Simulation of Avalanche Photodiodes Using APSYS

CROSSLIGHT Software Inc.

Contents

- APSYS model for APD simulation
- Modeling of InP/InGaAs SAGCM APD
- Modeling of InGaAs/AlGaAs RCE SAGCM APD
- Hot carrier model of GaAs/AlGaAs PIN APD
- Summary

APSYS model for APD simulation

Drift-diffusion and hydrodynamic models:

- **Drift-diffusion model (DD): Poisson's equation and electron/hole continuity equations.**
- **Hydrodynamic model (HD): Poisson's equation, electron/hole continuity equations and carrier energy balance equations.**
- **Optically induced carrier generation rate computed from absorption spectra based on interband transition model or imported externally.**
- **Transfer matrix method with improved theoretical expressions to deal with light beams propagating through multiple layers.**
- **Both small signal AC and large signal models available. The latter is preferred because effect of carrier screening is more significant at large signal.**
- **Various numerical techniques were developed to help convergence near breakdown.**

APSYS model for APD simulation

Impact ionization & excess noise factor

- Impact ionization models: Baraff's phonon scattering theory or Chynoweth's empirical formulas. Carrier energy dependence is used for HD model.
- Excess noise factor usually calculated vs APD multiplication gain M according to McIntyre's expression:

$$F = M\left\{1-(1-k_{\text{eff}})\left(\frac{M-1}{M}\right)^2\right\}$$

where $k_{eff} = \alpha/\beta$ is the ratio of electron/hole impact ionization coefficients. The coefficients may be computed directly by the APSYS program or obtained from field distribution using the Chynoweth model:

$$\alpha, \beta(\varepsilon) = A\exp[-(E_c/\varepsilon)^m]$$

Resonant condition

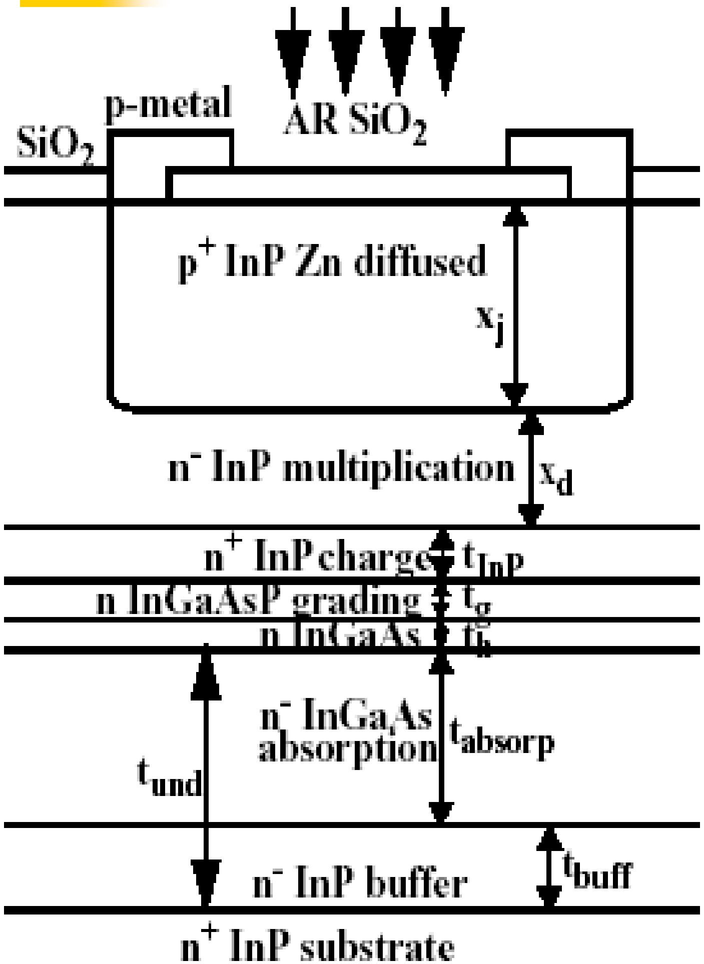
$$4n\pi L_t/\lambda + \psi_f + \psi_b = 2m\pi$$

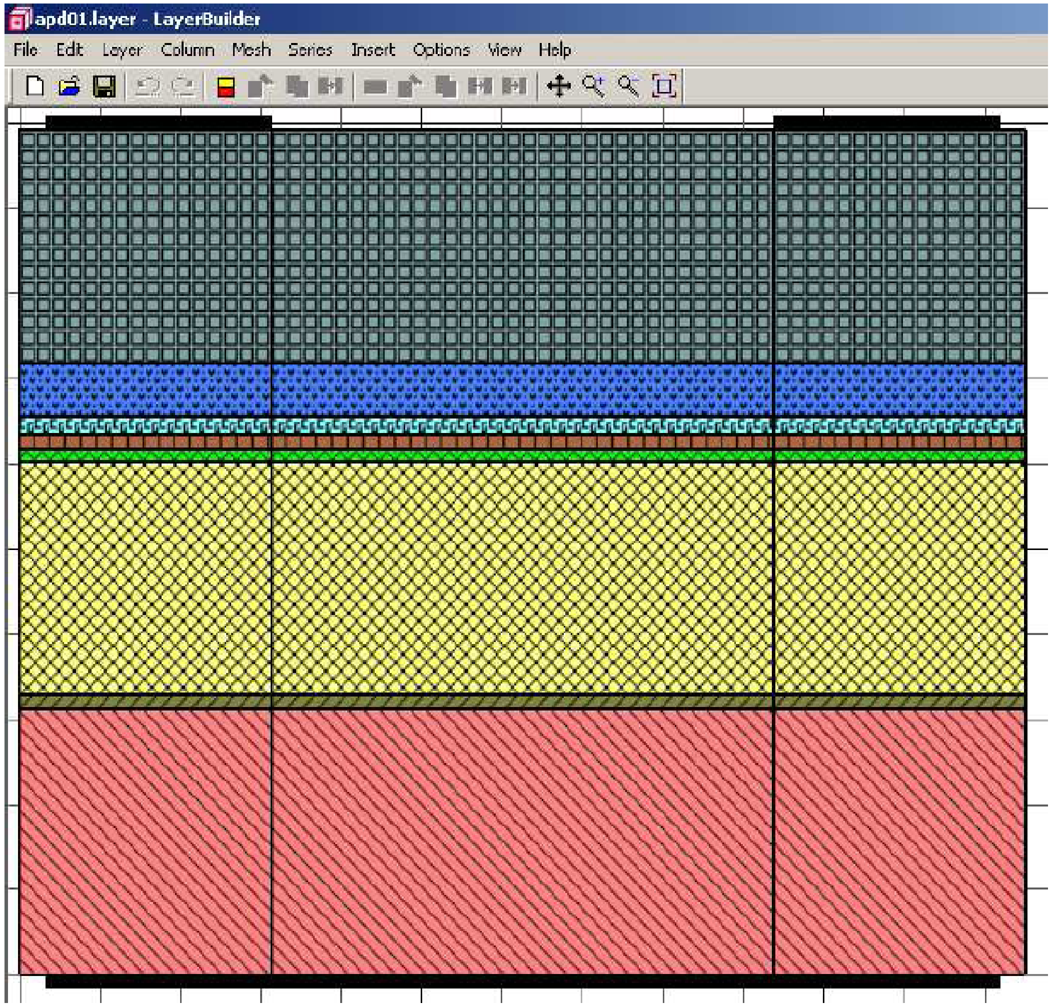
Here ψ_f and ψ_b are the phase shifts due to the penetration of lightwaves into the top and bottom mirror regions, respectively. L_t is the total cavity length.

Contents

- APSYS model for APD simulation
- **Modeling of InP/InGaAs SAGCM APD**
- Modeling of InGaAs/AlGaAs RCE SAGCM APD
- Hot carrier model of GaAs/AlGaAs PIN APD
- Summary

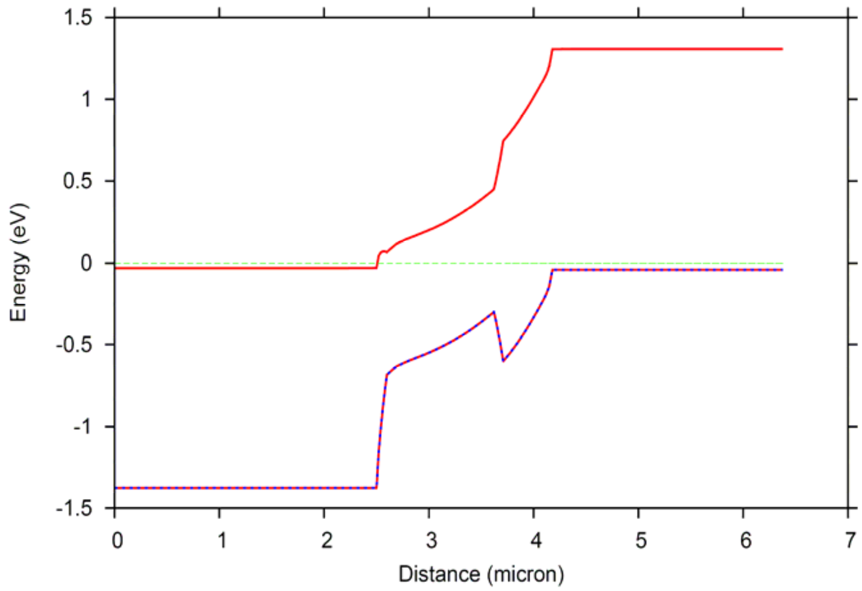
InP/InGaAs SAGCM APD structure





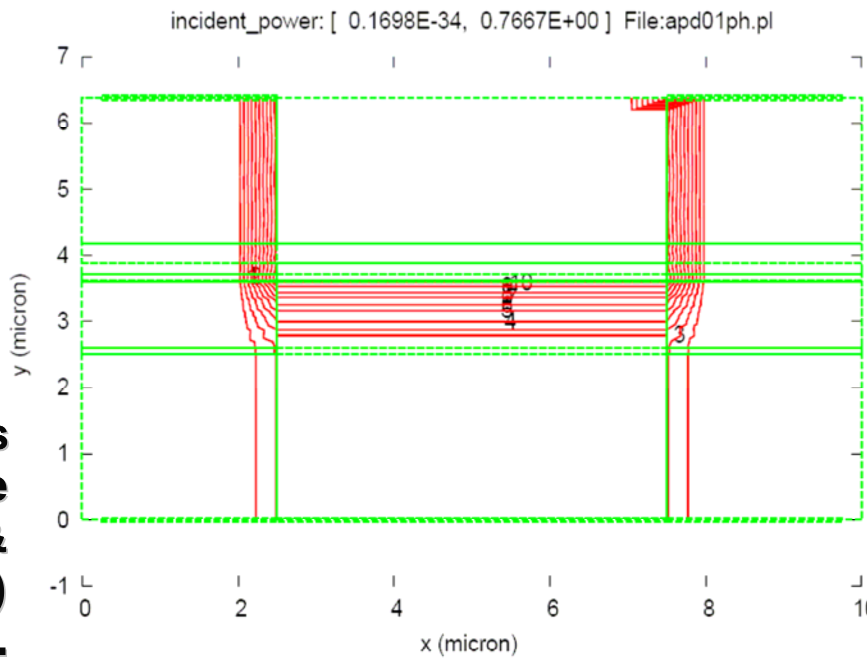
Central region were declared "active" so that absorption coefficient were computed by APSYS. Grading layer between InGaAs & InP were used.

Band diagram & optic power distribution



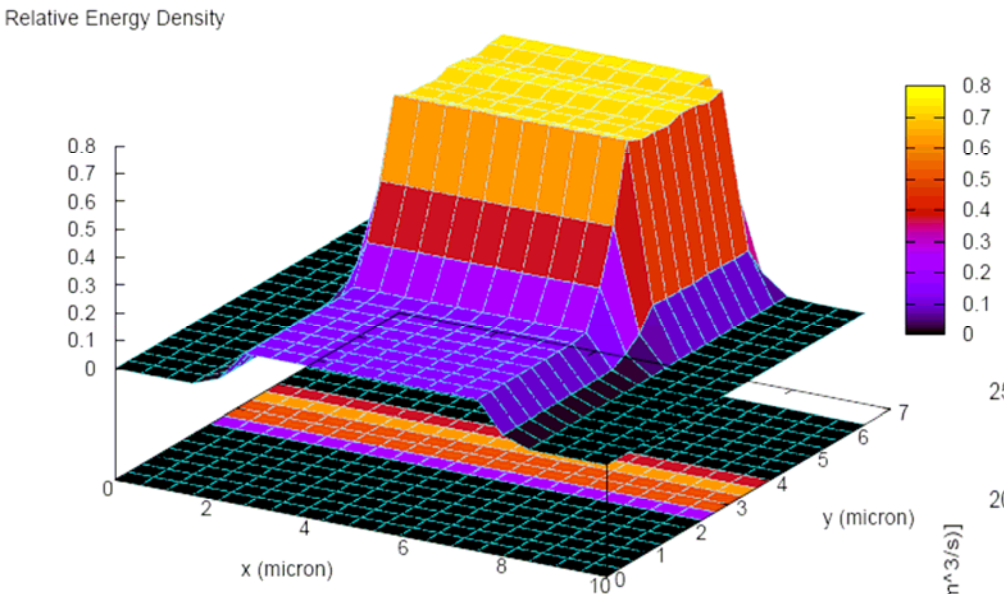
Band diagram at equilibrium (zero bias), 2nd column along y-direction.

Plot shows absorption in InGaAs region. So-called separate absorption, grading, charge & multiplication (SAGCM) structure.

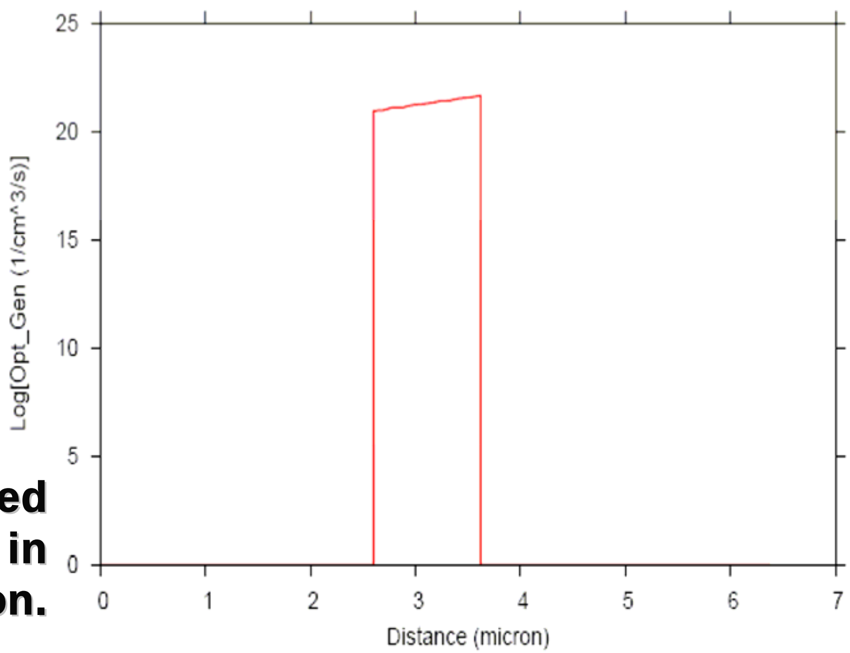


CROSSLIGHT Software Inc.

2D relative optic power density & optic generation rate



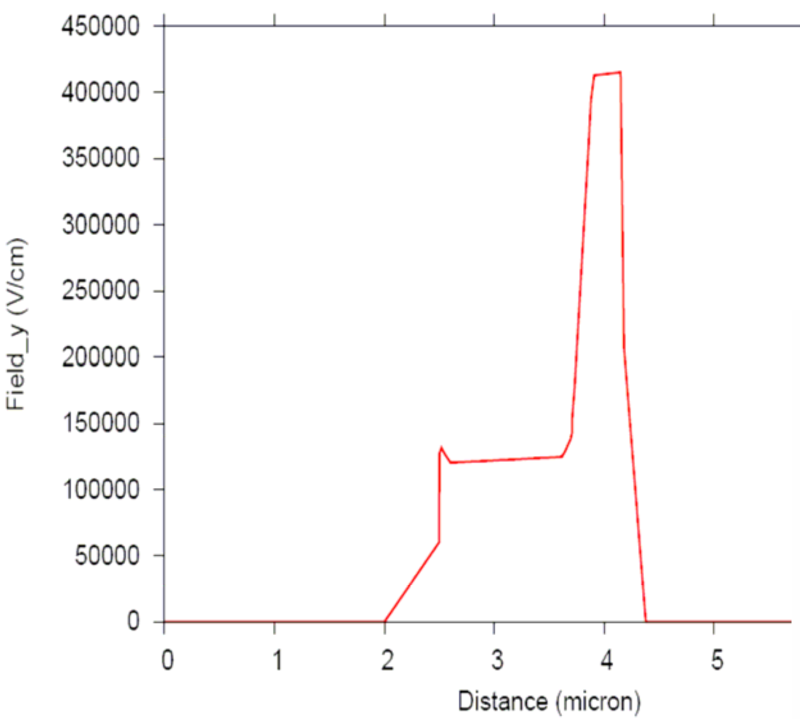
2D relative energy within the device. Absorption mostly in InGaAs region.

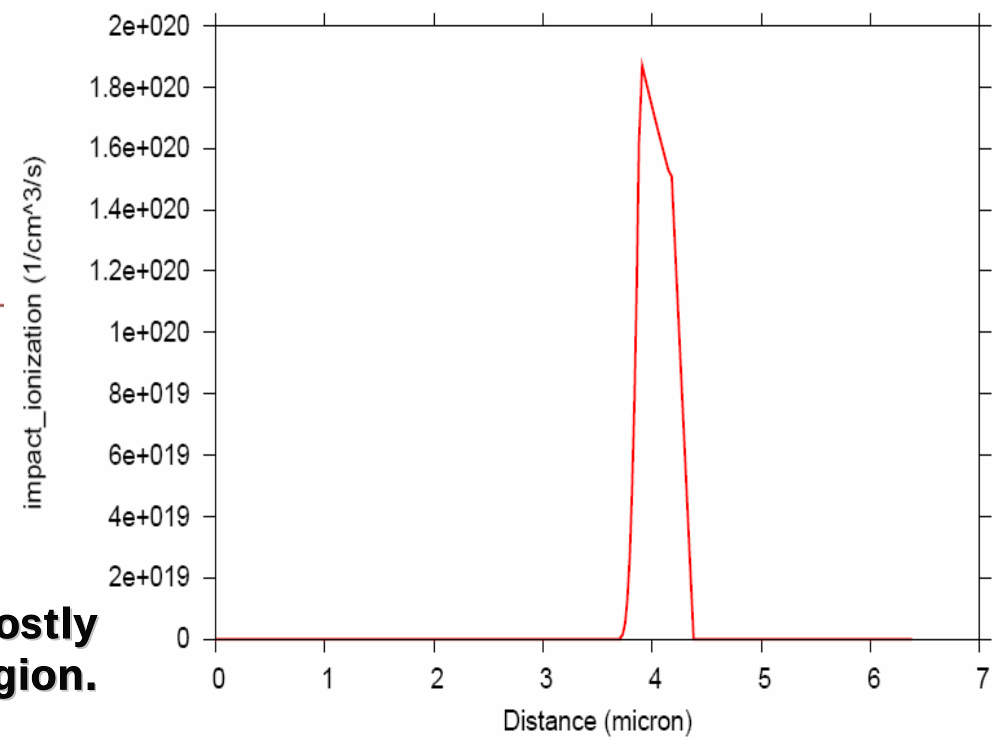


Photoabsorption generated electron-hole pair happens in InGaAs absorption region.

Electric field profile & impact ionization

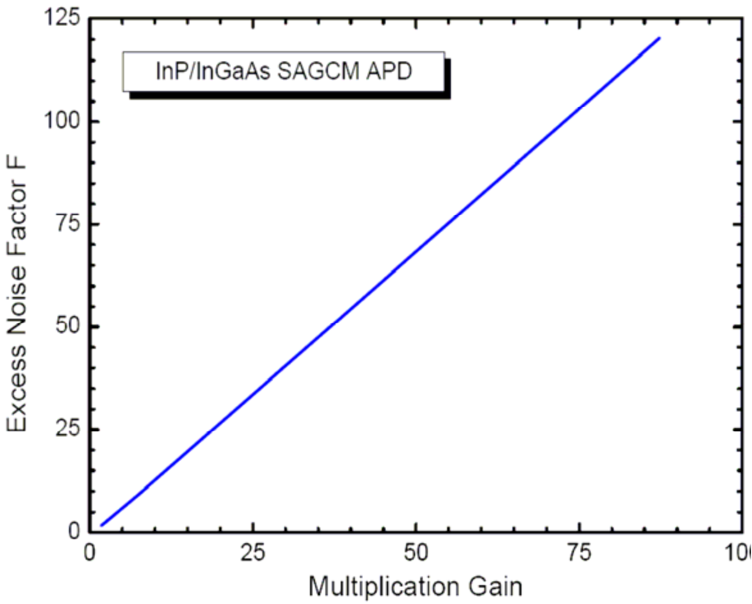
High electric field in the InP multiplication region & low electric field in the absorption region.



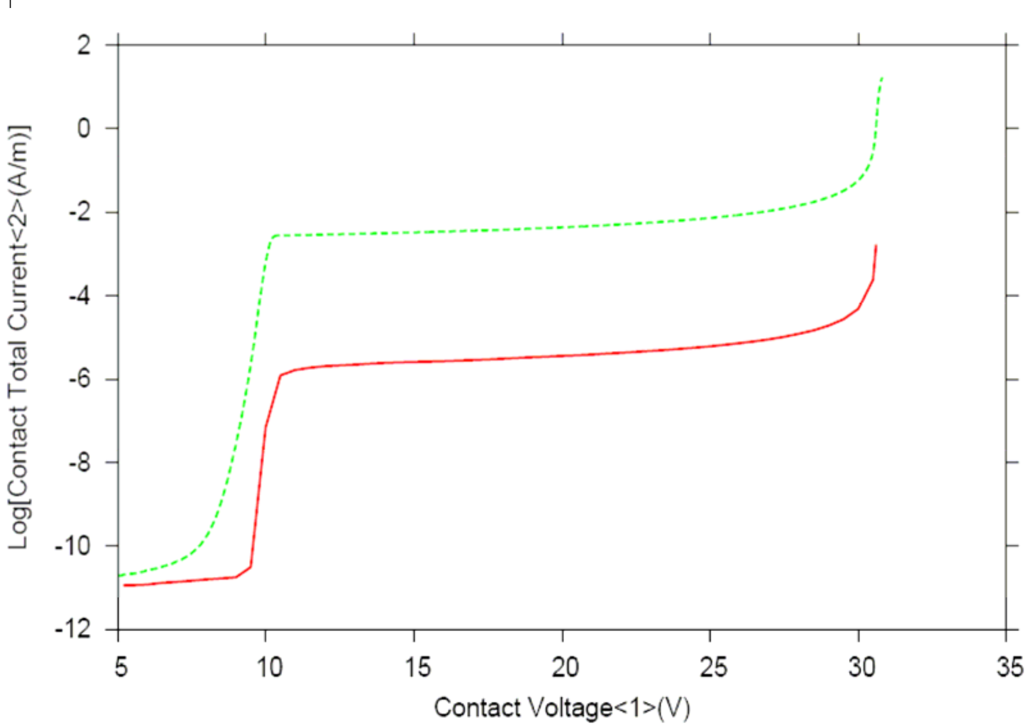


Impact ionization rate (at 30V) mostly in the InP multiplication region.

Excess noise factor & I-V curves



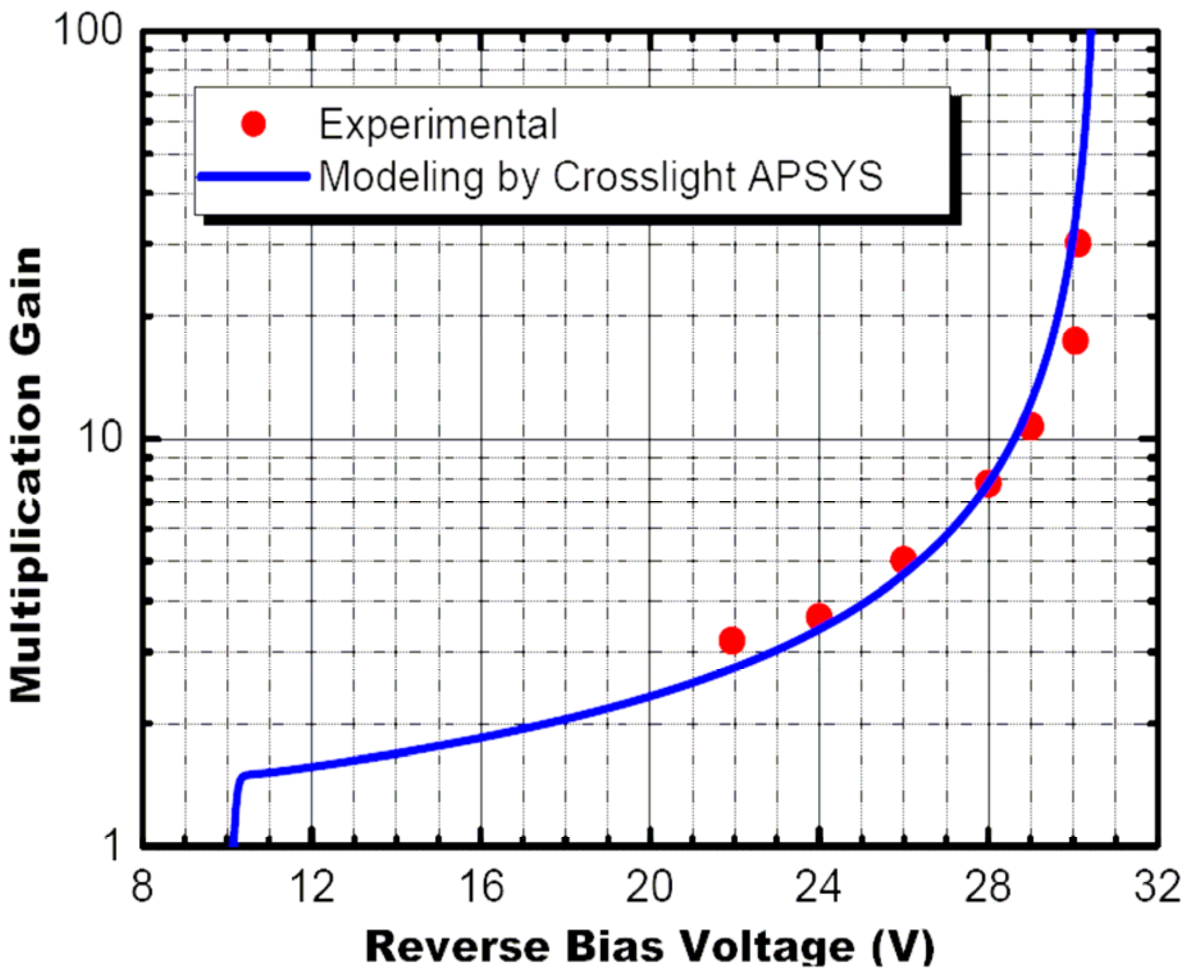
Excess noise factor computed based on McIntyre's expression and impact ionization coefficients.



Photocurrent and dark current.
Breakdown voltage near 30.45 V.

Multiplication gain

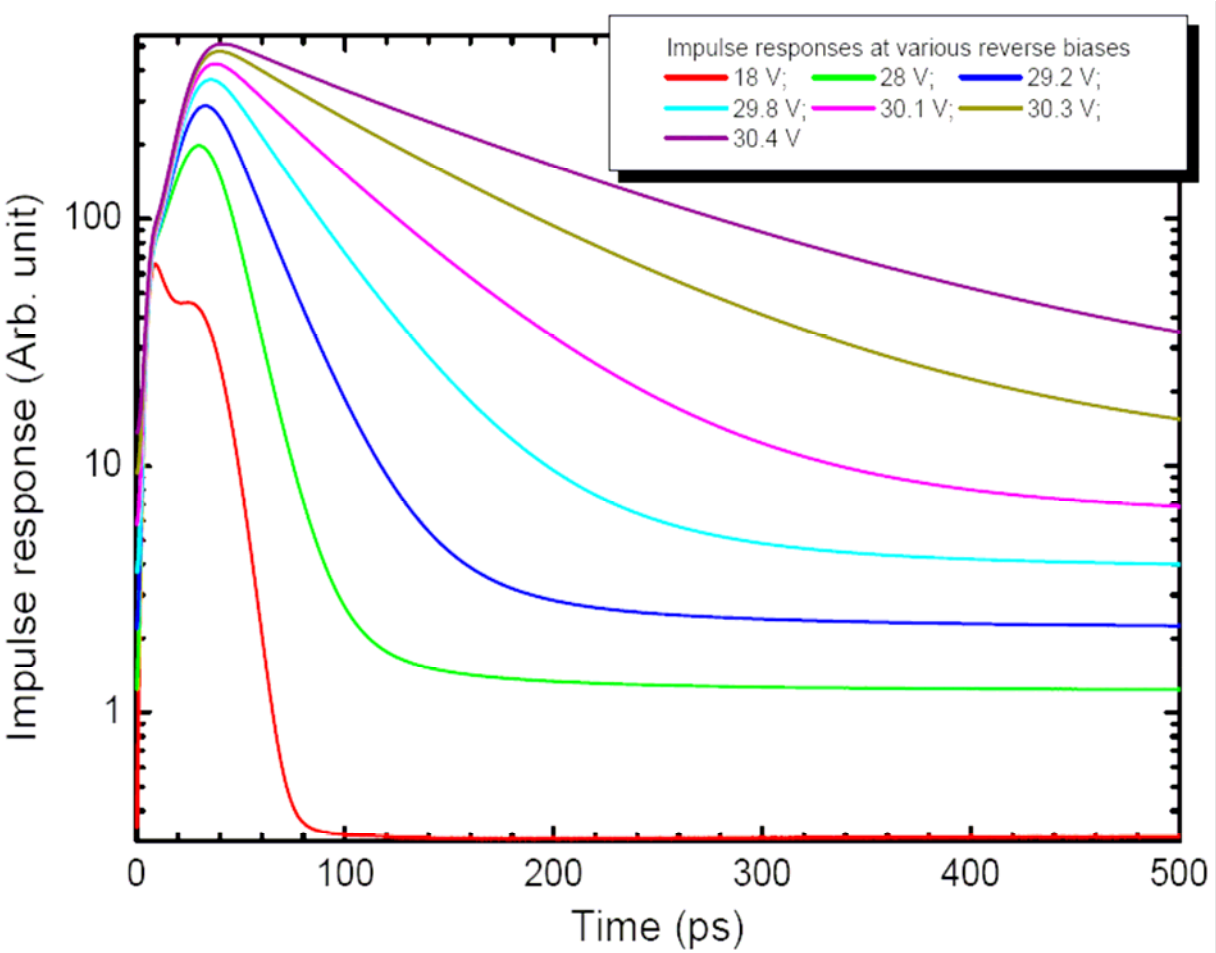
Scale photocurrent by the photocurrent where impact ionization just starts to get multiplication gain, or alternatively take the ratio of area under the impulse response curve with impact ionization over the one without impact ionization. The gain values obtained by the two methods agree usually with each other as long as enough time length for impulse response is taken.



Multiplication gain vs reverse bias extracted from the photo IV curve. In good agreement with experiment (Bandyopadhyay et al, IEEE J. Quantum Electron. 34 (4), pp. 691-699 (1998)).

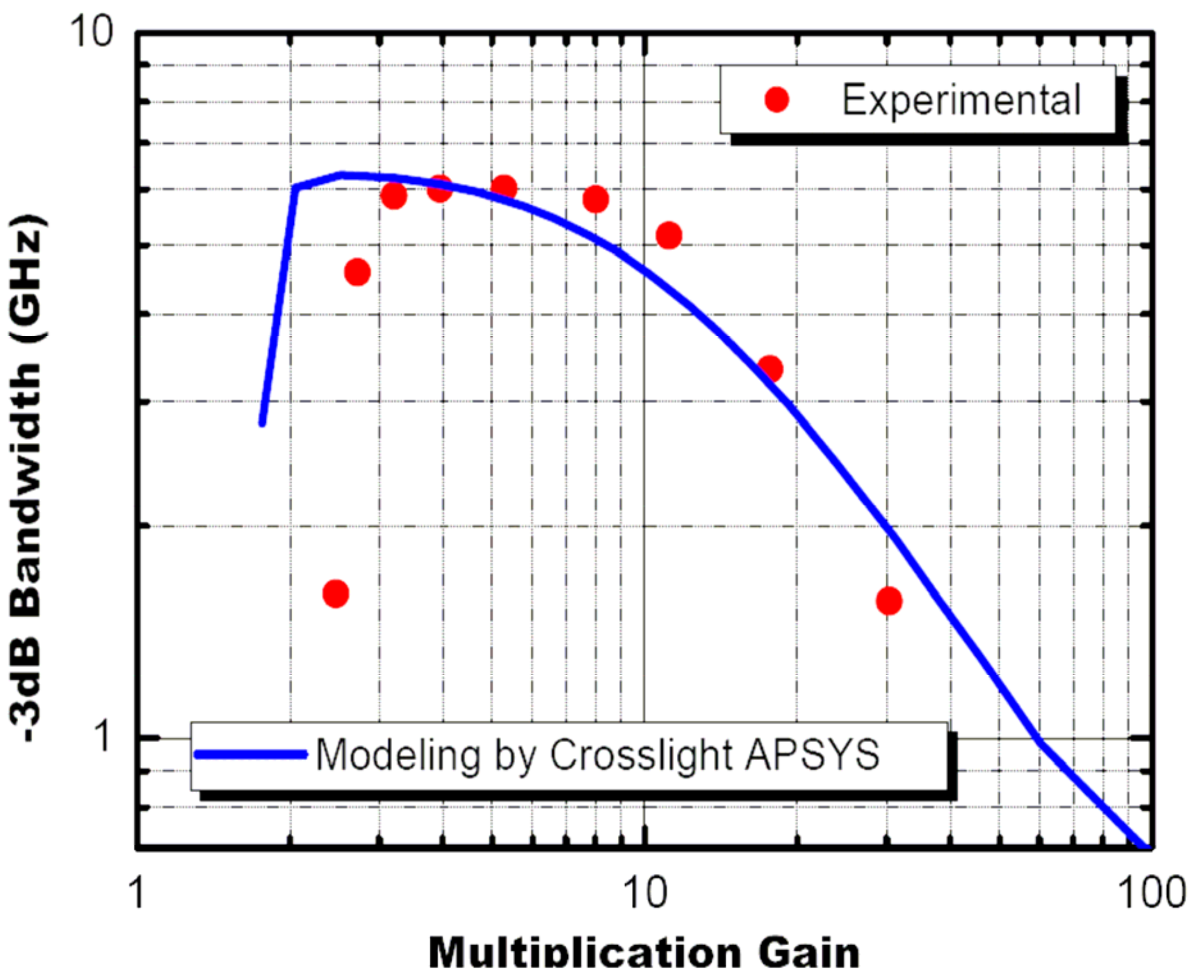
CROSSLIGHT Software Inc.

Impulse response



Impulse response is fast Fourier transformed (FFT) to frequency response from which the –3 dB bandwidth is evaluated.

Bandwidth

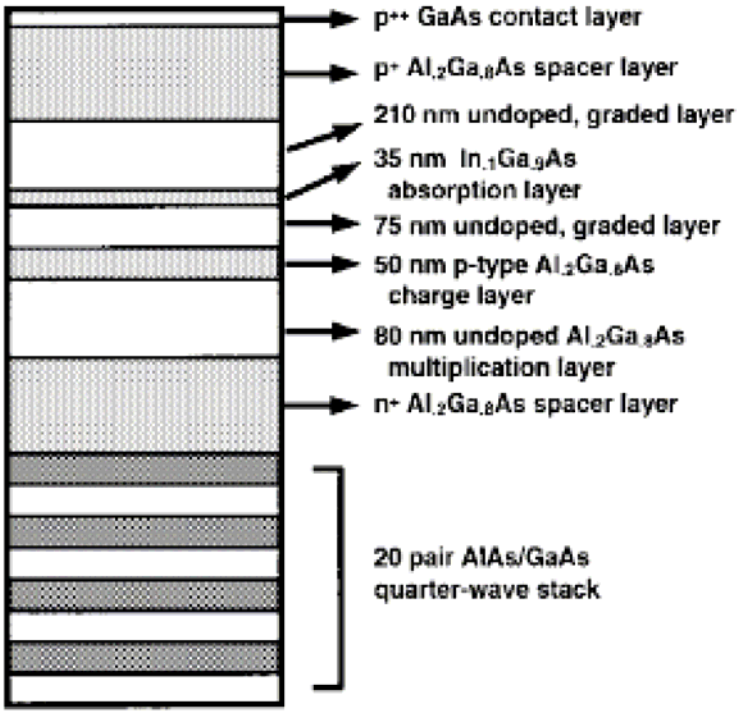


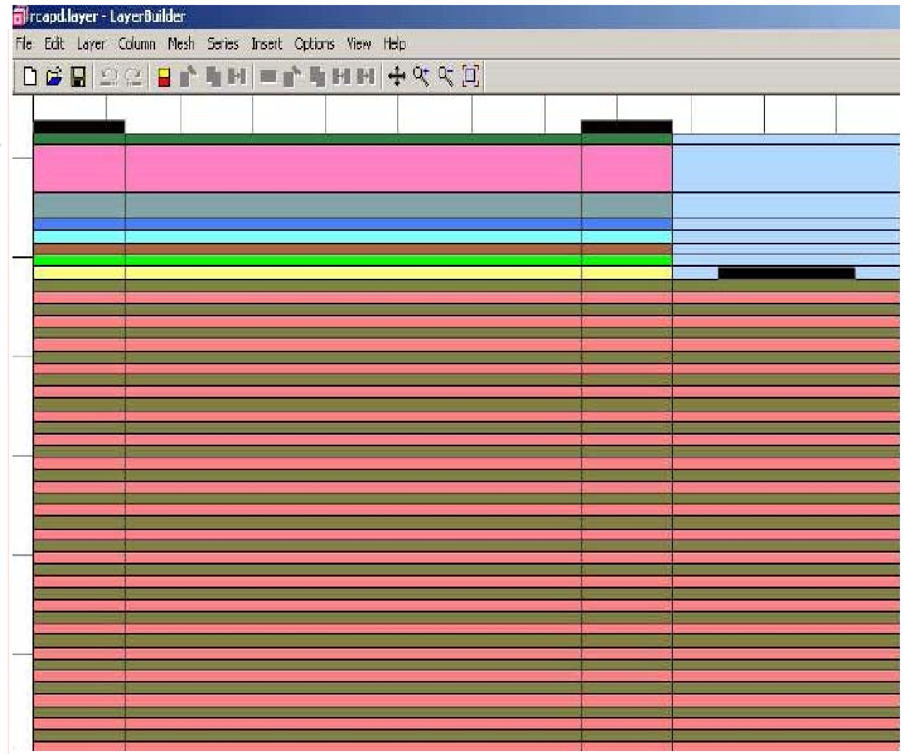
Consistent with experiment (Bandyopadhyay et al, IEEE J. Quantum Eletron. 34 (4), pp. 691-699 (1998)).

Contents

- APSYS model for APD simulation
- Modeling of InP/InGaAs SAGCM APD
- **Modeling of InGaAs/AlGaAs RCE SAGCM APD**
- Hot carrier model of GaAs/AlGaAs PIN APD
- Summary

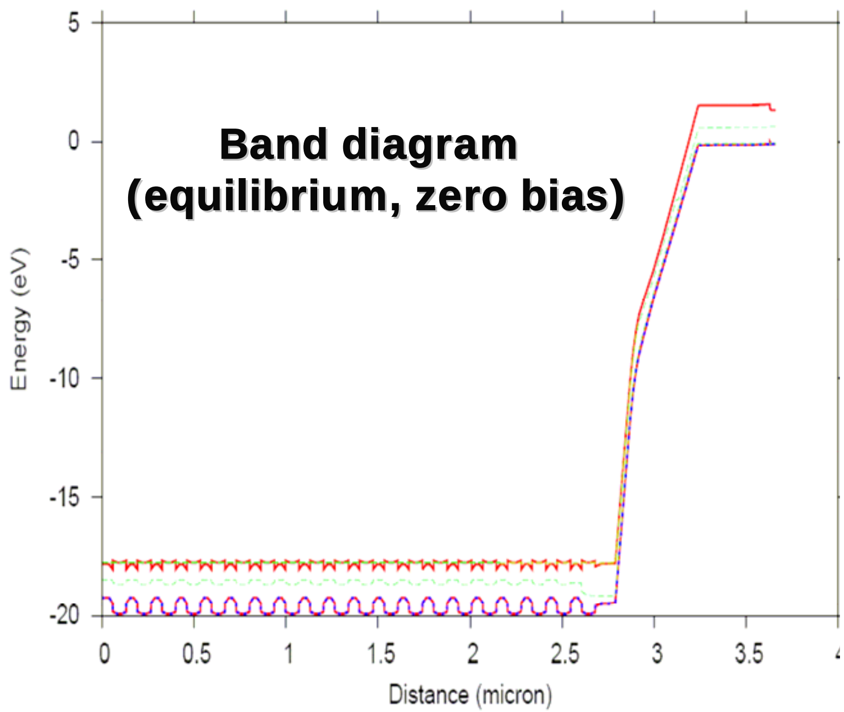
RCE SAGCM APD structure

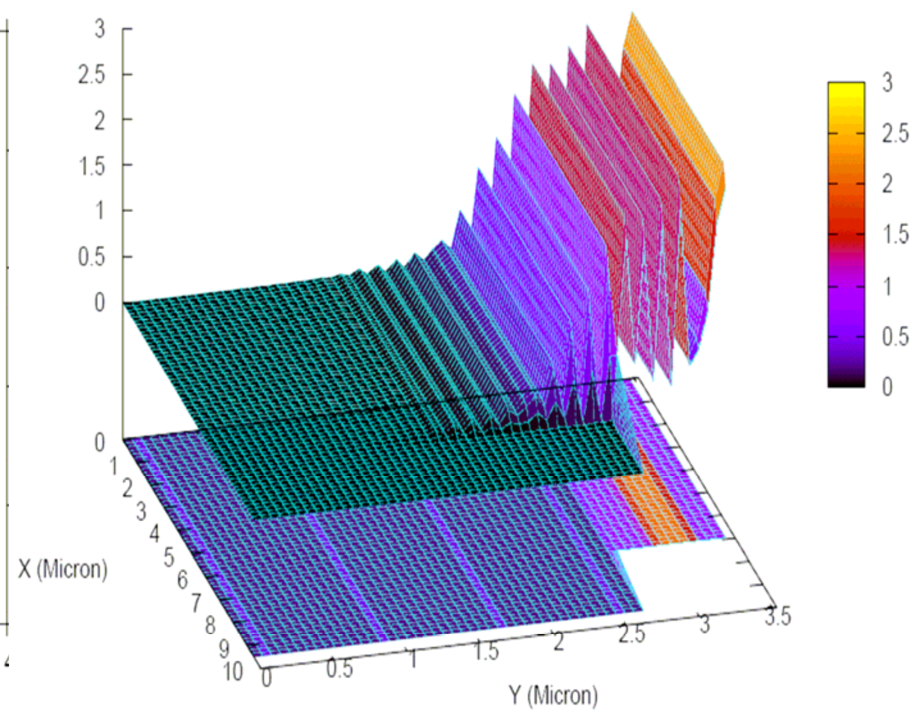




Schematic InGaAs/AlGaAs RCE SAGCM APD structure and schematic layer view generated by Crosslight APSYS simulator (see H Nie et al, *IEEE Photon. Technol. Lett.* 10, pp. 409-411, 1998; Y G Xiao et al, *J. Lightwave Technol.* 19, pp. 1010-1022, 2001).

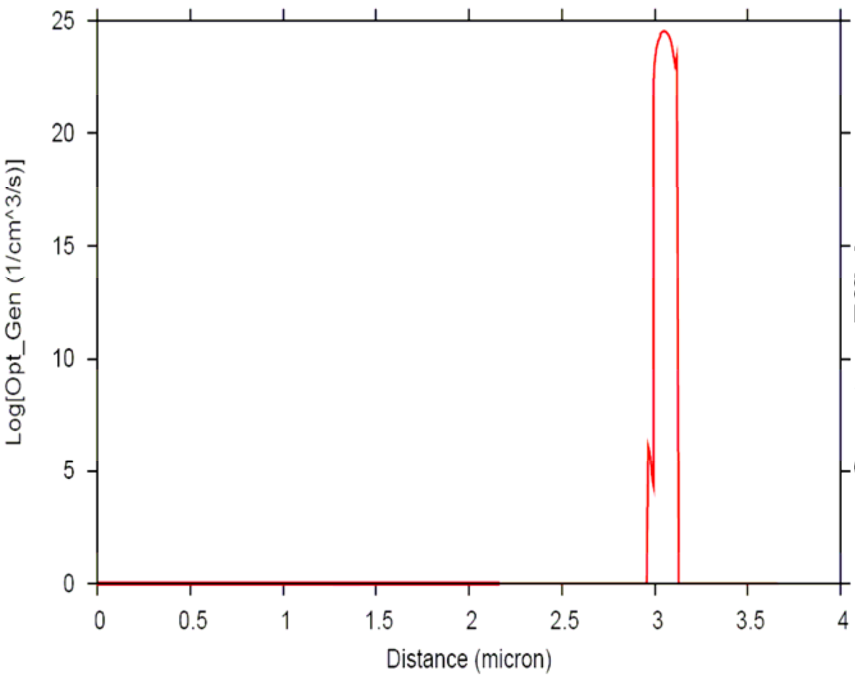
Band diagram & relative optic energy density

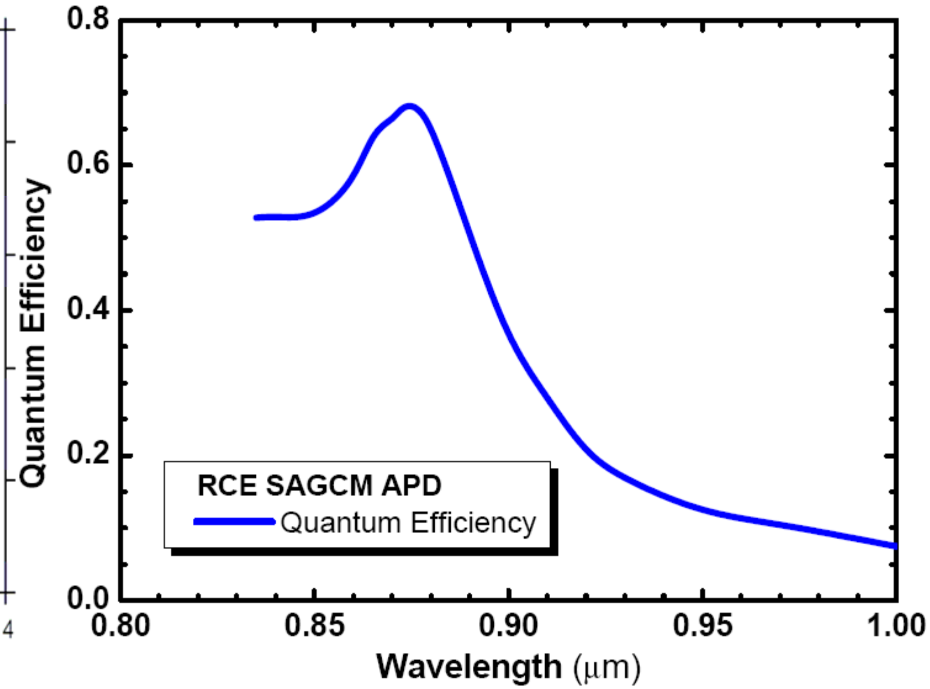




Resonant standing waves are clearly observed at the absorption region within the cavity.

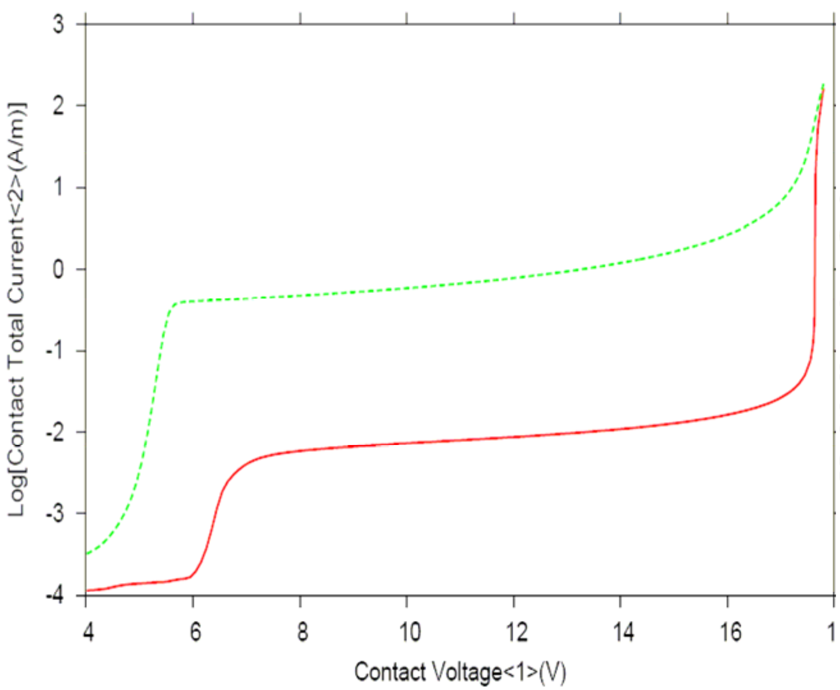
Optic generation rate & quantum efficiency

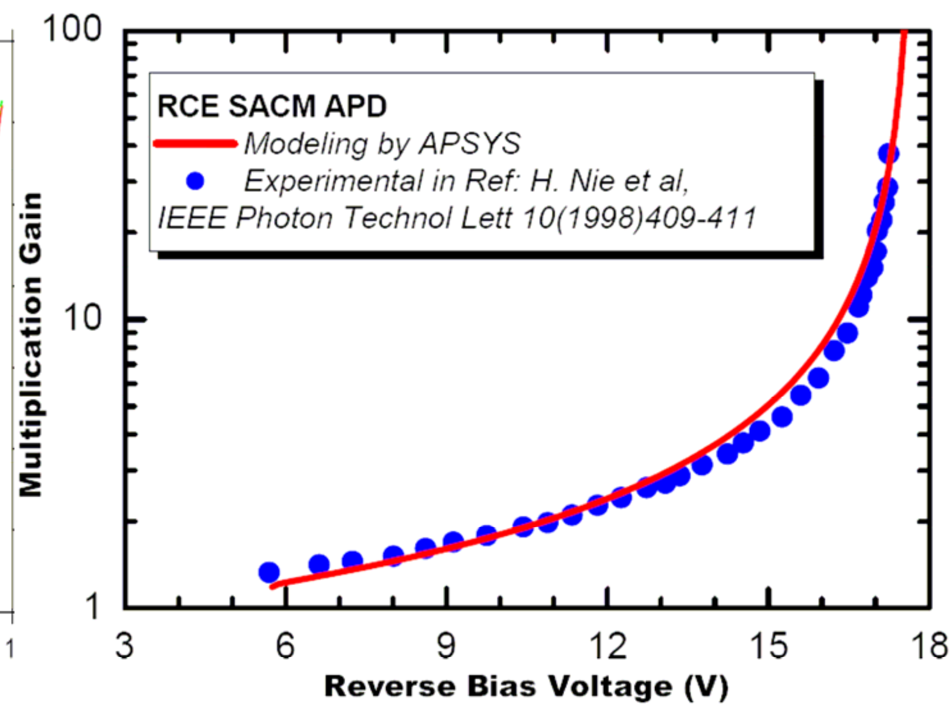




- **Enhanced absorption at the absorption layer & two neighbor grading layers is observed.**
- **Peak QE 68.4%, QE asymmetry due to the neighbor 2nd order (left) resonance peak for the GaAs-AlAs mirror structures used (see K Kishino et al *IEEE J Quantum Electron.* 27, pp. 2025–2034, 1991).**

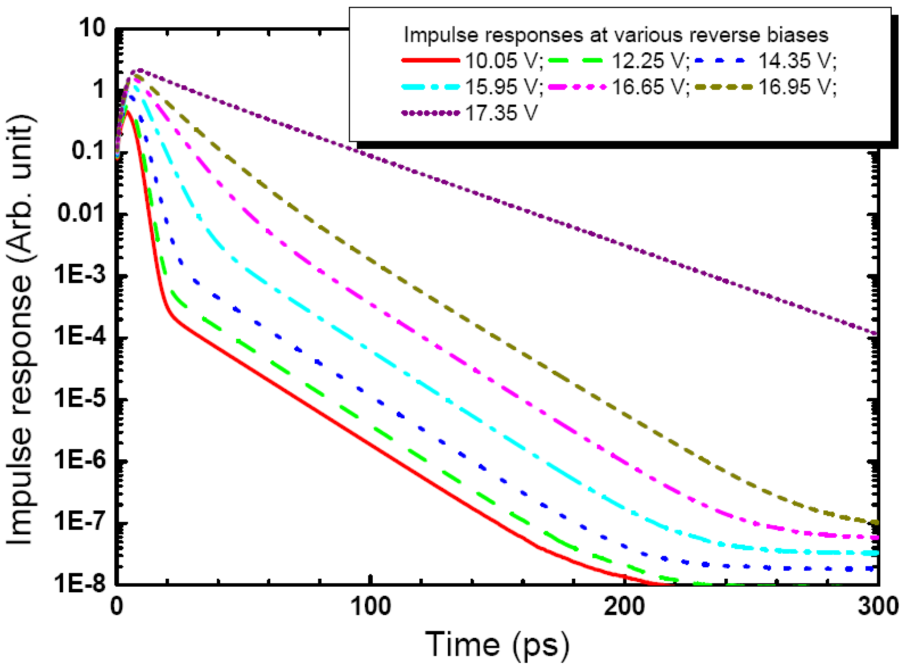
I-V curves & multiplication gain

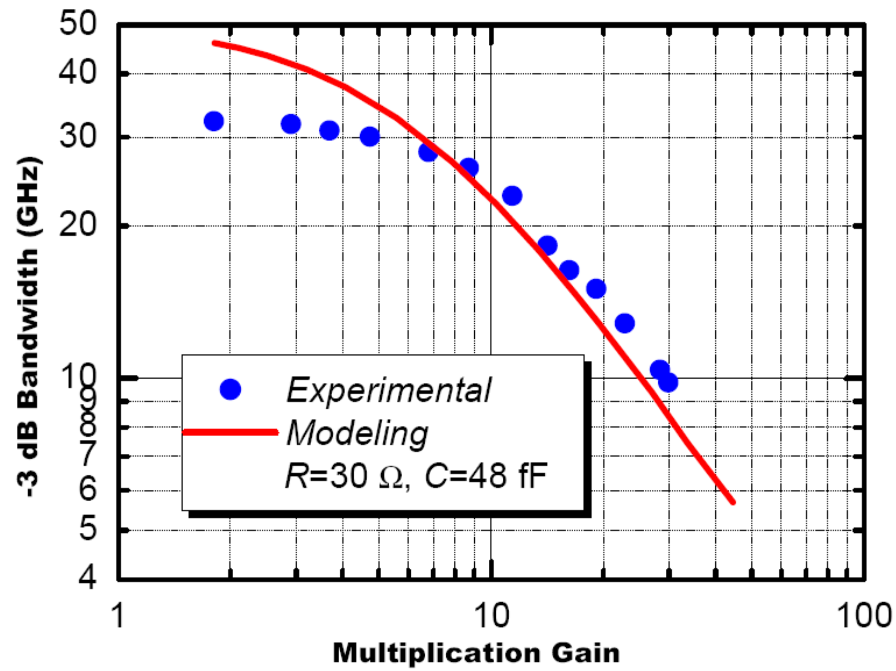




- **Unity gain at ~5.6V, & breakdown at ~ 17.6 V.**
- **Modeled multiplication gain consistent with the experimental (see H Nie et al, *IEEE Photon. Technol. Lett.* 10, pp. 409-411, 1998).**

Impulse response & bandwidth



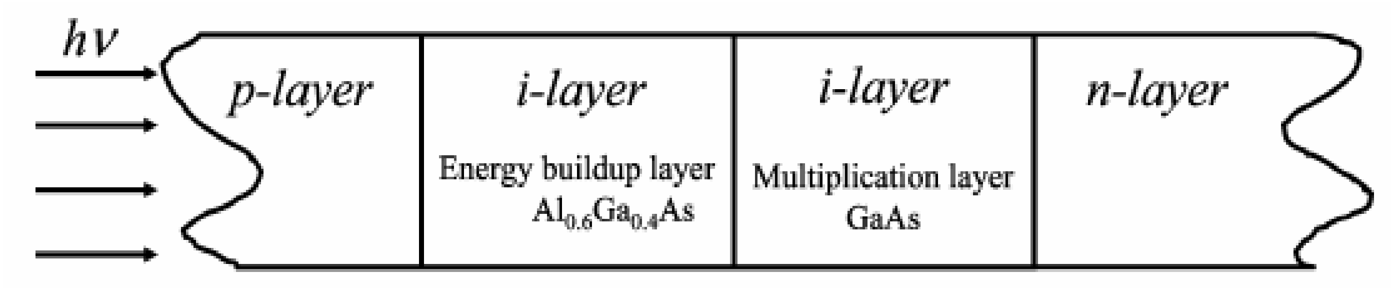


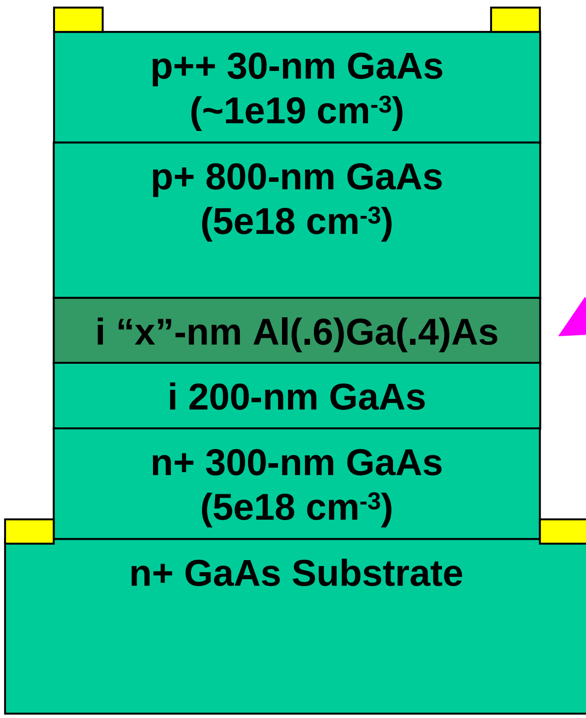
- **Gain-bandwidth product limit: taking long time to achieve the peak response & long relaxation time back to the dark background at large reverse biases.**

- **Bandwidth generally consistent with the experimental (need detailed C-V profile for more accurate modeling at low gain region) (Experimental see K Kishino et al *IEEE J Quantum Electron.* 27, pp. 2025–2034, 1991).**

Contents

GaAs/AlGaAs PIN APD structure

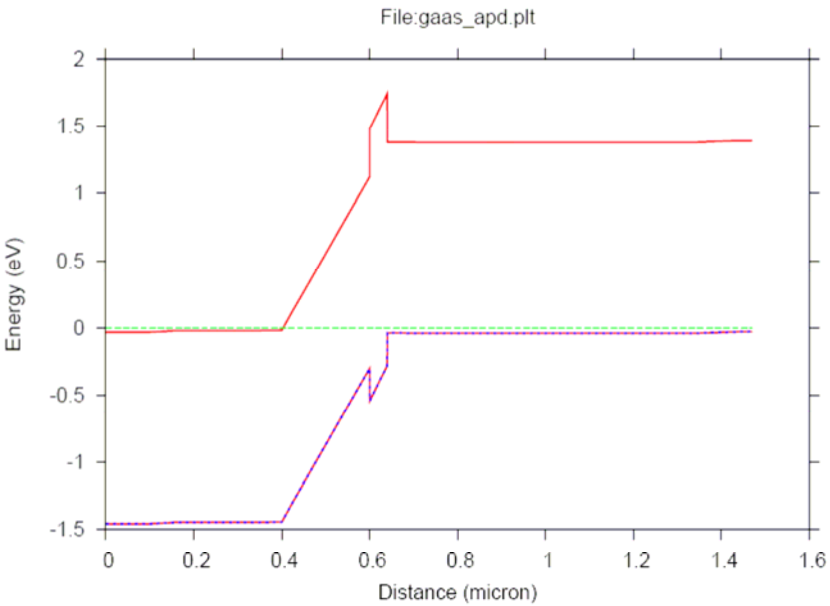




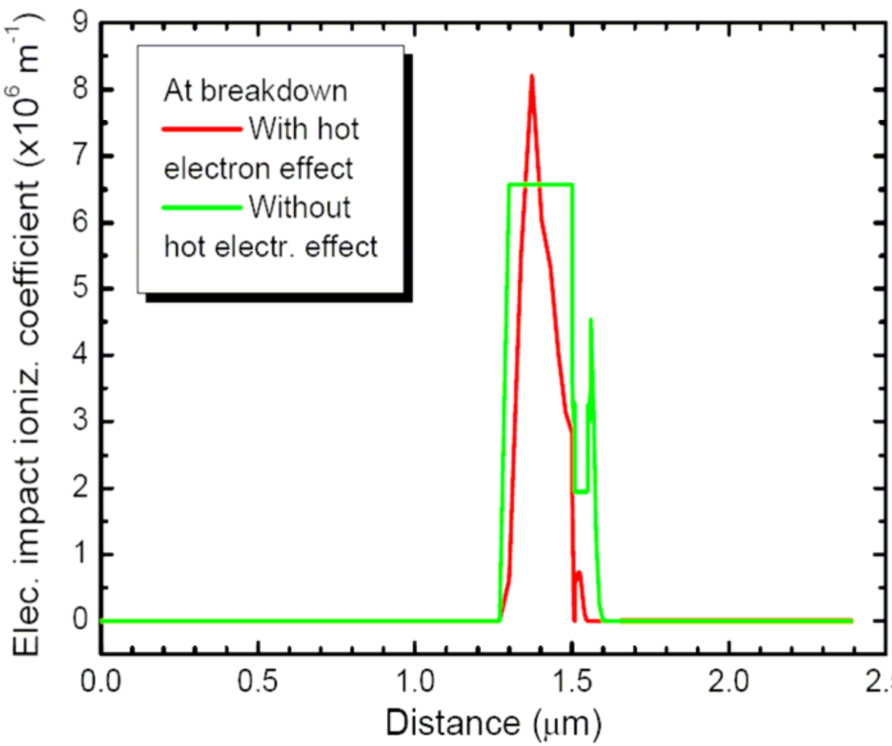
Intrinsic $Al_{.6}Ga_{.4}As$ layer for energy buildup purpose

See: Kwon et al, J. Lightwave Technol. Vol 23 No 5 (2005) pp 1896-1906

Band diagram & impact ionization rate



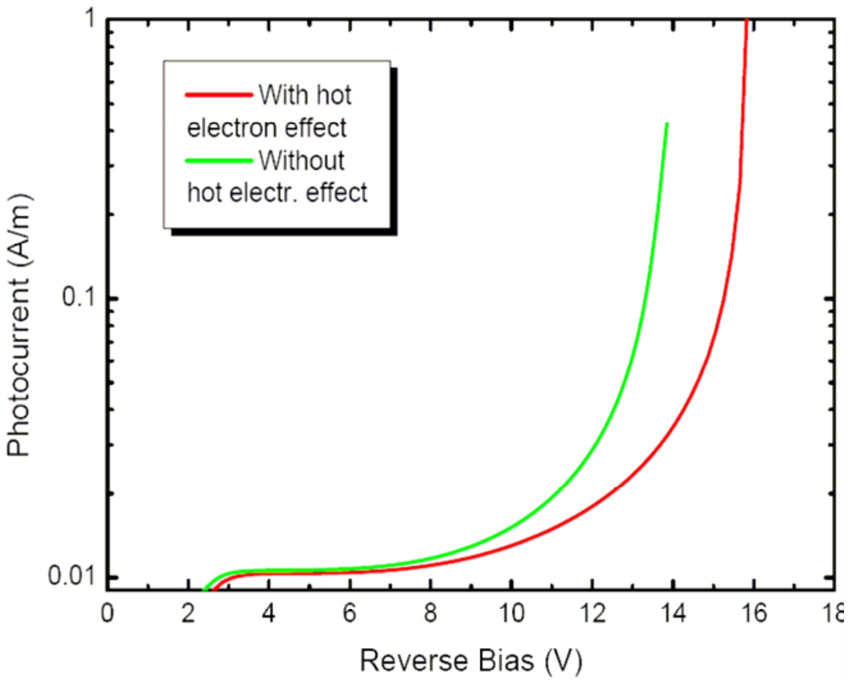
Band diagram at equilibrium (zero bias).



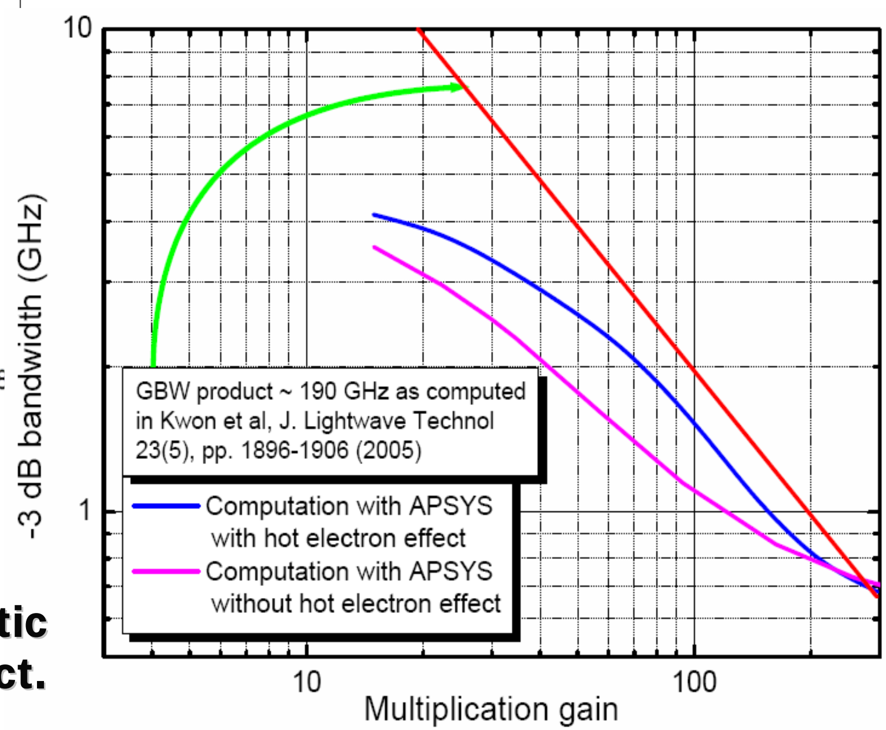
Hot electron effect shrinks the effective multiplication region since there is no ionization in the dark space (or low energy region).

CROSSLIGHT Software Inc.

I-V curves & bandwidth



High bias needed to achieve the same multiplication gain with hot electron effect.



The simulator predicted more realistic bandwidth with hot electron effect.

Summary

- Modeling of InP/InGaAs SAGCM APD, InGaAs/AlGaAs RCE SAGCM APD and GaAs/AlGaAs PIN APD presented with comparison with experiment or other theory.
- Typical physical properties like band diagram, photo-absorption & generation, impact ionization & electric field profile, & performance characteristics like photo- & dark-current, multiplication gain, excess noise factor, impulse response, & -3 dB bandwidth etc., presented for most of the simulated APDs.
- Computed multiplication gain and bandwidth are consistent with the experimental for InP/InGaAs SAGCM APD and InGaAs/AlGaAs RCE SAGCM APD.
- Some techniques for modeling also introduced. The APSYS could predict more realistic bandwidth with hot electron effect.