Computational Electronics—Past, Present, and Future

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INTRODUCTION—WHAT THE PAST HAS GIVEN US

While post people can relate the past with quite ancient history—greeks, romans, and so on, my ancient past in computational electronics begins only half a century ago. This is certainly ancient enough. But, at that time, semiconductor device simulation based upon partial differential equations had not yet appeared, even though the flow of transport was understood [1]. But, this changed quickly with Gummel's one dimensional simulation [2]. Within a few years, there were fully two-dimensional simulations of both bipolar and field-effect transistors [3,4,5]. The Monte Carlo technique was introduced by Kurosawa [6] to study hot carrier transport, and this soon appeared in device simulation [7]. It is important to note that such simulation techniques were difficult in these early days due to the generally slow behavior of the computers (as compared to today's performance). Yet, most of the numerical techniques in use today date from those days.

Monte Carlo techniques themselves have progressed through the introduction of molecular dynamics approaches to carrier-carrier scattering [8], carrier degeneracy [9], and non-equilibrium phonons [10]. The first of these has even been corrected for quantum effects such as the exchange interaction [11]. Inclusion of full energy bands has also appeared [12,13].

QUANTUM TRANSPORT APPEARS

The importance of quantum transport to semiconductor devices, as they continued to evolve to ever smaller sizes, was discussed more than three decades ago [14]. First, simulations of these were approximate with quantum hydrodynamic equations [15], or effective potentials [16]. But, then more effective transport simulations, including Green's functions, appeared for device simulation [17,18]. Today, full quantum simulations, incorporating scattering and full band structure, are possible.

WHAT DOES THE FUTURE HOLD

Predicting the future is always dangerous, as one generally underestimates the progress that can be made by our community. But, device sizes are progressing ever smaller, with normal 10 nm devices in the very near future, and single atom devices already existing [19]. There will be demand for more intensive simulations, even though too much of our community still uses the ancient tools, and is rediscovering past history. But, the development of still more advanced simulation techniques allows us to more precisely study the relevant physics, which in turn allows better understanding of the experiments, an excellent example of which is given in [19].

In this talk, I will try to highlight the past, and illuminate how it has affected the present. Finally, I will speculate on what the future may hold.

REFERENCES

[1] W. V. Van Roosbroeck, "Theory of flow of electrons and holes in germanium and other semiconductors," Bell Sys. Tech. J. **29**, 560 (1950).
[2] H. K. Gummel, "A self-consistent iterative scheme for one-dimensional steady state transistor calculations," IEEE Trans. Electron Dev. **11**, 455 (1964).
[3] H. H. Heimeier, "A two-dimensional numerical analysis of a silicon n-p-n transistor," IEEE Trans. Electron Dev. **20**, 708 (1973).
[4] W. L. Engl and O. Manck, "Two-dimensional analysis of bipolar transistor transients," IEDM Tech. Dig. 1973 (IEEE, New York, 1973) 381.

[5] M. S. Mock, “A two-dimensional mathematical model of the insulated-gate field-effect transistor,” Sol.-State Electron. **16**, 601 (1973).
[6] T. Kurosawa, “Monte Carlo calculation of hot electron problems,” in *Physics of Semiconductors* (Physical Society of Japan, Tokyo, 1966) 424.
[7] R. W. Hockney, R. A. Warriner, and M. Reiser, “Two-dimensional particle models in semiconductor-device analysis,” Electron. Lett. **10**, 484 (1974).
[8] C. Jacoboni, “Recent developments in the hot-electron problem,” in *Physics of Semiconductors* (Tipogravia Marves, Rome, 1976) 1195.
[9] P. Lugli and D. K. Ferry, “Degeneracy in the ensemble Monte Carlo method for high-field transport in semiconductors,” IEEE Trans. Electron Dev. **32**, 2431 (1985).
[10] P. Lugli and S. M. Goodnick, “Nonequilibrium longitudinal-optical phonon effects in GaAs-AlGaAs quantum wells,” Phys. Rev. Lett. **59**, 716 (1987).
[11] A. M. Kriman, M. J. Kann, D. K. Ferry, and R. Joshi, “Role of the exchange interaction in short-time relaxation of a high-density electron plasma,” Phys. Rev. Lett. **65**, 1619 (1990).
[12] H. Shichijo and K. Hess, “Band structure dependent transport and impact ionization in GaAs,” Phys. Rev. B **23**, 4197 (1981).
[13] S. E. Laux and M. V. Fischetti, “Monte Carlo simulation of submicrometer Si n-MOSFETs at 77 and 300K,” IEEE Electron Dev. Lett. **9**, 467 (1988).
[14] J. R. Barker and D. K. Ferry, “On the physics and modeling of small semiconductor devices,” Sol.-State Electron. **23**, 519 (1979); **23**, 531 (1979).
[15] J.-R. Zhou and D. K. Ferry, “Simulation of ultra-small GaAs MESFET using quantum moment equations,” IEEE Trans. Electron Dev. **39**, 473 (1992).
[16] D. K. Ferry, R. Akis, and D. Vasileska, “Quantum effects in MOSFETs: Use of an effective potential in 3D Monte Carlo simulation of ultra-short channel devices,” IEDM Tech. Dig. 2000 (IEEE, New York, 2000) 287.
[17] G. Klimeck, R. Lake, R. C. Bowen, W. R. Frensley, and T. S. Moise, “Quantum device simulation with a generalized tunneling formula,” Appl. Phys. Lett. **67**, 2539 (1995).
[18] M. J. Gilbert, R. Akis, and D. K. Ferry, “Modeling fully depleted SOI MOSFETs in 3D using recursive scattering matrices,” J. Comp. Electron. **2**, 329 (2003).
[19] Martin Fuechsle, J. A. Miwa, S. Mahapatra, H. Ryu, S. Lee, O. Warschkow, L. C. L. Hollenberg, G. Klimeck, and M. Y. Simmons, “A single-atom transistor,” Nature Nanotech., *in press*.