

A versatile tool for extraction of MOSFETs parameters

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Abstract—Extraction of MOSFET parameters is a very important task for the purposes of MOS integrated circuits characterization and design. A versatile tool for the MOSFET parameter extraction has been developed in the Institute of Electron Technology (IET). It is used to monitor the technologies applied for fabrication of several groups of devices, e.g., CMOS ASICs, SOI pixel detectors. At present two SPICE MOSFET models (LEVEL = 1, 2) have been implemented in the extraction tool. The LEVEL = 3 model is currently being implemented. The tool combines different methods of parameter extraction based on local as well as global fitting of models to experimental data.

Keywords—MOSFETs parameters, SPICE, least squares method.

1. Introduction

Simulations of MOS ICs (integrated circuits) require sufficiently accurate MOSFET models. Moreover, the parameters of these models should be determined in a reliable way. Parameter extraction is an important task for characterization groups in MOS ICs fabrication departments.

The complexity of parameter extraction is usually closely related to the complexity of the model itself. The complexity of the model typically grows with improving accuracy. The desired accuracy depends, of course, on the application. Simulations of analog ICs usually require more accurate models than simulations of digital ones. Moreover, analysis of sub-micron devices also requires complex models that account for numerous phenomena affecting small-geometry MOSFET operation [1].

Improvement of accuracy or increase of complexity usually results in a large number of model parameters (e.g., [2]). The parameters may be divided into several groups, such as primary parameters responsible for the main phenomena in the device (e.g., threshold voltage, mobility), secondary parameters describing less important phenomena (e.g., mobility degradation coefficients), parameters describing parasitic components (e.g., serial resistances of the leads), and fitting parameters that often have no explicit physical meaning [2] (e.g., dependence of channel size variation on channel length or width). In the case of complex models with a large number of parameters it is often difficult to establish relationships between them. This complicates the extraction task even more.

The extraction of MOSFET parameters may also be useful for the characterization of technology used for ICs fabrication. Hence reliable methodologies and tools for

the extraction of MOSFET model parameters are necessary. Several solutions are available commercially. The large IC-CAP package [3] seems to be one of the most widely used. It combines data acquisition with parameter extraction for a variety of most relevant models of semiconductor devices. More compact extractors may, however, be useful too, since they may be better suited to local needs. This paper presents the MOSTXX program (MOS transistor parameter extraction in Excel), which is an efficient tool for MOSFET parameter extraction. The program has been developed in the IET and is used for characterization of MOS technologies.

2. Parameter extraction – an overview

The extraction of MOSFET model parameters is based on the fitting of the simulated I - V characteristics to the corresponding experimental I - V data. The misfit (error) between the model and the data is defined as:

$$F_{err}(\mathbf{P}) = \sum_{i=1}^N \left[I^{mod}(\mathbf{V}_i, \mathbf{P}) - I^{mea}(\mathbf{V}_i) \right]^2, \quad (1)$$

where \mathbf{P} denotes a vector of parameters, \mathbf{V}_i is a vector of bias voltages for a given i th operation point (usually it consists of three voltages: substrate-source voltage V_{BS} , gate-source voltage V_{GS} and drain-source voltage V_{DS}), I^{mod} and I^{mea} denote simulated and measured currents at a given operation point, N is the number of operation points taken into account for extraction purposes.

The misfit definition (1) has been widely used also in sophisticated modeling and characterization tools, such as IC-CAP. The parameter vector \mathbf{P} can be determined via minimization of the error function F_{err} . Thus parameter extraction can be considered as a nonlinear least-squares problem.

The parameters may be determined using two methods, namely:

- “locally”, i.e., in a well-defined bias range (e.g., strong inversion at low drain-source voltage); only selected parameters may be determined in this way;
- “globally”, i.e., taking into account different bias conditions (e.g., a complete family of $I(V_{BS}, V_{GS}, V_{DS})$ data); all model parameters may be determined simultaneously.

The computational effort of the extraction algorithm strongly depends on model linearity, number of operating points

and number of parameters. In the case of a linear model the least-squares problem is significantly easier to solve. Moreover the solution is fast and reliable. The interpretation of the parameters obtained in this way is usually straightforward. This is the case, e.g., of local extraction of the threshold voltage V_T using $I-V_{GS}$ data in the strong inversion at low drain-source voltage. Potential difficulties may arise from the determination of the bias range where the model may be considered as linear. The “quality” of the measured data seems to be relevant at this point.

In the case of a nonlinear model the least-squares problem becomes a nonlinear programming task. This approach usually allows a set of parameters to be extracted at the same time. However, the solution is more time-consuming and strongly depends on the initial approximation of parameter values. An inappropriate starting point may lead to a local minimum of the error function. Problems may also arise from mutual relationships between parameters being searched. Threshold voltage parameters and the parameters describing channel-length modulation, for example, depend on the substrate doping concentration. This may lead to convergence problems or to non-physical values of the extracted parameters.

The local and global parameter extraction may be used independently. In practice, however, the following solution may be used. A set of local extraction algorithms is used to evaluate a set of parameters. These are next used as a starting point in global extraction.

3. MOSTXX program

MOSTXX is a tool for MOSFET parameter extraction. It has been developed in the MS Excel environment and implemented using the VBA-code. It is currently used for characterization of CMOS ICs. Its features are briefly described below.

3.1. Models

At present two MOSFET models are implemented in the MOSTXX software. These are:

- SPICE (LEVEL = 1) DC model,
- SPICE (LEVEL = 2) DC model,
- SPICE (LEVEL = 3) DC model.

Several other “sub-models” (extracted from the models mentioned above) are implemented for the purposes of local identification of parameters. These are:

- linear and parabolic functions useful for local extraction of several parameters;
- a model of the dependence of threshold voltage on substrate bias;
- a model of output conductance in saturation corresponding to the SPICE (LEVEL = 1) DC model;

- models of the effect of vertical electric field on carrier mobility corresponding to the SPICE (LEVEL = 2, 3) DC models;
- models of output conductance in saturation corresponding to the SPICE (LEVEL = 2, 3) DC models.

The models mentioned above are coded in the program as separate modules. They have a common, flexible interface to the routines that call them. This interface is defined by the vector of model parameters to be extracted, vector of auxiliary parameters that enable additional data to be transferred to the model, vector of bias voltages defining the operating point of the device, and finally the vector of first-order derivatives and the matrix of second-order derivatives of the model output variable (current, threshold voltage, conductance, etc.) versus parameters. The last two items are required by the procedures minimizing the error function.

The routines containing the VBA-codes of the model also have a common structure. Any procedure calculates the output variable and the corresponding derivatives of the output variable versus model parameters for a given operating point.

Standardization of the model-defining procedures enables straightforward implementation of a new model in the MOSTXX program.

3.2. Methods and computational tools

A number of algorithms of local and global parameter extraction are implemented in the MOSTXX program.

The linear least-squares method is used for the estimation of slopes and threshold voltages of $I(V_{GS})$ curves in strong inversion at low drain bias.

The DFP (Davidon-Fletcher-Powell) and BFGS (Broyden-Fletcher-Goldfarb-Shanno) methods [4], i.e., the quasi-Newton method of the minimization of an objective (error) function defined as a global deviation of the model from the experimental data (1), is used to extract complete sets of parameters of several models, namely the models of mobilities and complete models of $I-V$ characteristics. This method seems to be very efficient, fast and reliable under the assumption that a starting point for the set of the parameters to be found is reasonably close to the final solution. This can be easily achieved using data generated with local extraction method or using parameter values obtained previously for another similar device.

The DFP, BFGS algorithms require procedures of the minimization in direction [4]. An appropriate routine, efficiently combining the Newton and bi-section methods has been implemented in MOSTXX. The DFP algorithm extensively uses a variety of vector and matrix operations. MOSTXX has been equipped with a library of procedures performing these operations. Thus the implementation of any other optimization method may be done easily.

3.3. Operation

The general flowchart of MOSTXX program is shown in Fig. 1.

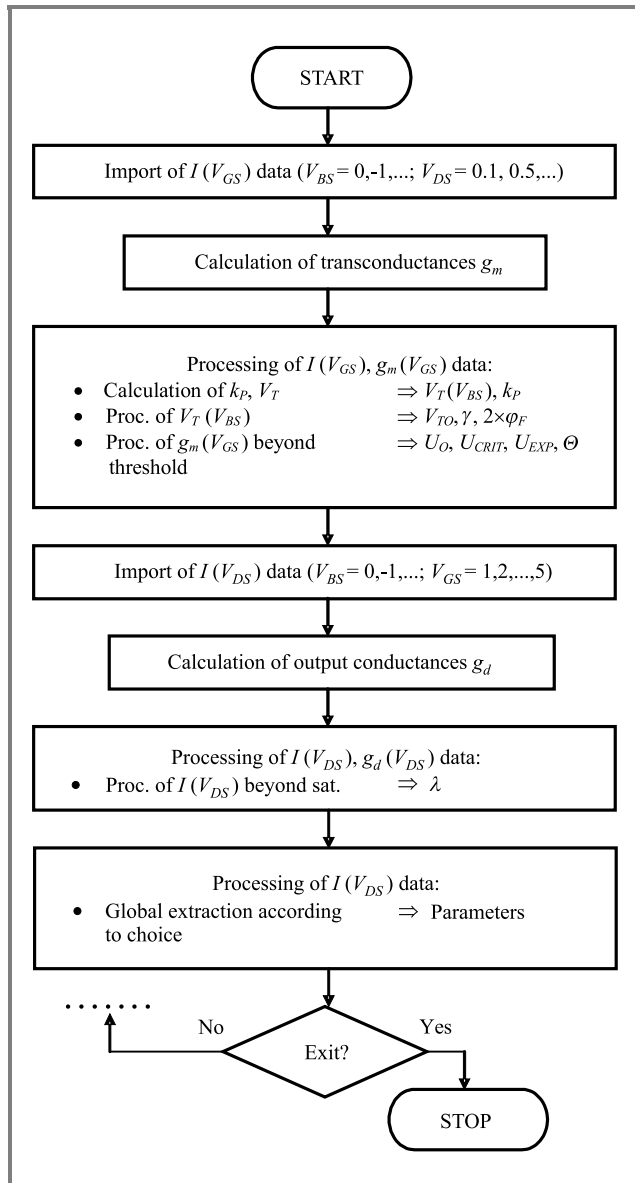


Fig. 1. Flowchart of MOSTXX; a typical sequence of extraction operations is shown.

MOSTXX operation starts with the arrangement of a workspace for the input and output data. It has been assumed that a single Excel worksheet corresponds to one family of the measured I - V characteristics only. It can be used for further processing of these data. Temporary as well as final results of the extraction from the measurement data are stored in this worksheet. There is also a special “summary” worksheet, where the final results of the extraction are stored in a manner enabling further statistical processing of the data. This worksheet plays a role of a local database of parameters.

Next the program displays the main form, giving the user an access to all program options. The availability of different form controls is related to the current status of data processing. This is recognized using contents of the current worksheet.

A set of operations is available after pressing appropriate controls on the form. These are briefly discussed below.

Import of measurement data. The program accepts I - V data in a simple ASCII format as well as data in the format used by the stand-alone METRICS measurement program [5] or semi-automatic METRICS/ELECT system [6]. The latter is particularly useful for wafer mapping purposes. In this case the program prompts the user to select the device data to be used for extraction (Fig. 2). The application automatically recognizes the structure of the I - V data, i.e., bias loops, number of points in loops, etc. The measurement data can be plotted. This option allows the user to accept the measured data before further processing or eventually reject them.

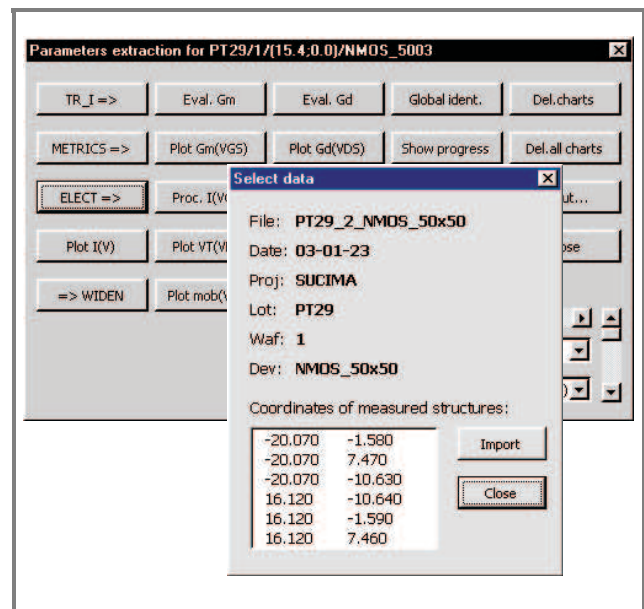


Fig. 2. Import of I - V data from the file written by the METRICS/ELECT system; additional form allows to select the device under test (DUT).

Calculation and visualization of transconductances.

This option is used, if the local extraction of the threshold voltage or extraction of mobility and parameters of its degradation due to the strong electric vertical field are to be done. Samples of $g_m(V_{GS})$ curves are shown in Fig. 3.

Extraction of the threshold voltage and its parameters.

The threshold voltage V_T is calculated using a linear fit of $I(V_{GS})$ data in the point where the corresponding transconductance curve reaches the maximum value. This processing is done for all the substrate bias V_{BS} values. Next the $V_T(V_{BS})$ characteristics are processed using the least-squares method and threshold voltage parameters are calculated (Fig. 4).

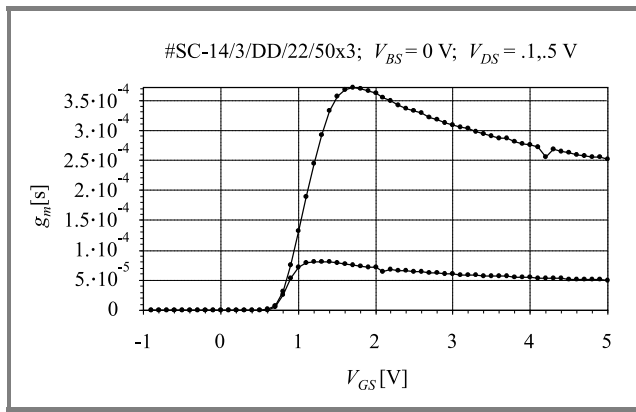


Fig. 3. Transconductances of an n-channel MOSFET ($W = 50 \mu\text{m}$, $L = 3 \mu\text{m}$).

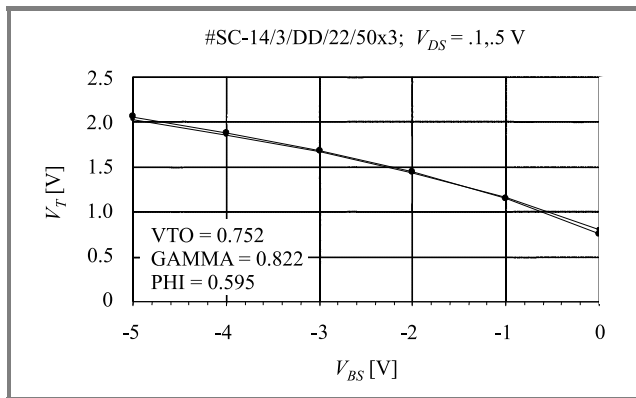


Fig. 4. Extraction of the parameters of the threshold voltage of an n-channel MOSFET ($W = 50 \mu\text{m}$, $L = 3 \mu\text{m}$).

Extraction of the mobility and its parameters. The low-field value of the mobility is calculated using the maximum value of the $g_m(V_{GS})$ data. Next, a range where the transconductance decreases (Fig. 3) is taken into account. The parameters of the mobility degradation are calculated using the least-squares method. Sample results are shown in Fig. 5. It is clear that the fit in the case of the SPICE (LEVEL = 2) mobility model containing 3 parameters is

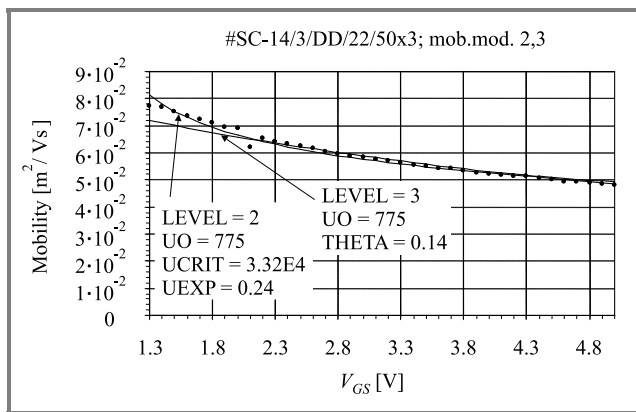


Fig. 5. Extraction of mobility parameters of an n-channel MOSFET ($W = 50 \mu\text{m}$, $L = 3 \mu\text{m}$) using two SPICE models.

better than in the case of the SPICE (LEVEL = 3) one containing 2 parameters only.

Calculation and visualization of output conductances g_d . This option must be used, if the local extraction of MOSFET parameters in the saturation range (e.g., λ in SPICE LEVEL = 1 model) is to be done. Samples of $g_d(V_{DS})$ curves are shown in Fig. 6.

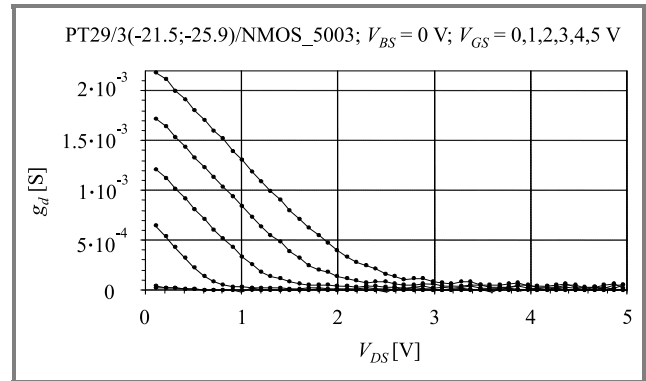


Fig. 6. Output conductances of an n-channel MOSFET.

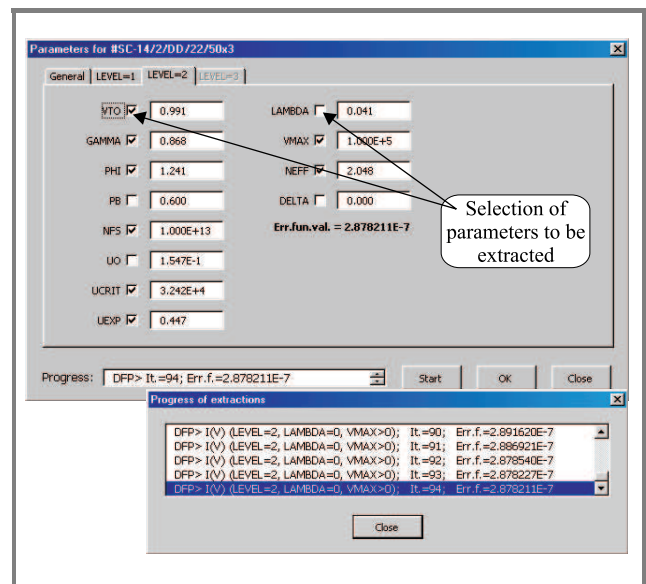


Fig. 7. Global extraction of n-channel MOSFET parameters.

Global extraction of parameters and visualization of modelled I - V characteristics. This is the most important option of the MOSTXX tool. It enables a set of parameter values to be determined that ensures the best fit of the model to the experimental data.

When the user selects this option an appropriate multi-tab form appears (Fig. 7). The user selects a model, choosing the appropriate tab. Then parameters to be extracted automatically should be checked. Otherwise they will be assumed constant during the minimization of the error function (1). The whole set of parameters may also be determined “manually”. After pressing the “OK” button a misfit (error function) value is displayed. Simultaneously,

if model characteristics charts are embedded in the worksheet, they are immediately updated. This method can be used to extract parameters “manually”, as well as to quickly investigate the effect of parameter variations on the model characteristics. Pressing the “OK” button also updates the appropriate cells in the current worksheet and in the “summary” worksheet, where the final extraction results are stored.

After pressing the “Start” button the minimization of the error function is initiated. The time required for calculations depends on the initial parameter values, the number of measured points, the number of parameters to be extracted and the complexity of the model formulae. Thus the “quality” and the efficiency of the VBA code of the model is very relevant to the extraction. The user may monitor the progress of the calculations watching successive error function values displayed in a list-box control. The contents of this field are available also after calculations are finished and may be displayed on demand (Fig. 7). This option may be particularly useful in the case of a wrong starting point, when the minimization does not converge. The user can then easily set a better initial approximation of the parameter values. The calculations are usually fast (several seconds for a whole family of I - V data) and reliable. The final misfit value is also displayed in the form.

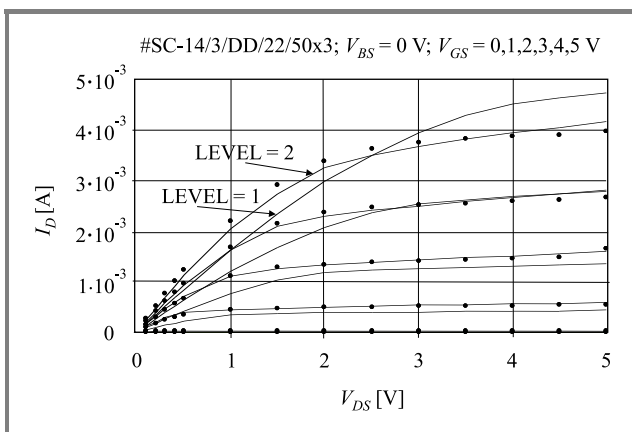


Fig. 8. Results of global extraction of a n-channel MOSFET ($W = 50 \mu\text{m}$, $L = 3 \mu\text{m}$) parameters.

As has been mentioned above, the I - V characteristics of the model may be plotted together with the experimental data. A sample of extraction results is shown in Fig. 8 for a n-channel MOSFET with channel dimensions: $W = 50 \mu\text{m}$, $L = 3 \mu\text{m}$. One can see that the results of the extraction based on the LEVEL = 2 model is quite satisfactory, while the fitting in the case of the LEVEL = 1 model is much worse. The results of parameter extraction for a p-channel MOSFET ($W = 50 \mu\text{m}$, $L = 50 \mu\text{m}$) parameters are shown in Fig. 9. In this case a good fit has been obtained using both models.

The most efficient way to use the MOSTXX software for parameter extraction is to perform first a series of local extractions of the threshold voltage and its parame-

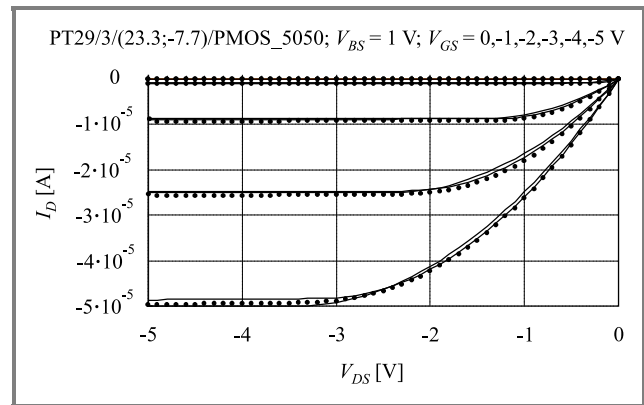


Fig. 9. Results of the global extraction of a p-channel MOSFET ($W = 50 \mu\text{m}$, $L = 50 \mu\text{m}$) parameters.

ters, mobility and its parameters and output conductance in the saturation range. The results of these calculations can be then used as the starting point for global parameter extraction.

3.4. Other features

The MOSTXX program operates in the MS Excel environment. Thus all Excel options are available. Additional non-standard calculations may be done easily.

The following MOSTXX advantages can be mentioned: good convergence, computational efficiency, the ability to perform calculations using incomplete data, for example only global parameter extraction may be done if $I(V_{DS})$ data is available for a single V_{BS} voltage only. Thus the manual mode of operation is very useful.

4. Future work

The presented tool is undergoing further development. The following goals are to be reached:

- Implementation of the BSIM3 model, which became a standard solution in the area of simulation of CMOS ICs.
- Implementation of BSIM3 SOI model; this task may be relevant if CMOS SOI technology is to be considered as a standard technology in the IET laboratory.
- Establishment of a link to the statistical process control (SPC) module.
- Translation of the VBA code into Delphi or C (a database project would then be required).

It is expected that MOSTXX will be a very useful tool for the characterization of MOS technologies in the IET. Due to its efficiency it could even be used as an on-line postprocessor in the measurement programs.

5. Conclusion

An efficient and versatile tool for MOSFET parameter extraction combining a set of identification methods has been developed in IET. Two standard MOSFET models are implemented in MOSTXX in the full form. The third one is implemented partially. Samples of the MOSTXX operation are shown. Further development of the program is planned.

Acknowledgment

Partially supported by E.C. Contract GRID-CT-2001-000561.

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Piotr B. Grabiec – for biography, see this issue, p. 45.