORTRAN headers:

```fortran
SUBROUTINE VARDEF (NAMOPT, NOV, NAMCKT, LCV, NCV)
CHARACTER*16 NAMOPT(*), NAMCKT(*)
NCV = 0
DO 10 I = 1, NOV
NCV = NCV + 1
NAMCKT(I) = NAMOPT(I)
WRITE(*, 900)
900 FORMAT('... VARDEF : too many circuit variables
...')
RETURN
ENDIF
10 CONTINUE
RETURN
END

SUBROUTINE VARMAP (VAROPT, NOV, VARCKT, LCV, NCV)
DOUBLE PRECISION VAROPT(*), VARCKT(*)
NCV = 0
DO 10 I = 1, NOV
NCV = NCV + 1
VARCKT(I) = VAROPT(I)
ELSE
WRITE(*, 900)
900 FORMAT('... VARMAP : too many circuit variables
...')
RETURN
ENDIF
10 CONTINUE
RETURN
END
```

4. EXAMPLE

The following simple example illustrates an application of parameter conversion. It appears that many of the (electrical) Gummel-Poon parameters of GaAs/GaAlAs Heterojunction Bipolar Transistor (HBT) depend on a few other parameters:

- \( \rho_b \) base contact resistance
- \( \rho_e \) emitter contact resistance
- \( \rho_c \) collector contact resistance

```fortran
SUBROUTINE VARMAP (VAROPT, NOV, VARCKT, LCV, NCV)
DOUBLE PRECISION VAROPT(*), VARCKT(*)
where:
VAROPT is a vector of DOUBLE PRECISION values of optimization variables,
NOV is the number of optimization variables,
VARCKT is a vector that returns the DOUBLE PRECISION values of circuit variables,
LCV is the limit of circuit variables (i.e., the length of VARCKT),
NCV is the number of circuit variables.
The 'standard' interfacing routines correspond to the case when the optimization variables are also circuit variables, i.e., both routines perform identity mappings:
SUBROUTINE VARDEF (NAMOPT, NOV, NAMCKT, LCV, NCV)
CHARACTER*16 NAMOPT(*), NAMCKT(*)
NCV = 0
DO 10 I = 1, NOV
NCV = NCV + 1
NAMCKT(I) = NAMOPT(I)
WRITE(*, 900)
900 FORMAT('... VARDEF : too many circuit variables
...')
RETURN
ENDIF
10 CONTINUE
RETURN
END
SUBROUTINE VARMAP (VAROPT, NOV, VARCKT, LCV, NCV)
DOUBLE PRECISION VAROPT(*), VARCKT(*)
NCV = 0
DO 10 I = 1, NOV
NCV = NCV + 1
VARCKT(I) = VAROPT(I)
ELSE
WRITE(*, 900)
900 FORMAT('... VARMAP : too many circuit variables
...')
RETURN
ENDIF
10 CONTINUE
RETURN
END
```
L _i_ transistor length

The first three parameters represent ohmic contacts (in Ω/cm²) of the base, emitter and collector, respectively. They are important for DC as well as dynamic performances of transistors. Approximate values of these parameters can be obtained through measurements of special test devices, for example TLM devices, however, such test devices are usually much larger, so the measured values do not correspond to the other, non-test devices accurately. The last parameter, L _o_, is very difficult to measure. At the same time it is very important to know it precisely, as many electrical parameters depend on it.

The relationships between these new parameters and the electrical ones are as follows:

- RE emitter resistance \( f_1(p_1, L_o) \)
- RC collector resistance \( f_2(p_1, L_o) \)
- RB zero bias base resistance \( f_3(p_1, L_o) \)
- RBM minimum base resistance at high currents \( f_4(p_1, L_o) \)
- CJE B-E zero-bias depletion capacitance \( f_5(L_i) \)
- CJC B-C zero bias depletion capacitance \( f_6(L_i) \)
- IS transport saturation current \( f_7(L_i) \)
- ISE B-E leakage saturation current \( f_8(L_i) \)
- ISC B-C leakage saturation current \( f_9(L_i) \)

In Fig. 1 the measurements and the initial simulated data are shown. Two DC measurements (common base and common emitter) and S parameters (AC measurements) for two bias points were fitted. In Fig. 2 the fitted characteristics are presented.

The example shows that parameter conversion can be used to reduce the set of optimization variables. It should be noted that, in general case, the new set of optimization variables needs a different fit strategy than the one used for electrical parameters. Furthermore, because of nonlinear dependencies between these two sets of parameters, simple constraints of technological parameters correspond to nonlinear constraints of electrical parameters; such constraints may be difficult to take into account because more powerful optimization methods are needed to deal with general (nonlinear) constraints. However, the most important aspect of parameter conversion seems to be in reasonably simple implementation of parameter dependencies that are introduced by functions \( f_i \) in the example, and which are ignored when optimization is performed with respect to electrical parameters.

5. CONCLUSIONS

An extension of FIT program to the extraction of technological and geometric parameters is presented. This new facility allows device modelling in terms more relevant to the technological process.

This approach can provide a feedback to manufacturing process and enables more realistic circuit optimization. Parameters dispersions and correlations can be taken into account more easily.

Extraction strategies formulated up to now in terms of electrical parameters can be expressed in terms of technological and geometric or "mixed" set of parameters.

Parameter conversion can be specified in a high level specification language, but such a language is not available at the moment.

It should be noted that the same mechanism of parameter conversion can also be used for defining additional parameters which presently do not exist in device models. In fact, this mechanism was used for implementation of a novel electrical-thermal model of heterojunction bipolar transistors for mixed-domain simulation of self-heating effects in GaAs devices [Wa92]. Other model enhancements can be implemented in a similar way.

6. REFERENCES


Fig. 1. Initial DC and AC measurements for HBT transistor

Fig. 2. Final fit of DC and AC characteristics using technological and geometric parameters