3D Optoelectronic Simulations for CCD Imagers

A.Ruckelshausen, R.Tobergte, P.Thyen
Arbeitsgruppe Mikroelektronik / Fachbereich Elektrotechnik
Fachhochschule Osnabrück, Germany

During the last decade CCD technology was successfully implemented in professional/ industrial and consumer applications. Due to an everincreasing variety of devices covering HDTV-sensors, low-cost image sensors or application-specific imagers, there is a need for technical innovations as well as for a reduction of development cycles. As a consequence, the simulation of the highly complex integrated devices prior to production is of importance. Moreover, the understanding of sensor artifacts or tolerances of sensor parameters can be supported.

Since electrical and optical sensor characteristics often require compromises caused by conflicting material properties, the optimization of both sensor aspects is of great interest. The topology of the small CCD-pixel structures as well as the electrical potentials require two- and even three-dimensional simulations. One major aspect to increase the signal-to-noise-ratio is the improvement of the light sensitivity of the CCD image sensor. The optoelectronic model combines a Monte-Carlo-based optical simulation using the new simulator HELIOS and an electrical device simulation based on the finite element method. The model is applied to frame transfer image sensors with vertical antiblooming [1,2].

Monte-Carlo Simulator HELIOS

The quantum efficiency (QE or η) of silicon imagers depends on the conversion of the incoming light into electron-hole pairs and the collection efficiency of the generated carriers within the silicon substrate. The QE can be directly converted to the spectral sensitivity of the CCD sensor. The simulation method is summarized in figure 1.

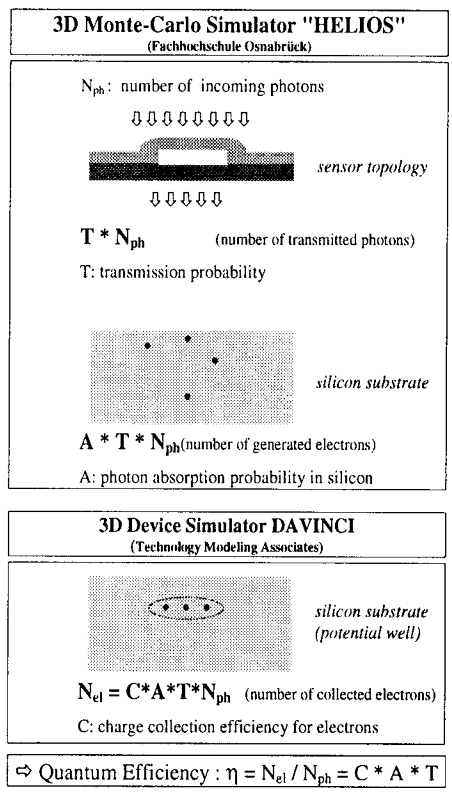

Figure 1: Method for quantum efficiency simulations for CCD imagers.

In the first simulation step the incoming light is simulated by using the Monte-Carlo-technique which allows a high flexibility in the choice of the pixel geometry. The position and angle of an incident photon as well as its wavelength are given. The photon is advanced by taking into account the optical properties of the corresponding layers, thereby causing reflection, transmission or absorption. Polarization effects are included. For the quasi onedimensional parts of the pixel interference effects are calculated and can be included by weighting the number of photons of the Monte-Carlo simulation. The non-planar three-dimensional geometry is created by joining together simple geometric objects (block, wedge, tetrahedron) as illustrated in figure 2 where the absorption coordinates as a result of a HELIOS-simulation for a simple test structure are shown.

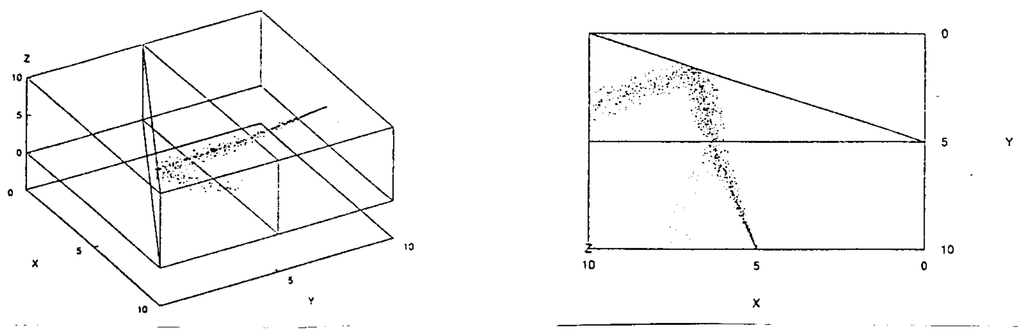

Figure 2: The points within the 3D test structure represent the absorption coordinates of the photons as simulated with HELIOS. The photons enter the test structure with an aperture angle of 10 degrees.. The projection of the simulation results in the xy-plane shows the absorption and reflection processes.

After passing the sensor topology the conversion of the photons to charge carriers is simulated by taking into account the corresponding silicon material parameters. As an example the two-dimensional distribution of generated electrons for a two-dimensional simulation of on-chip-lens structures shown in figure 3.

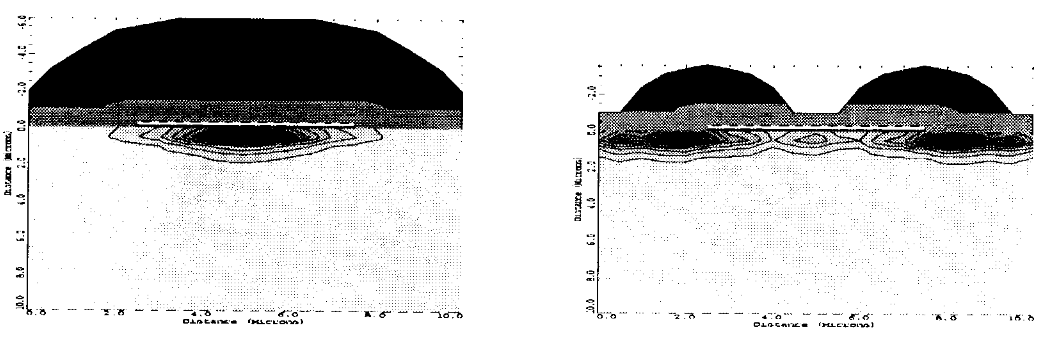

Figure 3: Distribution of the photogenerated electrons for a two-dimensional CCD pixel structure. The influence of the different microlens structures is shown for an illumination of the whole pixel with photons of λ=500 nm. (simulators: HELIOS, MEDICI).

Device Simulation

According to figure 1 the photogenerated electrons have to be collected in the CCD potential well in order to contribute to the pixel information. The 3D state-of-the-art device simulator DAVINCI [3], has been used to determine the collection efficiency which strongly depends on the pixel geometry, the doping profiles and the applied potentials. Simulations have also been performed in two dimensions by using MEDICI [3].

In frame transfer sensors with vertical antiblooming the pixel geometry consists of a MOS structure with a vertical n-p-n dopant profile. The doping concentrations and the applied potentials result in a potential well where photogenerated electrons are collected. After integration, the charge packet can be transported by changing gate potentials. A (half) pixel of the buried-channel device as simulated with DAVINCI is shown in figure 4. The charge packet is placed underneath the integrating polysilicon gate, while the blocking gates together with the lateral channel stop regions prevent charge flow to neighbouring pixels. On-state device simulations for electrons - potential changes caused by holes have not yet been included - have been performed in two ways to calculate the quantum efficiency [4]:

a) The photogenerated electrons are placed into the silicon substrate at the positions simulated by HELIOS. The electron flow - as simulated with DAVINCI - will be directed towards the potential well or the n-type substrate of the sensor device. The quantum efficiency is then given by the number of electrons collected in the pixel potential well divided by the corresponding number of incoming photons.

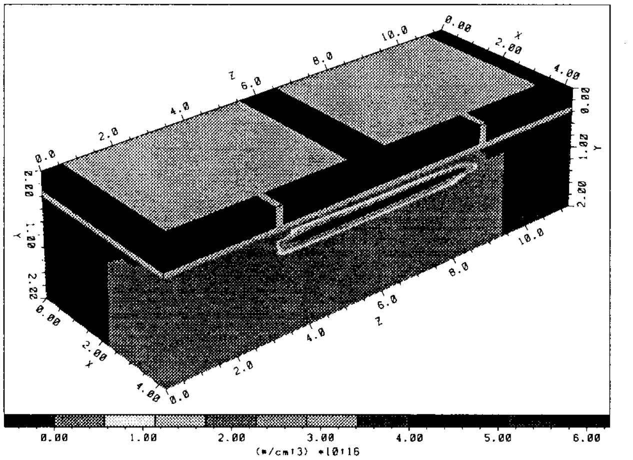

Figure 4: Simulation region of a (half) CCD-pixel for the 3D device simulator DAVINCI. The charge packet is located in the center of the structure beneath the integrating electrode. The polysilicon gates on top of the structure have "windows" for an improved blue sensitivity.

b) The collection efficiency for a given device geometry is simulated prior to the HELIOS-simulation by placing a small charge packet at a defined position in the 3D silicon structure. The transient device simulation yields the capture probability for the given coordinate. This procedure is repeated for the whole device, resulting in a 3D collection efficiency table. Thus the results of HELIOS can be directly transformed to the quantum efficiency. In practice, the reduced data avoid time consuming 3D device simulations.

Typical variations in the results for the two simulation models are about 2 percent quantum efficiency. Preliminary comparisons with measurements (spectral sensitivity for the whole pixel) show agreement within about 3 percent quantum efficiency.

Applications

The Monte-Carlo method (HELIOS) combined with device simulations - or reduced data from device simulation results - offers a high flexibilty for applications. The influence of pixel layout, doping profiles, applied potentials or materials can be examined as a function of the position, angle and wavelength of the incoming light. Moreover, the spectral sensitivity of the total pixel as an important device paramter can be determined. As an example, figure 5 shows results of a simulation for a four-phase CCD cell (method a). The charge collection efficiency - simulated by DAVINCI for the corresponding coordinates given by HELIOS - decreases as a function of wavelength due to the relation of the increasing absorption depth and the potential well, while the absorption processes in the polysilicon structures are less significant for longer wavelengths. Both aspects result in the typical QE-characteristic with its maximum at around 500 nm.

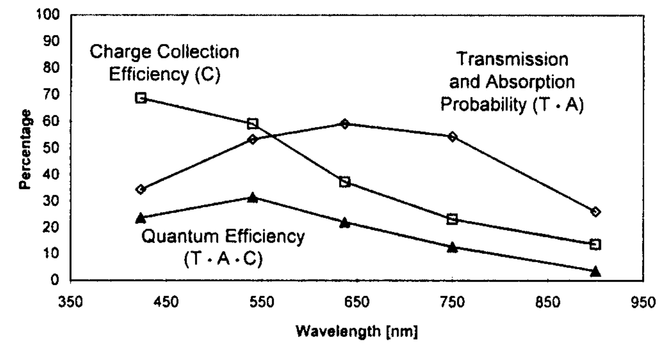

Figure 5: The quantum efficiency of a CCD pixel has been simulated according to fig. 1. Note that the transmission and absorption probability is related to the defined simulation region. The charge collection efficiency is simulated by DAVINCI for the given absorption coordinates calculated by HELIOS.

Other examples (fig. 6) show the variations of sensitivity within a pixel due to the poly silicon gates and the influence of reducing the thickness of the poly silicion gates.

Moreover, first simulations with light spots in horizontal and vertical positions as an input for MTF-calculations and optical crosstalk between neighbouring pixels as a function of the angle of the incident photons have been performed.

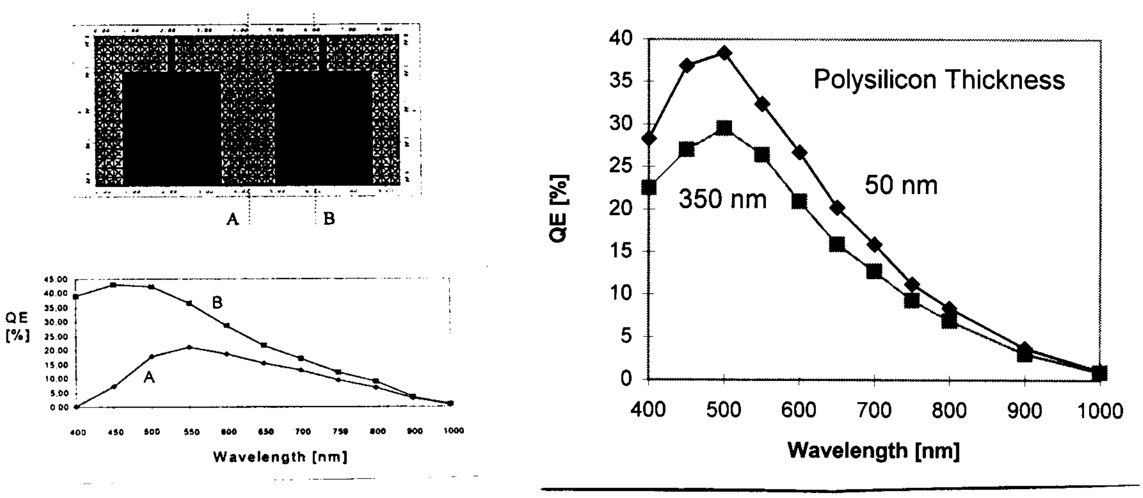

Figure 6 : The quantum efficiency QE has been simulated for different two-dimensional planes within a pixel (left). In the upper part the top view of the corresponding CCD structure with poly silicon gates is shown. The QE is simulated for a CCD pixel with polysilicon gates of different thickness (right).

Acknowledgement

The work has been supported by the „Ministerium für Wissenschaft und Kultur des Landes Niedersachsen" (Germany) in cooperation with Philips Imaging Technology / Eindhoven (The Netherlands). Students from the Fachhochschule Osnabrück have contributed to the development and application of the simulation methods.

References

[1] A.J.P. Theuwissen, "Solid-State Imaging with Charge-Coupled Devices", Kluwer Academic Publishers (1995)

[2] "Special Issue on Solid-State Image Sensors" , Philips Journal of Research, Vol 48, No.3, 1994 , pp.145-298

[3] Technology Modeling Associates, Palo Alto, CA, USA. DAVINCI Three-Dimensional Device Simulation Program, Version 3.1 User's Manual, 1995; MEDICI Two-Dimensional Device Simulation Program , Version 2.1 User's Manual, 1994.

[4] The HELIOS results have also been coupled with the DAVINCI-statement "PHOTOGEN" to simulate a time-dependent generation of carriers and determine the quantum efficiency.