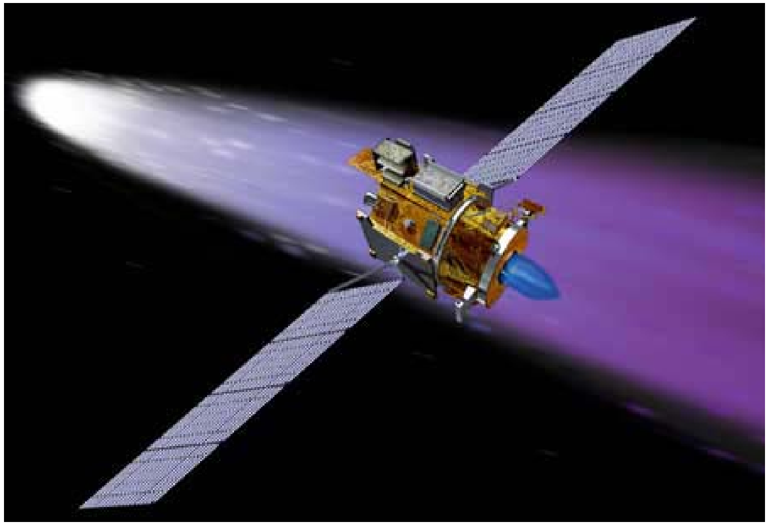
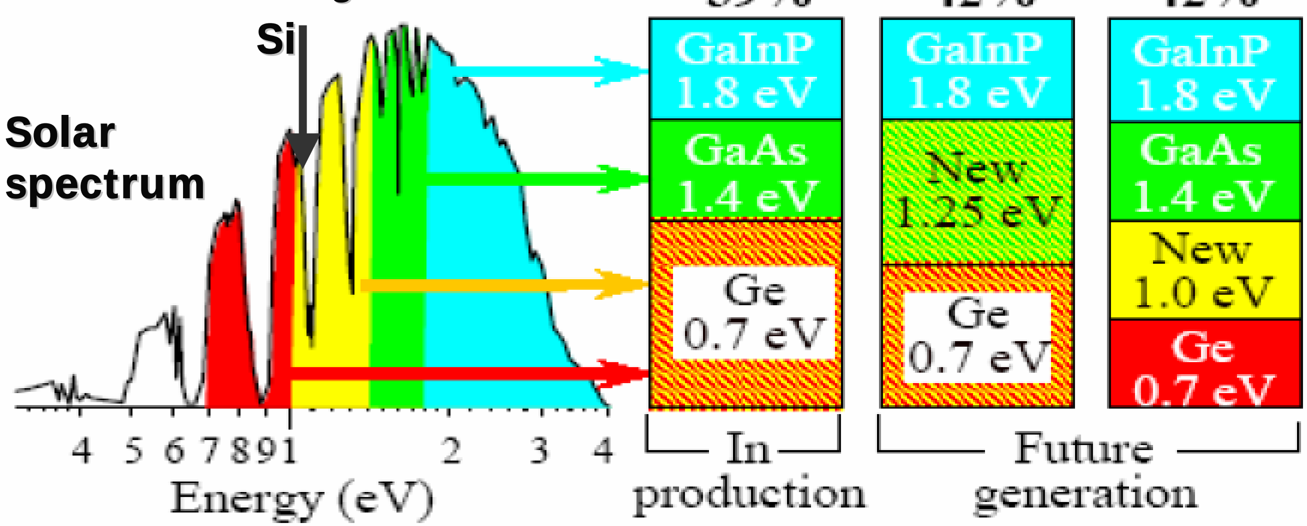
Simulation of multi-junction compound solar cells

Introduction

- Multi-junction (MJ) solar cells – space (e.g. NASA Deep Space 1) & terrestrial applications.
- More efficient & better radiation hardness.
- More sensitive to illumination spectra change.



source www.nrel.gov



CROSSLIGHT Software Inc.

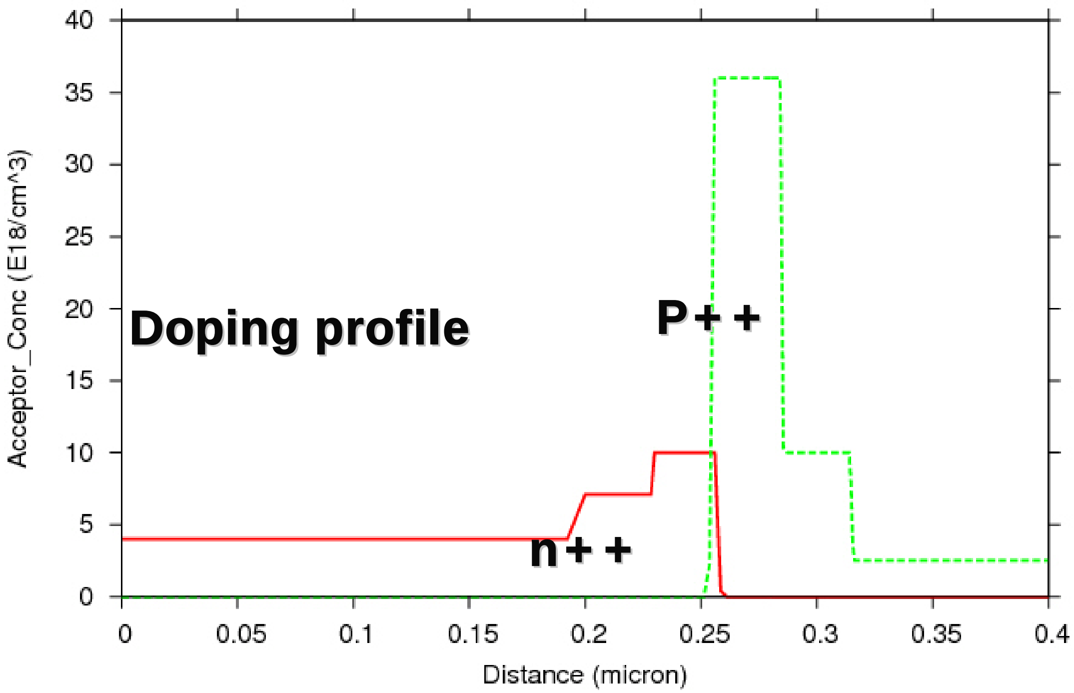
Introduction

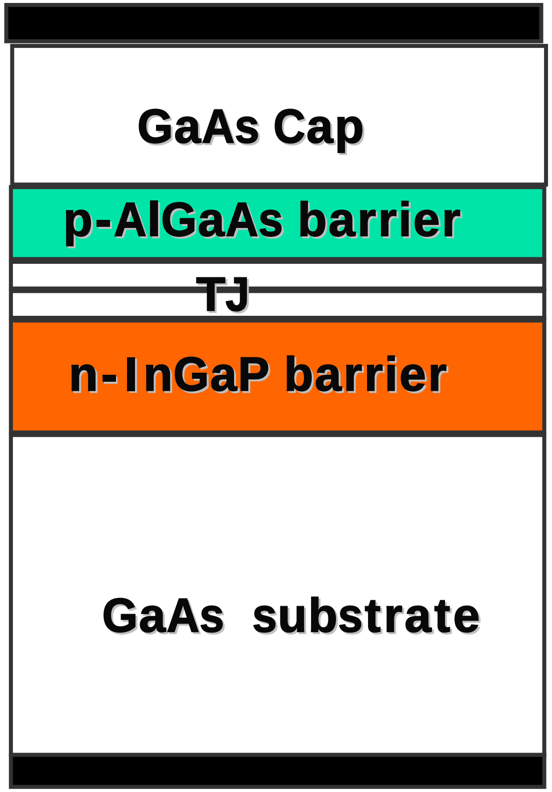
- Compound solar cells have many layers with different composition, thickness and doping density, need to be optimized.
- Better methods & software, especially with 2D/3D modeling capability in high demand.
- Save R&D time/cost & capability in optimizing device design. Better understanding & predicting the operation condition.
- In this work, based on drift-diffusion theory & Crosslight's APSYS, single, dual and triple junction solar cells are simulated and compared with experiments.

APSYS models related to solar cells

- Non-local quantum tunneling (intra- & inter-band) model – tunneling junctions.
- All physical processes – carrier generation, recombination, drift & diffusion with 2D / 3D modeling capability.
- Self-heating, series resistance, shadowing, and edge effects can be included.
- Multi-layer optics model – internal reflections & interferences.
- FDTD and Ray-tracing (RT) for edge effect & for cell with texture.
- Comprehensive material database for compound semiconductors

Tunnel Junction





Prog. Photov. Res. & Appl., 2008

Non-local Tunneling Model

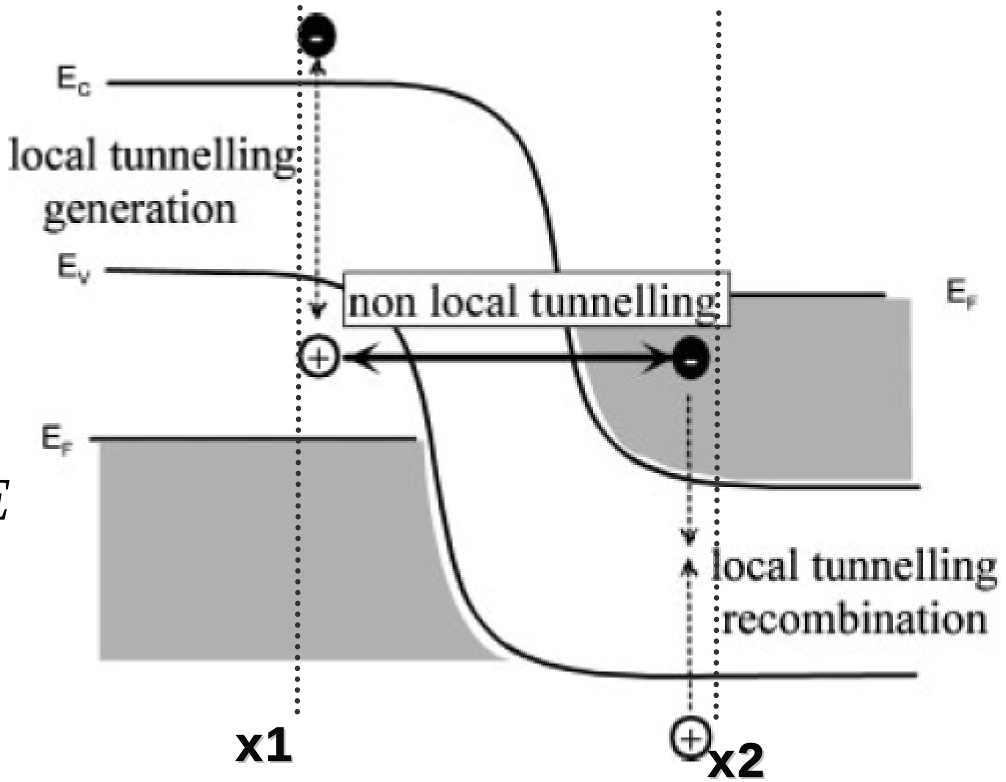
Based on WKB approx. tunneling probability

Tunneling probability:

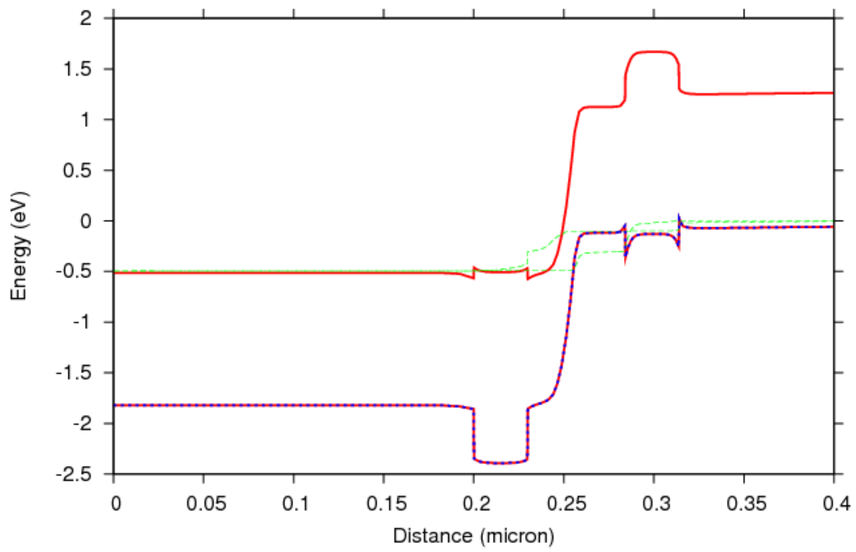
$$D = \exp(-2\int_{x1}^{x2} |k(x)|\, dx)$$

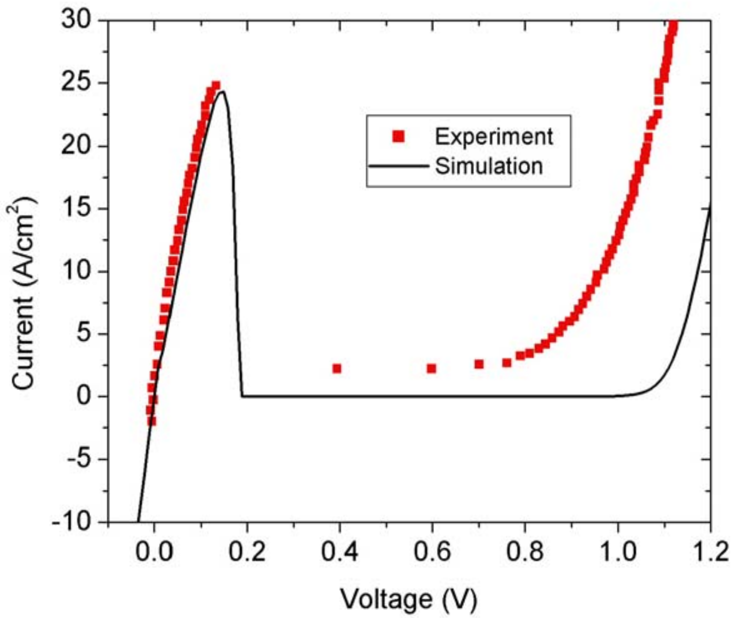
Tunneling current:

$$J_t = \int_{E_c}^{E_v} (F_c - F_v) D n_c(E) n_v(E) dE$$



I-V of Tunnel Junction



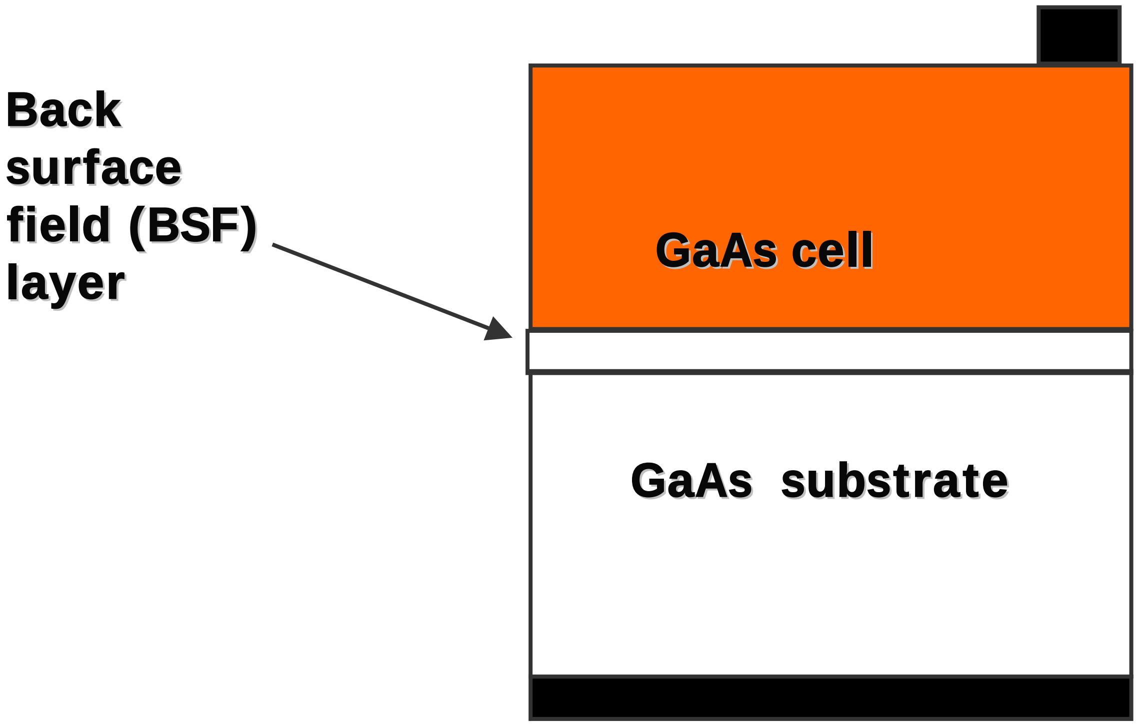


Band diagram at 0.5V reverse bias

Prog. Photov. Res. & Appl., 2008

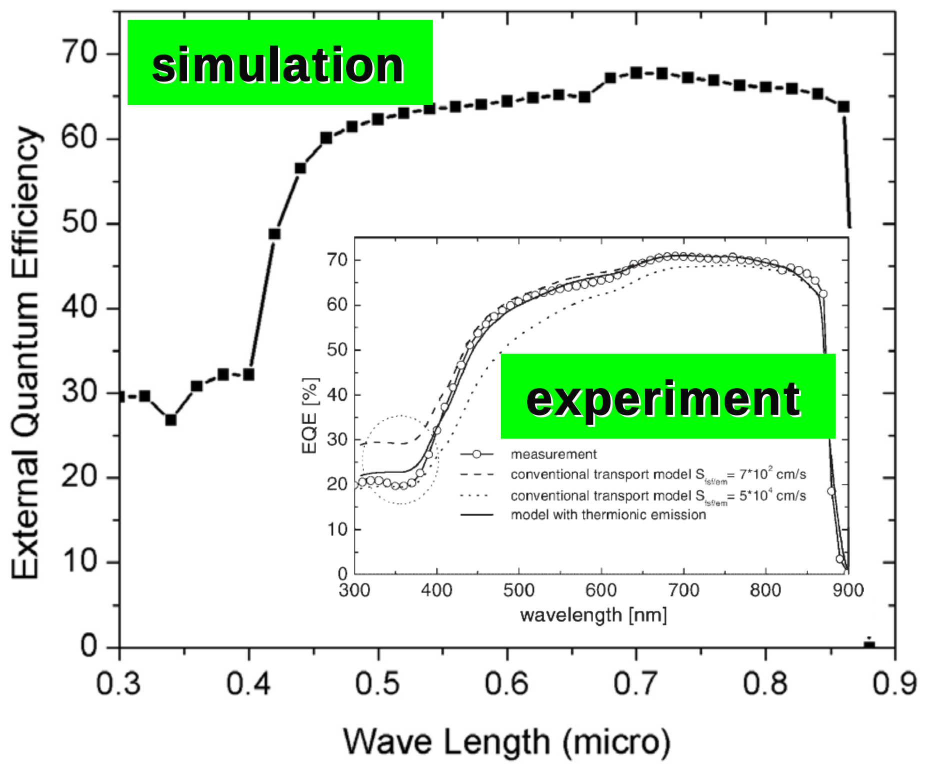
GaAs Solar Cell

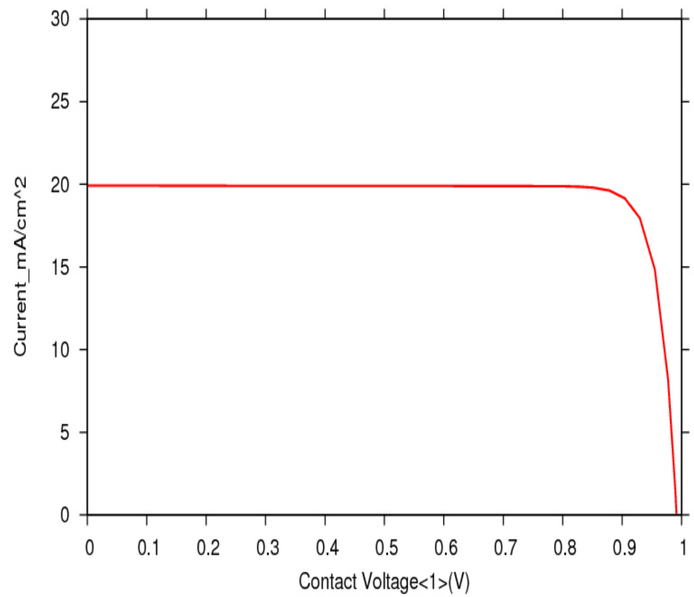
Note: no window and AFC layers



Progs. Photov. Res. & Appl. Vol.14, p. 683, 2006

EQE and I-V



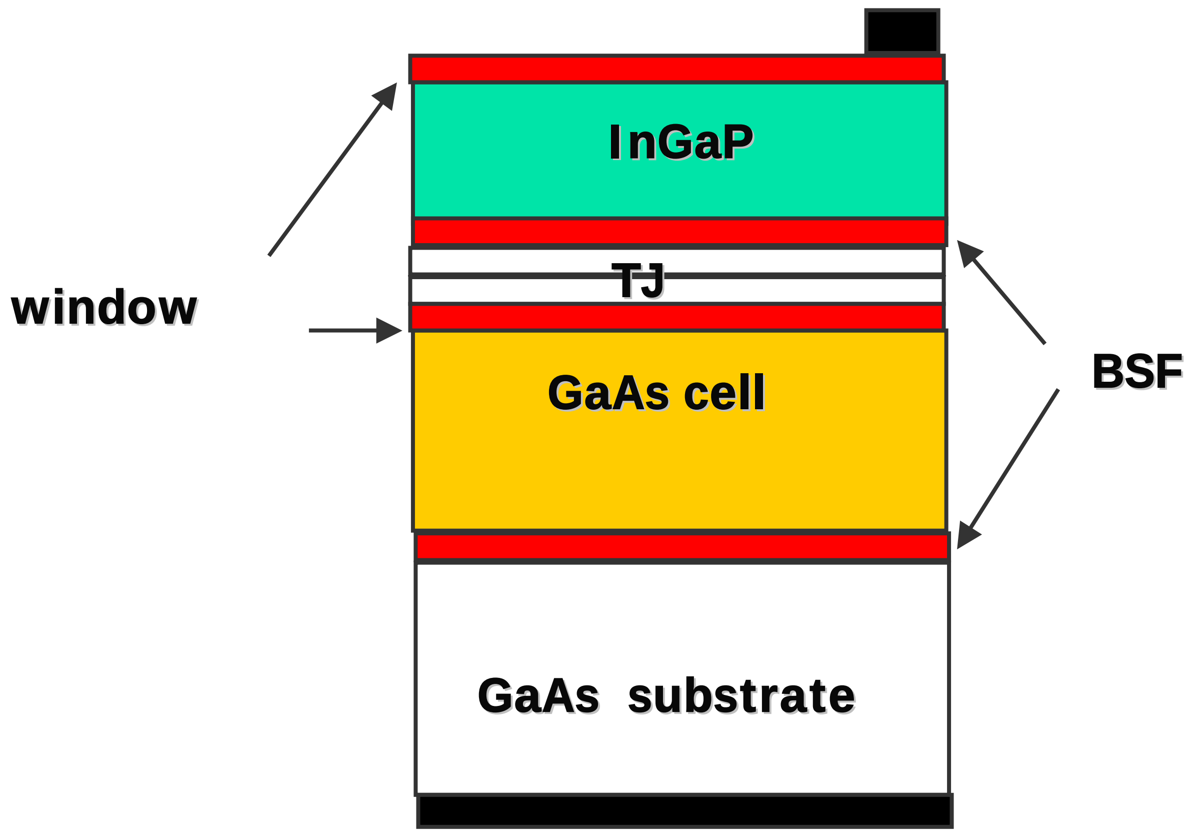


	Jsc	Voc
Simulation	19.92	0.991
Exp	19.3	0.991

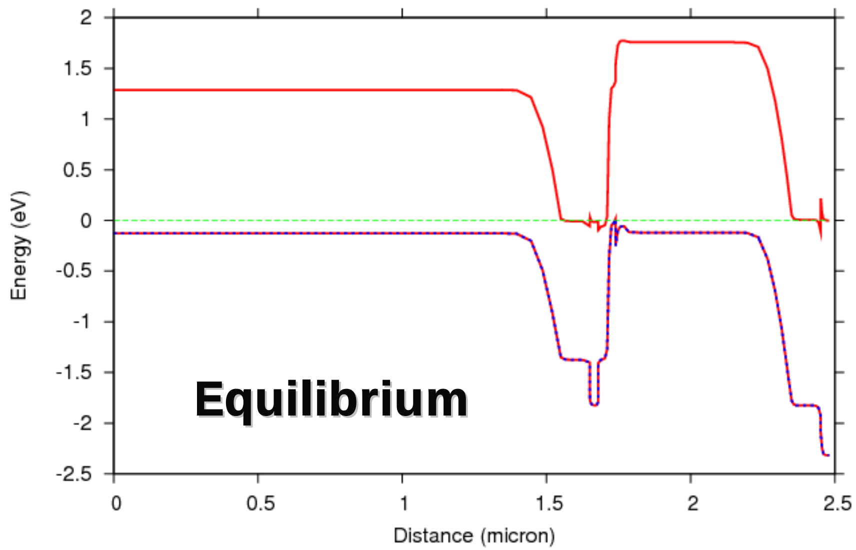
Progs. Photov. Res. & Appl. Vol. 14, p. 683, 2006

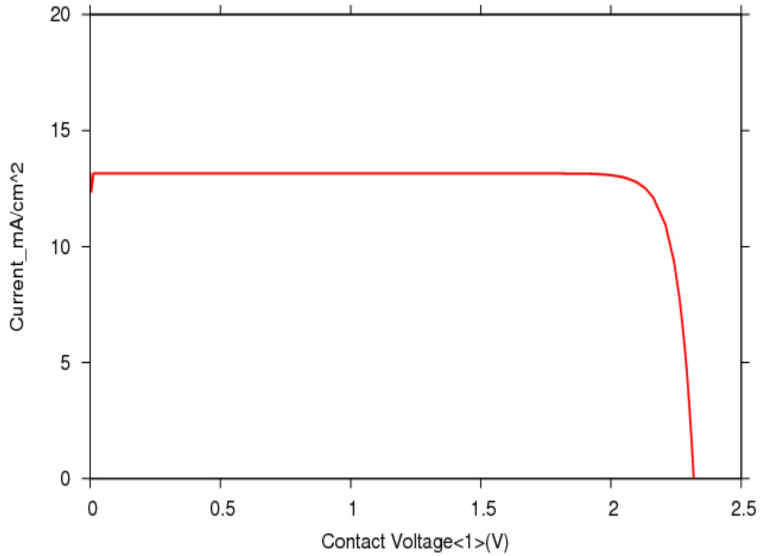
CROSSLIGHT Software Inc.

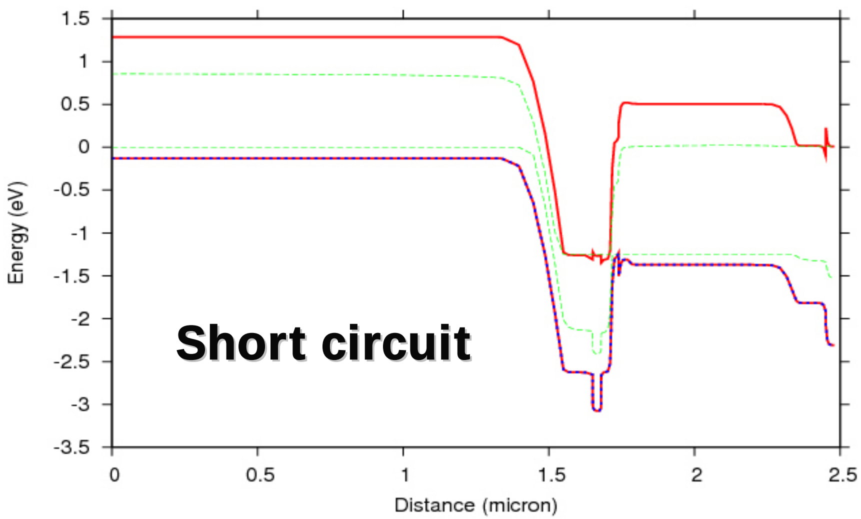
Dual-Junction



Band Diagrams and I-V

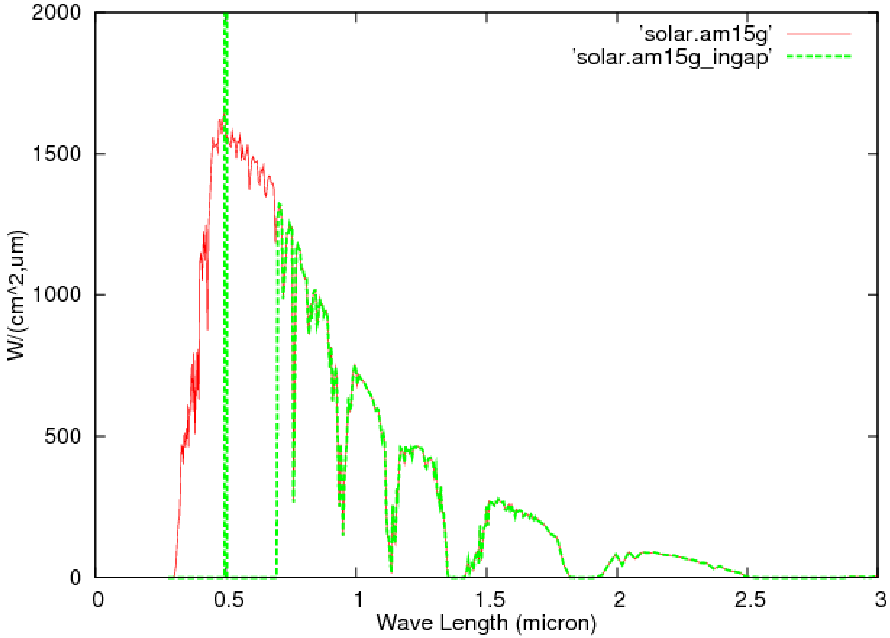


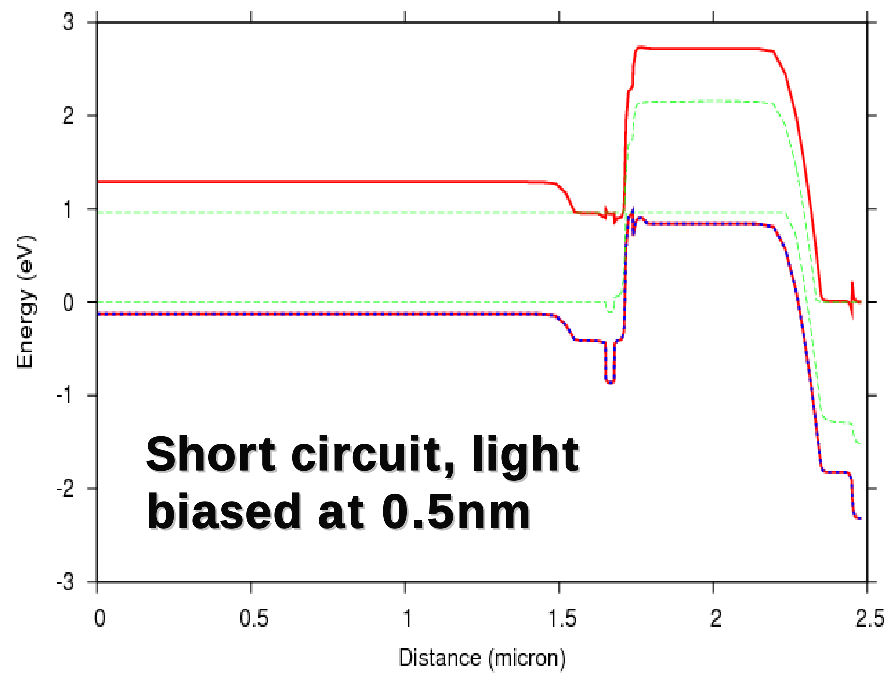




Band diagram at equilibrium (top) and short circuit (bottom), showing GaAs cell is current limiting, since it is reverse biased.

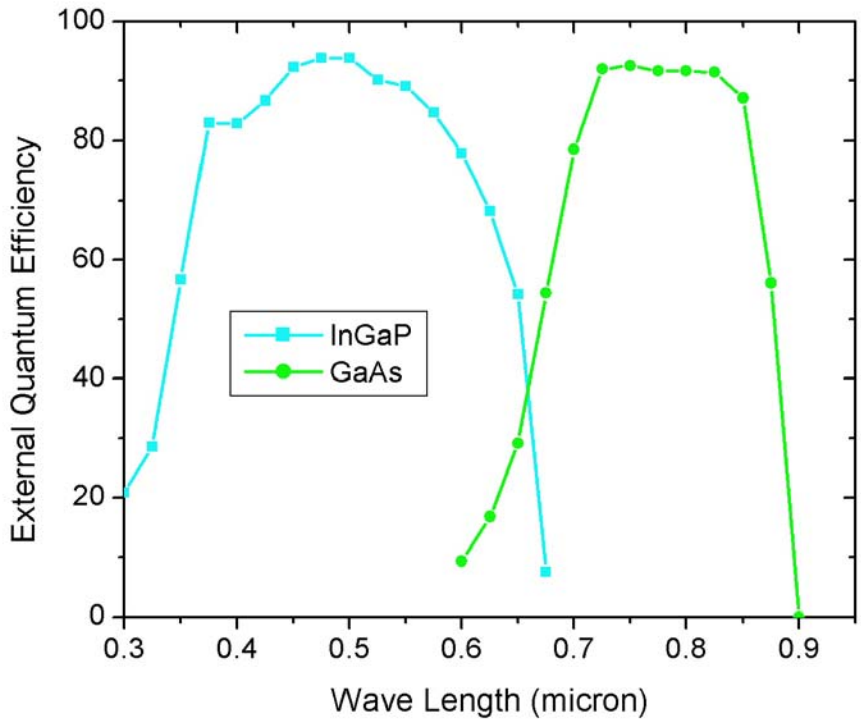
EQE Calculation



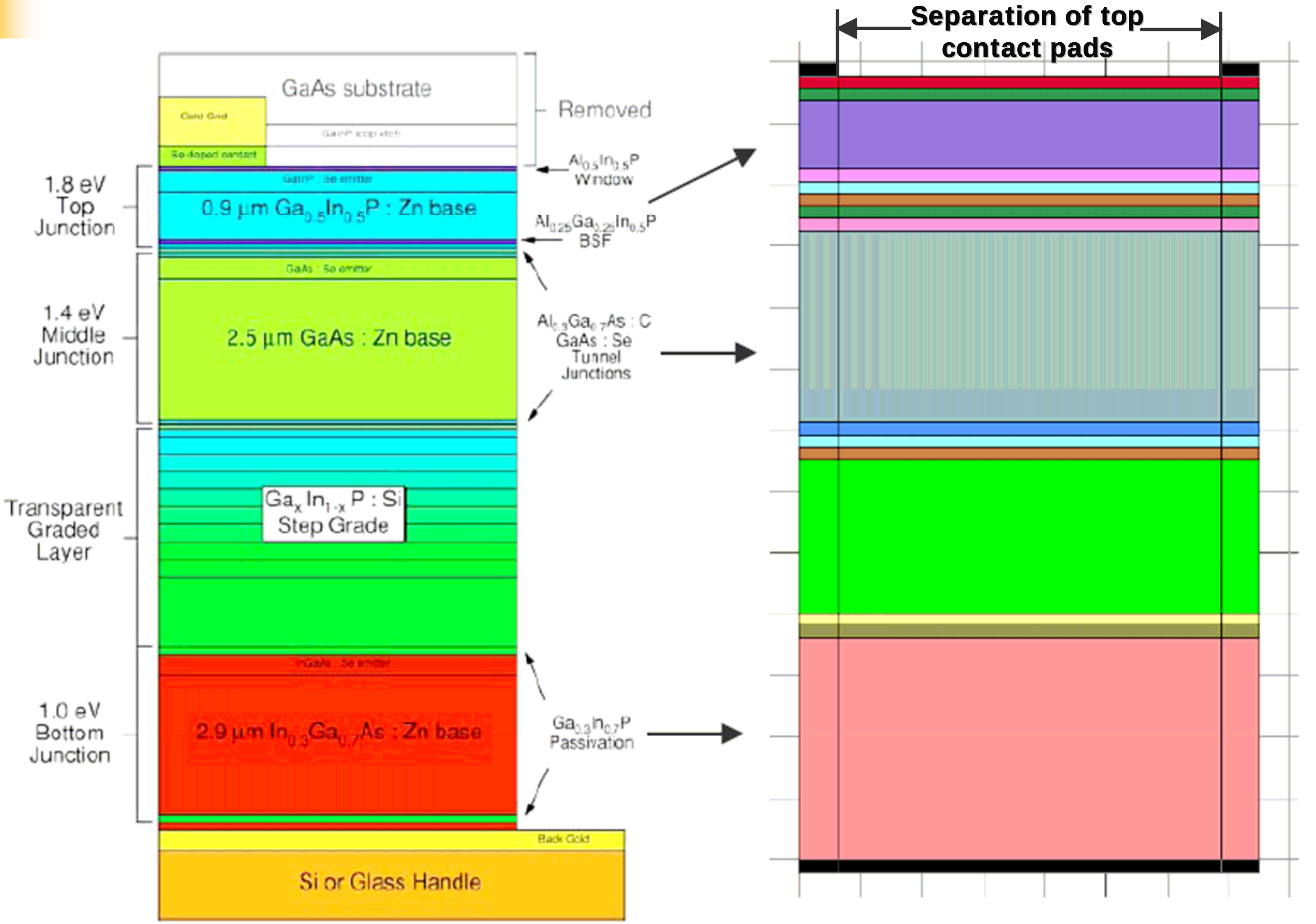


Light power for target sub-cell is filtered, with only 100 w/m^2 light bias at target wave length, so the target sub-cell is current limiting (reverse biased).

EQE of Dual-Junction Cell

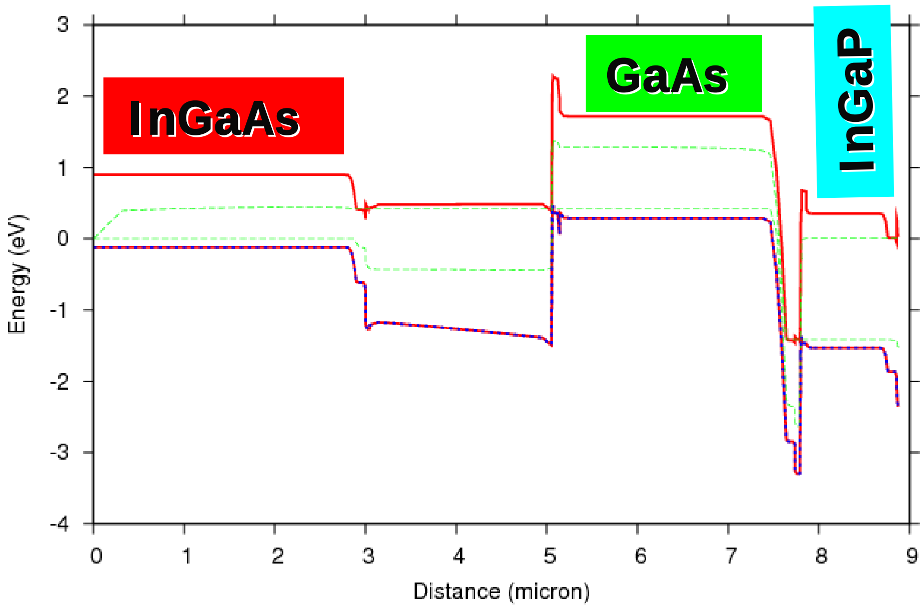


Inverted Triple-Junction

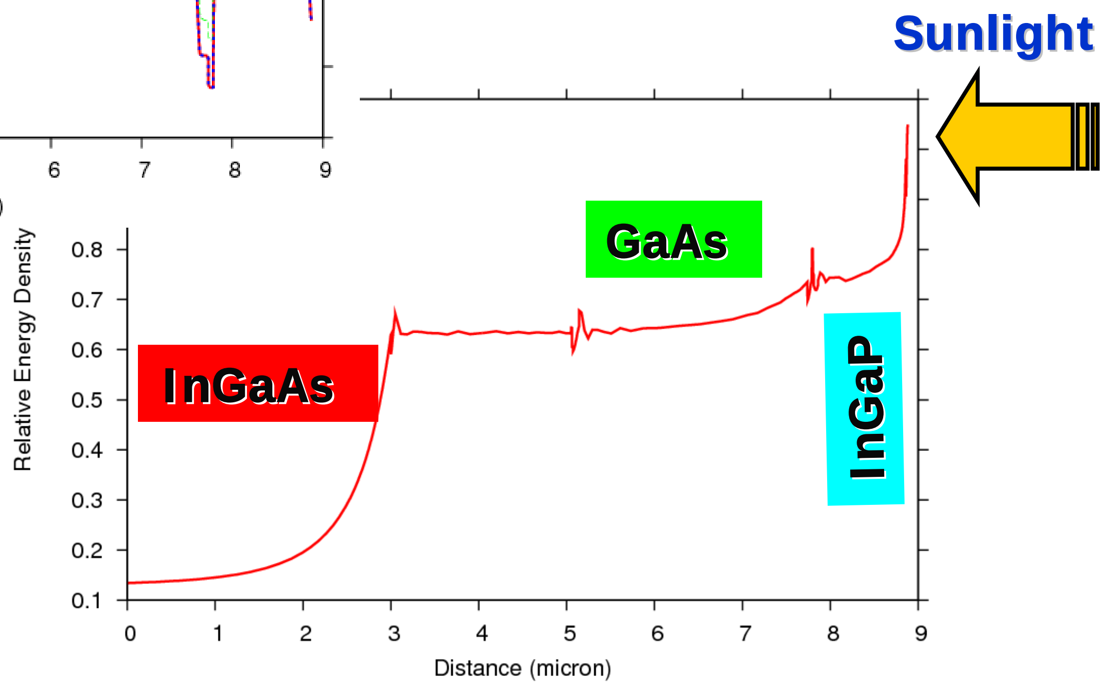


Geisz et al, APL 91, 023502 (2007)

Band Diagrams & Optical Generation

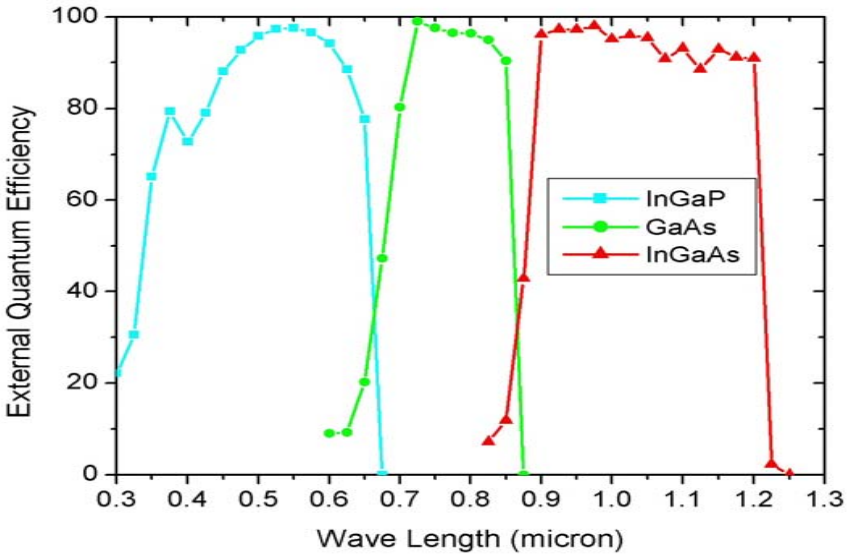


Band diagram at short circuit. GaAs is current limiting cell, which is at high reverse bias.



Relative incident power.

External Quantum Efficiency



Simulated

Geisz et al, APL 91, 023502 (2007)

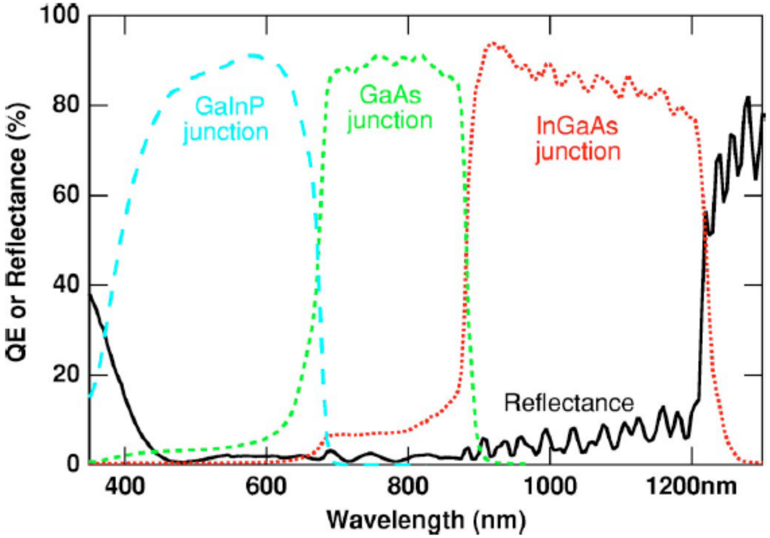
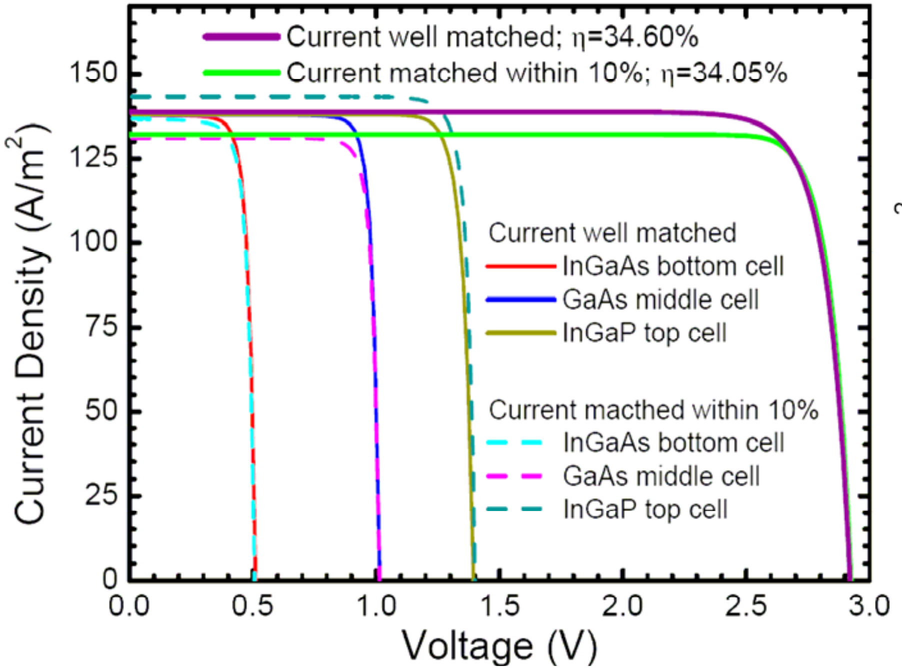
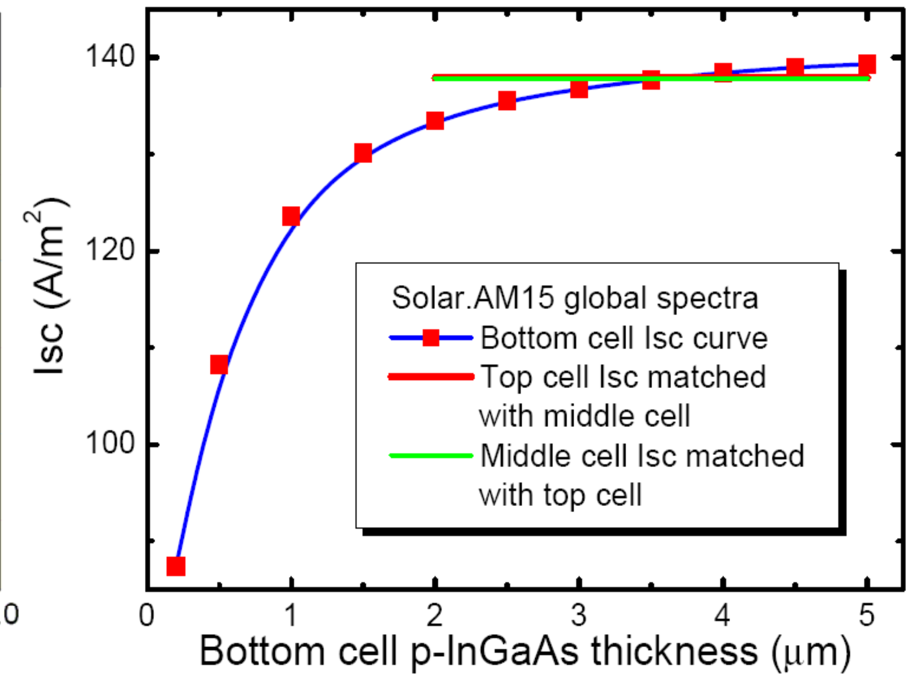


FIG. 3. External quantum efficiency and specular reflectance of the AM1.5G inverted triple-junction device.

I-V Curves: Current Matching



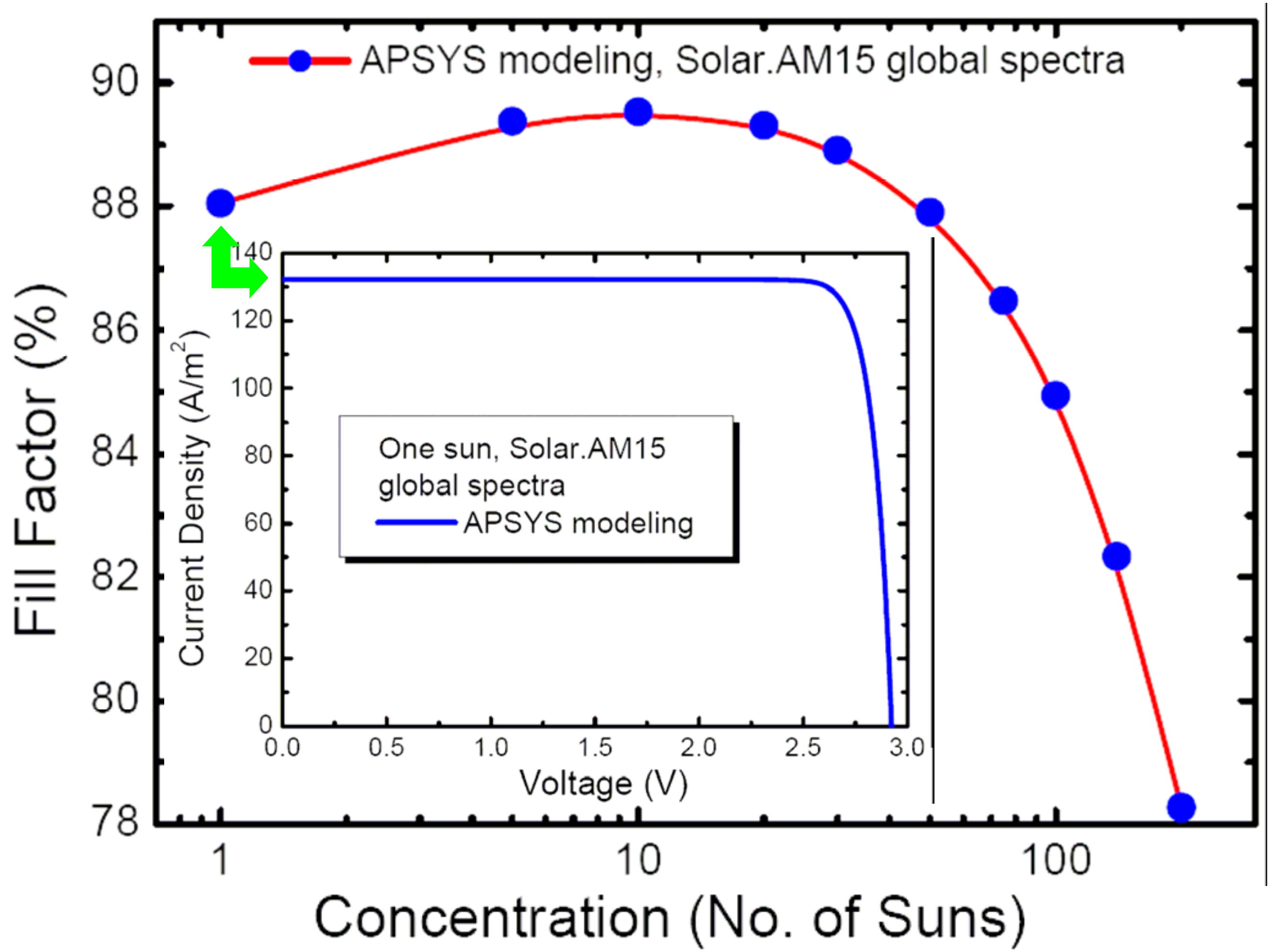


	Voc (V)	Isc (mA/cm²)	Efficiency (%)
Experimental	2.96	13.1	33.8
Modeling	2.93	13.2	34.1

Comparing the case when current matched within 10%.

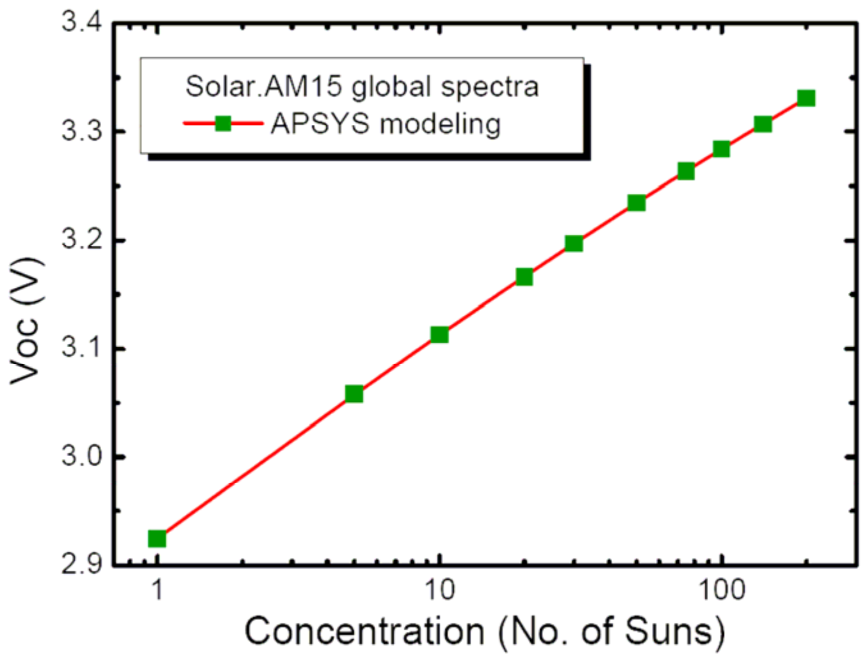
- **Conversion efficiency improved when current matched with middle & top subcells.**
- **Modeling results of Voc, Isc & efficiency comparable with experimental results.**

Multi-Sun Concentration: Fill Factor

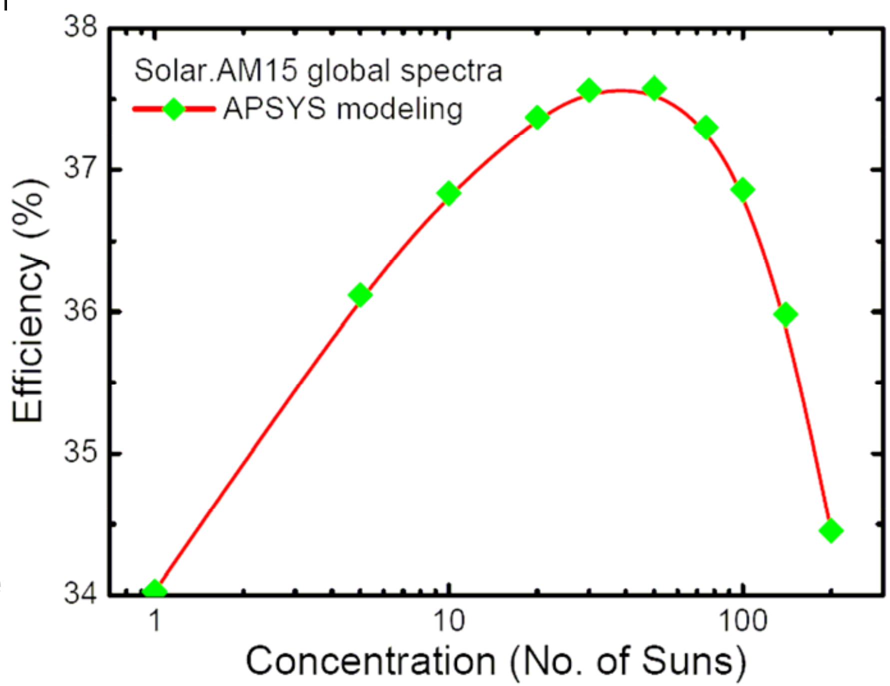


CROSSLIGHT
Software Inc.

Multi-Sun Concentration: Voc & Efficiency

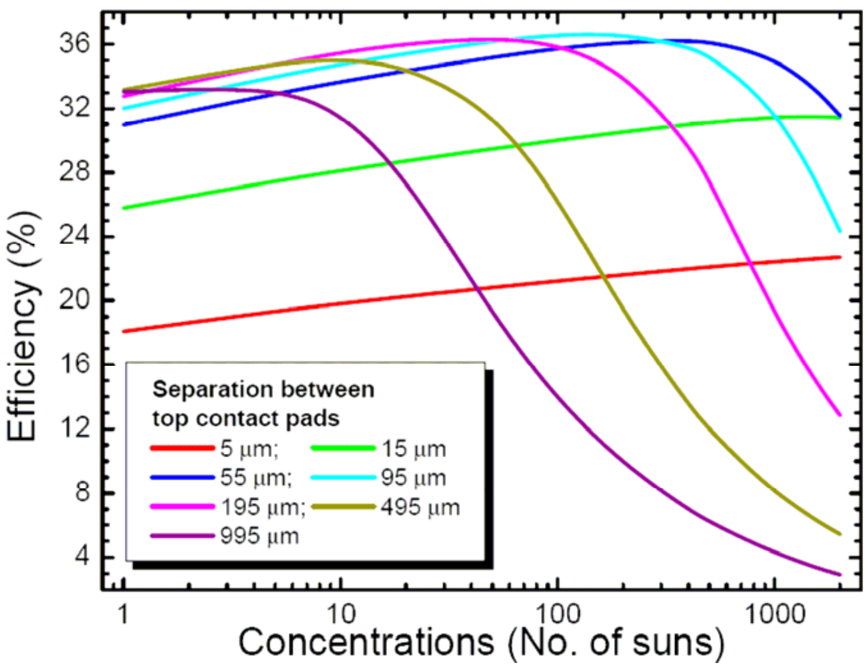


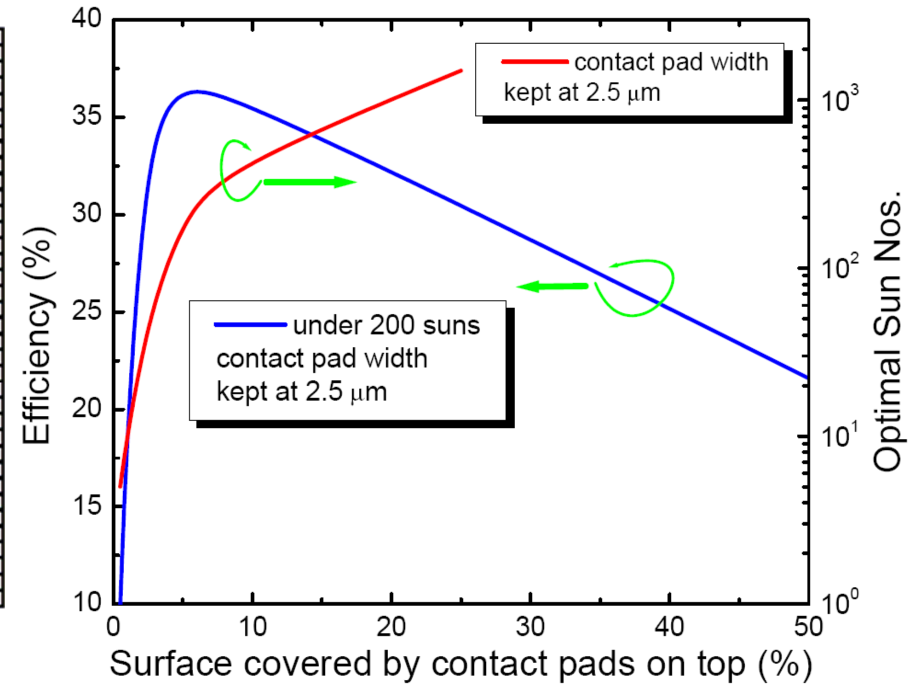
- V_{oc} is logarithmically proportional with concentration.



- **Cell efficiency enhanced versus sun No. initially due to enhanced Voc. Afterwards it decreases due to series resistance.**

Multi-Sun Concentration: Efficiency





- **Optimal sun number varies with contact pad separation, indicating different series resistance effect.**
- **At fixed sun number, optimal efficiency appears at certain top contact pad separation where a specific ratio covered by top contact pads is identified.**

3D InGaP/GaAs/Ge TJ Solar Cell Structure

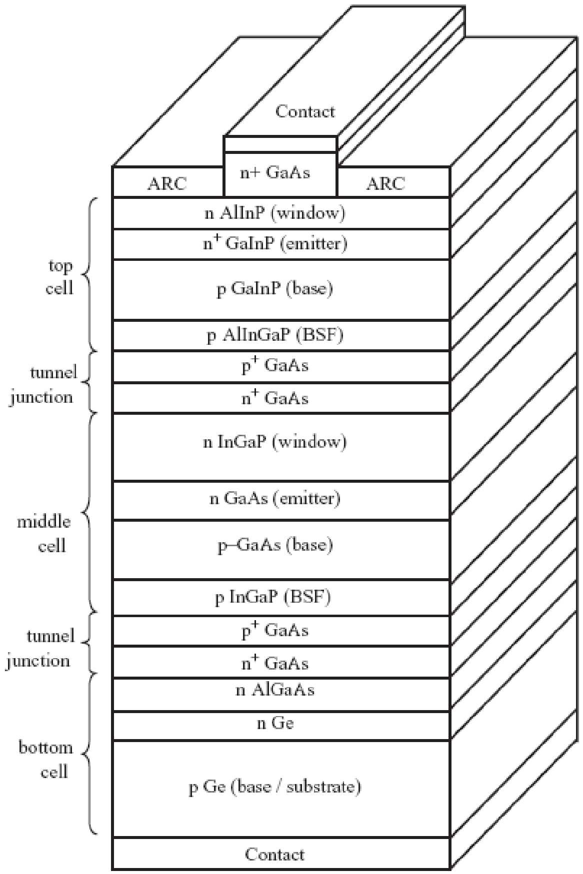
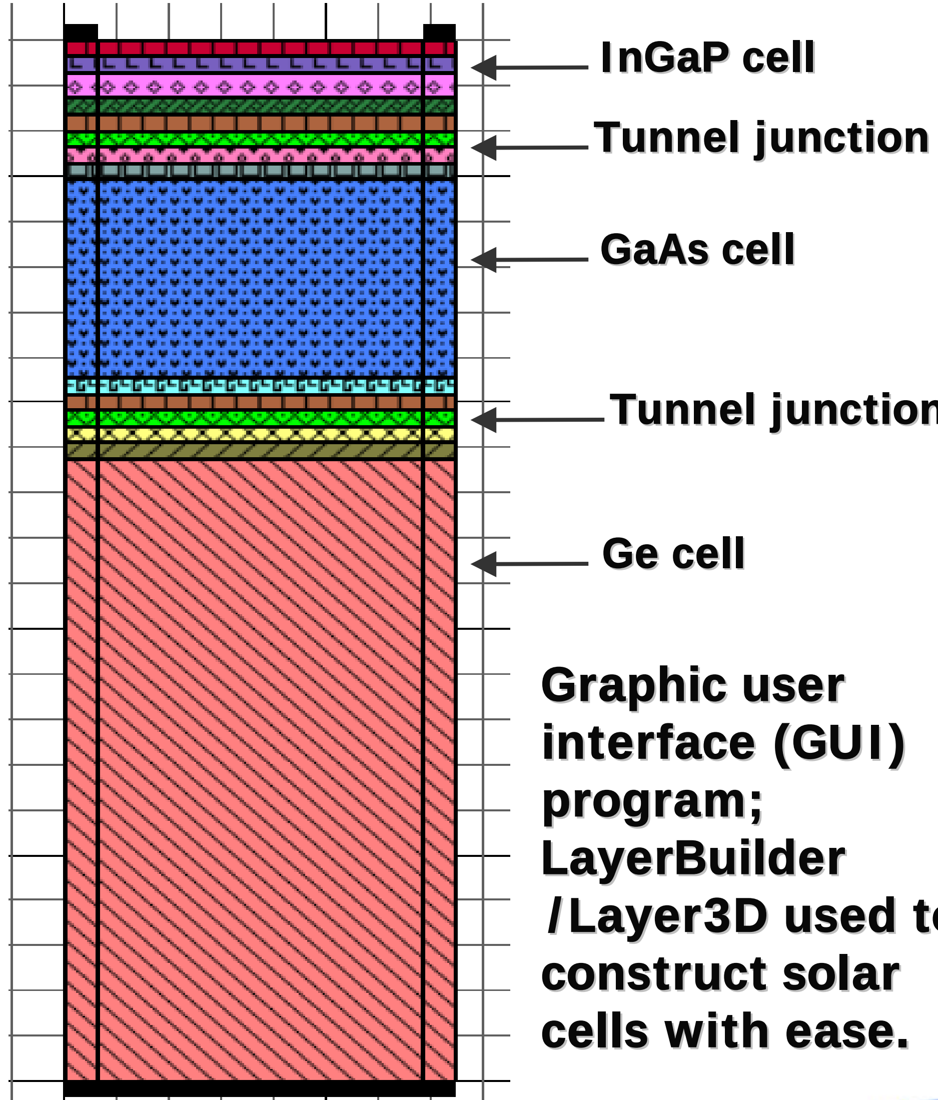


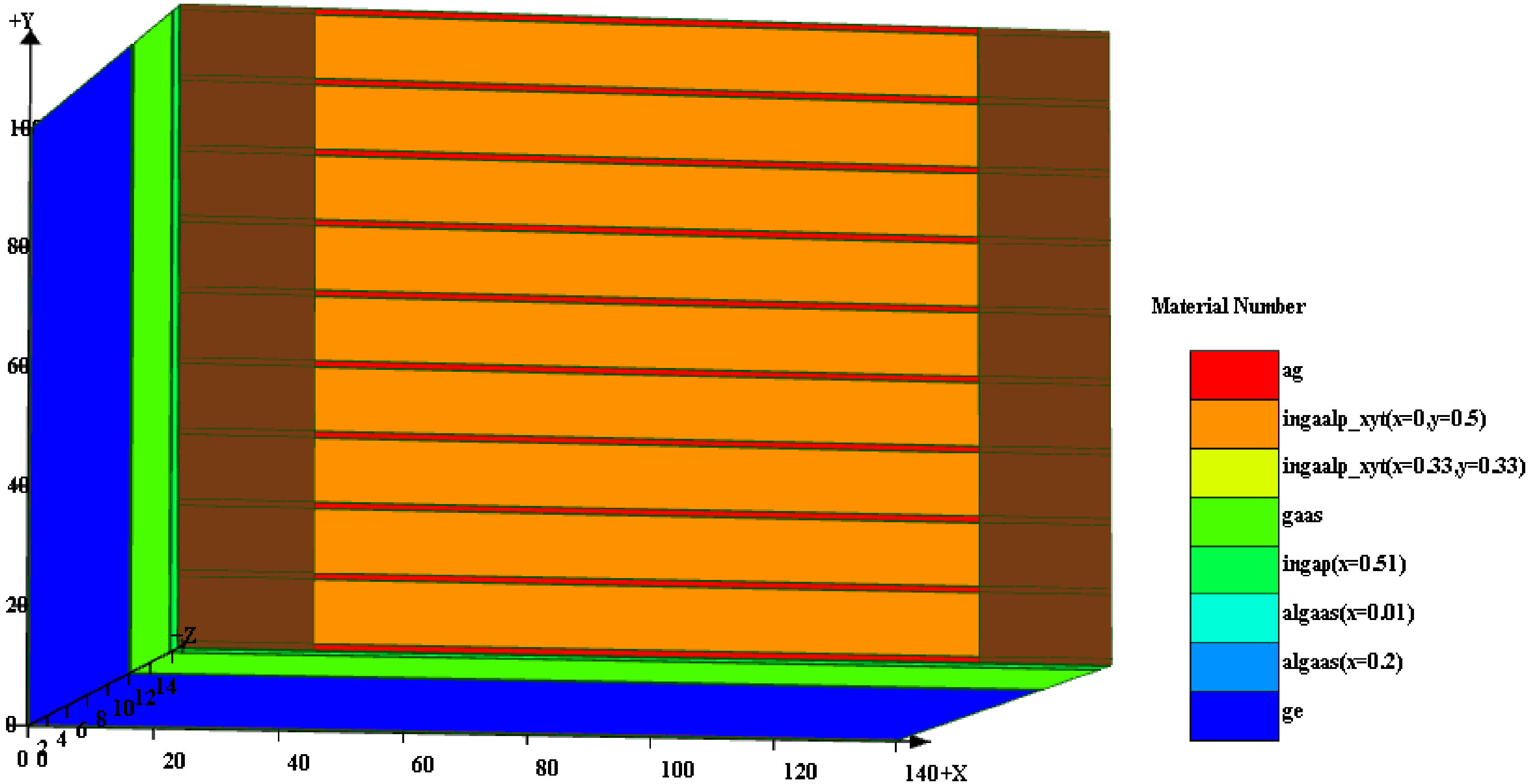
Fig. 9. 3D layout of the triple-junction model.

IEEE Trans. Elec. Devices, v. 46, p. 2116, 1999



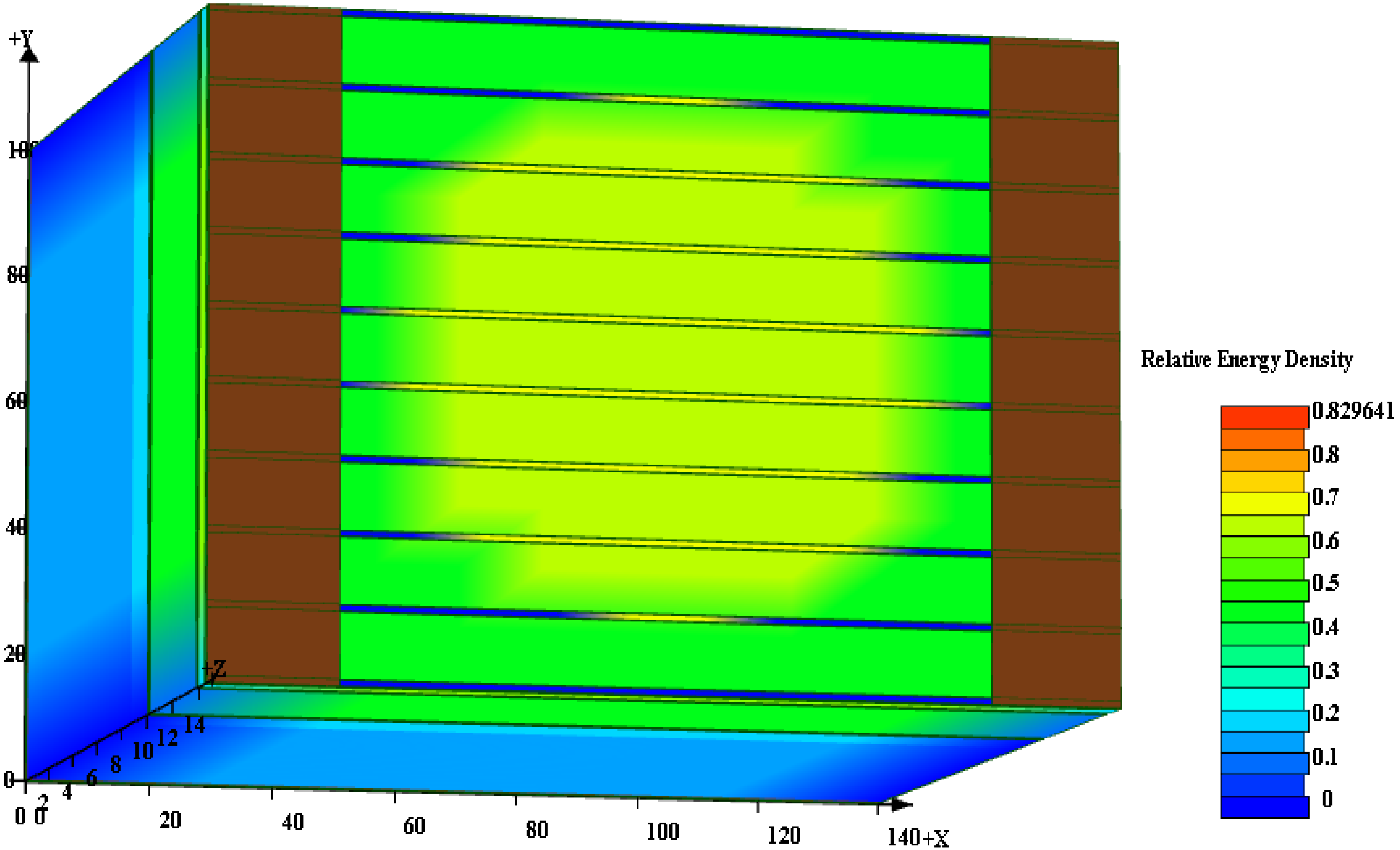
Graphic user interface (GUI) program; LayerBuilder /Layer3D used to construct solar cells with ease.

3D Material/Layer Structure



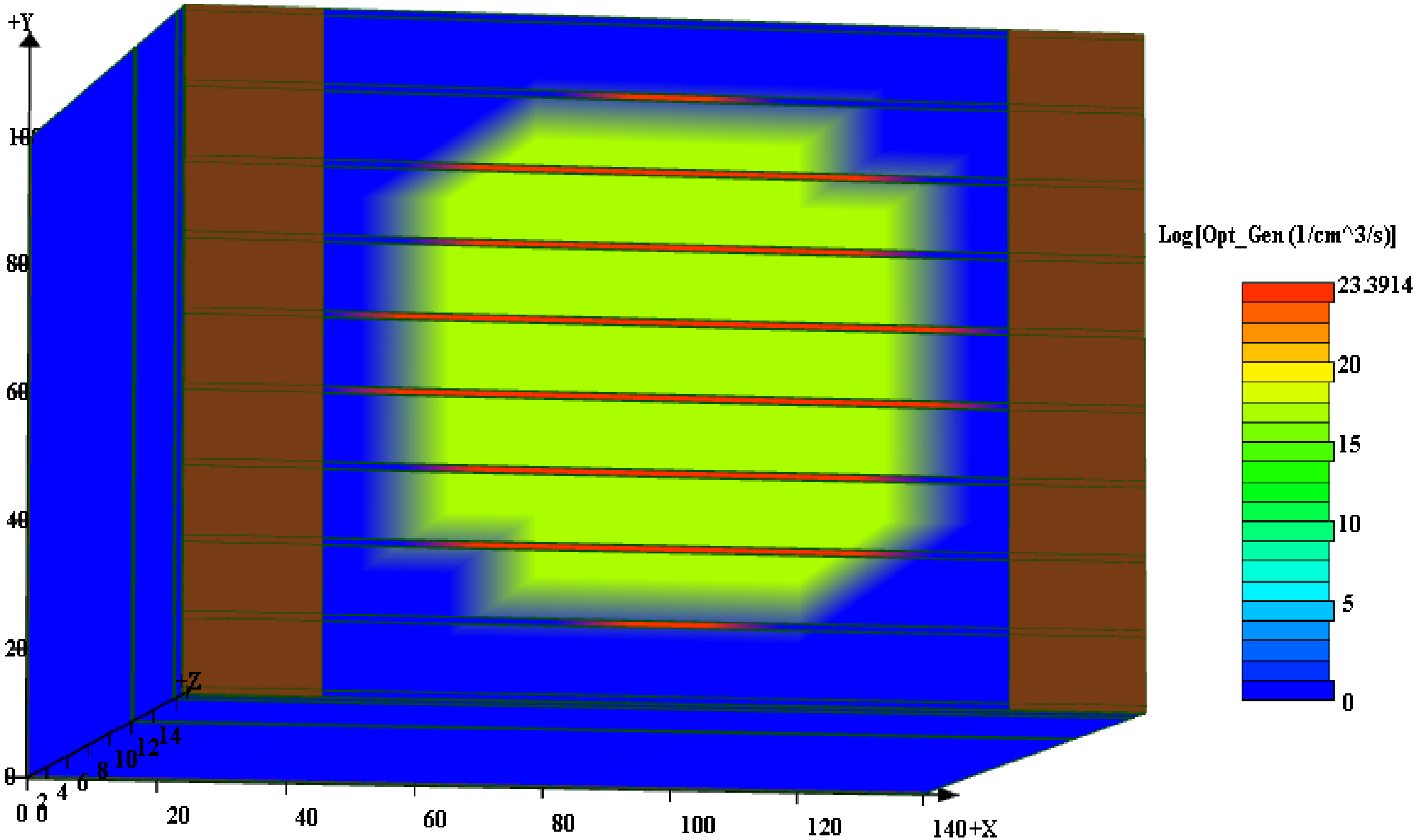
3D simulation results courtesy of C.K. Chao (INER - Taiwan) and J.J. Guo (Grand Technology Inc. - Taiwan)

3D incident_power

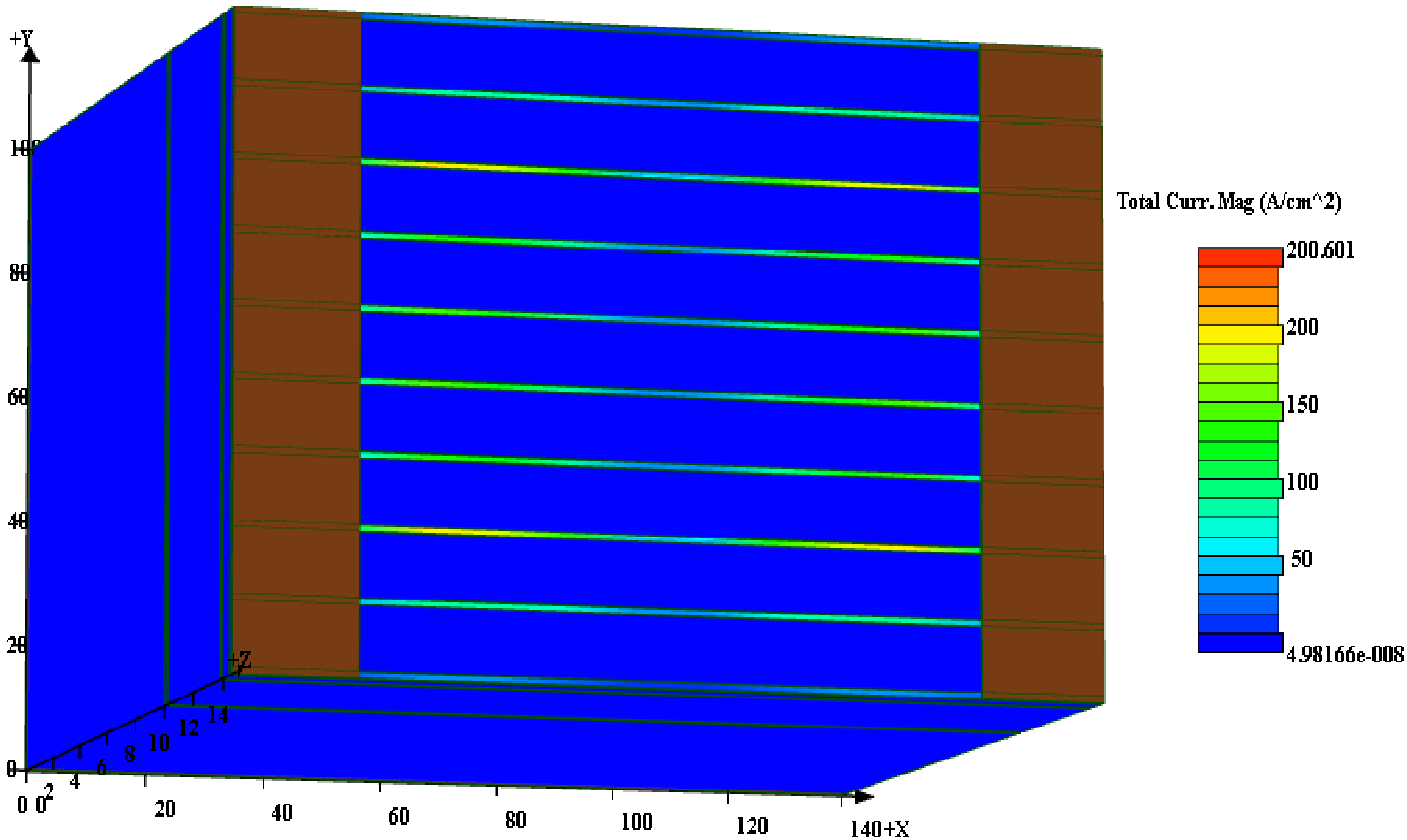


Simulated for Focused beam incident on center of top area.

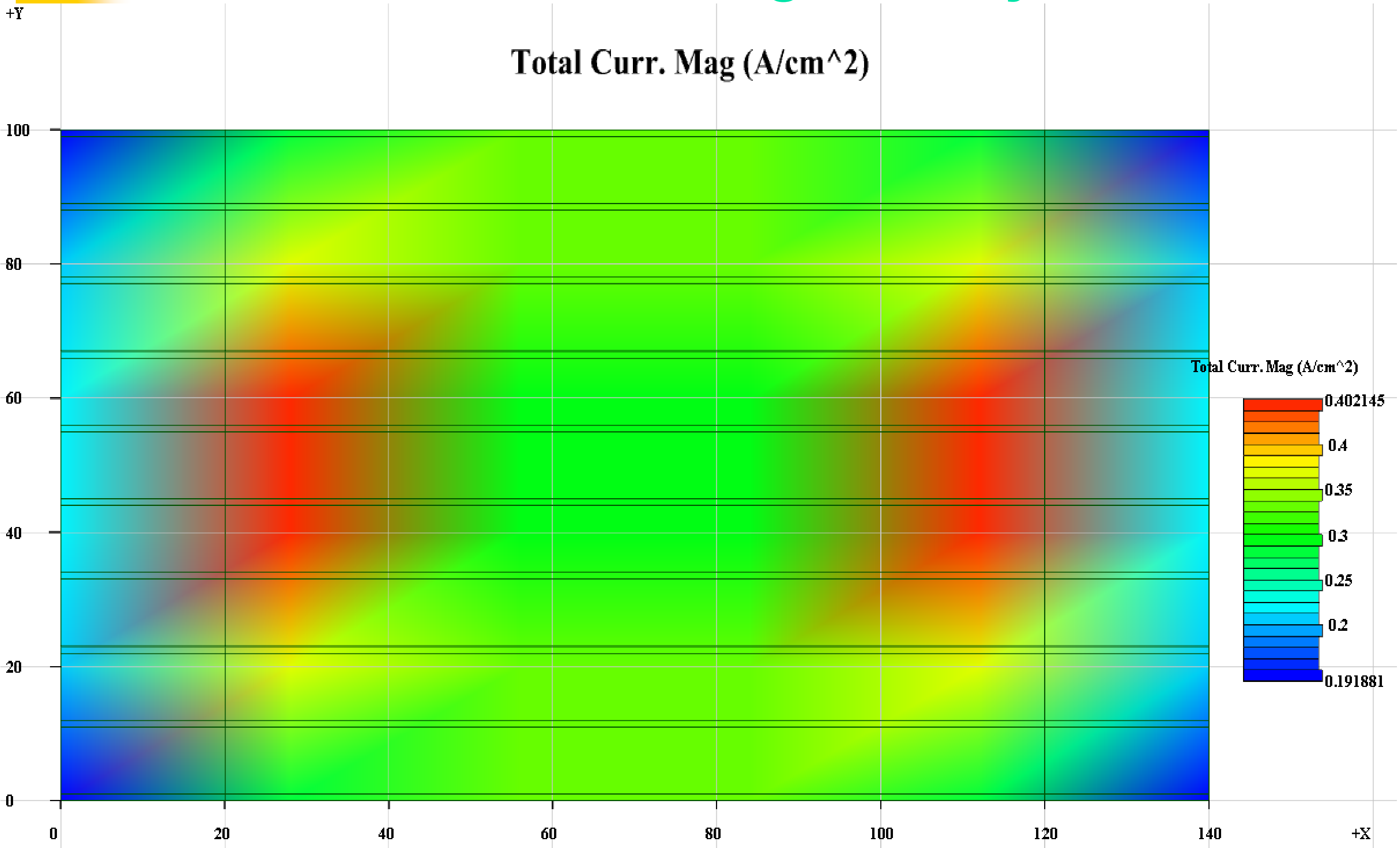
3D Optical Absorption/Generation



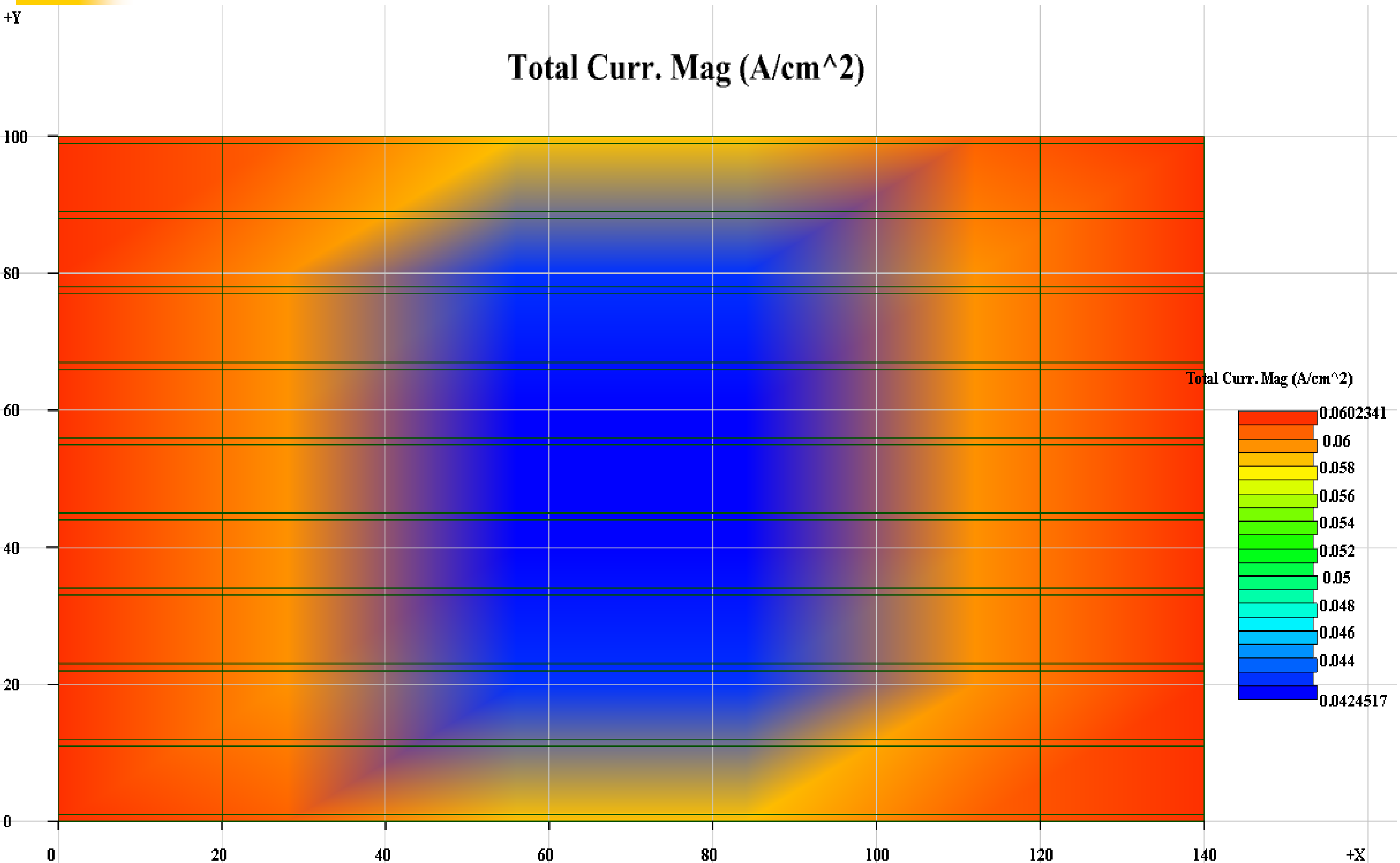
3D current magnitude



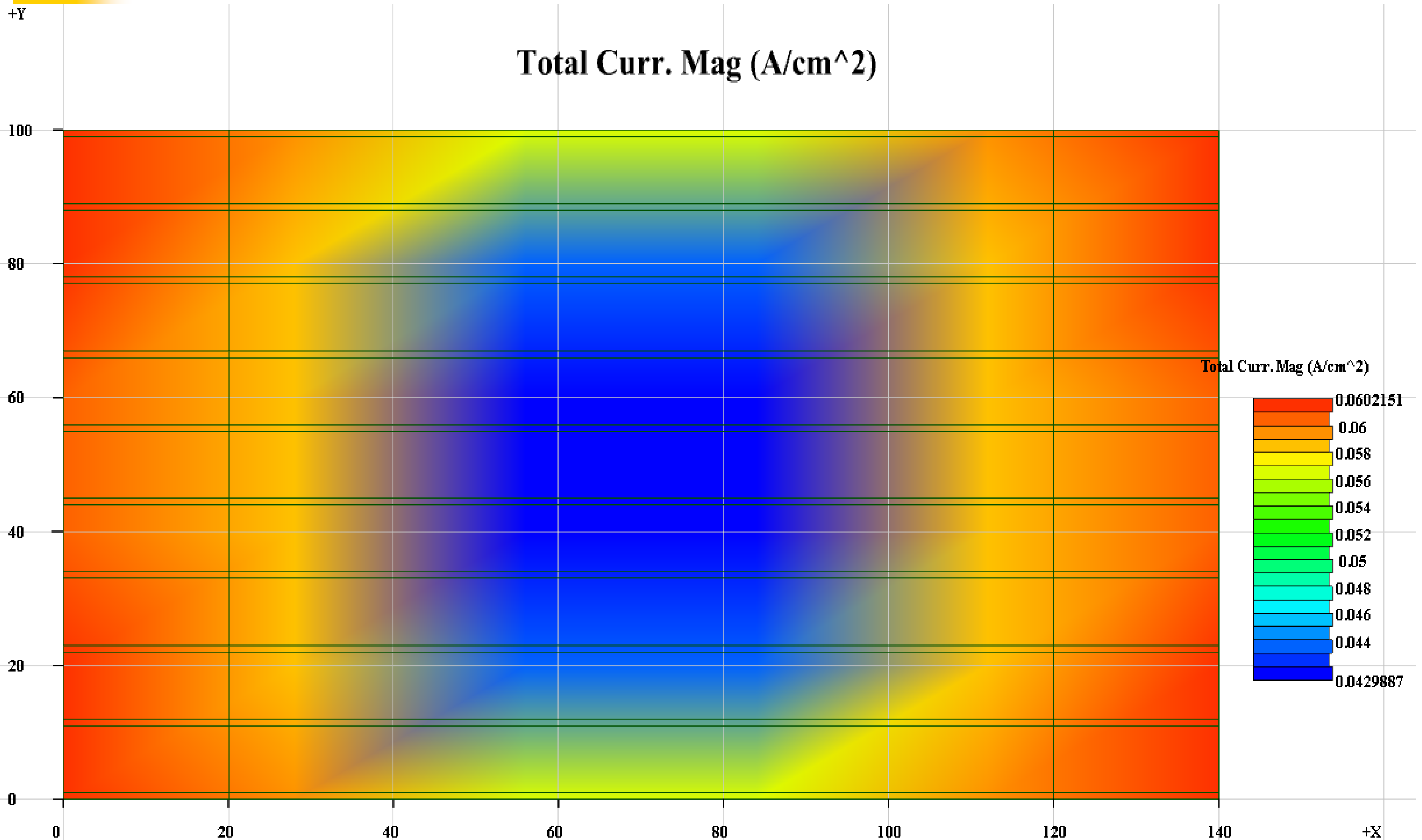
3D current magnitude y=14



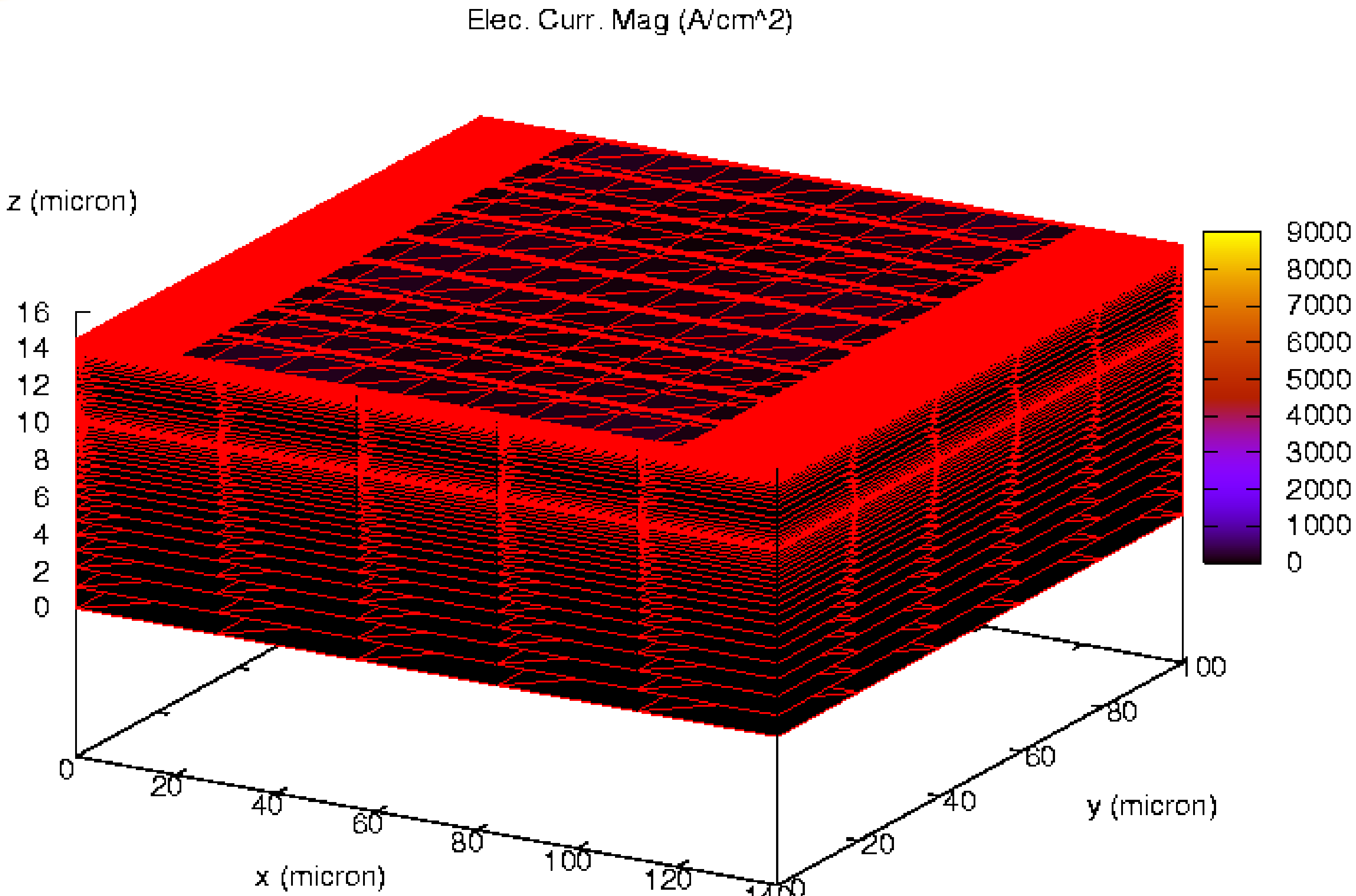
3D current magnitude y=7



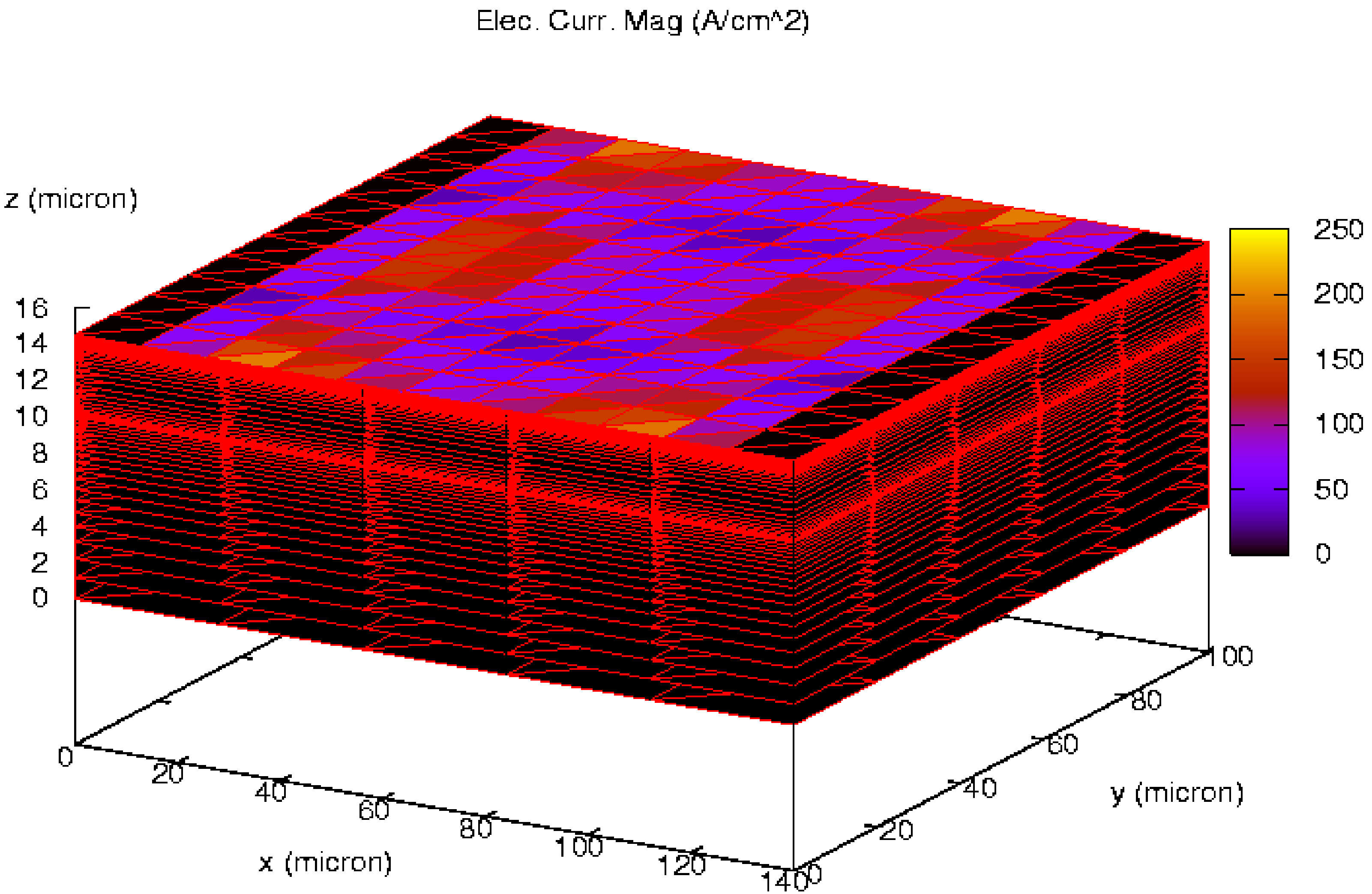
3D current magnitude y=0



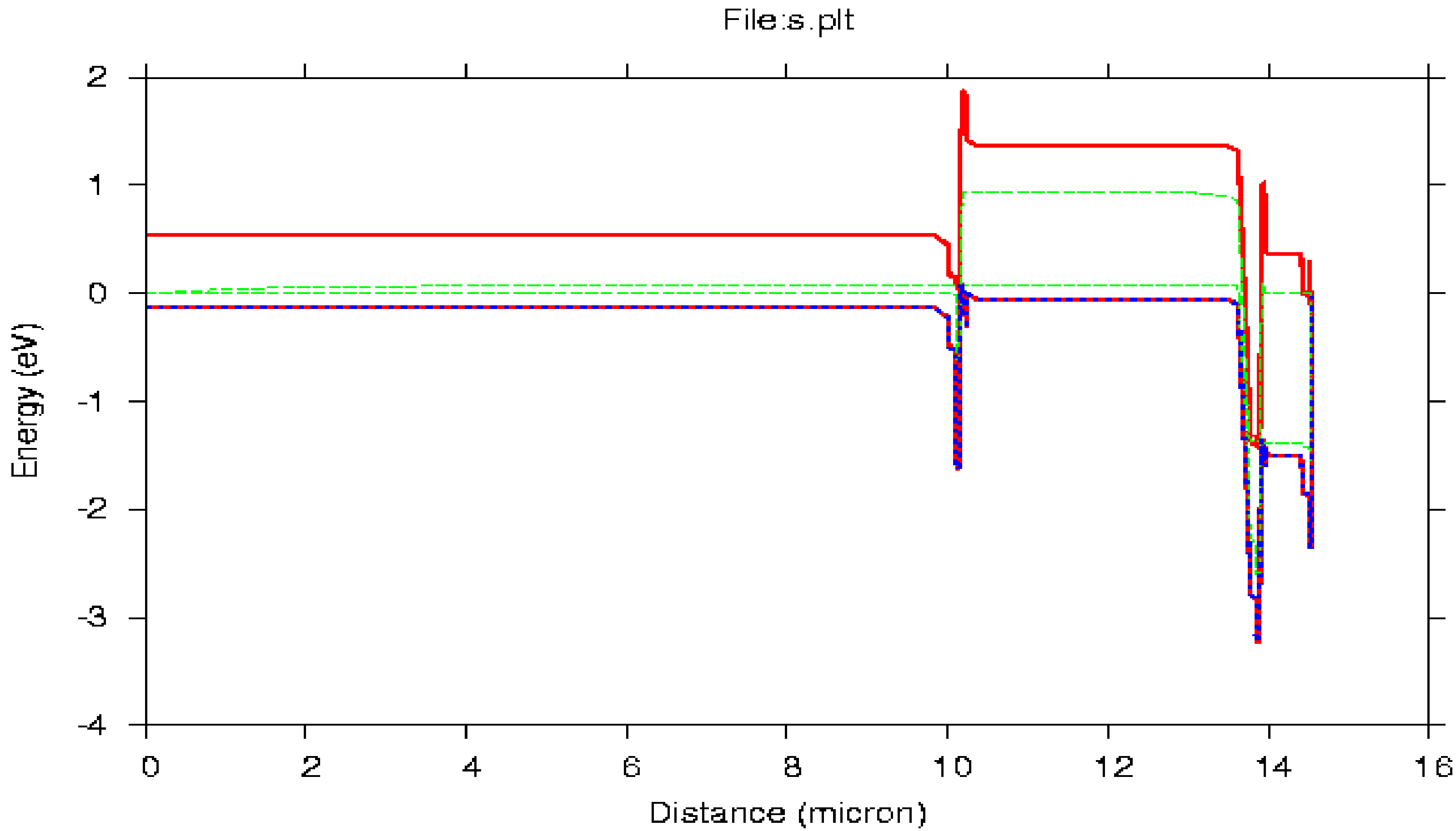
From Plane 1 to Plane 102



From Plane 1 to Plane 100

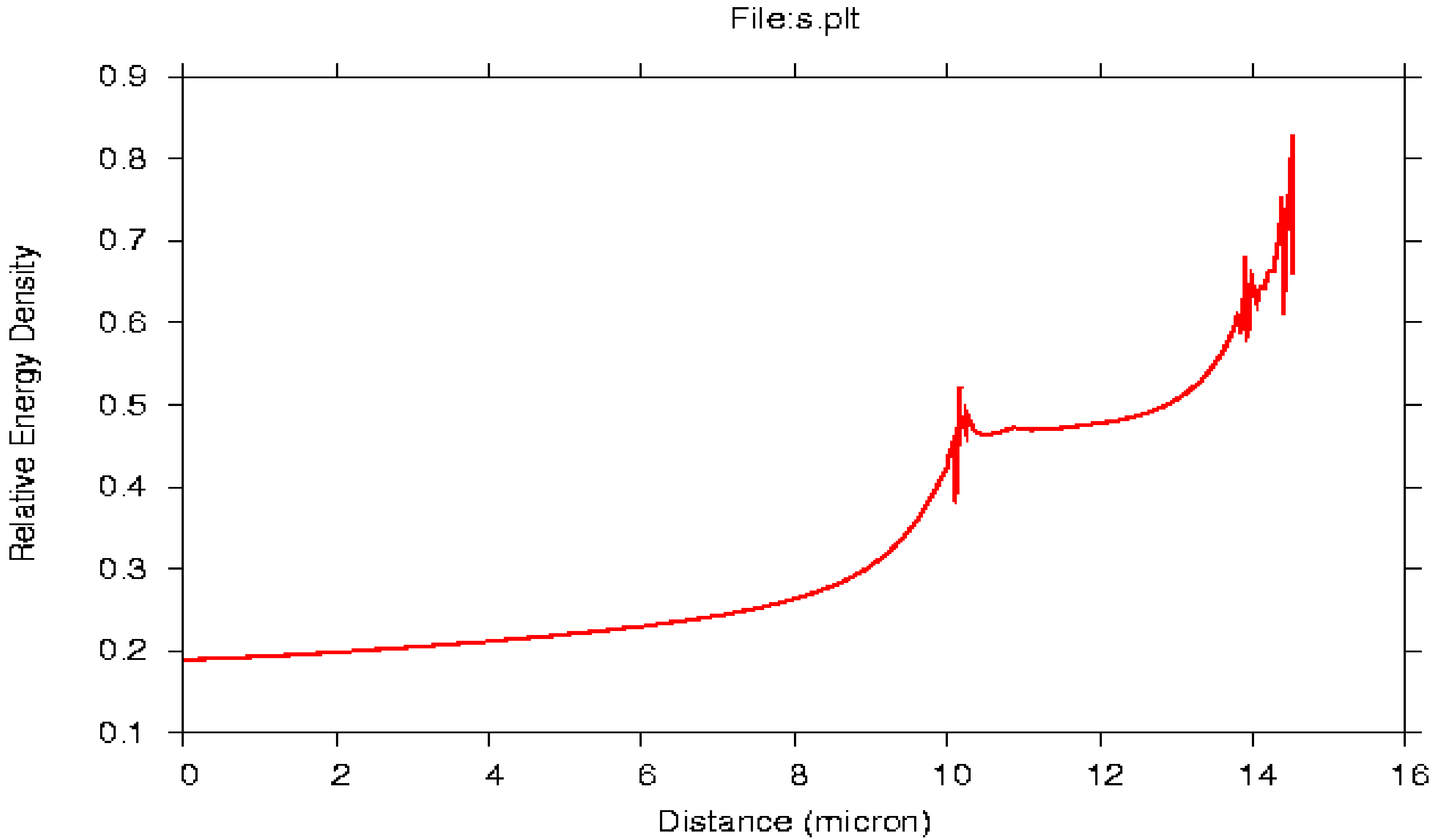


Energy Band Diagram



z-direction

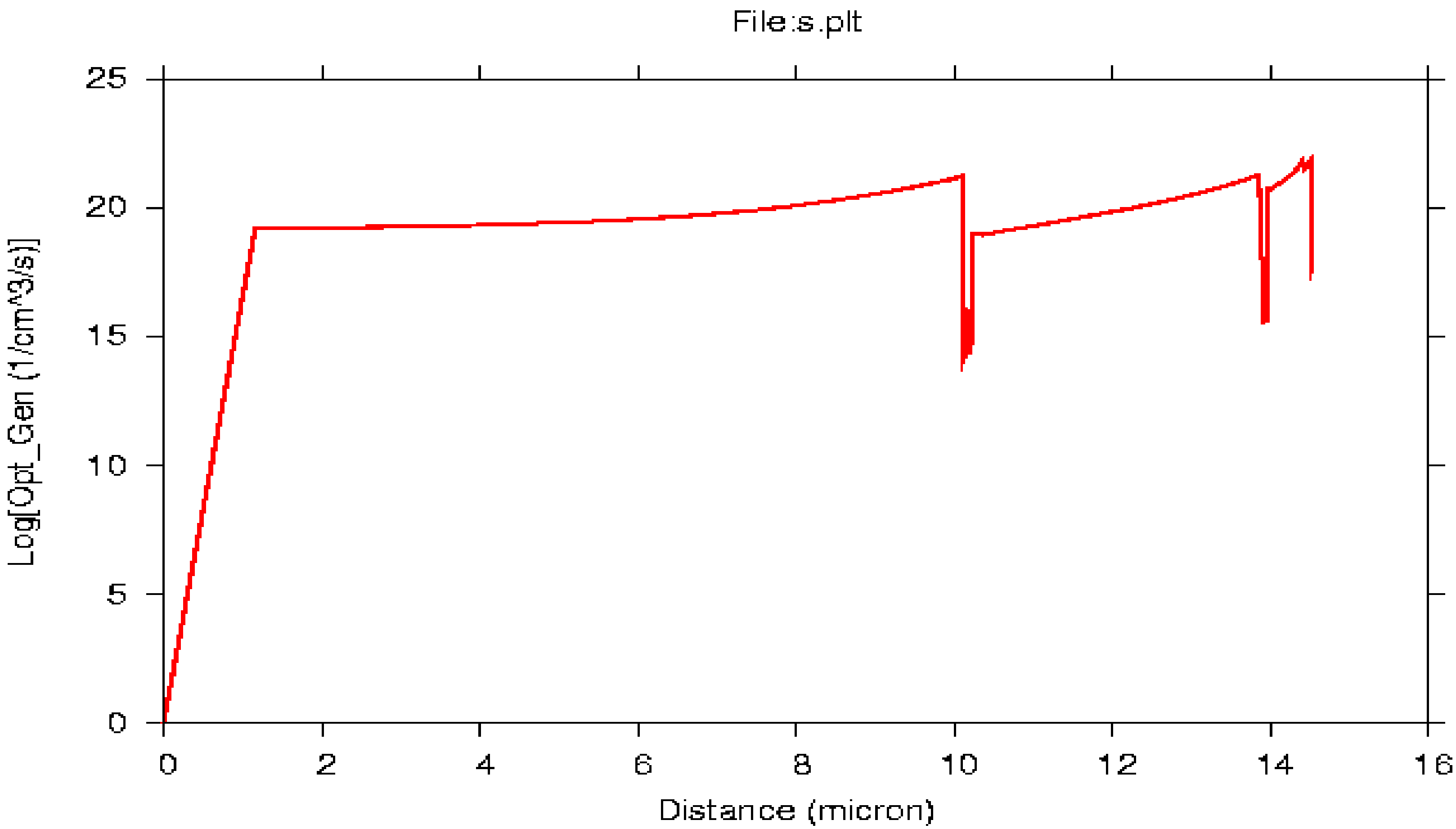
Incident Power at x=50 and y=70



z-direction

CROSSLIGHT Software Inc.

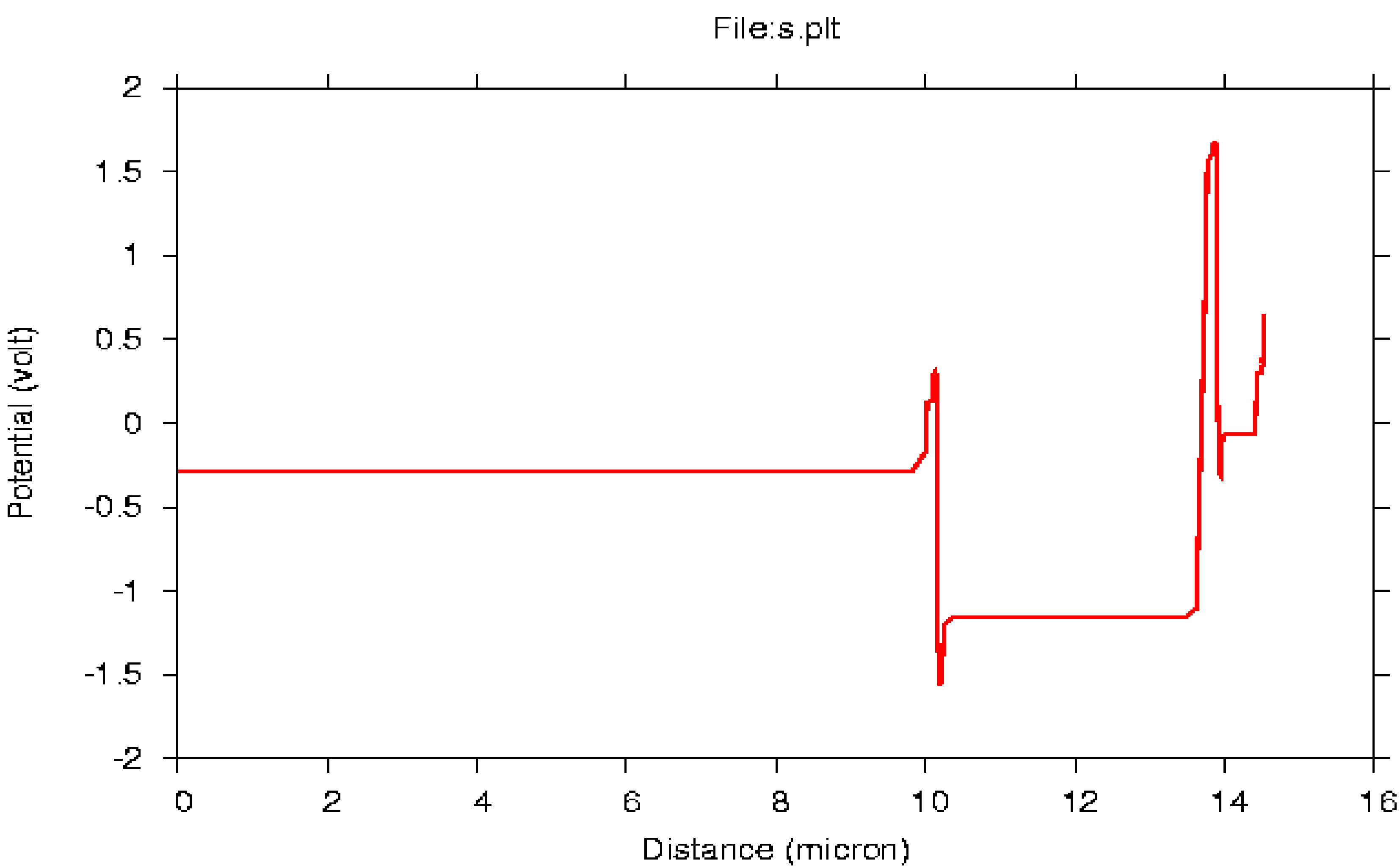
Optical Generation at x=50 and y=70



z-
direction

CROSSLIGHT
Software Inc.

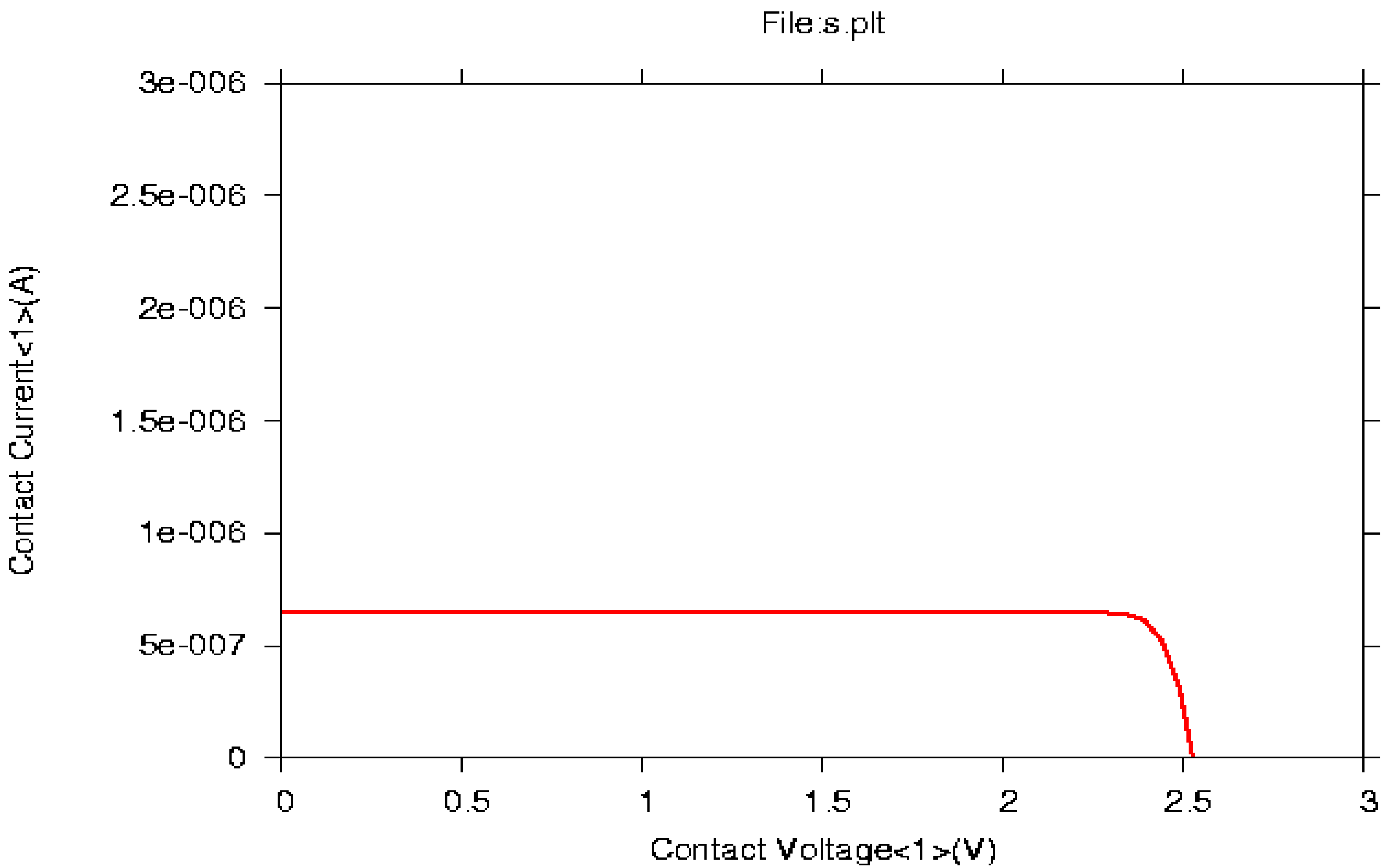
Potential distribution at x=50 and y=70



z-direction

CROSLIGHT Software Inc.

AM1.5 I-V Curve at T=300 K



CROSSLIGHT Software Inc.

Conclusion

- 2D & 3D simulations on compound single and multi-junction solar cells have been demonstrated.
- Non-local tunnel-junction model is calibrated with experiments
- Biased solar spectrum is used to obtain external quantum efficiency.
- Modeling results of I-V curve, Isc, Voc & efficiency consistent with experimental results.
- Modeling results for multi-sun concentration are also presented: optimal sun number varies with contact pad separation, indicating different series resistance effect.