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DFM Your Device?

Simulation Is the Answer

Design for Manufacturing (DFM) has taken off like a rocket in the electronics industry in recent years. Performing process and device simulations on CMOS transistors in a DFM flow have proven to be important in shortening the design cycle and reducing the production cost by improving yield. These are the key elements to why DFM mans the gate to the success of semiconductor foundries and companies.

What about optoelectronics? How far are we from achieiving DFM of optoelectronics? To answer this question, we need to examine the history of the development of optoelectronics innovation and simulation.

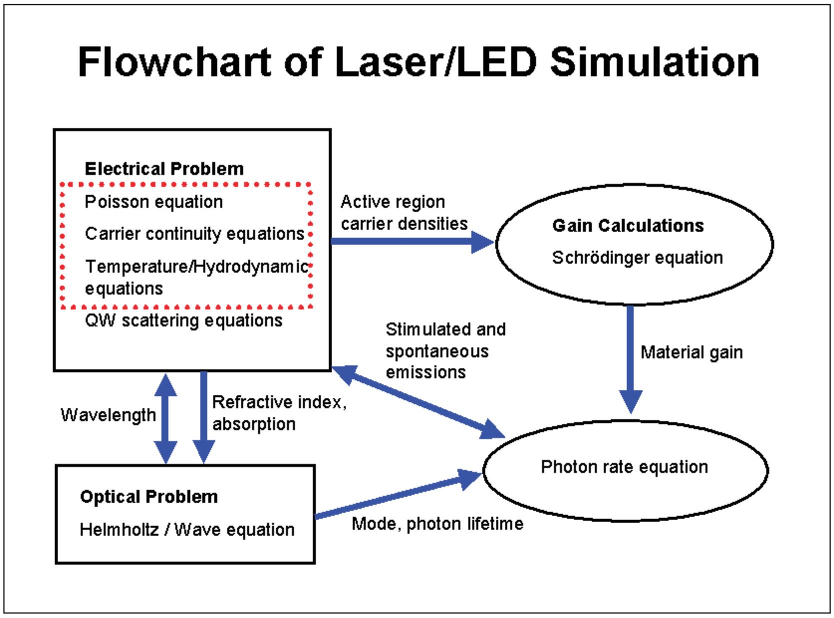

Figure 1: Flowchart connecting various equations needed in the simulation of a semiconductor laser/LED, adopted from Synopsys' Sentaurus Device —Optoelectronics. The equations encased in the red dotted box are used for silicon transistor simulation and are only a subset of the equations needed for a laser/LED simulation.

DFM Optical Challenges

Optoelectronics encompasses the devices that process light by means of electrical flow. At one end are the optical sensors that convert absorbed light into electrical signals. These devices are mostly based on silicon and they can be adapted easily into the DFM flow of electronics. At the other end are the active optical devices that convert electrical signals into light, such as lasers and light emitting diodes (LEDs), mainly constituted from III-V direct gap com-

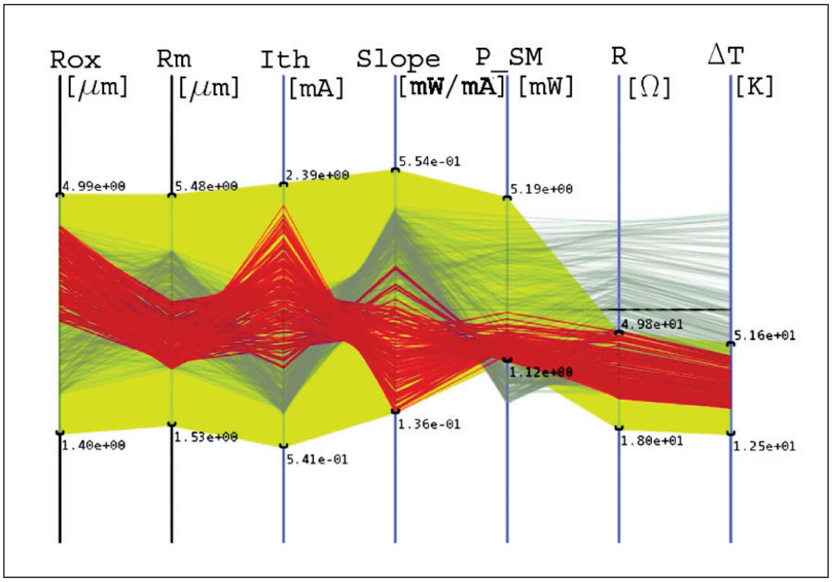

Figure 2: Parallel coordinate plot from Synopsys' Sentaurus TFM —PCM studio option showing correlation between design variation of metal contact radius (Rm) and oxide aperture radius (Rox), and desired output characteristics of threshold current (Ith), slope efficiency (slope), single mode power (P_SM), differential resistance (R), and maximum change in temperature (ΔT).

pound semiconductors. This article will focus mainly on active optoelectronics devices. Active optoelectronics devices are more difficult to simulate than silicon electronic transistors. Consider this: To simulate the working behavior of a transistor, one only needs to solve the Poisson equation, carrier continuity equations and thermal equation with relevant boundary conditions, and quantum-mechanical equations for very small transistors. To simulate a laser or LED, one needs to solve not only the same equations as for the transistor, but also equations that model electron and hole scattering into quantum wells (QWs), the probability of light production (optical gain calculations), the optical mode pattern of the laser/LED structure, and a coupling equation that balances the photon production (light treated as particles) with the electron-hole recombination (See Figure 1).

Besides the computational burden of solving the optoelectronic problem set, the growth technology of III-V compound semiconductors was not very mature, (i.e. producing high-quality and low-defect material was a problem). Material parameters were not well known, and if material parameters could not be calibrated, it didn't make sense to perform a complete 2D or 3D simulation. The optoelectronics industry relied mainly on experimental optimization — a costly and time-consuming process.

Calibrate OE Parameters

In the late 1990s, growth technology of III-V compound semiconductors began to reach a mature state. On top of that, computers were becoming more powerful. New models in quantum well scattering and transport were also developed. All these factors assimilate into a suitable stage for full 2D and 3D simulation of semiconductor lasers/LEDs. The problem of a laser/LED simulation is not only about solving a set of complicated equations simultaneously, but also about fulfilling the large parameter space associated with each device. Calibration of this parameter space is key to using the simulator as a predictive tool and hence DFM of optoelectronics.

The big question is how does one calibrate the parameter space of a semiconductor laser/LED? The answer hovers around which parameters are directly measurable and which have to be indirectly deduced. Do not forget that most of these parameters are functions of temperature, carrier density, etc. Therefore, they are constantly changing with different current injection conditions. There is also the constraint of measurable operating characteristics of the laser/LED — light power-current-voltage (L-I-V) characteristics, far field mode pattern, relative intensity noise (RIN), laser/LED output spectrum, and modulation response. Note that current spreading, temperature distribution, and even optical intensity within the laser/LED are not directly measurable in an experimental setting. Yet, these are the operating behaviors a designer needs to use for optimization and failure analysis. These non-measurable quantities, however, can only be obtained from accurate simulations.

As an example, one can take the following systematic route to calibrate the parameters of a laser simulation:

1. With the measured gain of the laser using, for example, the Hakki-Paoli technique, adjust the parameters of material gain computed from the k.p method. These parameters include the deformation potential, Luttinger Kohn parameters, and broadening effects. For ternary and quaternary QW material, one might want to interpolate these parameters from their respective binary constituents.
2. With the threshold current and thermal rollover characteristics, adjust the Shockley-Read-Hall (SRH) recombination lifetime, Auger recombination coefficients, optical losses, leakage current parameters, QW capture rate, etc.
3. With the current-voltage characteristics, adjust the SRH recombination lifetime, the Auger recombination coefficients, and carrier mobilities (i.e. resistance).
4. With the slope efficiency of the light power-current curve, determine the leakage current via the injection efficiency of the laser, and adjust the photon lifetime. The injection efficiency is another avenue for adjusting the SRH recombination lifetime and the Auger recombination coefficients.
5. With the modulation response, adjust the photon lifetime, carrier lifetimes, and any capacitances and inductances introduced in the device design. The carrier lifetime is affected by the SRH recombination lifetime and the Auger recombination coefficients.
6. With the relative intensity noise (RIN), further refinements of the parameters mentioned above can be done.
7. With the far field mode pattern, adjust the refractive index profile.

In a similar manner, a systematic calibration plan for LED simulation can be devised. The calibration of these parameters requires a robust laser/LED simulator that contains all the required advanced physical models and vectorial optical solvers. Synopsys' Sentaurus Device — Optoelectronics has essential advanced models that deliver predictive capability once it is calibrated.

Design vs. Output

Once the fundamental laser/LED parameters are calibrated, one would then be able to proceed to optimize various design constraints to achieve desirable and measurable optimal output characteristics. We consider three classes of devices: (1) Edge emitting lasers, (2) VCSELs, and (3) LEDs. For all these classes of devices, the common entity is the active QW design. Variations for the QWs include number, thickness, and strain and bandgap offset of QWs. The desired output behaviors are high internal quantum efficiency and output spectrum within a confined wavelength range. For each class of devices, the other device variations and desired output characteristics are outlined.

Edge emitting lasers. The ridge geometry has become the dominant design for edge emitting lasers. Possible design variations include width, height and slope of tapering of the ridge, thickness of the guiding layers, facet reflectivities, distributed feedback (DFB) and distributed Bragg reflector (DBR) grating design, heat sink position, current blocking region design, and doping of the bulk regions. Desired output characteristics include low threshold current, high slope efficiency, stable output wavelength, high thermal rollover point, optical mode shape and aspect ratio that conform to an optical fiber, large bandwidth for modulation response, high output light power, reduced filamentation, smallest peak temperature, least mode competition, least sideward power leakage, and least spatial hole burning.

VCSELs. The oxide confined VCSEL has become the commercial design standard for vertically emitting lasers. Possible design variations are radii of the metal contact and oxide apertures, radius of the mesa, number of pairs of DBRs, position of the heat sinks, doping distribution in the VCSEL, and tunneling junction design. Desired output characteristics could be low threshold current, high slope efficiency, stable output wavelength with minimal shifting, high thermal rollover point, single-mode purity, large bandwidth for modulation response, high output power, smallest peak temperature, least optical scattering losses, and least spatial hole burning.

LEDs. Common LED structures include the ATON and TIP (truncated inverse pyramid) designs that are trademarks of two major international LED companies. Possible design variations are slope of tapering of the ATON and TIP structures, height of the substrate region, patterned design of the contacts, doping distribution, positioning of the reflectors, and current blocking regions. Desired output characteristics could be the output spectrum, high extraction efficiency, maximal current spreading, directional radiation pattern, and photon recycling effects/enhancements.

The correlation between device design variation and desired output characteristics can be robustly and accurately simulated by Synopsys' Sentaurus Device. While it is very difficult to determine an exact set of design variations that will achieve a set of optimal output characteristics — including manufacturing process fluctuations — using process compact models (PCM) one can build a parallel coordinate plot showing how various design variation and manufacturing process fluctuations directly affect the designated output characteristics (See Figure 2). On top of the design variations and manufacturing process fluctuations, cost and time factors need to be included — some processing steps are more cost-effective and faster than others. All these factors must be taken in unison to determine the set of design parameters that will be most cost effective, be stable for manufacturing, and gain the maximum yield.

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