

# **SPACE 3D CAPACITANCE EXTRACTION USER'S MANUAL**

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## 1. Introduction

### 1.1 3D Capacitance Extraction

Parasitic capacitances of interconnects in integrated circuits become more important as the feature sizes on the circuits are decreased and the area of the circuit is unchanged or increased. For submicron integrated circuits - where the vertical dimensions of the wires are in the same order of magnitude as their minimum horizontal dimensions - 3D numerical techniques are even required to accurately compute the values of the interconnect capacitances.

This document describes the layout-to-circuit extraction program *space3d*, that is used to accurately and efficiently compute 3D interconnect capacitances of integrated circuits based upon their mask layout description. The 3D capacitances are part of an output circuit together with other circuit components like transistors and resistances. This circuit can directly be used as input for a circuit simulator like SPICE.

### 1.2 Space Characteristics

To compute 3D interconnect capacitances, *space3d* uses a boundary-element method. In the boundary-element method, elements are placed on the boundaries of the interconnects. This has as an advantage over the finite-element and the finite-difference method (where the domain between the conductors is discretized) that - especially for 3D situations - a lower number of discretization elements is used. However, a disadvantage of the boundary-element method is that in order to compute the capacitance matrix it requires the inversion of a full matrix of size  $N \times N$ , where  $N$  is the total number of elements. This takes  $O(N^3)$  time and  $O(N^2)$  memory.

To reduce the complexity of the above problem, *space3d* employs a new matrix inversion technique that computes only an approximate inverse. In practice, this means that only coupling effects are computed between “nearby” elements and that no coupling capacitances are found between elements that are far apart. For flat layout descriptions, this method has a computation complexity that is  $O(N)$  and a space complexity that is  $O(1)$ . As a result, *space3d* is capable of quickly extracting relatively large circuits (> 100 transistors), and memory limitations of the computer are seldom an insurmountable obstacle in using the program.

### 1.3 Documentation

Throughout this document it is assumed that the reader is familiar with the usage of *space* as a basic layout-to-circuit extractor, i.e. extraction of transistors and connectivity. This document only describes the additional information that is necessary to use *space3d* for

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3D capacitance extraction. The usage of *space* or *space3d* as a basic layout-to-circuit extractor is described in the following documents:

- **Space User's Manual**  
This document describes all features of *space* except for the 3D capacitance extraction mode. It is not an introduction to *space* for novice users, those are referred to the *Space Tutorial*.
- **Space Tutorial**  
The *Space Tutorial* provides a hands-on introduction to using *space* and the auxiliary tools in the system that are used in conjunction with *space*. It contains several examples.
- **Space Tutorial - Helios Version**  
The same tutorial as above, but now described under the assumption that the graphical user interface *helios* is used to run the extraction tools.
- **Manual Pages**  
For *space* and *space3d* as well as for other tools that are used in conjunction with *space*, manual pages are available describing (the usage of) these programs. The manual pages are on-line available, as well as in printed form. The on-line information can be obtained using the *icdman* program.
- **Xspace User's Manual**  
This manual describes the usage of *Xspace*, a graphical X Windows based interactive visualization tool of *space3d*. (*Xspace* is also part of *helios* and can best be run from there.)

Also available:

- **Space Substrate Resistance Extraction User's Manual**  
This manual describes how resistances between substrate terminals are computed in order to model substrate coupling effects in analog and mixed digital/analog circuits.

## 1.4 On-line Examples

Two examples are presented in this manual that are also available on-line. We will assume that the *Space Software* has been installed under the directory **/usr/cacd**. The examples are then found in the directories **/usr/cacd/share/demo/poly5** and **/usr/cacd/share/demo/sram** respectively.

## 2. Program Usage

### 2.1 General

3D capacitance extraction can be performed using one of the following versions of the *Space Software*: *space3d* (for batch mode extraction) and *Xspace* (for interactive extraction and mesh visualization). Both these tools can also be used from within the graphical user interface *helios*.

Normally, when performing a 3D capacitance extraction, a flat extraction will be executed. This implication can be disabled when turning on the parameter *allow\_hierarchical\_cap3d*.

### 2.2 Batch Mode Extraction

In order to use the 3D capacitance extraction mode of *space3d*, use the option **-3**. Also, use either the option **-c** or the option **-C**. In both cases, 3D ground and coupling capacitances are computed. However, only in the second case all these capacitances will be part of the output circuit. In the first case, all coupling capacitances will be reconnected to ground.

### 2.3 Interactive Extraction

For 3D capacitance extraction it may be helpful to use the *Xspace* visualization program. This program is not more an interactive version of the *space3d* program. But it runs *space3d* in batch mode for each new extraction. It is using a "display.out" file to show the results. The *Xspace* program runs under X Windows and uses a graphical window to, among other things, show the 3D mesh that is generated by the program. Interactively, the user can select the cell that is extracted, the options that are used, and the items that are displayed. However, for a complete graphical interface to all extraction tools, it is better to use the graphical user interface *helios* that includes *space3d* as well as *Xspace*.

For 3D capacitance extraction using *Xspace*, turn on "3D capacitance" and either "coupling cap" or "capacitance" in the menu "Options". To display also the 3D mesh, click on "DrawBEMesh" and "3 dimensional" (and possibly "DrawGreen") in the menu "Display". Then, after selecting the name of the cell in the menu "Database", the extraction can be started by clicking on "extract" in the menu "Extract".

To preview the mesh for 3D capacitance computation, use *Xspace* as described above and also turn on "BE mesh only".

### 3. Technology Description

#### 3.1 Introduction

For 3D extraction, the space element definition file is extended with a description of the vertical dimensions of the conductors, optionally, a description of the edge shapes of the conductors, and a description of the dielectric structure of the circuit. Information about these specifications is given below. For basic information about the development of an element definition file (technology file), see the Space User's Manual.

#### 3.2 Unit Specification

Optionally the unit for distances in the vertical dimension list and the unit for distances in the shape lists are specified in the unit specification of the element definition file. A unit for the vertical dimension list is specified by means of the keywords *unit* and *vdimension*, followed by the value of the unit. A unit for the edge/cross-over shape list is specified by means of the keywords *unit* and *shape*, followed by the value of the unit.

**Example:**

The following specifies a unit of 1 micron for distances that are given in the vertical dimension list and for distances that are given in a shape list:

```
unit vdimension      1e-6    # micron
unit shape           1e-6    # micron
```

#### 3.3 The Vertical Dimension List

Syntax:

```
vdimensions :
  name : condition_list(s) : mask : bottom thickness
  .
  .
  [ skip_cap3d : name1 name2 [: capacitance] ]
  [ keep_cap2d : cap2d-name ]
```

The vertical dimension list specifies for different conductors under different conditions (e.g. metal2 above polysilicon or metal2 above metal1) (1) *bottom*: the distance between the substrate and the bottom of the conductor (2) *thickness*: the thickness of the conductor. The vertical dimension list is included in the element definition file after the specification of the standard (non-3D) elements (see the Space User's Manual).

Optional "skip\_cap3d" can be specified for partial 2D surface capacitance extraction between the specified two vdimension names. This is especial useful for large conductor

plates and plates which lay very close to each other. The to use 2D surface capacitance value can be specified. A zero value skips the surface capacitance completely. Default the value is calculated from the dielectric structure.

The "keep\_cap2d" option can be specified for each 2D capacitance you want to keep during 3D capacitance extraction.

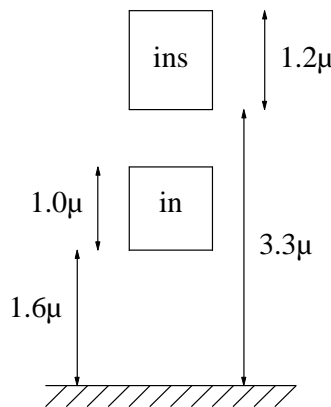
**Example:**

An example of an almost minimal technology file (with corresponding geometry) is given below. While minimal, this file can actually be complete (except for a specification of the dielectric structure) for 3D extraction for a double metal process in which only metal1 and metal2 capacitances are extracted.

```
unit vdimension      1e-6  # micron

conductors :
  metall : in  : in  : 0
  metal2 : ins : ins : 0

vdimensions :
  metall_shape : in  : in  : 1.6 1.0
  metal2_shape : ins : ins : 3.3 1.2
```



At a transition area, where a conductor goes from one bottom and thickness specification to another bottom and thickness specification, the slope of the conductor is determined by the parameter *default\_step\_slope* (see Section 4.2).

**NOTE:**

To prevent the overlap of different transition areas of one conductor (which currently results incorrect element meshes), the differences in bottom and thickness specifications of one conductor may not be too large (otherwise: increase the parameter *default\_step\_slope*).

See Section 3.8 for a specification of diffused conductors.

### 3.4 The Edge Shape List

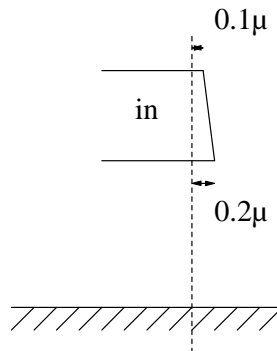
Syntax:

```
eshapes :
  name : condition_list(s) : mask : db dt
  .
  .
```

The edge shape list specifies for different conductors, the extension of each conductor in the x (or y) direction relative to the position of the original conductor edge in the layout. The first value (*db*) specifies the extension of the *bottom* of the conductor and the second value (*dt*) specifies the extension of the *top* of the conductor. Either extension may be negative. The edge shape list should be present in the element definition file after the vertical dimension list.

**Example:**

```
eshapes :
  metall_eshape : !in -in : in : 0.2 0.1
```



**NOTE:**

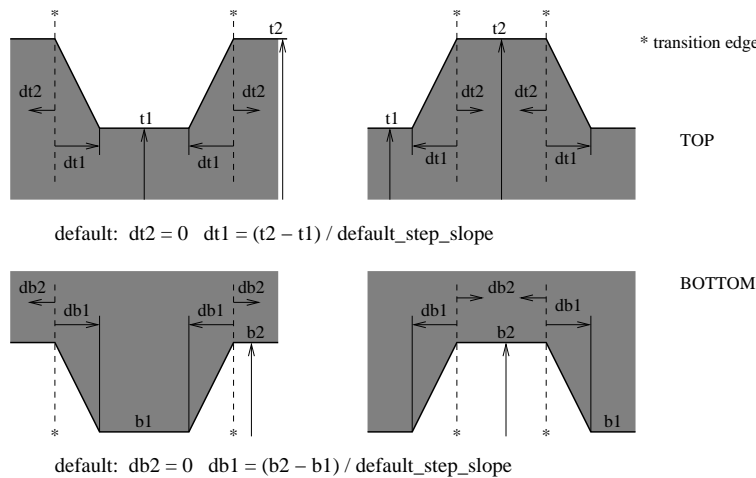
In some cases, the use of *eshapes* may cause mesh generation problems because e.g. at corners the order of mesh nodes can get mixed up. Because of that, when *db* and *dt* have (approximately) the same value, it is often better to use a *resize* statement (see Space User's Manual) instead of an *eshape* statement, since this option is less likely to cause mesh generation problems.

### 3.5 The Cross-over Shape List

Syntax:

```
cshapes :
  name : condition_list(s) : mask : db1 dt1 db2 dt2
  .
  .
```

The cross-over shape list specifies for different conductors, the extensions of the *bottom* and *top* of each conductor in the x (or y) direction relative to the position of a transition edge in the layout. The transition edge, is an edge (caused by another mask), where a conductor goes from one bottom and thickness specification to another bottom and/or thickness specification. Thus, there must be two vdimension specifications for the same conductor. The cross-over shape specification overrules the *default\_step\_slope* method (see Section 4.2).



Note that the first and third value ( $db1$  and  $db2$ ) specify the extension of the *bottom* of the conductor (at left and right side of the transition,  $db1$  to  $b1$  the lowest *bottom* value) and the second and fourth value ( $dt1$  and  $dt2$ ) specify the extension of the *top* of the conductor. Each extension value can may be negative. But be warned, some extension combinations can result in an incorrect mesh. The cross-over shape list should be present in the element definition file after the edge shape list.

#### Example:

```
vdimensions :                               # bottom thickness
  ver_cpg_of_caa : cpg !caa : cpg : 1.6 0.5
  ver_cpg_on_caa : cpg  caa : cpg : 1.8 0.4

cshapes :
  cpg_cshape : cpg !caa -caa : cpg : 0.1 0.1 0.1 0.0
```



### 3.6 Dielectric Structure

Syntax:

```
dielectrics :
  name permittivity bottom
  .
  .
```

Specifies the dielectric structure of the chip. This specification is included in the element definition file after the vertical dimension list and the shape lists. For each layer, *name* is an arbitrary label that will be used for error messages etc, *permittivity* is a real number giving the relative dielectric constant, and *bottom* specifies (in microns) the bottom of the dielectric layer. The value of *bottom* must be  $\geq 0$ . The first dielectric in the list specifies the lowest dielectric, the second dielectric the second lowest, etc. For the first dielectric layer *bottom* must be zero. The top of a dielectric layer is at the bottom of the next dielectric. The top of the last dielectric is at infinity. No dielectric layers means vacuum. If one or more dielectric layers are specified, a ground plane at zero is present.

**Example:**

```
dielectrics :
  # Dielectric consists of 5 micron thick SiO2
  # (epsilon = 3.9) on a conducting plane.
  SiO2  3.9  0.0
  air   1.0  5.0
```

**NOTE:**

If more than 3 dielectric layers are specified, you should pass the **-u** option to *tecc*. This enables the "unigreen" method, which is a different kind of computation that allows for more than 3 dielectric layers. Note that the "unigreen" method is not available in the public version.

### 3.7 Additional Parameters in the Dielectrics Section

This section discusses several additional parameters which may be specified in the *dielectrics* section of the technology file. **Specifying these parameters should not be necessary under normal circumstances.** They are present for advanced tuning of *space3d*. Note that these parameters will only be used when you specify the **-u** option to *tecc* (i.e., when the "unigreen" method is enabled).

Internally, *space3d* needs to compute voltage values at different locations in the dielectric layer structure, given a unit charge at some location. This computation is known as the "Green's function" computation. Let  $z_q$  be the elevation of the source point (i.e., of the unit charge), above the  $z = 0$  plane; let  $z_p$  be the elevation of the observation point; and let  $r$  be the lateral distance between source and observation point. In vacuum, the Green's

value can be computed from

$$g = \frac{1}{4\pi\epsilon} * \frac{1}{\sqrt{(z_p - z_q)^2 + r^2}}.$$

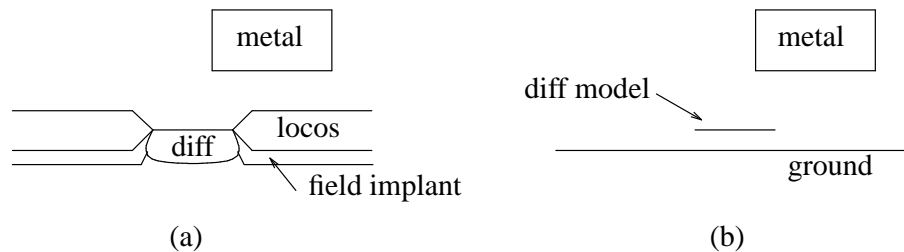
When one or more dielectric layers are present, this formula quickly becomes more complicated (this is due to the fact that a single charge will polarize the dielectric layers, which will result in surface charges at the interfaces of these layers). Hence, if computation speed is important, and if your technology is complicated, it might be worthwhile to simplify the layer structure somewhat, e.g. by merging layers for which the  $\epsilon_r$  are almost equal.

For small values of  $r$ , *space3d* uses an algorithm based on simulated annealing to compute  $g$ . For large values of  $r$ , *space3d* will switch to an interpolation method.

For the interpolation method, *space3d* needs to divide the layer structure into a grid. The actual computation of values on the grid is done by the technology compiler (*tecc*), as a preprocessing step. Thus, although computing Green's values on the grid may take quite some time, this time is only spent while compiling the technology file, and not when *space3d* is actually processing a layout. But note that this computation is not available in the public version.

### 3.8 Diffused Conductors

Diffused conductors (which for example implement the MOS transistor source and drain regions) are described in a somewhat different way than the poly-silicon and the metal conductors. The approach is illustrated in Figure 3.1.



**Figure 3.1.** Illustration of the heuristic approach to incorporate diffusion capacitances, physical structure (a) and 3D capacitance model (b).

Figure 3.1.a shows a cross-sectional view of a diffused conductor. The capacitance model employed by *space3d* for such a conductor is shown in Figure 3.1.b, where the diffused interconnect is replaced by a thin sheet conductor. Therefore, the user must specify in the element definition file a zero thickness for the conductor. The sheet

conductor is positioned half the thickness of the field oxide above the ground plane, which is flat and continuous, and must be thought of as modeling the top side of the diffused conductors.

Initially, the 3D capacitance extraction method will compute 3D capacitances between all conductors and ground. The 3D capacitances between non-diffused conductors mutually, between non-diffused conductors and ground and between non-diffused conductors and diffused conductors are inserted in the extracted circuit. However, the 3D capacitances between diffused conductors and ground and between diffused conductors mutually are better represented by junction capacitances that are computed using an area/perimeter method.

**NOTE:**

Therefore, the 3D capacitances between diffused conductors and ground, and between diffused conductors mutually, are discarded by the program. The junction capacitances that replace these capacitances have to be specified separately by the user in the element definition file.

See also Section 3.10.

Although this approach is purely heuristic, its results are satisfactory when the width of the diffusion paths is large enough compared to the height of the sheet conductors above the ground plane.

**NOTE:**

A conductor is defined as a diffused conductor within *space3d* if and only if in the element definition file the type of the conductor is specified as 'n' or 'p'.

### 3.9 Gate Capacitances

When extracting 3D capacitances, *space3d* assumes that the gate-channel capacitances of field-effect transistor are included in the simulation model that is used for the extracted transistor. Therefore it discards the 3D capacitance to ground for conductor parts that are a gate of a field-effect transistor and that are directly above the transistor area as defined in the element definition file.

Also the 3D coupling capacitances between gates and diffused conductors (drain/source areas; see Section 3.8) can be discarded by the program, depending whether they are present in the SPICE or other simulation model for the device. This is achieved by turning on the parameter `cap3d.omit_gate_ds_cap` in the parameter file.

### 3.10 Non-3D Capacitances

When extracting 3D capacitances, non-3D capacitances that are specified in the element definition file are not extracted, except for capacitances between a diffused conductor and

ground and capacitances between diffused conductors mutually (see also Section 3.8). However, when the parameter `cap3d.all_non3d_cap` is set, also all non-3D capacitances that are defined in the element definition file, are extracted.

## 4. 3D Capacitance Computation

### 4.1 Introduction

*Space3d* uses a boundary-element method to compute 3D capacitances (see Appendix A). Since there are several degrees of freedom with this method, there are also several parameters that can be set with *space3d* during 3D capacitance extraction. A brief description of these parameters is given below. For more background information on the parameters, the reader is referred to Appendix A.

The parameters are set in the space parameter file (see also the Space User's Manual). All lengths and distances are specified in micron and all areas are specified in square micron.

All parameters that have a name starting with "cap3d." may be used without this prefix if they are included between the lines "BEGIN cap3d" and "END cap3d". E.g.

```
BEGIN cap3d
max_be_area  1
be_window    3
END cap3d
```

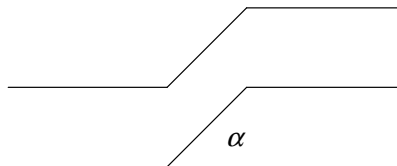
is equivalent to

```
cap3d.max_be_area  1
cap3d.be_window    3
```

### 4.2 Mesh Construction

cap3d.default\_step\_slope *slope* (default: 2.0)

Specifies the tangent of the slope of conductors (i.e. the tangent of  $\alpha$  in the figure below) at steps in height above the substrate (e.g. the transition of metal above polysilicon to metal not above polysilicon). It must hold that cap3d.default\_step\_slope > 0.



#### NOTE:

To prevent the overlap of different transition areas of one conductor (which currently results in incorrect element meshes), the value of parameter cap3d.default\_step\_slope may not be too small.

`cap3d.max_be_area` *area* (no default)

This parameter specifies (in square microns) the maximum area of boundary elements that are interior elements (i.e. elements that are not along the edges/corners of the conductors). This parameter has no default and must therefore always be specified when performing 3D capacitance extraction.

`cap3d.min_be_area` *area* (default: 1 square unit)

This parameter specifies (in square microns) the minimum area of boundary elements, which may be used (smaller areas are skipped, a warning message is given).

`cap3d.edge_be_ratio` *float* (default: 1)

This parameter specifies the ratio between the maximum size of interior elements and the maximum size of edge elements (edge elements are elements that are adjacent to the edges/corners of the conductors, interior elements are the other elements, see also the parameter `cap3d.max_be_area`). To efficiently compute accurate 3D capacitances it is advantageous to use smaller elements near the edges/corners of the conductors. This is achieved by using for `cap3d.edge_be_ratio` a value smaller than 1. Because the mesh refinement is done incrementally, the size of the elements will gradually decrease towards the edges/corners of the conductors. This is also influenced by the parameter `cap3d.edge_be_split`.

`cap3d.edge_be_split` *float* (default: 0.5)

If, during mesh refinement, a quadrilateral edge element is split into two elements (see also the description of the parameter `cap3d.edge_be_ratio`), this parameter specifies the ratio between the size of the element that becomes an edge element and the size of the element that becomes an interior element.

`cap3d.edge_be_split_lw` *float* (default: 4)

During mesh refinement, this parameter is used to determine the split direction of a quadrilateral element. Interior elements are always split perpendicular to their longest side. If the ratio between the longest side and the shortest side of an edge element does not becomes larger than `cap3d.edge_be_split_lw`, an edge element is split in a direction parallel to the edge direction. Otherwise, the edge element is split perpendicular to its longest side. The minimum value for `cap3d.edge_be_split_lw` is 2.

`cap3d.max_coarse_be_area` *float* (default: `cap3d.max_be_area`)

For conductors that are sheet conductors (thickness is zero) this parameter specifies (in square microns) the maximum area of the boundary elements. When this parameter is specified, edge elements of sheet conductors are not further refined compared interior elements. This parameter can for example be used to model large conductor planes with a much coarser element mesh.

cap3d.be\_shape *number* (default: 1)

Enforces a particular shape of the boundary element faces. Value 1 means no enforcement. Value 3 means triangular faces (is always used in "piecewise linear" mode). Value 4 means quadrilateral faces (is the default for constant shape functions).

### 4.3 Shape and Weight Functions

cap3d.be\_mode *mode* (default: 0c)

Specifies the type of shape functions and the type of weight functions that are used (see Section A.2).

mode	shape function	weight method
0c	piecewise constant	collocation
0g	piecewise constant	Galerkin
1g	piecewise linear	Galerkin

An example of a piecewise constant shape functions is given in Figure A.1.b. An example of a linear shape functions is given in Figure A.1.c. Given a certain accuracy, the Galerkin method, as compared to the collocation method, allows to use larger elements.

cap3d.mp\_min\_dist *distance\_ratio* (default: 2.0)

When the charge- and observation-elements are not too close together, the influence matrix element linking them can be calculated much faster (2 to 20 times) using a multipole expansion than by numerical integration. This parameter specifies a threshold value of the ratio between the charge-observation distance and the convergence radius of the multipole expansion: for larger distances the multipole expansion is used, for smaller distances numerical integration. Usually, a ratio of 1.5 is satisfactory. When setting the parameter to infinity, *all* influence matrix elements are calculated by numerical integration.

cap3d.mp\_max\_order *0 ... 3* (default: 2)

Specifies the highest multipole to be included in the multipole-expansion. For 0 only the monopole is included, for 1 also the dipole, and so forth. The highest implemented value is 3 (octopole), because on the one hand this typically suffices for a precision of one per mil, while on the other hand the required CPU time increases drastically with the number of multipoles.

#### 4.4 Accuracy of Elastance Matrix

`cap3d.green_eps error` (default: 0.001)

Positive real value specifying the relative accuracy for evaluating the entries in the elastance matrix.

`cap3d.max_green_terms number` (default: 500)

For dielectrics consisting of more than one layer, more than one term (iteration) will in general be necessary to find an approximation of the Green's function such that the error in the entries in the elastance matrix is within `cap3d.green_eps` (see above). This parameter specifies the value for the maximum number of terms that may be used. The upper bound of this parameter is 500.

#### 4.5 Window Size

`cap3d.be_window w`  
`cap3d.be_window wx wy`

Specifies the size (in micron) of the influence window. All influences between elements that are within a distance  $w$  will be taken into account, and all influences between elements that are more than a distance  $2w$  apart will not be taken into account (see Section A.3). If only one value is given, this value specifies the size of the window in the x direction and the y direction. If two values are given, the first value specifies the size of the window in the x direction and the second value specifies the size of the window in the y direction.

The extraction time is proportional to  $O(Nw^4)$ , where  $N$  is the number of elements. The memory usage of the program is  $O(w^4)$ . A reasonable value for `be_window` is 1-3 times the maximum height of the circuit. No default.

#### 4.6 Discarding 3D Capacitances

`cap3d.omit_gate_ds_cap boolean` (default: off)

Do not extract 3D capacitances between gates and diffused conductors (drain/source areas), see Section 3.9.

#### 4.7 Non 3D Capacitances

`cap3d.also_non3d_cap boolean` (default: off)

Extract also all non-3D capacitances, see Section 3.10.



#### 4.8 New Cap3D Parameters

`cap3d.connect_ground` *string* (default: @gnd)

The extraction is default using the @gnd node for ground plane connections. But you may choice "@sub" or "distributed" instead (the @-sign may be omitted). Distributed tries to use the substrate nodes directly below the cap3d nodes.

`cap3d.spider_hash` *boolean* (default: off)

The new *space3d* version does not use spider hashing to find existing spiders. Now, by problem geometries, there can be two spiders at the same position. However, this is not allowed for a piecewise linear be\_mode (1c/1g).

`cap3d.new_via_mode` *boolean* (default: on)

Now by vias, in new mode, all calculated cap values are assigned to the top conductor via nodes (and not more to bottom conductor nodes). This is better, because in case the bottom conductor is a diffused conductor the cap values can be lost.

`cap3d.contacts_sub` *boolean* (default: on)

Now, the contacts to substrate are also modeled. Thus, cap values for the surfaces of these contacts are now calculated.

`cap3d.new_refine` *boolean* (default: on)

This is an important new feature, because these mesh reductions results in a very fast cap3d extraction. However, these refinements work only for be\_mode "0c" and "0g".

`cap3d.new_convex` *boolean* (default: on)

Now, concave polygons are tried to be repaired (if possible) by shifting the spiders. Concave polygons can be created when using e/c-shape definitions.

#### 4.9 Example Parameter File

An example of parameter settings for 3D capacitance extraction is as follows:

```
BEGIN cap3d
max_be_area      1.0    # square micron
be_window        5.0    # micron
be_mode          0g     # pwc galerkin
connect_ground   distr
contacts_sub      off
default_step_slope 1.5
omit_gate_ds_cap  on
green_eps         0.002
END cap3d
```

#### 4.10 Run-time Versus Accuracy

The runtime of the program is largely dependent on the values of the parameters that are used. For example, if `max_be_area` is decreased (smaller elements are used), the accuracy will increase but also the number of elements will increase and the computation time will become larger. The larger the size of the window, the more accurate results are obtained but also longer extraction times will occur. The Galerkin method is more accurate than the collocation method, but it also requires more computation time.

Also, 3D capacitance computation for configurations consisting of 2 or 3 dielectric layers may require much more computation time than the same computation for configurations consisting of 1 dielectric layer. This is because the computation of the Green's functions requires much more time. In this case, the computation time can be decreased (on the penalty of some loss in accuracy) by increasing the value for the maximum error for the evaluation of the entries in the elastance matrix (`green_eps`).

## 5. Examples

### 5.1 Example of 5 Parallel Conductors

As a first example we show how *space3d* is used to compute 3D capacitances for a configuration consisting of 5 parallel conductors. To run the example, first create a project, e.g. with name "exam1", for an scmos\_n process and lambda of 0.05 micron:

```
% mkpr -l 0.05 exam1
available processes:
process id      process name
          1      nmos
          3      scmos_n
          ...
select process id (1 - 60): 3
mkpr: -- project created --
```

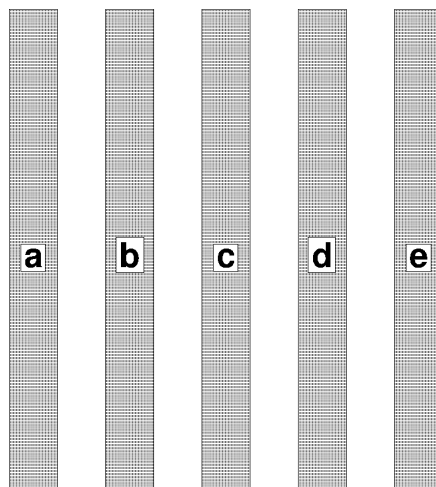
Next, go to the project directory and copy the example source files from the directory */usr/cacd/share/demo/poly5* (it is supposed that the demo directory has been installed under */usr/cacd*).

```
% cd exam1
% cp /usr/cacd/share/demo/poly5/* .
```

The layout description is put into the database using the program *cgi*.

```
% cgi poly5.gds
```

The layout of the configuration is shown below (e.g. use *dali* to inspect the layout). The conductors have a length of 5 micron, a width of 0.5 micron, a height of 0.5 micron and their separation is also 0.5 micron.



An appropriate element definition file (with name "tech.s") is as follows:

```
% cat tech.s
unit vdimension      1e-6  # micron

colors :
    cpG  red

conductors :
    resP : cpG : cpG : 0.0

vdimensions :
    dimP : cpG : cpG : 0.5 0.5

dielectrics :
    # Dielectric consists of 5 micron thick SiO2
    # (epsilon = 3.9) on a conducting plane.
    SiO2  3.9  0.0
    air   1.0  5.0
%
```

Furthermore, we use the following parameter file ("param.p"):

```
% cat param.p
BEGIN cap3d
be_mode      0c
max_be_area  0.5
be_window    1
END cap3d
%
```

Then, after having run *tecc* on the element definition file,

```
% tecc tech.s
```

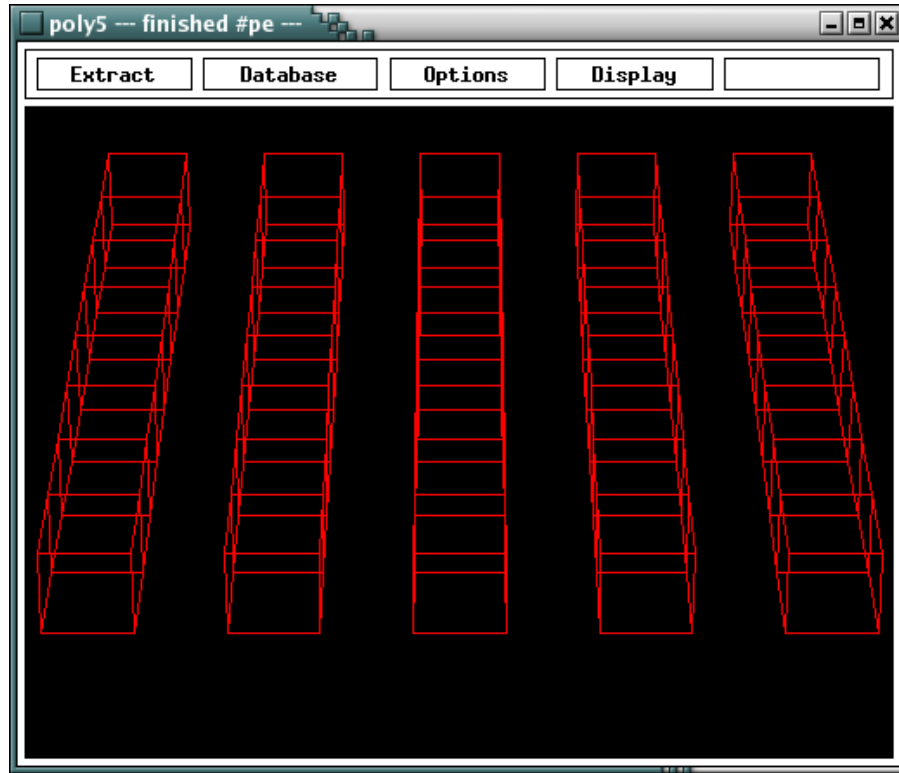
we extract a circuit description for the layout of the cell as follows:

```
% space3d -C3 -E tech.t -P param.p poly5
```

Alternatively *Xspace* can be used.

```
% Xspace -E tech.t -P param.p
```

Click button "poly5" in the menu "Database", click button "coupling cap" and "3D capacitance" in the menu "Options", click button "DrawBEMesh", "DrawGreen" and "3 dimensional" in the menu "Display", and click button "extract" in the menu "Extract". This will yield the following picture:



The circuit that has been extracted can be inspected using the program *xspice*

```
% xspice -a poly5
poly5

* Generated by: xspice 2.39 25-Jan-2006
* Date: 20-Jun-06 10:30:48 GMT
* Path: /users/space/exam1
* Language: SPICE

* circuit poly5 e d c b a
c1 a b 253.3136e-18
c2 a GND 624.1936e-18
c3 b c 253.3136e-18
c4 b GND 457.9544e-18
c5 c d 253.3136e-18
c6 c GND 457.9544e-18
c7 d e 253.3136e-18
c8 e GND 624.1936e-18
c9 d GND 457.9544e-18
* end poly5
```

Note that there are no capacitances between conductors that are more than a distance 2 \* `be_window` apart (e.g. conductor "a" and conductor "d" or conductor "a" and conductor

"e"). In the table below, the capacitances of conductor "a" are given as a function of the window size. In the column denoted by  $C_{s\ a}$ , the short-circuit capacitance of node "a" is given, which is the sum of all capacitances that are connected to "a". Note that the value of this capacitance is almost independent on the size of the window.

w	capacitances ( $10^{-18}$ F)					
( $\mu$ )	$C_{a\ gnd}$	$C_{a\ b}$	$C_{a\ c}$	$C_{a\ d}$	$C_{a\ e}$	$C_{s\ a}$
1	624.5	253.3	-	-	-	877.8
2	599.9	256.0	16.35	7.93	-	880.2
3	593.4	256.8	16.64	7.14	4.50	878.5
4	591.0	257.3	17.11	7.22	4.73	877.4
5	590.5	257.4	17.18	7.27	4.79	877.1

## 5.2 Example of CMOS Static RAM Cell

The next example consists of a cmos static RAM cell in 0.5 $\mu$  technology. To run the example, first create a project, e.g. with name "exam2", for an scmos\_n process and lambda of 0.25 micron:

```
% mkpr -l 0.25 exam2
available processes:
process id      process name
      1         nmos
      3         scmos_n
      ...
select process id (1 - 60): 3
mkpr: -- project created --
```

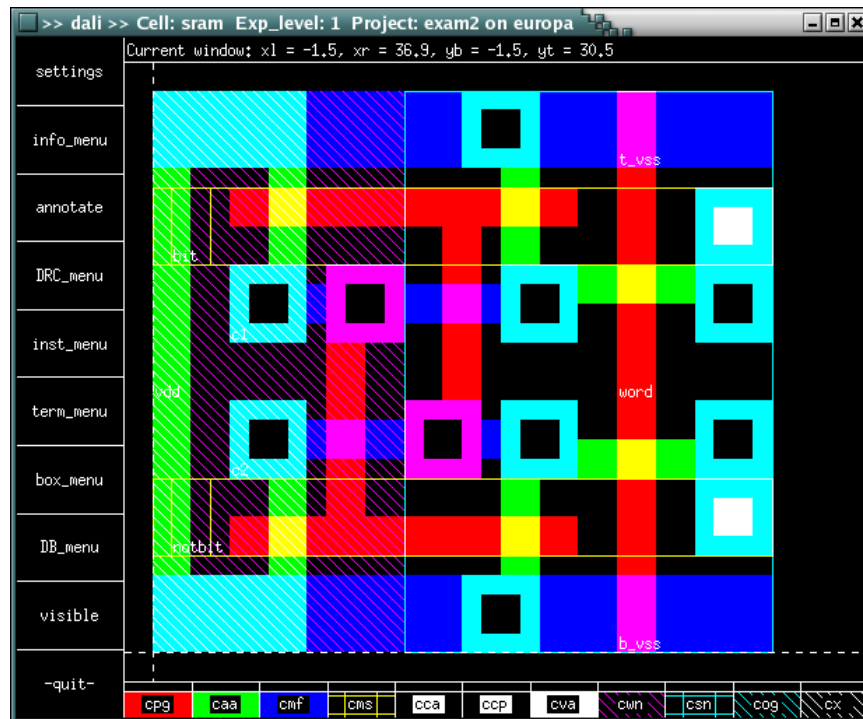
Next, go to the project directory and copy the example source files from the directory /usr/cacd/share/demo/sram.

```
% cd exam2
% cp /usr/cacd/share/demo/sram/* .
```

The layout of the ram cell is put into the database as follows:

```
% cgi sram.gds
```

Use the layout editor *dali* to inspect the layout of the sram, as shown below.



The following technology file ("sram.s") is used for extraction:

---

```

# space element definition file for scmos_n example process
# with vertical dimensions for conductors for 3D capacitance
# extraction.
#
# masks:
# cpg - polysilicon interconnect      ccp - contact metal to poly
# caa - active area                   cva - contact metal to metal2
# cmf - metal interconnect            cwn - n-well
# cms - metal2 interconnect           csu - n-channel implant
# cca - contact metal to diffusion     cog - contact to bondpads
#
# See also: maskdata

unit resistance      1      # ohm
unit c_resistance    1e-12 # ohm um^2
unit a_capacitance   1e-6  # aF/um^2
unit e_capacitance   1e-12 # aF/um
unit capacitance     1e-15 # fF
unit vdimension      1e-6  # um
unit shape           1e-6  # um

maxkeys 10

colors :
  cpg  red
  caa  green
  cmf  blue
  cms  gold
  cca  black
  ccp  black
  cva  black
  cwn  glass
  csu  glass
  cog  glass
  cx   glass

conductors :
  # name      : condition      : mask : resistivity : type
  cond_mf : cmf                : cmf  : 0.045       : m   # first metal
  cond_ms : cms                : cms  : 0.030       : m   # second metal
  cond_pg : cpg                : cpg  : 40          : m   # poly interconnect
  cond_pa : caa !cpg !csu : caa  : 70          : p   # p+ active area
  cond_na : caa !cpg  csu : caa  : 50          : n   # n+ active area

fets :
  # name : condition      : gate d/s
  nenh : cpg caa  csu : cpg  caa      # nenh MOS
  penh : cpg caa !csu : cpg  caa      # penh MOS

contacts :
  # name      : condition      : lay1 lay2 : resistivity
  cont_s : cva cms cmf      : cms  cmf  : 1         # metal to metal2
  cont_p : ccp cmf cpg      : cmf  cpg  : 100       # metal to poly

```



```

cont_a : cca cmf caa !cpg : cmf caa : 100 # metal to active area

capacitances :

# active area capacitances
# name      : condition                               : mask1 mask2 : capacitivity
acap_na : caa !cpg csn !cwn                               : @gnd caa : 100 # n+ bottom
ecap_na : !caa !-cpg -csn !-cwn -caa : @gnd -caa : 300 # n+ sidewall

acap_pa : caa !cpg !csn cwn                               : caa @gnd : 500 # p+ bottom
ecap_pa : !caa !-cpg !-csn cwn -cwn -caa : -caa @gnd : 600 # p+ sidewall

# polysilicon capacitances
acap_cpg_sub : cpg                               !caa : cpg @gnd : 49 # bot to sub
ecap_cpg_sub : !cpg -cpg !cmf !cms !caa : -cpg @gnd : 52 # edge to sub

# first metal capacitances
acap_cmf_sub : cmf                               !cpg !caa : cmf @gnd : 25
ecap_cmf_sub : !cmf -cmf !cms !cpg !caa : -cmf @gnd : 52

acap_cmf_caa : cmf caa !cpg !cca !cca : cmf caa : 49
ecap_cmf_caa : !cmf -cmf caa !cms !cpg : -cmf caa : 59

acap_cmf_cpg : cmf cpg !cpg : cmf cpg : 49
ecap_cmf_cpg : !cmf -cmf cpg !cms : -cmf cpg : 59

# second metal capacitances
acap_cms_sub : cms !cmf !cpg !caa : cms @gnd : 16
ecap_cms_sub : !cms -cms !cmf !cpg !caa : -cms @gnd : 51

acap_cms_caa : cms caa !cmf !cpg : cms caa : 25
ecap_cms_caa : !cms -cms caa !cmf !cpg : -cms caa : 54

acap_cms_cpg : cms cpg !cmf : cms cpg : 25
ecap_cms_cpg : !cms -cms cpg !cmf : -cms cpg : 54

acap_cms_cmf : cms cmf !cva : cms cmf : 49
ecap_cms_cmf : !cms -cms cmf : -cms cmf : 61

lcap_cms : !cms -cms =cms : -cms =cms : 0.07

vdimensions :
ver_caa_on_all : caa !cpg : caa : 0.30 0.00
ver_cpg_of_caa : cpg !caa : cpg : 0.60 0.50
ver_cpg_on_caa : cpg caa : cpg : 0.35 0.70
ver_cmf : cmf : cmf : 1.70 0.70
ver_cms : cms : cms : 2.80 0.70

eshapes :
cpg_edge : !cpg -cpg : cpg : 0 0
cmf_edge : !cmf -cmf : cmf : 0 0
cms_edge : !cms -cms : cms : 0 0

```

```

dielectrics :
    # Dielectric consists of 5 micron thick SiO2
    # (epsilon = 3.9) on a conducting plane.
    SiO2    3.9    0.0
    air     1.0    5.0

#EOF

```

Note that for the diffusion area a conductor of thickness 0 is used that is 0.30 $\mu$  above the substrate.

The contents of the parameter file ("sram.p") is as follows:

```

BEGIN cap3d
be_mode           0c
be_window         2.0
max_be_area       1.0
omit_gate_ds_cap  on
END cap3d

```

After running *tecc* on the element definition file,

```
% tecc sram.s
```

extraction in batch mode is done by using *space3d*.

```
% space3d -C3 -E sram.t -P sram.p sram
```

For interactive extraction, *Xspace* is used.

```
% Xspace -E sram.t -P sram.p
```

Click button "sram" in the menu "Database", click button "coupling cap" and "3D capacitance" in the menu "Options", click button "DrawBEMesh", "DrawGreen" and "3 dimensional" in the menu "Display", and click button "extract" in the menu "Extract". This will yield the following picture:



The extraction result is retrieved using *xspice*:

```
% xspice -a sram
sram

* Generated by: xspice 2.39 25-Jan-2006
* Date: 20-Jun-06 10:40:34 GMT
* Path: /users/space/exam2
* Language: SPICE

* circuit sram pbulk nbulk word vdd b_vss t_vss c1 c2 bit notbit
m1 vdd c1 c2 pbulk penh_0 w=500n l=500n
m2 vdd c2 c1 pbulk penh_0 w=500n l=500n
m3 b_vss c1 c2 nbulk nenh_0 w=500n l=500n
m4 t_vss c2 c1 nbulk nenh_0 w=500n l=500n
m5 notbit word c2 nbulk nenh_0 w=500n l=500n
m6 bit word c1 nbulk nenh_0 w=500n l=500n
c1 b_vss word 114.8418e-18
c2 b_vss vdd 43.84559e-18
c3 b_vss c2 74.079e-18
c4 b_vss c1 212.2091e-18
c5 b_vss notbit 610.2115e-18
c6 b_vss GND 1.80899f
c7 notbit bit 107.3522e-18
c8 notbit word 115.7189e-18
c9 notbit vdd 6.609528e-18
```

---

```
c10 notbit c2 360.549e-18
c11 notbit c1 66.39728e-18
c12 notbit GND 2.597814f
c13 t_vss word 114.8457e-18
c14 t_vss vdd 43.82952e-18
c15 t_vss bit 610.3344e-18
c16 t_vss c2 212.2316e-18
c17 t_vss c1 73.78773e-18
c18 t_vss GND 1.808788f
c19 word bit 115.8338e-18
c20 word c2 113.7943e-18
c21 word c1 111.6566e-18
c22 word GND 344.449e-18
c23 vdd bit 6.60235e-18
c24 vdd c2 56.77325e-18
c25 vdd c1 58.65703e-18
c26 vdd GND 9.5875f
c27 bit c1 360.2213e-18
c28 bit c2 67.05254e-18
c29 bit GND 2.597536f
c30 c2 c1 998.1198e-18
c31 c2 GND 5.426256f
c32 c1 GND 5.425883f
* end sram

.model penh_0 pmos(level=2 ld=0 tox=25n nsub=50e15 vto=-1.1 uo=200 uexp=100m
+ ucrit=10k delta=200m xj=500n vmax=50k neff=1 rsh=0 nfs=0 js=10u cj=500u
+ cjsw=600p mj=500m mjsw=300m pb=800m cgdo=300p cgso=300p)
.model nenh_0 nmos(level=2 ld=0 tox=25n nsub=20e15 vto=700m uo=600 uexp=100m
+ ucrit=10k delta=200m xj=500n vmax=50k neff=1 rsh=0 nfs=0 js=2u cj=100u
+ cjsw=300p mj=500m mjsw=300m pb=800m cgdo=300p cgso=300p)

vpbulk pbulk 0 5
rpbulk pbulk 0 100meg

vnbulk nbulk 0 0
rnbulk nbulk 0 100meg
```

## 6. Solving Problems

### 6.1 Long Computation Times

Although *space3d* has been implemented with emphasis on efficient 3D capacitance extraction methods, sometimes long extraction times may occur. This for example happens if too much time is spend on the computation of irrelevant details. This is for example the case if the size of the elements is chosen too small, if the window size is unnecessary large or if linear shape functions and the Galerkin method are used for too many elements. A good strategy to circumvent this problem is to first try an extraction with a parameter set that does not include many details. Next, a parameter set is used in which more details are included, and the extraction results are evaluated to inspect the influence of the parameters. See also Section 4.10.

### 6.2 Numerical Problems

If the elastance matrix (see Section A.2) is badly conditioned, *space3d* may be unable to invert this matrix and it may give error messages like "domain error(s) in sqrt". One reason for a badly conditioned elastance matrix is that there is too much difference in element sizes. A solution in this case is to split the large elements, either by decreasing the maximum size of the elements or by adding irregularities to the layout using a symbolic mask. If very thin conductors are used, the difference between the small vertical elements and the large horizontal elements may also become too large. In this case, it may for example be better to specify a zero thickness for the conductor in the element definition file. In general, the creation of small elements that are close to large elements, and the creation of long and narrow elements, should be avoided.

Also the use of the Galerkin method (be\_mode 0g or 1g) instead of the collocation method (be\_mode 0c) might help in the above case.

### 6.3 Negative Capacitances

Some element meshes may also give rise to negative capacitances. Negative capacitances may for example occur when conductors are close to each other and relatively large elements are used. A typical example is the situation where the bottom of a transistor gate approaches its adjacent drain/source regions. More accurate results (without negative capacitances) are then obtained by (1) decreasing the maximum size of the elements and/or (2) increasing the height of the bottom of the gate above the substrate. If necessary, the parameters *min\_coup\_cap* and/or *no\_neg\_cap* can be set to remove the remaining (small) negative capacitances.

#### 6.4 Mesh Generation Problems

If *space3d* gives error messages like "mesh.c, 846: assertion failed" or "refine.c, 507: assertion failed", there is something wrong with mesh generation. This problem is often caused by the modeling of the steps in height above the substrate of the conductors. If the slope of a conductor near such a transition area is too small, different transition areas may overlap and the program will not be able to generate a correct mesh (see Section 3.3 and Section 4.2).

Mesh generation problems may also be caused by the use of *eshapes* (see Section 3.4) and by the fact that, because of the use of a window (parameter *cap3d.be\_window*), long and narrow mesh elements may be generated. Sometimes, problems due to the first cause are solved by using a *resize* statement in the element definition file (see Space User's Manual) instead of an *eshape* statement.

## Appendix A: 3D Capacitance Model

### A.1 Introduction

*Space3d* uses a boundary-element method to compute 3D capacitances. A brief description of this method is given in Section A.2. For the solution of the boundary-element equations, a large matrix needs to be inverted. The approximate matrix inversion technique that is used for this is described in Section A.3.

### A.2 The Boundary-Element Method

Consider a domain  $V$  that contains  $M$  conductors. Our purpose is to find the short-circuit capacitance matrix  $C_s$  that gives the relation between the conductor charges  $Q^T = [Q_1, Q_2, \dots, Q_M]$  and the conductor potentials  $\Phi^T = [\Phi_1, \Phi_2, \dots, \Phi_M]$  as

$$Q = C_s \Phi. \quad (\text{A.1})$$

The potential  $\phi(p)$  at a point  $p$  in  $V$  can be expressed as [1, 2]

$$\phi(p) = \int_V G(p, q) \rho(q) dq, \quad (\text{A.2})$$

where  $\rho(q)$  is the charge distribution in  $V$  and  $G(p, q)$  is the Green's function for  $V$ . In order to solve A.2, the boundary-element method subdivides the surfaces of the conductors in elements  $S_1, S_2, \dots, S_N$  (the elements may partly be overlapping), and approximates the charge distribution  $\rho(q)$  by

$$\rho(q) \approx \tilde{\rho}(q) = \sum_{i=1}^N \alpha_i f_i(q), \quad (\text{A.3})$$

where  $\alpha_1, \alpha_2, \dots, \alpha_N$  are unknown variables to be determined and  $f_1, f_2, \dots, f_N$  are  $N$  independent shape functions (also called basis functions). The  $f_i$ 's have the property that

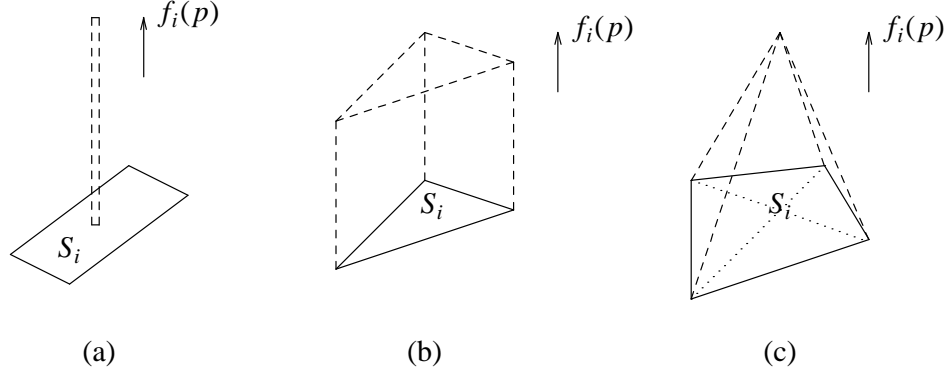
$$\int_{S_j} f_i(q) dq = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \quad (\text{A.4})$$

Some examples of shape functions are given in Figure A.1.

An approximation for the potential distribution is then obtained by insertion of A.3 into A.2:

$$\tilde{\phi}(p) = \sum_{i=1}^N \alpha_i \int_{S_i} G(p, q) f_j(q) dq. \quad (\text{A.5})$$

Next,  $N$  independent linear equations are obtained by introducing a set of  $N$  independent weight functions  $w_1, w_2, \dots, w_N$  that are defined on the sub-areas  $S_1, S_2, \dots, S_N$  and that



**Figure A.1.** Different types of shape or basis functions that can be used to model the surface charge density on the conductors (a) Dirac, (b) constant:  $f$  is described by the top of the wedge, (c) linear:  $f$  is described by the 4 slanting planes of the pyramid.

are used to "average out" the error in  $\tilde{\phi}(p)$ :

$$\int_{S_i} w_i(p) \left[ \tilde{\phi}(p) - \phi(p) \right] dp = 0 \quad (i = 1 \cdots N). \quad (\text{A.6})$$

By insertion of A.5, the above set of equation may be rewritten as

$$\sum_{j=1}^N \alpha_j \int_{S_i} \int_{S_j} G(p, q) f_j(q) w_i(p) dq dp = \int_{S_i} w_i(p) \phi(p) dp \quad (i = 1 \cdots N). \quad (\text{A.7})$$

Now, let  $F$  be an  $N \times M$  incidence matrix in which

$$F_{ij} = \begin{cases} 1 & \text{if } S_i \text{ is on conductor } j \\ 0 & \text{otherwise.} \end{cases} \quad (\text{A.8})$$

Then, Equation A.7 may be written as a set of  $N \times N$  equations,

$$G \alpha = W F \Phi, \quad (\text{A.9})$$

where  $G$  is an  $N \times N$  matrix that has entries

$$G_{ij} = \int_{S_i} \int_{S_j} G(p, q) f_j(q) w_i(p) dq dp, \quad (\text{A.10})$$

$\alpha^T = [\alpha_1, \alpha_2, \dots, \alpha_N]$ , and  $W$  is an  $N \times N$  matrix that has entries



$$W_{ij} = 0, \quad i \neq j, \quad (\text{A.11a})$$

$$W_{ii} = \int_{S_i} w_i(p) dp. \quad (\text{A.11b})$$

The conductor charges are found from A.9 as

$$Q = F^T \alpha = F^T G^{-1} W F \Phi. \quad (\text{A.12})$$

Thus, the short-circuit capacitance matrix  $C_s$  is obtained from A.12 as

$$C_s = F^T G^{-1} W F. \quad (\text{A.13})$$

In the Galerkin boundary-element method [3] the weight functions  $w_i$  are chosen equal to the shape functions. This way, the evaluation of  $G$  requires the computation of a double surface integral, but  $G$  becomes symmetrical, which is advantageous for computing the inverse of the elastance matrix.

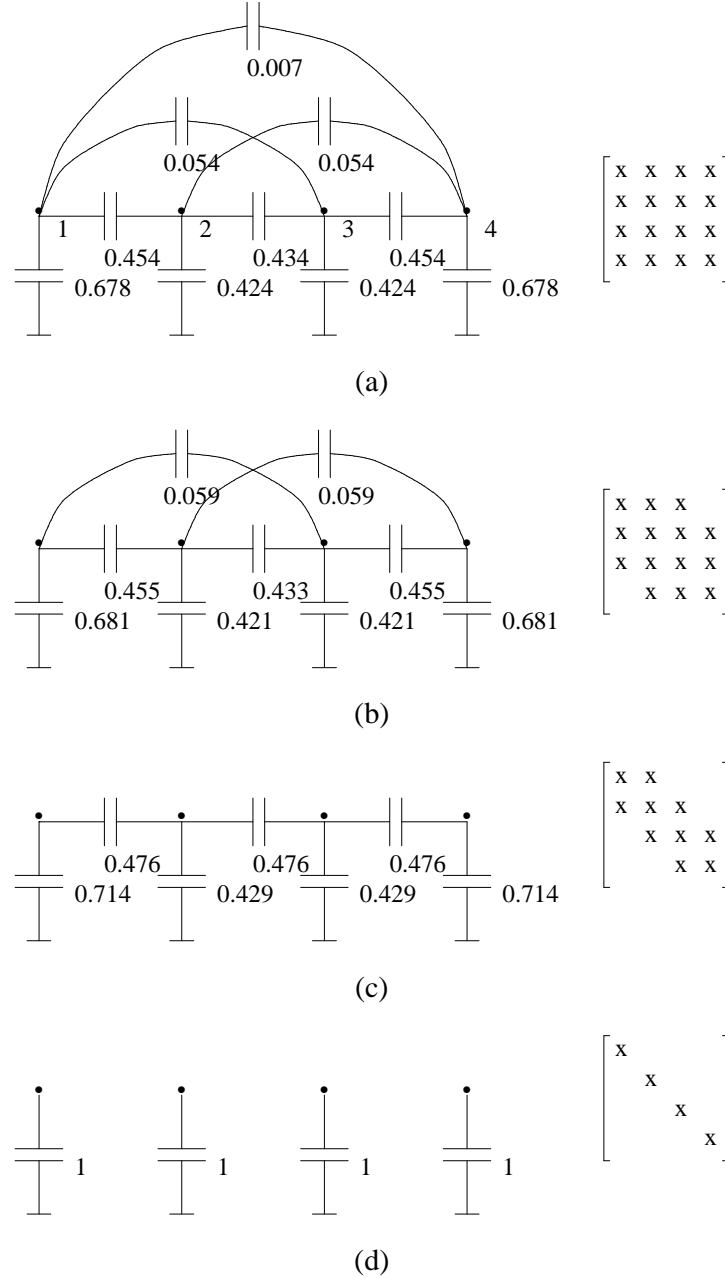
In the collocation boundary-element method [4], the weight functions  $w_i$  are chosen equal to Dirac functions. In this case the computation of  $G$  requires the evaluation of only single surface integrals.  $G$  is artificially made symmetrical by using the average of the two entries that are at a symmetrical position.

### A.3 Approximate Matrix Inversion

Normally, the inversion of the elastance matrix  $G$  in A.13 requires  $O(N^3)$  time and  $O(N^2)$  space. To allow fast extraction times, also for large circuits, *space* is capable of computing an approximate inverse for  $G$ . Therefore, it utilizes a matrix inversion technique that takes as input a matrix that is specified on a stair-case band around the main diagonal and produces as output a matrix in which only non-zero entries occur for the positions that correspond to positions in the stair-case band. The basic idea is illustrated in Figure A.2. In Figure A.2, different approximations are computed for a simple boundary-element mesh that consists of 4 elements and that is described by the following elastance matrix:

$$\begin{bmatrix} 1.0 & 0.4 & 0.2 & 0.1 \\ 0.4 & 1.0 & 0.4 & 0.2 \\ 0.2 & 0.4 & 1.0 & 0.4 \\ 0.1 & 0.2 & 0.4 & 1.0 \end{bmatrix} \quad (\text{A.14})$$

For practical layouts the method proceeds as follows. First, the layout is subdivided into strips of width  $w$  (see Figure A.3). All influences between elements that are within a distance  $w$  will be taken into account, and all influences between elements that are more than a distance  $2w$  apart will not be taken into account. Next, a banded approximation according to Figure A.2 is computed - whereby only influences are taken into account between elements that are in the  $y$  direction within a distance  $w$  - for (1) each pair of

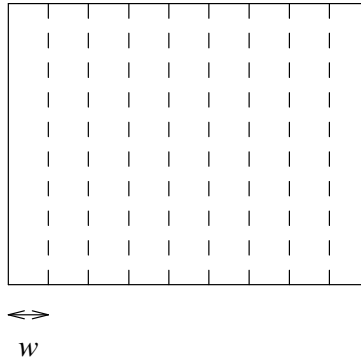


**Figure A.2.** (a) Exact solution, (b) only diagonals 1-3 are computed, (c) only diagonals 1-2 are computed, (d) only the main diagonal is computed.

adjacent strips and (2) each single strip except for the first and last strip. The results that are obtained for the pairs of strips are added to the total result and the results that are obtained for the single strips are subtracted from the total result [5, 6, 7].

By executing all steps of the extraction method as a scanline is swept over the layout from left to right, the extraction method can be implemented to have a computation

complexity that is  $O(Nw^4)$  and a memory usage that is  $O(w^4)$ . So, when  $w$  is kept constant, which is reasonable if one type of technology is used, the computation complexity of the method is linear with the size of the circuit and the space complexity is constant.



**Figure A.3.** A layout subdivided into strips of width  $w$ .

Note that the calculated Green values of a single strip are written to temporary files (space1.xxxxxx and space2.xxxxxx). The program is using one of the directories of environment variable SPACE\_TMPDIR. If you want to check these Green buffers you can use parameter:

`debug.check_green` *boolean* (default: off)

If "on" the Green values are recalculated and checked against the values read from the Green buffer. Thus you can check the Green buffers used.

---

**References**

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