Optoelectronic Simulation: An Industrial R&D Perspective

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Rapid deployment of sophisticated optoelectronic devices with increasingly stringent performance requirements and the necessity to meet aggressive cost targets requires extensive use of simulation tools in the design process. The substantially more mature silicon integrated circuit business integrates simulation into each step of technology development from process development through device design and into circuit design. The suite of available tools forms a hierarchy from circuit design tools based on empirical compact models down through microscopic device and material process simulations and even to more fundamental simulations (e.g. atomic scale theory of material properties and Monte Carlo simulations of hot carrier physics). These simulation tools form a closely linked chain within which the results of one level of simulation can be fed into the next level. Within the silicon industry, substantial resources are devoted to tool development, model verification for each step in the technology and generation of compact models for circuit design. The projections for simulation needs (for TCAD) are included in the SRC roadmaps for the industry. As the optoelectronics industry matures, we can expect simulation to take on a similarly central role. However, the present status of simulation for the optoelectronics industry is fragmentary, at best.

The optoelectronics industry is driven by the explosion in demand for communications bandwidth. Aggregate bandwidth is doubling every 10 months. This dramatic increase is achieved through a combination of increasing data rate per channel, increased channel allocation utilizing more wavelengths sent simultaneously over a single fiber link and the utilization of new fiber bundles in large metro areas. This drives three important developments at the chip or module level. First, components must operate at higher data rates. At this time, 40 Gbit/sec devices are in development requiring significant advances in the technology. Second, more sophisticated optical components such as widely tunable lasers are needed to manage the complexity associated with many wavelength channels. This is finally fueling the development of integrated optical components. The need to find all-optical solutions for regeneration at high data rate will also drive novel integrated optical components. We can expect an increase of complexity from the present state of the art (chips with of order five addressable functions). Third, utilization of fiber bandwidth in metro applications requires low cost components. However, the performance requirements for such components are also stringent, e.g. demand for 10 Gbit/sec uncooled devices. Design refinement for improved performance and yield requires better understanding as well as process control.

I argue that these trends support substantial investment in simulation capability within the optoelectronics industry. However, there are several challenges. First, the commercially available tools are fragmentary, only meeting a fraction of the simulation needs for device design. Second, design engineers have only limited experience with simulation tools. Third, calibration and verification of simulation tools requires commitment of resources and is a prerequisite to effective use in design. Fourth, there is a natural tension between the value of shared (commercial) tools across the industry and the value of maintaining proprietary advantages within each company. Fifth, there is a lag between the development of tools and the needs of the technology.

Even restricting the scope to optoelectronic chip design, diverse simulation tools are needed ranging from empirical models through detailed, microscopic models. These include equivalent circuit models, microwave models, traveling wave models (e.g. for DFB lasers), optical mode models, optical beam propagation models, drift-diffusion models, high-field carrier transport models and models of the properties of quantum wells. We employ all of these types of simulations, using a mixture of commercial tools and software that has been developed internally. Commercial tools are just starting to offer integration of multiple functions, e.g. transverse optical modes and traveling model of DFB laser performance. No commercial tool covers the full range. Tools that extend to subsystem or optical system simulation offer only partial functionality for discrete components. In the absence of either a unified simulation environment or well defined data interchange protocols, one of the challenges has been the difficulty of combining disparate simulation tools. This also inhibits transfer to non-experts (in simulation), e.g. to design engineering staff members.

Reflecting the experience with simulation in silicon technology, development of predictive, microscopic simulation tools brings substantial value as the technology matures. One of our research programs over a period of several years has focused on extending the drift-diffusion type simulation to semiconductor lasers. The *LASER* simulator has been described in detail elsewhere [1]. Briefly, it is designed to simulate the two dimensional cross section of a laser diode with a multiple-quantum well active layer. The cavity loss (a property of the longitudinal optical cavity) is externally specified. For each bias condition of the laser, the electron and hole currents, the bound carrier population in each quantum well, the optical mode profile and the photon population in each optical mode are determined selfconsistently. The properties of the quantum wells are calculated quantum mechanically including the optical gain. A microscopic model for electron and hole capture links the bound carrier populations to the bulk carrier populations. The material parameters (including recombination models and intervalence band absorption) are taken from the literature. We have made extensive verification studies for 1.3 μm lasers that show that the simulations accurately reproduce the measured properties of the lasers. This includes static L-I-V, optical gain spectra, optical loss, dynamic impedance and laser modulation response. The simulations also predict the variation of these measured properties with doping in the active layer.

The value of predictive simulation includes fresh insight to the laser operation, targeted design applications and the generation of new compact models.

[1] M.A. Alam, M.S. Hybertsen, R.K. Smith, and G.A. Baraff, “Simulation of Semiconductor Quantum Well Lasers,” IEEE Transactions on Electron Devices, Vol. 47, No. 10, pp. 1917-1925, 2000.