Luminous

Optoelectronic Device Simulator

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Overview

- Luminous 2D/3D is an advanced device simulator specially designed to model light absorption and photogeneration in planar and non-planar semiconductor devices
- Solutions for general optical sources are obtained using geometric ray tracing or beam propagation methods
- These features enables Luminous 2D/3D to account for arbitrary topologies, internal and external reflections and refractions, polarization dependencies, dispersion and coherence effects
- Luminous 2D/3D is fully integrated within ATLAS with a seamless link to S-Pisces and Blaze device simulators, and other ATLAS device technology modules

Key Benefits

- Luminous 2D/3D can simulate multiple mono-chromatic or multispectral optical sources, and provides special parameter extraction capabilities unique to optoelectronics
- DC, AC, transient, spectral and spatial responses of general device structures can be simulated in the presence of arbitrary optical sources
- Forward geometric ray trace and beam propagation methods permit detailed analysis of photogeneration and anti-reflective coatings
- Incorporates an ANSI C-Interpreter module that permits a user to define optical wavelength dependent generation equations for any region within a device

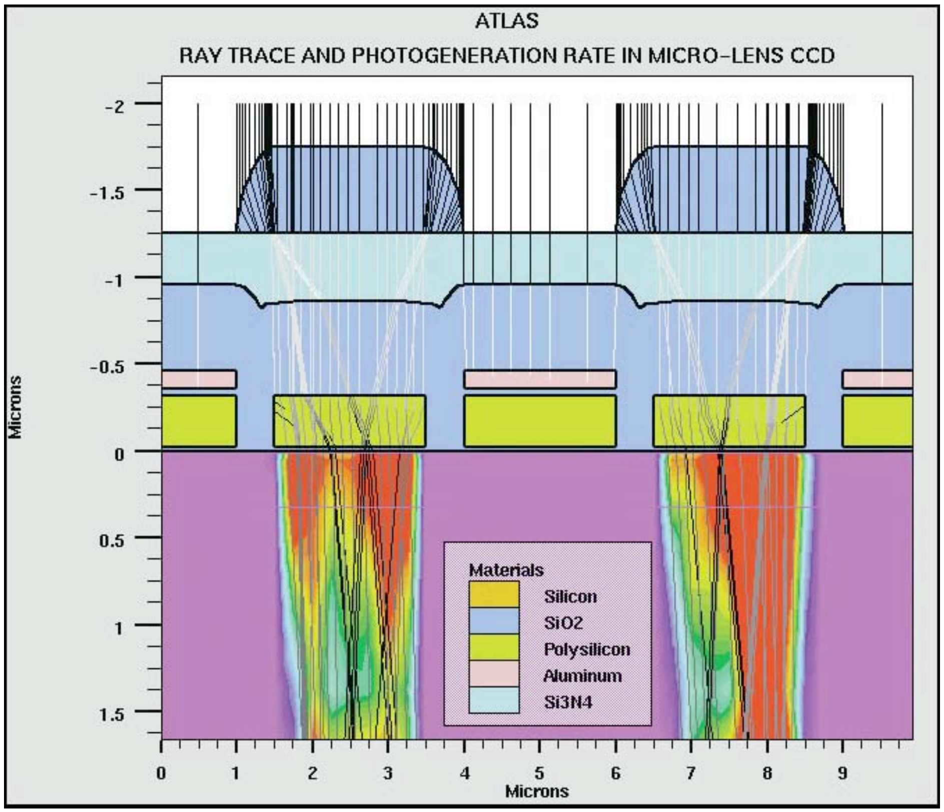
Key Benefits (con't)

- Individual wavelength detection from a multitude of incident wavelengths can therefore be detected through the use of the C-Interpreter generated photogeneration rates assigned to different regions
- When implemented with Blaze, complicated multi heterostructure materials can be simulated for detailed optical detection
- Seamless link with other TCAD software and ease of use within the DeckBuild and TonyPlot environments

Applications

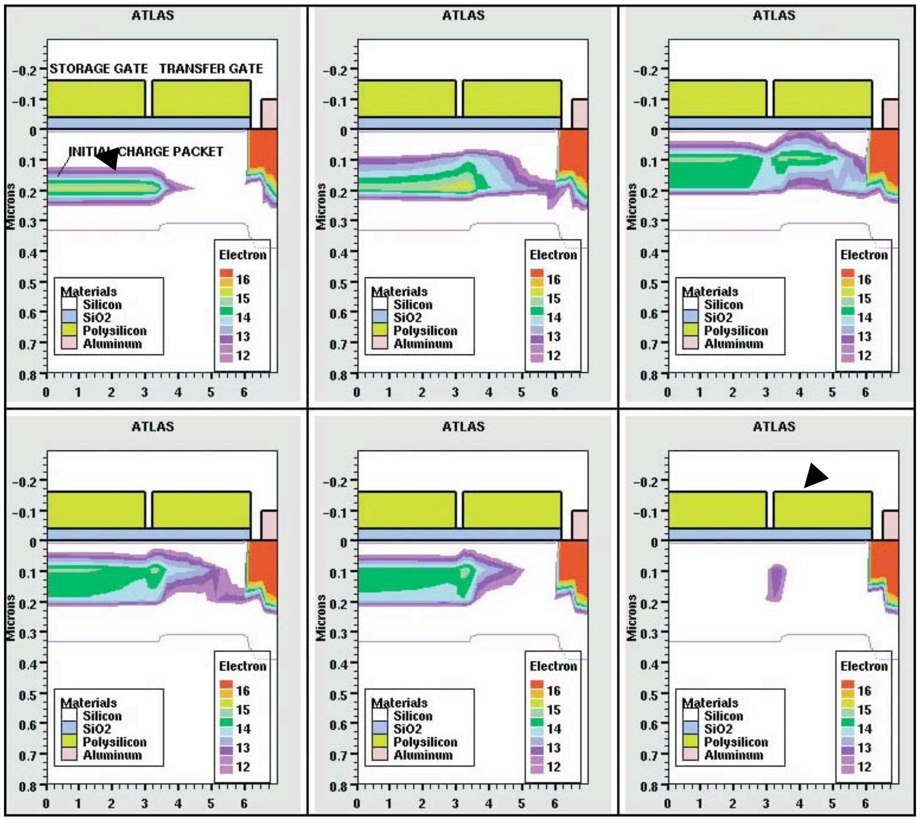
- Charge Coupled Devices (CCD)
- Solar cells
- Photodiodes, avalanche photodiodes and reach through avalanche photodetectors
- Photoconductors, phototransistors, MSMs and optoelectronic imaging arrays
- Effects of anti-reflective coatings
- Investigating and optimizing quantum efficiency

Charged Coupled Devices (CCDs)



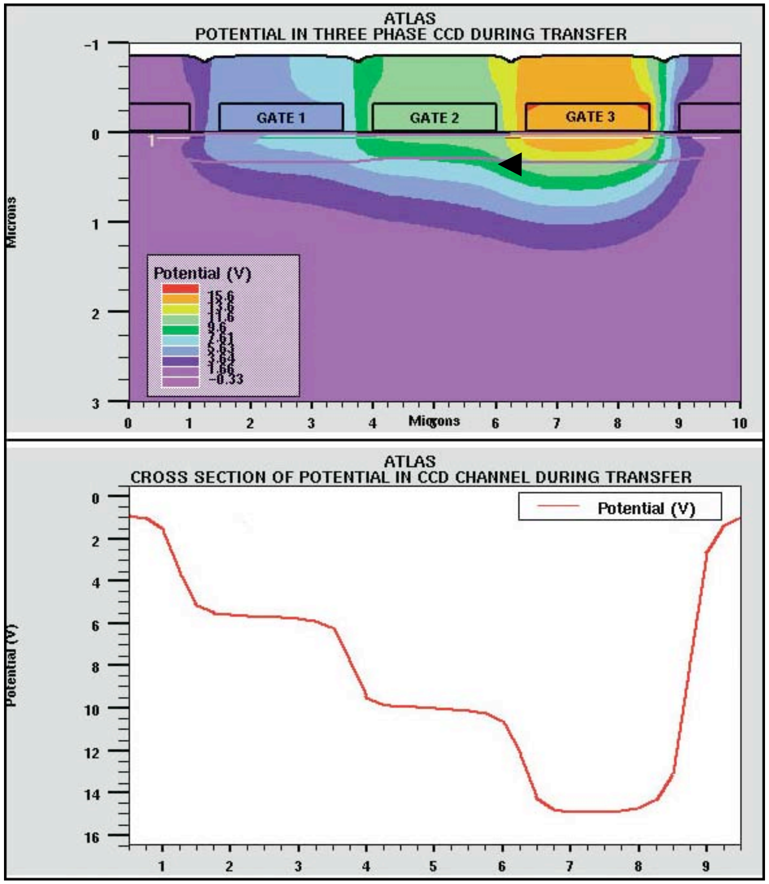
- Device structure plot of a microlens CCD created Silvaco's advanced process simulator ATHENA
- The geometric ray trace data generated by Luminous 2D/3D is overlaid on the structure
- The photogeneration rate is calculated based on the local optical intensity provided by the ray tracing and generation rate equations

Charged Coupled Devices (CCDs)



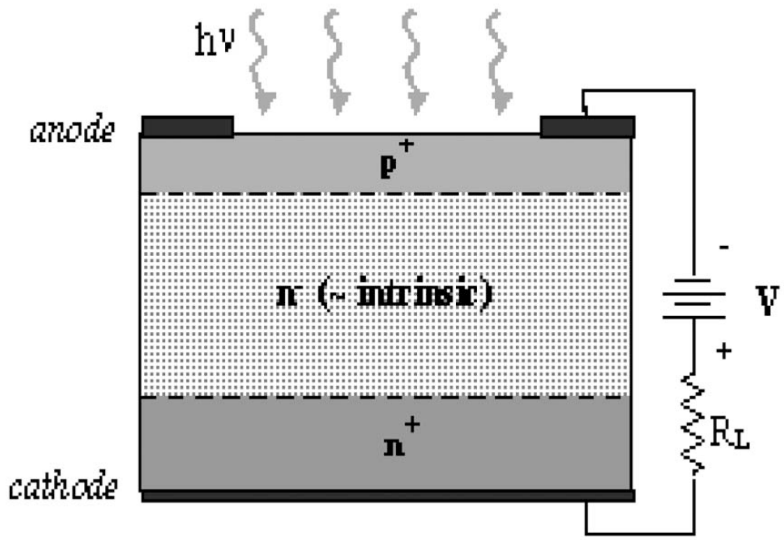
- TonyPlot is used to display the charge transfer throughout the device
- As can be seen, the charge transfer proceeds from the initial storage gate to the next storage gate
- The time sequence of electron concentration contours during charge transfer in a buried channel CCD
- This type of analysis is used to extract charge well capacity and charge transfer efficiency

Charged Coupled Devices (CCDs) (con't)



- A common application of Luminous 2D/3D is the evaluation of potential in a CCD channel during a transfer cycle
- The evaluation of vertical crosssections at several x-axis locations is used to illustrate the peak potential across the device channel18

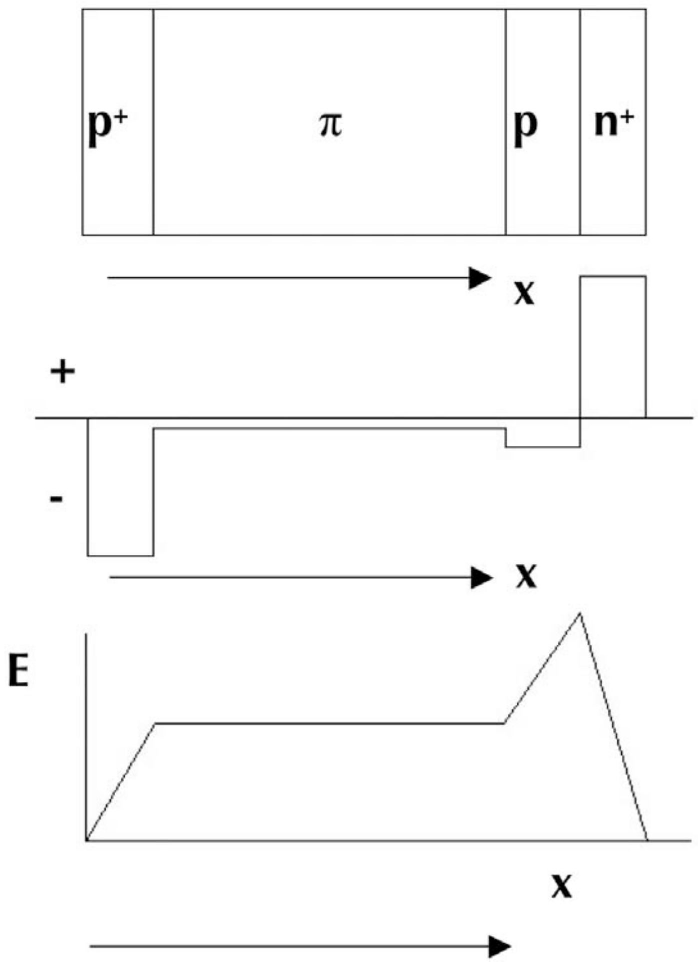
Separate Absorption Multiplication (SAM) Reach Through APDs



This diagram shows a pn photodiode with an intrinsic section used to improve photon detection. The material is silicon throughout and is consequently limited in its wavelength detection range but has improved multiplication noise.

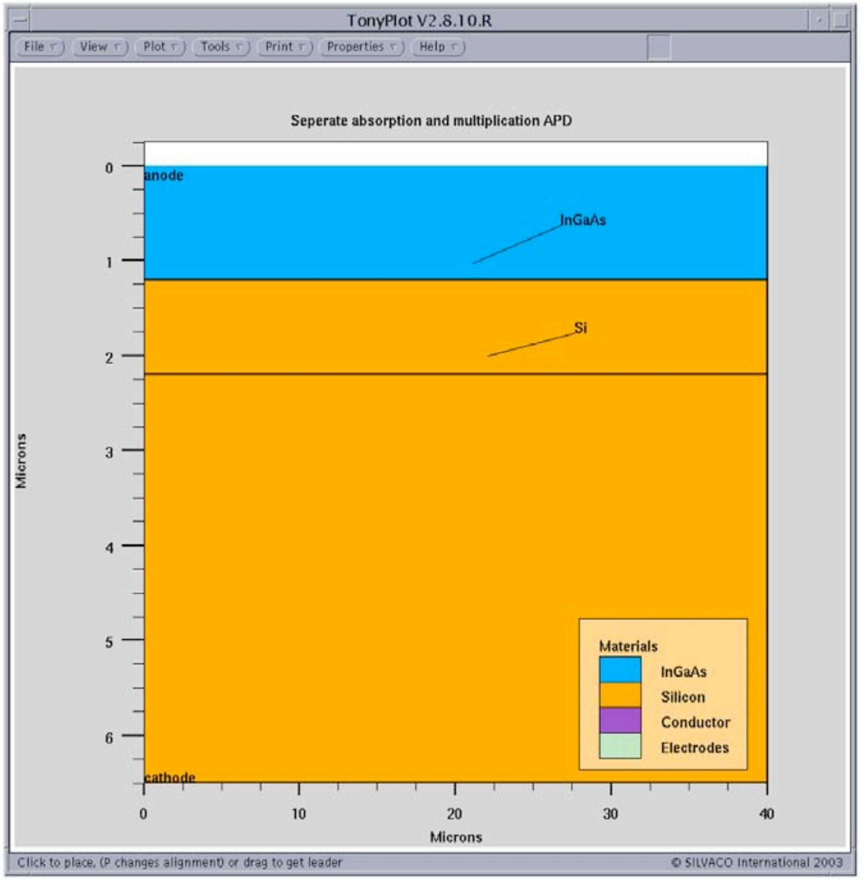
- Minimization of avalanche multiplication noise is important
- Electron and hole ionization capability is characterized by their ionization coefficients α_e and α_h
- The ionization ratio $k = \alpha_h / \alpha_e$ is used to characterize the performance of an APD
- APDs should be fabricated from materials promoting single carriers to impact ionize where $k=0$ or $k=\infty$
- In silicon $\alpha_e \gg \alpha_h$ making an ideal material for an electron based APD

Separate Absorption Multiplication (SAM) Reach Through APDs (con't)



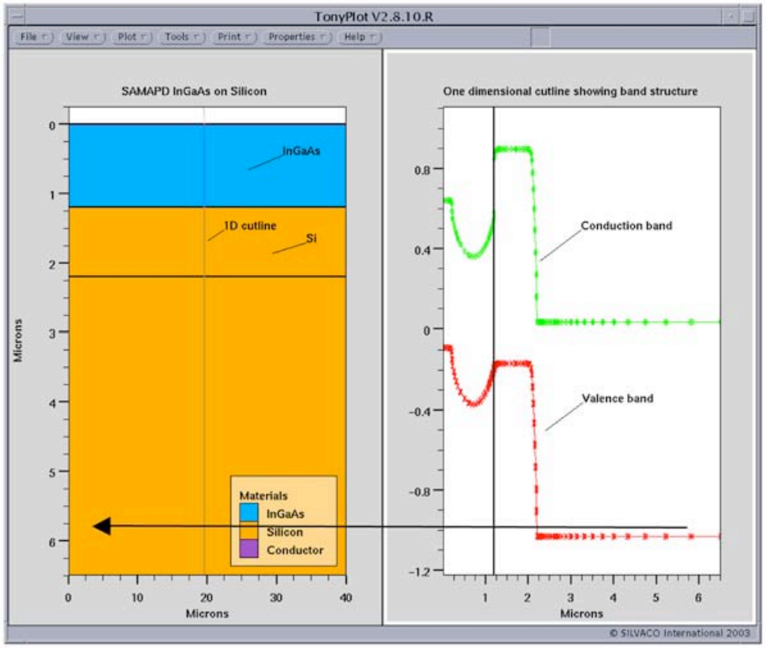
- The APD should maximize photon absorption. However, the multiplication region should be thin to minimize secondary ionizations
- Greater electric field uniformity is also achieved
- These two conflicting requirements require an APD in which the absorption and multiplication regions are separate
- This results in a separate absorption multiplication (SAM) avalanche photo detector

Separate Absorption Multiplication (SAM) Reach Through APDs (con't)



- Advanced heterostructures can be important to detect different wavelengths of light such as III-V materials used to detect infra red and ultraviolet radiation
- Popular devices comprised therefore of III-V materials to detect the light and silicon materials to promote avalanche of carriers
- A typical example of a separate absorption and multiplication region APD is shown here. This device has been created using ATLAS together with Blaze

Separate Absorption Multiplication (SAM) Reach Through APDs (con't)



- Blaze is a device simulator capable of modeling several type II-IV and type III-V materials
- Blaze accounts for the effects of position dependent band structures by modifying the charge transport equations associated within ATLAS
- Shown here is a one dimensional cutline which runs from the anode to the cathode of the previous device
- As you can see the bandgap alignment is present. This region will be where most of the carriers will be generated

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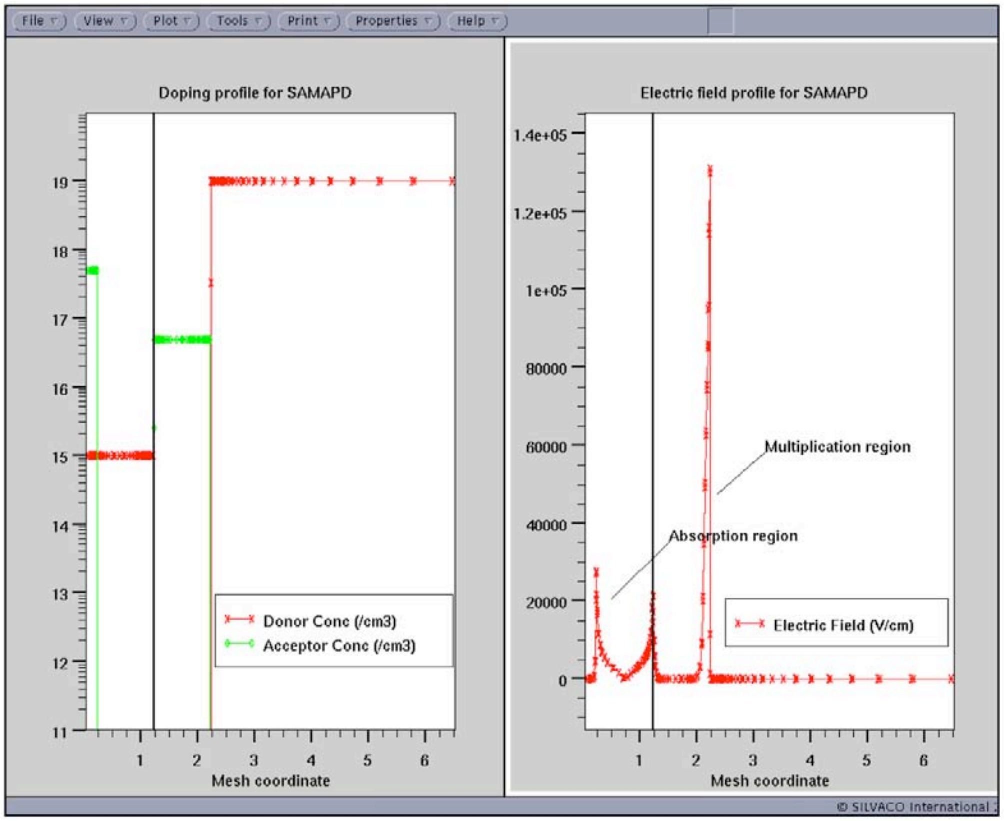
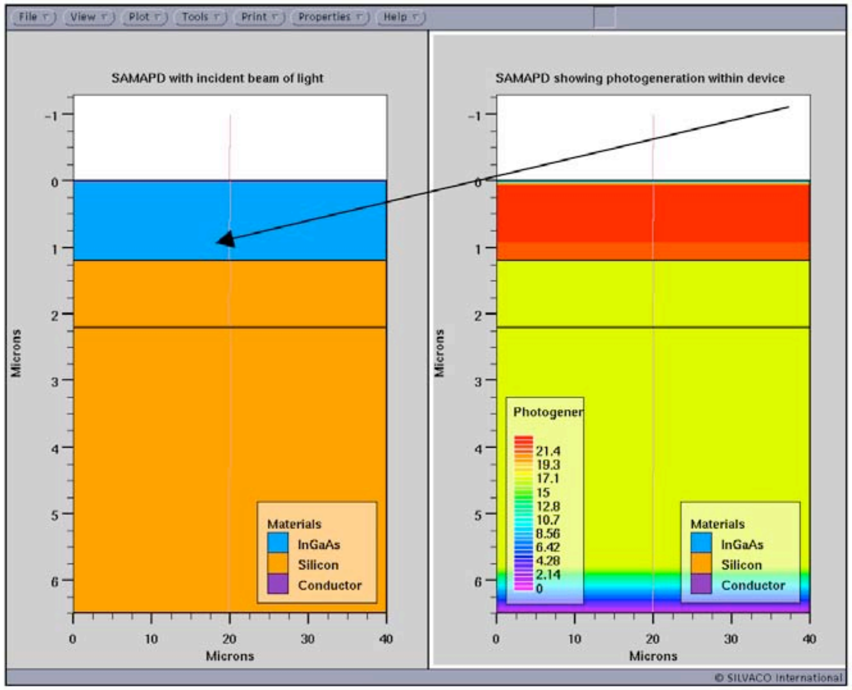
Separate Absorption Multiplication (SAM) Reach Through APDs (con't)



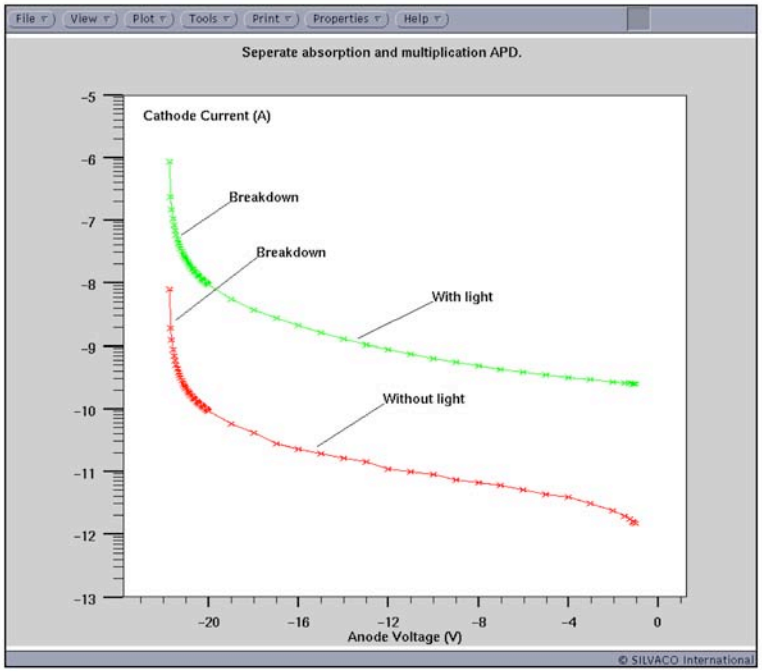
- The doping profile and electric field derived from a one dimensional cutline are shown
- Separate regions exist for the absorption and multiplication of carriers

Separate Absorption Multiplication (SAM) Reach Through APDs (con't)



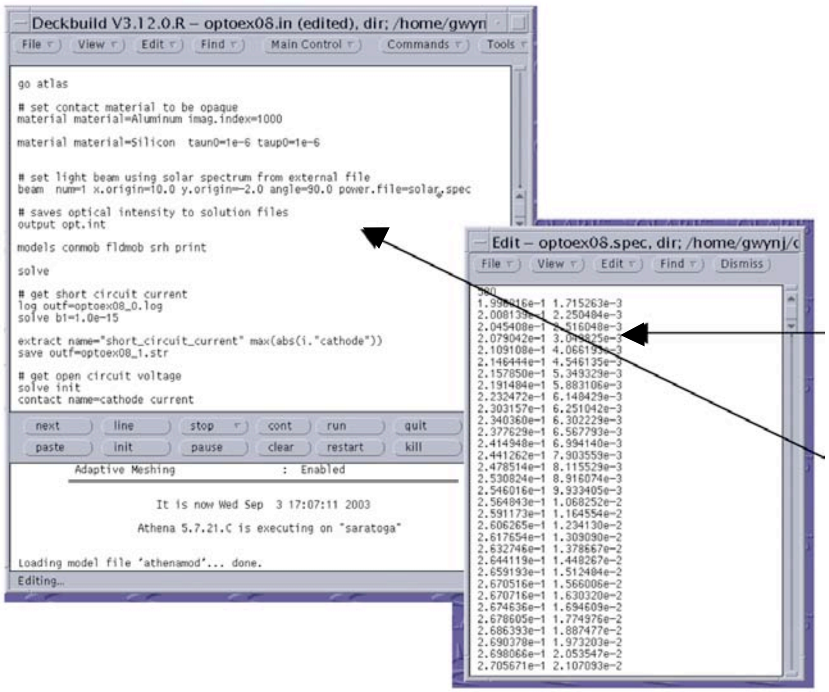
- The photogeneration rate is calculated in the presence of a beam defined in Luminous
- The photogeneration rate is plotted within the device using TonyPlot
- Shown here is the photogeneration rate for a wavelength of 1.0um and a beam intensity of 0.5Watts/cm^2
- The optical beam is shown as the single line above the device. This is for display purposes only and does not represent the width of the incident beam

Separate Absorption Multiplication (SAM) Reach Through APDs (con't)



- Shown here is the light and dark responses of the SAMAPD
- As you can see there is significant increase in current with the presence of light
- Breakdown is seen to occur at high voltage typically around 22V
- The breakdown is analyzed using Selberherr's impact ionization model
- Further factors can be take into account such as band to band tunneling which generally occurs in devices of this kind

Multi Wavelength Photodetectors with C-interpreter



- Luminous can also simulate multi-spectral sources from an external file
- The multi-spectral source is first defined using a external text editor using two columns, wavelength and intensity and saved as a file
- This file in then implemented using the 'power.file' command on the beam statement
- Ray trace is then performed for each individual wavelength and corresponding intensity selected within a specified window

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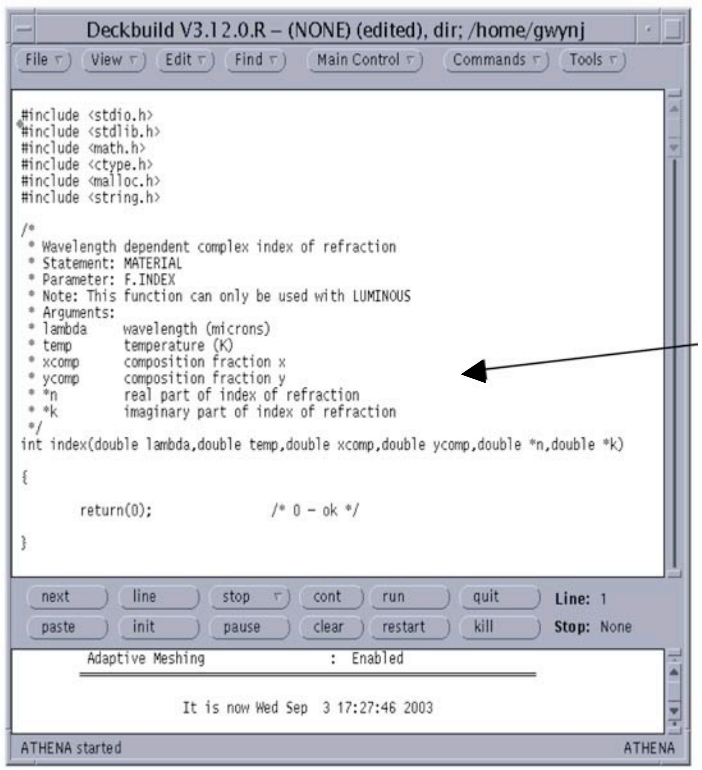
Multi Wavelength Photodetectors with C-interpreter



- Luminous also offers the opportunity of defining in-house developed photogeneration rate equations away from the default expressions
- The ANSI C C-interpreter module is used for this purpose
- Through using this module, the user can assign different photogeneration rates that are wavelength dependent to different regions within a device
- This permits photon detection from a multitude of wavelengths

Multi Wavelength Photodetectors with C-interpreter

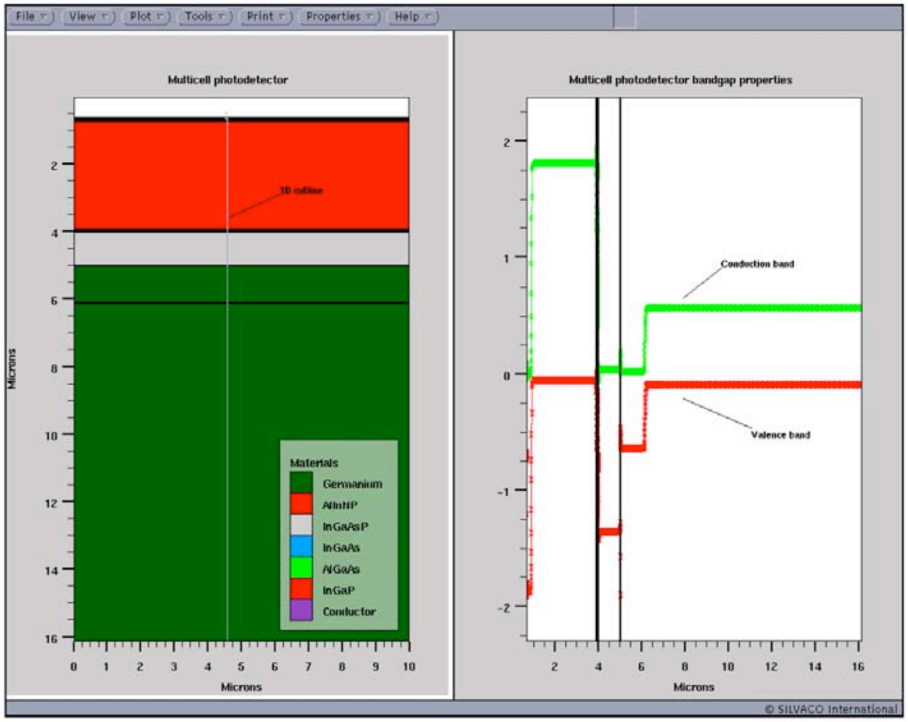
$$\alpha = \begin{cases} 0 & \text{if} \quad E_\lambda < E_g \\ A\dfrac{\sqrt{E_\lambda - E_g}}{E_\lambda} & \text{otherwise} \end{cases}$$

where,

$$E_\lambda = \frac{hc}{q\lambda} = \frac{1.24\text{eV}}{\lambda\ (\mu\text{m})}$$

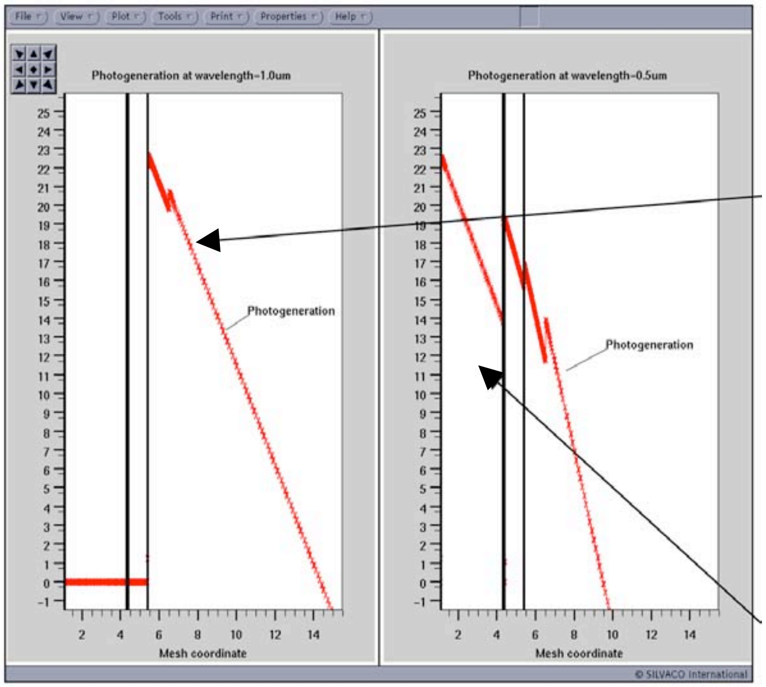
- Shown here are typical expressions used for photogeneration rates that are wavelength determined
- A simple if statement can be used to assign the different expressions to a certain region
- These expressions are simply coded into C and are then inputted using the f.index C-Interpreter module

Multi Wavelength Photodetectors with C-Interpreter



- This example shows the bandgap engineering effect used to detect different wavelengths from a multispectral source
- The bandgaps are approximately 2.0eV, 1.0eV and 0.5eV
- These should be able to detect light at wavelengths 0.5um, and 1.0um individually and collectively

Multi Wavelength Photodetectors with C-Interpreter (con't)



- Shown here is the photogeneration of carriers throughout the device
- At 1.0um wavelength, photogeneration only occurs in the lower region which has the smaller bandgap
- As the wavelength decreases the energy of the photons increase and photogeneration of carriers is possible in the wider bandgap regions
- At 0.5um wavelength, photogeneration is present in all regions and is prevalent in the upper regions

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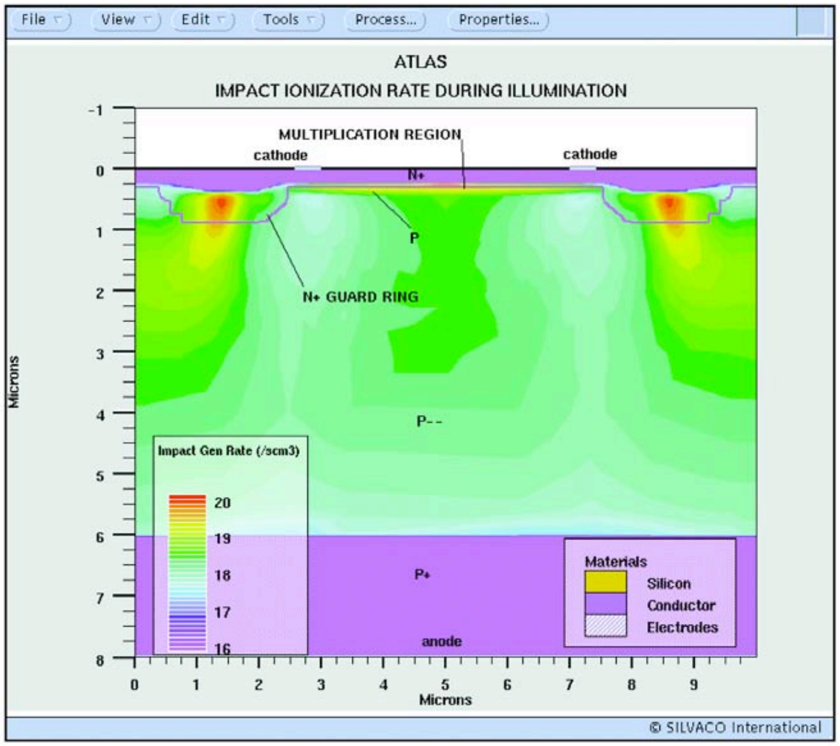
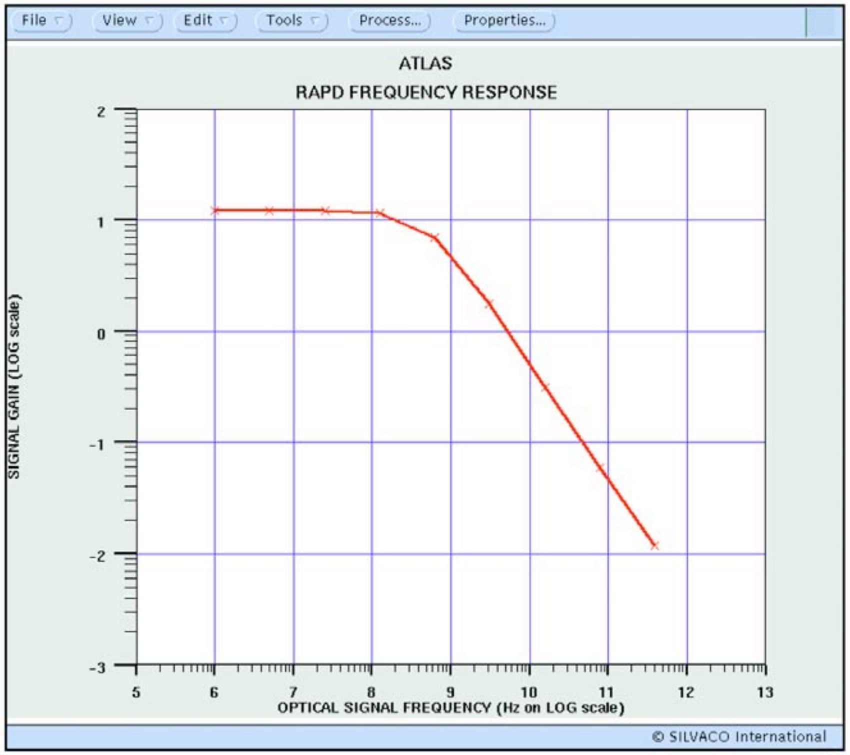
High Speed Photodectors



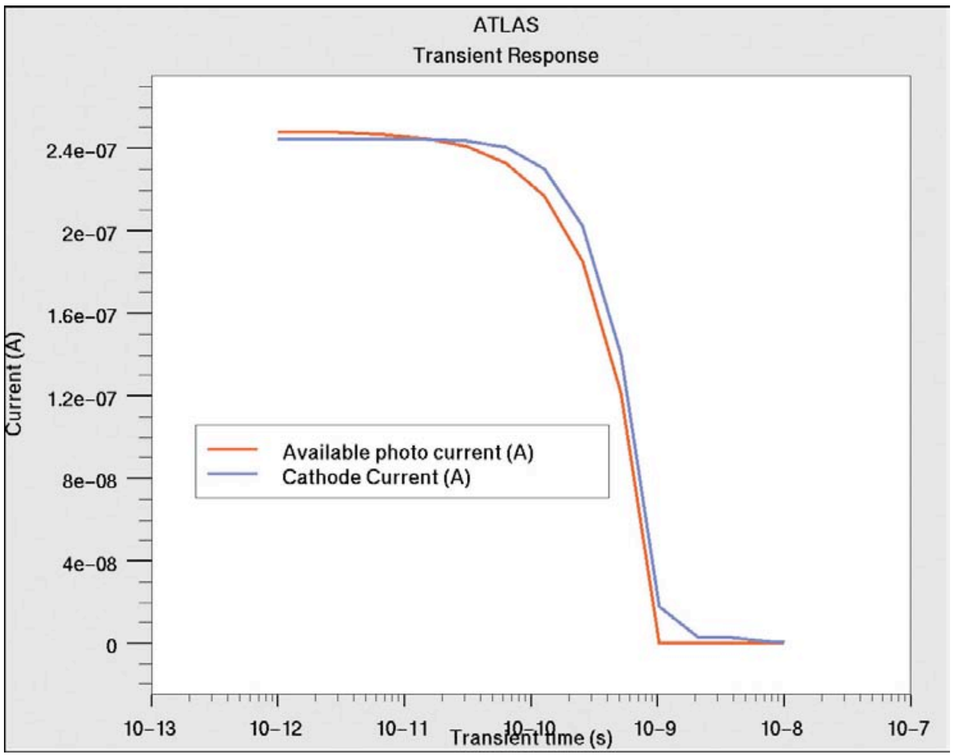
- Luminous 2D/3D can also analyze photodetectors used in high speed and low noise applications, such as communications hardware.
- Shown here is a typical reach through avalanche photodetector created using ATLAS
- Impact ionization rate contours at operating bias for a Reach Through Avalanche Photodiode (RAPD) are shown
- The peak impact ionization region is in the intended multiplication region

High Speed Photodectors (con't)



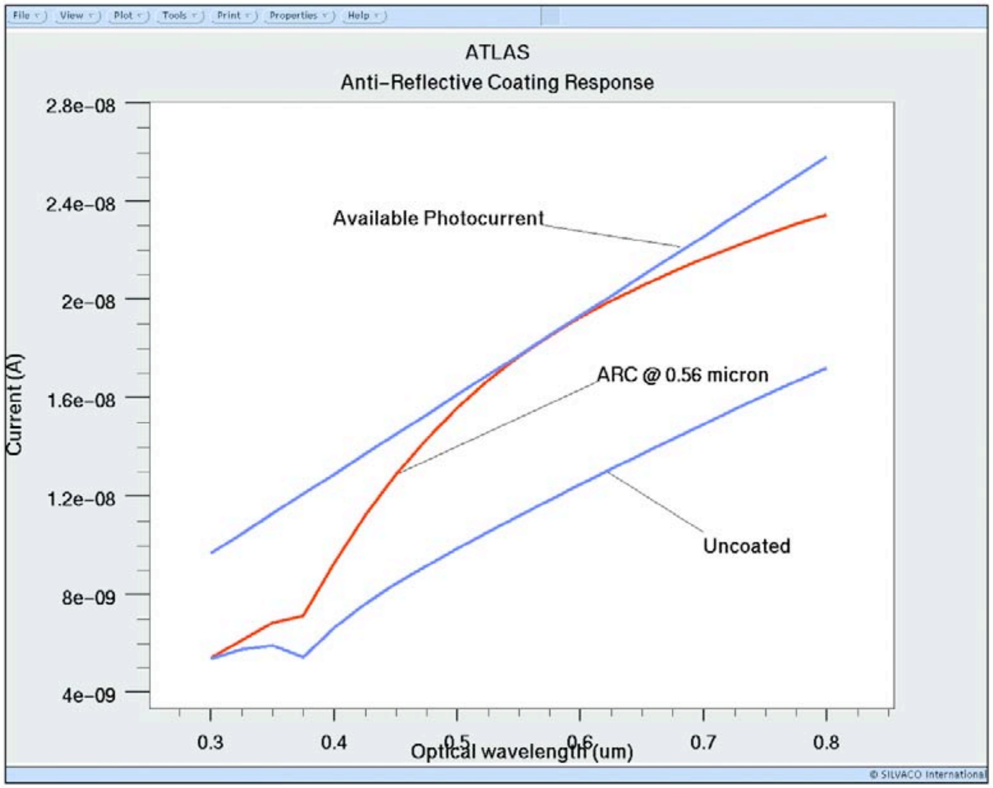
- Response to a high frequency variable light source is shown
- Important device characteristics, such as quantum efficiency, spectral response, and frequency response are easily extracted using Luminous 2D/3D

High Speed Photodectors (con't)



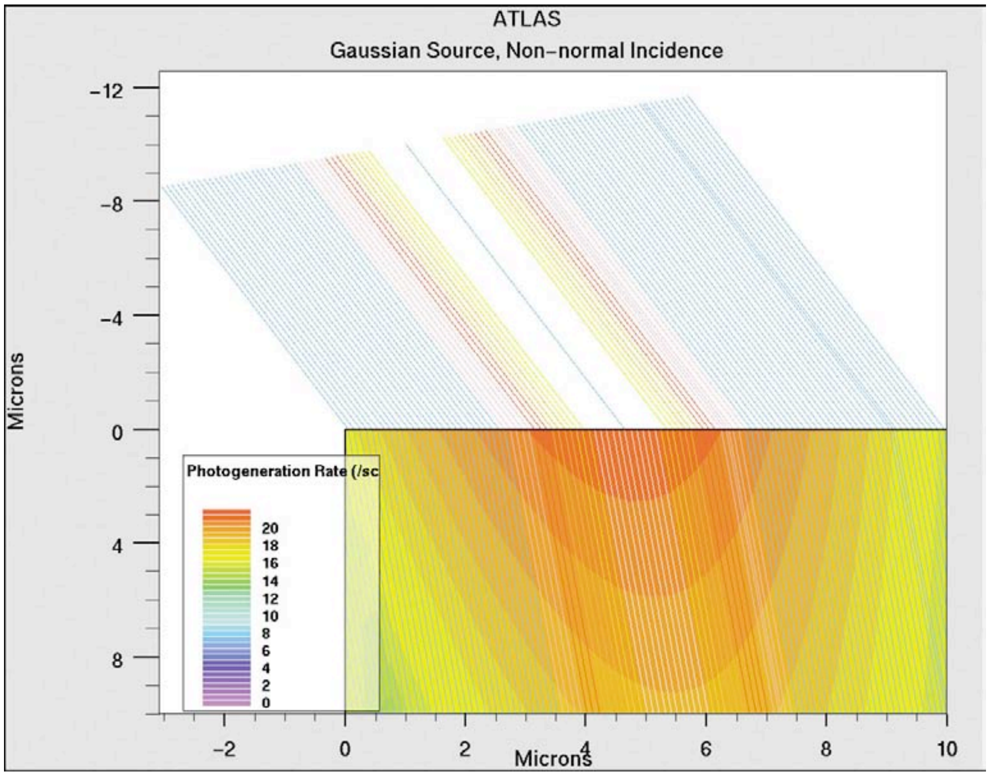
- Luminous 2D/3D also permits simulation of transient response
- The lag between a rapid turn-off of the light and the resultant photodetected current is shown
- This type of analysis allows the user to design and optimize the switching and response time of the photodetector

High Speed Photodectors (con't)



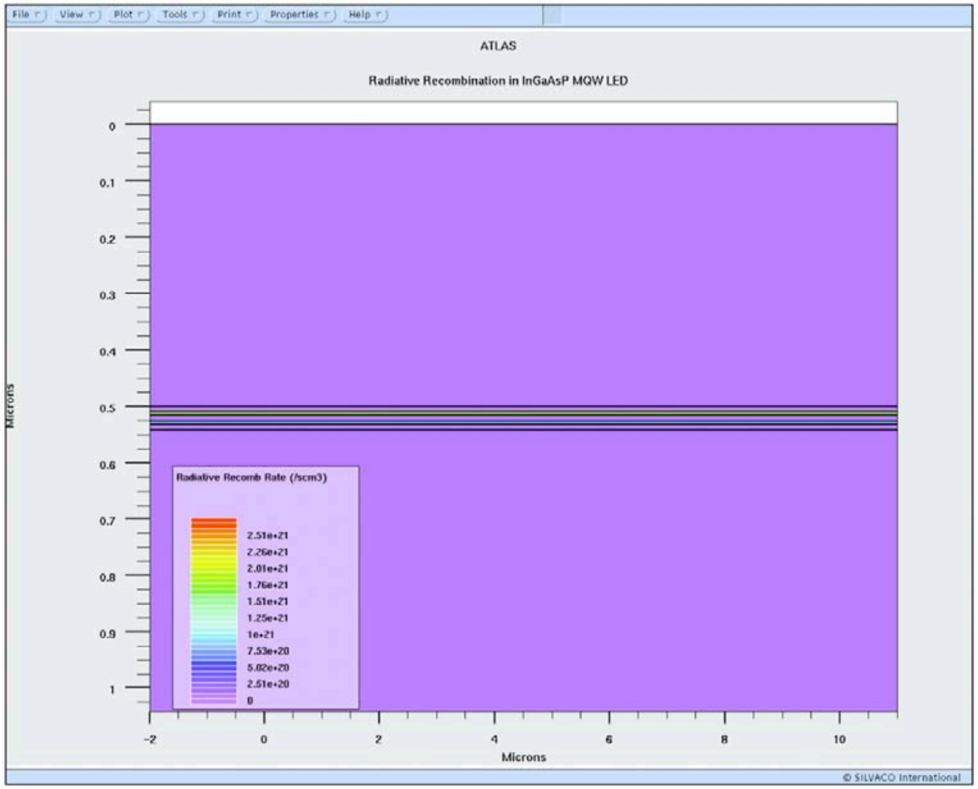
- Luminous 2D/3D allows the specification and simulation of anti-reflective coatings
- A comparison of the spectral response of a device with and without an anti-reflective coating as compared to the ideal response

High Speed Photodectors (con’t)



- Gausian source intensity with non-normal incidence and periodic boundaries
- Luminous 2D/3D allows very general specification of the optical source

Multiple Quantum Well (MQW) Light Emitting Diodes



- The simulated radiative recombination rate in an InGaAsP multiple quantum well light emitting diode
- We note that the radiative recombination rate is confined to the two quantum wells near the center of the device
- This calculation accounts for the effects of quantum confinement and strain

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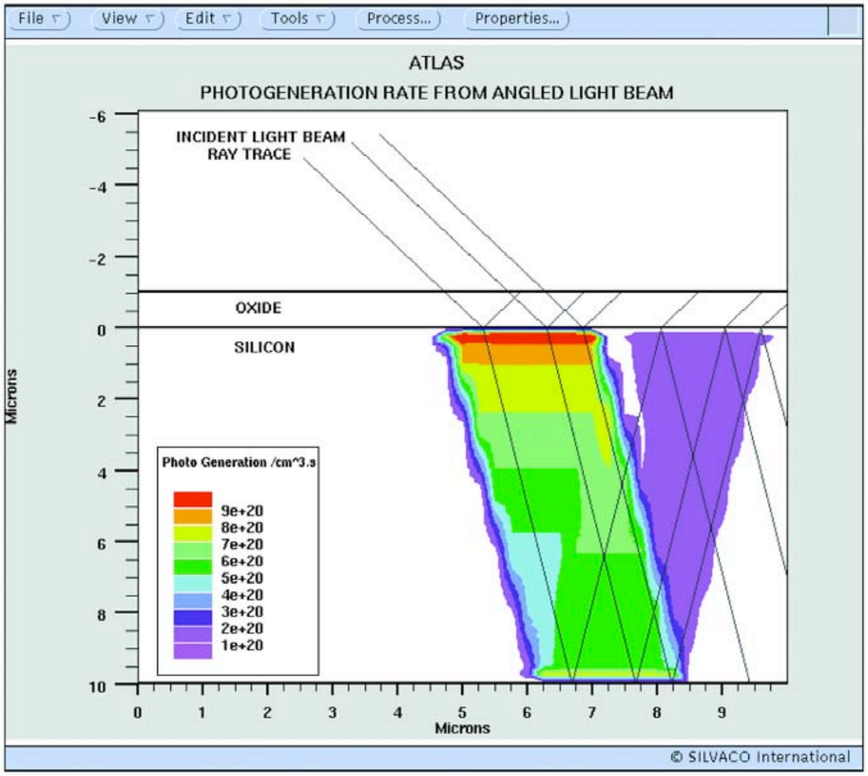
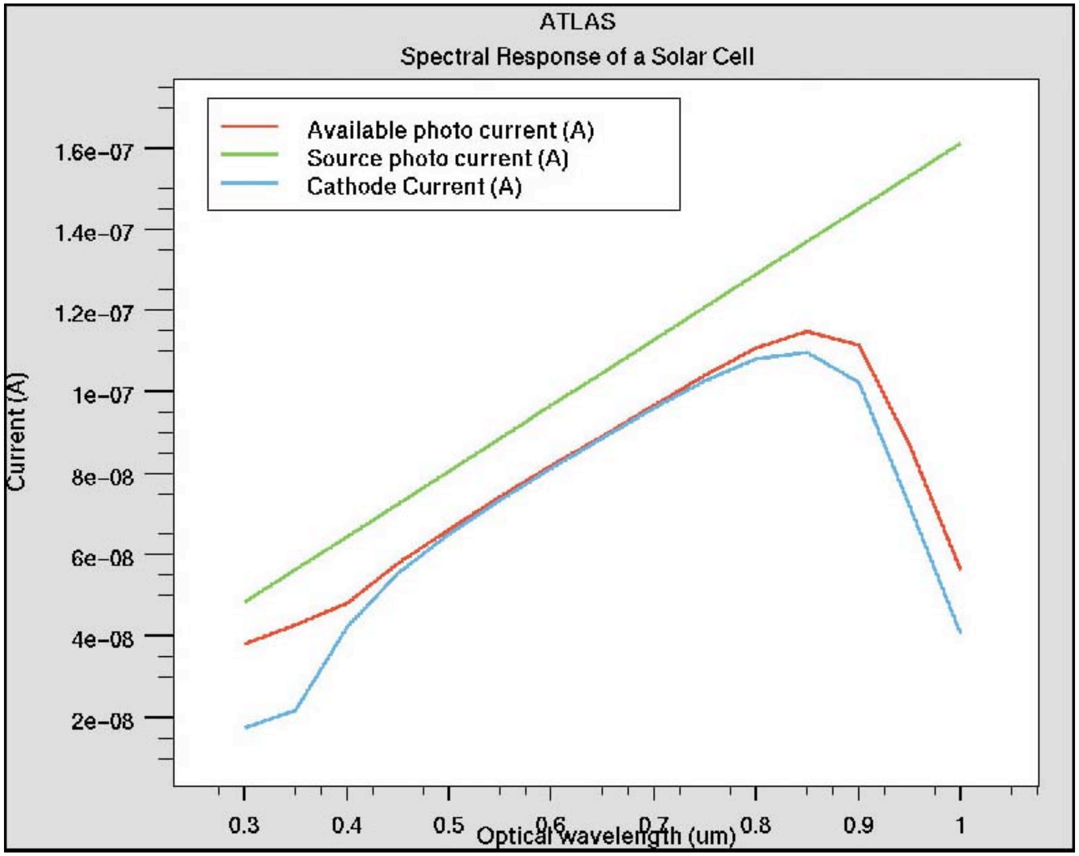
Solar Cells



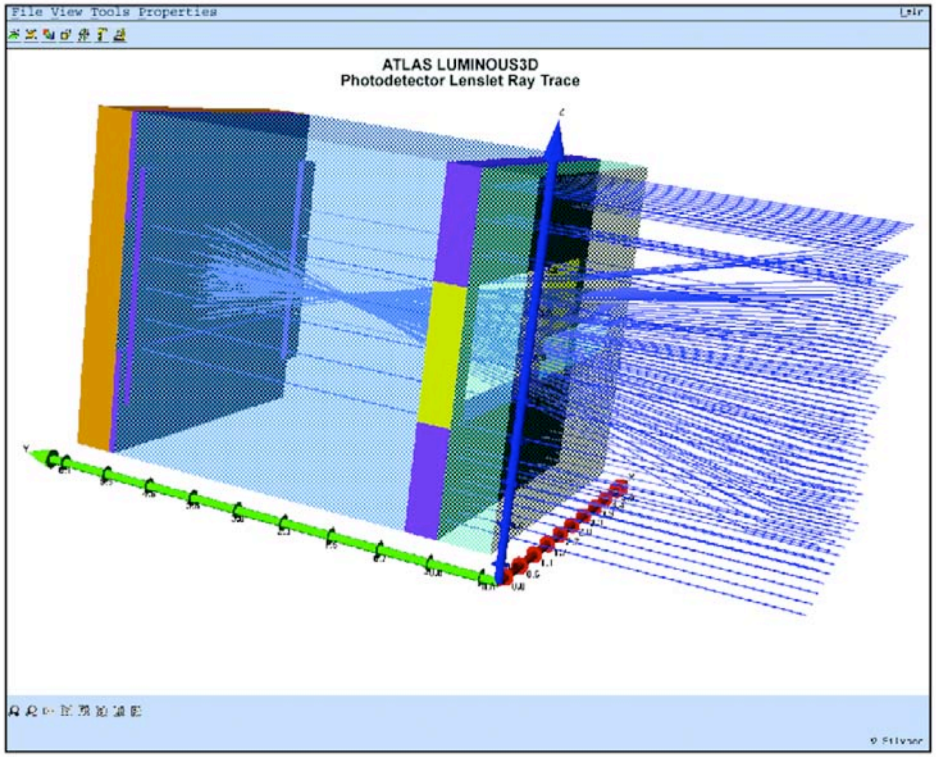
- Solar cell characteristics, such as collection efficiency, spectral response, open circuit voltage, and short circuit current can be extracted with Luminous 2D/3D
- Simulation of photogeneration rates from an angled light beam
- The ray trace features in Luminous 2D/3D enable the analysis of advanced designs

Solar Cells



- The green curve is the current from the light source, and the blue curve is the actual terminal current
- By varying the incident wavelengths, a spectral response can be modeled

3D Simulation



- Luminous 3D allows the simulation of complex structures to address three dimensional issues. In this case, the user has defined a lenslet above the photodetector to focus the light into the device
- This figure shows the top and view of the resultant ray trace

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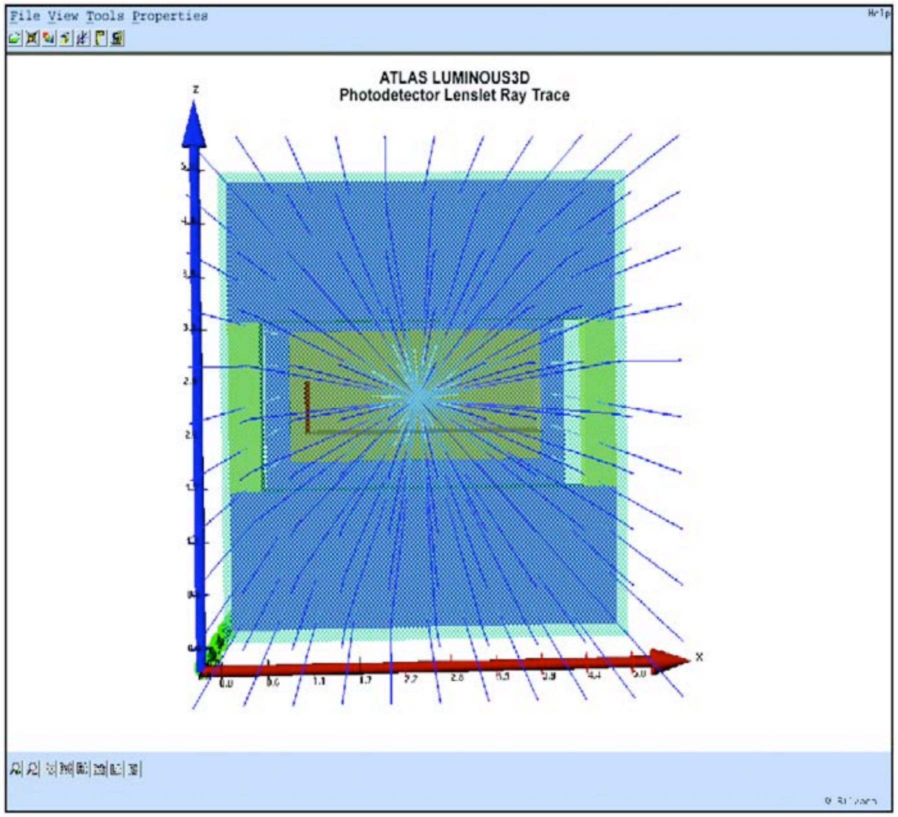
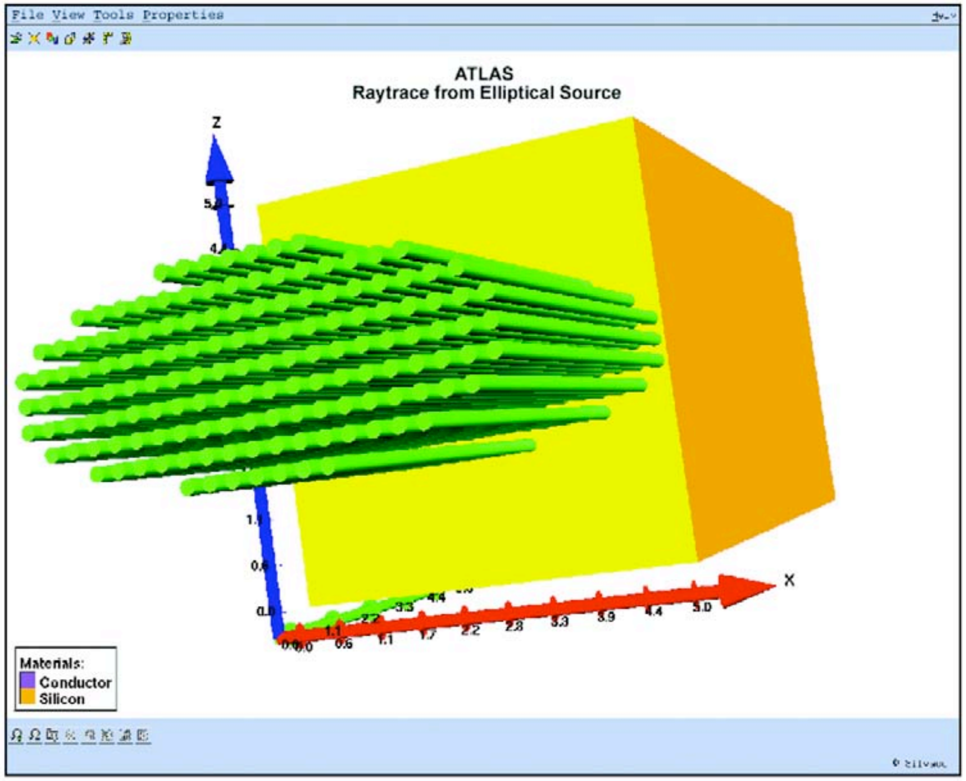
3D Simulation



- The orientation of a 3D structure is simple using TonyPlot3D
- Advanced cut-lines can be performed throughout the device and at any angle showing detailed results such as photogeneration or the ray trace throughout a specific region
- Here the ray trace is shown from a side view of a horizontal cutline plane through the center of the device

3D Simulation



- This diagram illustrates a ray trace from an elliptical source
- In 3D, the user may also define a circular or elliptical optical source, as well as the default uniform illumination

Conclusion

- Silvaco's advanced Luminous 2D/3D optical device simulator has been discussed
- Several optical effects can be analyzed and understood
- Geometric ray tracing is performed for planar and non-planar topologies thus characterizing internal and external reflections and refractions, polarization dependencies, dispersion and photogeneration
- Photogeneration rates can use default expressions or in-house developed expressions via the c-interpreter, resulting in accurate and identifiable wavelength detection from both single and multi-spectral sources
- Luminous 2D/3D can run seamlessly with Silvaco's other TCAD tools such as TFT2D/3D and MixedMode
- In particular, Luminous 2D/3D can be implemented with Blaze to simulate complicated heterostructure devices for varying wavelength detection
- Ease of use within the DeckBuild and TonyPlot environment