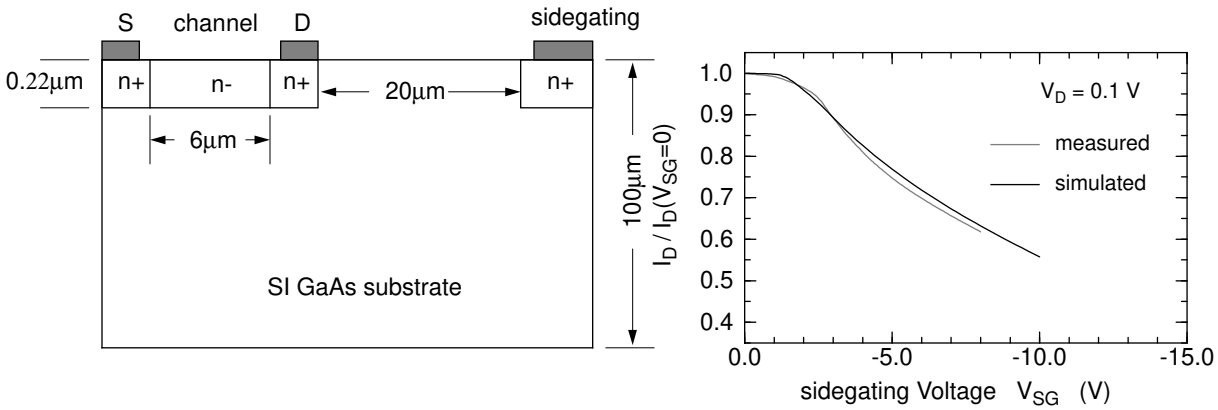

Figure 2. Simulation structure for investigation of the sidegating effect in GaAs MESFETs (left) and comparison of measured and simulated drain current when there is a biased Schottky contact nearby.

case, the "trap" levels are actually the discrete eigen-energy levels in the quantum well and the mobile carriers over the well resemble those in the energy band. The key issues are to find the equivalent trapping parameters such as the capture cross sections and emission probabilities. By the detailed quantum mechanical analysis [2] we indeed found the formulae for the capture of thermal electrons into quantum-well states due to collisions between electrons, between electron and plasmons, and due to the emission of optical phonons in polar semiconductors. The same analysis can be extended to the more complicated valence bands, enabling the extraction of parameters for hole quantum-well capture. We have simulated a quantum well laser built on GaAs/AlGaAs. The structure and the simulated band diagram at the thermal equilibrium are shown in Figure 3. In the confined region, which is formed by GaAs layer in the $Al_{0.3}Ga_{0.7}As$ substrate, there are three quantum wells made of $Ga_{0.8}In_{0.2}As$ material. Note that in the band diagram simulated, the vacuum energy level (E_{vac}) is also shown and is shifted downward by 3eV in order to show the bandgap region clearly. Despite of the abrupt material interfaces, the vacuum level is continuous, a key feature in the heterostructure simulation.

SUMMARY AND ACKNOWLEDGEMENT

In summary, with the development of the dynamic trapping model and its extension to apply to the analysis of carrier transition between eigen-energy levels in the quantum well, both classical and quantum semiconductor devices can be simulated using a unified approach.

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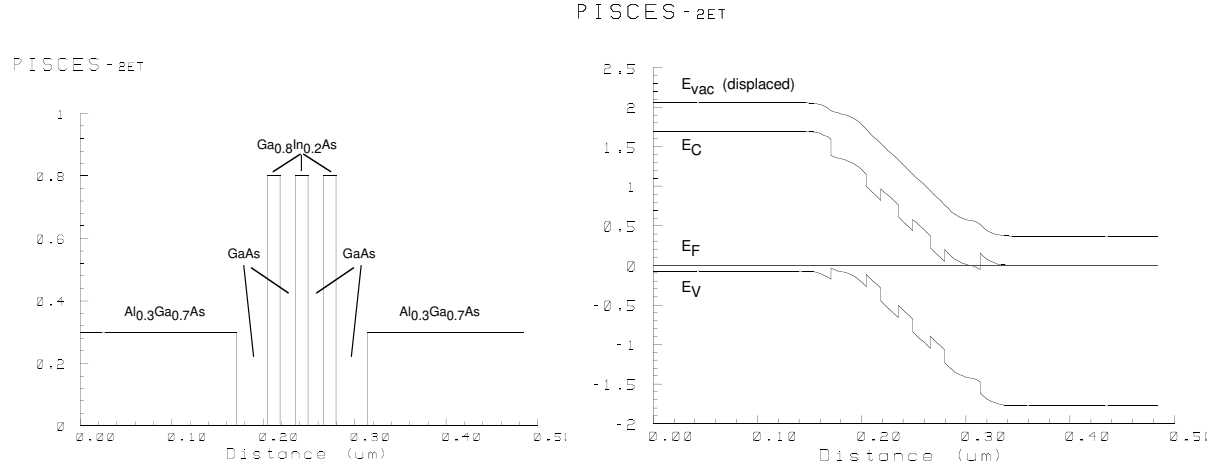

Figure 3. Structure and materials of the quantum well laser (left) and its simulated band diagram at the thermal equilibrium (right).

[1] Y.Liu, Z.Yu, R.W.Dutton, M. Deal: *IEDM Tech. Digest,* 911 (1994).
[2] W.A.Harrison: Private communication (1994).

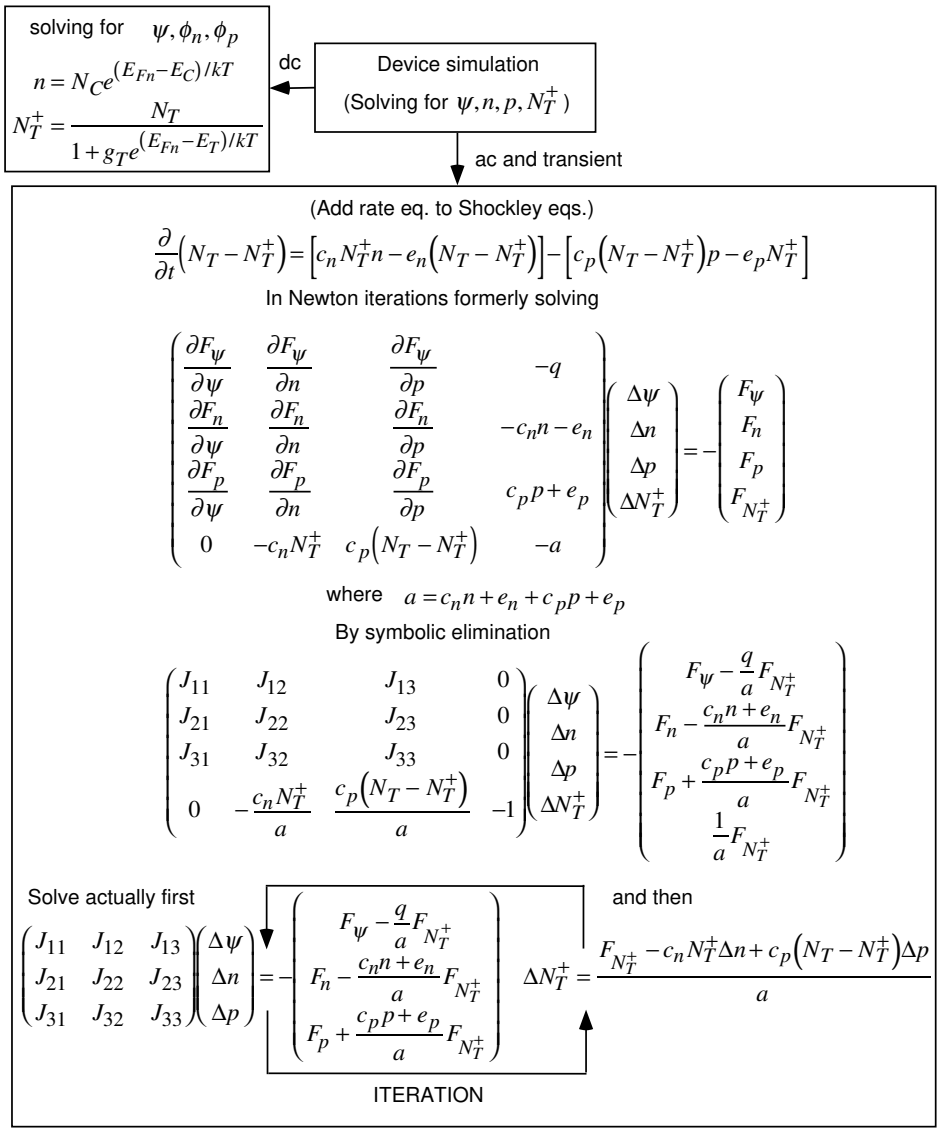

Figure 1. Flowchart for the numerical algorithm of the dynamic trapping model. Only the donor type of traps is taken as an example.

MESFETs it refers to the phenomenon that the drain current in one MEFSET device is affected by the bias applied to a neighboring devices. It has been known for long time that this sidegating effect is caused by the presence of traps in the semi-insulating substrate. But the quantitative analysis and thorough understanding of the major mechanisms were not possible until device simulation with full trapping model becomes available.

In our investigation of the sidegating effects, test structures were first made and the experimental data are compared to the simulation results. The detailed discussion can be found in [1]. The main findings and results are summarized as follows. Two mechanisms are responsible for the enhanced electron-trapping. One is the formation of the high-field domain (i.e., Gunn domain) at the channel-substrate interface due to the negative differential mobility of electrons in GaAs and the other is the double injection in the parasitic Schottky-i-n structure which is due to the overlapping between the gate contact and the substrate. The simulation structure and the comparison between measured and simulated drain current are shown in Figure 2. It can be seen that the agreement is almost perfect.

SIMULATION OF QUANTUM WELL LASERS

Because the rate equation for traps essentially describes the carrier transition among the energy bands (conduction and valence) and discrete levels in the bandgap, it can readily be adopted for the modeling of carrier transport over the quantum well region in the quantum well lasers. In the quantum well

DYNAMIC TRAPPING MODEL FOR ANALYSIS OF GaAs MESFETs AND QUANTUM WELL LASERS

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ABSTRACT

A numerically efficient, dynamic trapping model has been developed for semiconductor device simulation. All analysis modes -- *dc*, *ac*, and time transient -- are available for full account of the trap effects on the device characteristics. The application of this model to the simulation of GaAs MESFETs reveals several important mechanisms responsible for the sidegating effect which deteriorates the circuit performance of MESFETs. A quantitative agreement between the simulation and experiment results is achieved. With equivalent trapping parameters (e.g. capture and emission cross sections) calculated from the quantum mechanical analysis, the model can be extended to describe the carrier transition among discrete eigen-energy levels in and transport across the quantum well region in quantum well lasers. An example of the quantum well laser analysis will be given.

NUMERICAL ALGORITHM FOR DYNAMIC TRAPPING MODEL

Traps in semiconductor (both bulk and interfaces) are characterized by the parameters of trap type (donor or acceptor), energy level (E_T), and capture (c_n, c_p) and emission (e_n, e_p) for electrons and holes. Their effects on device characteristics are fully described by the rate equation (refer to Figure 1). The common practice in the device simulation is to include this rate equation(s) in the set of semiconductor equations, i.e., Poisson's and carrier continuity equations, and solve the electrostatic potential (ψ), carrier concentrations (n and p), and ionized trap densities (e.g. N_T^+ for donor type of traps) simultaneously by either direct (i.e. Newton-Raphson) or indirect (e.g. Gummel) method. The consequence of this approach is to increase the size of the matrix which is required during the numerical iteration significantly and the change of the simulation code due to addition of extra equation(s) is considerable. On the other hand, all rate equations have a nice feature of locality, i.e. all concerned variables -- carrier concentrations and ionized trap densities -- in the equation are related to each other only locally. Thus one should be able to symbolically solve for the ionized trap densities using the original independent variables (n, p and possibly ψ) and to substitute these expressions back to the Poisson's and continuity equations. The advantage from using this transformation is the saving of memory space and maintaining the convergence behavior of the previous (non-trapping) code. Because no additional independent variable and equation are introduced, the code change to include the trapping effect is much simpler. In Figure 1, we illustrate the process of the formal transformation from the view point of Newton-Raphson method using one donor-type traps as an example. In essence, by exploring the locality nature of the trap rate equation, the complete Jacobian matrix including traps as independent variables can be transformed to a lower block triangular matrix, allowing the solution of n, p, ψ separate from that of traps. This separation can be realized at both the dc and transient levels, thus the name of "dynamic" trapping model.

The model has been implemented in PISCES-2ET, a 2D device simulator with capability of simulating lattice and carrier temperatures. The first practical application of this model is for the investigation of the sidegating effects in GaAs MESFETs and the results will be discussed in the next section.

ANALYSIS OF SIDEGATING EFFECTs IN GaAs MESFETs

The sidegating effects are unique for devices built on the semi-insulating substrate. For GaAs