SimuLED Tutorials

STR-Group Ltd
March, 2016

Tutorial 1

SiLENSe 5.10 & SiLENSe Laser Edition 5.10

Specifying a New Problem in SiLENSe:

Simulation of InGaN MQW LED Heterostructure

Creating a new project for InGaN MQW heterostructure

This tutorial shows how to create a new project similar to 'MQW-example' supplied with the software, specify all necessary input data, run simulations, and prepare input data for SpeCLED. It includes the following steps:

Step 1: Choosing material data and creating new project

Step 2: Specification of the heterostructure layers

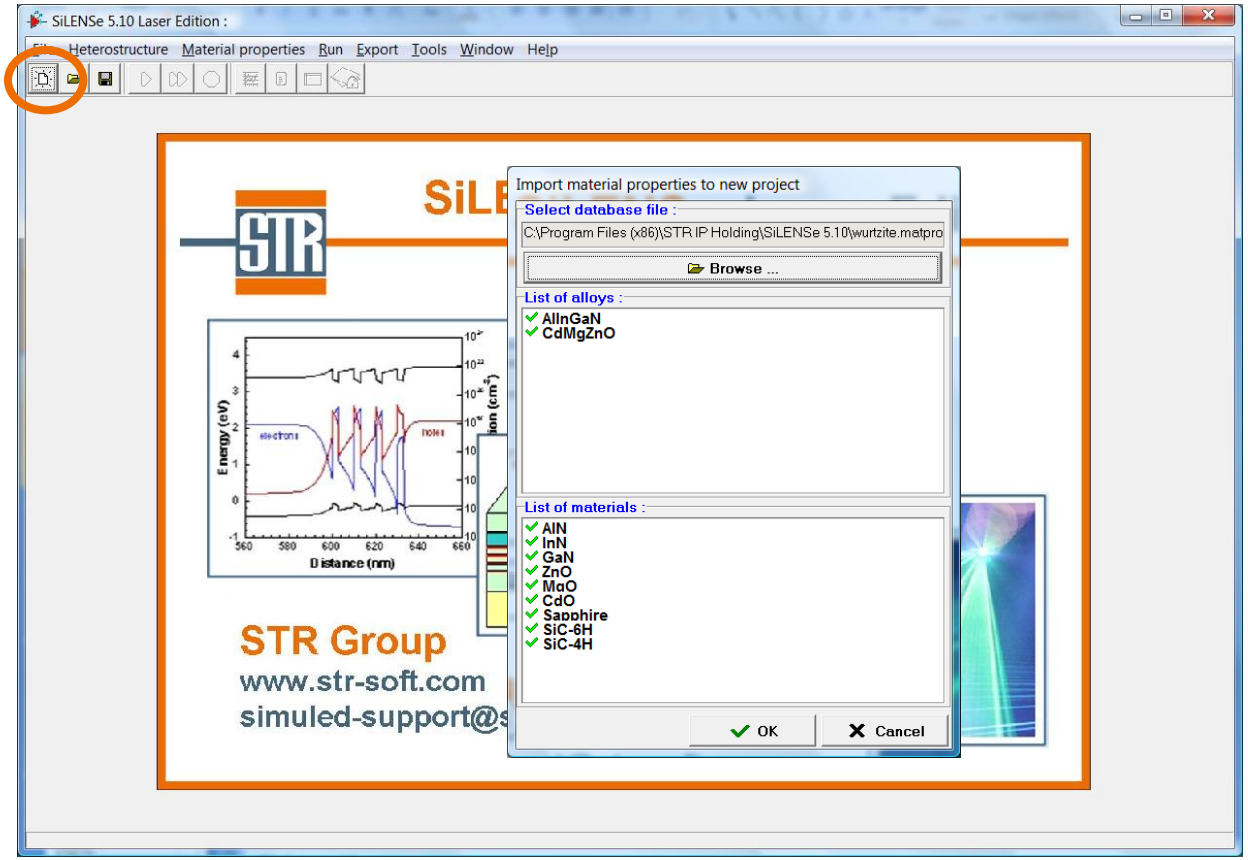
Step 3: Specification of global parameters (like temperature)

Step 4: Simulation of the band diagram, carrier concentration, carrier transport; inspecting results

Step 5: Simulation of carrier energy levels, wave functions, and emission spectrum; inspecting results

Step 6 (optional): Preparing input data for SpeCLED

Step 1: Creating a new project



1. Open SiLENSe and press **New** button from the toolbar.

A modal window appears where the user is prompted to browse a database file (*.matprop) with materials properties.

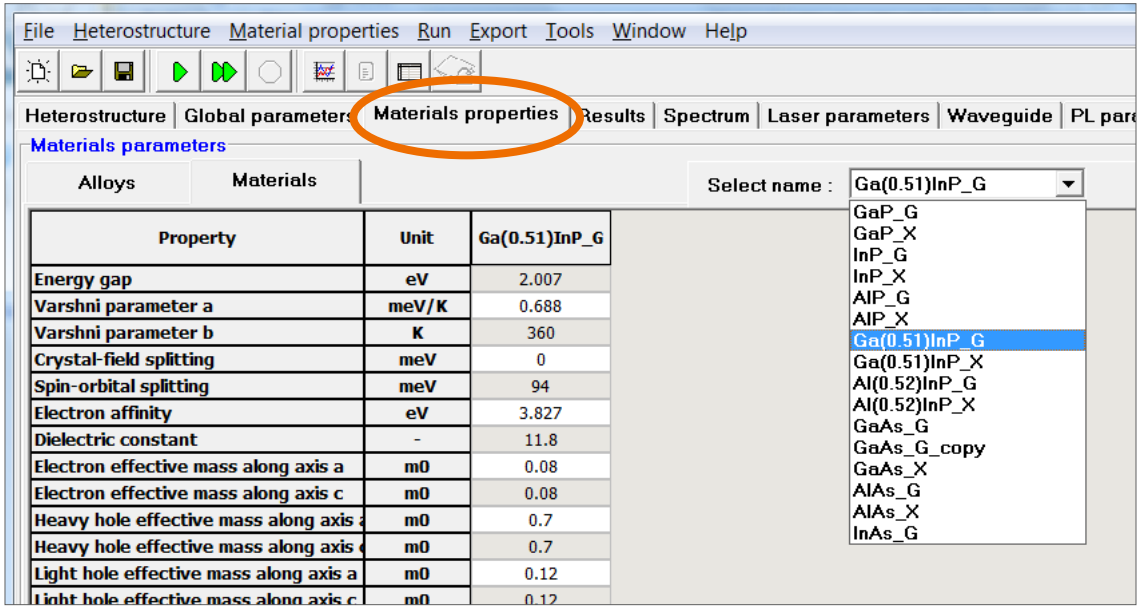
2. Choose **wurtzite** database supplied with SiLENSe. It includes properties of two systems with wurtzite crystal symmetry, namely, AlInGaN and MgZnO.

Lists of available materials and alloys shows data contained in the chosen database file. **Green mark** and **red cross** indicate good and insufficient data.

3. Press **OK** to create the project.

SiLENSe comes with two databases of material properties, **wurtzite** and **zinc_blende.** The user can edit the data contained in these databases using a separate Properties Editor **(ProEdit.exe)** and create new custom *.matprop files.

Step1 (Continued): Materials vs. Alloys in SiLENSe database



In specification of materials properties, SiLENSe distinguishes between materials of fixed composition (like GaN, AlN, InN) and their alloys where composition may be continuously varied with one or more degree of freedom (like $Al_xGa_{1-x}N$, $In_xGa_{1-x}N$, $Al_xIn_yGa_{1-x-y}N$) and properties calculated through the respective properties of materials and bowing parameters (both are stored in the respective *.matprop file).

Note that ternary and quaternary compounds can also be treated by the software as materials when they have fixed composition and properties described in the database explicitly with no option of composition variation and respective adjustments, see the example above, where $Ga_{0.51}In_{0.49}P$ alloy is specified as a material. Because of its importance is might be useful to specify its properties explicitly. Also, it may be used later as a basic material for AlGaInP alloys lattice matched to GaAs.

Step1 (Continued): Inspecting material properties

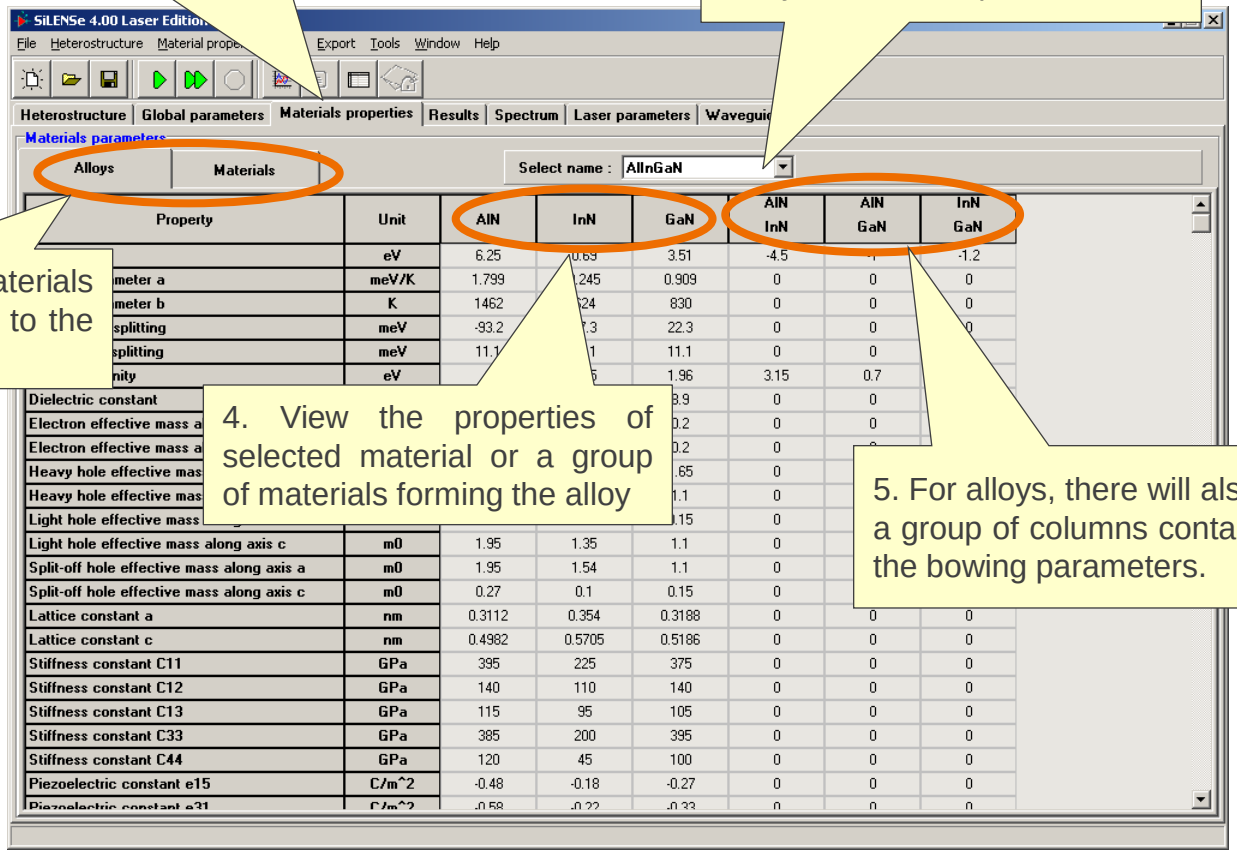
1. Open Materials Properties tab for read-only inspection of the properties

3. Select the desired material or alloy from the drop down menu

2. Choose between materials and alloys by switching to the respective tab

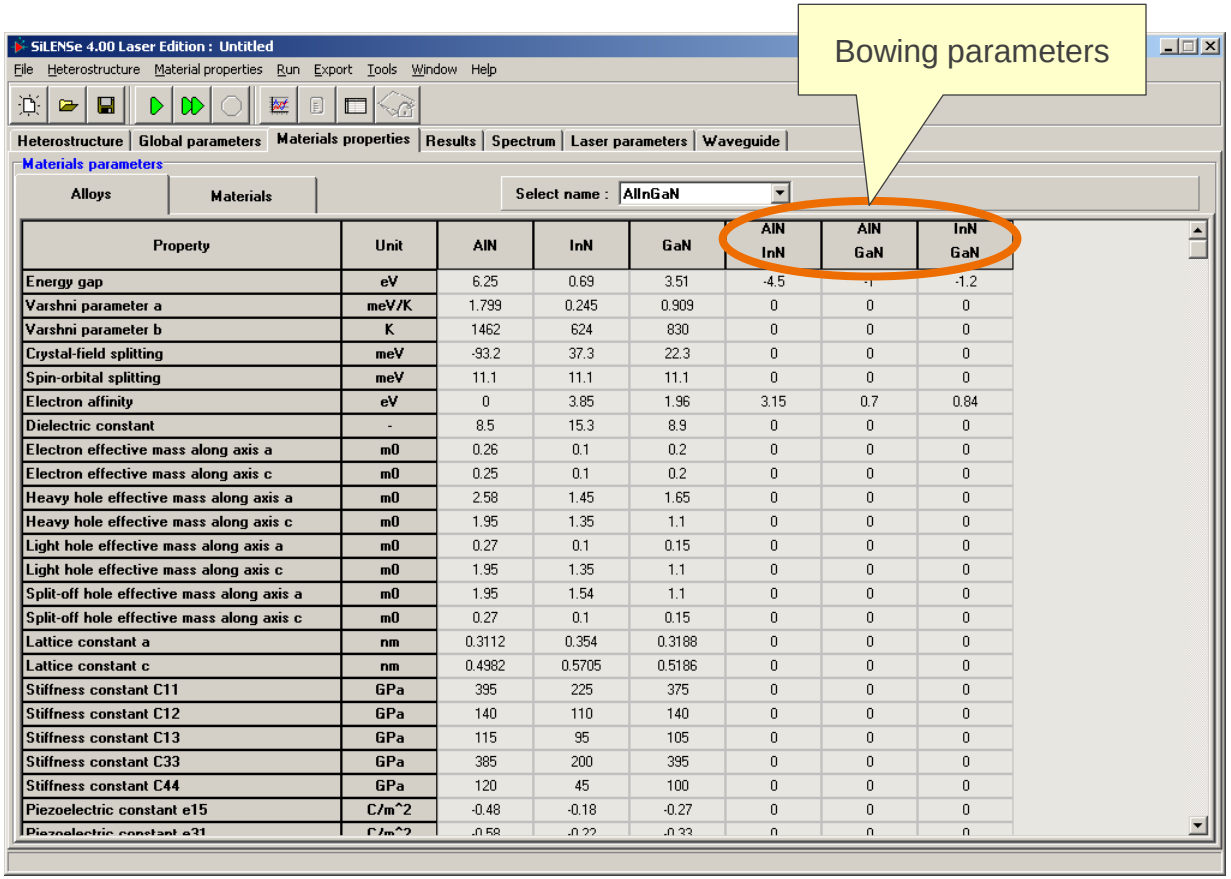
4. View the properties of selected material or a group of materials forming the alloy

5. For alloys, there will also be a group of columns containing the bowing parameters.



Property	Unit	AlN	InN	GaN	AlN InN	AlN GaN	InN GaN
	eV	6.25	0.69	3.51	-4.5	-1	-1.2
meter a	meV/K	1.799	2.245	0.909	0	0	0
meter b	K	1462	624	830	0	0	0
splitting	meV	-93.2	7.3	22.3	0	0	0
splitting	meV	11.1	1	11.1	0	0	
nity	eV		5	1.96	3.15	0.7	
Dielectric constant				8.9	0	0	
Electron effective mass a				0.2	0	0	
Electron effective mass a				0.2	0		
Heavy hole effective mas				.65	0		
Heavy hole effective mas				1.1	0		
Light hole effective mass				0.15	0		
Light hole effective mass along axis c	m0	1.95	1.35	1.1	0		
Split-off hole effective mass along axis a	m0	1.95	1.54	1.1	0		
Split-off hole effective mass along axis c	m0	0.27	0.1	0.15	0		
Lattice constant a	nm	0.3112	0.354	0.3188	0	0	0
Lattice constant c	nm	0.4982	0.5705	0.5186	0	0	0
Stiffness constant C11	GPa	395	225	375	0	0	0
Stiffness constant C12	GPa	140	110	140	0	0	0
Stiffness constant C13	GPa	115	95	105	0	0	0
Stiffness constant C33	GPa	385	200	395	0	0	0
Stiffness constant C44	GPa	120	45	100	0	0	0
Piezoelectric constant e15	C/m^2	-0.48	-0.18	-0.27	0	0	0
Piezoelectric constant e31	C/m^2	-0.58	-0.22	-0.33	0	0	0

Step 1 (Continued): Bowing parameters



Property	Unit	AlN	InN	GaN	AlN InN	AlN GaN	InN GaN
Energy gap	eV	6.25	0.69	3.51	-4.5	-1	-1.2
Varshni parameter a	meV/K	1.799	0.245	0.909	0	0	0
Varshni parameter b	K	1462	624	830	0	0	0
Crystal-field splitting	meV	-93.2	37.3	22.3	0	0	0
Spin-orbital splitting	meV	11.1	11.1	11.1	0	0	0
Electron affinity	eV	0	3.85	1.96	3.15	0.7	0.84
Dielectric constant	-	8.5	15.3	8.9	0	0	0
Electron effective mass along axis a	m0	0.26	0.1	0.2	0	0	0
Electron effective mass along axis c	m0	0.25	0.1	0.2	0	0	0
Heavy hole effective mass along axis a	m0	2.58	1.45	1.65	0	0	0
Heavy hole effective mass along axis c	m0	1.95	1.35	1.1	0	0	0
Light hole effective mass along axis a	m0	0.27	0.1	0.15	0	0	0
Light hole effective mass along axis c	m0	1.95	1.35	1.1	0	0	0
Split-off hole effective mass along axis a	m0	1.95	1.54	1.1	0	0	0
Split-off hole effective mass along axis c	m0	0.27	0.1	0.15	0	0	0
Lattice constant a	nm	0.3112	0.354	0.3188	0	0	0
Lattice constant c	nm	0.4982	0.5705	0.5186	0	0	0
Stiffness constant C11	GPa	395	225	375	0	0	0
Stiffness constant C12	GPa	140	110	140	0	0	0
Stiffness constant C13	GPa	115	95	105	0	0	0
Stiffness constant C33	GPa	385	200	395	0	0	0
Stiffness constant C44	GPa	120	45	100	0	0	0
Piezoelectric constant e15	C/m^2	-0.48	-0.18	-0.27	0	0	0
Piezoelectric constant e31	C/m^2	-0.58	-0.22	-0.33	0	0	0

By default, most properties have zero bowing parameters, that means that linear interpolation is used to calculate the property for alloy of given composition.

Note the sign of the bowing parameters! **Negative bowing means decreasing** of the property compared to the linear interpolation (an opposite definition is often used)

It is assumed that user does not need to change properties during everyday work. Instead, it is recommended to work with the same chosen set of material properties for all simulations for self-consistency of the whole research project. When necessary, editing of materials properties to be done with **Properties Editor** tool **MatProp.exe** (not discussed in this tutorial). One can update materials properties by using **Materials Properties->Import** menu item.

Step 2: Adding heterostructure layers

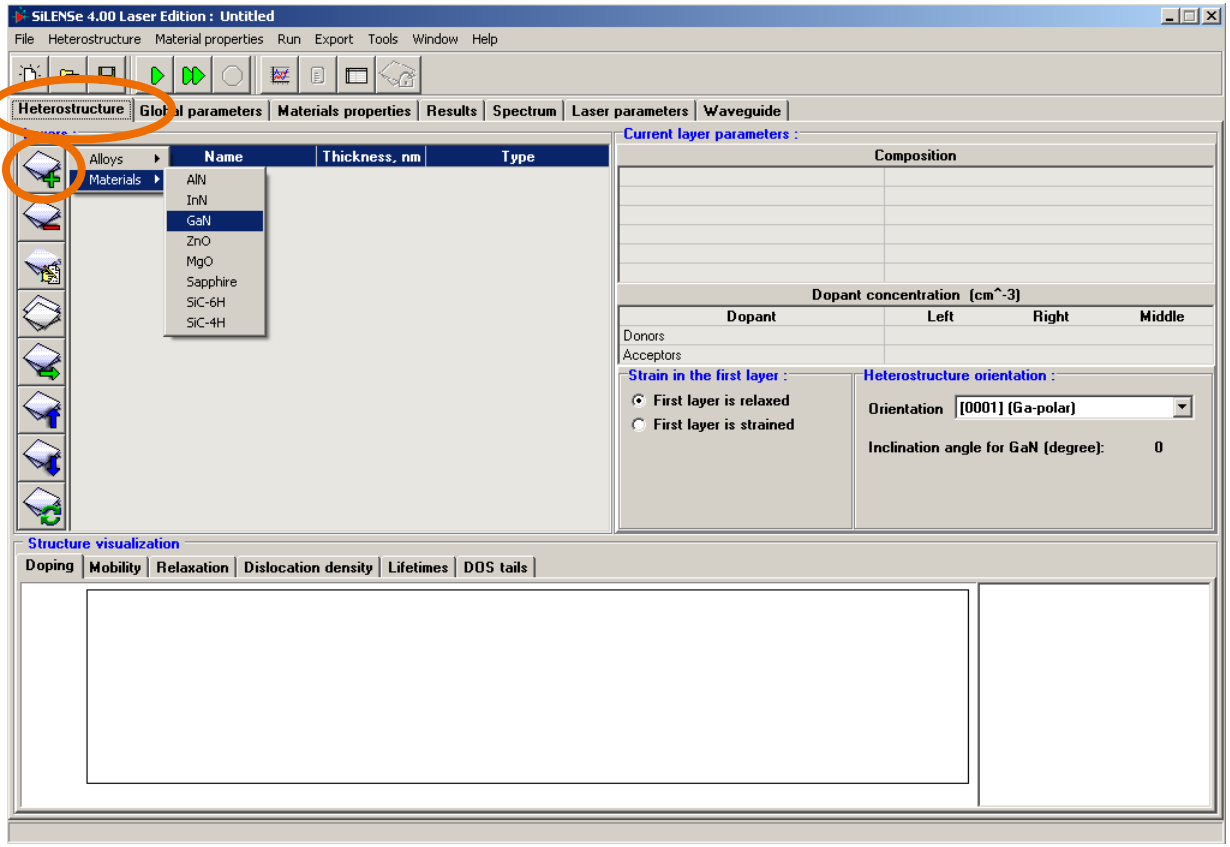
Heterostructure tab allows one to specify the heterostructure layers:

1. Press **Add Layer** button to add a new layer.

2. A pop-up menu appears allowing one to choose belween **Materials** and **Alloys.** Both items contain submenus with list of available materials and alloys.

3. You can choose either **Materials->GaN** to add GaN layer or, alternatively, **Alloys->AlInGaN.** In the latter case you will also have to specify composition as $Al_0In_0Ga_1N$.

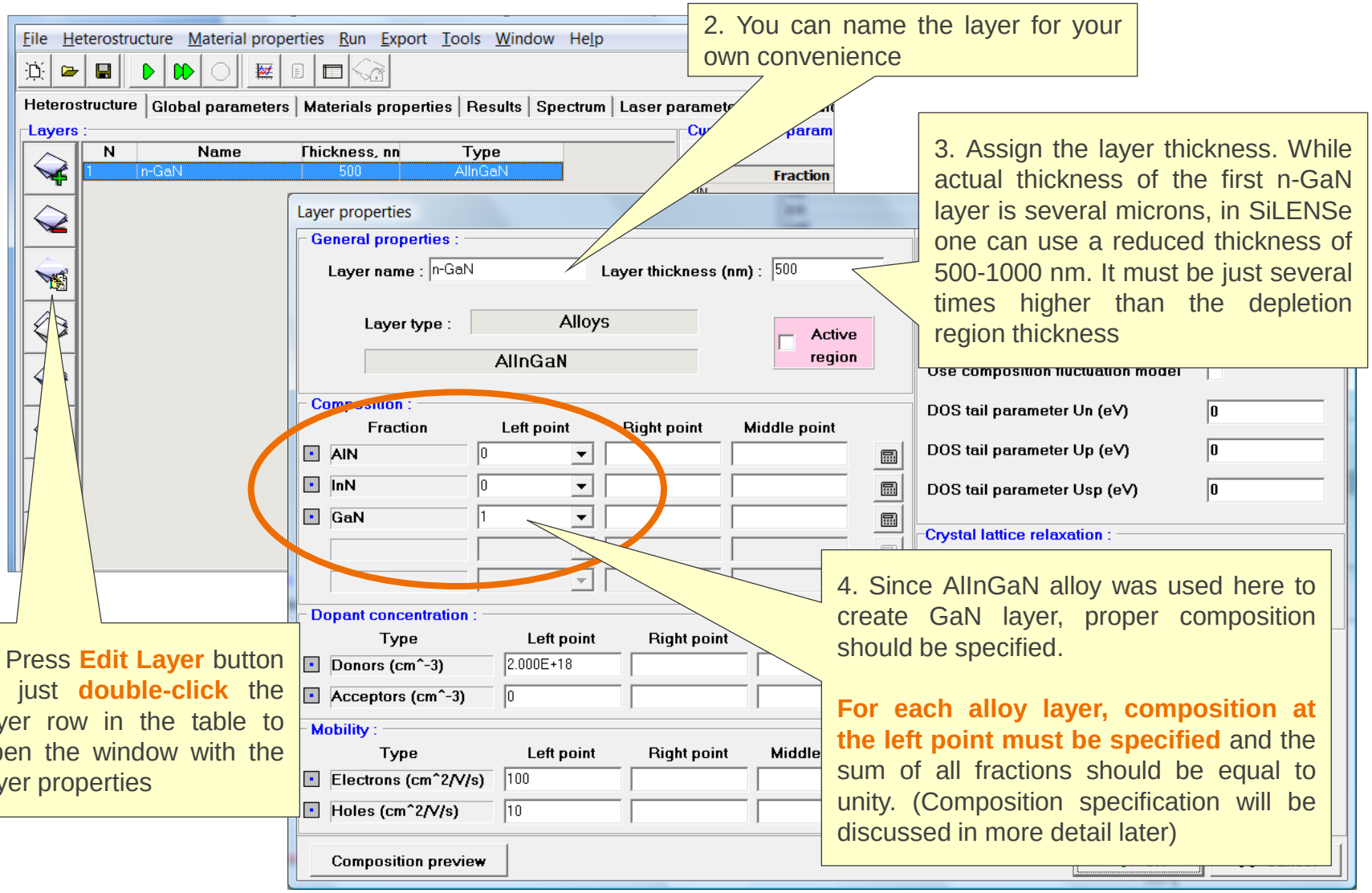
Note that later on you can also copy-paste existing layers to create new ones.



Heterostructure has to start with n-type layer and end with p-type layer.

No nucleation and buffer layers to be specified.

Step 2 (Continued): Layer thickness and composition



2. You can name the layer for your own convenience

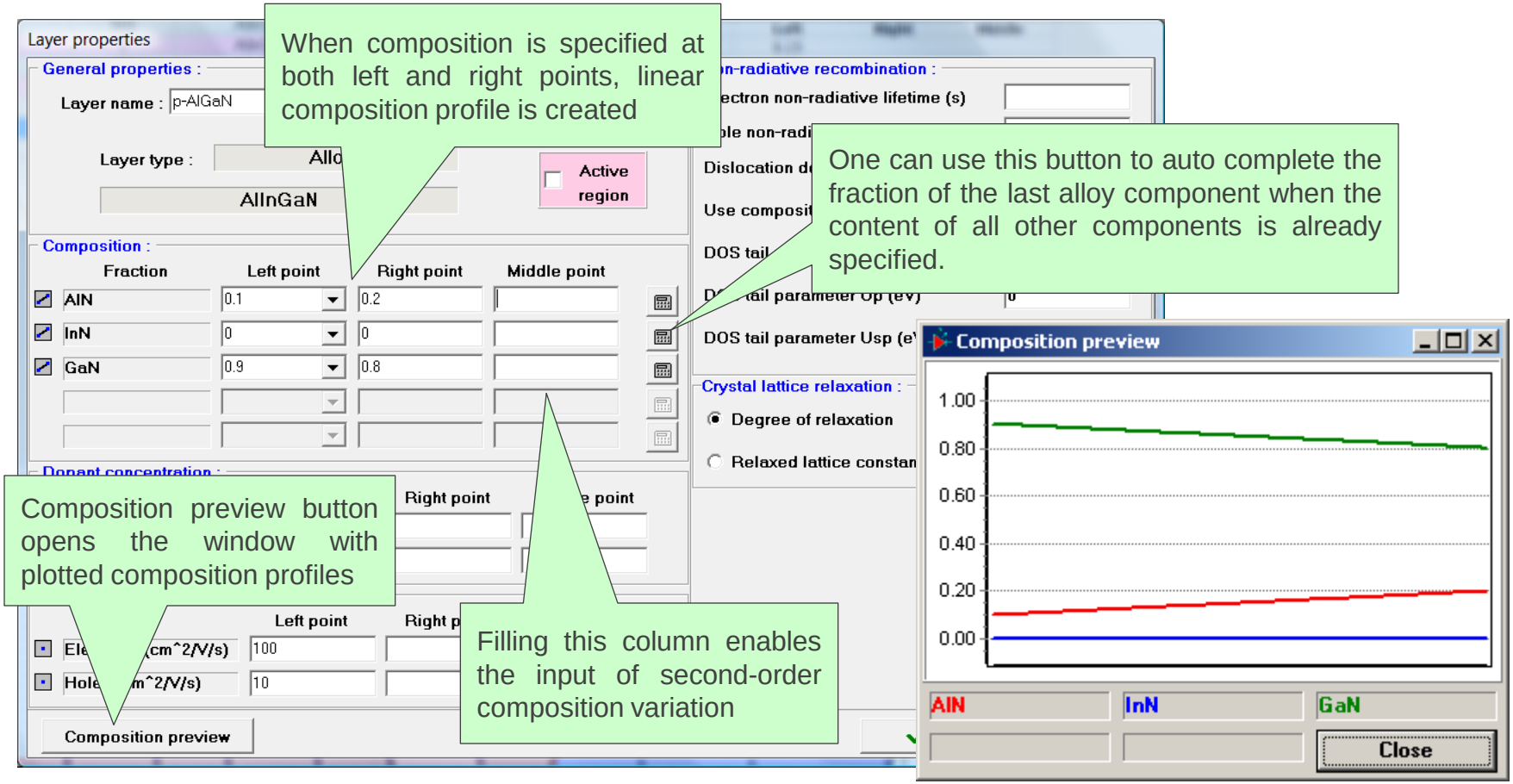
3. Assign the layer thickness. While actual thickness of the first n-GaN layer is several microns, in SiLENSe one can use a reduced thickness of 500-1000 nm. It must be just several times higher than the depletion region thickness

1. Press **Edit Layer** button or just **double-click** the layer row in the table to open the window with the layer properties

4. Since AlInGaN alloy was used here to create GaN layer, proper composition should be specified.

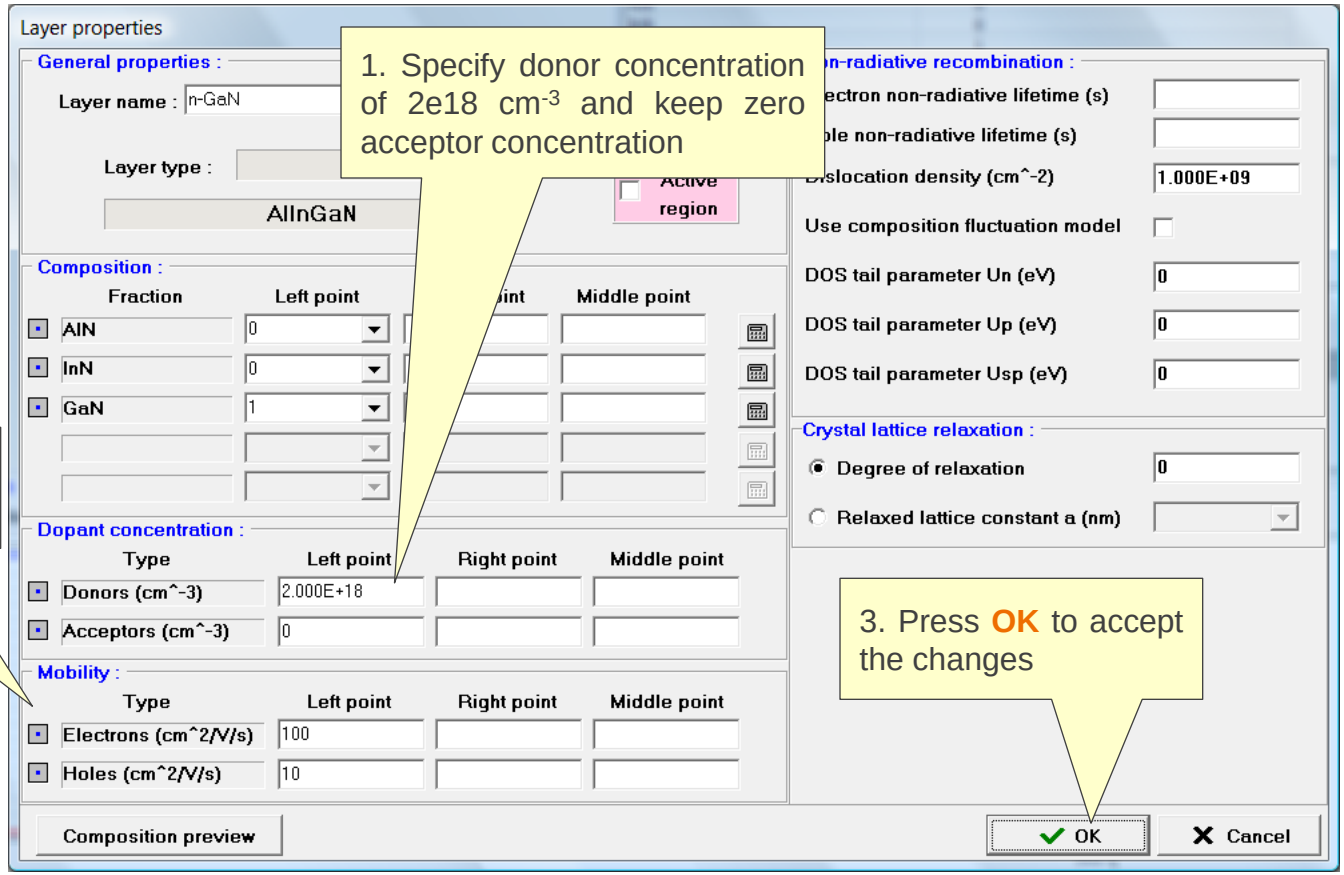
For each alloy layer, composition at the left point must be specified and the sum of all fractions should be equal to unity. (Composition specification will be discussed in more detail later)

Additional information: graded composition



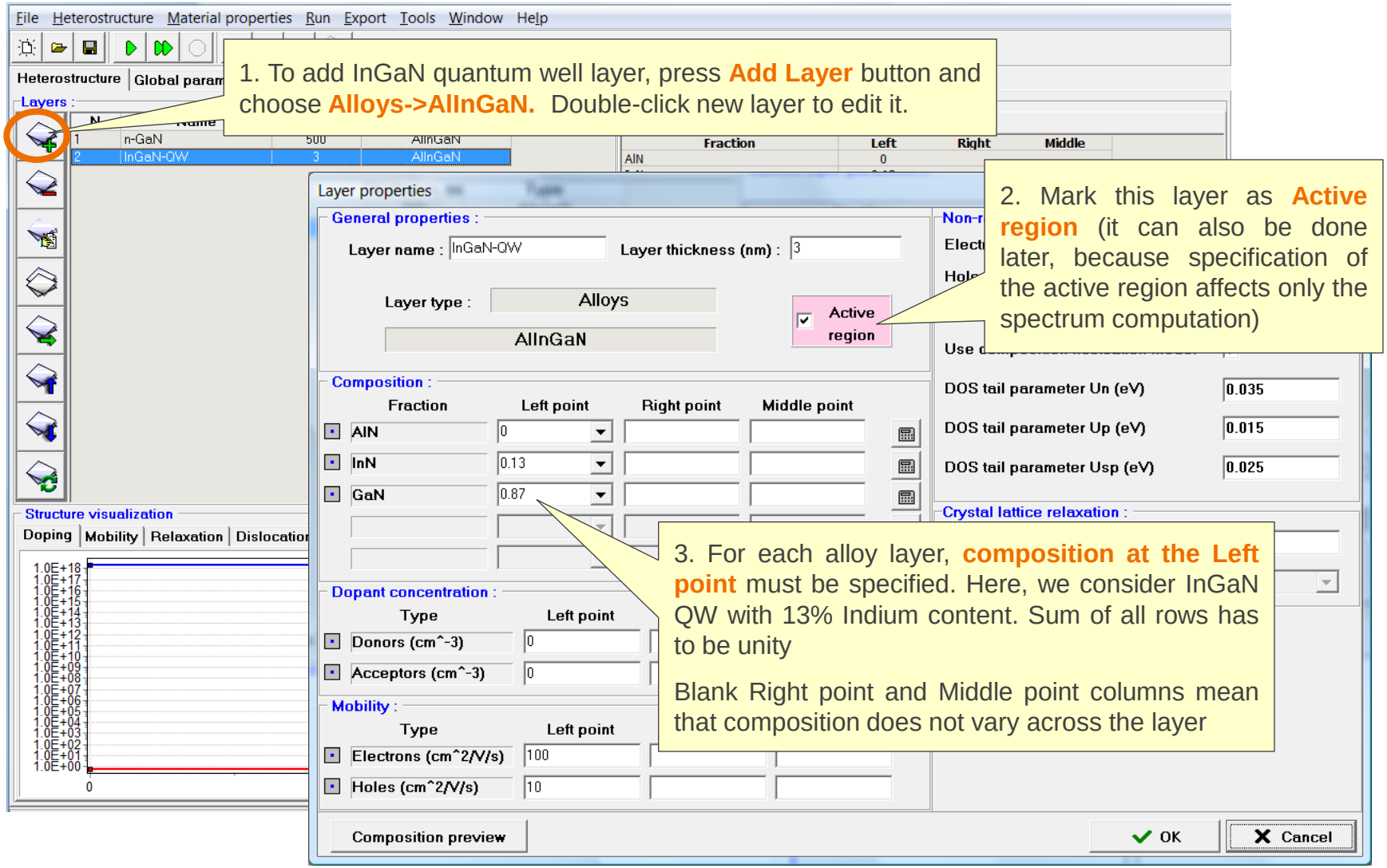
Layer composition may be specified by using a **custom function,** defined by user by a script or by a table which can be imported from a text file. To use function, one need pick up the function name in the respective drop-down list. One can edit functions by using **Heterostructure->Functions** menu item. The **auto** menu item means that this component is determined automatically to make total composition equal to 1.

Step 2 (Continued): Specification of the doping and mobility



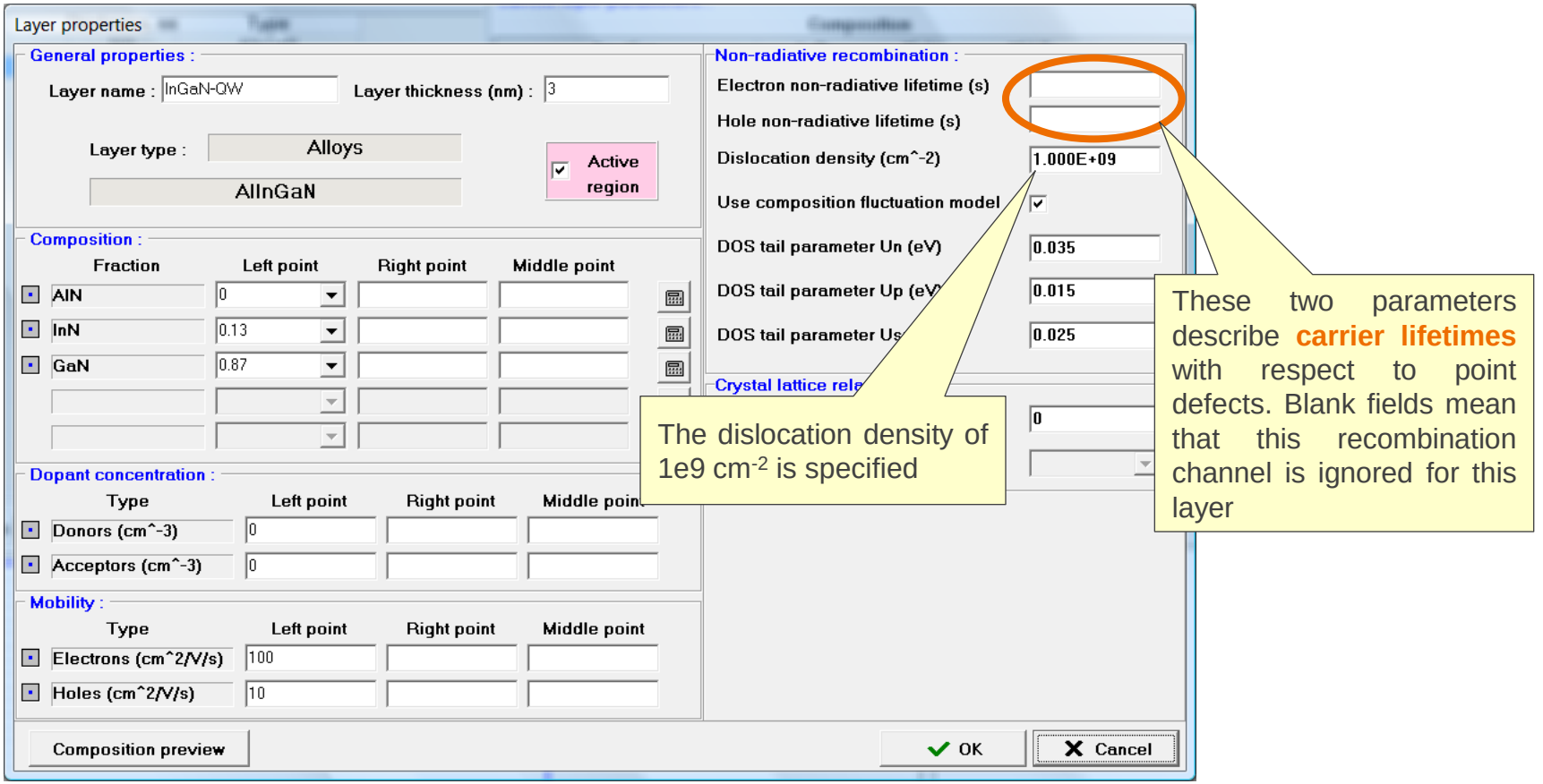
Note that **dopant concentration** means exactly the **concentration of the doping atoms**, NOT the carrier concentration which is calculated by the program! Hole concentration in, for instance, III-nitrides may be ~50 times lower than Mg concentration because of high activation energy.

Step 2 (Continued): Adding InGaN quantum well layer



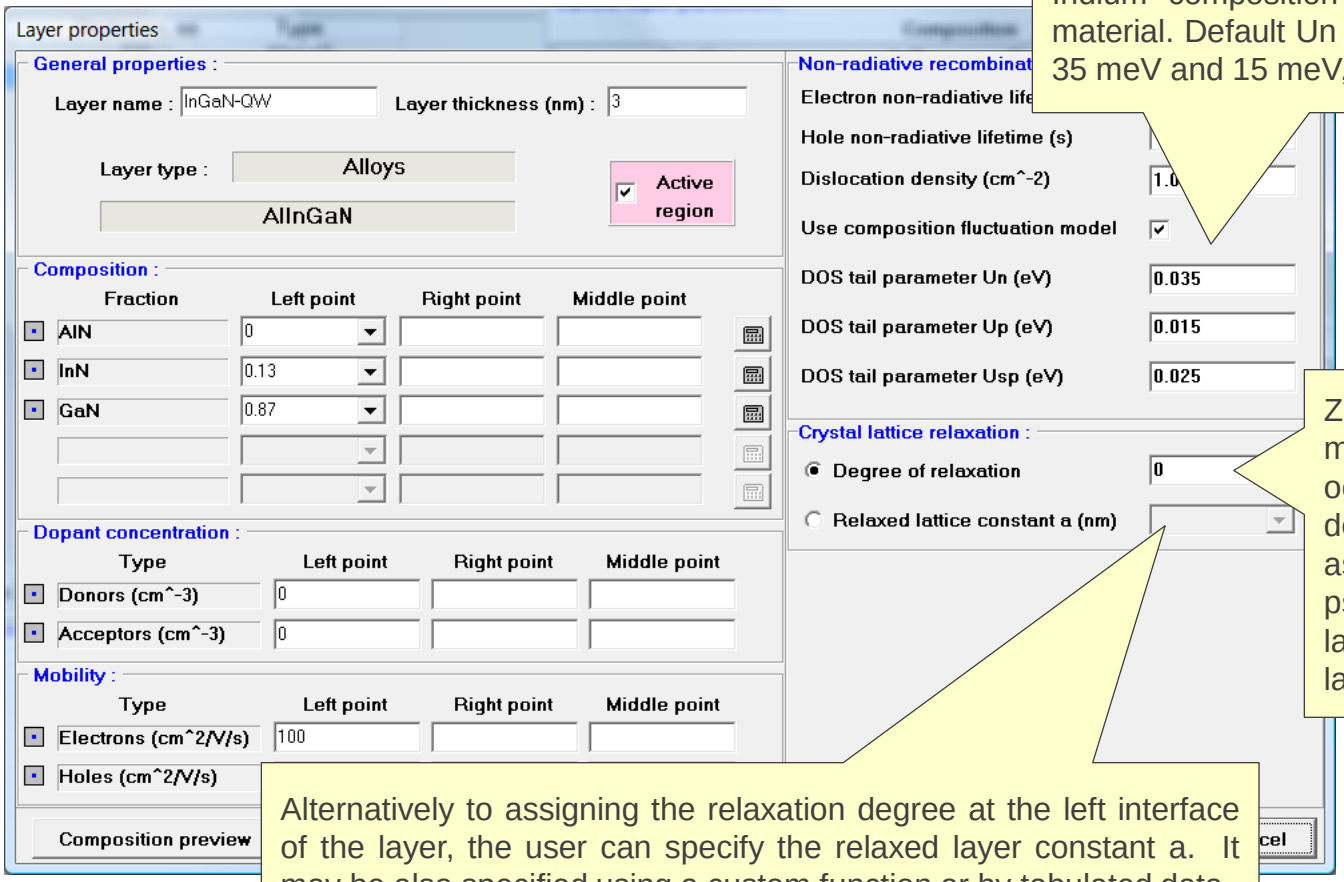
Step 2 (Continued): Shockley-Read-Hall recombination

In SiLENSe, there are two ways to specify the rate of non-radiative Shockley-Read-Hall recombination. One is direct specification of the carrier lifetimes due to point defects. The other way is to use an original model which relates the carrier lifetimes with the dislocation density. Both mechanisms contribute to the total non-radiative recombination rate independently, see Theory manual for details.



Step 2 (Continued): Composition fluctuation and relaxation

Section **Composition fluctuations** allows the user to input parameters related to Indium composition fluctuations in InGaN material. Default Un and Up parameters are 35 meV and 15 meV, respectively



Zero degree of relaxation means that no relaxation occurs in this layer (by default, heterostructure is assumed to be grown pseudomorphically, i.e. all layers have the same lattice constant)

Alternatively to assigning the relaxation degree at the left interface of the layer, the user can specify the relaxed layer constant a. It may be also specified using a custom function or by tabulated data

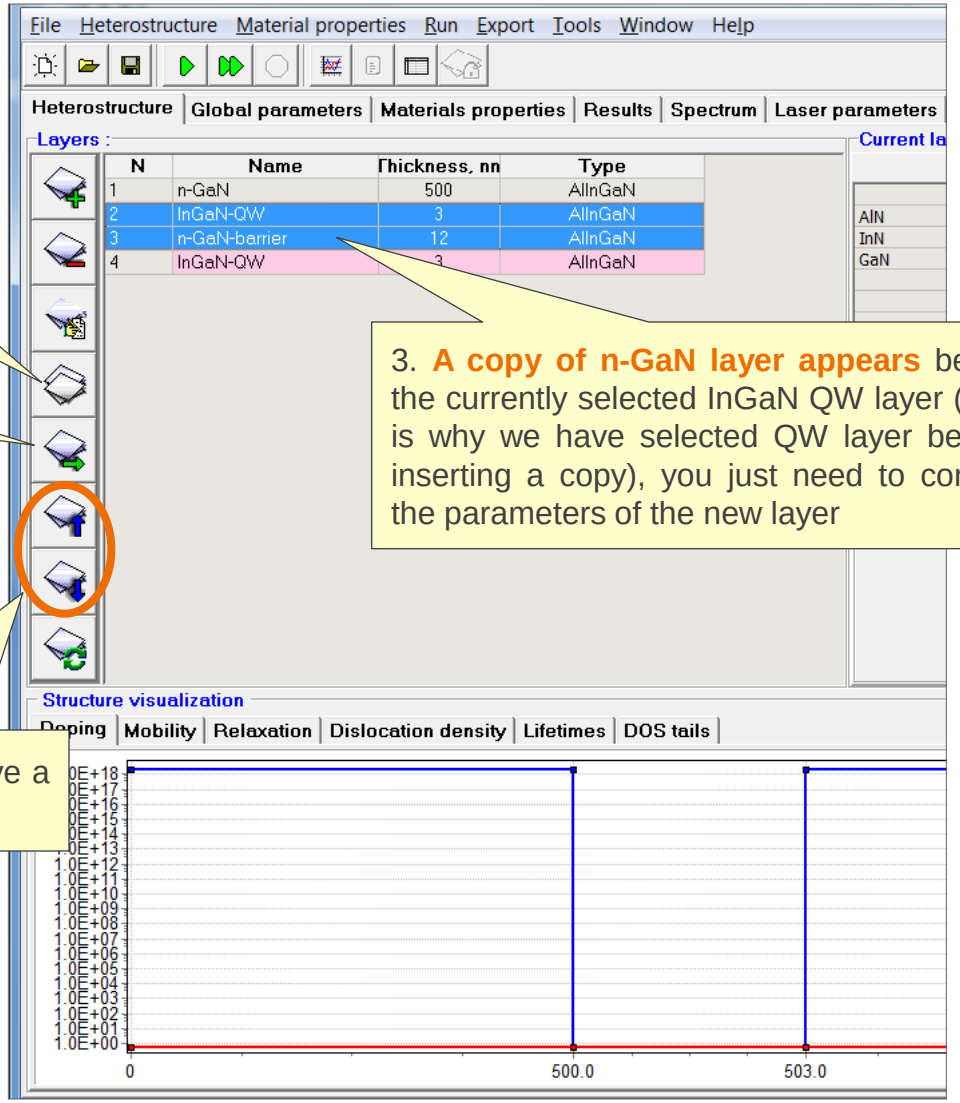
Step 2 (Continued): Copy, paste and move layers

1. To add GaN MQW barrier layer, select n-GaN layer and press **Copy Layer To Buffer** button

2. Select InGaN QW layer and use **Insert Layer From Buffer** button

3. **A copy of n-GaN layer appears** below the currently selected InGaN QW layer (that is why we have selected QW layer before inserting a copy), you just need to correct the parameters of the new layer

These buttons allow one to move a selected layer up and down



Step 2 (Continued): Creating periodic structures

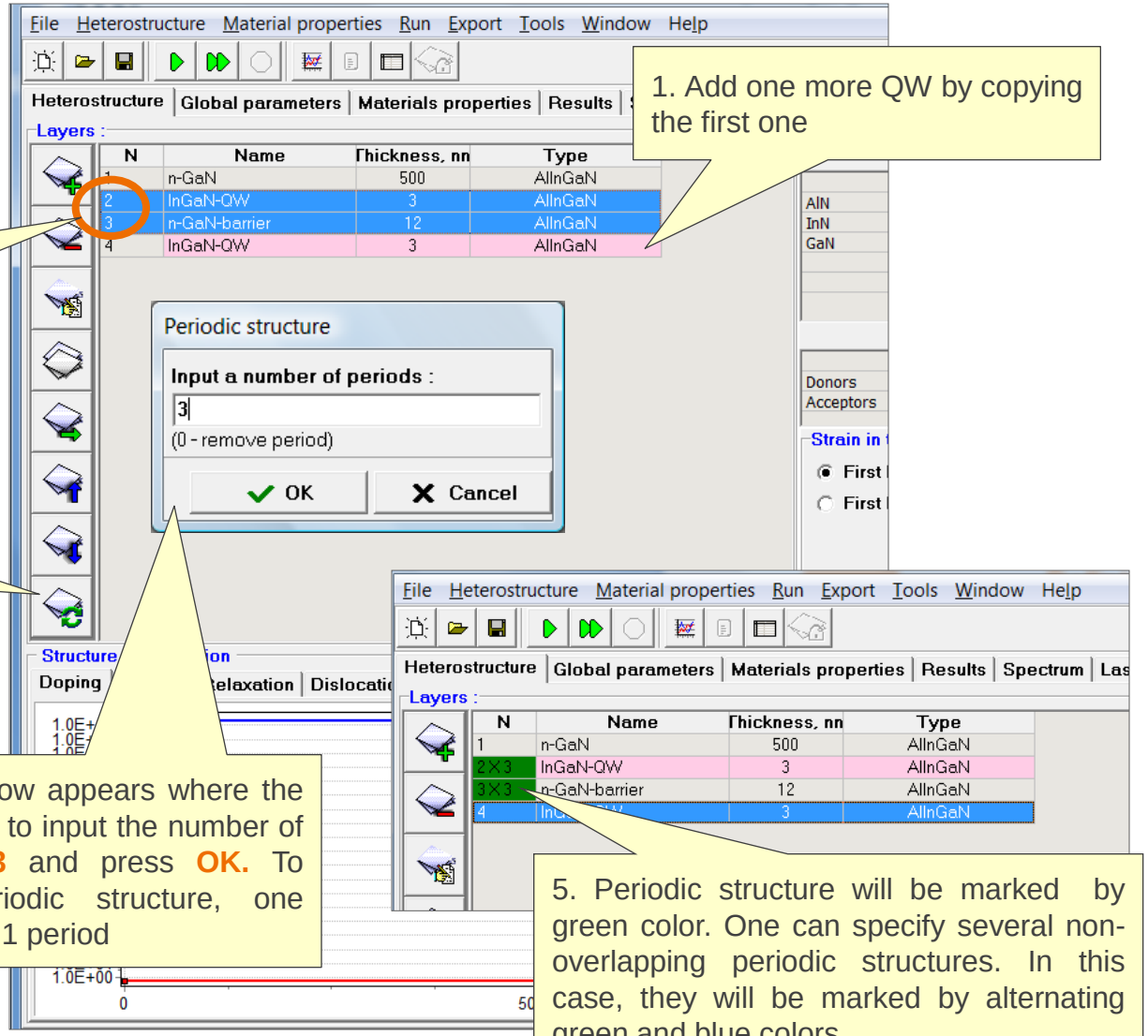
1. Add one more QW by copying the first one

2. Select two layers, first QW and the barrier

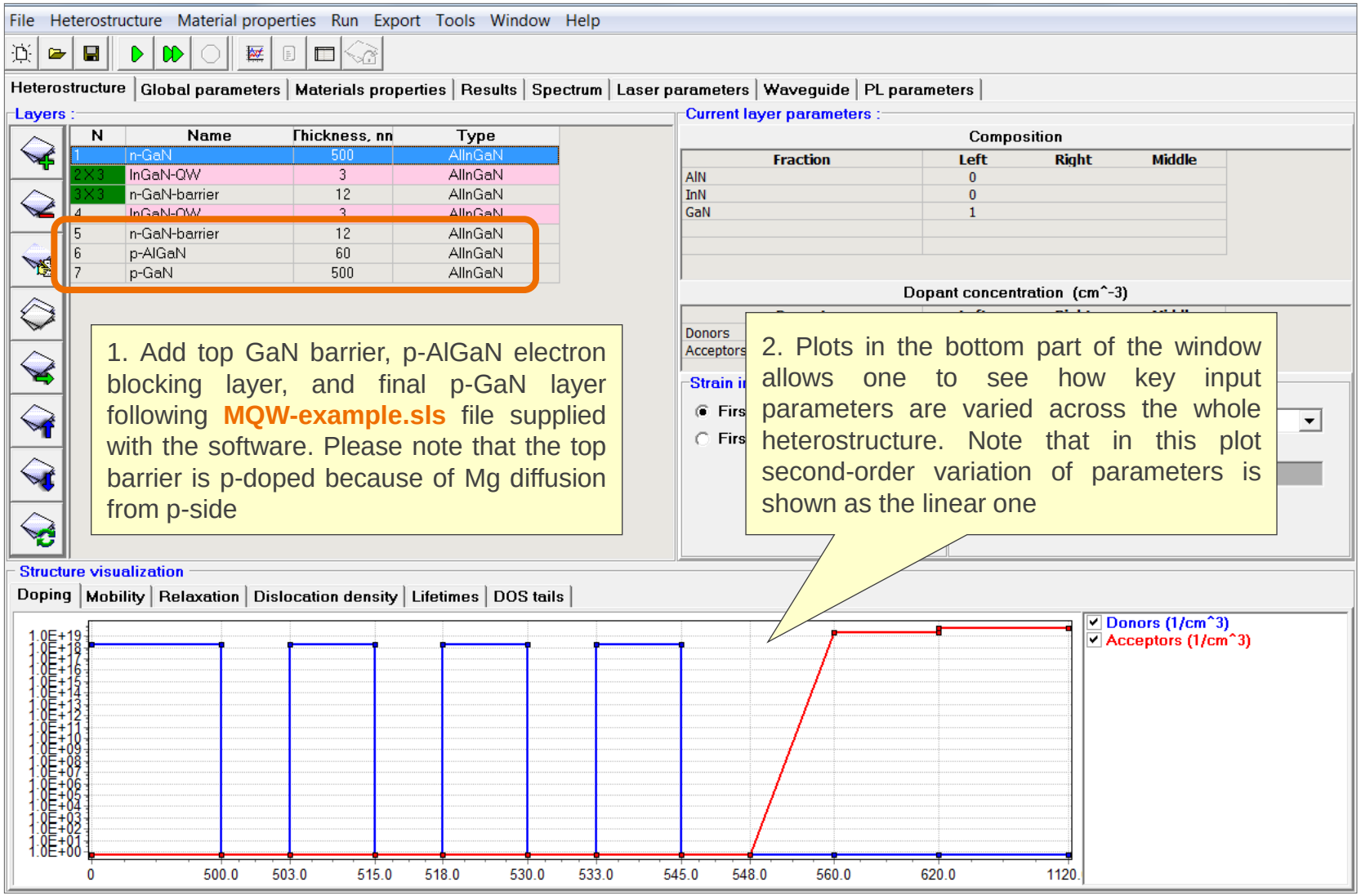
3. Click **Edit Periodic Structure** button

4. A modal window appears where the user is prompted to input the number of periods. Input **3** and press **OK.** To delete the periodic structure, one should input 0 or 1 period

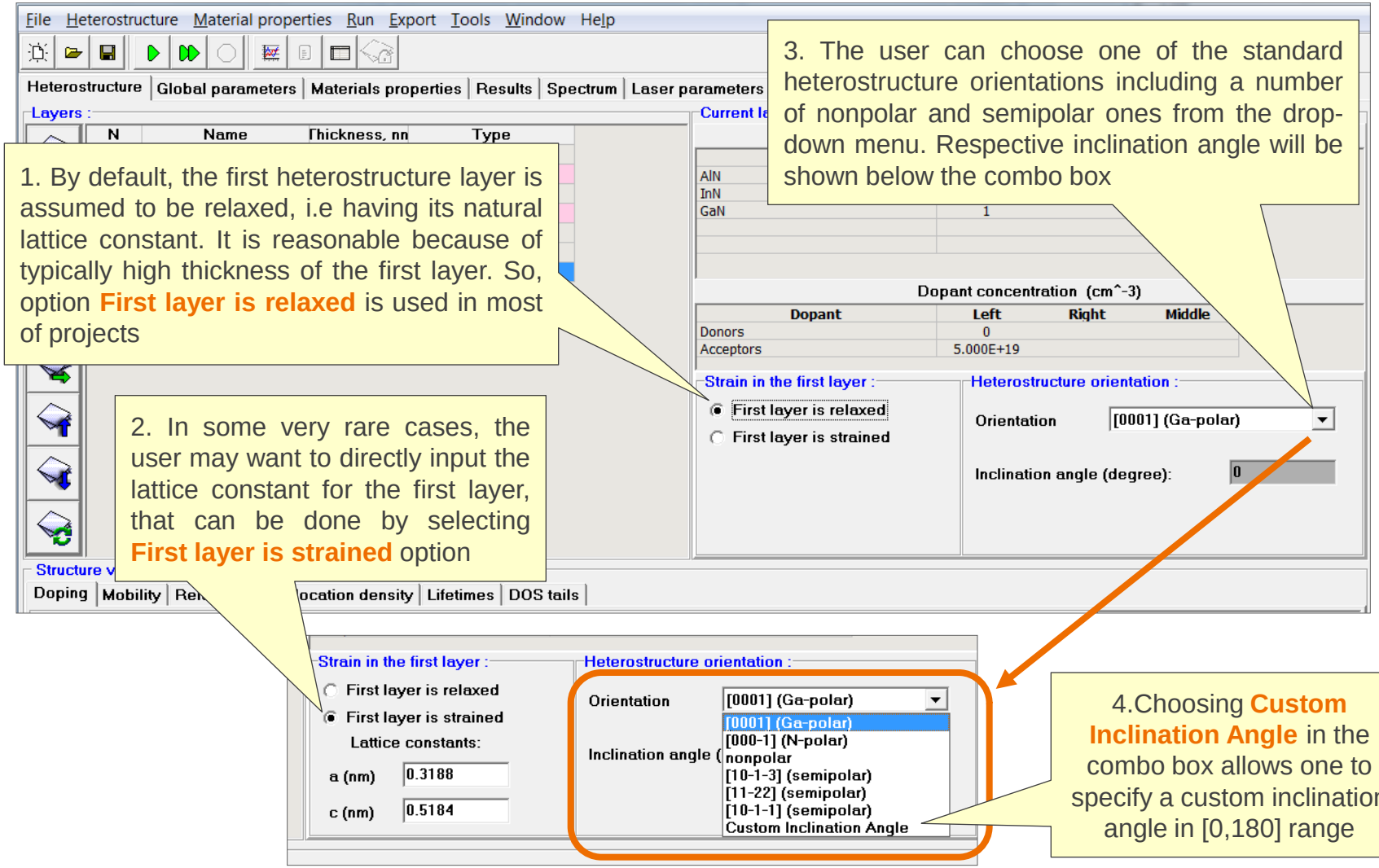
5. Periodic structure will be marked by green color. One can specify several non-overlapping periodic structures. In this case, they will be marked by alternating green and blue colors



Step 2 (Continued): Finalizing the structure



Step 3: Specification of polarity and lattice constant



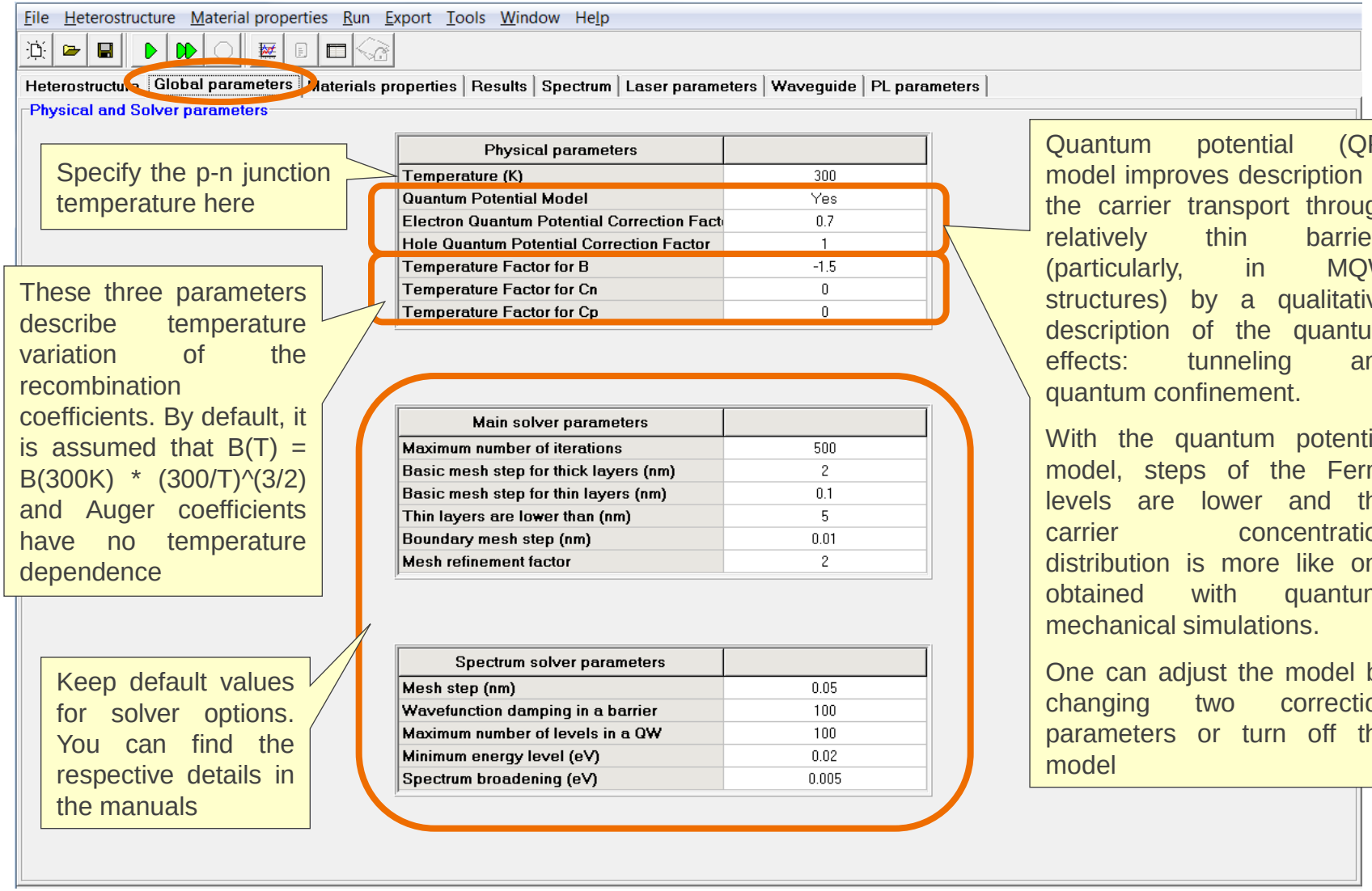
1. By default, the first heterostructure layer is assumed to be relaxed, i.e having its natural lattice constant. It is reasonable because of typically high thickness of the first layer. So, option **First layer is relaxed** is used in most of projects

2. In some very rare cases, the user may want to directly input the lattice constant for the first layer, that can be done by selecting **First layer is strained** option

3. The user can choose one of the standard heterostructure orientations including a number of nonpolar and semipolar ones from the drop-down menu. Respective inclination angle will be shown below the combo box

4.Choosing **Custom Inclination Angle** in the combo box allows one to specify a custom inclination angle in [0,180] range

Step 3 (Continued): Temperature and solver options



Specify the p-n junction temperature here

These three parameters describe temperature variation of the recombination coefficients. By default, it is assumed that B(T) = B(300K) * (300/T)^(3/2) and Auger coefficients have no temperature dependence

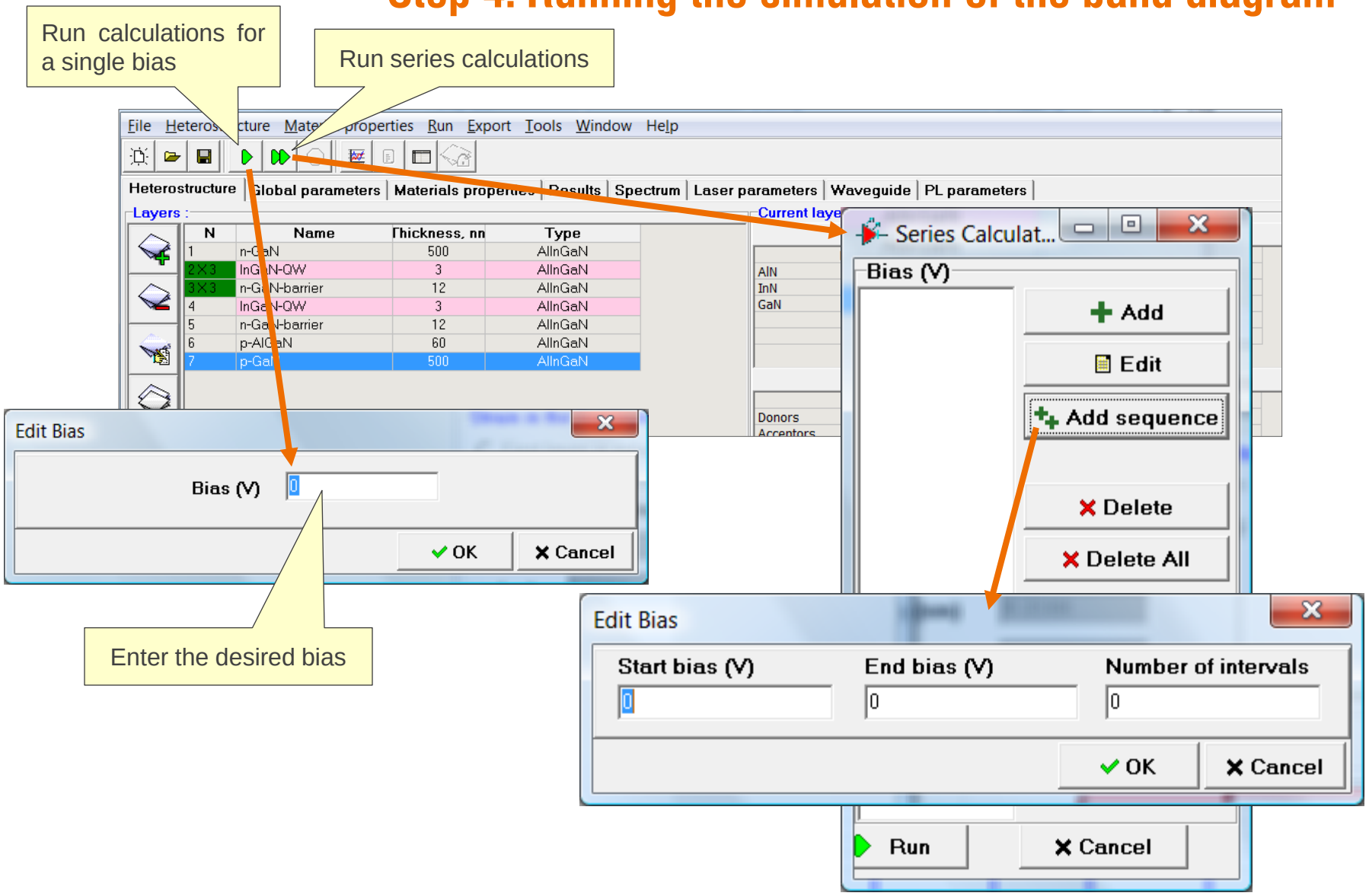
Keep default values for solver options. You can find the respective details in the manuals

Quantum potential (QP) model improves description of the carrier transport through relatively thin barriers (particularly, in MQW structures) by a qualitative description of the quantum effects: tunneling and quantum confinement.

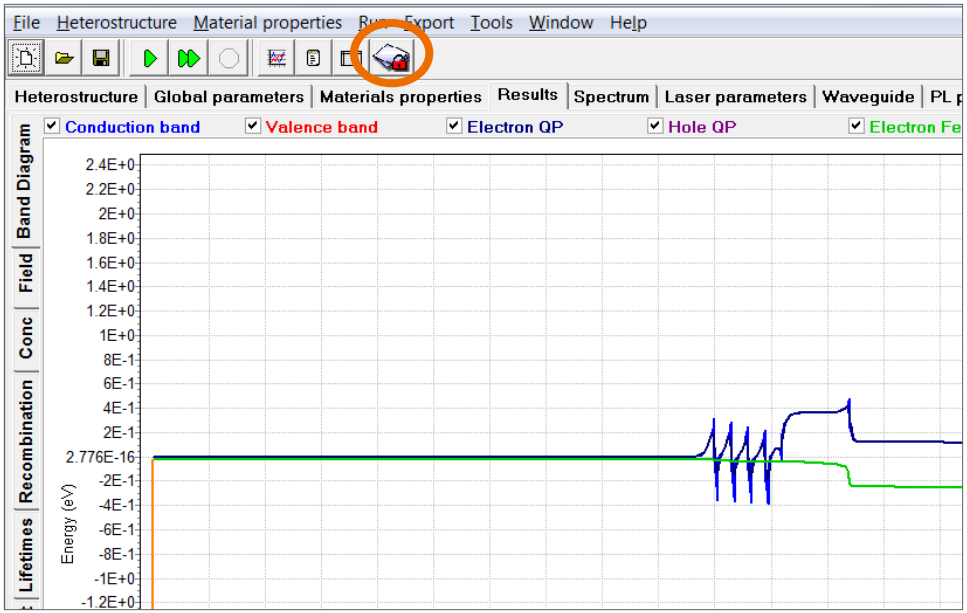
With the quantum potential model, steps of the Fermi levels are lower and the carrier concentration distribution is more like one obtained with quantum-mechanical simulations.

One can adjust the model by changing two correction parameters or turn off the model

Step 4: Running the simulation of the band diagram



Step 4 (Continued): Consistency of input data and simulation results, “locking” of the input data



In SiLENSe, all completed results are considered as a part of the project file and saved with it. To keep self-consistency between the input data and results, the project input data are **“locked”** as at least one result is computed.

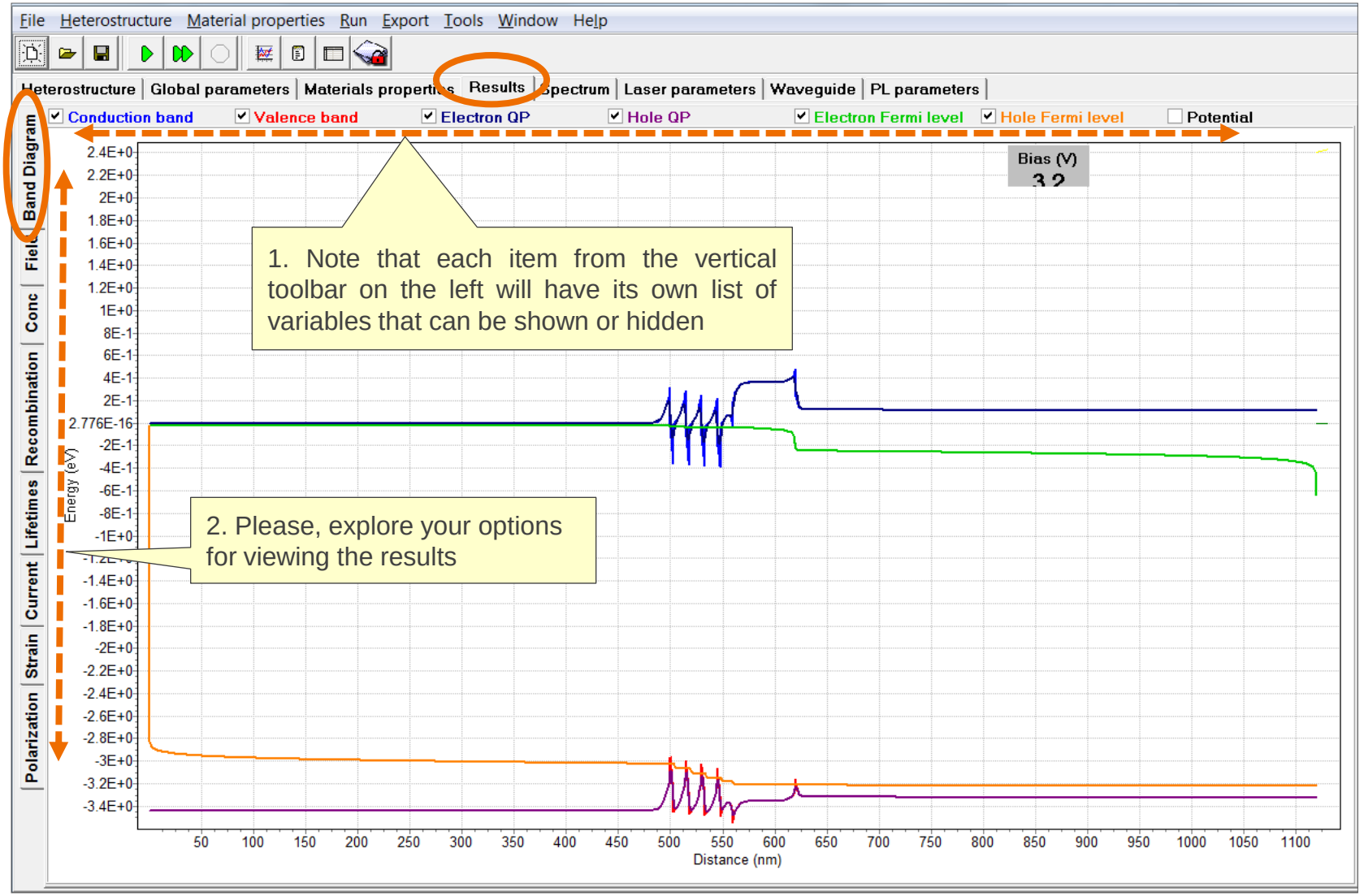
For “locked” project, most of the buttons for editing heterostructure are disabled. Edit Layer button is enabled, while most of the layer properties appear in read-only mode, that is shown by the grey color of the text fields.

The only properties one can change for “locked” project is the Layer name, the Active region flag, and the Usp parameter (since the latter two do not effect the band diagram simulation)

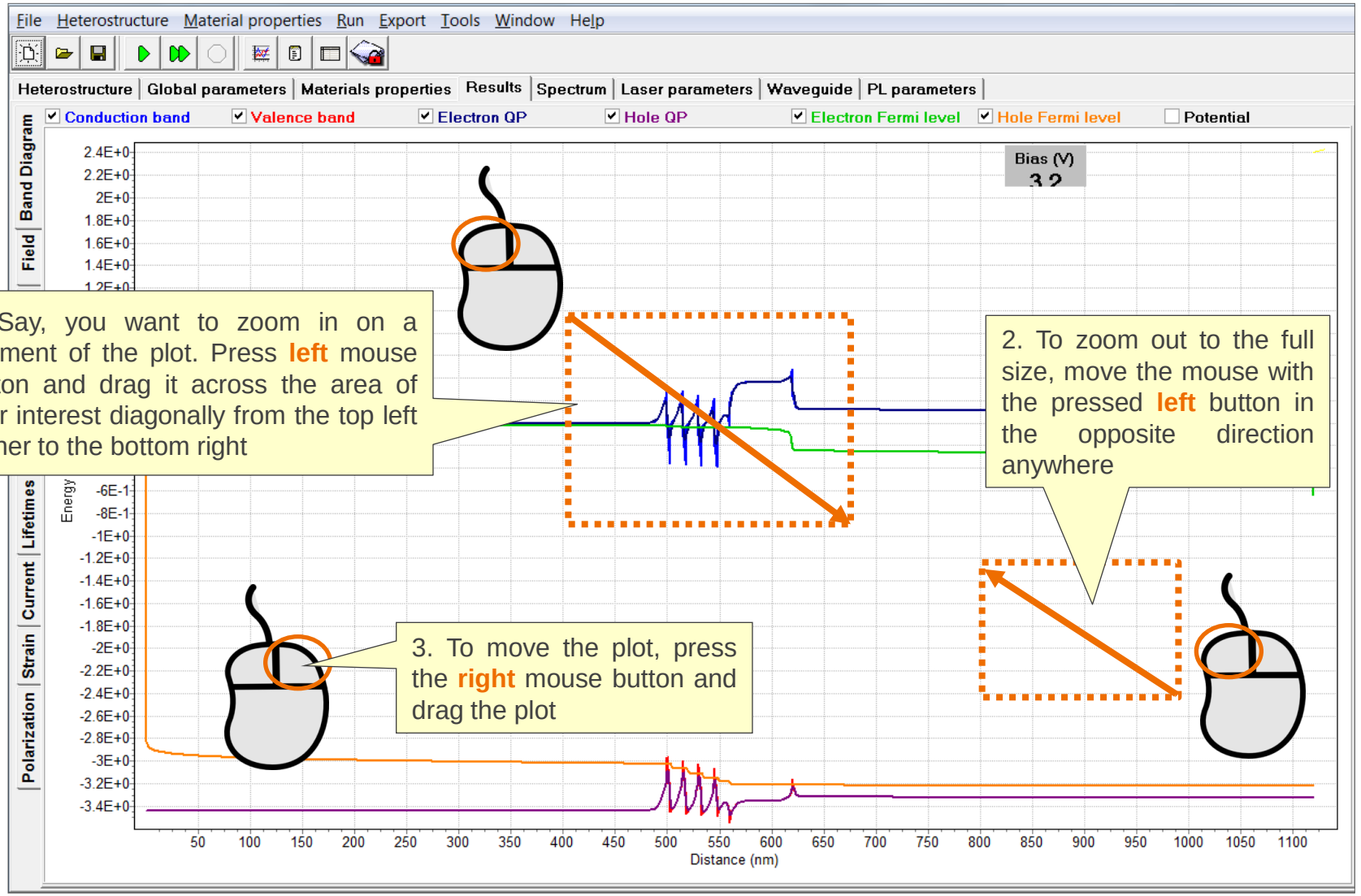
To be able to edit input data, one needs to previously clear all the results by **clicking the lock button** and thus unlock the editing.

These restrictions may look strange at the first glance, but they guarantee that simulation results stored in the project file are always consistent with the input data. So, you do not need to worry about remembering what parameters the results you see correspond to, you can just check them in the project file.

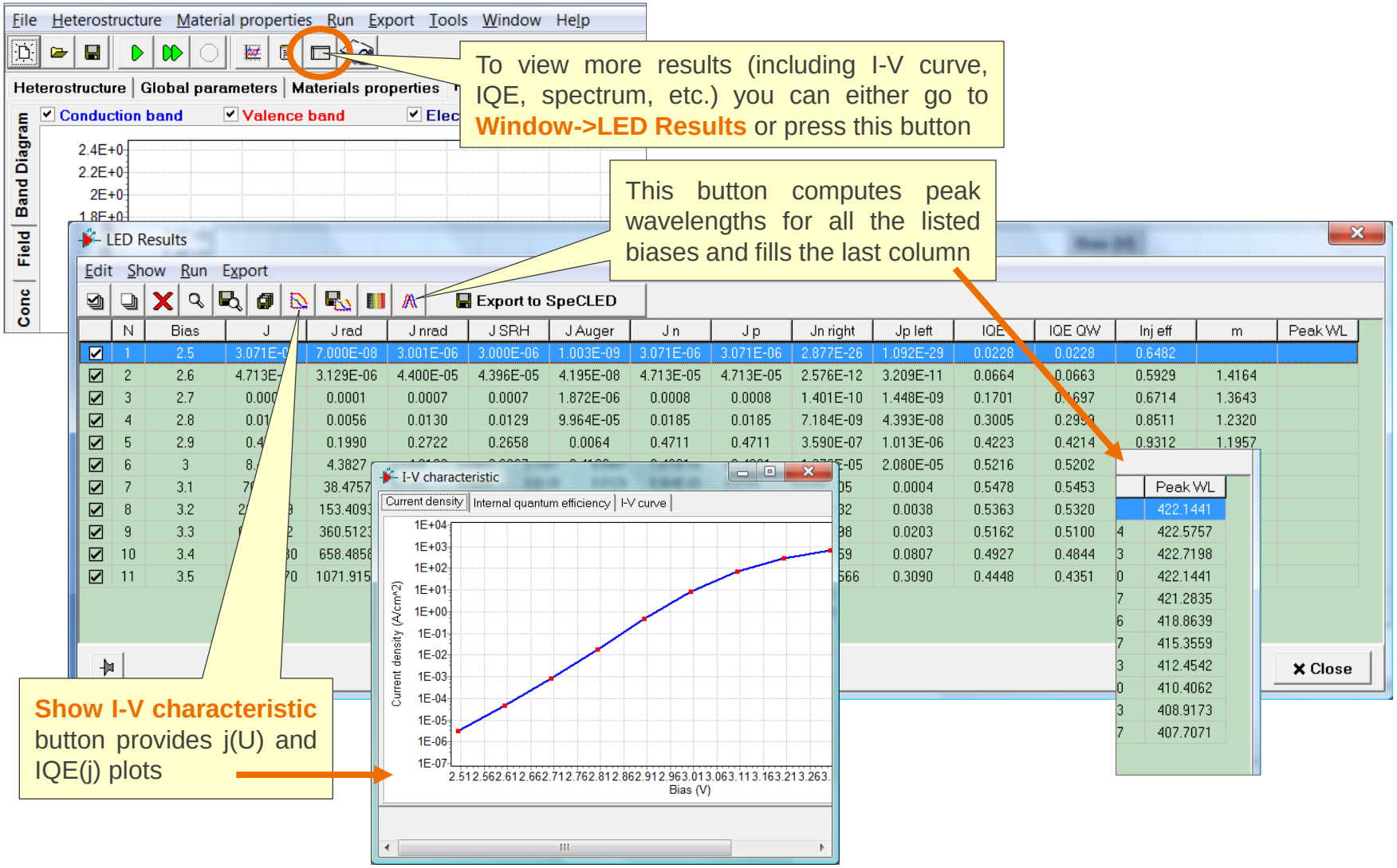
Step 4 (Continued): Results tab



Step 4 (Continued): Neat tricks with zooming and moving



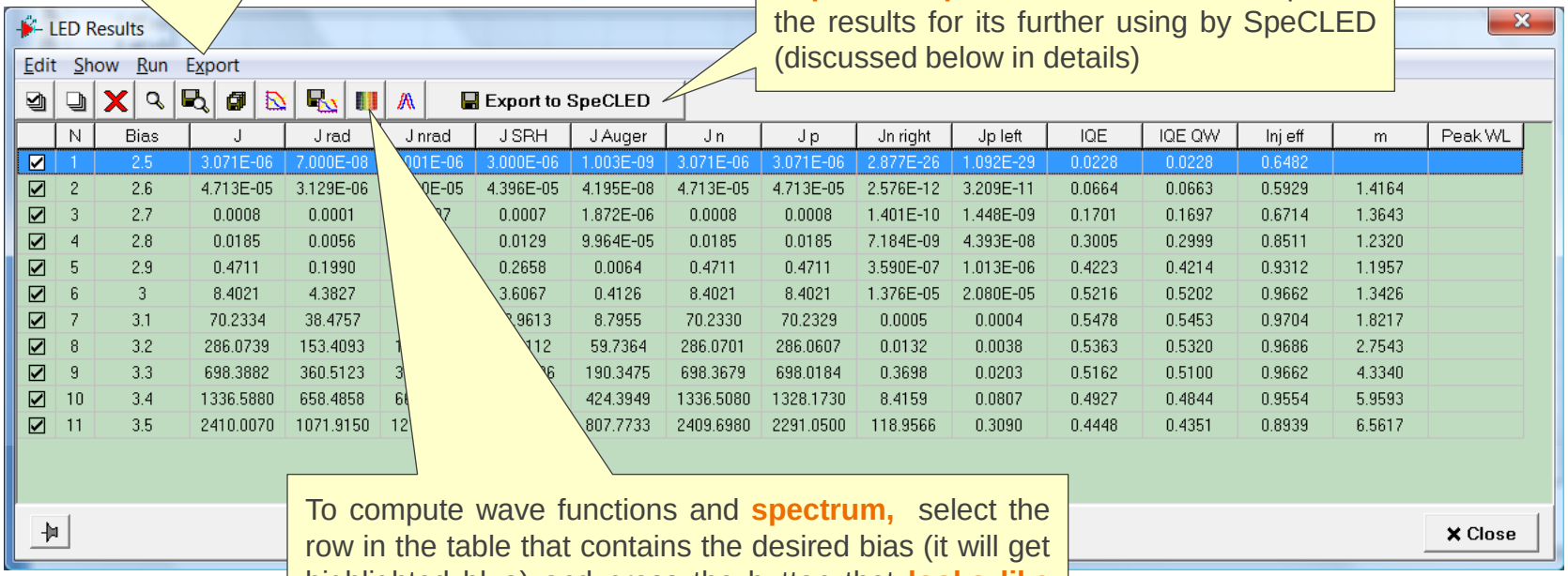
Step 4 (Continued): LED results



Step 4 (Continued): More LED results

There are several ways to export the computed results in ASCII format, try the icons below and the **Export** section of the menu

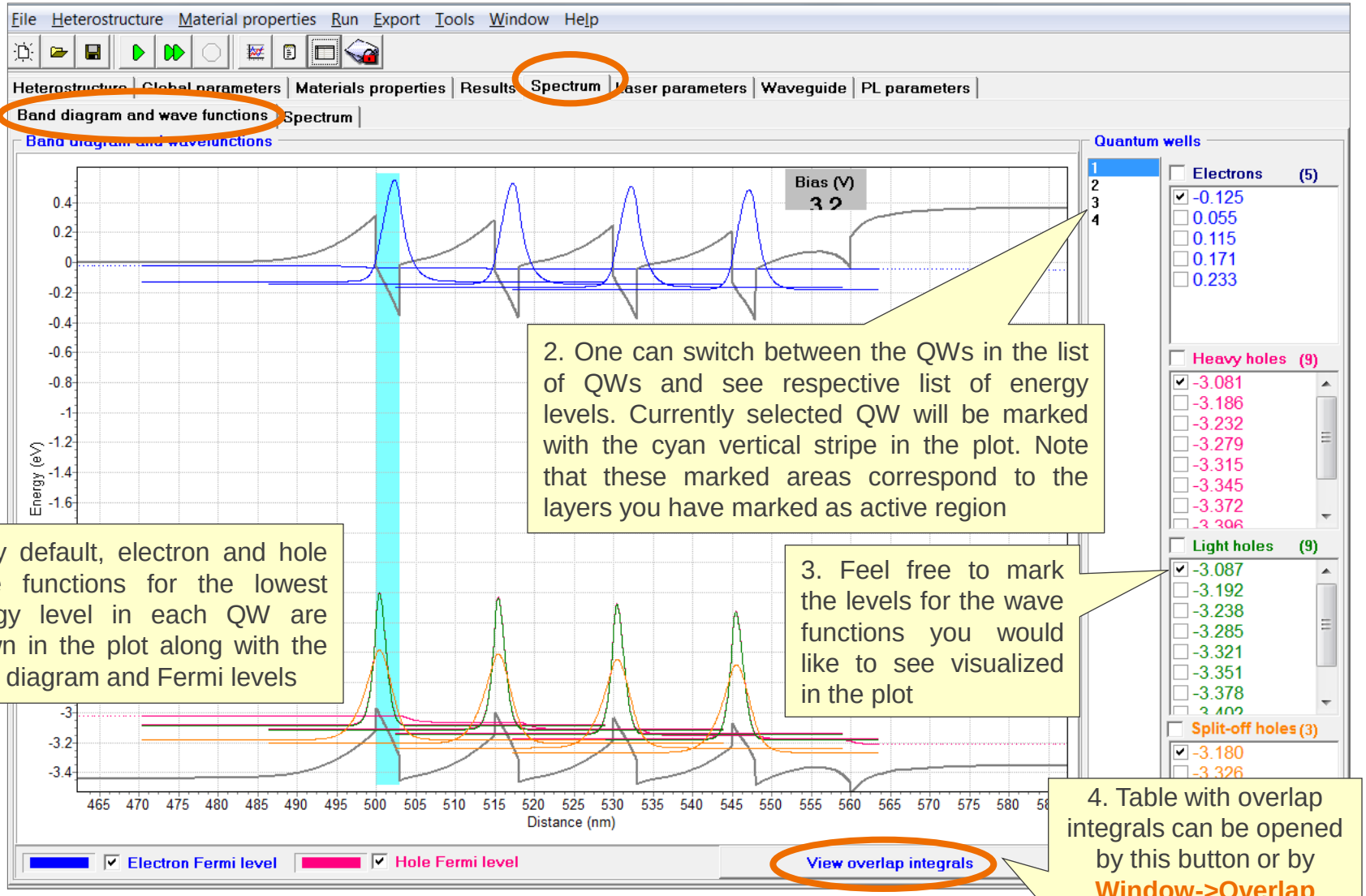
Export to SpeCLED button starts export of the results for its further using by SpeCLED (discussed below in details)



	N	Bias	J	J rad	J nrad	J SRH	J Auger	J n	J p	Jn right	Jp left	IQE	IQE QW	Inj eff	m	Peak WL
☑	1	2.5	3.071E-06	7.000E-08	001E-06	3.000E-06	1.003E-09	3.071E-06	3.071E-06	2.877E-26	1.092E-29	0.0228	0.0228	0.6482		
☑	2	2.6	4.713E-05	3.129E-06	0E-05	4.396E-05	4.195E-08	4.713E-05	4.713E-05	2.576E-12	3.209E-11	0.0664	0.0663	0.5929	1.4164	
☑	3	2.7	0.0008	0.0001	7	0.0007	1.872E-06	0.0008	0.0008	1.401E-10	1.448E-09	0.1701	0.1697	0.6714	1.3643	
☑	4	2.8	0.0185	0.0056		0.0129	9.964E-05	0.0185	0.0185	7.184E-09	4.393E-08	0.3005	0.2999	0.8511	1.2320	
☑	5	2.9	0.4711	0.1990		0.2658	0.0064	0.4711	0.4711	3.590E-07	1.013E-06	0.4223	0.4214	0.9312	1.1957	
☑	6	3	8.4021	4.3827		3.6067	0.4126	8.4021	8.4021	1.376E-05	2.080E-05	0.5216	0.5202	0.9662	1.3426	
☑	7	3.1	70.2334	38.4757		9613	8.7955	70.2330	70.2329	0.0005	0.0004	0.5478	0.5453	0.9704	1.8217	
☑	8	3.2	286.0739	153.4093	1	112	59.7364	286.0701	286.0607	0.0132	0.0038	0.5363	0.5320	0.9686	2.7543	
☑	9	3.3	698.3882	360.5123	3	6	190.3475	698.3679	698.0184	0.3698	0.0203	0.5162	0.5100	0.9662	4.3340	
☑	10	3.4	1336.5880	658.4858	6		424.3949	1336.5080	1328.1730	8.4159	0.0807	0.4927	0.4844	0.9554	5.9593	
☑	11	3.5	2410.0070	1071.9150	12		807.7733	2409.6980	2291.0500	118.9566	0.3090	0.4448	0.4351	0.8939	6.5617	

To compute wave functions and **spectrum,** select the row in the table that contains the desired bias (it will get highlighted blue) and press the button that **looks like spectrum.** Once the computations are complete, **Spectrum** tab is opened, see the next slide

Step 5: Energy levels, wave functions, spectrum



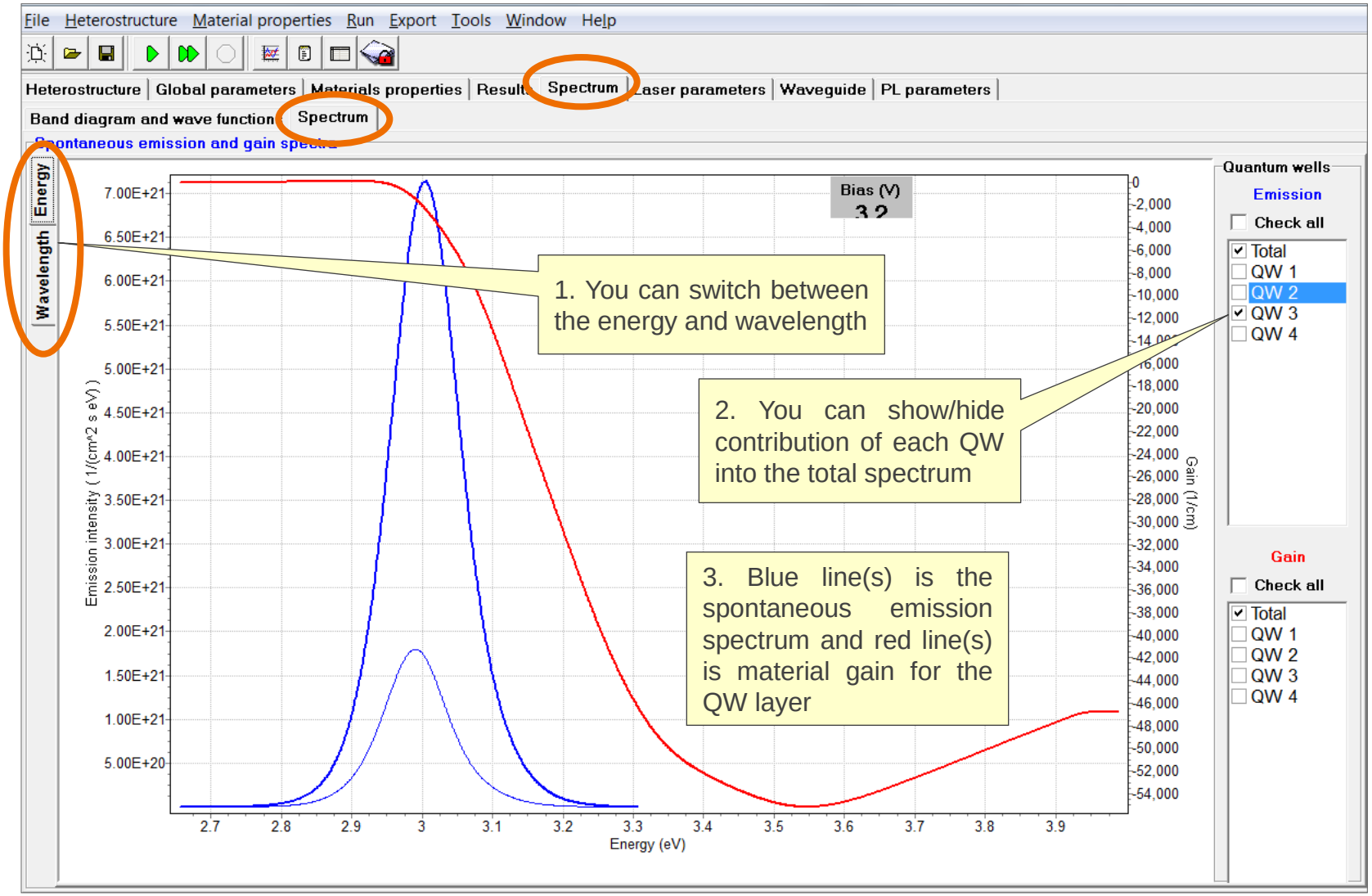
1. By default, electron and hole wave functions for the lowest energy level in each QW are shown in the plot along with the band diagram and Fermi levels

2. One can switch between the QWs in the list of QWs and see respective list of energy levels. Currently selected QW will be marked with the cyan vertical stripe in the plot. Note that these marked areas correspond to the layers you have marked as active region

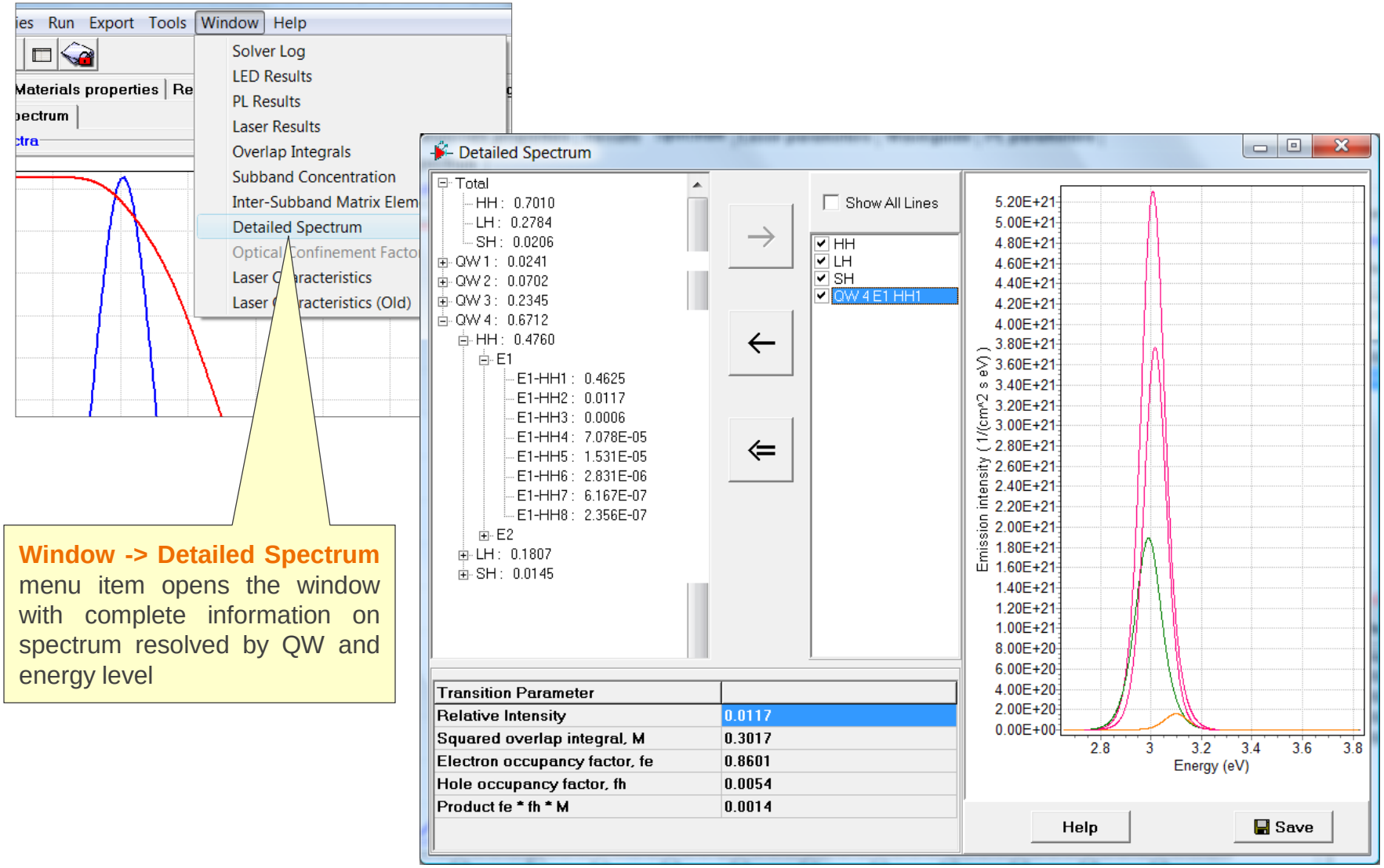
3. Feel free to mark the levels for the wave functions you would like to see visualized in the plot

4. Table with overlap integrals can be opened by this button or by **Window->Overlap Integrals** menu item

Step 5 (Continued): Emission and gain spectrum

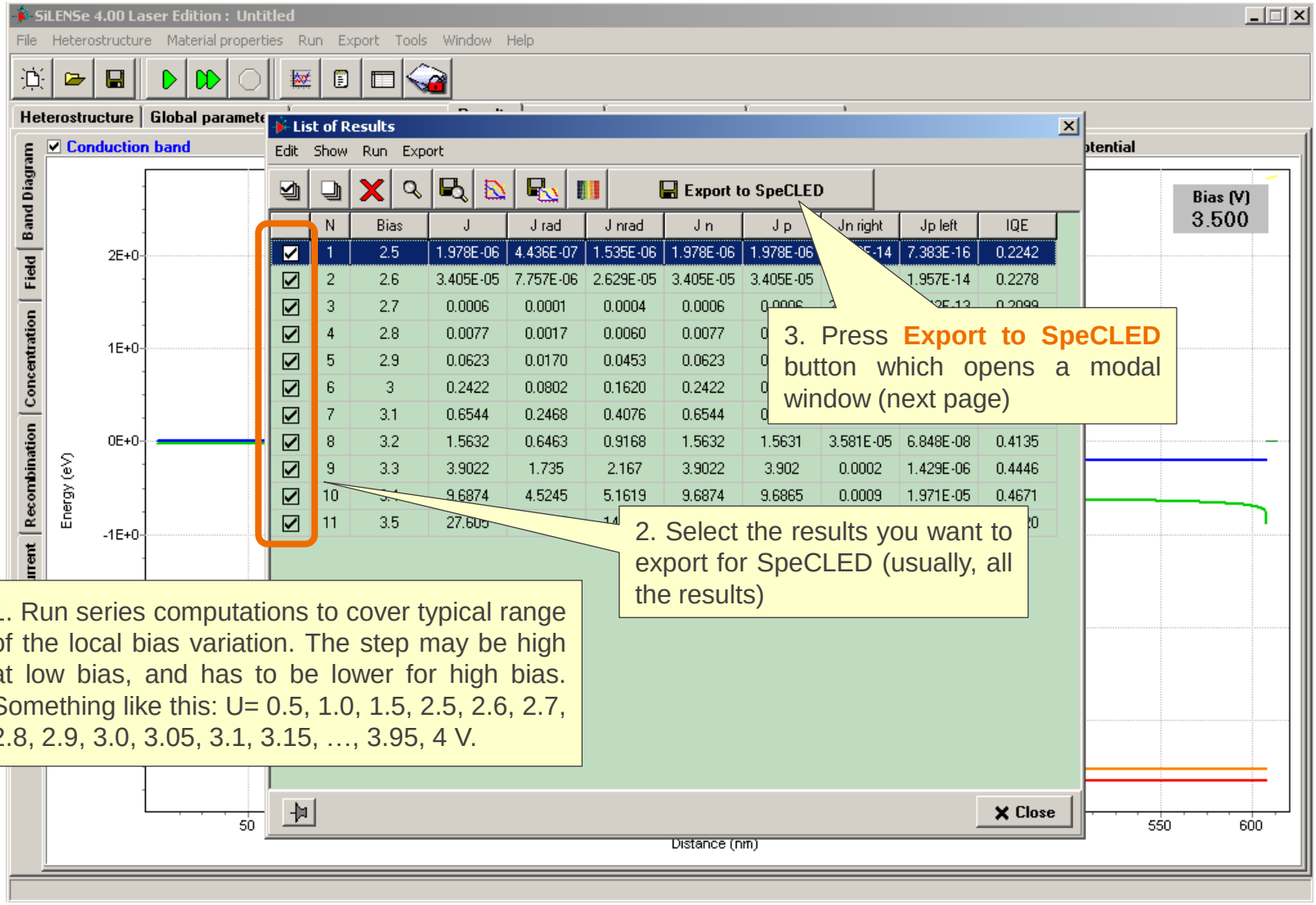


Step 5 (Continued): Detailed spectrum

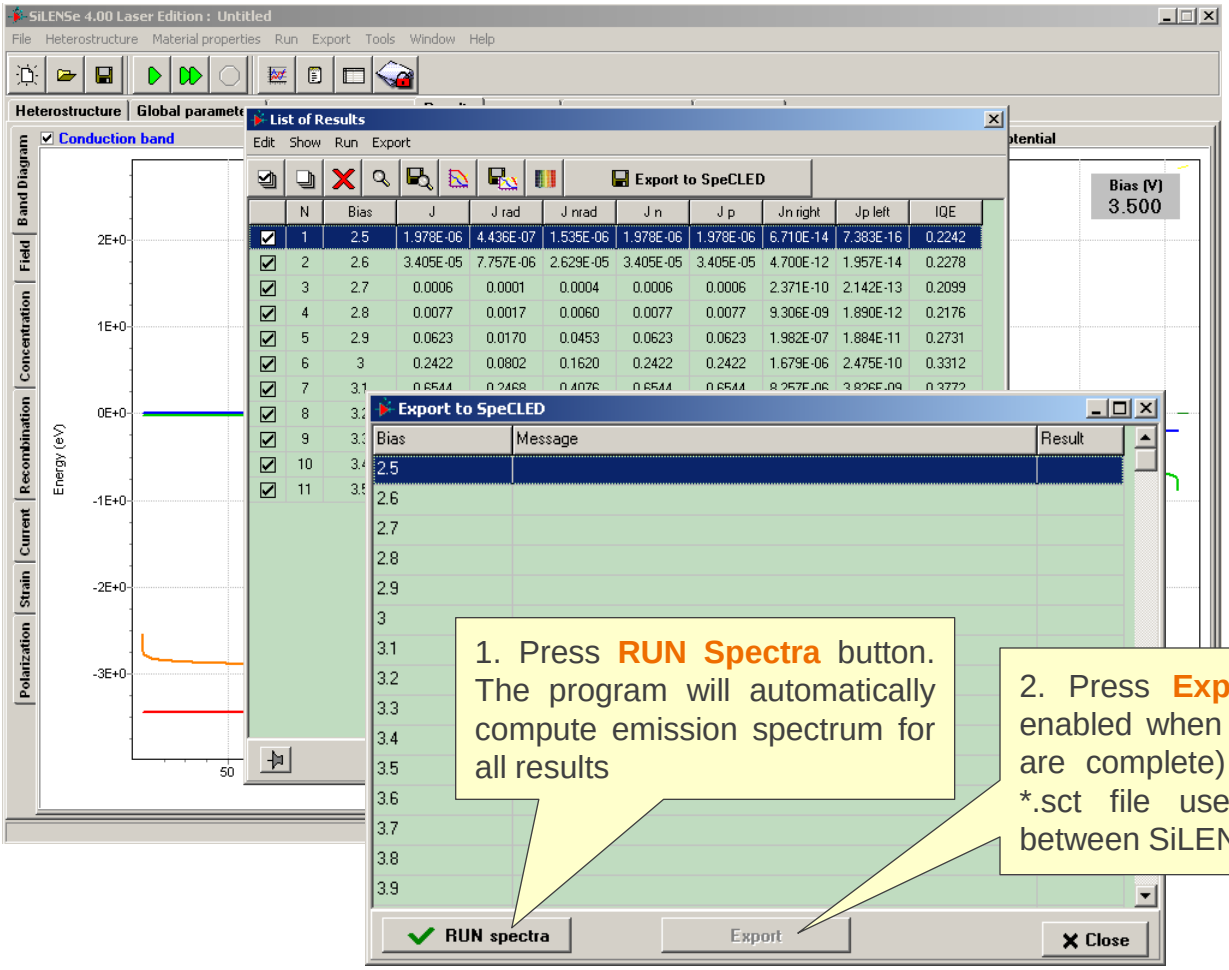


Window -> Detailed Spectrum menu item opens the window with complete information on spectrum resolved by QW and energy level

Step 6: Preparing input data for SpeCLED



Step 6 (Continued): Preparing input data for SpeCLED



1. Press **RUN Spectra** button. The program will automatically compute emission spectrum for all results

2. Press **Export** button (it appears enabled when spectrum computations are complete) and save data to an *.sct file used for data exchange between SiLENSe and SpeCLED

3. To run **SpeCLED** simulations with account for self-heating effects, one needs to repeat the described steps for a certain temperature range with a step of 10-50K (for instance, T = 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 500 K)

End of Tutorial 1

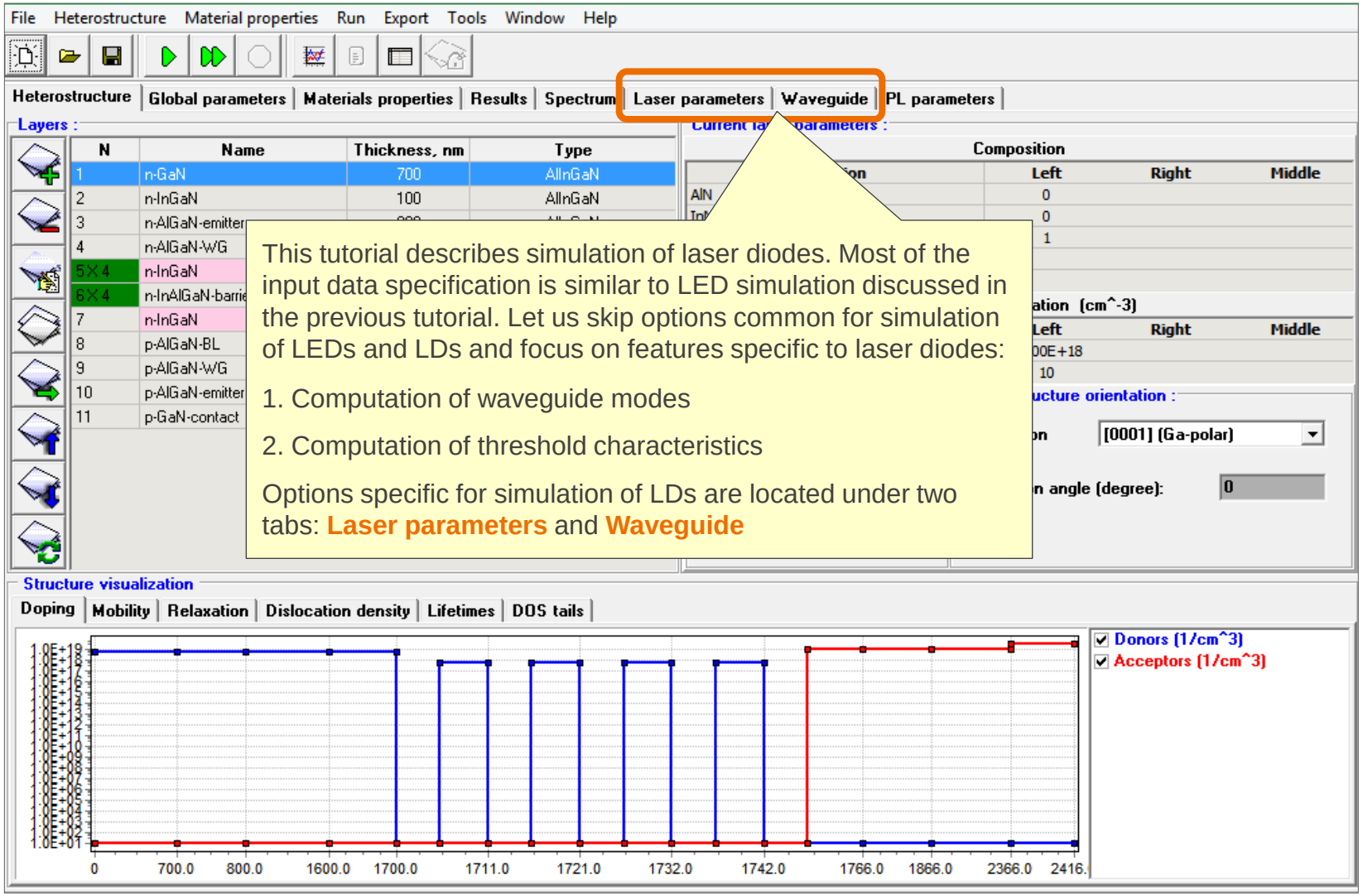
Tutorial 2

SiLENSe 5.10 & SiLENSe Laser Edition 5.10

Using SiLENSe for Modeling of Lasers:

Simulation of InGaN MQW UV laser diode

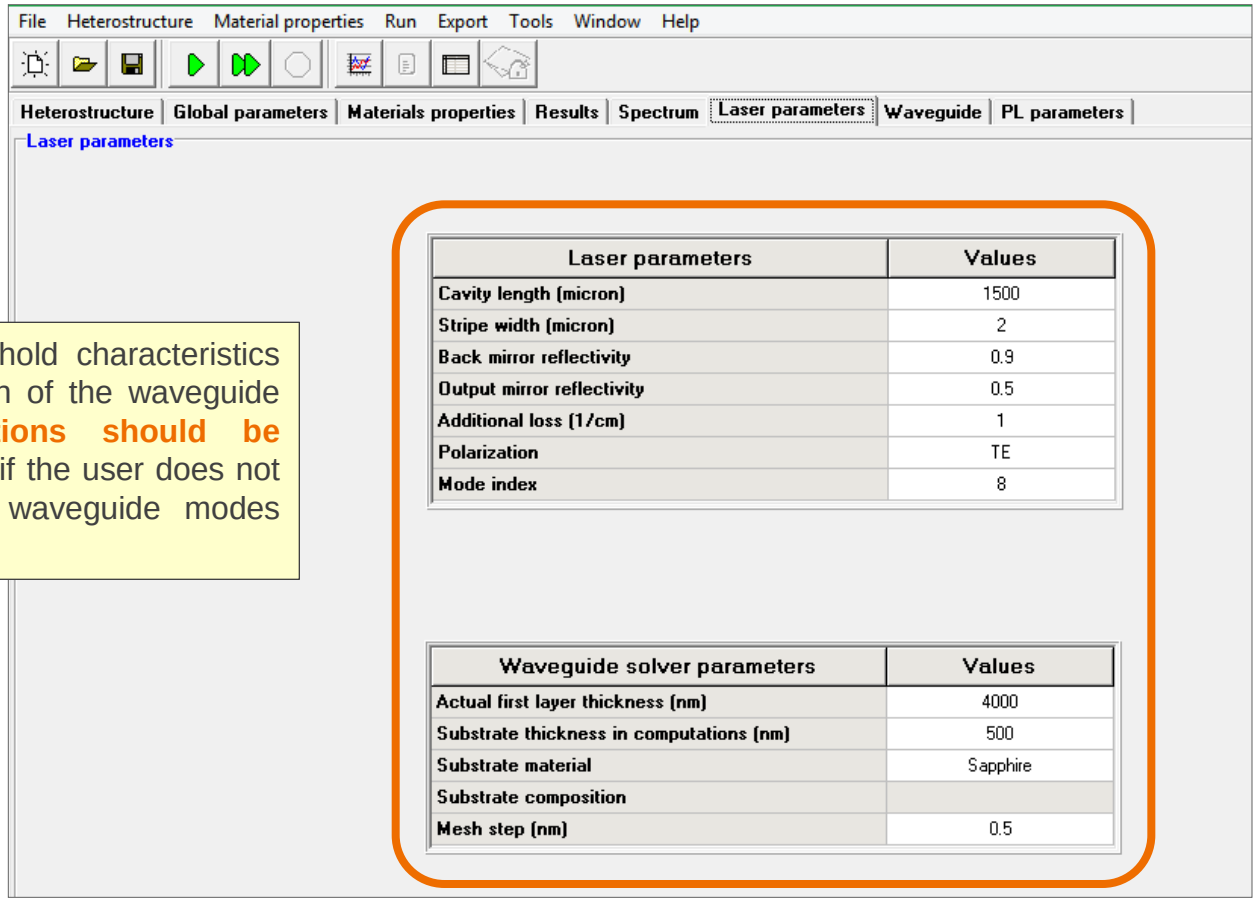
Features specific to laser diodes



Specifying options specific for LDs

Computation of the waveguide modes is done independently from computation of the band diagram. However, it also uses the **Heterostructure** and **Materials properties** input data. Laser parameters tab contains a number of additional input data for simulation of LDs. They are split into two sections specific to computation of the waveguide modes and to computation of the threshold characteristics, respectively.

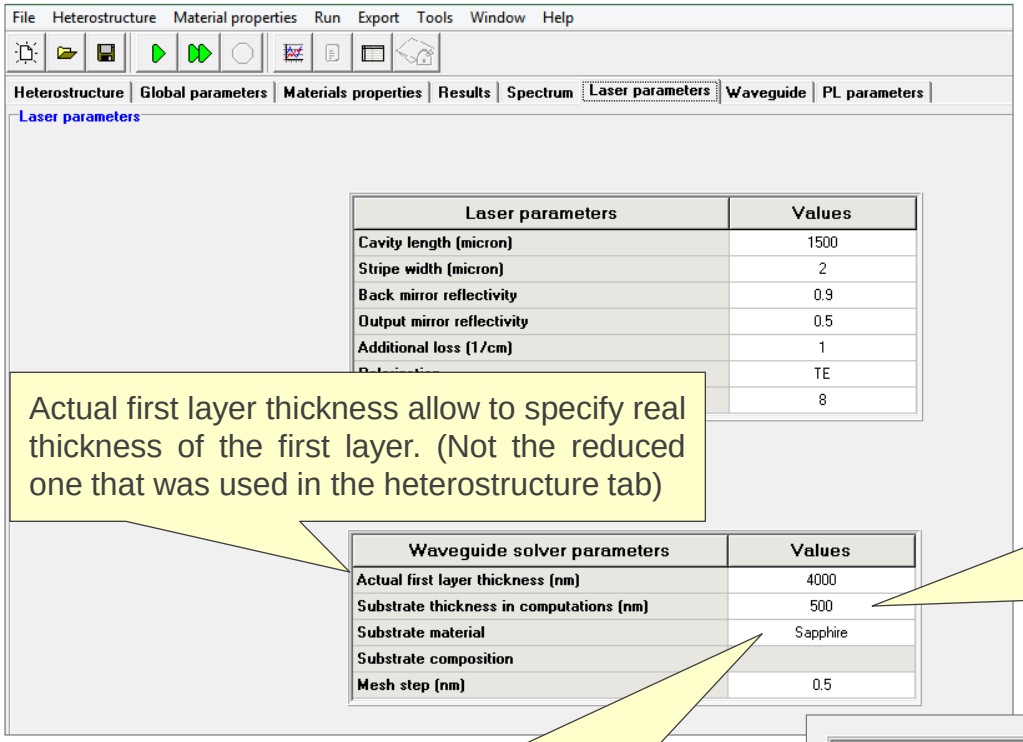
Computation of the threshold characteristics implicitly calls computation of the waveguide modes, so **both sections should be specified correctly** even if the user does not run computation of the waveguide modes directly!



Laser parameters	Values
Cavity length (micron)	1500
Stripe width (micron)	2
Back mirror reflectivity	0.9
Output mirror reflectivity	0.5
Additional loss (1/cm)	1
Polarization	TE
Mode index	8

Waveguide solver parameters	Values
Actual first layer thickness (nm)	4000
Substrate thickness in computations (nm)	500
Substrate material	Sapphire
Substrate composition	
Mesh step (nm)	0.5

Specifying parameters for computation of waveguide modes

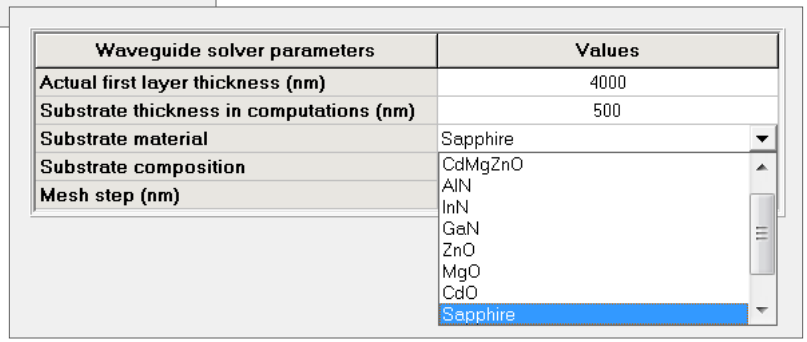


Unlike the carrier transport in LEDs, waveguide modes may depend on the substrate. As you might remember, some reduced thickness is specified for the first and last layers at the stage of the heterostructure modeling, because remote parts of homogeneous bulk n-region do not affect p-n junction and the light generation. However, whole **first layer and even substrate may be important for computation of the waveguide modes**

Actual first layer thickness allow to specify real thickness of the first layer. (Not the reduced one that was used in the heterostructure tab)

Substrate usually has a thickness ~100 times higher than the heterostructure. However, confined modes exponentially decay in the substrate. Substrate thickness in computations should be at least 2-3 decay lengths

To choose the substrate material, click in the respective input field. A drop-down list will appear. If the material you choose is an allow, specification of composition will be required

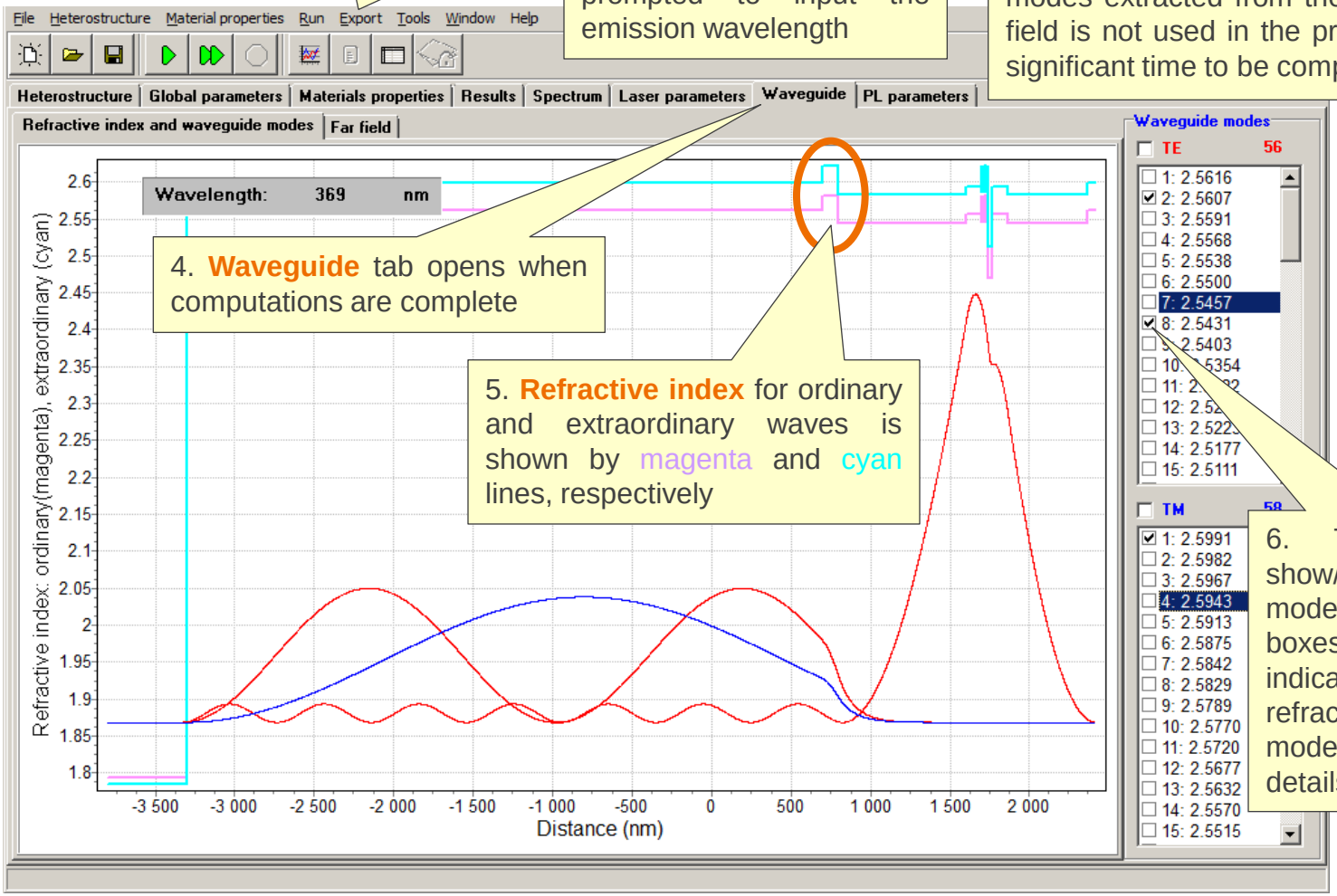


Computation of waveguide modes

1. Use **Run -> Waveguide Modes** to launch computations from the menu

2. A modal window appears where the user is prompted to input the emission wavelength

3. Next, the user is asked if he/she wants to compute far-field distribution of the modes extracted from the laser edge (far-field is not used in the program, but takes significant time to be computed)

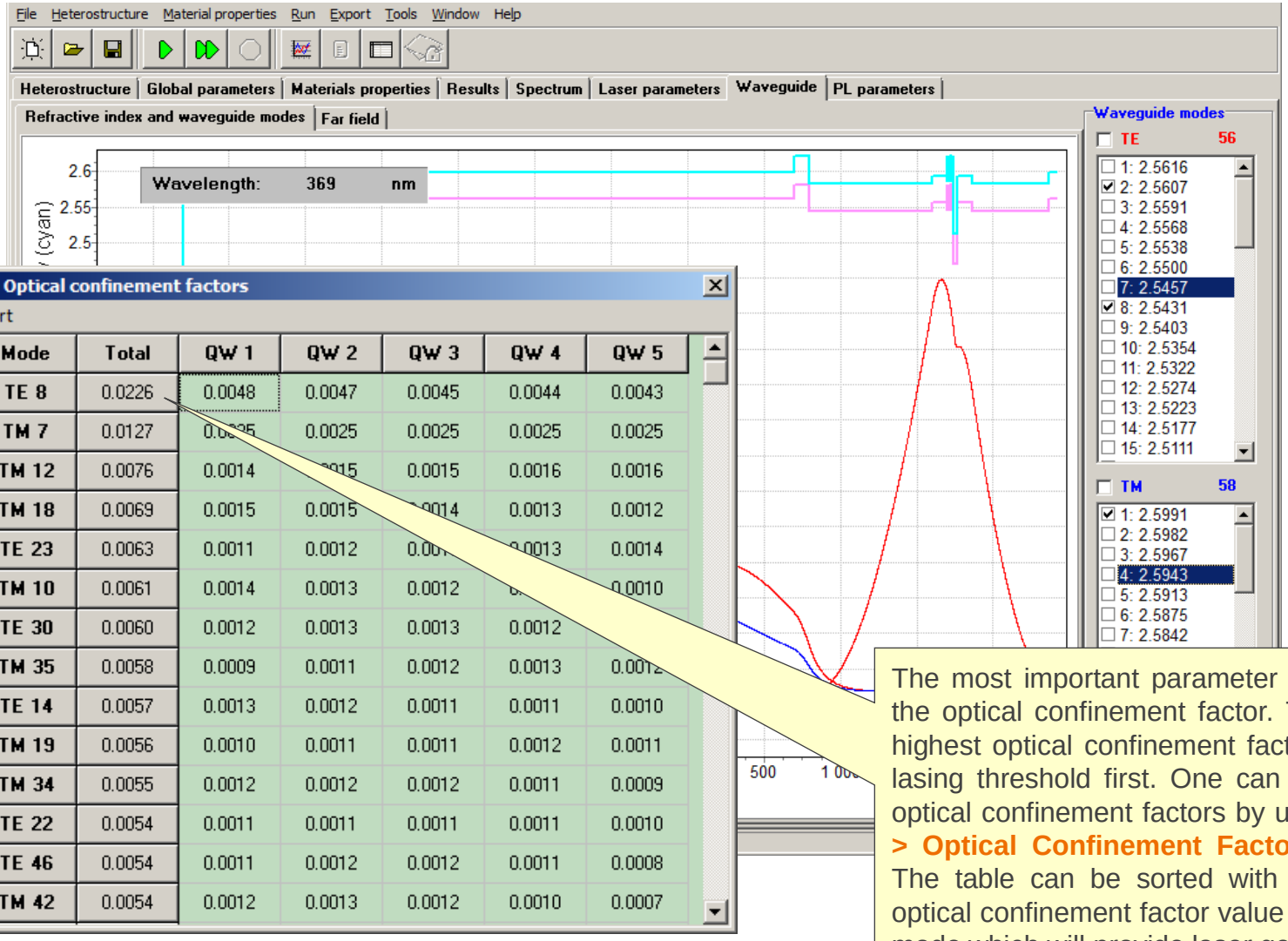


4. **Waveguide** tab opens when computations are complete

5. **Refractive index** for ordinary and extraordinary waves is shown by magenta and cyan lines, respectively

6. The user can show/hide individual modes by the check boxes. The value indicates “effective refractive index” of the mode (see manual for details)

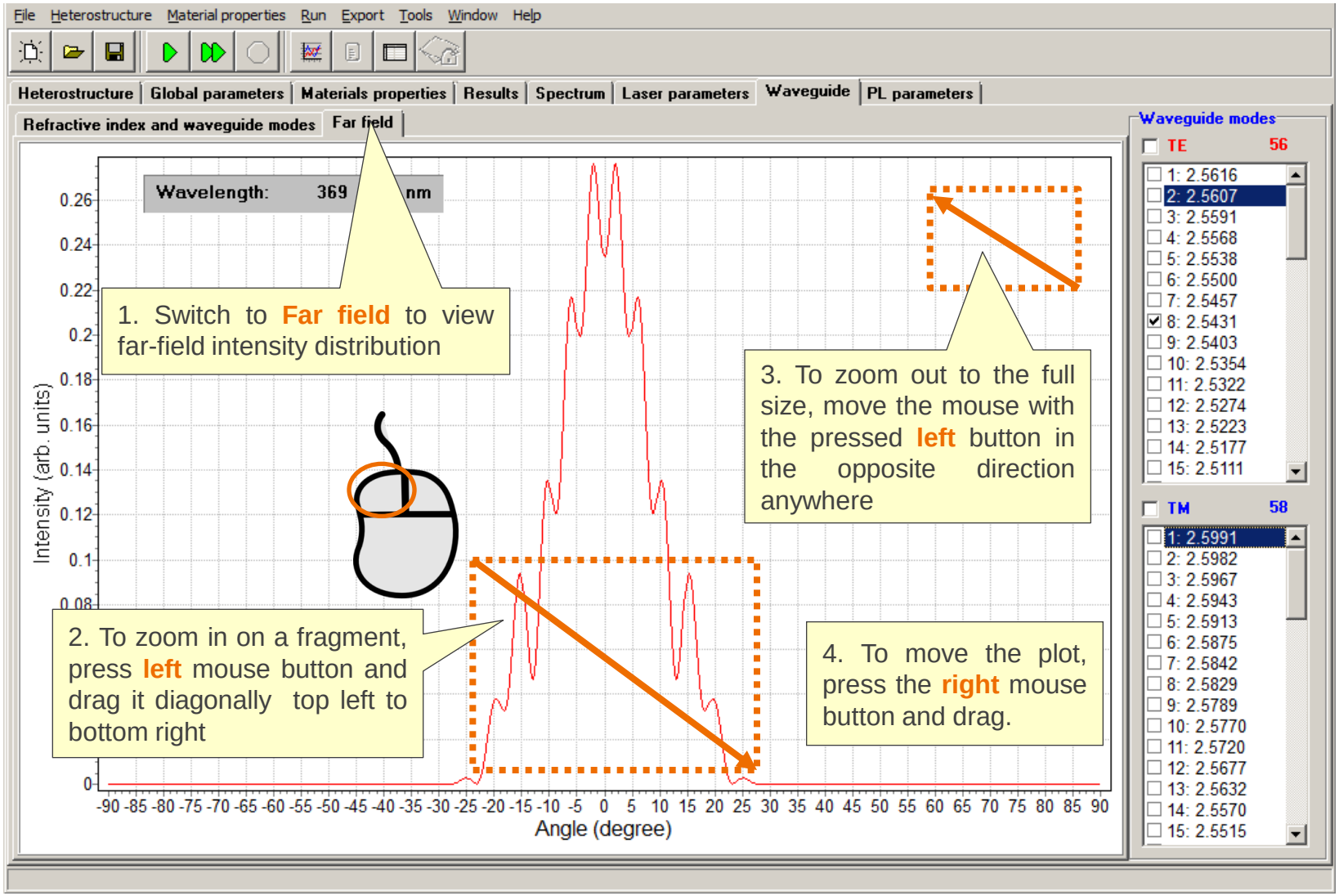
Viewing the confinement factors



Mode	Total	QW 1	QW 2	QW 3	QW 4	QW 5
TE 8	0.0226	0.0048	0.0047	0.0045	0.0044	0.0043
TM 7	0.0127	0.0025	0.0025	0.0025	0.0025	0.0025
TM 12	0.0076	0.0014	0.0015	0.0015	0.0016	0.0016
TM 18	0.0069	0.0015	0.0015	0.0014	0.0013	0.0012
TE 23	0.0063	0.0011	0.0012	0.0013	0.0013	0.0014
TM 10	0.0061	0.0014	0.0013	0.0012	0.0011	0.0010
TE 30	0.0060	0.0012	0.0013	0.0013	0.0012	0.0010
TM 35	0.0058	0.0009	0.0011	0.0012	0.0013	0.0012
TE 14	0.0057	0.0013	0.0012	0.0011	0.0011	0.0010
TM 19	0.0056	0.0010	0.0011	0.0011	0.0012	0.0011
TM 34	0.0055	0.0012	0.0012	0.0012	0.0011	0.0009
TE 22	0.0054	0.0011	0.0011	0.0011	0.0011	0.0010
TE 46	0.0054	0.0011	0.0012	0.0012	0.0011	0.0008
TM 42	0.0054	0.0012	0.0013	0.0012	0.0010	0.0007

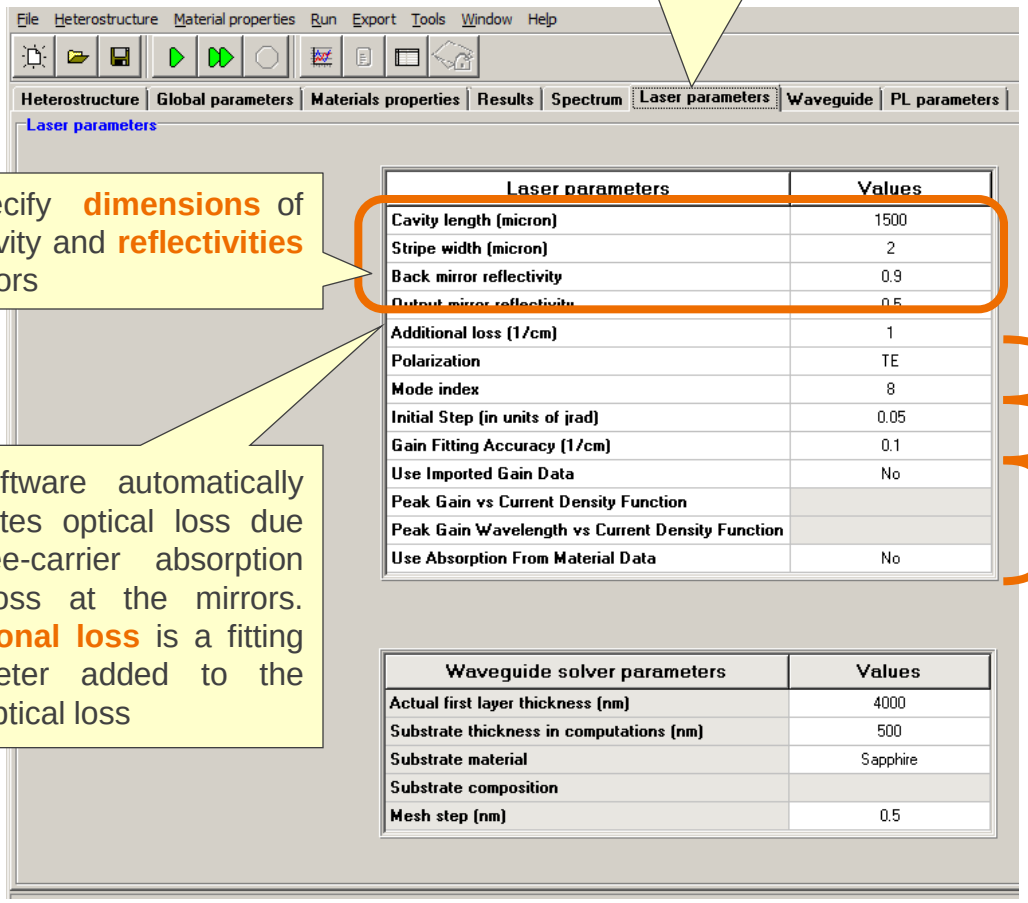
The most important parameter of the mode is the optical confinement factor. The mode with highest optical confinement factor reaches the lasing threshold first. One can see a table of optical confinement factors by using **Window -> Optical Confinement Factors** menu item. The table can be sorted with respect to the optical confinement factor value to help find the mode which will provide laser generation

Viewing the far-field intensity distribution



Parameters for computation of threshold characteristics and laser output power beyond the threshold

1. Go back to **Laser parameters** tab



2. Specify **dimensions** of the cavity and **reflectivities** of mirrors

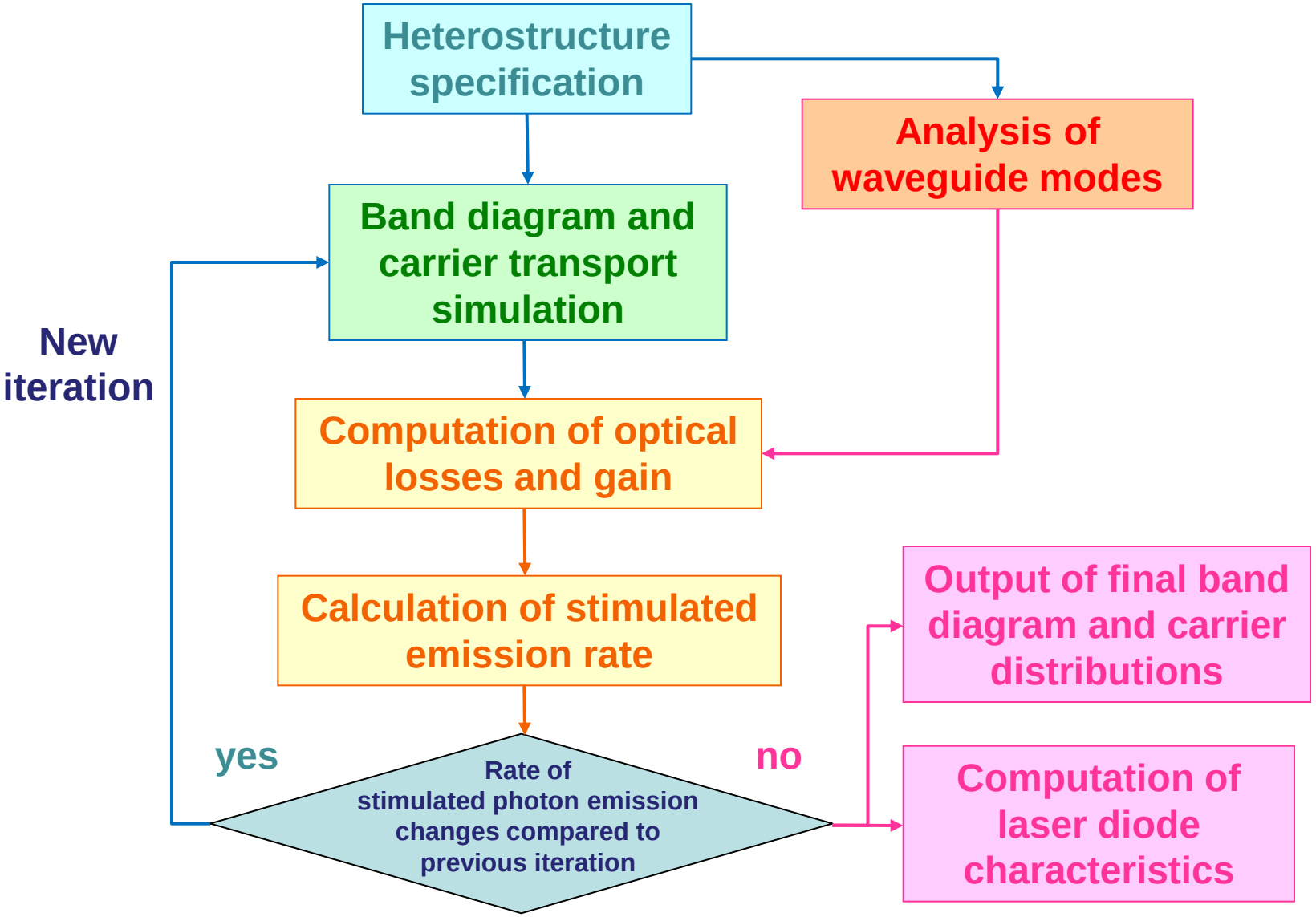
4. Software automatically computes optical loss due to free-carrier absorption and loss at the mirrors. **Additional loss** is a fitting parameter added to the total optical loss

5. Computations of the threshold characteristics are done with respect to a certain waveguide mode. You need to specify the **polarization (TE or TM)** and **Mode index** of the mode having highest optical confinement factor (see before how to find such a mode)

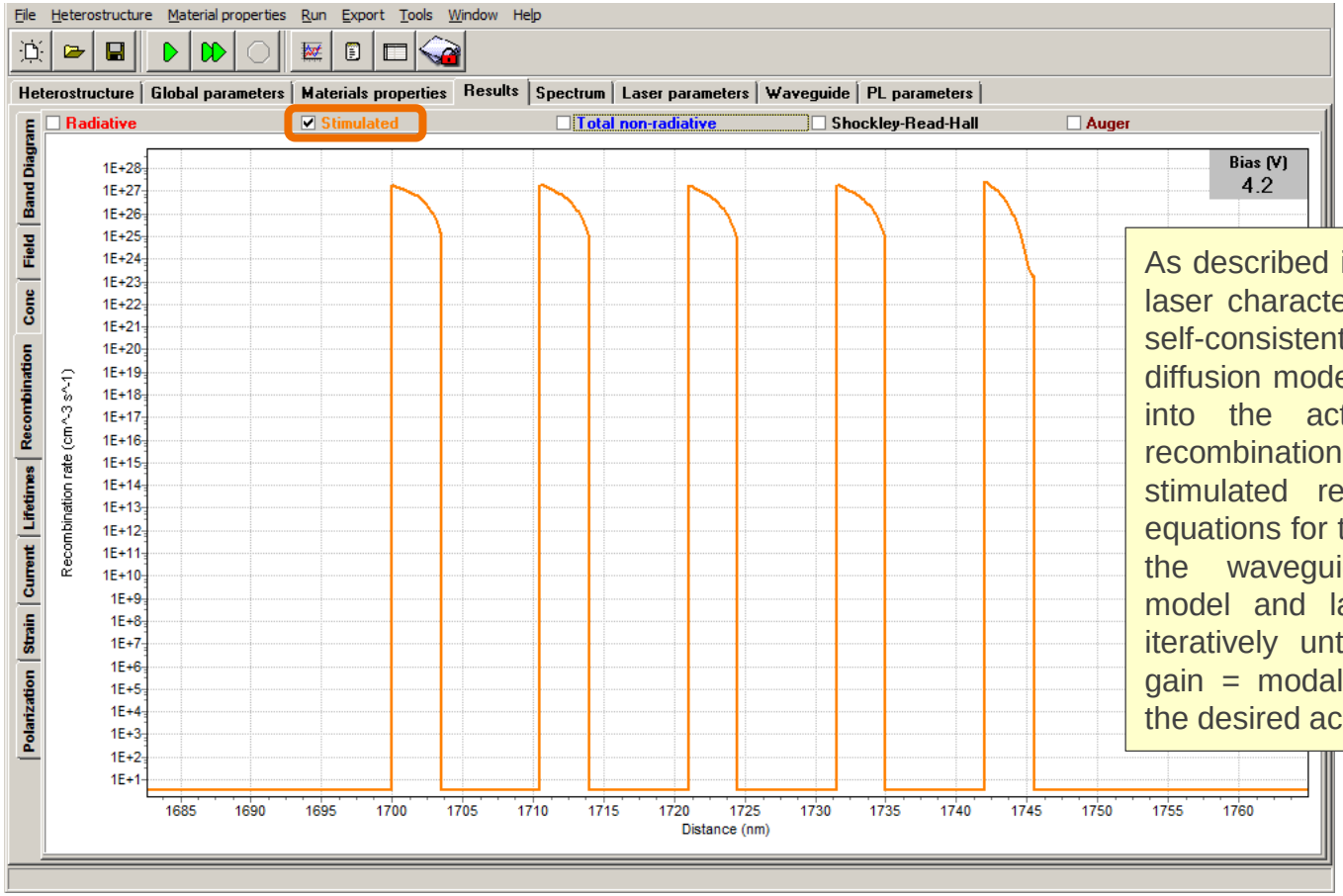
6. Solver settings for self-consistent calculation of the stimulated recombination rate.

7. Options for using imported data on gain instead of ones taken from spectrum calculation. Rarely used option.

Computation flow in self-consistent laser model



Computation of laser characteristics

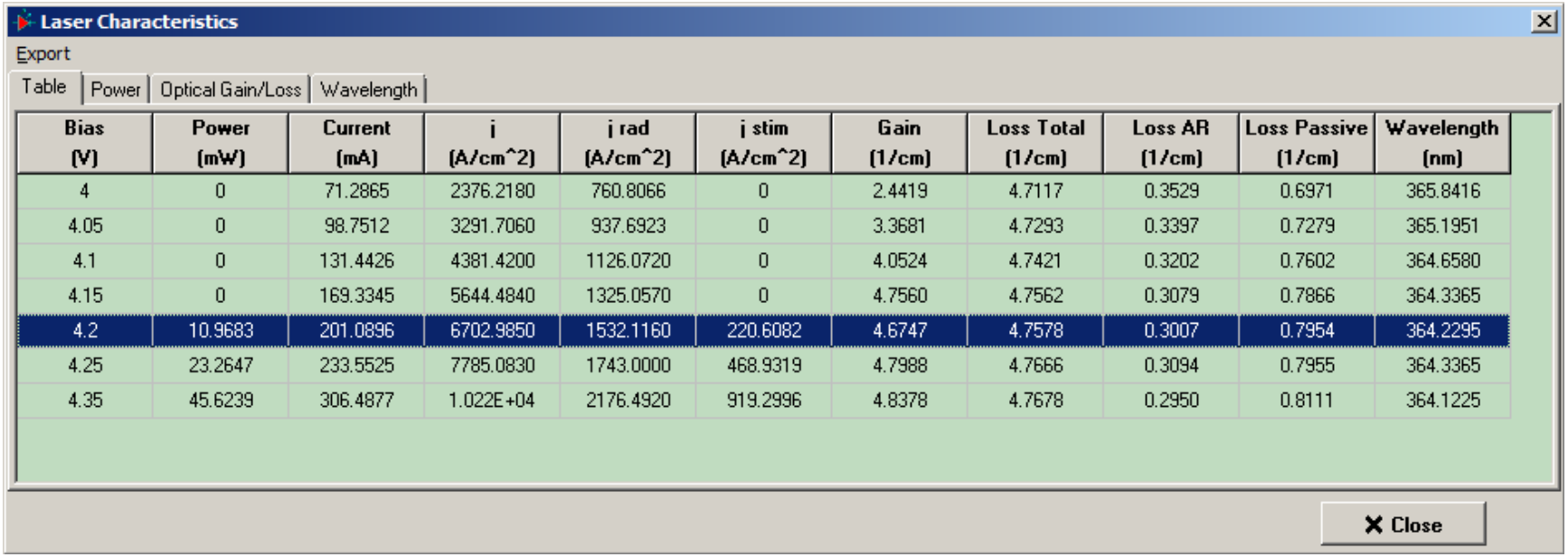


As described in the previous slide, the laser characteristics are computed by self-consistent solution of the drift-diffusion model for the carrier injection into the active region and their recombination there (including stimulated recombination) and rate equations for the number of photons in the waveguide. So, drift-diffusion model and laser model are solved iteratively until the condition “modal gain = modal losses” is fulfilled with the desired accuracy.

Use **Run -> Single Calculation With Laser** or **Run -> Single Calculation With Laser** menu item and specify a bias or a set of biases similarly it is done for LED calculations (see the previous tutorial).

Drift-diffusion calculations look very similar to LED calculation. The only difference is that stimulated recombination is accounted for in the QW layers.

Viewing computed laser characteristics



Laser Characteristics

Export

Table | Power | Optical Gain/Loss | Wavelength

Bias (V)	Power (mW)	Current (mA)	j (A/cm^2)	j rad (A/cm^2)	j stim (A/cm^2)	Gain (1/cm)	Loss Total (1/cm)	Loss AR (1/cm)	Loss Passive (1/cm)	Wavelength (nm)
4	0	71.2865	2376.2180	760.8066	0	2.4419	4.7117	0.3529	0.6971	365.8416
4.05	0	98.7512	3291.7060	937.6923	0	3.3681	4.7293	0.3397	0.7279	365.1951
4.1	0	131.4426	4381.4200	1126.0720	0	4.0524	4.7421	0.3202	0.7602	364.6580
4.15	0	169.3345	5644.4840	1325.0570	0	4.7560	4.7562	0.3079	0.7866	364.3365
4.2	10.9683	201.0896	6702.9850	1532.1160	220.6082	4.6747	4.7578	0.3007	0.7954	364.2295
4.25	23.2647	233.5525	7785.0830	1743.0000	468.9319	4.7988	4.7666	0.3094	0.7955	364.3365
4.35	45.6239	306.4877	1.022E+04	2176.4920	919.2996	4.8378	4.7678	0.2950	0.8111	364.1225

Close

Laser Characteristics window appears after the end of computations

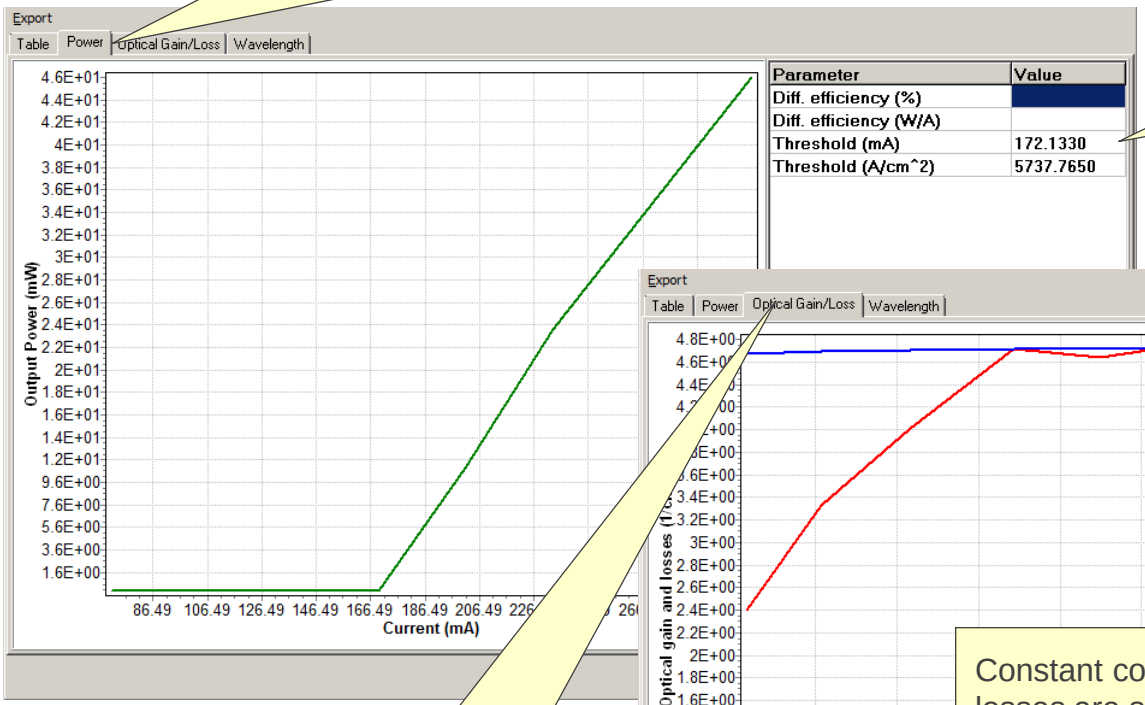
(later one can open it by using **Window -> Laser Characteristics** menu item)

First tab of the window contains a table. From the “Power” column, one can see that threshold is somewhere between 4.15V and 4.2V bias or between 170 mA and 200 mA current, respectively. If necessary, one can split this interval by several bias point by running additional laser computations. Use **Export** menu to store the table as a text file. Other tabs of the window contains a number of plots and some additional values.

Similarly to LED results, the band diagram, carrier concentrations, etc. are stored in the project file. One can see them by using **Laser Results** window (**Window -> Laser Results** menu item). It works very similar to **LED Results** window described in the previous tutorial.

Viewing the results for threshold characteristics

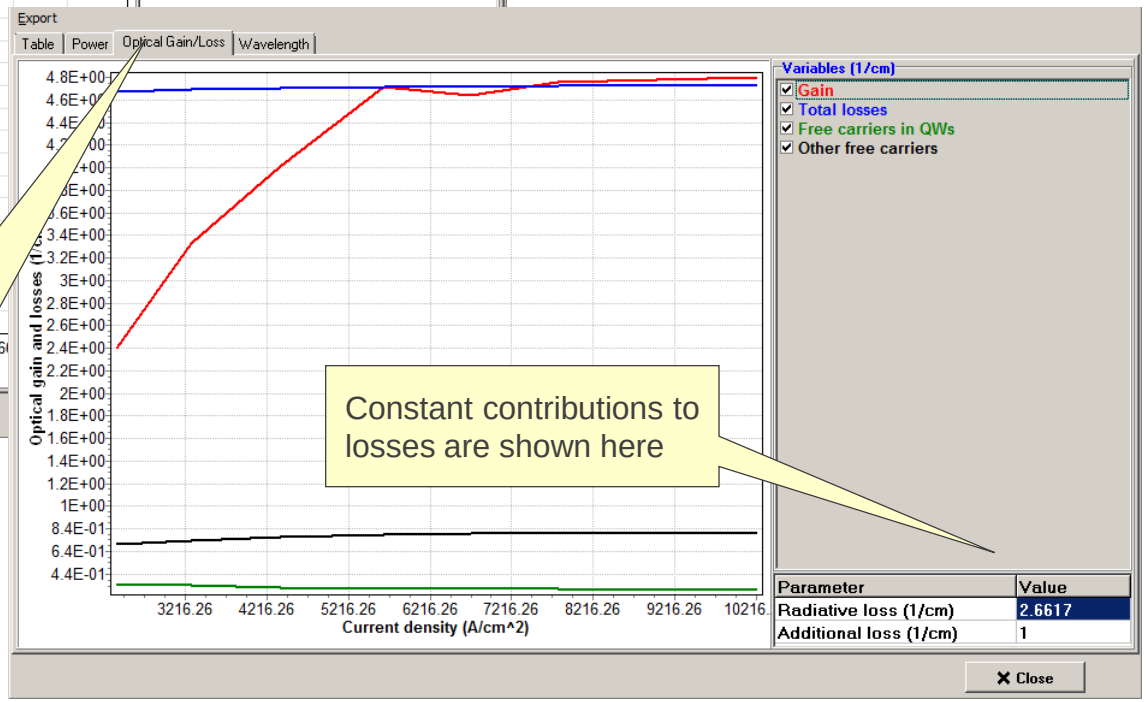
Power tab contains a plot of the output power as a function of current (note that SiLENSe always assumes the linear power increase above the threshold)



Parameter	Value
Diff. efficiency (%)	
Diff. efficiency (W/A)	
Threshold (mA)	172.1330
Threshold (A/cm^2)	5737.7650

Threshold current and the respective current density are shown here

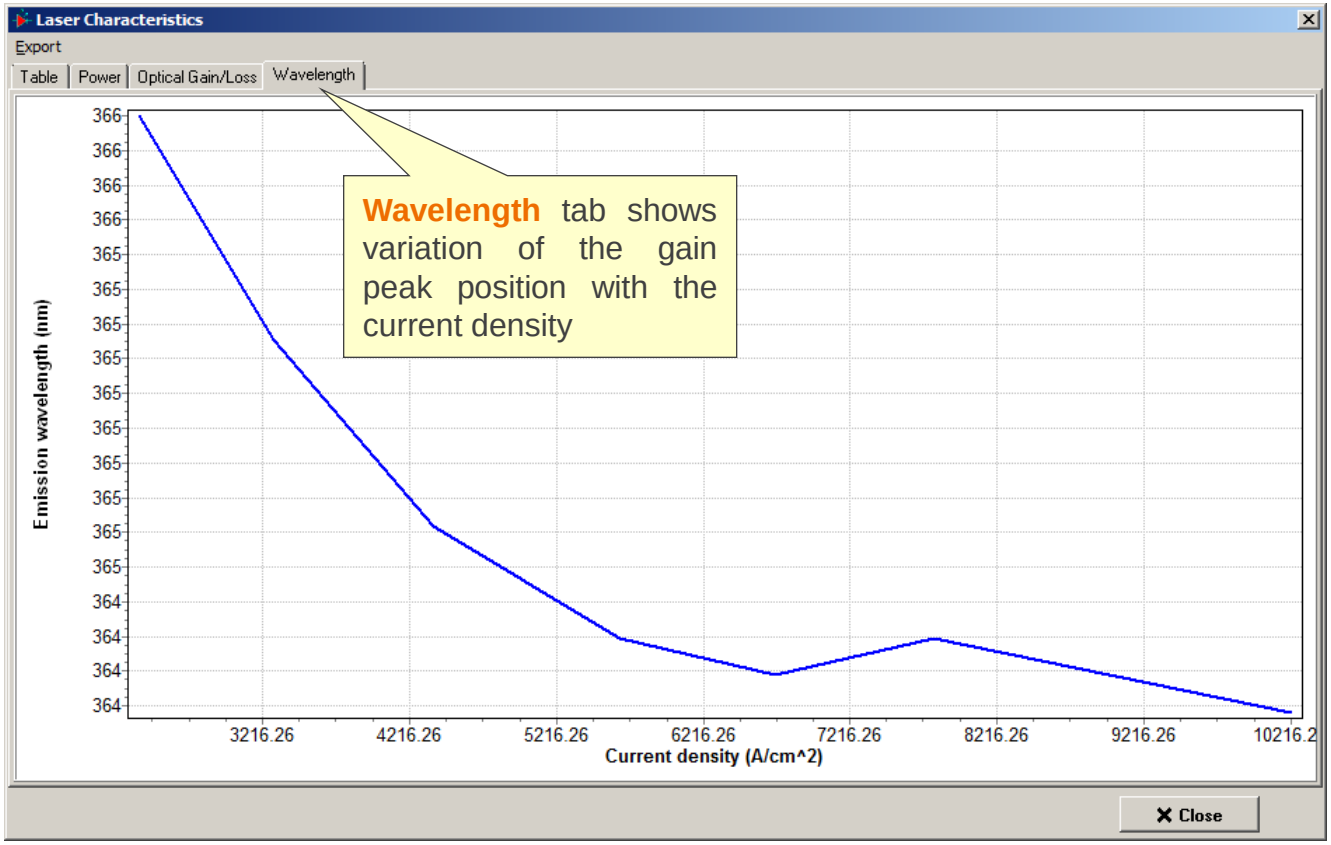
Optical Gain/Loss tab shows variation of the gain and loss as a function of current density



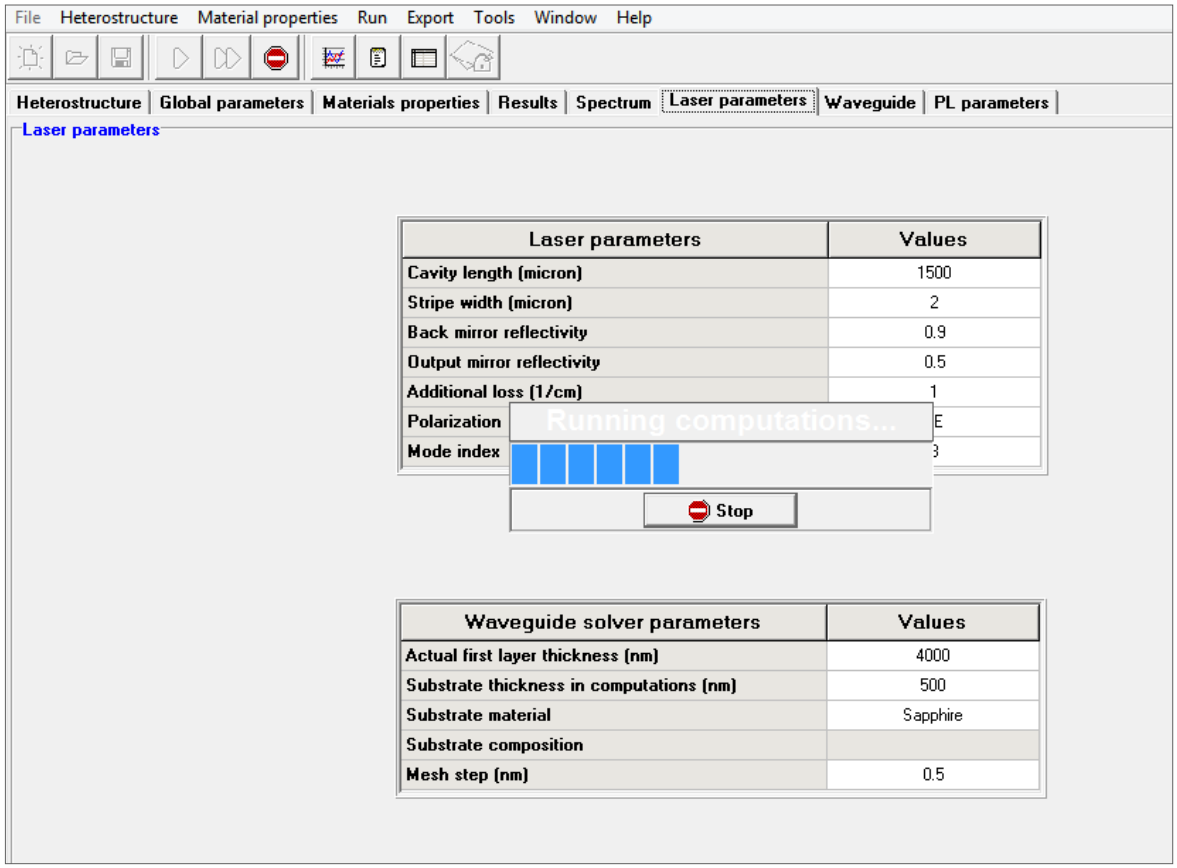
Parameter	Value
Radiative loss (1/cm)	2.6617
Additional loss (1/cm)	1

Constant contributions to losses are shown here

Viewing the results (Continued)



Computation of threshold characteristics (old model)



Simulation results for the old laser model are similar to that for the model with self-consistent treatment of the stimulated recombination. The only difference is that laser output power beyond the threshold is extrapolated linearly by using differential quantum efficiency estimated from the threshold characteristics.

Old model for computations of threshold characteristics uses LED results of band diagram computation. In this simplified model, where is no self-consistent account of the stimulated recombination rate in the drift-diffusion model.

1. First, one needs to run computation of the band diagram and current density for a bias/current range covering the threshold bias/current.

2. Then use **Run->Laser Characteristics (Old)** menu item. During computations, the program seeks for the threshold by doing following tasks for each bias

- Computes gain spectrum and finds its maximum
- Computes the waveguide modes at the wavelength of max gain
- Computes modal gain
- Computes optical losses
- Compares gain and loss