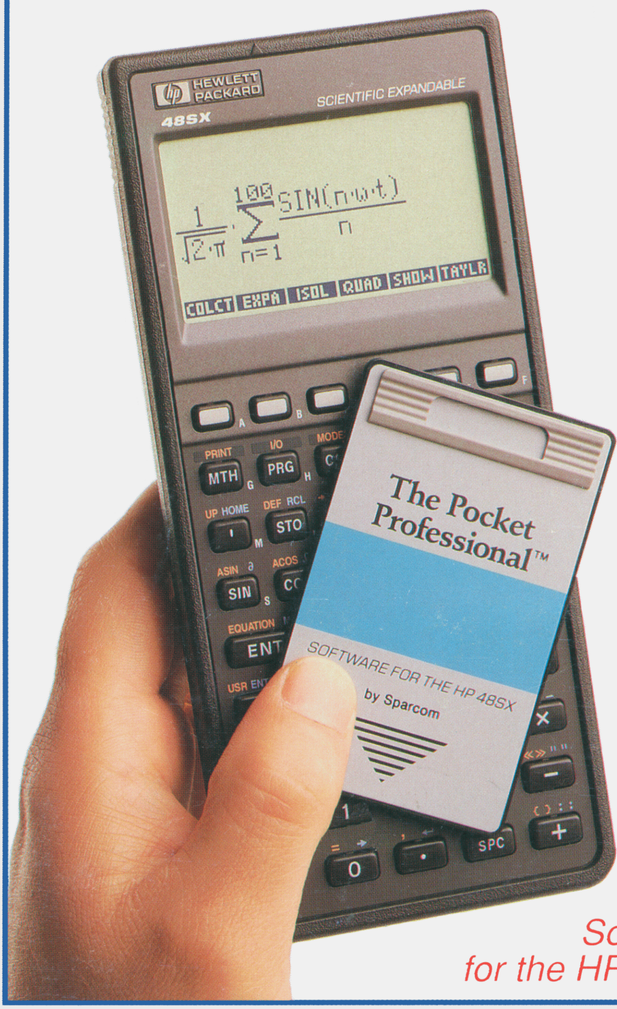
Sparcom

Pocket Professional™

OWNER'S MANUAL



Software
for the HP 48SX

Notice

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Acknowledgements

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The Pocket Professional™

Solid State Electronics Pac

Owner's Manual

SPARCOM®

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Chapter 1
Getting Started

In This Chapter

Sparcom's Pocket Professional– software is the first of its kind, developed to provide speed, efficiency and portability to students and professionals in the technical fields. When you slide the Pocket Professional– Solid State Electronics Pac into your HP 48SX, your calculator is instantly transformed into an electronic "textbook," ready to efficiently solve your problems in solid state electronics. The Pac is organized into five sections: An equation library, analysis functions, reference data, constants library and ASCII table, all available in an efficient, menu-driven format.

This chapter covers:

- ☐ Installing and Removing the Card
- ☐ RAM Requirements and the SPARCOM/SSELED Directory
- ☐ Using the Main Menu
- ☐ Moving Around the Screen
- ☐ Viewing Items Too Wide for the Display
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- ☐ System Flags

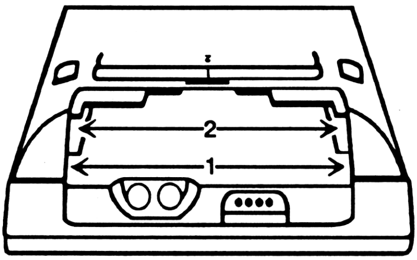
Installing and Removing the Card

The HP 48SX has two ports for installing plug-in cards. You can install your Solid State Pac card in either port. Be sure to **turn off the HP 48SX** while installing or removing the card. Otherwise, user memory may be erased.

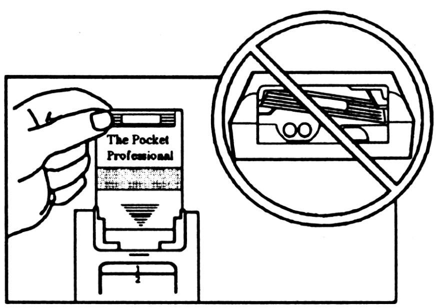
To Install the Application Card

1. Turn the HP 48SX off. Do not press [ON] until you have completed the installation procedure.

2. Remove the port cover. Press against the grip lines and push forward. Lift the cover to expose the two plug-in ports, as shown below:



3. Select either empty port for the Pocket Professional™ card, and position the card just outside the slot. Point the triangular arrow on the card toward the HP 48SX port opening, as shown below:



4. Slide the card firmly into the slot. After you first feel resistance, push the card about 1/4 inch further, until it is fully seated.

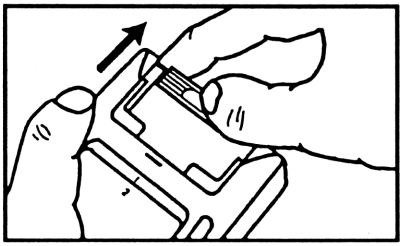
5. Replace the port cover.

To Remove an Application Card

1. Turn the HP 48SX off. Do not press [ON] until you have completed the removal procedure.

2. Remove the port cover. Press against the grip lines and push forward. Lift the cover to expose the two plug-in ports, as shown above.

3. Press against the card's grip and slide the card out of the port, as shown below:

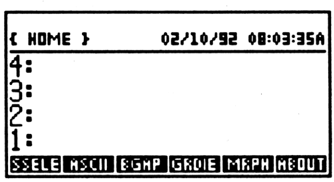


4. Replace the port cover.

Accessing the Solid State Electronics Pac

After you turn on your HP 48SX by pressing [ON], there are three ways to start the Pac.

Method 1: Press [⬅] [LIBRARY] to display all libraries available to the HP 48SX. Find and press **SSELE** to enter the Solid State Pac library directory. The screen displays new menu keys (soft keys) along the bottom, as shown:



Press **SSELE** (the first soft key) to start the application. To display a screen containing the revision number and product information about the Solid State Electronics Pac, press **ABOUT** (the sixth soft key).

Method 2: Type [α] [α] MATH [ENTER] to start the application.

Method 3: Add the command **SSELE** to the CST (custom) menu. (For more information, refer to Chapter 15 of the HP 48SX *Owner's Manual,* "Customizing the Calculator.") After the command has been added to CST, press [CST] **SSELE** to start the application.

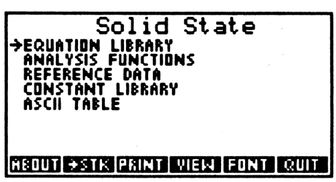
RAM Requirements and the SPARCOM Directory

The Solid State Electronics Pac requires a minimum of 1.7K free RAM in your HP 48SX to be unused in order to work correctly. This RAM is used for temporary storage during menu display and calculations. We recommend that you have at least 4000 bytes free when you operate the Solid State Pac. In a very few cases, more RAM will be required, and in most cases, less is necessary, but if you have at least 4K free, you should have no trouble. (For more information, refer to Chapter 5 of the HP 48SX *Owner's Manual*, "Calculator Memory.")

When you execute the Solid State Pac for the first time, the software creates the sub directory SSELED under the HOME/SPARCOM directory of the HP 48SX, using a small amount of free RAM. All operations performed by the Solid State Pac take place in the SSELED directory. It is, therefore, the only place where global variables are created or purged by the Pac. You may purge this directory (using the command PGDIR) if you are very low on RAM, but you will lose all variable values. If you purge the SSELED sub directory, the Solid State Pac will automatically recreate it the next time you execute the Pac. (For more information, refer to Chapter 7 of the HP 48SX *Owner's Manual*, "Directories.")

Using the Main Menu

After you start the application, the Main menu appears:



The Main menu lists the eight major subjects. A subject is selected by moving the arrow to the desired item and pressing ENTER.

Items in the Main Menu

Each item in the Main menu is briefly described below and is discussed in detail in the remainder of this manual.

Item	Description
Equation Library	Key equations in solid state under 11 categories.
Analysis	Three functions commonly needed.
Reference data	Provides quick reference data such as properties of Si, GaAs, donor and acceptor levels.
Constants	Several commonly used constants.
ASCII Table	Gives a table of ASCII characters.

Summary of Operations

Key	Action
ABOUT	Displays a screen containing the revision number and product information about the Solid State Pac. Pressing any key erases the screen and returns to the Main menu.
FONT	Toggles between the small and large fonts.
PRINT	Prompts for ONE or ALL to select items, and then sends those items to an IR printer.
QUIT	Quits the Solid State Electronics Pac to the HP 48SX stack.
→STK	Prompts for ONE or ALL to select items, and then copies those items to the stack. The items are placed in a list if ALL was chosen.
VIEW	Displays the entire text of an item too wide to fit on the screen, up to one entire screen size. If the item fits on the screen, this key is non-functional.
ATTN	Quits the Solid State Pac to the HP 48SX stack.
ENTER	Moves down one level in the menu structure.
ON MTH	Dumps the current screen to an IR printer.

Moving Around the Screen

Use the [▲] or [▼] to move the arrow up and down in a menu. Press [⬑][▼] to move the arrow to the bottom of the screen, or to page down one screen at a time if the arrow is already at the bottom of the screen. Press [⬑][▲] to move the arrow to the top of the screen, or to page up one screen at a time. Press [⮣][▼] to move the arrow to the end of the menu or press [⮣][▲] to move the arrow to the beginning of the menu.

Viewing Items Too Wide for the Display

If the text of a menu item is too wide to fit within the display, an ellipsis (...) appears at the end of the line. On some screens, the [VIEW] soft key will be present—press [VIEW] to display the entire text of an item, up to one entire screen size. Once the full text has been displayed, press [ENTER] or [ATTN] to return to the menu. At all screens, including those screens where [VIEW] is not present, pressing [⮣][VISIT] will perform the same function. If an item does fit entirely on the screen, [VIEW] or [⮣][VISIT] will beep and do nothing.

Scrolling Equations Too Wide for the Display

Equations can be viewed in Equation writer format by moving the arrow to the desired equation and pressing [ENTER]. This builds and displays the Equation writer form of the equation. If the Equation writer form fits on the screen, pressing [ENTER] returns to the list of equations from which the equation was selected. If the Equation writer form is too large for the screen, the cursor keys are activated for scrolling, and pressing [ATTN] returns to the list of equations from which the equation was selected. If the Equation writer form is too tall for the screen, the help messages are not displayed, so as not to obscure any part of the equation, but the cursor keys are still activated.

> **WARNING: While the HP 48SX is building the Equation writer format version of an equation, any key presses may cause strange behavior, resulting in no display of the equation. Therefore, do not press any keys until the equation has been drawn, erased, and re-drawn with the accompanying messages. If you change your mind during a long equation build, press [ATTN] to abort the build process and return to the equation screen.**

Changing the Font Size

The default font for the Solid State Pac displays information in condensed, uppercase letters only. Pressing FONT will toggle the information to a larger font, which is case-sensitive:

```
        Solid State
→Equation Library
 Analysis Functions
 Reference Data
 Constant Library
 ASCII Table

ABOUT →STK PRINT VIEW FONT QUIT
```

The font size will remain the same until FONT is pressed again.

Using the Search Mode

When menu lists are long, it is faster to locate an item using the search mode. To initiate a search, press [α] to display the following screen:

```
                              PRG
{ HOME SPARCOM SSELED }
Search for:



◆
←SKIP SKIP→ ←DEL DEL→ INS ■
```

The HP 48SX is now locked in alpha-entry mode, as indicated by the alpha annunciator at the top of the screen. Alpha entry mode activates the white capital letters printed to the lower right of many keys. (For more information, see the section below entitled, "Alpha Lock," and refer to Chapter 2 of the HP 48SX *Owner's Manual*, "The Keyboard and Display.")

To perform a search, enter the first letter or letters of the desired string and press [ENTER]. The search function is case-sensitive, and will scan through all information in the current menu. To enter a lower-case letter in the alpha entry mode, precede the letter with [◄]. To abort the search, press [ATTN].

Editing Text Entries

The soft keys present at the search screen and at many data input screens are command line editing keys. They allow you to edit the search string or input data. Their functions are summarized below:

Key	Action
←SKIP	Moves the cursor to the beginning of the current word.
SKIP→	Moves the cursor to the beginning of the next word.
←DEL	Deletes all characters in the current word prior to the cursor.
DEL→	Deletes all characters in the current word between the cursor's current position and the first character of the next word.
INS	Toggles between insert and type-over modes.
[ATTN]	Clears the command line if there is text present, or aborts text entry if the command line is already blank.
[ENTER]	Accepts the current command line as the entry and returns to the previous menu or list.

(For more information, refer to Chapter 3 of the HP 48SX *Owner's Manual*, "The Stack and Command Line.")

Alpha Lock

System flag –60 controls whether or not Alpha Lock mode is set. The default setting for flag –60 is clear, which means that pressing [α] places the HP 48SX in alpha-entry mode for only one character, and you must press [α] [α] to lock alpha-entry mode. If flag –60 is set, however, then pressing [α] only once locks alpha-entry mode. The examples in this manual assume that flag –60 is clear, so that each [α] keystroke turns on alpha-entry mode only for the following character. (For more information, refer to Chapter 2 of the HP 48SX *Owner's Manual*, "The Keyboard and Display.")

How to Load Data from the Stack

At all data input screens, it is possible to load in values from the HP 48SX stack, even while the Solid State Pac is executing. This is achieved through a limited version of the Interactive Stack, which operates from inside the input routine. To activate the Interactive Stack, press [▲], or if that doesn't work, press [←][EDIT] to display the EDIT menu and then press [↑STK]. At this point, unless the stack is empty, the screen will display the contents of the stack. You may move the arrow up and down the stack with [▲] and [▼], and when you reach the desired value, press [ECHO] to copy it onto the command line for editing. To exit the Interactive Stack and return to the command line, press [ENTER] or [ATTN]. After returning to the command line, you can edit the value with the editing soft keys described above. (For more information, refer to Chapter 3 of the HP 48SX *Owner's Manual*, "The Stack and Command Line.")

System Flags

Flag Preservation

Executing the Solid State Pac will not change the flag settings or stack depth on your HP 48SX, unless you push →STK at some point to leave results on the stack. For your convenience, most flag settings are preserved during operation of the Solid State Pac, including the alpha-lock setting. However, for the software to operate properly, some system flags are temporarily modified during execution:

- ☐ Angle mode is set to Degrees
- ☐ Clock display is turned off
- ☐ Radix mark is set to "." (period)
- ☐ User Mode is turned off

When you press ATTN or QUIT to exit the Solid State Pac to the HP 48SX stack, or when you press HALT at the solver screen to access the HP 48SX stack, all system and user flags are restored to their previous settings.

WARNING: Pressing ATTN multiple times in rapid succession may abort the Solid State Pac without resetting the state of your HP 48SX. Do not do this! The Pac is designed to be tolerant of any user operation, including a few ATTN presses, but it cannot properly restore your stack and flag settings if you push ATTN too many times in a row.

User Flags Controlling Font Size and Units

The display font size is controlled by the setting of user flag 57. If flag 57 is clear, the small display font will be used; if flag 57 is set, the large display font will be used. Changes in the display font during operation of the Solid State Pac are preserved after you quit to the HP 48SX stack.

The state of units (on or off) is controlled by the setting of user flag 61. If flag 61 is clear, units are on; if flag 61 is set, units are off. Changes in the units status during operation of the Solid State Pac are preserved after you quit to the HP 48SX stack.

Chapter 2
An Equation Library Tutorial

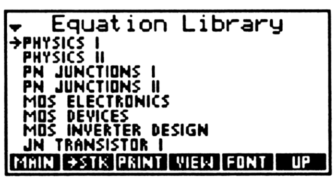
In this chapter

The equation library contains 250 equations organized into eleven categories and 59 topics, all related to Solid State Electronics.

The Categories Screen

To get to the categories screen section, follow these steps:

1. Press [←] [LIBRARY] to display all libraries available to the HP 48SX.
2. Find and press SSELE to enter the Solid State library directory.
3. Press the first softkey, SSELE, to start the application.
4. At the Main menu, move the arrow to Equation Library using the [▼] key and press [ENTER]. The screen shown below shows a listing of the constants library available to the user.

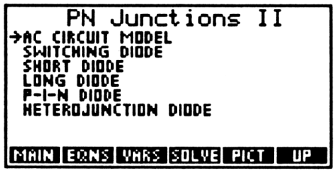


This is the categories screen and shows the eleven categories of equations in the Solid State Electronics Pac.

The Topics Screen

Each of the eleven categories of equations contains a series of related topics. Each topic includes a title, an equation or set of equations, a complete list of variables and descriptions, a default set of units for all variables, and (usually) a picture to illustrate the topic.

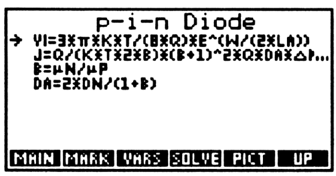
Example: Investigate the category of PN Junctions II. To examine this category, move the arrow to PN Junctions II (by pressing [▲] and [▼]) and press [ENTER]. The following screen will be displayed:



This is the topics screen and shows the six topics of equations in the PN Junctions II category.

The Equations Screen

Example (cont.): We have just chosen PN Junctions II from the Equation Library menu. A topic is selected by moving the arrow to the desired item and pressing ENTER. Let's investigate the equation set for a p-i-n Diode. To do this, move the arrow to p-i-n Diode (by pressing ▲ and ▼) and press ENTER or EQNS. The following screen will be displayed:

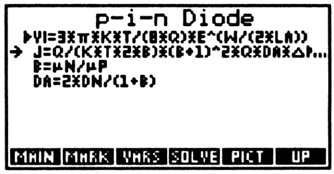


This is the equations screen and shows the four equations that describe a p-i-n diode.

Solving a Single Equation

Example (cont.): Calculate the voltage in the current region, given a temperature of 300_K, a intrinsic region width of 20_μm, and an ambipolar diffusion length of 7.0711_μm.

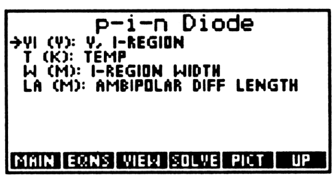
The first step in solving this problem is to select the equation necessary to solve it. Since we are interested in only the voltage in the i-region, it makes sense to only solve the first equation. To do this, mark the equation by moving the arrow to the first equation and pressing MARK. Observe that after marking an equation, the arrow is automatically incremented one location for convenience, so that more than one equation can easily be marked:



To make sure this is the equation we want, we can display it in the EquationWriter format. To do this, move the arrow back to the marked equation by pressing [▲]. Press [ENTER] to display the equation in EquationWriter format. After the "Building equation" message, you will see the equation. When you have finished viewing the equation, press [ATTN] to return to the equation screen.

The Variables Screen

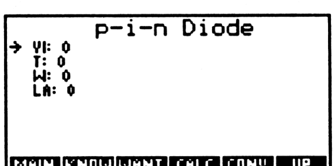
Before solving the equation, let's check the variable screen. Press VARS to display all the variables used in the current set of equations. After the "Updating subset" message, the following screen is displayed:



This is the variables screen and shows the names, descriptions, and default units for all of the variables used by the marked equations. (All variables are shown if no equations are marked.)

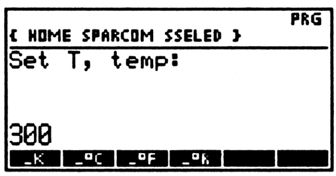
The Solver Screen

Now, let's solve the equation. First, press SOLVE. After the "Loading data" and "Formatting data" messages, the following screen is displayed:



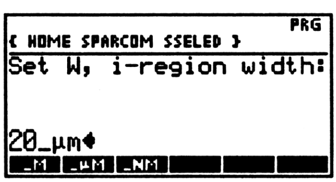
This is the solver screen and shows the names and values of all the variables used by the marked equations. By default, no units are present, so we should turn them on by pressing UNITS. After the "Appending units_" and "Formatting data_" messages, the solver screen will reappear, with the default units shown next to the variable values:

Now, set the value of T to 300_K. Make sure the arrow is pointing at T, and press ENTER. Enter the value for T by typing 300:

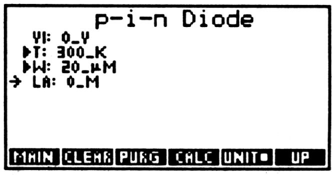


Press ENTER to accept the value (the default units of K will be attached) and return to the solver screen.

The triangular tag next to T indicates that the value is user-defined, or known. Observe that after entering a value, the arrow is automatically incremented one location for convenience, so that more than one value can easily be entered. Since the arrow is now pointing to W, press ENTER to enter 20_m for W. Enter the value by typing 20 and then pressing the 2nd softkey:

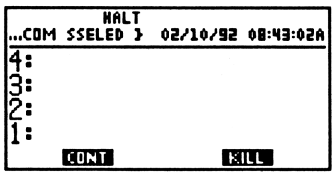


Press ENTER to accept the value and return to the solver screen:

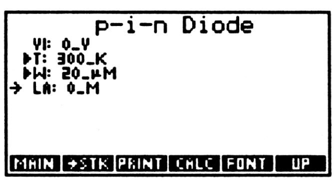


Using the HP 48SX Stack for Calculations

There is one more known value that must be entered before we can solve the equation. However, to enter the value of _m for LA, we must first evaluate the square root. This cannot be done inside the Solid State Electronics Pac, so press [NXT] [NXT] HALT to temporarily suspend execution:

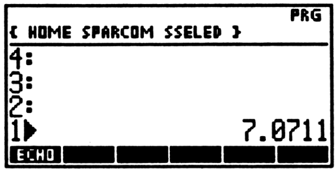


Now, we have full use of the HP 48SX stack and functions, so type 50 and press [√x]. While we are at the stack, we can also perform other operations, such as changing the display notation. Change it to FIX 4 by typing 4 [SPC] [α] [α] FIX [ENTER]. Then press CONT to continue operation. After the "Formatting Data_" message, the solver screen will reappear:



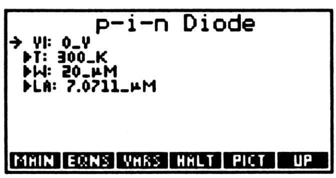
Make sure the arrow is pointing to LA and press [ENTER]:

Press [▲] to activate the Interactive Stack:

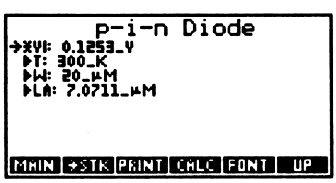


Press ECHO to copy the value in stack level 1 onto the command line for editing. Then press ENTER or ATTN to exit the Interactive Stack and return to the command line to finish entering the value for LA:

Press ← to remove the extra space, and press second softkey to append units of microns to the value. Then press ENTER to return to the solver screen:



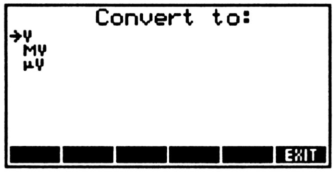
Now that all the known values have been entered, press NXT CALC to solve the equation. After the "Storing values" and "Updating knowns" messages, you will see an informational message explaining which equation is being solved for which variable. After the root is found, the found value will be displayed briefly, and the solver screen will reappear:



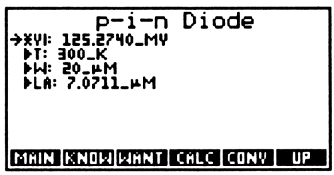
The asterisk tag next to VI indicates that its value was just found in the last calculation.

Converting a Value

Now, let's find out what the value of VI is in millivolts. Make sure the arrow is pointing at VI and press [NXT] [NXT] [CONV]:



This is a list of all the dimensionally consistent units to which you can convert the value of VI. Move the arrow down to MV and press [ENTER]. After the "Converting value" message, the solver screen will reappear with the new converted value:



Copying a Result to the Stack

To copy the final result to the stack, make sure the arrow is pointing at VI and press [NXT] [NXT] [→STK]:

Select [ONE] to copy only the value of VI to the stack, tagged with the variable name. Now, quit the Pac by pressing [ATTN]. You will see both the value we placed there earlier, when finding $\sqrt{50}$, and also the value of VI, tagged with the variable name.

This concludes the example.

Solving Multiple Equations

Just as a single equation can be used by marking it, so can multiple equations be marked. The most common choice is to simply solve all of the equations—this is achieved by marking either all or none of the equations and pressing SOLVE. The advantage of solving all of the equations at once is that you don't need to first determine which equations are necessary to solve a problem. The disadvantage of solving all of the equations at once is that many more variables will be solved for than you are interested in. For this reason, a variable can be marked as wanted.

Using the Wanted Feature

At the solver screen, pressing KNOW toggles a variable between known (user-specified) and unknown. (When a value is entered into a variable, it is automatically marked as known.) Similarly, pressing WANT toggles a variable between wanted (user-desired) and unwanted. If no variables are marked as wanted, pressing CALC will cause the solver to systematically search through all the equations, solving for all possible variables. However, if one or more variables are marked as wanted, then the solver will terminate immediately upon finding values for all of the wanted variables.

Managing Units and Solving

The solver can work either with units or without units. In general, the solving operations work much faster when units are off, but you may want to work with units in order to view answers in the desired units. There are several important points to the behavior of the unit manager as it relates to the solver that you should understand:

1. When units are on, values can be entered in any unit, as chosen from the menu presented at the entry screen. The default SI unit is always the first softkey, and entering a value without appending a unit will cause the default unit to be appended.
2. When units are off, all values are considered to be SI units, so that equations can be solved without yielding inaccurate results. If a value is entered with a unit from the entry screen, the value is automatically converted to the default SI units, and then the unit is stripped. Thus, if units are off, and 2_cm is entered for a variable, you will see .02 at the solver screen, because the value has been automatically converted to meters.
3. When units are on, the units of a desired or wanted variable can be specified in advance, in a manner similar to specifying a guess. Simply enter a value

in the desired units into the variable. Then press KNOW to toggle the variable back to an unknown state, or press WANT to mark the variable as wanted. Then press CALC to solve for the variable; the answer will be returned in the specified units. The alternative to this process is to press CONV to convert the found value to the desired units, after the solving operation has been completed.

4. When CALC is pressed, all the values in the variables are stored in global copies of the variables, inside the { SPARCOM SSELED } directory. Therefore, after many uses of the Solid State Electronics Pac, you may begin to notice that variables already seem to contain values when you go to solve equations. This is normal—the Pac is automatically loading in the existing values from the global variables for convenience, as long as the units are dimensionally consistent with the units required for the variable.

Since solving with units takes a noticeably longer time, the following procedure is recommended to yield the quickest results. This procedure assumes that there is only one, or possibly two, variables in which you are interested, and that the units on the other known variables are irrelevant. Start with units turned off (i.e., the softkey appears as UNITS, not as UNIT■). Enter all known values in the correct units by making use of the automatic conversion feature. All of the values will therefore be consistent unitless SI values. Then solve for the desired variable(s). After the solver has completed, turn units on, to append SI units to all variables. Then, select the desired variable(s), and press CONV to convert them to the final units. This procedure gives the best of both worlds: no units for fast solving, but units for convenient results.

What Does Multiple Equation Solver Mean?

The Sparcom solver is a systematic solver, not a simultaneous one. For example, it can solve this set of equations, provided it is given a user-specified value of either x or y:

$$x + y + z = 5$$

$$x + y = 3$$

However, it cannot solve this set of equations, when neither x or y is known in advance:

$$x + y = 2$$

$$x - y = 0$$

It iterates through a set of equations, searching for an equation with only one unknown variable. When an equation satisfying this requirement is found, it utilizes the HP 48SX root-finder (programmable command ROOT) to solve for the unknown variable. After the value is found, that variable is marked as found, and the solver continues to search. The solver does not terminate its search until one of four conditions occurs:

1. All equations are solved, and all variables found.
2. All variables marked as wanted are found.
3. No more equations can be solved, because all remaining unsolved equations have more than one unknown variable.
4. A solving error occurs, such as Divide By Zero or Bad Guess(es).

All variables for which values are found in a solving operation are marked with an asterisk tag at the solver screen. If a variable is not marked with an asterisk, then it was either not marked as wanted, or a value for it was not found because of too many unknowns.

Speeding Up Computing Time

Once you set these parameters, pressing CALC activates the HP 48SX root-finder to calculate the solution(s). The root-finder requires an initial value on which to base its search. You can provide a guess for the HP 48SX to use; if you don't do so, the solver will supply a guess of 1. The root-finder then generates pairs of intermediate values and interpolates between them to find the solution. The time required to find the root depends on how close the initial guess is to the actual solution.

You can speed up computing time by providing a guess close to the expected solution. At the solver screen, enter your guess into the variable. Upon returning to the solver screen, the variable will be marked as known; press KNOW to toggle the variable back to unknown. Then press CALC, and the HP 48SX will use the stored value for the variable as its initial starting point.

"Bad Guess(es)" Message

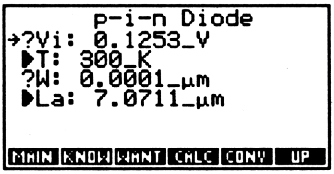
If the HP 48SX displays the "Bad Guess(es)" message at some point after you press the CALC softkey, it indicates an error has been made in setting up the problem. Go back through the setup process and check for error in specifying data.

Plotting One Equation

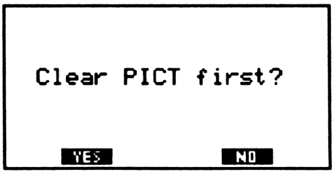
Any equation in the Equation Library that is of the form y=f(a,b,c . . .) can be easily plotted using the Solid State Electronics Pac. To plot an equation, the dependent variable on the left (y) and the desired independent variable (a or b or c . . .) on the right side must be unknown (no triangular tag). However, all other variables must be known.

Finding and Selecting the Equation

Continuing the above example, we plot the variation of Vi of a p-i-n diode as a function of width of the i-region W. Select the equation using MARK and SOLVE to ensure that variables Vi and W are tagged using the WANT key and the variables T and LA are tagged by KNOW key and are accepted to have a known value. The variables designated as WANT are tagged by a ? "question mark" as shown in the screen display shown below.

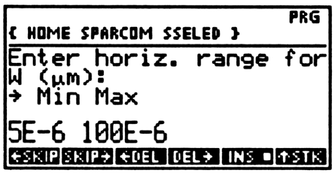


There should be only two unknowns in the equation to be plotted. To proceed the plotting operation, bring back the equation list in this topic by pressing the softkey EQNS and move the pointer to the equation to be plotted. Access the plotting function by pressing NXT NXT PLOT. The calculator will prompt you to see if any previous pictures need to be cleared. Press YES softkey to proceed.

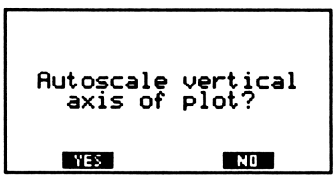


The calculators will give report its progress by displaying Purging variables ..., Storing Values... followed by a prompt for the horizontal range of W as shown below:

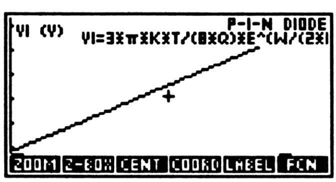
For the purposes of illustration, we have chosen to use 5E-6 and 100E-6 as the range for W. Enter the value as 5E-6 100E-6 and press ENTER as shown below.



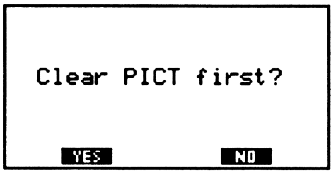
Upon entering the values, the calculator will prompt for vertical axis ranges as shown below. We choose the auto scale feature of the HP 48SX for illustrating this example and this is accomplished by pressing the softkey YES.



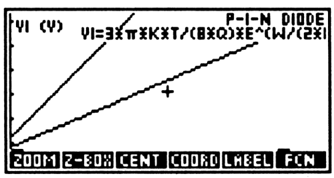
The system displays Autoscaling plot... for a short time followed by the display ATTN to exit the plotting routine. After a few seconds, the plotting process starts with the horizontal and vertical axis clearly labeled with appropriate units. The result is shown below.



At this level, you have access to all the graphics capabilities of the HP 48SX. For instance the FCN gives way to ROOT, ISECT, SLOPE, AREA, EXTRA. A new plot can overlay on top of the existing plot if we wish to examine the behavior for a new parameter. For example, let make a new plot for the equation just plotted with a new value for 3E-6 for W. Once again select the equation and press SOLVE. The variables are listed as shown before. Move the pointer to W and enter the new value of 3E-6. Switch back to the equation level using the key EQNS and select the softkey PLOT. The calculator prompts the user if you wish to erase the previous plot as shown in the display below.



If you answer YES, the previous plot will be erased. If you answer NO, the plotting routine will skip asking the user for input of the range of the horizontal variable and start plotting the selected equation with new value of parameters as shown in the screen display below.



Once plot is complete, the FCN key capabilities are applicable only to the the graph just plotted. To exit the plot screen press ATTN to return to screen showing equations.

Summary of Operations

Categories Screen

Key	Action
FONT	Toggles between the small and large fonts.
MAIN	Returns to the Main menu.
PRINT	Prompts for ONE or ALL to select items, and then sends those items to an IR printer.

→STK	Prompts for ONE or ALL to select items, and then copies those items to the stack. The items are placed in a list if ALL was chosen.
UP	Moves up one level in the menu structure.
VIEW	Displays the entire text of an item too wide to fit on the screen, up to one entire screen size. If the item fits on the screen, this key is non-functional.
ATTN	Quits the Solid State Pac to the HP 48SX stack.
ENTER	Moves down one level in the menu structure.
ON MTH	Dumps the current screen to an IR printer.

Topics Screen

Key	Action
EQNS	Displays the equation screen for the current topic.
FONT	Toggles between the small and large fonts.
MAIN	Returns to the Main menu.
PICT	Displays a picture for the current item
SOLVE	Displays the solver screen of the current topic.
VARS	Displays the variable screen for the current topic including descriptions and default units.
PRINT	Prompts for ONE or ALL to select items, and then sends those items to an IR printer.
→STK	Prompts for ONE or ALL to select items, and then copies those items to the stack. The items are placed in a list if ALL was chosen.
UP	Moves up one level in the menu structure.
ATTN	Quits the Solid State Pac to the HP 48SX stack.
ENTER	Moves down one level in the menu structure.

ON MTH	Dumps the current screen to an IR printer.

Equations Screen

Key	Action
FONT	Toggles between the small and large fonts.
MAIN	Returns to the Main menu.
PICT	Displays a picture for the current item
SOLVE	Displays the solver screen of the current topic.
MARK	Toggles the selected equation between marked and unmarked status, adding or removing a triangular tag. Only variables in the marked set of equations will appear in the solver and variable screens. If no equations are marked, all will be used.
VARS	Displays the variable screen for the current topic, including descriptions and default units.
PRINT	Prompts for ONE or ALL to select items, and then sends those items to an IR printer.
→STK	Prompts for ONE or ALL to select items, and then copies those items to the stack. The items are placed in a list if ALL was chosen.
UP	Moves up one level in the menu structure.
↱ VISIT	Displays the entire text of an item too wide to fit on the screen, up to one entire screen size. Once the full text has been displayed, pressing ENTER or ATTN returns to the menu. If the item fits on the screen, this key is non-functional.
ATTN	Quits the Solid State Pac to the HP 48SX stack.
ENTER	Moves down one level in the menu structure.
ON MTH	Dumps the current screen to an IR printer.

Solver Screen

Key	Action
CALC	Stores variable values and systematically iterates through the set of marked equations in an attempt to find values for all wanted variables. Also, stores the known and found values into global variables into the { SPARCOM SSELED } directory.
CLEAR	Resets values of the current variables to zero, but does not change the global copies, which only change during CALC operations.
CONV	Converts a variable to different units, if units are on.
EQNS	Displays the equations screen for the current topic.
FONT	Toggles between the small and large fonts.
HALT	Halts the Pac so that the user can perform operations on the HP 48SX stack. Pressing CONT or ⬅ CONT returns to the Pac, while pressing KILL or PRG CTRL KILL terminates the Pac.
KNOW	Toggles the selected variable between known and unknown status, adding or removing a triangular tag.
PURG	Purges the global copies (in the { SPARCOM SSELED } directory) of the current set of variables, but does not change the values currently set inside the Pac.
UNIT▫	Indicates that units are currently turned on. Pressing this key turns off units, automatically converting all variables to SI units and then stripping the units.
UNITS	Indicates that units are currently turned off. Pressing this key turns on units, automatically converting all variable values to SI units and then stripping the units.
VARS	Displays the variable screen for the current topic, including descriptions and default units.
VIEW	Displays the entire text of an item too wide to fit on the screen, up to one entire screen size. Once the full test has been displayed, pressing ENTER or ATTN returns to the menu. If the item fits on the screen, this key is non-functional.

WANT	Toggles the selected variable between wanted and unwanted status, adding or removing a question mark tag.
PICT	Displays a picture for the current item, if one exists.
SOLVE	Displays the solver screen of the current topic.
PRINT	Prompts for ONE or ALL to select items, and then sends those items to an IR printer.
→STK	Prompts for ONE or ALL to select items, and then copies those items to the stack. The items are placed in a list if ALL was chosen.
UP	Moves up one level in the menu structure.
VIEW	Displays the entire text of an item too wide to fit on the screen, up to one entire screen size. If the item fits on the screen, this key is non-functional.
ATTN	Quits the Solid State Pac to the HP 48SX stack.
ENTER	Moves down one level in the menu structure.
ON MTH	Dumps the current screen to an IR printer.

Notes:

Chapter 3
Equation Library

In This Chapter

The Equation Library contains over 250 equations organized in 11 main categories. Each category contains several topics. Each topic includes an equation set, a complete list of variables, often a figure illustrating the equation set, and a set of units for all variables. This chapter describes these topics and provides one or more examples using the equation set. The result shown in our examples have been rounded off to the fourth decimal place.

- ☐ Physics I
- ☐ Physics II
- ☐ PN Junctions I
- ☐ PN Junctions II
- ☐ MOS Electronics
- ☐ MOS Devices
- ☐ MOS Inverter Design
- ☐ Jn Transistor I
- ☐ Jn Transistor II
- ☐ Microwave Devices
- ☐ IC Technology

Physics I

The following topics are included in this category. Calculations of basic properties from first principles forms the basis of this category.

- Carrier Density
- Fermi Level
- Carrier Mobility
- Thermal Properties
- Hot Electrons

Carrier Density

There are seven equations under this topic. They represent key relationships between free electron and hole densities, density of states in conduction and valence bands, density of states effective mass for electrons and holes.

1. $n = Nc \cdot e^{\frac{-(Ec - Ef)}{k \cdot T}}$

2. $p = Nv \cdot e^{\frac{-(Ef - Ev)}{k \cdot T}}$

3. $ni^2 = n \cdot p$

4. $Nc = 2 \cdot MC \cdot \left(\frac{2 \cdot \pi \cdot mn \cdot k \cdot T}{h^2}\right)^{1.5}$

5. $Nv = 2 \cdot \left(\frac{2 \cdot \pi \cdot mp \cdot k \cdot T}{h^2}\right)^{1.5}$

6. $mn = me \cdot \left(ml \cdot mt^2\right)^{1/3}$

7. $mp = me \cdot \left(mlh^{1.5} + mhh^{1.5}\right)^{2/3}$

Variable	Description	Units
n	free electron density	1_1/m^3
Nc	density of states, conduction band	1_1/m^3
Ec	conduction band	1_eV
Ef	Fermi level	1_eV
T	temperature	1_K
p	free hole density	1_1/m^3
Nv	density of states, valence band	1_1/m^3
Ev	valence band energy level	1_eV
mn	effective mass of electrons	1
ml	longitudinal mass, electrons	1
mt	transverse mass, electrons	1_kg
mp	effective mass, holes	1_kg
mlh	light hole mass	1
mhh	heavy hole mass	1
MC	# conduction band minima	1
ni	intrinsic carrier density	1_1/m^3

Example 1: Properties of electrons and holes in silicon are measured by relative longitudinal, transverse mass for electrons and light and heavy masses for holes. These values are 0.98, 0.19, 0.16 and 0.49 respectively. Find the density of states effective mass for electrons and holes.

Use equations 6 and 7.

Given	Result
ml = 0.98	mn=2.9905E-31_kg
mt = 0.19	mp=5.0029E-31_kg
mlh = 0.16	
mhh = 0.49	

Example 2: Using the values of effective masses calculated in the above example, find the values of density of states in the conduction and valence band of Silicon at 300_K.

Assume that there are 4 equivalent minima at the conduction band. Use equations 4 and 5.

Given	Result
mn = 2.9905E-31_kg	Nc = 1.8880E19_1/cm^3
mp = 5.0029E-31_kg	Nv = 1.0213E19_1/cm^3
T = 300_K	
MC = 4	

Example 3: Using the values of Nc and Nv calculated in the above examples, find the values of free electron and hole densities if Ec is 1.12_eV above Ev and Ef is .045_eV below the conduction band.

Use the first three equations to solve for p, n and ni. However, be sure to remember that energy levels specified here are not specified to the same reference. The first task therefore is to convert to the same reference level. In this example we chose Ev to be the reference, thus Ec=1.12_eV and Ef=1.12 - 0.045 and equals 1.075_eV.

Given	Result
Nc = 1.8880E19_1/cm^3	n = 3.3115E18_1/cm^3
Nv = 1.0213E19_1/cm^3	p = 8.9120_1/cm^3
T = 300_K	ni = 5.4325E9_1/cm^3
Ec = 1.12_eV	
Ev = 0_eV	
Ef = 1.075_eV	

Fermi Level

There are five equations in this topic. The first two equations cover the ionization of donors and acceptors as a function of donor and acceptor energy levels, the Fermi level, donor and acceptor degeneracy and temperature. The third equation is a generalized charge balance relationship from which Fermi level can be computed at any given temperature. The fourth equation computes electron density for a fully ionized donor and acceptor density and the last equation signifies the relationship between electron and hole densities at thermal equilibrium.

$$1.\ Ndi = Nd \cdot \left(1 - \frac{1}{1 + \frac{1}{9D} \cdot e^{(Ed - Ef)/(k \cdot T)}}\right)$$

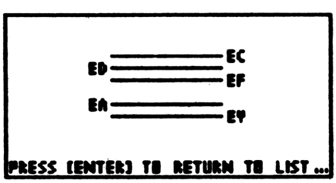
$$2.\ Nai = \frac{Na}{1 + \frac{1}{gA \cdot e^{(Ea - Ef)/(k \cdot T)}}}$$

$$3.\ Nc \cdot e^{-\frac{(Ec - Ef)}{k \cdot T}} + \frac{Na}{1 + gA \cdot e^{\frac{Ea - Ef}{k \cdot T}}} = Nv \cdot e^{\frac{-(Ef - Ev)}{k \cdot T}}$$

$$\ldots + \frac{Nd}{1 + \frac{1}{9D} \cdot e^{\frac{Ef - Ed}{k \cdot T}}}$$

$$4.\ n = \frac{1}{2} \cdot \left(Nd - Na + \sqrt{(Nd - Na)^2 + 4 \cdot ni^2}\right)$$

$$5.\ p = \frac{ni^2}{n}$$



Variable	Description	Units
Ec	conduction band level	1_eV

Ef	Fermi level	1_eV
T	temperature	1_K
Ev	valence band level	1_eV
Nai	ionized acceptor density	1_1/m^3
Na	acceptor density	1_1/m^3
gA	acceptor degeneracy	1
Ndi	ionized donor density	1_1/m^3
Nd	donor density	1_1/m^3
gD	donor degeneracy	1
Ed	donor level	1_eV
Ea	accep level	1_eV
n	free electron density	1_1/m^3
p	free hole density	1_1/m^3
ni	intrinsic density	1_1/m^3
Nc	density of states, electrons	1_1/m^3
Nv	density of states, holes	1_1/m^3

Example 1: A semiconductor has been doped with 3E17 donor per cm^3 and 1E17 acceptors per cm^3. It has an intrinsic carrier density of 1.35E10_1/cm^3. Find the free electron and hole densities.

Assume that the dopants are fully ionized. Use equations 4 and 5.

Given	Result
Na = 1E17_1/cm^3	n = 2.0000E17_1/cm^3
Nd = 3E17_1/cm^3	p = 911.25_1/cm^3
ni = 1.35E10_1/cm^3	

Example 2: A semiconductor has been doped with 3E17 donor per cm^3. The donor degeneracy is 1. At 300_K find the ionized donor density is Ed is located 0.035_eV below the conduction band and Ef is located 0.20_eV below the conduction band.

Use equation 1. Since Ed and Ef are referenced to the same level, we can enter these numbers directly.

Given	Result
Nd = 3E17_1/cm^3	Ndi = 5.0642E14_1/cm^3
gD = 1	
T = 300_K	
Ed = 0.035_eV	
Ef = 0.20_eV	

Example 3: A semiconductor has been doped with 1E17 acceptors per cm^3. The acceptor degeneracy is 2. At 300_K find the ionized acceptor density is Ea is located 0.055_eV above the valence band and Ef is located 0.075_eV above the valence band.

Use equation 2. Since Ea and Ef are referenced the same way, we can enter these numbers directly.

Given	Result
Na = 1E17_1/cm^3	Nai = 4.319516_1/cm^3
gA = 1	
T = 300_K	
Ea = 0.05_eV	
Ef = 0.075_eV	

Example 4: A semiconductor has been doped with 1E17 acceptors and 3E17 donors per cm^3. The acceptor degeneracy is 2. The donor degeneracy is 1. At 300_K given given Nc and Nv to be 1.880E19_1/cm^3 and 3.2120E18_1/cm^3 respectively find the Fermi level if Ec is 1.12_eV above valence band, Ed is 0.035_eV below conduction band and Ea is 0.085_eV above valence band.

Use equation 3 to solve this problem, but first convert all energy levels to the same base. We use valence band as a reference for this example and arrive at Ed = 1.12 - .035 or 1.085_eV.

Given	Result
Na = 1E17_1/cm^3	Ef = 1.0009_eV
Nd = 3E17_1/cm^3	
T = 300_K	
Nc = 1.880E19_1/cm^3	
Nv = 3.2120E18_1/cm^3	
Ev = 0eV	
Ec = 1.12_eV	
Ed = 1.085_eV	
Ea = 0.085_eV	
gD = 2	
gA = 1	

Carrier Mobility

These two equations represent carrier mobility from lattice scattering and ionized impurity scattering.

1. $$\mu l = \frac{\sqrt{8 \cdot \pi} \cdot q \cdot hb^4 \cdot c11}{3 \cdot Eds^2 \cdot mc^{2.5} \cdot (k \cdot T)^{1.5}}$$

2. $$\mu i = \frac{\frac{64 \cdot \sqrt{\pi} \cdot \varepsilon r^2 \cdot (2 \cdot k \cdot T)^{1.5}}{Ni \cdot q^3 \cdot mc^5} \cdot 1}{LN\left(1 + \left(\frac{12 \cdot \pi \cdot \varepsilon r \cdot k \cdot T}{q^2 \cdot Ni^{1/3}}\right)^2\right)}$$

Variable	Description	Units
μl	lattice mobility	1_m^2/(V*s)
c11	elastic coefficient	1_Pa
Eds	band edge shift	1_eV
T	temperature	1_K
μi	impurity scattering	1_m^2/(V*s)
εr	relative permittivity	1
Ni	ionized impurity density	1_1/m^3
mc	conductivity effective mass	1_kg

Example 1: Find the electron mobility at 300_K for silicon due to lattice scattering if band dilation is 10_eV and elastic constant is 2.5E12_dyn/cm^2.

Use equation 1 in solving this problem.

Given	Result
Eds = 10_eV	μl = 2454.3739_cm^2/(V*s)
c11 = 2.5E12_dyn/cm^2	
T = 300_K	
mc = 3.0E-31_Kg	

Example 2: Find the electron mobility at 300_K for silicon due to ionized impurity scattering if relative permittivity is 11.7, conductivity effective mass is 3.0E-31_kg and doping density is 1E187_1/cm^3.

Use the second equation to solve for mobility.

Given	Result
εr = 11.7	μi = 1099.3115_cm^2/(V*s)
Ni = 1E18_1/cm^3	

mc = 3.0E-31_kg
T = 300_K

Thermal Properties

Two equations listed here describe the thermoelectric and thermal conductivity behavior of a semiconductor. The first equation details thermoelectric power in terms electron and hole density and mobility along with location of Fermi level relative conduction and valence bands. In addition a new parameter 's' introduced here expresses the relationship between relaxation time and electron energy. The second equation describes the thermal conductivity of a semiconductor and contribution from the lattice (i.e., phonons) and the free carriers.

$$1.\ \ Pe = \frac{\frac{-k}{q}\cdot\left(\left(2.5 - s + \frac{Ec - Ef}{k\cdot T}\right)\cdot n\cdot \mu n - \left(2.5 - s + \frac{Ef - Ev}{k\cdot T}\right)\cdot p\cdot \mu p\right)}{n\cdot \mu n + p\cdot \mu p}$$

$$2.\ \ Kt = KL + \frac{k^2\cdot\sigma\cdot T}{q^2}\cdot(2.5 - s) + \frac{\frac{k^2\cdot\sigma\cdot T}{q^2}\cdot\left(5 - \frac{2\cdot s\cdot Eg}{k\cdot T}\right)^2\cdot(n\cdot p\cdot \mu n\cdot \mu p)}{(n\cdot \mu n + p\cdot \mu p)^2}$$

Variable	Description	Units
Pe	thermoelectric power	1_V/K
s	scatter parameter	1
Ec	conduction band level	1_eV
Ev	valence band level	1_eV
Ef	Fermi level	1_eV
T	temperature	1_K
n	free electron density	1_1/m^3
μn	electron mobility	1_1/m^3
p	free hole density	1_1/m^3
μp	hole mobility	1_m^2/(V*s)
Kt	thermal conductivity	1_W/(m*K)
KL	lattice thermal conductivity	1_W/(m*K)
σ	electrical conductivity	1_S/m
Eg	band gap	1_eV

Example 1: A semiconductor material has an electron density and mobility of 1E16_1/cm^3 and 1200_cm^2/(V*s) respectively. The corresponding numbers for holes is 2E4_1/cm^3 and 400_cm^2/(V*s). The electrical conductivity is

1.2744_S/cm. The scattering parameter is 2, conduction band level and Fermi levels are 1.12_eV and 1.0009_eV above valence band. Find the thermoelectric power for this material.

Use equation 1 to solve.

Given	Result
s = 2	P = -0.0004_V/K
Ec = 1.12_eV	
Ef = 1.0009_eV	
Ev = 0_eV	
T = 300_K	
n = 1E16_1/cm^3	
μn = 1200_cm^2/(V*s)	
p = 2E4_1/cm^3	
μp = 400_cm^2/(V*s)	

Example 2: The contribution to thermal conductivity from carriers is usually very small as illustrated from above example. A material has a thermal conductivity due to lattice vibrations of 0.25_W/(cm*K). The density and mobility values for electrons are carried over from the previous example. The bandgap is assumed to be 1.12_eV and the electrical conductivity is 1.2744_S/cm. Find the thermal conductivity.

Use equation 2 to solve for Kt.

Given	Result
KL = 0.25_W/(cm*K)	Kt = 0.2500_t/(cm*K)
n = 1E16_1/cm^3	
μn = 1200_cm^2/(V*s)	
p = 2E4_1/cm^3	
μp = 400_cm^2/(V*s)	
Eg = 1.12_eV	
σ = 1.2744_S/cm	
s = 2	

Hot Electrons

Two equations in this topic cover the impact of high electric fields on free electrons. The first equation characterizes electron energy as an effective temperature Te, in terms of ambient temperature T, low field mobility, applied electric field and velocity of sound. The second equation characterizes drift velocity in terms of Te, T, low field mobility and electric field.

1. $$\frac{Te}{T} = \frac{1}{2} \cdot \left(1 + \sqrt{1 + \frac{3 \cdot \pi}{8} \cdot \left(\frac{\mu o \cdot E}{c} \right)^2} \right)$$

2. $$vd = \mu o \cdot E \cdot \sqrt{\frac{T}{Te}}$$

Variable	Description	Units
Te	effec carrier temperature	1_K
T	ambient temperature	1_K
μo	low field mobility	1_m^2/(V*s)
E	electric field	1_V/m
c	sound velocity	1_m/s
vd	drift velocity	1_m/s

Example: A semiconductor with a low field mobility of 1250_cm^2/(V*s) is subject to an electric field of 1E4_V/cm. The velocity of sound in this material is 1E6_cm/s at 300_K. Find the electron temperature and drift velocity.

Use both equations in the set to solve the problem.

Given	Result
μo = 1250_cm^2/(V*s)	Te = 2190.6489_K
T = 300_K	
E = 10000_V/cm	
c = 1E6_cm/s	

Physics II

This category covers six key areas of second order effects of common interest in semiconductor electronics. The topics covered are:

- Hall Effect
- Magneto resistance
- Thermoelectric Effect
- Thermo-magnetic Effect

- Franz-Keldysh Effect
- Cyclotron Resonance

Hall Effect

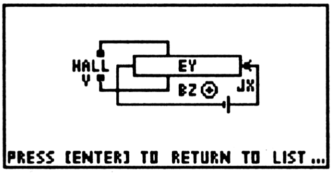
Four equations are described in this equation set describing the Hall effect. The first equation computes the lateral electric field induced due to the magnetic field. The second equation computes the so called Hall coefficient in terms of carrier densities, their mobilities and conductivity. The third equation defines electrical conductivity while the final equation shows the relationship between the Hall coefficient and the Hall mobility.

1. $Ey = \dfrac{q \cdot (p \cdot \mu p^2 - n \cdot \mu n^2) \cdot Bz \cdot Jx}{\sigma^2}$

2. $R = \dfrac{q \cdot (p \cdot \mu p^2 - n \cdot \mu n^2)}{\sigma^2}$

3. $\sigma = q \cdot (n \cdot \mu n + p \cdot \mu p)$

4. $\mu H = R \cdot \sigma$



Variable	Description	Units
Ey	electric field	1_V/cm
n	electron density	1_1/cm^3
μn	electron mobility	1_cm^2/(V*s)
p	hole density	1_1/cm^3
μp	hole mobility	1_cm^2/(V*s)
Bz	magnetic field	1_Wb/m^2
Jx	current density	1_A/cm^2
R	Hall coefficient	1_cm^3/C
σ	electrical conductivity	1_S/cm
μH	Hall mobility	1_cm^2/(V*s)

Example 1: A germanium Hall sample showed the following measurements. Donor doping density is 1E16_1/cm^3 and minority carrier density is 2E12_1/cm^3. Electron and hole mobilities are 3000 and 700 cm^2/(V*s) respectively. Calculate the electrical conductivity. Donor doping implies n is 2E16_1/cm^3.

Using equation 3 we get

Given	Result
n = 1E16_1/cm^3	σ = 4.8068_S/cm
p = 2E12_1/cm^3	
µn = 3000_cm^2/(V*s)	
µp = 700_cm^2/(V*s)	

Example 2: Continuing the above example, find the Hall coefficient and Hall mobility.

Given	Result
n = 1E16_1/cm^3	R = -624.0789_cm^3/C
p = 2E12_1/cm^3	µH = -2999.8223_cm^2/(V*s)
µn = 3000_cm^2/(V*s)	
µp = 700_cm^2/(V*s)	
σ = 4.8068_S/cm	

Example 3: The Hall sample above is subject to a magnetic field of 0.5_Wb/m^2 and a current density of 12.5_A/cm^2. Find the lateral Hall electric field.

Use equation 1 to find the Hall field.

Given	Result
n = 1E16_1/cm^3	Ey = -0.3901_V/cm
p = 2E12_1/cm^3	
µn = 3000_cm^2/(V*s)	
µp = 700_cm^2/(V*s)	
σ = 4.8068_S/cm	
Bz = 0.5_Wb/m^2	
Jx = 12.5_A/cm^2	

Magneto resistance

Four equations are listed in this equation set describe the Hall effect. The first equation shows the effect of variation of resistivity with magnetic field, while the second equation computes the energy relaxation time dependent factor. The third equation shows the variation of resistance due to magnetic field and the impact of Hall mobility on magneto-resistance.

1. $$\frac{\Delta\rho}{\rho o} = \frac{x \cdot Ro^2 \cdot Bz^2}{\rho o^2}$$

2. $$x = \frac{(2.5 - 3 \cdot s)\,! \cdot (2.5 - s)!}{(2.5 - 2 \cdot s)\,!^2} - 1$$

3. $$\frac{\Delta R}{R} = \frac{\Delta\rho}{\rho o} + \frac{\mu H^2 \cdot Bz^2}{1 + \frac{\Delta\rho}{\rho o}}$$

Variable	Description	Units
Δρ	change in resistivity	1_Ω*cm
ρo	resitivity at Bz=0	1_Ω*cm
x	coefficient	1
Ro	low field Hall coefficient	1_cm^3/C
Bz	magnetic field	1_Wb/m^2
ΔR	change in resistance	1_Ω
R	resistance at Bz=0	1_Ω
μH	Hall mobility	1_cm^2/(V*s)
s	scatter parameter	1

Example 1: A sample of silicon has a resistivity of 2.5_Ω*cm and is subjected to a magnetic field of 1.5_Wb/m^2. The low field Hall coefficient is 125_cm^3/C. Assuming that the scattering parameter is 2, find ΔR.

Use 1200_cm^2/(V*s) for Hall mobility. Solve for all the 3 equations.

Given	Result
Ro = 125_cm^3/C	x = -1.0667
ρo = 2.5_Ω*cm	Δr = -.00015_Ω*cm
Bz = 1.5_Wb/m^2	ΔR/R = 3.2342E-2
s = 2	
R = 1_Ω*cm	

μH = 1200_cm^2/(V*s)

Thermoelectric Effect

Two equations listed here show equations of interest in thermoelectric problems. The first equation shows the Peltier coefficient relationship while the second equation shows the Z factor, a thermoelectric figure of merit.

1. $Pe = T \cdot \Theta t$

2. $Z = \frac{\sigma}{Kt} \cdot \Theta t^2$

Variable	Description	Units
P	thermoelectric power coefficient	1_V/K
n	electron density	1_1/cm^3
p	hole density	1_1/cm^3
μn	electron mobility	1_cm^2/(V*s)
μp	hole mobility	1_cm^2/(V*s)
Nc	density of states,electrons	1_1/cm^3
Nv	density of states, holes	1_1/cm^3
sn	scatter parameter,electrons	1
sp	scatter parameter,holes	1
Pe	Peltier coefficient	1_V
θt	thermoelectric power	1_V/K
Z	thermoelectric figure of merit	1_1/K
σ	conductivity	1_S/cm
Kt	thermal conductivity	1_W/(m*K)
T	temperature	1_K

Example 1: Compute free carrier contribution to thermoelectric power of a semiconductor with the following characteristics. The density of states for electron and holes are 1.5E19_1/cm^3 and 2E18_1/cm^3 respectively; the electron and hole densities are 4E13_1/cm^3 5E6_1/cm^3 respectively. The electron and hole scattering parameters are 2 and 1.5 respectively. Assume that mobilities of electrons and holes are 1200 and 300 cm^2/(V*s).

Use equation 1 to solve the problem.

Given	Result
n = 4E13_1/cm^3	P = -1.739E-3_V/K
p = 5E6_1/cm^3	
Nc = 1.5E19_1/cm^3	

Nv = 2E18_1/cm^3
μn = 1200_cm^2/(V*s)
μp = 300_cm^2/(V*s)
sn = 2
sp = 1.5

Example 2: A semiconductor material has a thermoelectric power of 8E-3_V/K, a thermal conductivity of .28_W/(cm*K) and an electrical conductivity of 12.4_S/cm. At 300_K find the Peltier coefficient and the figure of merit.

Use both equations to solve for the unknowns.

Given	Result
T = 300_K	Pe = 2.4_V
θt = 8E-3_V/K	Z = 2.8843E-3_1/K
σ = 12.4_S/cm	
Kt = 0.28_W/(cm*K)	

Thermo-magnetic Effect

Four equations are listed in this topic cover the Ettinghausen effect, Nerst coefficient, Righi-Leduc mobility and a coefficient resulting from scattering parameter.

1. $P = \dfrac{-r \cdot s \cdot k \cdot T \cdot \mu}{q \cdot Kt}$

2. $Qe = \dfrac{-k \cdot \mu \cdot r \cdot s}{q}$

3. $SRL = \dfrac{-n \cdot k^2 \cdot \mu^2 \cdot T \cdot r \cdot (5 - 4 \cdot s + 2 \cdot s^2)}{2 \cdot q \cdot Kt}$

4. $r = \dfrac{(2.5 - 2 \cdot s)! \cdot 2.5!}{(2.5 - s)!^2}$

Variable	Description	Units
P	Ettingshausen coef	1_m^3*K/(W*S)
s	scatter parameter	1
T	temperature	1_K
μ	mobility	1_cm^2/(V*s)

Kt	thermal conductivity	1_W/(m*K)
Qe	Nerst coefficient	1_m^2/(s*K)
SRL	Righi-Leduc mobility	1_cm^2/(V*s)
n	electron density	1_1/cm^3
r	coefficient	1

Example 1: A semiconductor has the following properties; thermal conductivity is 0.28_W/(cm*K), mobility of 6500_cm^2/(V*s), scattering parameter is 1.5,an electron density of 3.8E17_1/cm^3. At room temperature calculate the Ettinghausen coefficient.

Solve equations 1 and 4 from this set.

Given	Result
s = 1.5	r = 5.8905
T = 300_K	P = -5.3026
μ = 6500_cm^2/(V*s)	
Kt = 0.28_W/(cm*K)	

Example 2: Use the above example to compute Nerst coefficient and Righi-Leduc mobility.

Solve equations 2,3 and 4 to extract Qe and SRL.

Given	Result
s = 1.5	Qe = 5.8905
T = 300_K	SRL = -5.3026
μ = 6500_cm^2/(V*s)	
Kt = 0.28_W/(cm*K)	
n = 3.8E17_1/cm^3	

Franz-Keldysh Effect

The single equation in this topic describes an effective length associated with photon assisted tunneling through the energy barrier of bandgap.

$$1.\ l = \left(\frac{hb^2}{2 \cdot me \cdot q \cdot E}\right)^{1/3}$$

Variable	Description	Units
l	effective length	1_cm
E	electric field	1_V/cm

Example 1: Find the electric field when the characteristic length is 12.5_nm.

Given	Result
12.5_nm	E = 195.0726_V/cm

Cyclotron Resonance

Two equations included in this topic relate to the helical motion of electrons moving in a magnetic field B and the radius of the helix. These properties are called cyclotron frequency and cyclotron radius.

1. $\omega c = \frac{q}{m} \cdot B$

2. $rc = \sqrt{\frac{hb}{q \cdot B}}$

Variable	Description	Units
ωc	cyclotron frequency	1_Hz
m	mass	1_kg
B	magnetic field	1_T
rc	cyclotron radius	1_cm

Example 1: Find the cyclotron radius and frequency for an electron subjected to a magnetic field of 9_T.

First equation computes radian frequency, while the second equation computes the cyclotron radius.

Given	Result
m = 9.1031E-31_kg	ωc = 1.5840E12_r/s
B = 9_T	rc = 8.5519E-9_m

PN Junctions I

This category covers seven topics of importance in PN junction theory. The equations chosen reflect a balance between practical application and theoretical interest.

- PN Junction Properties
- Step Junction Capacitance
- Linear Junction Capacitance
- Junction Currents
- High Injection Current
- Recombination Current
- Junction Breakdown

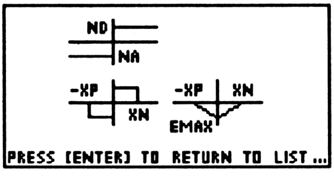
PN Junction Properties

Three equations in this topic cover basic properties of PN junctions. The first equation defines built-in voltage of a junction. The second equation computes effective junction area given the mask dimensions, junction depth and a lateral encroachment factor. The final equation calculates the Debye length, a characteristic electrostatic shield length.

1. $Vbi = \frac{k \cdot T}{q} \cdot LN\left(\frac{Nd \cdot Na}{ni^2}\right)$

2. $Aj = c \cdot d + \frac{2 \cdot c \cdot \pi}{2} \cdot xj + \frac{2 \cdot d \cdot \pi}{2} \cdot xj + 2 \cdot \pi \cdot xj^2 \cdot f^2$

3. $Ld = \sqrt{\left(\frac{\varepsilon r \cdot k \cdot T}{q^2 \cdot Nd}\right)}$



Variable	Description	Units
Vbi	built-in voltage	1_V
T	temperature	1_K
Nd	donor density	1_1/m^3
Na	acceptor density	1_1/m^3
Aj	junction area	1_m^2
c	drawn length	1_m
d	drawn width	1_m
xj	junction depth	1_m
Ld	Debye length	1_m
εr	relative permittivity	1
f	encroachment factor	1
ni	intrinsic density	1_1/m^3

Example 1: Find the built-in voltage for a PN junction with donor and acceptor densities of 3E18_1/cm^3 and 2E15_1/cm^3. Assume room temperature and and intrinsic density of 1.4E10_1/cm^3.

Use the first equation to solve for Vbi.

Given	Result
Nd = 3E18_1/cm^3	Vbi = 0.8028_V
Na = 2E15_1/cm^3	
ni = 1.4E10_1/cm^3	
T = 300_K	

Example 1: The mask dimensions for a PN junction diode are 125_μ and 275_μ. If the junction depth is 1.25_μ find the effective junction area. Assume that lateral encroachment effectiveness is 75%.

Use the second equation to solve for junction area.

Given	Result
c = 125_μ	Aj = 35951.3187_μ^2
d = 275_μ	
xj = 1.25_μ	
f = 0.75	

Example 2: Find the Debye length at 300_K for a piece of silicon doped with 3E16 donors per cm^3.

Use equation 3 to find Debye length.

Given	Result
εr = 11.8	Ld = 2.3705E-2_μ
Nd = 3E16_1/cm^3	
T = 300_K	

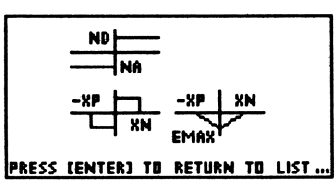
Step Junction Capacitance

The three equations in this topic describe fundamental properties of a step junction. The first equation computes depletion region width, the second equation calculates junction capacitance (sometimes called diffusion capacitance) and the last equation specifies maximum electric field in the depletion region.

$$1.\ xd = \sqrt{\frac{2 \cdot \varepsilon r}{q} \cdot \left(\frac{1}{Nd} + \frac{1}{Na}\right) \cdot (Vbi - Va)}$$

$$2.\ Cj = \sqrt{\frac{q \cdot \varepsilon r}{2 \cdot \left(\frac{1}{Nd} + \frac{1}{Na}\right)} \cdot (Vbi - Va)}$$

$$3.\ Emax = \frac{2 \cdot (Vbi - Va)}{xd}$$



Variable	Description	Units
xd	depletion layer width	1_μ
Nd	donor density	1_1/cm^3

Na	acceptor density	1_1/cm^3
Vbi	built-in voltage	1_V
Va	applied voltage	1_V
Cj	capacitance per unit area	1_F/cm^2
Emax	maximum electric field	1_V/cm
εr	relative permittivity, Si	1

Example 1: A silicon step junction has a acceptor density of 3E18_1/cm^3 and a donor density of 1E16_1/cm^3. Assuming that the built in voltage is 0.78_V and an applied voltage of -10_V. Use all the 3 equations to solve the problem.

Given	**Result**
εr = 11.8	xd = 1.1877_μ
Nd = 1E16_1/cm^3	Cj = 8796.8111_pF/cm^2
Na = 3E18_1/cm^3	Emax = 181527.8605_V/cm
Vbi = 0.78_V	
Va = -10_V	

Linear Junction Capacitance

Five equations in this set describe properties of a linearly graded junction. The first two equations focus on characteristic voltages Vbi and Vg. These voltages reflect unique doping profiles fo linearly graded junctions. The last three equations reflect junction properties such as depletion layer width, junction capacitance and maximum electric field in a depletion region.

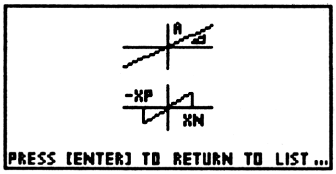
1. $$Vbi = \frac{2 \cdot k \cdot T}{q} \cdot LN\left(\frac{a \cdot xd}{2 \cdot ni}\right)$$

2. $$Vg = \frac{2 \cdot k \cdot T}{3 \cdot q} \cdot LN\left(\frac{a^2 \cdot \varepsilon r \cdot k \cdot T}{8 \cdot q^2 \cdot ni^3}\right)$$

3. $$xd = \left(\frac{12 \cdot \varepsilon r \cdot (Vbi - Va)}{q \cdot a}\right)^{1/3}$$

4. $$Cj = \left(\frac{q \cdot a \cdot \varepsilon r^2}{12 \cdot (Vbi - Va)}\right)^{1/3}$$

5. $$Emax = \frac{3 \cdot (Vbi - Va)}{2 \cdot xd}$$



Variable	Description	Units
Vbi	built-in voltage	1_V
T	temperature	1_K
a	doping gradient constant	1_1/cm^4
ni	intrinsic density	1_1/cm^3
Vg	gradient voltage	1_V
εr	relative permittivity	1
xd	depletion layer width	1_μ
Va	applied voltage	1_V
Cj	junction capacitance per unit area	1_F/cm^2
Emax	maximum electric field	1_V/cm

Example 1: Find the gradient voltage for a linearly graded junction if the doping gradient constant is 1E22_1/cm^4. Assume room temperature and intrinsic density of 1.4E10_1/cm^3.

Use equation 2 to find Vg.

Given	Result
T = 300_K	Vg = 0.7476_V
εr = 11.8	
ni = 1.4E10_1/cm^3	
a = 1E22_1/cm^4	

Example 2: Continuing the above example, compute the depletion layer width for an applied voltage of 10_V.

Given	Result
Vbi = .8028_V	Cj = 36225.9170_pF/cm^2
εr = 11.8	xd = =0.2884_μ
Va = -10_v	Emax = -478340.3641_V/cm
a = 1E22_1/cm^4	

Junction Currents

Five equations in this category describe the key relations in computing current in an ideal PN junction. The first equation defines the so called saturation current density. The next two equations define the electron and hole diffusion lengths in P and N regions respectively. The fourth equation connects the saturation current density, applied voltage and the actual current density. The last equation reduces the current density to actual current.

1. $Js = \dfrac{q \cdot Dp \cdot ni^2}{Nd \cdot Lp} + \dfrac{q \cdot Dn \cdot ni^2}{Na \cdot Ln}$

2. $Lp = \sqrt{Dp \cdot \tau p}$

3. $Ln = \sqrt{Dn \cdot \tau n}$

4. $J = Js \cdot \left(e^{(q \cdot Va)/(k \cdot T)} - 1\right)$

5. $I = Aj \cdot J$

Variable	Description	Units
Js	saturation current density	1_A/cm^2
Dp	diffusion coefficient, holes	1_cm^2/s
Lp	hole diffusion length	1_μ
Dn	diffusion coefficient, electrons	1_μ
Ln	electron diffusion length	1_μ
τp	hole lifetime	1_s
τn	electron lifetime	1_s
J	total current density	1_A/cm^2
Va	applied voltage	1_V
T	temperature	1_K
Aj	junction area	1_cm^2
I	total current	1_A
Nd	donor density	1_1/cm^3
Na	acceptor density	1_1/cm^3
ni	intrinsic density	1_1/cm^3

Example 1: Compute the electron and hole diffusion lengths if the diffusion coefficients for electrons and holes are 35 and 12.5_cm^2/s respectively. Assume that the electron and hole lifetimes are 50_ns and 80_ns.

Given	Result
Dp = 12.5_cm^2/s	Lp = 7.9057_μ
Dn = 35_cm^2/s	Ln = 16.7332_μ
τp = 50_ns	
τn = 80_ns	

Example 2: Continuing the above example, compute the saturation current density if donor and acceptor densities are 1E16_1/cm^3 and 3E18_1/cm^3.

Assume that ni is 1.4E10_1/cm^3.

Given	Result
Nd = 1E16_1/cm^3	Js = 4.9871E-5_μA/cm^2
Na = 3E18_1/cm^3	
7.9057_μ	
16.7332_μ	
Dp = 12.5_cm^2/s	
Dn = 35_cm^2/s	
ni = 1.4E10_1/cm^3	

Example 3: Continuing the above example, find the junction current at room temperature when the forward bias of 0.3_V is applied. Assume that the junction area to be 8500_μ^2.

Given	Result
Va = 0.3_V	J = 5.4653E-3_mA/cm^2
T = 300_K	
Aj = 8500_μ^2	

High Injection Currents

The current density at high injection levels needs to be modified from ideal cases as shown in this relationship shown here.

$$1.\ Jp = \frac{2 \cdot q \cdot Dp \cdot ni}{Lp} \cdot \left(e^{(q \cdot Vo)/(2 \cdot k \cdot T)} - \frac{pn}{ni} \right)$$

Variable	Description	Units
Jp	current density	1_A/cm^2
Dp	diffusion coefficient	1_cm^2/s

ni	intrinsic carrier density	1_1/cm^3
Lp	diffusion length	1_μ
Vo	depletion layer voltage drop	1_V
pn	hole density	1_1/cm^3
T	temperature	1_K

Example 1: Compute the room temperature hole current density in a PN junction with hole diffusion coefficient of 12.5_cm^2/, and intrinsic density of 1.4E10_1/cm^3. Assume that the hole diffusion length is 8_μ and voltage drop is 1_V and minority hole density is 4E4_1/cm^3.

Given	Result
Dp = 12.5_cm^2/s	Jp = 17591.7464_A/cm^2
ni = 1.4E10_1/cm^3	
Lp = 8_μ	
Vo = 1.0_V	
pn = 4E4_1/cm^3	
T = 300_K	

Recombination Currents

Six equations in this category describe recombination characteristics of carriers in a PN junction. The first equation describes the recombination rate for a semiconductor junction at a trap level Et, and characteristics times τpo and τno. Note that the recombination rate U is present only when the product of electron and hole densities deviates from ni^2. The second and third equation define the characteristic time constants τpo and τno. The fourth equation calculates the so called surface recombination velocity. The last two equations compute the current density due to recombination mechanism and compares it to the total current density in a PN junction.

$$1.\ U = \frac{p \cdot n - ni^2}{\tau no \cdot \left(p + ni \cdot e^{(Et-Ei)/(k \cdot T)}\right) + \tau po \cdot \left(n + ni \cdot e^{(Et-Ei)/(k \cdot T)}\right)}$$

$$2.\ \tau no = \frac{1}{Nt \cdot vt \cdot \sigma n}$$

$$3.\ \tau po = \frac{1}{Nt \cdot vt \cdot \sigma p}$$

$$4.\ s = \frac{Nst \cdot vt \cdot \sigma \cdot Na}{p + n + 2 \cdot ni}$$

5. $$Jr = \frac{q \cdot xd \cdot ni^2 \cdot \left(e^{(q \cdot Va)/(k \cdot T)} - 1\right)}{2 \cdot ni \cdot \tau o \cdot \left(e^{(q \cdot Va)/(2 \cdot k \cdot T)} + 1\right)}$$

6. $$\frac{Jt}{Jr} = \frac{2 \cdot ni}{xd} \cdot \left(\frac{Ln}{Na} + \frac{Lp}{Nd}\right) \cdot e^{(q \cdot Va)/(2 \cdot k \cdot T)}$$

Variable	Description	Units
U	recombination rate	1_1/(cm^3*s)
p	hole density	1_1/cm^3
n	electron density	1_1/cm^3
ni	intrinsic carrier density	1_1/cm^3
τno	lifetime	1_s
Et	trap energy level	1_eV
Ei	intrinsic Fermi level	1_eV
T	temperature	1_K
τpo	hole lifetime	1_s
Nt	trap density	1_1/cm^3
vt	thermal velocity	1_cm/s
σn	electron capture cross sectional area	1_cm^2
σp	hole capture cross sectional area	1_cm^2
s	surface recombination velocity	1_cm/s
Nst	surface state density	1_1/cm^3
Na	acceptor density	1_1/cm^3
σ	capture cross section	1_cm^2
Jr	recombination current density	1_A/cm^2
xd	depletion layer width	1_cm
Va	applied voltage	1_V
Jt	total current density	1_A/cm^2
Ln	electron diffusion length	1_cm
Lp	hole diffusion length	1_cm
Nd	donor density	1_1/cm^3
τo	lifetime	1_s

Example 1: The depletion region in a silicon PN junction has electron and hole life times of 40_ns and 60_ns respectively. The electron and hole densities are 1E16_1/cm^3 and 3E14_1/cm^3; the trap is located 0.1_eV above the intrinsic Fermi level. Assume that ni is 1.4E10_1/cm^3. Find the recombination rate.

Solve equation 1 to get the recombination rate.

Given	Result
p = 3E14_1/cm^3	U = 4.9014E21_1/(cm^3*s)
n = 1E16_1/cm^3	
ni = 1.4E10_1/cm^3	
τno = 40_ns	
τpo = 60_ns	
Et = 0.1_eV	
Ei = 0_eV	
T = 300_K	

Example 2: Compute the electron capture cross section in the above example if the thermal velocity is 1.2E7_cm/s. Assume that the trap density is 1E16_1/cm^3.

Use equations 2 and 3.

Given	Result
τno = 40_ns	σn = 2.0833E-16_cm^2
τpo = 60_ns	σp = 1.3889E-16_cm^2
vt = 1.2E7_cm/s	
Nt = 1E16_1/cm^3	

Example 3: Compute the surface recombination velocity for the following situation. Electron and hole density is 1E16_1/cm^3 and 3E14_1/cm^3 respectively; ni is 1.4E10_1/cm^3 and surface state density is 1E12_1/cm^3. The capture cross section area is 1E-15_cm^2 and acceptor density is 1E15_1/cm^3.

Use equation 4 to solve for s.

Given	Result
Nst = 1E12_1/cm^3	s = 1165.0454_cm/s
Na = 1E15_1/cm^3	
p = 1E16_1/cm^3	
n = 3E14_1/cm^3	
ni = 1.4E10_1/cm^3	
σ = 1E-15_cm^2	
vt = 1.2E7_cm/s	

Example 4: Find the recombination current density at room temperature for a 0.25_V bias. Assume that the depletion region width is 2_μ, intrinsic density is 1.4E10_1/cm^3 and lifetime is 0.1_μs.

Use equation 5 for computing this current.

Given	**Result**
ni = 1.4E10_1/cm^3	Jr = 282.3051_μA/cm^2
τo = 0.1_μs	
xd = 2_μ	
Va = 0.25_V	
T = 300_K	

Junction Breakdown

Three equations in this topic cover the multiplication factor in a PN junction, the breakdown voltage of a PN junction for a step junction and a linearly graded junction.

1. $$M = \frac{1}{1 - \left(\frac{Vr}{BV}\right)^{n}}$$

2. $$BVsj = \frac{\frac{\varepsilon r \cdot Em}{2 \cdot q} \cdot 1}{Nb}$$

3. $$BVlj = \frac{4}{3} \cdot Em^{1.5} \cdot \sqrt{\frac{2 \cdot \varepsilon r}{q}} \cdot \sqrt{\frac{1}{a}}$$

Variable	**Description**	**Units**
M	multiplication factor	1
Vr	reverse applied voltage	1_V
BV	breakdown voltage	1_V
n	exponent for M	1
BVsj	step junction breakdown voltage	1_V
εr	relative permittivity	1
Em	maximum electric field	1_V/cm
Nb	doping density	1_1/cm^3
BVlj	linear junction breakdown voltage	1_V
a	doping gradient constant	1_1/cm^4

Example 1: Find the breakdown voltage for a step junction and a linearly graded junction if doping density of 1E16_1/cm^3 on the lightly doped side. Assume that doping gradient is 1E22_1/cm^4.

Assume that the material is silicon.

Given	Result
Em = 1E5_V/cm	BVsj = 73.3617_V
Nb = 1E15_1/cm^3	BVlj = 2.7974_V
a = 1E22_1/cm^4	
εr = 11.8	

PN Junctions II

This category covers seven topics of importance in PN junction theory. The equations chosen reflect a balance between practical application and theoretical interest.

- AC Circuit Model
- Switching Diode
- Short Diode
- Long Diode
- p-i-n Diode
- Heterojunction Diode

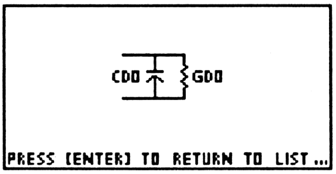
AC Circuit Model

A simple small signal circuit model for a PN junction is described by two equations described here; the first equation focuses on conductance per unit area while the second equation shows the expression for capacitance per unit area.

$$1.\ Gdo = \frac{q}{k \cdot T} \cdot \left(\frac{q \cdot Dp \cdot pno}{Lp} + \frac{q \cdot Dn \cdot npo}{Ln} \right) \cdot e^{(q \cdot Vo)/(k \cdot T)}$$

$$2.\ Cdo = \frac{q}{k \cdot T} \cdot \left(\frac{q \cdot Lp \cdot pno}{2} + \frac{q \cdot Ln \cdot npo}{2} \right) \cdot e^{(q \cdot Vo)/(k \cdot T)}$$

Variable	Description	Units
Gdo	conductance/unit area	1_S/cm^2
T	temperature	1_K
Dp	hole diffusion coefficient	1_cm^2/s
pno	equilibrium hole density in n material	1_1/cm^3
Lp	hole diffusion length in n material	1_m
Dn	electron diffusion coefficient	1_cm^2/s
Ln	electron diffusion length in p-material	1_cm
Vo	applied bias	1_V
Cdo	capacitance per unit area	1_F/cm^2



Example 1: At 300_K, calculate the capacitance and conductance per unit area for a step junction diode. The minority carrier density on p side 7E2_1/cm^3 and 6.67E4_1/cm^3 on the n side. A forward bias of 0.4_V has been applied. Electron and hole diffusion coefficients are 35 and 12.5_cm^2/s respectively. Diffusion lengths for electrons and holes are 8 and 12_μ.

Use both equations to solve for Gdo and Cdo.

Given	Result
npo = 7E2_1/cm^3	Cdo = 880.8094_pF/cm^2
pno = 6.67E4_1/cm^3	Gdo = 3.453E-2_S/cm^2
Dp = 12.5_cm^2/s	
Dn = 35_cm^2/s	
Ln = 8_μ	
Lp = 12_μ	
T = 300_K	
Vo = 0.4_V	

Switching Diode

Charge characteristics for a switching diode are described by the following equation set.

1. $Cd = \frac{q \cdot Qpo}{k \cdot T} \cdot e^{(q \cdot Va)/(k \cdot T)}$

2. $Qpo = Jpo \cdot \tau p$

3. $Qpo = q \cdot pno \cdot Lp$

4. $Qpo = \frac{q \cdot pno \cdot (WB - xn)}{2}$

Variable	Description	Units
Cd	diffusion capacitance	1_F
Qpo	hole charge in n-region	1_C/cm^3
T	temperature	1_K
Va	applied voltage	1_V
τp	hole lifetime	1_s
Jpo	hole current density	1_A/cm^2
pno	equilibrium hole density in n	1_1/cm^3
Lp	diffusion length of holes	1_cm
WB	short diode width	1_cm
xn	depletion layer width in n	1_cm

Example 1: A switching diode is attempting to switch a current density of 125_A/cm^2 at room temperature. The diode is biased at 0.25_V and has a hole lifetime of 50_ns.

Use equations 2 and 3.

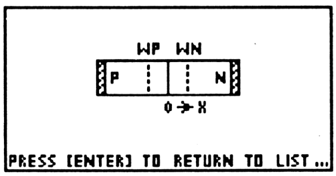
Given	Result
T = 300_K	Qpo = 0.00000625_C/cm^2
V = 0.25_V	Cdo = 3.8299E12_pF/cm^2
τp = 50_ns	
Jpo = 125_A/cm^2	

Short Diode

In a short base diode, (a special case for a narrow base transistor) region available for excess minority carrier recombination is does not contribute to the current density.

1. $Jt = q \cdot ni^2 \cdot \left(\frac{Dp}{Nd \cdot Wn} + \frac{Dn}{Na \cdot Wp}\right) \cdot \left(e^{(q \cdot Va)/(k \cdot T)} - 1\right)$

Variable	**Description**	**Units**
Jt	total current density	1_A/cm^2
ni	intrinsic carrier density	1_1/cm^3
Dp	diffusion coefficient of holes	1_1/cm^3
Nd	donor density	1_1/cm^3
Wn	width of n-region	1_cm
Dn	diffusion coefficient for electrons	1_cm^2/s
Na	acceptor density	1_1/cm^3
Wp	width of p-region	1_cm
Va	applied voltage	1_V
T	temperature	1_K



Example 1: Calculate the current density in a short diode with the following parameters. Intrinsic density is 1.4E10_1/cm^3; hole and electron diffusion coefficients 12.5 and 35_cm^2/s. The donor and acceptor density is 1E16_1/cm^3 and 1E15_1/cm^3. the depletion region widths are 2.5_μ on the n side and 0.85_μ on the p side. Assume that a 0.75_V has been applied to the diode.

Given
Nd = 1E15_1/cm^3
Na = 1E16_1/cm^3
Dp = 12.5_cm^2/s
Dn = 35_cm^2/s
ni = 1.4E10_1/cm^3
T = 300_K
Va = 0.75_V
Wn = 2.5_μ
Wp = 0.85_μ

Result
Jt = 11383.5651_A/cm^2

Long Diode

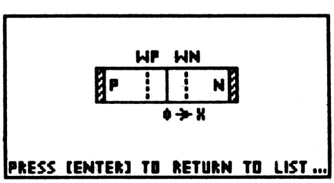
Long base diode exemplifies the case wherein the injected carriers have to traverse a distance much larger than the diffusion length. Three equations in this set identify hole current, electron current and total current.

$$1.\ Jp = \frac{q \cdot Dp \cdot ni^2}{Nd \cdot Lp} \cdot \left(e^{(q \cdot Va)/(k \cdot T)} - 1\right) \cdot e^{-((x-xn)/Lp)}$$

$$2.\ Jn = \frac{q \cdot Dn \cdot ni^2}{Na \cdot Ln} \cdot \left(e^{(q \cdot Va)/(k \cdot T)} - 1\right) \cdot e^{(x+xp)/Ln}$$

$$3.\ Jt = Jn + Jp$$

Variable	Description	Units
Jp	hole current density	1_A/cm^2
Dp	diffusion coefficient of holes	1_cm^2/s
ni	intrinsic density	1_1/cm^3
Nd	donor density	1_1/cm^3
Lp	diffusion length of holes	1_1/cm^3
Va	applied voltage	1_V
x	distance from the junction plane	1_cm
xn	depletion layer width in n-region	1_cm
Jn	electron current density	1_A/cm^2
Dn	electron diffusion coefficient	1_cm^2/s
Na	acceptor density	1_1/cm^3
Ln	electron diffusion length	1_cm
xp	depletion region width in p-region	1_cm
Jt	total current density	1_A/cm^2
T	temperature	1_K



Example 1: Calculate the contribution from electrons for a long diode at a bias of 0.75_V and room temperature. The intrinsic density is 1.4E10_1/cm^3, diffusion coefficient is 35_cm^2/s, diffusion length is 9_μ and an acceptor density of 1.5E16_1/cm^3. Compute the current density at the junction plane.

Use equation 2 to calculate the current density. Assume x and xp to be 0.

Given	Result
Dn = 35_cm^2/s	Jn =323.6904 _A/cm^2
Va = 0.4_V	
x = 0_m	
xn = 0_m	
T = 300_K	
Ln = 9_μ	
Na = 1.5E16_1/cm^3	
ni = 1.4E10_1/cm^3	

p-i-n Diode

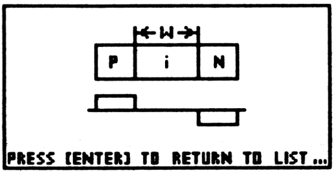
Four equations are included under the topic p-i-n diode. This structure consists of an "i" region sandwiched between a "p" and "n" region. This structure has wide application in microwave circuits as a switch. The first equation computes Vi, the voltage drop in the "i" region. The second equation gives the expression for current density for a given electric field in the "i" region. The last two equations supplement the equation for current by adding calculation for ambipolar diffusion and mobility ratio.

1. $Vi = \dfrac{3 \cdot \pi \cdot k \cdot T}{8 \cdot q} \cdot e^{W/(2 \cdot La)}$

2. $J = \dfrac{q}{k \cdot T \cdot 2 \cdot b} \cdot (b+1)^2 \cdot q \cdot Da \cdot \Delta n \cdot E$

3. $b = \dfrac{\mu n}{\mu p}$

4. $Da = \dfrac{2 \cdot Dn}{1 + b}$



Variable	Description	Units
Vi	voltage drop in i-region	1_V

T	temperature	1_K
W	i-region width	1_cm
La	ambipolar diffusion length	1_cm
J	current density	1_A/cm^2
b	mobility ratio	1
Da	ambipolar diffusion coefficient	1_cm^2/s
Δn	excess carrier density	1_1/cm^3
E	electric field	1V/cm
μn	electron mobility	1_cm^2/(V*s)
μp	hole mobility	1_cm^2/(V*s)
Dn	electron diffusion coefficient	1_cm^2/s

Example 1: Find the voltage across the intrinsic region of a p-i-n diode where "i" region is 6_μ wide, and ambipolar diffusion length is 1.5_μ.

Assume room temperature and use equation 1 to solve the problem.

Given	Result
T = 300_K	Vi = 0.2250_V
W = 6_μ	
La = 1.5_μ	

Example 1: Find the current density if the injected carrier density is 1E13_1/cm^3, electric field is 100V/cm and the electron and hole mobilities are 1250 and 425_cm^2/(V*s) respectively. Assume that electron diffusion coefficient is 35_m^2/(V*s) and room temperature operation.

Use equations 2,3 and 4 to solve the problem.

Given	Result
μn = 1250_cm^2/(V*s)	Da = 17.7612_cm^2/s
μp = 425_cm^2/(V*s)	b = 2.9412
Δn = 1E13_1/cm^3	
T = 300_K	
Dn = 35_cm^2/s	

Hetero-junction Diode

Seven equations under this topic cover the basic device electronics for a hetero-junction device. The first two equations express depletion region width in each half of the hetero-junction device. The third equation evaluates capacitance of the heterojunction.The next three equations cover the inter-relationship between "built-in voltages" and voltages characteristic of each segment of the hetero-junction. The last two equations cover the current density, applied voltage relations.

1. $x1 = \sqrt{\dfrac{2 \cdot Na2 \cdot \varepsilon 1 \cdot \varepsilon 2 \cdot (Vbi - V)}{q \cdot Nd1 \cdot (\varepsilon 1 \cdot Nd1 + \varepsilon 2 \cdot Na2)}}$

2. $x2 = \sqrt{\dfrac{2 \cdot Nd1 \cdot \varepsilon 1 \cdot \varepsilon 2 \cdot (Vbi - V)}{q \cdot Na2 \cdot (\varepsilon 1 \cdot Nd1 + \varepsilon 2 \cdot Na2)}}$

3. $C = \sqrt{\dfrac{q \cdot Nd1 \cdot Na2 \cdot \varepsilon 1 \cdot \varepsilon 2}{2 \cdot (\varepsilon 1 \cdot Nd1 + \varepsilon 2 \cdot Na2) \cdot (Vbi - V)}}$

4. $V = V1 + V2$

5. $Vbi = Vb1 + Vb2$

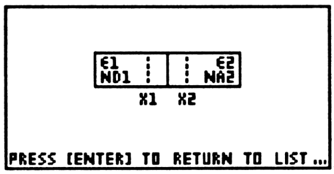
6. $\dfrac{Vb1 - V1}{Vb2 - V2} = \dfrac{Na2 \cdot \varepsilon 2}{Nd1 \cdot \varepsilon 1}$

7. $Jo = \dfrac{q \cdot A \cdot T \cdot Vbi}{k} \cdot \left(e^{-((q \cdot Vbi)/(k \cdot T))} - 1\right)$

8. $J = Jo \cdot \left(1 - \dfrac{V}{Vbi}\right) \cdot \left(e^{-((q \cdot V)/(k \cdot T))} - 1\right)$

Variable	Description	Units
x1	depletion layer in # 1	1_cm
x2	depletion layer in # 2	1_cm
Na2	acceptor density in # 2	1_1/cm^3
ε2	relative permittivity of # 2	1
Nd1	donor density in # 1	1_1/cm^3
ε1	relative permittivity in # 1	1
Vbi	built-in voltage	1_V
V	applied voltage	1_V
C	capacitance	1_F

V1	voltage in # 1	1_V
V2	voltage in # 2	1_V
Vb1	built-in voltage in # 1	1_V
Vb2	built-in voltage in # 2	1_V
Jo	saturation current density	1_A/cm^2
A	Richardson's constant	1_A/(cm^2*K^2)
T	temperature	1_K
J	current density	1_A/cm^2



Example 1: A hetero-junction structure is constructed as follows: material 1 has a donor density of 1E16_1/cm^3 and a relative permittivity of 11.8. material 2 has an acceptor density of 2E17_1/cm^3 and a relative permittivity of of 9.6. If Vbi is 0.75_V find the depletion layer widths in both materials and the hetero-junction capacitance when the applied bias is 3.5_V.

Use equations 1 and 2 to compute depletion region widths and equation 3 to compute capacitance.

Given	Result
Na2 = 2E17_1/cm^3	x1 = 0.7226_μ
Nd1 = 1E16_1/cm^3	x2 = 0.0361_μ
ε2 = 9.6	C = 13621.0733_pF/cm^2
ε1 = 11.8	
Vbi = 0.75_V	
V = 3.5_V	

MOS Electronics

Subjects covered in this category focus on basic electronic properties of MOS structures. Surface properties, MOS capacitor, properties of charge coupled devices are included in this category.

- MOS Capacitor

- Surface Properties
- CCD Electronics

MOS Capacitor

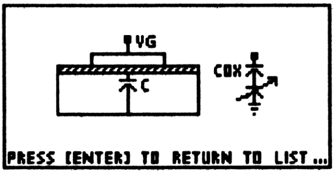
There are three equations in this this topic. They show the relationship between flat band voltage, work function, fixed charge, capacitance and oxide thickness and the variation of capacitance with applied bias.

1. $VFB = \Phi\, ms - \dfrac{Qss}{Cox}$

2. $Cox = \dfrac{\varepsilon ox}{tox}$

3. $\dfrac{C}{Cox} = \dfrac{1}{\left(1 - \dfrac{2 \cdot Cox^2 \cdot (VG - VFB)}{q \cdot NA \cdot \varepsilon s}\right)^{1/2}}$

Variable	**Description**	**Units**
VFB	flat-band voltage	1_V
Φms	work function voltage	1_V
Qss	surface state charge	1_V
Cox	capacitance per unit area	1_F/m^2
εox	relative permittivity,oxide	1
tox	oxide thickness	1_cm
C	capacitance per unit area	1_F/cm^2
εs	relative permittivity, Si	1
VG	gate voltage	1_V
NA	substrate doping density	1_1/cm^3



Example 1: A 15_nm thick oxide with a permittivity of 3.9 is on a semiconductying material with a work function value of 0.75_V. Surface state density is 1E-10_C/cm^2. Find the flat band voltage and the oxide capacitance per unit area.

Use the first two equations to solve for the unknown variables.

Given	Result
ϕms = 0.75_V	VFB = 0.7496_V
Qss = 1E-10_C/cm^2	Cox = 230208.8833_pF/cm^2
εox = 3.9	
tox = 15_nm	

Example 2: Continuing the above example, the semiconductor material in question has an acceptor density of 1E15_1/cm^3 with a relative permittivity of 11.8. For a gate bias of 6_V, find the effective capacitance per unit area.

Given	Result
VFB = 0.7496_V	C = 3521.0205_pF/cm^2
Cox = 230208.8833_pF/cm^2	
εs = 11.8	
VG = 6_V	
Na = 1E15_1/cm^3	

Surface Properties

There are seven equations in this topic. The first two equations cover free electron and hole densities at the surface expressed in terms of electron and hole densities of the material. The third equation describes the surface electric field in terms of critical electronic parameters of the system. The fourth equation connects surface electric field and mobile surface charge. The fifth equation is a basic threshold voltage equation in MOS electronics connecting process and material properties with inversion characteristics. The last two equations define Fermi potential and Debye length, two extremely useful parameters in MOS electronics.

1. $ns = np \cdot e^{(q \cdot \Phi s)/(k \cdot T)}$

2. $ps = Na \cdot e^{(q \cdot \Phi s)/(k \cdot T)}$

3. $Es = \dfrac{\sqrt{2} \cdot k \cdot T}{q \cdot Ld} \cdot \left(e^{-\frac{(q\Phi s)}{(kT)}} - \dfrac{q \cdot \Phi s}{k \cdot T} - 1 + \dfrac{np}{Na} \cdot \right.$

$$\ldots\left(\left(e^{\frac{(q\cdot\Phi s)}{(k\cdot T)}}-\frac{q\cdot\Phi s}{k\cdot T}\cdot e^{\frac{(q\cdot Vd)}{(k\cdot T)}}-1\right)\right)^{.5}$$

4. $Qs = -\varepsilon s\cdot Es$

5. $VT = \frac{-(Qss+QSDm)\cdot tox}{\varepsilon ox}+\Phi ms+2\cdot\Phi f$

6. $\Phi f = \frac{k\cdot T}{q}\cdot LN\left(\frac{Na}{ni}\right)$

7. $Ld = \sqrt{\left(\frac{\varepsilon s\cdot k\cdot T}{q^2\cdot Na}\right)}$

Variable	Description	Units
ns	electron surface density	1_1/cm^3
np	bulk electron density	1_1/cm^3
Φs	surface potential	1_V
T	temperature	1_K
ps	surface hole density	1_1/cm^3
Es	surface electric field	1_V/cm
Qs	surface charge	1_C/cm^3
εs	relative permittivity, Si	1
VT	threshold voltage	1_V
Qss	surface state charge	1_C/cm^3
QSDm	maximum depletion charge density	1_C/cm^3
tox	oxide thickness	1_cm
Φms	metal-Si work function potential	1_V
Φf	Fermi potential	1_V
ni	intrinsic carrier density	1_1/cm^3
εox	relative permittivity, oxide	1
Ld	Debye length	1_cm
Na	acceptor density	1_1/cm^3
Vd	modified depletion voltage	1_V

Example 1: Calculate Debye length and fermi potential for a p-type semiconductor doped with 2.5E16_1/cm^3 acceptors. Assume room temperature operation, a relative permittivity of 11.8 and an intrinsic density of 1.4E10_1/cm^3.

Use equations 6 and 7 to solve for these unknowns.

Given	Result
Na = 2.5E16_1/cm^3	Ld = 0.821_μ
εs = 11.8	φf = 0.3126_V
T = 300_K	
ni = 1.4E10_1/cm^3	

Example 2: Compute the electric field and charge density at the surface of the semiconductor described in the example above. Use 2*φf for surface potential φs and a depletion layer voltage of 1.5_V. Assume electron density to be 8000_1/cm^3 in the p-type material.

Use equations 3 and 4 to solve for the quantities in question.

Given	Result
Na = 2.5E16_1/cm^3	Es = 103240.6837_V/cm
np = 8000_1/cm^3	Qs =-1.0787E-7 _C/cm^2
Vd = 1.5_V	
Ld = 0.0821_μ	
T = 300_K	
φs = 0.6252_V	
εs = 11.8	

CCD Electronics

Six equations in this topic describe the basic equations of interest for charge coupled devices, which are essentially an array of closely spaced MOS diodes. The first equation couples charge voltage and flat band voltage to gate voltage. Equations 2 and 3 evaluate the surface potential and charge density for n-channel devices. Equation 4 defines charge voltage, a useful parameter and is defined to be positive for n-channel CCD. the last two equations define a characteristic constant and channel transit time parameter.

1. $VG = VO - VFB$

2. $\Phi s = VG + \frac{Qn}{Cox} - VO \cdot \left(\sqrt{1 + \frac{2 \cdot \left(VG + \frac{Qn}{Cox} \right)}{VO}} - 1 \right)$

3. $Qn = -\left(VG - \Phi s - \sqrt{2 \cdot VO \cdot \Phi s} \right) \cdot Cox$

$$4.\ VO = \frac{q \cdot \varepsilon s \cdot NB}{Cox^2}$$

$$5.\ K = \frac{\pi^2 \cdot Dn}{4 \cdot \mu n} + \frac{\pi \cdot L \cdot Ex}{2}$$

$$6.\ ttr = \frac{L^2}{\mu n}$$

Variable	**Description**	**Units**
Φs	surface potential	1_V
VG	reduced gate voltage	1_V
Qn	electron charge density	1_C/cm^3
Cox	oxide capacitance per unit area	1_F/cm^2
VO	charge voltage	1_V
εs	relative permittivity, Si	1
NB	bulk doping density	1_1/cm^3
K	constant	1_V
Dn	electron diffusion coef	1_cm^2/s
μn	electron mobility	1_cm^2/(V*s)
L	channel length	1_cm
Ex	lateral electric field	1_V/cm
ttr	transit time per unit voltage	1_s/V
VFB	flat-band voltage	1_V

Example 1: Find the channel voltage for a CCD structure with a doping of 1E15_1/cm^3 and an oxide capacitance of 6500_pF/cm^2.

Assuming that the semiconductor material is silicon, we use 11.8 for relative permittivity and solve for VO using equation 4.

Given	**Result**
εs = 11.8	VO = 3.962_V
NB = 1E15_1/cm^3	
Cox = 6500_pF/cm^2	

Example 1: Calculate the surface potential for the example when 6_V is applied to the gate.

Use equations 2 and 3 to solve for surface potential ϕs.

Given	Result
VG = 6_V	ϕs = 2.0018_V
VO = 3.9620_V	
Qn = -1E-10_C/cm^2	
Cox = 6500_pF/cm^2	

Example 2: Compute the transfer constant and transit time for a surface CCD given Dn is 35_cm^2/s and an electron mobility of 1250_cm^2/(V*s); channel length is 2_µ and an electric field of 875_V/cm.

Use the last two equations to solve for the parameters in question.

Given	Result
Dn = 35_cm^2/s	K = 0.0718_V
µn = 1250_cm^2/(V*s)	ttr = 32_ps*V
L = 2_µ	
Ex = 875_V/cm	

MOS Devices

Six topics are covered in this category. They include device parameters, basic properties of a MOS transistor, subthrehold current characteristics, velocity saturation effects, small geometry effects and temperature effects.

- Device Parameters
- MOS Transistor
- Subthrehold Current
- Velocity Saturation Effects
- Small Geometry Effects
- Temperature Effects

Device Parameters

Six equations characterize device parameters in MOS technology. The first equation computes oxide capacitance per unit area. The second equation computes effective device constant given geometry of the device, along with some material properties. The third equation calculates Fermi potential for a substrate material. The fourth equation specifies th space charge density in the depletion region underneath the surface in terms of substrate voltage, doping density and Fermi potential. The last two equations specify threshold voltage in terms of material parameters and process parameters.

1. $Cox = \frac{\varepsilon ox}{tox}$

2. $\beta = \frac{W - \Delta W}{L - \Delta L} \cdot \mu \cdot Cox$

3. $\Phi p = \frac{k \cdot T}{q} \cdot LN\left(\frac{NA}{ni}\right)$

4. $Qd = \sqrt{2 \cdot \varepsilon s \cdot q \cdot NA \cdot (2 \cdot \Phi p + VSB)}$

5. $VT = VFB + 2 \cdot \Phi p + \frac{Qd}{Cox} + \delta VT$

6. $VFB = \Phi ms - \frac{Qf}{Cox} - \frac{Qss}{Cox}$

Variable	Description	Units
Cox	oxide capacitance per unit area	1_F/cm^2
εox	relative permittivity, oxide	1
tox	oxide thickness	1_cm
β	device constant	1_A/V^2
W	device width	1_cm
ΔW	field encroachment	1_cm
L	device length	1_cm
ΔL	channel encroachment	1_cm
μ	mobility	1_cm^2/(V*s)
Φ_p	Fermi potential	1_V
T	temperature	1_K
NA	substrate doping	1_1/cm^3
ni	intrinsic density	1_1/cm^3
Qd	bulk charge density	1_C/cm^3
εs	relative permittivity, Si	1
VSB	source to substrate voltage	1_V
VT	threshold voltage	1_V
VFB	flat-band voltage	1_V
Φ_{ms}	work func	1_V
Qf	interface charge	1_C/cm^3
Qss	surface state charge	1_C/cm^3

δVT	change in threshold, VT	1_V

Example 1: Compute the Fermi potential, gate oxide capacitance and and device constant for a MOS structure with a 20_nm oxide thickness, 12μ drawn width, 2_μ gate length, 0.35_μ lateral encroachment. Assume room temperature operation, intrinsic carrier density of 1.4E10_1/cm^3 and an oxide permittivity of 3.9, acceptor density of 3E15_1/cm^3 and an electron mobility of 600_cm^2/(V*s).

Solve for unknowns using equations 1, 2 and 3.

Given	Result
Na = 3E15_1/cm^3	ϕp = 0.3173_V
tox = 20_nm	β = 7.3144E-4_A/V^2
W = 12_μ	Cox = 172656.6625_pF/cm^2
ΔL = 0.35_μ	
ΔW = 0.35_μ	
L = 2_μ	
μ = 600_cm^2/(V*s)	

Example 2: Continuing the example above find the charge contribution from the depletion region when subjected to a substrate bias of 5_V.

Use equation 4 to find the depletion charge density.

Given	Result
ϕp = 0.3173_V	Qd = -7.5228E-8_C/cm^2
Na = 3E15_1/cm^3	
εs = 11.8	
VSB = 5_V	

Example 3: Solve for flat-band voltage using the example above if the metal work function is 0.8_V, interface charge is 1E-10_C/cm^2 and the surface state charge is 1.2E-8_C/cm^2.

Use equation 6 to solve for flat-band voltage.

Given	Result
ϕms = 0.8_V	VFB = 0.7299_V
Qf = 1E-10_C/cm^2	
Qss = 1.2E-8_C/cm^2	

Cox = 1.72656.6625_pF/cm^2

Example 4: Calculate the threshold voltage for the MOS system if δVT is 0_V. Use equation 5 to solve for VT.

Given	Result
Cox = 172656.6625_pF/cm^2	VT = 1.8003_V
Qp = 0.3173_V	
Qd = 7.5228E-8_C/cm^2	
δVT = 0_V	
VFB = 0.7299_V	

MOS Transistor

Five equations in this set focus on MOS transistor properties. The first equation covers the expression for drain current in terms of gate voltage, drain voltage, device constant. This equation automatically uses the correct expression for computing the drain current based on the relationship between gate voltage, drain voltage and threshold voltage. The second equation shows the relationship between drain saturation voltage and gate voltage, substrate properties, MOS device properties. The relationship in equation 3 connects the transconductance for the MOS transistor. The fourth equation gives an order of magnitude computation for transit time for a carriers in the channel. The last equation calculates the conductance of the MOS device at low drain voltages.

1. $IDS = \beta \cdot \left((VGS - VT) \cdot VDS - \frac{VDS^2}{2} \right)$

2. $VDsat = \ldots$

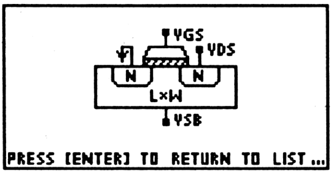
$$VGS - VFB - 2 \cdot \Phi p - \frac{\varepsilon s \cdot q \cdot NA}{Cox^2} \cdot \left(\sqrt{1 + \frac{2 \cdot Cox^2}{\varepsilon s \cdot q \cdot NA} \cdot (VGS - VFB - VSB)} - 1 \right)$$

3. $gmsat = \beta \cdot VDsat$

4. $Ttr = \frac{\frac{4}{3} \cdot L^2}{\mu n \cdot (VGS - VT)}$

5. $go = \beta \cdot (VGS - VT)$

Variable	Description	Units
IDS	drain current	1_A
β	device constant	1_A/V^2
VGS	gate voltage	1_V
VT	threshold voltage	1_V
VDS	drain to source voltage	1_V
VDsat	drain saturation voltage	1_V
VFB	flat-band voltage	1_V
Φp	Fermi potential	1_V
εs	relative permittivity, Si	1
NA	substrate doping	1_1/cm^3
Cox	oxide capacitance per unit area	1_F/cm^2
VSB	substrate to source voltage	1_V
gmsat	transconductance	1_mA/V
Ttr	carrier transit time	1_s
μn	mobility	1_cm^2/(V*s)
L	channel length	1_cm
go	zero bias conductance	1_S



Example 1: Find the drain current for a n-MOS transistor with a device constant of 7.5E-4_A/V^2 and a VT of 0.85_V. Use the conditions of 2_V and 5_V for gate voltage and assume that the drain voltage is held at 4_V.

Solve equation 1 for the two values of gate voltage.

Given	Result
β = 7.5E-4_A/V^2	IDS = 0.4459_mA
VT = 0.85_V	
VGS = 2_V	
VDS = 4_V	
and if:	
VGS = 5_V	IDS = 8.55_mA

Example 2: Compute the drain saturation voltage at a gate voltage of 5_V given the flat-band voltage to be 0.8_V, Fermi potential to be 0.3_V, doping density to be 1.5E15_1/cm^3, and oxide capacitance of 12500_pF/cm^2. Assume the material to be silicon and the substrate bias is 0_V.

Use equation 2 to solve for VDsat.

Given	Result
VGS = 5_V	VDsat = 3.2483_V
VFB = 0.8_V	
ϕp = 0.3_V	
εs = 11.8	
Na = 1.5E15_1/cm^3	
Cox = 12500_pF/cm^2	
VSB = 0_V	

Example 3: Find transconductance for the above transistor while in saturation and conductance at low drain bias. What is electron transit time through the channel?

Use equations 3, 4 and 5 to solve for the parameters of interest.

Given	Result
β = 7.5E-4_A/V^2	gmsat = 2.3625_mA/V
VGS = 4_V	ttr = 2.8219E-11_s
VT = 0.85_V	go = 2.4625E-3_S
μn = 600_cm^2/(V*s)	
L = 2_μ	
VDsat = 3.15_V	

Sub-threshold Current

Three equations are listed in this topic. The first equation defines a characteristic constant representing a scaling factor. The second and third equations are a coupled representing surface potential and drain current at gate voltages below threshold.

$$1.\ a = 2 \cdot \left(\frac{\varepsilon s}{\varepsilon ox}\right) \cdot \left(\frac{tox}{LD}\right)$$

2. $$\Phi s = VG - VFB - \frac{a^2}{\frac{2 \cdot q}{(k \cdot T)}} \cdot \left(\sqrt{1 + \frac{4}{a^2} \cdot \left(\frac{q}{k \cdot T} \cdot (VG - VFB) - 1 \right)} - 1 \right)$$

3. $$ID = \mu \cdot \left(\frac{W}{L} \right) \cdot \left(\frac{a \cdot \varepsilon ox}{2 \cdot \left(\frac{q}{k \cdot T} \right)^2 \cdot tox} \right) \cdot \left(\frac{ni}{NA} \right)^2 \cdots$$

$$\cdot \left(1 - e^{-\frac{(q \cdot VD)}{(k \cdot T)}}\right) \cdot e^{\frac{(q \Phi s)}{(k \cdot T)}} \cdot \sqrt{\frac{(q \cdot \Phi s)}{(k \cdot T)}}$$

Variable	Description	Units
a	gate parameter	1
εs	relative permittivity, Si	1
LD	Debye length	1_cm
εox	relative permittivity, Oxide	1
tox	oxide thickness	1_cm
φs	surface potential	1_V
VG	gate voltage	1_V
VFB	flat-band voltage	1_V
T	temperature	1_K
ID	drain current	1_A
μ	mobility	1_cm^2/(V*s)
W	device width	1_cm
L	device length	1_cm
ni	intrinsic density	1_1/cm^3
NA	doping density	1_1/cm^3
VD	drain voltage	1_V

Example 1: Compute the gate parameter for a silicon MOS gate structure with a 15_nm gate oxide, Debye length of 7.5_μ and an oxide permittivity of 3.9. Use equation 1.

Given	Result
εs = 11.8	a = 12.1026
LD = 7.5_nm	
εox = 3.9	

tox = 15_nm

Example 2: Continuing the above example, the MOS device has a drain voltage of 0.25_V, gate voltage of 0.5_V, a flat band voltage of 0.25_V. Assume the structure to be 12_μ wide and the gate is 2_μ long, oxide capacitance is 230208.8833_pF/cm^2, electron mobility of 600_cm^2/(V*s). Use intrinsic density of 1.4E10_1/cm^3.

Use equations 2 and 3 to solve the problem.

Given	Result
a = 12.1026	φs = 0.04326_V
VG = 0.5_V	ID = 2.7842E-15_A
VD = 0.25_V	
T = 300_K	
ni = 1.4E10_1/cm^3	
NA = 1.5E15_1/cm^3	
VFB = 0.2_V	
μ = 600_cm^2/(V*s)	
W = 12_μ	
L = 2_μ	

Velocity Saturation Effects

The carrier mobility is modified by gate voltage and channel voltage in a MOS device. The equation in this topic presents one model for carrier mobility.

$$1.\ \mu = \frac{\mu o}{1 + \dfrac{\Phi \cdot \varepsilon ox \cdot (VGS - VC)}{\varepsilon s \cdot tox}}$$

Variable	Description	Units
μ	mobility	1_cm^2/(V*s)
μo	low field mobility	1_cm^2/(V*s)
θ	field coefficient	1_cm/V
εox	relative permittivity, oxide	1
VGS	gate voltage	1_V
VC	channel voltage	1_V
εs	relative permittivity, Si	1
tox	oxide thickness	1_cm

Example 1: Compute the channel voltage for a MOS structure if the mobility reduction is 50%. Assume that the gate voltage is 10_V, the relative permittivites of oxide and silicon are 3.9 and 11.8 respectively and we have a 20_nm oxide.

The mobilities μ and μo are not specified but a ratio is given. Thus we could use values of 0.5 and 1 for μ and μo and solve for VC.

Given	Result
μ = 0.5_cm^2/(V*s)	VC = 7.9829_V
μo = 1_cm^2/(V*s)	
εox = 3.9	
εs = 11.8	
VGS = 10_V	
tox = 20_nm	
θ = 3E-6_cm/V	

Small geometry Effects

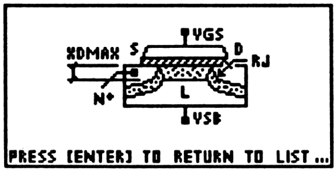
Two equations in this topic cover the effect of geometry on threshold voltage. The first equation gives an estimate of reduction in threshold voltage due to short channel length. The second equation on the other hand shows an effective increase in the threshold voltage due to a narrow channel.

$$1.\ \delta VT=\frac{-rj}{(Cox\cdot L)}\cdot\sqrt{2\cdot\varepsilon s\cdot q\cdot NA\cdot(2\cdot\Phi p+VSB)}\cdot\left(\sqrt{1+\frac{2\cdot xdmax}{rj}}-1\right)$$

$$2.\ \delta VT=\frac{\pi\cdot q\cdot NA\cdot xdmax^2}{2\cdot Cox\cdot W}$$

Variable	Description	Units
δVT	change in VT	1_V
rj	junction radius	1_cm
Cox	capacitance per unit area	1_F/cm^2
L	device length	1_cm
εs	relative permittivity, Si	1
NA	substrate doping	1_1/cm^3
φp	Fermi potential	1_V

VSB	substrate voltage	1_V
xdmax	maximum depletion region width	1_cm
W	device width	1_cm



Example 1: Find change in the threshold voltage for a showt channel device with the following parameters: xdmax = 1_μ, rj = 0.5_μ, doping density of 1.5E15_1/cm^3, substrate bias of 3_V, channel length of 1_μ and an gate oxide capacitance of 230000_pF/cm^2.

Use equation 1.

Given	Result
rj = 0.5_μ	δVT = -0.1143_V
rj = 0.5_μ	
xdmax = 1_μ	
Cox = 230000_pF/cm^2	
L = 1_μ	
φp = 0.3_V	
VSB = 3_V	

Example 2: Compute the change in VT for a narrow channel device in the above example if the channel width is 2_μ.

Use equation 2.

Given	Result
Na = 1.5E15_1/cm^3	δVT = 0.821_V
xdmax = 1_μ	
Cox = 230000_pF/cm^2	
W = 2_μ	

Temperature Effects

Three equations are included under this topic. The first equation repeats the equation for bulk Fermi potential. The second equation tracks the change in bulk

Fermi potential due to temperature changes. The third equation computes changes in threshold voltage due to temperature changes.

$$1.\ \Phi b = \frac{k \cdot T}{q} \cdot LN\left(\frac{NA}{ni}\right)$$

$$2.\ \Delta\Phi b = \frac{1}{T} \cdot \left(\frac{Eg}{2 \cdot q} - \Phi b\right) \cdot \Delta T$$

$$3.\ \Delta VT = \Delta\Phi b \cdot \left(2 + \frac{1}{Cox} \cdot \sqrt{\frac{\varepsilon s \cdot q \cdot NA}{\Phi}}_{b}\right)$$

Variable	Description	Units
ΔΦbo	bulk potential change	1_V
T	temperature	1_K
Eg	band gap	1_eV
NA	doping density	1_1/cm^3
ni	intrinsic density	1_1/cm^3
ΔT	temperature change	1_K
ΔVT	VT change	1_V
Cox	oxide capacitance per unit area	1_F/cm^2
εs	relative permittivity, Si	1
Φb	bulk Fermi potential	1_V

Example 1: Compute the bulk Fermi potential at room temperature for silicon with a doping level of 5E15_1/cm^3. Calculate the change in bulk potential for a 25_ change in temperature. Use 1.4E10_1/cm^3 for intrinsic density and 1.12_eV for band gap.

Solve the problem using equations 1 and 2.

Given	Result
T = 300_K	ϕb = 0.3305_V
NA = 5E15_1/cm^3	Δϕb = 0.0191_V
ni = 1.4E10_1/cm^3	
Eg = 1.12_eV	
ΔT = 25_K	

Example 2: Compute the change in threshold voltage for the example above if the semiconductor used is silicon.

Use equation 3 to solve for ΔVT.

Given	Result
ϕb = 0.3305_V	ΔVT = 0.0424_V
Cox = 230000_pF/cm^2	
NA = 5E15_1/cm^3	
εs = 11.8	
Δϕb = 0.0191_V	
ΔT = 25_K	

MOS Inverter Design

Six topics are included in this categories. The categories include design equations of n-MOS inverter with saturated load, non-saturated load, depletion load and a resistor load. Also included are CMOS inverter and conditions for setting up the circuit.

- Circuit Set-Up
- Saturated Load
- Non-Saturated Load
- Depletion Load
- Resistor Load
- CMOS Inverter

Circuit Set-Up

Four equations are included in this category. the first two equations compute device constants for the driver and the load transistors. The third equation calculates γ, the body coefficient. The fourth equation explicitly specifies the threshold voltage of the load device.

1. $\beta l = \frac{Wl}{Ll} \cdot \left(\frac{\varepsilon ox \cdot \mu n}{tox}\right)$

2. $\beta d = \frac{Wd}{Ld} \cdot \left(\frac{\varepsilon ox \cdot \mu n}{tox}\right)$

3. $\gamma = \frac{tox}{\varepsilon ox} \cdot \sqrt{2 \cdot \varepsilon s \cdot q \cdot Na}$

$$4.\ VtL = Vto + \gamma \cdot \left(\sqrt{Vsb + 2 \cdot \Phi f} - \sqrt{2 \cdot \Phi f}\right)$$

Variable	Description	Units
βl	load device constant	1_A/V^2
Wl	load device width	1_cm
Ll	load device length	1_cm
εox	relative permittivity, oxide	1
tox	oxide thickness	1_cm
βd	drive device constant	1_A/V^2
Wd	driver device width	1_cm
Ld	driver device length	1_cm
γ	body coefficient	1_V^.5
εs	relative permittivity, Si	1
Na	doping density	1_1/cm^3
VtL	threshold voltage for load device	1_V
Φf	Fermi potential	1_V
Vsb	substrate voltage	1_V
μn	mobility	1_cm^2/(V*s)
Vto	zero bias threshold voltage	1_V

Example 1: Find the load and driver constants for an inverter pair where the driver size is 8_μ x 2_μ while the load is 15_μ x 6_μ. Assume that oxide permittivity is 3.9 and electron mobility is 500_cm^2/(V*s), and oxide is 20_nm thick.

Use equations 1 and 2 to compute βl and βd.

Given	Result
Wd = 8_μ	βd = 3.4531E-4_A/V^2
Ld = 2_μ	βl = 1.1510E-4_A/V^2
Ll = 6_μ	
Wl = 15_μ	
μ = 500_cm^2/(V*s)	
tox = 20_nm	

Example 2: Compute body coefficient for silicon oxide MOS structure where the bulk doping is 5E15_1/cm^5.

use equation 3 to solve for γ.

Given	Result
$\varepsilon ox = 3.9$	$\gamma = 0.2370\_V\text{^}.5$
$\varepsilon s = 11.8$	
Na = 5E15_1/cm^3	
tox = 20_nm	

Example 3: Given a threshold change of 0.5_V for the MOS structure above, compute the necessary bias needed for the substrate. Assume that ϕf is 0.33_V.

Vto and Vtl are not specified here, but their difference is specified. Thus we can solve the problem by assuming that Vto = 0_V and Vtl = 0.5_V and use equation 4.

Given	Result
Vto = 0_V	Vsb = 7.8804_V
Vtl = 0.5_V	
ϕf = 0.33_V	
$\gamma = 0.2370\_V\text{^}.5$	

Saturated Load

Five equations listed under this topic cover the primary equations of interest in inverter design. The first equation expresses relationship between input and output voltages by matching currents in the load and the driver transistors. The next two equations model the discharge and charge time for a load capacitor CL. The fourth equation evaluates the average delay time for this inverter. The last equation computes power dissipated in the load device.

1. $$\frac{\beta l}{2} \cdot (Vdd - Vout - Vtl)^2 = \beta d \cdot \left((Vin - Vto) \cdot Vout - \frac{1}{2} \cdot Vout^2\right)$$

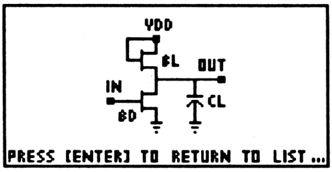
2. $$td = \frac{CL}{\beta d \cdot (V1 - Vto)} \cdot \left(\frac{2 \cdot Vto}{V1 - Vto} + LN\left(\frac{2 \cdot (V1 - Vto)}{Vo} - 1\right)\right)$$

3. $$tc = \frac{CL}{\beta l \cdot (Vdd - Vtl)} \cdot \left(\frac{V1 - Vo}{Vo}\right)$$

4. $$\tau d = \frac{1}{2} \cdot (tc + td)$$

5. $$Pdc = \frac{\frac{1}{2} \cdot Vdd \cdot \beta l}{2} \cdot (Vdd - Vout - Vtl)^2$$

Variable	Description	Units
βl	load device constant	1_A/V^2
βd	driver device constant	1_A/V^2
Vo	output voltage (LOW)	1_V
Vtl	load transistor threshold voltage	1_V
Vto	zero bias threshold	1_V
Vout	output voltage	1_V
Vdd	supply voltage	1_V
Pdc	power in the load	1_W
Vin	input voltage	1_V
td	discharge time	1_s
CL	load capacitance	1_F
V1	output voltage (HIGH)	1_V
tc	charge time	1_s
τd	delay time	1_s



Example 1: Using the transistor pair forming an inverter drives a 0.75_pF capacitive load. Find the charge and discharge times if the logic levels of interest are 2.4_V and 0.8_V.

Assume TTL supply level and use equations 2 and 3 to get the charge and discharge times.

Given	Result
βl = 2.1582E-4_A/V^2	tc = 1.8290E-9_s
βd = 3.4531E-4_A/V^2	td = 2.6965E-9_s
V1 = 2.4_V	
Vo = 0.8_V	
CL = 0.75_pF	
Vdd = 5_V	
Vtl = 1.2_V	
Vto = 0.75_V	

Non Saturated Load

This topic presents six equations covering a load transistor biased so that it operates in the non-saturated or linear region. The first equation expresses relationship between input and output voltages by matching currents in the load and the driver transistors. The next two equations model the discharge and charge time for a load capacitor CL. The concept of a parameter m is introduced in the fourth equation. The fifth equation evaluates average delay time in this inverter. The last equation computes power dissipated in the load device.

1. $$\frac{\beta l}{2}\cdot\left(\left(VGG - Vout - Vtl\right)\cdot\left(Vdd - Vout\right) - \frac{1}{2}\cdot\left(Vdd - Vout\right)^2\right)$$

$$\ldots = \beta d\cdot\left(\left(Vin - Vto\right)\cdot Vout - \frac{1}{2}\cdot Vout^2\right)$$

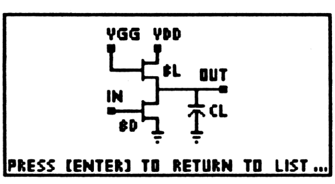
2. $$td = \frac{CL}{\beta d\cdot(V1 - Vto)}\cdot\left(\frac{2\cdot Vto}{V1 - Vto} + LN\left(\frac{2\cdot(V1 - Vto)}{Vo} - 1\right)\right)$$

3. $$tc = \frac{2\cdot CL}{\beta l\cdot Vdd}\cdot\left(\frac{m}{1-m}\right)\cdot LN\left(\frac{\left(1 - \frac{m\cdot V1}{Vdd}\right)\cdot\left(1 - \frac{Vo}{Vdd}\right)}{\left(1 - \frac{m\cdot Vo}{Vdd}\right)\cdot\left(1 - \frac{V1}{Vdd}\right)}\right)$$

4. $$m = \frac{Vdd}{2\cdot(VGG - Vtl) - Vdd}$$

5. $$\tau d = \frac{1}{2}\cdot(tc + td)$$

6. $$Pdc = \frac{\frac{1}{2}\cdot Vdd\cdot\beta l}{2}\cdot(Vdd - Vout - Vtl)^2$$



Variable	Description	Units
βl	load device constant	1_A/V^2
βd	driver device constant	1_A/V^2

Vo	output voltage (LOW)	1_V
Vto	zero bias threshold voltage	1_V
Vtl	thrload transistor threshold voltage	1_V
Vout	output voltage	1_V
VGG	load transistor gate bias	1_V
Vdd	supply voltage	1_V
Vin	input voltage	1_V
Pdc	power in the load device	1_W
td	discharge time	1_s
CL	capacitive load	1_F
V1	output voltage (HIGH)	1_V
tc	charge time	1_s
m	bias parameter	1
τd	delay time	1_s

Example 1: Using the transistor pairs used in the example under saturated load we extend the characterization by converting the load device into a linear mode by applying 12_V bias to its gate. Find the charge and discharge times and the bias parameter m.

Assume TTL supply level and use equations 2, 3 and 4 to get the charge and discharge times.

Given	Result
βl = 2.1582E-4_A/V^2	tc = 2.8733E-10_s
βd = 3.4531E-4_A/V^2	td = 2.6965E-9_s
V1 = 2.4_V	m = 0.3012
Vo = 0.8_V	
CL = 0.75_pF	
Vdd = 5_V	
Vtl = 1.2_V	
Vto = 0.75_V	
VGG = 12_V	

Depletion Load

Five equations listed under this topic cover the primary equations of interest in inverter design. The first equation expresses relationship between input and output voltages by matching currents in the load and the driver transistors. The next two equations model the discharge and charge time for a load capacitor CL. The fourth equation evaluates the average delay time for this inverter. The last equation computes power dissipated in the load device.

1. $$\frac{\beta l}{2} \cdot Vtl^2 = \beta d \cdot \left((Vin - Vto) \cdot Vout - \frac{1}{2} \cdot Vout^2 \right)$$

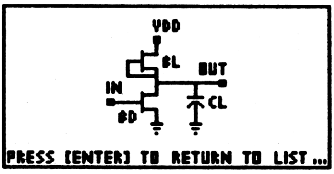
2. $$td = \frac{CL}{\beta d \cdot (V1 - Vto)} \cdot \left(\frac{2 \cdot Vto}{V1 - Vto} + LN\left(\frac{2 \cdot (V1 - Vto)}{Vo} - 1 \right) \right)$$

3. $$tc = \frac{\frac{2 \cdot CL}{\beta l} \cdot (V1 - Vo)}{Vtl^2}$$

4. $$\tau d = \frac{1}{2} \cdot (tc + td)$$

5. $$Pdc = \frac{\frac{1}{2} \cdot Vdd \cdot \beta l}{2} \cdot Vtl^2$$

Variable	Description	Units
βl	load device constant	1_A/V^2
βd	driver device constant	1_A/V^2
Vo	output voltage (LOW)	1_V
Vtl	depletion threshold voltage	1_V
Vout	output voltage	1_V
Vin	input voltage	1_V
Vto	zero bias threshold voltage	1_V
td	discharge time	1_s
CL	load capacitance	1_F
V1	output voltage (HIGH)	1_V
tc	charging time	1_s
τd	delay time	1_s
Pdc	power in the load	1_W
Vdd	supply voltage	1_V
Vto	driver threshold voltage	1_V



Example 1: An inverter is designed with a depletion mode transistor with a geometry of 10_μ x 6_μ and a driver with a device geometry of 10_μ x 2_μ. Assume that the mobility of electrons is 500_cm^2/(V*s). using an output swing of 0.8_V to 2.4_V and a load capacitance of 0.25_pF find the charge and discharge times. The driver transistor has a threshold of 0.75_V and the depletion threshold is -4.0_V.

First of all compute device constants from the MOS transistors using the circuit set-up topic.

Given	Result
tox = 20_nm	βd = 4.3164E-4_A/V^2
Wl = 10_μ	βl = 1.4388E-4_A/V^2
Ll = 6_μ	
Wd = 010_μ	
Ld = 2_μ	
μn = 500_cm^2/(V*s)	
εox = 3.9	

Switch topics to Depletion mode analysis and enter the following values. Equations 2 and 3 in the topic help evaluate the rise and fall times of interest.

Given	Result
βl = 1.43884E-4_A/V^2	tc = 3.4751E-10_s
βd = 3.4531E-4_A/V^2	td = 7.1907E-10_s
V1 = 2.4_V	
Vo = 0.8_V	
CL = 0.25_pF	
Vdd = 5_V	
Vtd = -4_V	
Vto = 0.75_V	

Resistor Load

Five equations set up a MOS inverter with a resistive load. The first equation sets up load current to equal driver current to compute the output voltage. The second and third equation compute the discharge and charging time. The fourth equation calculates the average delay while the last equation covers power dissipated in the load.

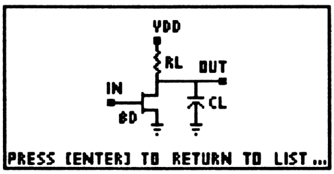
1. $$\frac{Vdd - Vout}{Rl} = \beta d \cdot \left((Vin - Vto) \cdot Vout - \frac{1}{2} \cdot Vout^2\right)$$

2. $$td = \frac{CL}{\beta d \cdot (V1 - Vto)} \cdot \left(\frac{2 \cdot Vto}{V1 - Vto} + LN\left(\frac{2 \cdot (V1 - Vto)}{Vo} - 1 \right) \right)$$

3. $$tc = Rl \cdot CL \cdot LN\left(\frac{Vdd - Vo}{Vdd - V1} \right)$$

4. $$\tau d = \frac{1}{2} \cdot (tc + td)$$

5. $$Pdc = \frac{\frac{1}{2} \cdot Vdd \cdot (Vdd - Vo)}{Rl}$$



Variable	Description	Units
βd	driver device constant	1_A/V^2
Vdd	supply voltage	1_V
Vo	output voltage (LOW)	1_V
Vout	output voltage	1_V
Rl	load resistor	1_Ω
Vin	input voltage	1_V
Vto	zero bias threshold voltage	1_V
td	discharge time	1_s
CL	output capacitance	1_F
V1	output voltage (HIGH)	1_V
tc	charge time	1_s
τd	device delay	1_s
Pdc	power in the load	1_W

Example 1: A 10_kΩ resistor acts as a pull-up load for a MOS inverter whose drive transistor is specified by the example in the previous topic. With a 0.25_pF capacitive load, find the charge and discharge times if the logic levels of interest are 2.4_V and 0.8_V.

Assume TTL supply level and use equations 2 and 3 to get the charge and discharge times.

Given
Rl = 10000_kΩ
βd = 4.3164E-4_A/V^2
V1 = 2.4_V
Vo = 0.8_V
CL = 0.25_pF
Vdd = 5_V
Vto = 0.75_V

Result
tc = 1.1989E-9_s
td = 7.1907E-10_s

CMOS Inverter

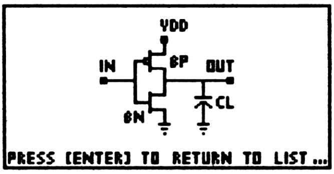
Four equations are included in this topic. The first two define the p-channel and n-channel device constants. The third and fourth equations compute input high and input low voltages that can be achieved using the geometries of the transistor pair.

$$1.\ \beta p = \frac{Wp}{Lp}\cdot \mu p \cdot \left(\frac{\varepsilon ox}{tox}\right)$$

$$2.\ \beta n = \frac{Wn}{Ln}\cdot \mu n \cdot \left(\frac{\varepsilon ox}{tox}\right)$$

$$3.\ ViH = \frac{2\cdot Vout + Vtn + \frac{\beta p}{\beta n}\cdot (Vdd - Vtp)}{1+\frac{\beta p}{\beta n}}$$

$$4.\ ViL = \frac{2\cdot Vout - Vdd - Vtp + \frac{\beta n}{\beta p}\cdot Vtn}{1+\frac{\beta n}{\beta p}}$$



Variable	Description	Units
βp	p transistor device constant	1_A/V^2
Wp	p-channel device width	1_cm
Lp	p-channel transistor length	1_cm
μp	hole mobility	1_cm^2/(V*s)
εox	relative permittivity, oxide	1
tox	oxide thickness	1_cm
βn	n-channel transistor device constant	1_A/V^2
Wn	n-channel transistor width	1_cm
Ln	n-channel transistor length	1_cm
μn	electron mobility	1_cm^2/(V*s)
ViH	input voltage (HIGH)	1_V
Vout	output voltage	1_V
Vtn	n-channel threshold voltage	1_V
Vtp	p-channel threshold voltage	1_V
Vdd	supply voltage	1_V
ViL	input voltage	1_V

Example 1: A CMOS inverter is designed with the following device geometries:

p -channel device: 12_μ x 2_μ, threshold -0.8_V, mobility 200_cm^2/(V*s) n -channel device: 4_μ x 2_μ, threshold 0.8_V, mobility 550_cm^2/(V*s) oxide thickness 20_nm. Find the device constants for n and p channel devices.

Use equations 1 and 2 to find the parameters of interest.

Given	Result
Wp = 10_μ	βn = 1.8992E-4_A/V^2
Lp = 2_μ	βp = 1.7266_A/V^2
Wn = 4_μ	
Ln = 2_μ	
μn = 550_cm^2/(V*s)	
μp = 200_cm^2/(V*s)	
tox = 20_nm	
Vto = 0.75_V	

Example 2: A CMOS inverter is designed with the following device geometries: p -channel device: 12_μ x 2_μ, threshold -0.8_V, mobility 200_cm^2/(V*s) n -channel device: 4_μ x 2_μ, threshold 0.8_V, mobility 550_cm^2/(V*s) oxide thickness 20_nm.

First find the device constants for n and p channel devices using equations 1 and 2 in the topic circuit setup to find the parameters of interest.

Following this step, use equations 3 and 4 in this topic to compute input levels low and high.

Given	Result
Wp = 10_μ	βn = 1.8992E-4_A/V^2
Lp = 2_μ	βp = 1.7266_A/V^2
Wn = 4_μ	
Ln = 2_μ	
μn = 550_cm^2/(V*s)	
μp = 200_cm^2/(V*s)	
tox = 20_nm	
Vto = 0.75_V	
εox = 3.9	

Given	Result
Vtp = -.8_V	ViL = 3.1809_V
Vtn = .8_V	ViH = 3.1809_V
Vdd = 5_V	
Vout = 0_V and 5_V (two cases)	
βn = 1.8992E-4_A/V^2	
βp = 1.7260E-4_A/V^2	
tox = 20_nm	
Vto = 0.75_V	

Junction Transistor I

The main topics included in this category are:

- Ideal BJT
- Base Recombination
- Ebers-Moll Equations
- Early Effect
- Punch-Through/Avalanche

Ideal BJT

Five equations in this topic cover the basic equations of importance in a bipolar transistor. The first equation computes emitter current in terms of device geometry, doping levels and emitter and collector voltages. The second equation calculates collector current in terms of device geometry, doping levels and emitter and collector voltages. The third equation gives base current in terms of device geometry, doping levels and emitter and collector voltages. The last two equations define common emitter and common base current gains in terms of device geometry and doping levels.

1. $IE = ni^2 \cdot q \cdot A \cdot \left(\frac{DE}{NAE \cdot LE} + \frac{DB}{W \cdot NDB}\right) \cdot \left(e^{(q \cdot VEB)/(k \cdot T)} - 1\right) -$

$\ldots \frac{ni^2 \cdot q \cdot A \cdot DB}{W \cdot NDB} \cdot \left(e^{(q \cdot VCB)/(k \cdot T)} - 1\right)$

2. $IC = \frac{ni^2 \cdot q \cdot A \cdot DB}{NDB \cdot W} \cdot \left(e^{(q \cdot VEB)/(k \cdot T)} - 1\right) - ni^2 \cdot q \cdot A \cdot$

$\ldots \left(\frac{DC}{NAC \cdot LC} + \frac{DB}{NDB \cdot W}\right) \cdot \left(e^{(q \cdot VCB)/(k \cdot T)} - 1\right)$

3. $IB = \frac{ni^2 \cdot q \cdot A \cdot DE}{LE \cdot NAE} \cdot \left(e^{(q \cdot VEB)/(k \cdot T)} - 1\right) + \frac{ni^2 \cdot q \cdot A \cdot DC}{LC \cdot NAC} \cdot$

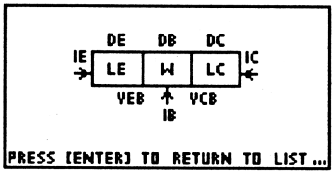
$\ldots \left(e^{(q \cdot VCB)/(k \cdot T)} - 1\right)$

4. $\alpha dc = \frac{1}{1 + \left(\frac{DE}{DB}\right) \cdot \left(\frac{NDB}{NAE}\right) \cdot \left(\frac{W}{LE}\right)}$

5. $\beta dc = \left(\frac{DB}{DE}\right) \cdot \left(\frac{NAE}{NDB}\right) \cdot \left(\frac{LE}{W}\right)$

Variable	Description	Units
IE	emitter current	1_A
ni	intrinsic density	1_1/cm^3
A	junction area	1_cm^2
DE	electron diffusion coefficient	1_cm^2/s
NAE	emitter doping	1_1/cm^3
LE	electron diffusion length	1_cm
DB	base hole diffusion coefficient	1_cm^2/s
W	base width	1_cm
NDB	base doping density	1_1/cm^3

VEB	base-emitter voltage	1_V
T	temperature	1_K
VCB	collector-base voltage	1_V
IC	collector current	1_A
DC	collector hole diff coefficient	1_cm^2/s
NAC	collector doping density	1_1/cm^3
LC	diffusion length electrons	1_cm
IB	base current	1_A
VCB	collector-base voltage	1_V
αdc	common emitter current gain	1
βdc	common base current gain	1



Example 1: A bipolar transistor is constructed from silicon with the following geometry:

Emitter : doping density 6E17_1/cm^3, diffusion length 2_μ and diffusion coefficient 27_cm^2/s.

Base : doping density 4E15_1/cm^3, base width 2.5_μ and diffusion coefficient 10_cm^2/s.

Collector : doping density 1E15_1/cm^3, diffusion length 2.5_μ and diffusion coefficient 32.5_cm^2/s.

Use emitter base voltage of 0.6_V and collector base voltage of -6_V. Assume that the junction area is constant at 1275_μ^2 and the intrinsic density is 1.4E10_1/cm^3. Calculate the ideal emitter, base and collector currents and αdc and βdc.

The problems is solved for the sake of convenience in two steps. In the first step enter the values for input variables and compute the currents IE, IB and IC. In the second step calculate αdc and βdc using the last two equations in this topic.

Given	**Result**
ni = 1.4E10_1/cm^3	IE = 4.9168E-5_A
NAE = 6E17_1/cm^3	IC = 4.8086E-5_A
LE = 2_μ	IB = .0819E-6_A
DE = 27_cm^2/(V*s)	αdc = 0.978

NDB = 4E15_1/cm^3
W = 2.5_μ
DB = 10_cm^2/s
NAC = 1E15_1/cm^3
LC = 2.5_μ
DC = 32.5_cm^2/s
A = 1275_μ^2
VEB = 0.6_V
VCB = -6_V

βdc = 44.44

Base recombination

Three equations cover the essentials of computing impact of recombination currents in the base. The first two equations detail calculation of emitter and collector currents while the third equation summarizes the base current in terms of emitter and collector currents.

$$1.\ IE = \frac{ni^2 \cdot q \cdot A \cdot \left(\frac{DE}{NAE \cdot LE} + \frac{DB}{W \cdot NDB}\right) \cdot \left(e^{(q \cdot VEB)/(k \cdot T)} - 1\right)}{TANH\left(\frac{W}{LB}\right)} - \ldots$$

$$\ldots \frac{ni^2 \cdot q \cdot A \cdot \left(\frac{DB}{LB \cdot NDB}\right) \cdot \left(e^{(q \cdot VCB)/(k \cdot T)} - 1\right)}{SINH\left(\frac{W}{LB}\right)}$$

$$2.\ IC = \frac{ni^2 \cdot q \cdot A \cdot \left(\frac{DB}{NDB \cdot LB}\right) \cdot \left(e^{(q \cdot VEB)/(k \cdot T)} - 1\right)}{SINH\left(\frac{W}{LB}\right)} - \ldots$$

$$\ldots \frac{ni^2 \cdot q \cdot A \cdot \left(\frac{DB}{NDB \cdot LB} + \frac{DC}{NAC \cdot LC}\right) \cdot \left(e^{(q \cdot VCB)/(k \cdot T)} - 1\right)}{TANH\left(\frac{W}{LB}\right)}$$

$$3.\ IB = IE - IC$$

Variable	Description	Units
IE	emitter current	1_A
ni	intrinsic density	1_1/cm^3

A	junction area	1_cm^2
NAE	emitter doping density	1_1/cm^3
DE	diffusion coefficient	1_cm^2/s
LE	diffusion length	1_cm
DB	diffusion coefficient	1_cm^2/s
LB	diffusion length	1_cm
NDB	base doping density	1_1/cm^3
W	base width	1_cm
VEB	base-emitter voltage	1_V
T	temperature	1_K
VCB	base-collector voltage	1_V
IC	collector current	1_A
DC	diffusion coefficient	1_cm^2/s
LC	diffusion length	1_cm
NAC	collector doping density	1_1/cm^3
IB	base current	1_A

Example 1: A bipolar transistor is constructed from silicon with the following geometry:

Emitter : doping density 6E17_1/cm^3, diffusion length 2_μ and diffusion coefficient 27_cm^2/s.

Base : doping density 4E15_1/cm^3, base width 2.5_μ and diffusion coefficient 10_cm^2/s, base diffusion length 1.8_μ.

Collector : doping density 1E15_1/cm^3, diffusion length 2.5_μ and diffusion coefficient 32.5_cm^2/s.

Use emitter base voltage of 0.6_V and collector base voltage of -6_V. Assume that the junction area is constant at 1275_μ^2 and the intrinsic density is 1.4E10_1/cm^3.

Calculate the base recombination current contribution to emitter, collector and base currents.

Given	Result
ni = 1.4E10_1/cm^3	IE = 5.56877E-5_A
NAE = 6E17_1/cm^3	IC = 3.5515E-5_A
LE = 2_μ	IB = 2.0173E-5_A
DE = 27_cm^2/(V*s)	
NDB = 4E15_1/cm^3	
LB = 1.8_μ	
W = 2.5_μ	

DB = 10_cm^2/s
NAC = 1E15_1/cm^3
LC = 2.5_μ
DC = 32.5_cm^2/s
A = 1275_μ^2
VEB = 0.6_V
VCB = -6_V

Ebers-Moll Equations

Twelve equations are included in this topic representing the all the equations of interest in Ebers-Moll formulation of large signal switching properties of bipolar transistors. The equations define forward and reverse currents If and Ir, the three terminal currents IE, IB and IC, saturation current, forward and reverse common base current gains, and collector-emitter voltage when the transistor is fully saturated.

1. $If = Ifo \cdot \left(e^{(q \cdot VEB)/(k \cdot T)} - 1\right)$

2. $Ir = Iro \cdot \left(e^{(q \cdot VCB)/(k \cdot T)} - 1\right)$

3. $IE = If - \alpha R \cdot Ir$

4. $IC = \alpha F \cdot If - Ir$

5. $IB = (1 - \alpha F) \cdot If + (1 - \alpha R) \cdot Ir$

6. $Is = \alpha F \cdot Ifo$

7. $Is = \alpha R \cdot Iro$

8. $\beta F = \dfrac{\alpha F}{1 - \alpha F}$

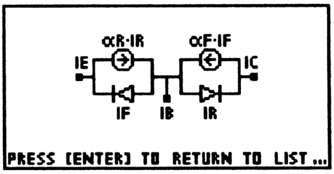
9. $\beta R = \dfrac{\alpha R}{1 - \alpha R}$

10. $ICEO = \dfrac{\alpha F \cdot (1 - \alpha R) \cdot Iro}{1 - \alpha F} + Iro$

11. $ICEO = ICBO \cdot (\beta F + 1)$

12. $$VCEsat=\frac{k\cdot T}{q}\cdot LN\left(\frac{1+\frac{IC}{IB}\cdot(1-\alpha R)}{\alpha R\cdot\left(1-\frac{\frac{IC}{IB}\cdot(1-\alpha F)}{\alpha F}\right)}\right)$$

Variable	Description	Units
If	forward current	1_A
Ifo	forward current constant	1_A
VEB	base-emitter voltage	1_V
T	temperature	1_K
Ir	reverse current	1_A
Iro	reverse current constant	1_A
VCB	collector-base voltage	1_V
IE	emitter current	1_A
αR	reverse current gain	1
IC	collector current	1_A
αF	forward current gain	1
IB	base current	1_A
Is	saturation current	1_A
ICEO	CE leakage at IB=0	1_A
βF	forward current gain	1
ICBO	CB leakage at IB=0	1_A
βR	reverse beta	1
VCEs	CE voltage when fully saturated	1_V



Example 1: The saturation current for a bipolar transistor is 0.05_pA. The forward and reverse α's are 0.98 and 0.12 respectively. Fins forward and reverse current constants.

Use equations 6 and 7 to solve for the appropriate currents.

Given	Result
Is = 0.05_pA	Ifo = 5.102E-14_A

αr = 0.12	Iro = 4.1667E-13_A
αf = 0.98	

Example 2: Continuing the above example, bias the transistor with an emitter base voltage of 0.6_V and a collector base voltage of -5_V. At room temperature compute the forward and reverse currents.

Solve equations 1 and 2 for the parameters in question.

Given	Result
Ifo = 5.102E-14_A	If = 6.1275E-4_A
Iro = 4.1667E-13_A	Ir = -4.1667E-13_A
VEB = 0.6_V	
VCB = -5_V	
T = 300_K	

Example 3: Continue the above example and evaluate IE, IC and IE.

Use equations 3, 4 and 5.

Given	Result
If = 6.1275E-4_A	IE = 6.1275E-4_A
Ir = -4.1667E-13_A	IC = 6.0050E-4_A
αr = 0.12	IB = 1.2255E-5_A
αf = 0.98	

Example 4: Calculate forward and reverse β's and ICEO and ICBO currents.

Use equations 8 and 9.

Given	Result
Iro = 4.1667E-13_A	βf = 49
αf = 0.98	βr = 0.1364
αr = 0.12	ICBO = 3.6767E-13_A
	ICEO = 1.8383E-11_A

Example 5: Calculate the saturation voltage at room temperature for this transistor when acting as a switch. Assume base and collector currents to be 10_mA and 16_mA. Use αf abnd αr from the above example.

Use equation 12 to get the voltage.

Given	Result
T = 300_K	VCEsat = 0.07839_V
IB = 10_mA	
IC = 16_mA	

Early Effect

Four equations are included in this topic. The qualities of interest to compute include effect on saturation current, β and base transit time. Also included is the equation specifying VA.

1. $IS = \dfrac{IS0}{1 + \dfrac{VBC}{VA} + \dfrac{VBE}{VB}}$

2. $\beta f1 = \dfrac{\beta f0}{1 + \dfrac{VBC}{VA} + \dfrac{VBE}{VB}}$

3. $\tau B = \dfrac{\tau B0}{\left(1 + \dfrac{VBC}{VA} + \dfrac{VBE}{VB}\right)^2}$

4. $VA = \dfrac{q \cdot NB \cdot W^2}{\varepsilon s}$

Variable	Description	Units
IS	saturation current	1_A
IS0	ideal saturation current	1_A
VBC	base-collector voltage	1_V
VA	Early voltage	1_V
βf1	forward collector-base current gain	1
βf0	ideal collector-base current gain	1
τB	base transit time	1_s
τB0	ideal base transit time	1_s
VBE	base-emitter voltage	1_V
VB	inverse Early voltage	1_V
NB	base doping density	1_1/cm^3
W	base width	1_cm
εs	relative permittivity, Si	1

Example 1: Calculate Early voltage for a transistor with the following parameters.

Emitter : doping density 6E17_1/cm^3, diffusion length 2_μ and diffusion coefficient 27_cm^2/s.

Base : doping density 4E15_1/cm^3, base width 2.5_μ and diffusion coefficient 10_cm^2/s.

Collector : doping density 1E15_1/cm^3, diffusion length 2.5_μ and diffusion coefficient 32.5_cm^2/s.

Assume that the transistor is made of silicon.

Use equation 4 to compute the Early voltage.

Given	Result
εs = 11.8	VA = 38.3374_V
W = 2.5_μ	
NB = 4E15_1/cm^3	

Example 2: Using the above example, compute βf1 if βf is 49. Assume that VBE is 0.6_V and VBC is 5_V. Reverse Early voltage is assumed to be 50_V.

Use equation 2.

Given	Result
βf = 49	βf1 = 42.8914
VBE = 0.6_V	
VA = 38.3374_V	
VB = 50_V	
VBC = 5_V	

Punch-Thru/Avalanche

The equation listed in this topic describes carrier multiplication characteristic.

$$1.\ M = \frac{1}{1 - \left(\dfrac{VBC}{BVCBO}\right)^{n}}$$

Variable	Description	Units
M	multiplication factor	1
VBC	base-collector voltage	1_V

BVCBO	breakdown voltage CB junction open	1_V
n	power constant	1

Example 1: A base collector junction biased at 9.5_V results in a multiplication factor of 10. Assume that the breakdown voltage is 10_V. Find the power constant in the equation.

Given	Result
M = 10	n = 2.05
VBC = 9.5_V	
BVCBO = 10_V	

Junction Transistor II

Four topics are covered in this category. They are:

- Charge Control
- Turn-On Transient
- Turn-Off Transient
- AC Model

Charge Control

Six equations are listed here to emphasize the key features of the Gummel-Poon charge control model. The first equation computes base charge in terms of charge contributions from the base, emitter-base and collector-base junctions, and effect of applied voltages across each of the junctions. Recombination current in the base as well as forward and reverse currents used in the Ebers-Moll formulation are computed in an alternative form here.

$$1.\ QB = \frac{QBO + QJE + QJC}{2} +$$

$$\sqrt{\left(\frac{QBO+QJE+QJC}{2}\right)^2 + IS \cdot QBO\left(B \cdot \tau F\left(e^{\frac{q \cdot VBE}{k \cdot T}} - 1\right) + \tau R\left(e^{\frac{q \cdot VCB}{k \cdot T}} - 1\right)\right)}$$

$$2.\ Irec = IEB + ICB$$

3. $$IEB = I1 \cdot \left(e^{(q \cdot VBE)/(k \cdot T)} - 1\right) + I2 \cdot \left(e^{(q \cdot VBE)/(meb \cdot k \cdot T)} - 1\right)$$

4. $$ICB = I3 \cdot \left(e^{(q \cdot VBE)/(mcb \cdot k \cdot T)} - 1\right)$$

5. $$If = \frac{IS \cdot QBO \cdot \left(e^{(q \cdot VBE)/(k \cdot T)} - 1\right)}{QB}$$

6. $$Ir = \frac{IS \cdot QBO \cdot \left(e^{(q \cdot VCB)/(k \cdot T)} - 1\right)}{QB}$$

Variable	Description	Units
QB	base charge	1_C
QBO	ideal base charge	1_C
QJE	emitter-base junction charge	1_C
QJC	collector-base junction charge	1_C
IS	saturation current	1_A
B	multiplication factor	1
τF	forward base transit time	1_s
τR	reverse base transit time	1_s
VBE	base-emitter voltage	1_V
VCB	collector-base voltage	1_V
T	temperature	1_K
Irec	base recombination current	1_A
IEB	emitter-base diode current	1_A
ICB	coll-base diode current	1_A
I1	current 1	1_A
I2	current 2	1_A
I3	current 3	1_A
If	ideal forward current	1_A
Ir	ideal reverse current	1_A
meb	emitter-base junction factor	1
mcb	collector-base junction factor	1

Example 1: A bipolar transistor is constructed with the following parameters:

Emitter : emitter base junction charge is 1.5E-10_C,junction voltage 0.6_V.
Collector : collector base junction charge is 1E-10_C,junction voltage is -6_V.

Characteristic currents I1, I2 and I3 are 10E-13_A, 1.5E-13_A and 15E-12_A respectively. Assume all junction factors to be unity, and we are operating at room temperature. Assume that forward and reverse transit time are 5_ns and 3.5_ns and the saturation current is 7E-12_A, ideal base charge is 4E-10_C. Use the multiplication factor B to be 2. Compute base charge, forward and reverse currents and the recombination current.

Use the first equation to compute QB, equations 5 and 6 to compute forward and reverse currents, and equations 3, 4 and 2 to solve for recombination current.

Given	Result
QBO = 4E-10_C	QB = 9.896E-10_C
QJE = 1.5E-10_C	IEB = 1.3811E-2_A
QJC = 1E-10_C	ICB = 0.1801_A
B = 2	Irec = 0.1939_A
IS = 7E-12_A	If = 3.3976E-2_A
VBE = 0.6_V	Ir = -2.829E-12_A
VCB = -6_V	
T = 300_K	
τF = 5_ns	
τR = 3.5_ns	
I1 = 10E-13_A	
I2 = 1.5E-13_A	
I3 = 15E-12_A	
meb = 1	
mcb = 1	

Turn-On Transient

Two equations in this category describe the transient behavior of base current and collector saturation current.

1. $QB = IB \cdot \tau B \cdot \left(1 - e^{-t/\tau B}\right)$

2. $ICsat = \dfrac{IB \cdot \tau B}{\tau t} \cdot \left(1 - e^{-\tau r/\tau B}\right)$

Variable	Description	Units
QB	base charge	1_C
IB	base current	1_A
τB	base charge time	1_s
t	time	1_s

ICsat	collector saturation current	1_A
τt	transit time	1_s
τr	rise time	1_s

Example 1: Compute the collector saturation current given the following information: base current is 10_mA, base charge time 5_ns, rise time is 1.5_ns, and base transit time is 2_ns.

Solve the second equation.

Given	Result
IB = 10_mA	ICsat = 6.4795E-3_A
τB = 5_ns	
τt = 2_ns	
τr = 1.5_ns	

Turn-Off Transient

Turn off time is computed for two important cases, i.e., base current is switched from its initial value to 0 and base current is switched from its initial value to the negative of its initial value.

$$1.\ \tau sd1 = \tau B \cdot LN\left(\frac{IB \cdot \tau B}{ICsat \cdot \tau t}\right)$$

$$2.\ \tau sd2 = \tau B \cdot LN\left(\frac{2 \cdot IB \cdot \tau B}{ICsat \cdot \tau t \cdot \left(1 + \frac{IB \cdot \tau B}{ICsat \cdot \tau t}\right)}\right)$$

Variable	Description	Units
τsd1	switch time for IB→0	1_s
τB	base time	1_s
IB	base current	1_A
ICsat	collector saturation current	1_A
τt	transit time	1_s
τsd2	switch time for IB→ -IB	1_s

Example 1: Compute the turn off time when the base current is switched from IB to 0 and IB to -IB for a transistor with the following parameters.

Base transit time 2_ns, base charge time 5_ns, base current 10_mA, collector saturation current 4_mA.

Solve all equations in the set.

Given	Result
IB = 10_mA	τsd1 = 9.1629_ns
ICsat = 4_mA	τsd2 =2.777236_ns
τB = 5_ns	
τt = 2_ns	

AC Model

Seven equations in this topic evaluate the key small signal parameters for a hybrid pi circuit model.

1. $gm = \frac{\alpha F \cdot q \cdot IE}{k \cdot T}$

2. $g\pi = \frac{q \cdot (1 - \alpha F)}{k \cdot T} \cdot IE$

3. $r\pi = \frac{k \cdot T}{q \cdot (1 - \alpha F) \cdot IE}$

4. $CJC = \frac{CJCO}{\left(1 - \frac{VCB}{Vbi}\right)^m}$

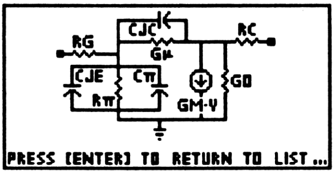
5. $CJE = \frac{CJEO}{\left(1 - \frac{VEB}{Vbi}\right)^m}$

6. $CD = \frac{q \cdot I}{k \cdot T} \cdot \left(\frac{\tau p}{2}\right)$

7. $C\pi = \frac{q \cdot IE}{k \cdot T} \cdot \tau t$

Variable	Description	Units
gm	transconductance	1_A/V
αF	common emitter current gain	1

T	temperature	1_K
IE	emitter current	1_A
$g\pi$	low frequency input conductance	1_S
$r\pi$	low frequency input resistance	1_Ω
CJC	collector-base capacitance	1_F
CJCO	collector-base capacitance at VBC=0_V	1_F
VCB	collector-base voltage	1_V
Vbi	built-in voltage, emitter-base junction	1_V
CJE	emitter-base capacitance	1_F
CJEO	emitter-base at VEB=0	1_F
CD	diode diffusion capacitance	1_F
I	current	1_A
τp	hole lifetime	1_s
$C\pi$	emitter-base jn diffusion capacitance	1_F
τt	base transit time	1_s
m	parameter	1
VEB	emitter-base voltage	1_V



Example 1: Construct a room temperature hybrid π equivalent circuit for the following transistor:

Emitter current is 10_mA, forward α is 0.99, collector base capacitance is 0.25_pF at zero bias, base emitter capacitance is 1_pF at zero bias, base transit time is 2_ns, built-in voltage for the base emitter junction is 0.8_V.

A bias of 0.6_V is applied to the base emitter junction. Assume that hole lifetime is 10_ns and a bias current is 10_mA.

Compute using all equations.

Given	**Result**
αF = 0.99	gm = 0.3791_S
T = 300_K	gπ = 7.7363E-3_S
IE = 10_mA	rπ = 129.2602_Ω
CJCO = 0.25_pF	CJC = 2.9412E-14_F
VCB = -6_V	CJE = 4_pF
Vbi = 0.8_V	CD = 1934.0833_pF

CJEO = 1_pF
I = 10_mA
τp = 10_ns
τt = 2_ns
m = 1
VEB = 0.6_V

Cπ = 773.6333_pF

Microwave Devices

Four microwave device types are included in this category. They categories covered are:

- IMPATT Diode
- Tunnel Diode
- Gunn Diode
- BARITT Diode

IMPATT Diode

Five equations are included in this topic to describe the behavior of IMPATT diodes. The first equation computes breakdown voltage in terms of device parameters. Space charge resistance, frequency of operation and maximum power delivered to a load are parameters awaiting computation in this set.

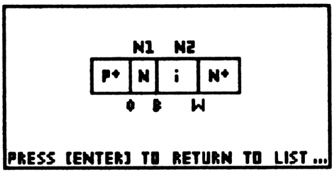
1. $$VB = Em \cdot b + 1.2 \cdot \left(Em - \frac{q \cdot Qo}{\varepsilon s}\right) \cdot (W - b)$$

2. $$W = \frac{\varepsilon s}{q \cdot N2} \cdot \left(Em - \frac{q \cdot Qo}{\varepsilon s}\right) + b$$

3. $$RSC = \frac{(W - xA)^2}{2 \cdot A \cdot \varepsilon s \cdot vs}$$

4. $$f = \frac{vs}{2 \cdot (W - xA)}$$

5. $$Pm = \frac{Em^2 \cdot vs^2}{8 \cdot \pi \cdot Xc \cdot f^2}$$



Variable	Description	Units
VB	breakdown voltage	1_V
Em	maximum electric field	1_V/cm
b	clump width	1_cm
Qo	impurity density in clump	1_1/cm^2
εs	relative permittivity, Si	1
W	depletion region width	1
N2	doping density in region 2	1_1/cm^3
RSC	space charge resistance	1_Ω
xA	avalanche width	1_cm
A	area	1_cm^2
vs	drift velocity	1_cm/s
f	frequency	1_Hz
Xc	capacitive reactance	1_Ω
Pm	maximum input power	1_W

Example 1: Calculate the breakdown voltage for a Reed or IMPUTE diode from the following data: maximum electric field is 1.5E5V/cm, intrinsic region width is 2_μ and clump width is 0.2_μ. The density in the clump is 1.5E-11_/cm^2. Assume the material to be silicon and use 1E15_1/cm^3 as doping density in region 2.

Use the first two equations to solve the problem.

Given	Result
Em = 1.5E5_V/cm	VB = 120.3787_V
Qo = 1.5E-11_/cm^2	W = 6.7610E-6_m
b = 0.2_μ	
N2 = 1E15_1/cm^3	
εs = 11.8	

Example 2: Continuing the above example, compute space charge resistance if the avalanche width is 0.2_μ. Find the frequency if the drift velocity is 1E7_cm/s. Use a diode area of 1200_μ^2.

Use the equations 3 and 4.

Given	Result
εs = 11.8	RSC = 1695.8674_Ω
W = 6.721_μ	f = 7.6675_GHz
xA = 0.2_μ	
A = 1200_μ^2	
vs = 1E7_cm/s	

Tunnel Diode

The single equation included here models the current voltage characteristic in terms of peak and valley voltages and peak and valley current densities.

$$1.\ J = \frac{Jp \cdot V}{Vp} \cdot e^{1-(V/Vp)} + Jv \cdot e^{A2 \cdot (V-Vv)} + Jo \cdot e^{\frac{(q \cdot V)}{(k \cdot T)}}$$

Variable	Description	Units
J	total current density	1_A/cm^2
Jp	peak current	1_A/cm^2
V	applied voltage	1_V
Vp	peak voltage	1_V
Jv	valley current density	1_A/cm^2
A2	constant	1_1/V
Jo	saturation current density	1_A/cm^2
T	temperature	1_K
Vv	valley voltage	1_V

Example 1: A tunnel diode is characterized by the following parameters:

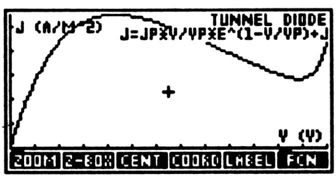
Peak voltage is 0.25_V valley voltage is 0.75_V.

Peak current density is 100000_A/cm^2 while valley current density is 100_A/cm^2. The characteristic constant has a value of 1.6_1/V. Plot the tunnel diode characteristics on the screen and study the negative resistance region of the diode. Assume room temperature operation and that the saturation current density is 1E-9_A/m^2.

Set up the variable as given

Given
Jp = 1E7_A/cm^2
Vp = 0.25_V
Jv = 1_mA/cm^2
T = 300_K
Vv = 0.7_V
A2 = 1.6_1/V
Jo = 1_μA/cm^2

The screen shown below shows a plot of the current voltage characteristic of a tunnel diode. The peak and valley currents and the negative resistance regions are clearly evident in the plot. The parameter ranges chosen for the plot is 0 to 0.75_V on the horizontal axis, while the vertical axis was auto scaled.



Gunn Diode

Eight equations summarize key relationships describing behavior of Gunn diodes. The first three equations describe impact of carrier distribution of light and heavy electrons in the intervally scattering model. The remaining equations focus on device performance parameters such as RF power output, conversion efficiency, domain width excess domain voltage.

1. $$v = \frac{n1 \cdot \mu1 + n2 \cdot \mu2}{n1 + n2} \cdot E$$

2. $$n2 = n1 \cdot R \cdot e^{(-\Delta E)/(k \cdot T)}$$

3. $$v = \frac{\mu1 \cdot E}{1 + R \cdot e^{(-\Delta E)/(k \cdot T)}}$$

4. $$Prf = \frac{\frac{VM - VT}{2} \cdot (IT - IV)}{2}$$

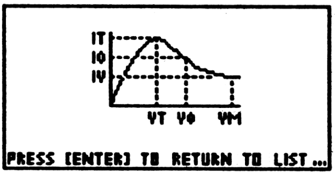
5. $$Po = Vo \cdot Io$$

6. $\eta = \dfrac{Prf}{Po}$

7. $d = \dfrac{\varepsilon s}{q \cdot no} \cdot (Ed - Er)$

8. $Vex = \dfrac{\varepsilon s \cdot (Ed - Er)^2}{2 \cdot q \cdot no}$

Variable	Description	Units
v	drift velocity	1_cm/s
μ1	high mobility	1_cm^2/(V*s)
μ2	low mobility	1_cm^2/(V*s)
n1	light electron density	1_1/cm^3
n2	heavy electron density	1_1/cm^3
E	electric field	1_V/cm
R	density of states ratio	1
ΔE	energy separation	1_eV
T	temperature	1_K
Prf	rf power	1_W
VM	voltage at minima	1_V
VT	threshold voltage	1_V
IT	threshold current	1_A
IV	valley current	1_A
Po	dc power	1_A
Vo	dc voltage	1_V
Io	dc current	1_A
η	conversion efficiency	1
d	domain width	1_cm
εs	relative permittivity	1
no	doping density	1_1/cm^3
Ed	domain field	1_V/cm
Er	outside field	1_V/cm
Vex	excess voltage	1_V



Example 1: Find the domain width for a Gunn diode if the domain field is 1E5_V/cm and outside field is 100_V/cm. Assume that GaAs has a density of 1E15_1/cm^3 and a dielectric constant of 10.9.

Use equation 7.

Given	Result
εs = 10.9	d = 6.0176E-6_m
Ed = 1E5_V/cm	
Er = 100_V/cm	
no = 1E15_1/cm^3	

BARITT Diode

Four equations cover the properties of BARITT diodes.

1. $VRT = \left(\frac{q \cdot ND \cdot W^2}{2 \cdot \varepsilon s}\right) - W \cdot \sqrt{\frac{2 \cdot q \cdot ND \cdot (Vbi - V1)}{\varepsilon s}}$

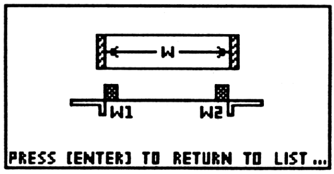
2. $VFB = \frac{q \cdot ND \cdot W^2}{2 \cdot \varepsilon s}$

3. $Jp = Ap \cdot T^2 \cdot e^{\frac{(-q \cdot \Phi Bp)}{(k \cdot T)}} \cdot e^{\frac{(-q \cdot (VFB - V)^2)}{(4 \cdot k \cdot T \cdot VFB)}}$

4. $J = \frac{q \cdot vs \cdot ND \cdot V}{VFB}$

Variable	Description	Units
VRT	reach-thru voltage	1_V
ND	doping density	1_1/cm^3
εs	relative permittivity, Si	1
W	depletion region width	1_cm
Vbi	built-in voltage	1_V
V1	voltage in region 1	1_V
VFB	flat-band voltage	1_V
Jp	thermionic current	1_A
Ap	Richardson's constant	1_A/(cm^2*K^2)
T	temperature	1_K
Φ_{Bp}	barrier potential	1_V
V	applied voltage	1_V
J	current density	1_A/cm^2

vs	drift velocity	1_cm/s



Example 1: Compute the flat band voltage and the current density for a BARITT diode assuming the following. Doping density is 1E15_1/cm^3, applied voltage is 0.95_V, 2_μ depletion region and the material is silicon.

Use equations 2 and 4 to solve this problem. The value of vs has not been specified and we assume a typical value of 1E5_cm/s, a few orders of magnitude below the thermal velocity.

Given	Result
εs = 11.8	VFB = 3.067_V
ND = 1E1‘5_1/cm^3	J = 4.989_A/cm^2
W = 2_μ	
V = 0.955_V	
vs = 1E5_cm/s	

IC Technology

This category covers topics of interest in IC technology.

- Crystal Growth
- Epitaxial Deposition
- Oxidation
- Etching
- Photo lithography
- Dry Etching
- Metalization

Crystal Growth

In this topic we list three equations outlying characteristics of growing a crystal from a melt using Czochralski method.

1. $Cs = ko \cdot Co \cdot (1-x)^{ko-1}$

2. $ke = \dfrac{ko}{ko + (1-ko) \cdot e^{(V \cdot B)/D}}$

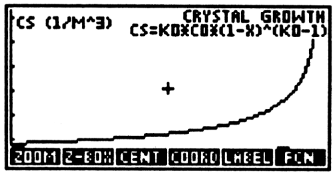
3. $Vmax = \dfrac{ks \cdot \Theta}{L \cdot \rho}$

Variable	Description	Units
Cs	solid concentration	1_1/cm^3
ko	seggregation coefficient	1
Co	init melt concentration	1_1/cm^3
x	solid melt fraction	1
ke	effective seggregation coefficient	1
V	pull rate	1_cm/s
D	melt diffusion coefficient	1_cm^2/s
B	boundary layer thickness	1_cm
Vmax	maximum pull rate	1_cm/s
ks	solid thermal conductivity	1_W/(m*K)
L	heat of fusion	1_J/kg
ρ	density	1_kg/m^3
θ	thermal gradient	1_K/cm

Example 1: Find the solid concentration for a system with an intial concentration of 1E17_1/cm^3, a seggregation coefficient of 0.5, when 50% melt has been converted to a solid.

Use equation 1 to solve; the results are shown below and a plot of Cs is shown as a function of melt fraction.

Given	Result
ko = 0.5	Cs = 7.0711E16_1/cm^3
x = 0.5	
Co = 1E17_1/cm^3	



Epitaxial Deposition

Four equations characterize key relationships for epitaxial growth. The first equation establishes the turbulence level by computing Reynold's number. Boundary layer thickness is computed in the second equation. Reactant flux and film thickness is computed in the last pair of equations.

1. $$Re = \frac{Dr \cdot v \cdot \rho}{\mu}$$

2. $$y = \sqrt{\frac{Dr \cdot x}{Re}}$$

3. $$J = \frac{D \cdot (ng - ns)}{y}$$

4. $$t = \frac{(Pn - .5 + Pi) \cdot Wn}{2 \cdot \left(n^2 - SIN^2(\Theta)\right)}$$

Variable	**Description**	**Units**
Re	Reynold's number	1
Dr	reaction tube diameter	1_cm
v	velocity	1_cm/s
ρ	density	1_g/cm^3
μ	viscosity	1_P
x	distance in the reaction chamber	1_cm
y	boundary layer thickness	1_cm
J	reactant flux	1_1/(cm^2*s)
ng	gas concentration	1_1/cm^3
ns	surface concentration	1_1/cm^3
D	diffusion coefficient in gas	1_cm^2/s
t	epitaxial thickness	1_cm
Pn	order of extrema	1
Pi	correction factor	1

Wn	extremum spectra	1_m
n	refractive index	1
θ	incident light angle	1_°

Example 1: Find the Reynold's number for a a system with a reaction tube diameter of 10_in, a gas density of 0.000005_g/cm^3, flowing at a velocity of 100_ft/s. Assume the viscosity to be 0.1_P.

Use equation 1.

Given	Result
Dr = 10_in	Re = 3.8710
ρ = 0.000005_g/cm^3	
μ = 0.1_P	
v = 100_ft/s	

Oxidation

Five equations describe the oxide growth using the classic models described in semiconductor literature.

1. $xs = \frac{xox \cdot Nox}{Ns}$

2. $xox^2 + A \cdot xox = B \cdot (t + \tau)$

3. $A = 2 \cdot D \cdot \left(\frac{1}{ks} + \frac{1}{hc}\right)$

4. $B = \frac{2 \cdot D \cdot C}{N1}$

5. $\tau = \frac{xi^2 + A \cdot xi}{B}$

Variable	Description	Units
xs	silicon consumed	1_cm
xox	oxide thickness	1_cm
Nox	SiO2 molecular density	1_1/cm^3
Ns	Si molecular density	1_1/cm^3
A	constant	1_cm
B	parabolic constant	1_cm^2/s

D	diffusion coefficient	1_cm^2/s
C	SiO2 concentration	1_1/cm^3
N1	oxidant molecular density	1_1/cm^3
τ	time effective of xi	1_s
xi	initial oxide thickness	1_cm
ks	surface reaction rate constant	1_cm/s
hc	mass transfer coefficient	1_m/s
t	time	1_s

Example 1: Find the thickness of silicon consumed in thermal oxidation for a 0.5_μ thick oxide growth. Assume that molecular density of silicon is 4.901E22_1/cm^3 while the value for SiO2 is 2.208E22_1/cm^3.

Use equation 1.

It is useful to recognize how the values used for Nox and Ns were deduced. Remember that molecular weight of Si is 28_g/mol while molecular weight of SiO2 is 60_g/mol. The density of these is 2.28_g/cm^3 and 2.2_g/cm^3 respectively. Convert this information to molecular density of Si and SiO2 using the fact that one mole of any substance contains a fixed number of molecules represented by the Avogadro's number.

Given	Result
xox = 0.5_μ	xs = 0.2253_μm
Nox = 2.208E22_1/cm^3	
Ns = 4.901E22_1/cm^3	

Example 2: Find the oxide thickness grown in 1 hour for silicon at 1200_°C when an initial oxide layer of 5_nm was formed on the material. Use 0.05_μ for constant A and 0.27_μ^2/h is the parabolic constant.

Use equations 2 and 5. First calculate τ using equation 5 and substitute in equation 2. This is done by solving this set together.

Given	Result
xi = 5_nm	τ = 3.6667_s
t = 3600_s	xox = 0.4955_μ
A = 0.05_Gm	
B = 0.27_μ^2/h	

Etching

Six equations are included in this describing wet etch characteristics. Computations include minimum geometry length, degree of anisotropy, total etch time, uniform etch characteristic, mask edge recession and selectivity parameter.

1. $$l = df \cdot \left(1 - \frac{2 \cdot hf}{df} \cdot (1 - Af)\right)$$

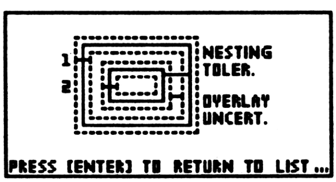
2. $$Af = 1 - \frac{rl}{rv}$$

3. $$tt = \frac{hf}{rf} \cdot \left(\frac{(1+\delta)\cdot(1+\Delta)}{1-\varphi f}\right)$$

4. $$Ufm = \frac{(1+\delta)\cdot(1+\Delta)\cdot(1-\varphi m)}{1-\varphi f}$$

5. $$W = \frac{\frac{2 \cdot rv}{rf} \cdot hf \cdot (1-\delta)\cdot(1-\Delta)}{1-\varphi f} \cdot \left(\frac{1}{TAN(\Theta)} + \frac{rl}{rv}\right)$$

6. $$Sfm = \frac{hf}{W} \cdot Ufm \cdot \left(\frac{1}{TAN(\Theta)} + (1 - Am)\right)$$



Variable	Description	Units
l	minimum feature length	1_cm
df	final dimension	1_cm
hf	mean film thickness	1_cm
Af	anisotropy degree	1
rl	lateral etch rate	1_cm/s
rv	vertical etch rate	1_cm/s
tt	total etch time	1_s
rf	mean etch rate	1_cm/s

δ	thick variation parameter	1
Δ	fraction over etch time	1
φr	rate variation parameter	1
Ufm	uniformity factor	1
ϕm	mask uniformity etch rate parameter	1
W	mask edge recession	1_cm
θ	resist angle	1_°
Sfm	selectivity of film	1
Am	etch anisotropy, mask	1

Example 1: Compute the degree of anisotropy for a system where the vertical rate is 3 times the lateral etch rate.

Solve the problem using equation 2. Exact values are not given for rl and rv but relative values are. Use rl =1 and rv becomes 3.

Given	Result
rl = 1_cm/s	Af = 0.6667
rv = 3_cm/s	

Photo lithography

Four equations in this category focus on nesting tolerance, mask modulus, contrast and number of pixels.

$$1.\ T = 3 \cdot \sqrt{\left(\frac{\sigma f1}{2}\right)^2 + \left(\frac{\sigma f2}{2}\right)^2 + \sigma r^2}$$

$$2.\ Mm = \frac{Imax - Imin}{Imax + Imin}$$

$$3.\ C = \frac{Imax}{Imin}$$

$$4.\ Nm = \frac{S \cdot Lp^2}{q}$$

Variable	Description	Units
T	nesting tolerance	1
σf1	level 1 tolerance	1
σf2	level 2 tolerance	1

σr	register tolerance	1
Mm	mask modulus	1
Imax	maximum intensity	1
Imin	minimum intensity	1
C	contrast	1
S	dosage	1_C/cm^2
Lp	pixel dimension	1_cm
Nm	pixels	1

Example 1: Compute the nesting tolerance and mask modulus for a photo masking system where the level 1 and 2 tolerances are 20% and 25%. Use 25% for register tolerance. The intensity ranges from a low of 2 to a high of 4.

Use equations 1 and 2.

Given	Result
σf1 = 0.2	T = 0.8906
σf2 = 0.25	Mm = 0.3333
σr = 0.25	
Imax = 4	
Imin = 2	

Dry Etching

This topic is covered by two equations computing residence time and etch rate.

1. $tr = \frac{V}{F} \cdot \left(\frac{p}{STP}\right)$

2. $R = \frac{\beta \cdot \tau \cdot G}{1 + K \cdot \beta \cdot \tau \cdot \theta}$

Variable	Description	Units
tr	residence time	1_s
V	plasma volume	1_cm^3
p	pressure	1_Pa
F	flow rate	1_cm/s
R	etch rate	1_cm/s
β	reaction rate constant	1_cm/s
τ	lifetime	1_s
G	generation rate	1_1/s

K	constant	1_1/cm^3
ϕ	etchable surface area	1_cm^2

Example 1: Calculate residence time for a plasma etc system where the pressure is 1.5_Pa, flow rate of 15_cm^3/s in a plasma volume of 125_cm^3.

STP in the equation refers to pressure at standard temperature.

Given	Result
V = 125_cm^3	tr = 1.2337E-4_s
p = 1.5_pa	
F = 15_cm^3/s	

Metallization

Three equations describe depletion rate under three conditions.

1. $D = \dfrac{Rt}{4 \cdot \pi \cdot ro^2}$

2. $D1 = \dfrac{Do}{\left(1 + \left(\dfrac{L}{H}\right)^2\right)^2}$

3. $D2 = \dfrac{Do}{\left(1 + \left(\dfrac{L}{H}\right)^2\right)^{1.5}}$

Variable	Description	Units
D	depletion rate	1_kg/(m^2*s)
Rt	loss rate	1_kg/s
D1	depletion rate	1_kg/(m^2*s)
Do	depletion rate, H away	1_kg/(m^2*s)
L	distance from substrate	1_cm
H	distance from source	1_cm
D2	depletion rate, small source	1_kg/(m^2*s)
ro	spherical dome radius	1_cm

Example 1: Calculate the depletion rate for a spherical dome 12_cm radius. Assume that loss rate is 0.1_g/s.

Use equation 1.

Given	Result
Rt = .1_g/s	D = 4.6052E-3_kg/(m^2*s)
ro = 12_cm	

Chapter 4

Reference Data

In This Chapter

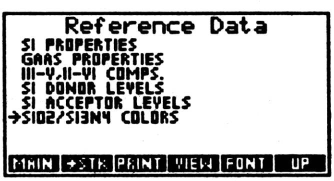
Reference Data serves as an electronic lookup table containing important properties of common semiconductor materials. This section contains information in the following subjects:

- ☐ Silicon Properties
- ☐ GaAs Properties
- ☐ II-V and II-VI Compounds
- ☐ Silicon Donor levels
- ☐ Silicon Acceptor levels
- ☐ SiO2/Si3N4 Colors

Using Reference Data

To get to the Reference Data section, follow these steps:

1. Press [⬅] [LIBRARY] to display all libraries available to the HP 48SX.
2. Find and press SSELE to enter the Solid State Electronics library directory.
3. Press the first softkey, SSELE, to start the application.
4. At the Main menu, move the arrow to Reference Data using the [▼] key and press [ENTER]. The screen below shows the six main subjects containing reference data.



Items in the Reference Data Menu

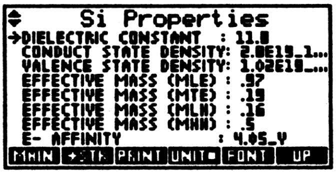
Each entry in the Reference Data menu is described below along with a summary of functions available to the user via soft keys.

Summary of Operations

Key	Action
FONT	Toggles between the small and large fonts.
MAIN	Returns to the Main menu.
PRINT	Prompts for ONE or ALL to select items, and then sends those items to an IR printer.
→STK	Prompts for ONE or ALL to select items, and then copies those items to the stack. The items are placed in a list if ALL was chosen.
UP	Moves up one level in the menu structure.
VIEW	displays the entire text of an item too wide to fit on the screen, up to one entire screen size. If the item fits on the screen, this key is non-functional.
ATTN	Quits the Solid State Pac to the HP 48SX stack.
ENTER	Moves down one level in the menu structure.
ON MTH	Dumps the current screen to an IR printer.

Silicon Properties

Upon choosing Si Properties from the Reference Data menu, the following screen appears:

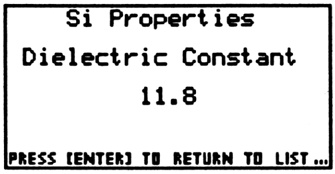


Twenty eight properties of silicon are listed in this table in four screens. The properties listed are:

- ☐ Atoms
- ☐ Atomic weight
- ☐ Breakdown field
- ☐ Crystal structure
- ☐ Density
- ☐ Dielectric constant
- ☐ Conduction band density of states
- ☐ Valence band density of states
- ☐ Longitudinal effective mass, electrons
- ☐ Transverse effective mass, electrons
- ☐ Light hole effective mass
- ☐ Heavy hole effective mass
- ☐ Electron affinity
- ☐ Bandgap at 300_K
- ☐ Intrinsic carrier concentration
- ☐ Lattice constant
- ☐ Thermal Expansion Coefficient
- ☐ Melting Point
- ☐ Minority Carrier Life
- ☐ e- Mobility
- ☐ Hole Mobility
- ☐ Raman Phonon Energy
- ☐ Specific Heat
- ☐ Thermal Conductivity
- ☐ Thermal Diffusivity
- ☐ Vapor Press (1600_°C)
- ☐ Vapor Press (930_°C)
- ☐ Work Function

NOTE: The values are unjustified because the small font is proportionally spaced; switching to the large font will align the numerical data in the same column.

Example: Look up the value of dielectric constant of Silicon. First, move the arrow down to dielectric constant by pressing [↰][▼]. Now, press UNITS to turn on units.

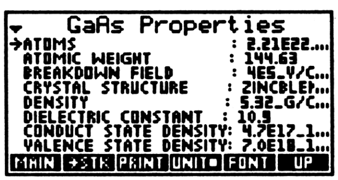


Press [STO] to save the data to the stack as a tagged object, or [ENTER] or [ATTN] to return to the Si Properties menu without saving the data on the stack.

> **NOTE: Toggling units at the Si Properties screen changes the same user flag as does toggling units at the solver screen, so changes to the units setting here will persist if you later return to the solver screen.**

GaAs Properties

Upon choosing GaAs Properties from the Reference Data menu, the following screen appears:



Twenty eight properties of Gallium Arsenide are listed in this table in four screens. The properties listed are:

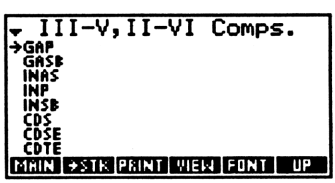
- ☐ Atoms
- ☐ Atomic weight
- ☐ Breakdown field
- ☐ Crystal structure
- ☐ Density
- ☐ Dielectric constant
- ☐ Conduction band density of states
- ☐ Valence band density of states
- ☐ Longitudinal effective mass, electrons

- ☐ Transverse effective mass, electrons
- ☐ Light hole effective mass
- ☐ Heavy hole effective mass
- ☐ Electron affinity
- ☐ Bandgap at 300_K
- ☐ Intrinsic carrier concentration
- ☐ Lattice constant
- ☐ Thermal Expansion Coefficient
- ☐ Melting Point
- ☐ Minority Carrier Life
- ☐ e- Mobility
- ☐ Hole Mobility
- ☐ Raman Phonon Energy
- ☐ Specific Heat
- ☐ Thermal Conductivity
- ☐ Thermal Diffusivity
- ☐ Vapor Press (1600_°C)
- ☐ Vapor Press (930_°C)
- ☐ Work Function

> **NOTE: The values are unjustified because the small font is proportionally spaced; switching to the large font will align the numerical data in the same column.**

II-V, II-VI Compounds

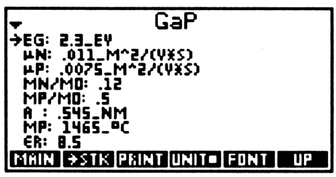
Upon choosing II-V, II-VI Compounds from the Reference Data menu, the following screen appears:



A list of II-V and II-VI compounds whose properties are available is shown in the screen above. The compounds covered include GaP, GaSb, InAs, InP, InSb, CdS, CdSe, CdTe,ZnS, ZnSe and ZnTe. The properties listed are

- ☐ Eg, energy band gap
- ☐ µn, electron mobility
- ☐ µp, hole mobility
- ☐ mn/me, effective mass of electrons
- ☐ mp/me, effective mass of holes
- ☐ a, lattice constant
- ☐ MP, melting point
- ☐ εr, dielectric constant
- ☐ density

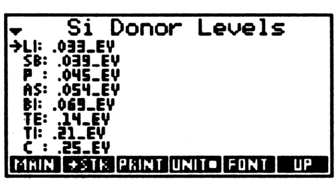
The properties of the semiconductor materials listed above are accessed by pressing selecting the material by moving the pointer using the ▼ and pressing ENTER. The properties are accessed as described previously.

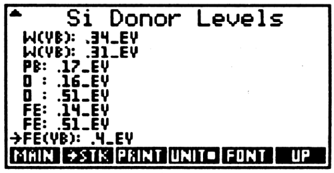


NOTE: The uppercase and lower-case letters alternate columns, due to limitations of the pixel resolution of the HP 48SX screen.

Si Donor Levels

Upon choosing Si Donor Levels from the Reference Data menu, the following screen appears:



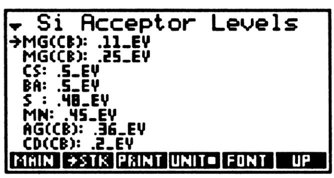


The screen shows a list of donors followed by an energy level. Forty eight donors have been listed in this table. On occasion, you find the donor name followed by (VB). This indicates that the donor energy level is referenced to the valence band rather than the conduction band.

Data access is the same as described previously.

Si Acceptor Levels

Upon choosing Si Acceptor Levels from the Reference Data menu, the following screen appears:

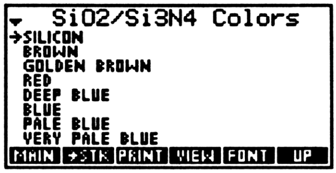


The screen shows a list of acceptors followed by an energy level. Thirty nine acceptors have been listed in this table. On occasion, you find the acceptor name followed by (CB). This indicates that the acceptor energy level is referenced to the conduction band rather than the valence band.

Data access is the same as described previously.

SiO2/SiN3 Colors

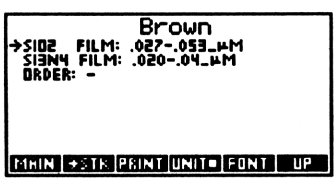
Upon choosing SiO2/Si3N4 Colors from the Reference Data menu, the following screen appears:



Nineteen categories are listed here under which SiO2/Si3N4 film colors are tabulated. The items listed are

- ☐ Silicon
- ☐ Brown
- ☐ Golden Brown
- ☐ Red
- ☐ Deep Blue
- ☐ Blue
- ☐ Pale Blue
- ☐ Very Pale Blue
- ☐ Silicon
- ☐ Light yellow
- ☐ Yellow
- ☐ Orange Red
- ☐ Red
- ☐ Dark Red
- ☐ Blue
- ☐ Blue-Green
- ☐ Light Green
- ☐ Orange Yellow
- ☐ Red

Light Green and pressing [ENTER] the following screen appears.



The data is be accessed as described previously.

Chapter 5
Constant Library

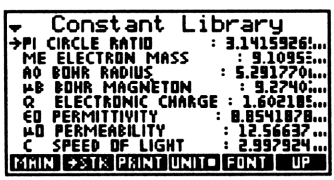
In This Chapter

Constants Data serves as an electronic lookup table containing important constants used by scientists in solid state electronics.

Using Constant Library

To get to the Constant Library section, follow these steps:

1. Press [↰] [LIBRARY] to display all libraries available to the HP 48SX.
2. Find and press [SSELE] to enter the Solid State library directory.
3. Press the first softkey, [SSELE], to start the application.
4. At the Main menu, move the arrow to Constant Library using the [▼] key and press [ENTER]. The screen shown below shows a listing of the constants library available to the user.



Items in the Constants Library Menu

Each entry in the Constants Library Data menu is described below along with a summary of functions available to the user via soft keys.

Summary of Operations

Key	Action
[FONT]	Toggles between the small and large fonts.

MAIN	Returns to the Main menu.
PRINT	Prompts for ONE or ALL to select items, and then sends those items to an IR printer.
→STK	Prompts for ONE or ALL to select items, and then copies those items to the stack. The items are placed in a list if ALL was chosen.
UP	Moves up one level in the menu structure.
VIEW	Displays the entire text of an item too wide to fit on the screen, up to one entire screen size. If the item fits on the screen, this key is non-functional.
ATTN	Quits the Solid State Pac to the HP 48SX stack.
ENTER	Moves down one level in the menu structure.
ON MTH	Dumps the current screen to an IR printer.

Listing of all Constants.

The list below is a complete listing of all the constants available to the user by the Solid State card.

Seventeen constants are listed in our library. They are

- ☐ Pi, Circle ratio
- ☐ me, electron mass
- ☐ ao, Bohr radius
- ☐ µB, Bohr magneton
- ☐ q, electronic charge
- ☐ εo, permittivity of vacuum
- ☐ µo, permeability of vacuum
- ☐ c, speed of light
- ☐ h, Plank's constant
- ☐ hb, Dirac's constant
- ☐ k, Boltzmann's constant
- ☐ Stefan-Boltzmann's constant
- ☐ c1, 1st radiation constant
- ☐ c2, 2nd radiation constant
- ☐ NA, Avogadro's number

- ☐ R, molar gas constant
- ☐ molar volume at STP

> **NOTE: The values are unjustified because the small font is proportionally spaced; switching to the large font will align the numerical data in the same column.**

Example: Look up the value of q, the electronic charge. First, move the arrow down to q by pressing [←][▼]. Now, press [UNITS] to turn on units.

```
   Constant Library
 q  electronic charge
   1.6021892E-19_C

PRESS [ENTER] TO RETURN TO LIST...
```

Press [STO] to save the data to the stack as a tagged object, or [ENTER] or [ATTN] to return to the Constants Library menu without saving the data on the stack.

> **NOTE: Toggling units at the Constant Library screen changes the same user flag as does toggling units at the solver screen, so changes to the units setting here will persist if you later return to the solver screen.**

User Access to constants

The user can access the constants from the constants library using the function SCON outside the application card. For example, to access the speed of light, simply type '$c' and type SCON. The user can access these constants as a part of any program by using the function SCON($c).

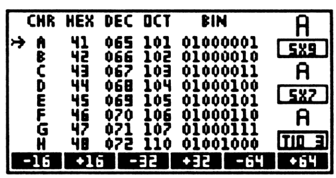
Notes:

Chapter 6
ASCII Table

Using ASCII Table

To get to the ASCII table section, follow these steps:

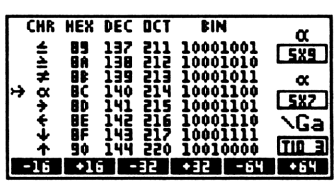
1. Press [⬅] [LIBRARY] to display all libraries available to the HP 48SX.
2. Find and press SSELE to enter the Solid State library directory.
3. Press the second softkey, ASCII, to start the ASCII table application.
4. At the Main menu, move the arrow to ASCII Table using the [▼] key and press [ENTER]. The screen below shows the ASCII table screen:



This function displays hexadecimal, octal, binary and ASCII equivalents for the decimal numbers 0 through 255.

Example:

Suppose you want to find the binary equivalent of the ASCII α character. Enter the ASCII Table, The first screen displays characters at decimal number 065 (although ASCII characters beginning at decimal 0 are available). Use the [▼] cursor key to scroll down the list until you find the α character (decimal 140). Look under the BIN heading to find the binary equivalent of α.



Since the search mode is not available in the ASCII table, you need to use the -16 +16 -32 +32 -64 +64 softkeys to jump forward or backward 16, 32, or 64 characters at a time.

The HP48SX Character Set

The top two boxes at the far right of the ASCII listing display the selected character in the HP 48SX small (5X7) and medium (5X9) fonts. The third box displays the I/O character and translate code setting required to download data from a personal computer to the HP 48SX. (See the *HP 48SX Owner's Manual* for complete instructions.)

To quit the ASCII Table application simply press the ATTN key

Appendix A
Warranty and Service

Pocket Professional Support

You can get answers to your questions about using your Pocket Professional card from Sparcom. If you don't find the information in this manual or in the HP 48SX *Owner's Manual*, contact us in writing, at :

Sparcom Corporation
Attn: Technical Support Dept.
897 NW Grant Avenue, Corvallis, OR 97330, U.S.A. (503) 757-8416

or send E-mail:

from **Internet:**	support@sparcom.com
from **Compuserve:**	>Internet:support@sparcom.com
from **FidoNet:**	To:support@sparcom.com

Limited One-Year Warranty

What Is Covered

The Pocket Professional is warranted by Sparcom Corporation against defects in material and workmanship for one year from the date of original purchase. If you sell your card or give it as a gift, the warranty is automatically transferred to the new owner and remains in effect for the original one-year period. During the warranty period, we will repair or replace (at no charge) a product that proves to be defective, provided you return the product and proof of purchase, shipping prepaid, to Sparcom.

What Is Not Covered

This warranty does not apply if the product has been damaged by accident or misuse or as the result of service or modification by any entity other than Sparcom Corporation.

No other warranty is given. The repair or replacement of a product is your exclusive remedy. ANY OTHER IMPLIED WARRANTY OF MERCHANTABILITY OR FITNESS IS LIMITED TO THE ONE-YEAR DURATION OF THIS WRITTEN WARRANTY. IN NO EVENT SHALL SPARCOM CORP. BE LIABLE FOR CONSEQUENTIAL DAMAGES. Products are sold on the basis of specifications applicable at the time of manufacture. Sparcom shall have no obligation to modify or update products, once sold.

If the Card Requires Service

Sparcom will repair a card, or replace it with the same model or one of equal or better functionality, whether it is under warranty or not.

Service Charge

There is a fixed charge for standard out-of-warranty repairs. This charge is subject to the customer's local sales or value-added tax, wherever applicable. Cards damaged by accident or misuse are not covered by fixed charges. These charges are individually determined based on time and material.

Shipping Instructions

If your card requires service, ship it to Sparcom Corporation, 897 NW Grant Avenue, Corvallis, OR 97330, U.S.A.

- Include your return address and a description of the problem.
- Include proof-of-purchase date if the warranty has not expired.
- Include a purchase order, along with a check, or credit card number and expiration date (VISA or MasterCard) to cover the standard repair charge.
- Ship your card, postage prepaid, in adequate protective packaging to prevent damage. Shipping damage is not covered by the warranty, so insuring the shipment is recommended.

Cards are usually serviced and reshipped within five working days.

Environmental Limits

The reliability of the Pocket Professional depends upon the following temperature and humidity limits:

- Operating temperature: 0 to 45 °C (32 to 113 °F).
- Storage temperature: -20 to 60 °C (-4 to 140 °F).
- Operating and storage humidity: 90% relative humidity at 40 °C (104 °F) maximum.

Notes:

Appendix B
Summary of Operations

Key	Action
ABOUT	Displays a screen containing the revision number and product information about the Solid State Pac. Pressing any key erases the screen and returns to the previous menu or to the HP 48SX stack.
AREA	Displays the area under the function defined by the X axis value of the mark and cursor.
CALC	Stores variable values and systematically iterates through the set of marked equations in an attempt to find values for all wanted variables. Also, stores the known and found values into global variables in the SSELED directory.
CENT	Redraws the plot with the cursor position at the center of the screen.
CLEAR	Resets values of the current variables to zero, but does not change the global copies, which only change during CALC operations.
CONV	Converts a variable to different units, if units are on.
COORD	Displays the coordinates of the cursor position.
EQNS	Displays the equation screen for the current topic.
EQWR	Displays the selected equation in the EquationWriter.
EXIT	Returns to the Graphics environment menu.
EXTR	Moves the cursor to the nearest extremum on the function.
F'	Plots the first derivative of the function.
F(X)	Displays the function value at the X axis value of the cursor, and moves the cursor to that point on the function.
FCN	Displays the Function menu for analyzing function plots.
FONT	Toggles between the small and large fonts.

HALT	Halts the Pac so that operations can be performed on the HP 48SX stack. Pressing CONT or ⬅ ON returns to the Pac, while pressing KILL or PRG CTRL KILL terminates the Pac.
KEYS	Toggles display of the softkeys on and off.
KNOW	Toggles the selected variable between known and unknown status, adding or removing a triangular tag.
MAIN	Returns to the Main menu.
MARK	If at the equations screen, toggles the selected equation between marked and unmarked status, adding or removing a triangular tag. Only variables in the marked set of equations will appear in the solver and variable screens. If no equations are marked, all will be used. If in the Graphics environment, places a mark (X) at the cursor location.
PICT	Displays a picture for the current item, if one exists.
PLOT	Plots the selected equation, prompting for x-axis and y-axis values. Plotting is only allowed for equations of the form y=f(a,b,...), where all but one of the variables on the right-hand side of the equation are held constant (i.e., known).
PRINT	Prompts for ONE or ALL to select items, and then sends those items to an IR printer.
PURGE	Purges the global copies (in the SSELED subdirectory) of the current set of variables, but does not change the values currently set inside the Pac.
QUIT	Quits the Solid State Pac to the HP 48SX stack.
REPL	Pastes in a graphics object (GROB) from the stack at the cursor location.
ROOT	Moves the cursor to the nearest root and displays the coordinate of the root.
SLOPE	Displays the slope of the function at the X axis value of the cursor, and moves the cursor to the point at which the slope was calculated.
SOLVE	Displays the solver screen of the current topic for the Pac, or starts an item-specific solving process for other sections.

→STK	Prompts for ONE or ALL to select items, and then copies those items to the stack. The items are placed in a list if ALL was chosen.
SUB	Copies the rectangle bounded by the mark and the cursor location to the stack as a graphics object (GROB).
UNIT■	Indicates that units are currently turned on. Pressing this key turns off units, automatically converting all variable values to SI units and then stripping the units. For the Constants Library, no conversion is necessary.
UNITS	Indicates that units are currently turned off. Pressing this key turns on units, automatically appending standard SI units to the values or constants.
up	Moves up one level in the menu structure.
VARS	Displays the variable screen for the current topic, including descriptions and default units.
VIEW	Displays the entire text of an item too wide to fit on the screen, up to one entire screen size. If the item fits on the screen, this key is non-functional.
WANT	Toggles the selected variable between wanted and unwanted status, adding or removing a question mark tag.
Z-BOX	Zooms in on the rectangle defined by the mark and the cursor.
ZOOM	Displays the ZOOM menu, which rescales and recenters the plot.
[α]	Enters the search screen mode, whereby the user can search the current menu for a particular string. Pressing [ATTN] aborts the search operation.
[ATTN]	If pressed at a menu, [ATTN] quits the Solid State Pac to the HP 48SX stack. If pressed at most other times, [ATTN] aborts the current operation and returns to the last menu displayed.

ENTER	In general, ENTER "zooms in" on the selected item. For equations, ENTER builds and displays the EquationWriter form of the equation. For functions, ENTER executes the selected function. For menu choices, ENTER moves down one level in the menu structure. For pictures, ENTER displays the picture. For text, ENTER displays the screen title, the item label, and the item, all expanded to one screen. For variables, ENTER prompts for a value for the variable.
ON MTH	Dumps the current screen to an IR printer.
↱ ARG	Displays the entire text of an item too wide to fit on the screen, up to one entire screen size. Once the full text has been displayed, pressing ENTER or ATTN returns to the menu. If the item fits on the screen, this key is non-functional.

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Notes:

Sparcom

Sparcom Corporation
897 NW Grant Avenue
Corvallis, OR 97330

To order any **Sparcom** product that your retailer does not carry,
call: (503) 757-8416 or FAX (503) 753-7821