3D CMOS Photodiode modelling and simulator design

by Paul Ellinghaus and Jannes Venter

The Carl and Emily Fuchs Institute for Microelectronics has been involved in cutting-edge semiconductor research since its inception. As a main focus of interest, CMOS (complementary metal-oxide semiconductor) is arguably the most successful semiconductor technology to date.

Cutting-edge research is conducted in the Carl and Emily Fuchs Institute for Microelectronics at the University of Pretoria.

This technology is rapidly approaching fundamental limits regarding device size scaling as dimensions are already in the same order as the material lattice constants. Hence, there is a strong drive for research in non-classical CMOS technology extensions, such as SiGe BiCMOS, microelectromechanical systems (MEMS) devices and optical CMOS-based systems. Electronic design aids are crucial to the design of optical detectors (photodiodes). One of the main research activities involves CMOS photonics and the modelling of the electrical-optical interactions in these devices.

The ongoing pursuit of the semi-conductor industry to uphold Moore's Law, which effectively states that the density of transistors doubles every two years, has led to phenomenal increases in processing power. The continuation of this trend is seriously hampered by the 'interconnect dilemma', as it has come to be known in semiconductor industry jargon. The continuous decrease in transistor dimensions to achieve the density increase predicted by Moore requires a corresponding downward scaling of the metal interconnects that connect the various devices and subsystems on an integrated circuit. The scaling of these interconnects causes an increase in their resistance and capacity, resulting in limited bandwidth and high power consumption, which pose severe limitations to further performance increases.

Optical interconnects are envisaged to provide a viable solution to the dilemma at hand by exploiting the low attenuation and large bandwidth characteristic of optical communication, which is extensively used in telecommunications, albeit on a macro scale. An implementation of optical inter- and intrachip communication will require the complete optoelectronic system to be realisable in process technology already in use in the manufacture of digital electronic circuits (CMOS). The basic building blocks of an optical communication link are a transmitter (light source), a medium (optical fibre/waveguide) and a receiver (photodiode).

The realisation of a light source using silicon technology, like CMOS, presents a formidable challenge. INSiAVA (Pty) Ltd, a subsidiary of the University of Pretoria led by Prof Monuko du Plessis, has made considerable headway in solving this problem. So much so that this company has attracted interested glances from international players like Intel, also in the pursuit of 'siliconising' photonics.

The realisation of a light source might present the major stumbling block, but the importance of the optical receiver, in which the photodiode plays a crucial role, should not be discounted, as optical signals will have to be converted to electrical energy at several instances in an optical clock and data distribution network. As is all too often the case in engineering, with the design of a photodiode one encounters various trade-offs. The existing trade-offs allow the determination of an optimal design for a specific application; the photodiode used in an optical receiver requires a high bandwidth while providing the maximal responsivity possible.

As a result of the complex semiconductor device physics involved, the optimisation of a photodiode design is only feasible using a computer-aided design approach with semiconductor device simulation software like ATLAS from Silvaco. Software like ATLAS provides a complete device simulation framework offering extensive parameters to be considered, but the cost of such simulation software is rarely financially feasible for the resource-constrained CMOS device engineer. Developing customised simulation software using already available computing platforms allows a cost-effective alternative with the added advantages of gaining improved insight into simulation techniques and having vast customisation possibilities.

Paul Ellinghaus, who was a final-year student in electrical, electronic and

INSiAVA: casting light on an international computing dilemma

As integrated circuit devices (computer chips) become smaller, the transistor speed becomes faster. However, the metal interconnect lines and oxide layers are becoming smaller, and since the chip size remains the same to get more functionality per chip, the interconnect delay increases.

Optical interconnects may solve the interconnect problem. Using photons at the speed of light, instead of electrons, could increase the speed of interconnects regardless of device dimensions. This ideally requires an optical source on the chip.

The University has registered two USA patents on silicon-based devices as optical sources and ways to improve their efficiency. Two more provisional patents on efficiency improvement were filed in 2007.

The technology, known as injection-enhanced silicon in avalanche (INSiAVA), emerged from research conducted by the Carl and Emily Fuchs Institute for Microelectronics (CEFIM) in the Department of Electrical, Electronic and Computer Engineering.

The key advantage of INSiAVA is that light is generated within the silicon itself. Optical interconnects require a fast-switching, efficient light source.

The research attracted local venture capital in 2007.

The University of Pretoria has established a company, INSiAVA (Pty) Ltd, that owns the intellectual property emanating from this ongoing silicon photonics research project.

This company is continuing the research and development of the first silicon-based photonic interconnects solution for light-based chip-to-chip communication on the printed circuit boards of computers.

This novel optical technology has the potential to solve the chip-to-chip and on-chip interconnect problems facing the computing industry. The technology replaces the copper interconnects with optical interconnects, which send signals by means of photons, not electrons.

It is envisaged that the first applications will be in products that rely on a high switching speed. These include video applications, for instance in the entertainment and security industry, and imaging, such as medical imaging or geographic information systems. Sensor applications may also be among the first to realise the commercial potential of INSiAVA technology.

Chip-to-chip optical interconnects could send data a thousand times faster. This potential advantage creates a huge market for all computing applications, making it a truly 'billion unit' application.

computer engineering at the time, designed such a CMOS photodiode simulator under the supervision of Jannes Venter.

The simulation of a CMOS photodiode requires various considerations: geometry description of the photodiode, the attenuation of light in the structure, and the movement of charge carriers, along with their generation and recombination. All these processes are well described by existing mathematical models and equations – the so-called basic semiconductor equations (Selberherr, 1984). The solution of these equations is a non-trivial matter, especially when considering three-dimensional structures. An analytical solution of these equations is not practicable; a numerical solution technique, like the finite element method (FEM), offers a viable alternative.

This method has been widely adopted in all forms of simulation software. It entails subdividing a structure into many tiny elements. The solution of the equations to be solved is approximated in each element using simple mathematical functions. By assembling all the equations generated in each element, a system of linear equations is formed that can be easily solved by enforcing appropriate boundary conditions of the structure that arise from physical considerations. FEM allows arbitrarily shaped elements to be used to discretise a volume, thereby allowing structures to be more accurately approximated. It also allows a localised mesh refinement (smaller element sizes) in areas that require greater accuracy. This allows greater computational efficiency.

The developed simulator subdivides the photodiode structure (an n-well/p-substrate – in its simplest form) into bulk regions and depletion regions and calculates the generated photocurrent in each. FEM is used to solve the carrier continuity equations, part of the basic semiconductor equations, to calculate the photocurrent in the bulk regions. The photocurrent in the depletion region(s) is calculated by determining the number of generated carriers in the region under certain simplifying assumptions.

The simulation model calculates the total generated photocurrent at a given time instance. This provides the framework to devise the transient response of the photodiode under a time-varying optical stimulus. The frequency response and spectral responsivity of the photodiode are obtained by solving equations in the frequency domain obtained by applying a Laplace transform on the original time domain equations.

The simulator was developed on a MATLAB platform, which is widely used in the engineering industry. The photodiode responses predicted by the simulator compare favourably to other published simulation results and measurements (Liu, 2001). The simulator results are novel in that they consider a three-dimensional structure, as opposed to the conventional two-dimensional simulators. It is evident that a simple self-developed simulator provides a useful design tool that is an affordable alternative to expensive simulation software packages.

References

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