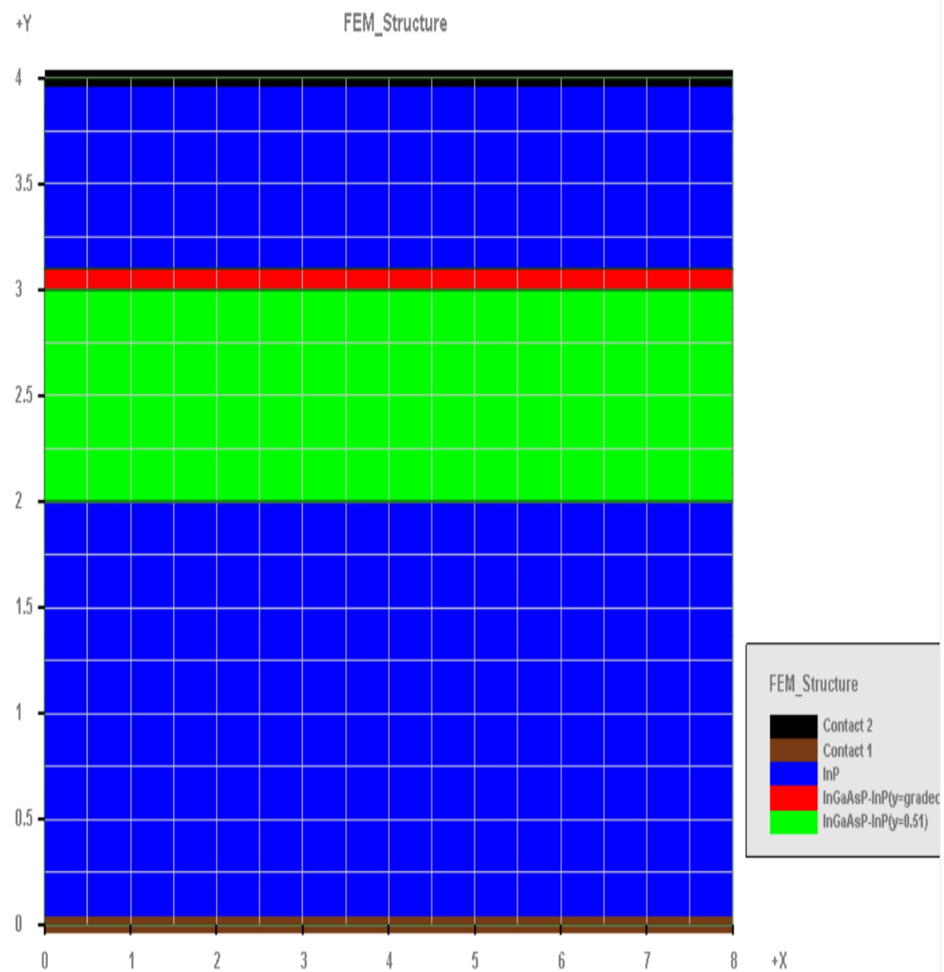
Crosslight APSYS Simulation of APD Excess Noise

- Gain Propagation
- Dead-Space Physics
- McIntyre Comparison

Motivation

- Excess noise limits APD sensitivity
- Excess noise determines SNR
- Existing theory assumes uniform field



What is Excess Noise?

- M = average multiplication
- S = multiplication variance information
- F = excess noise factor

Given N the number of carriers generated for each e-h pair

$M=\langle N \rangle$

$$S = \langle N^2 \rangle$$

$$F = \frac{S}{M^2}$$

CROSSLIGHT

Classical McIntyre Theory

- Uniform field assumption
- Widely used benchmark

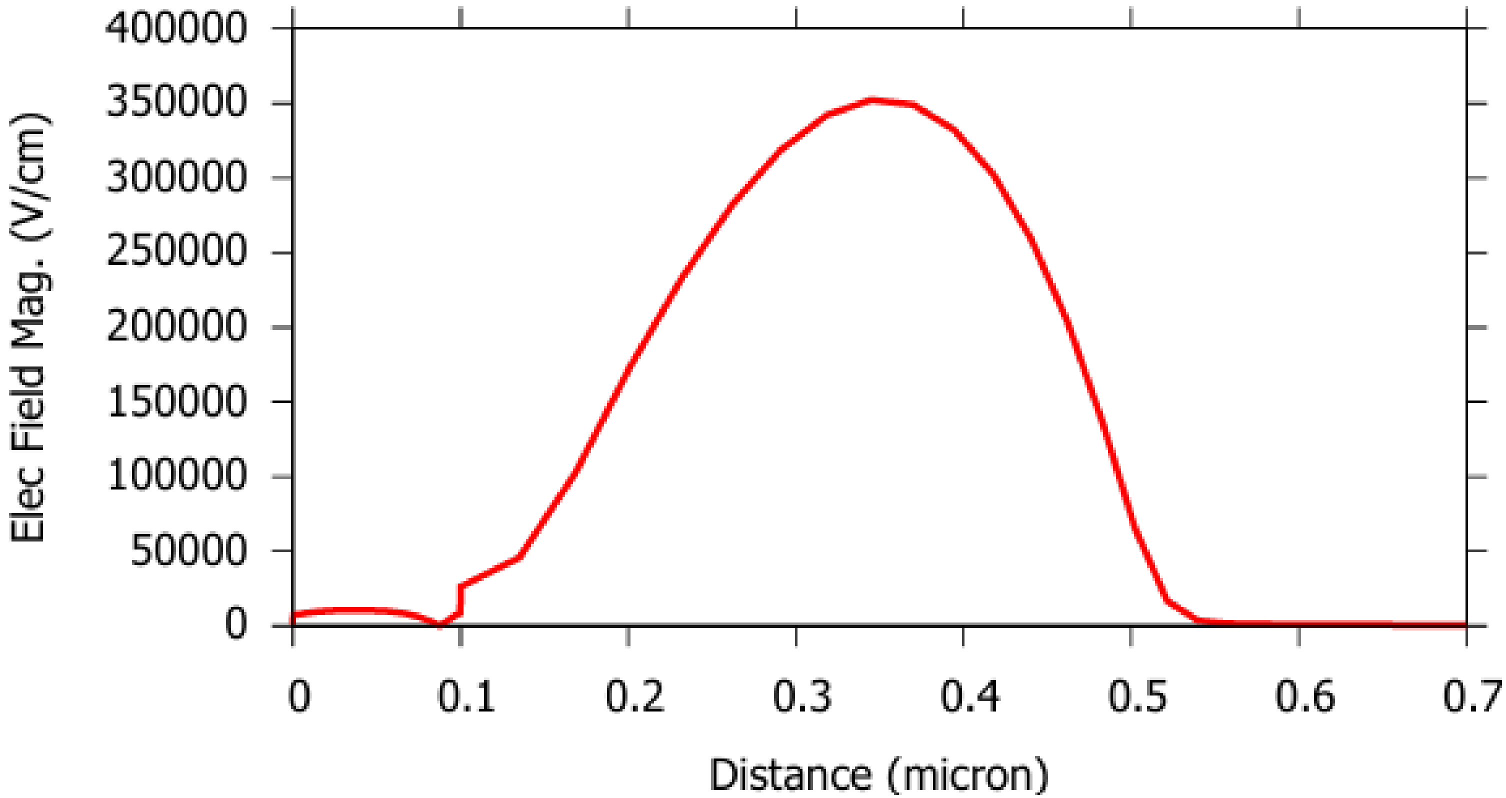
$$F = kM + \left(2 - \frac{1}{M}\right)(1 - k),$$

where

$$k = \frac{\beta}{\alpha}.$$

The gain-propagation model may therefore be viewed as a numerical generalization of McIntyre theory to arbitrary non-uniform electric-field distributions.

Why McIntyre Is Not Enough



Uniform field does not exist in real APD

APSYS-Based Gain Propagation

$$p_e = 1 - e^{-\alpha \Delta x}$$

$$p_h = 1 - e^{-\beta \Delta x}$$

Carrier → Slice → Branching

Gain Propagation Concept

Electron enters

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Possible ionization

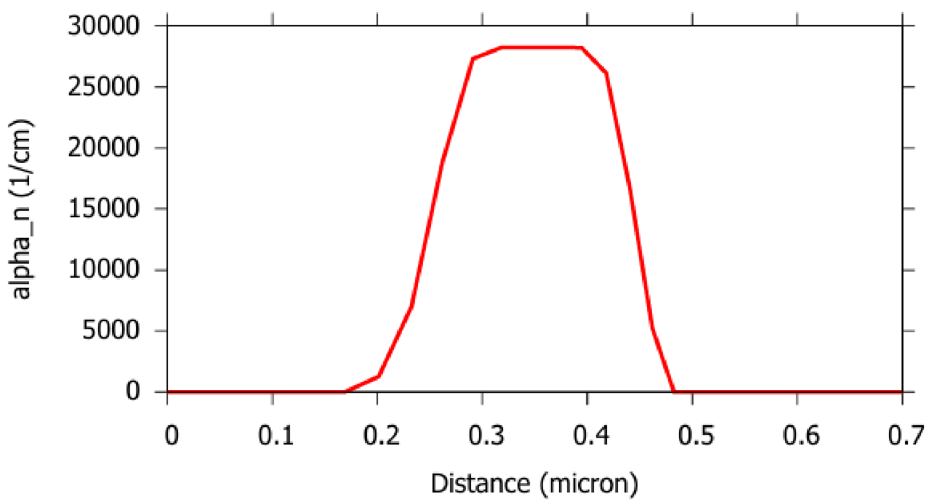
↓

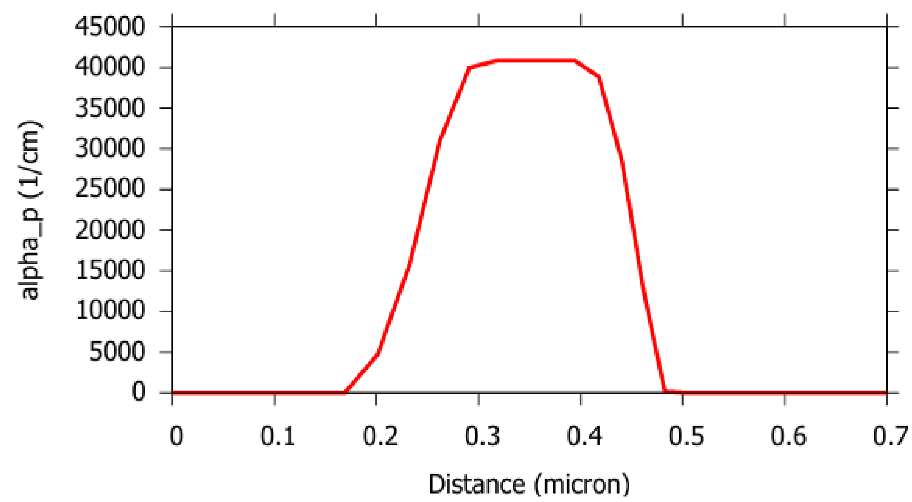
Additional electron-hole pair

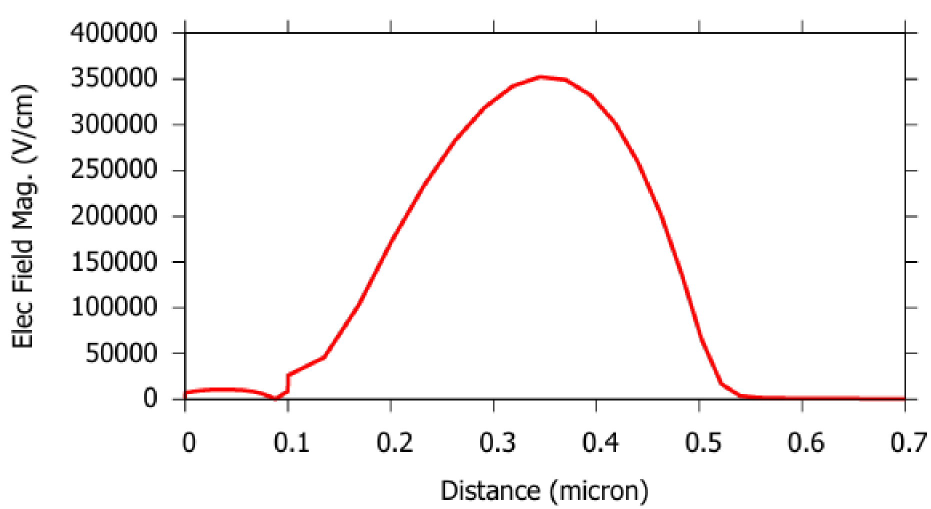
↓

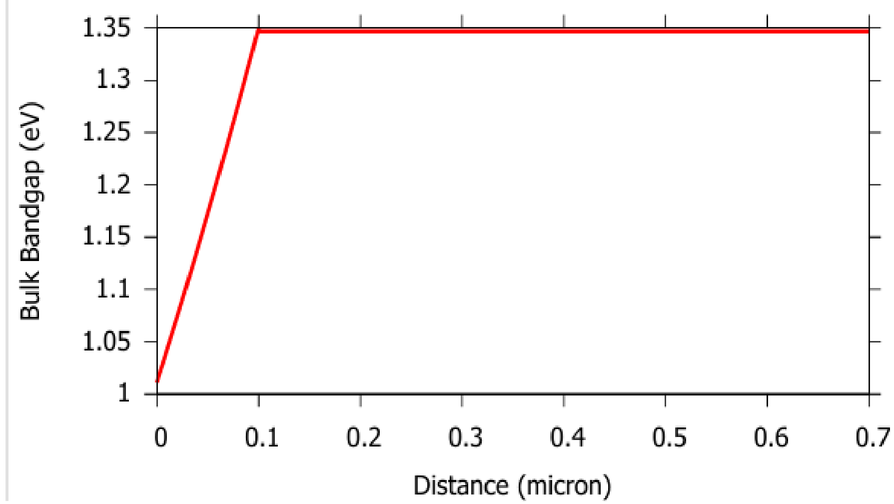
Propagation

APSYS Inputs









Local Non-Uniform Model

Local Non-Uniform Model

Equation:

$$p_e(x) = 1 - e^{-\alpha(x)\Delta x}$$

$$p_h(x) = 1 - e^{-\beta(x)\Delta x}$$

..

- Directly uses APSYS α and β

Dead-Space Physics

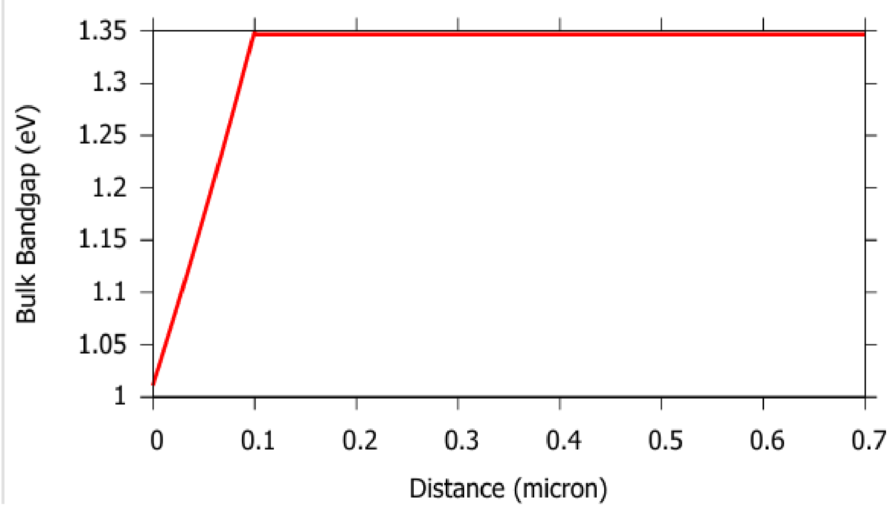
$$\Delta\varepsilon = \int qE(x)dx$$

$$\Delta\varepsilon \geq E_{th}$$

Bandgap-Based Threshold

$$E_{th,e} = C_e E_g$$

$$E_{th,h} = C_h E_g$$



Dead-Space Illustration

Carrier born

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Acceleration

↓

Dead-space distance

↓

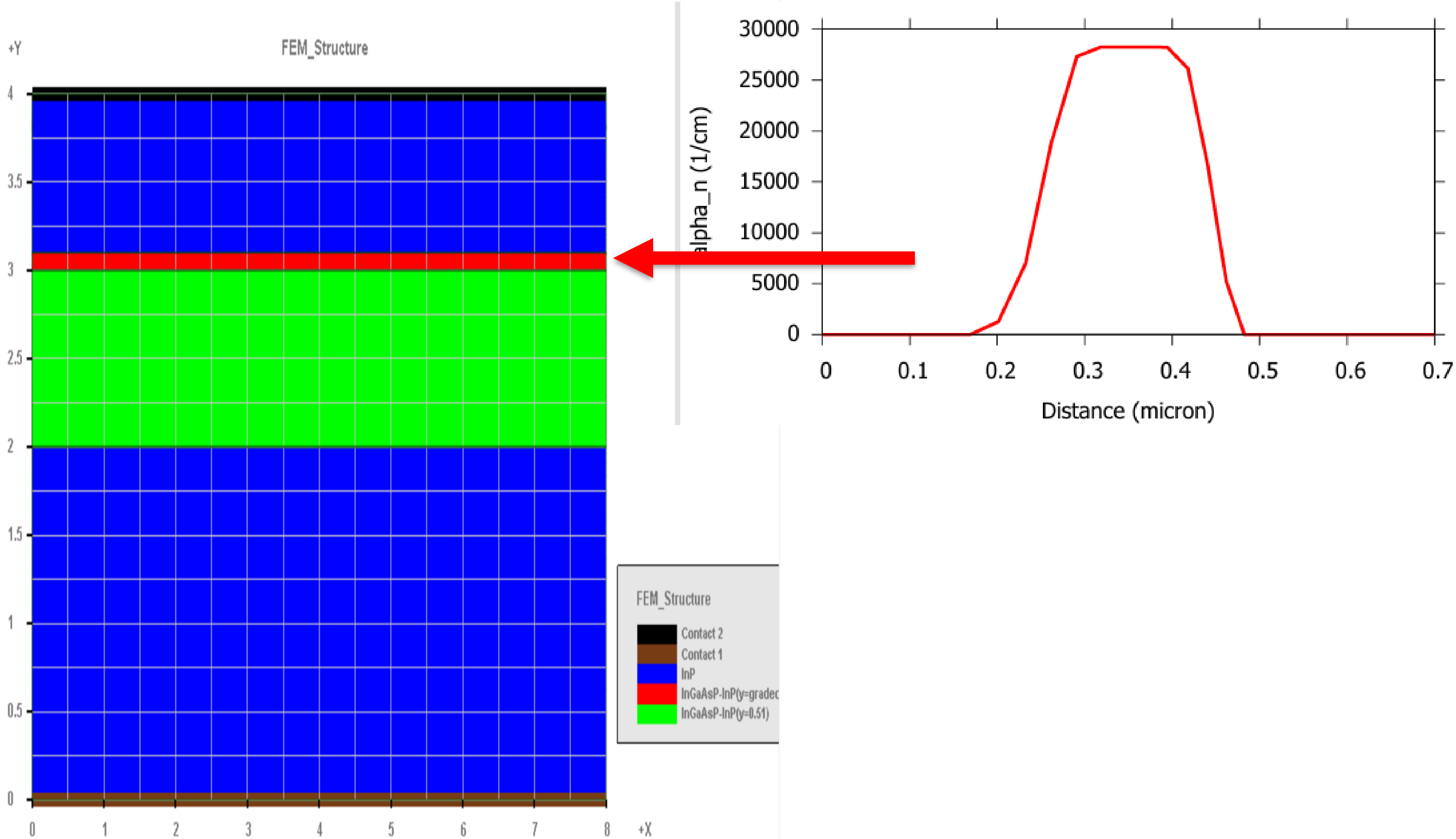
First possible ionization

APSYS Workflow

- APSYS→αβE Eg→Interpolation→M,S,F.
- APSYS automates this work flow by implementing a bias_output command in .sol

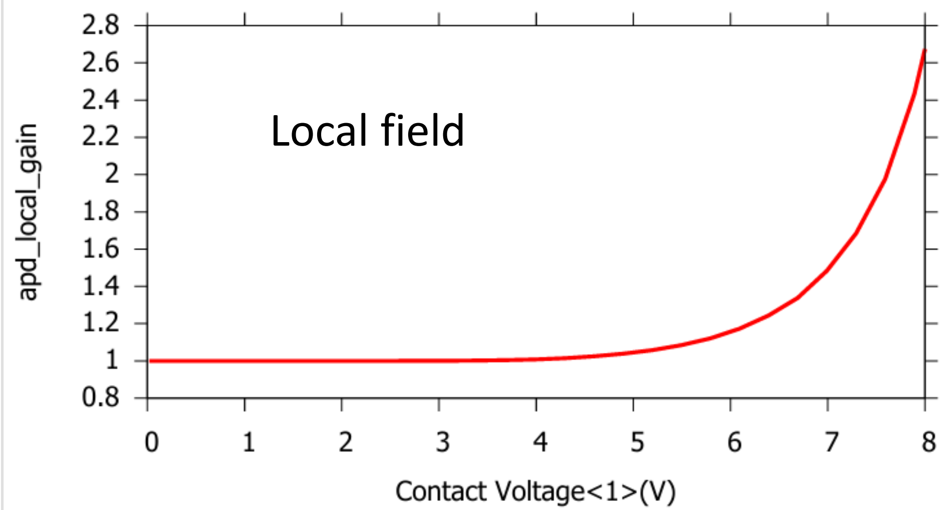
```
bias_output_ii_integral variable=apd_gain_noise_par &&
  method=excess_noise n_side_down=no &&
  point1=(0.5 3. 0) point2=(0.5, 3.7 0)
```

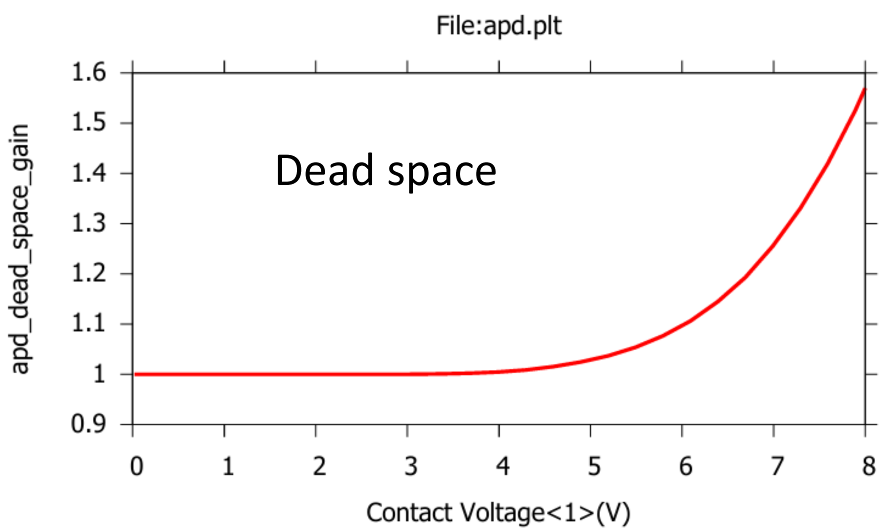
Simulation Example

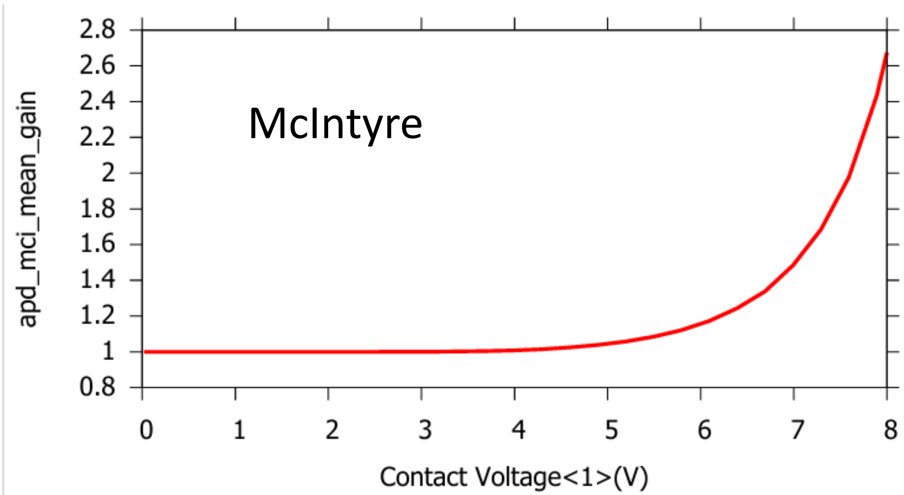


Gain versus Bias

- gain comparison
- McIntyre model borrows mean gain from local field model.

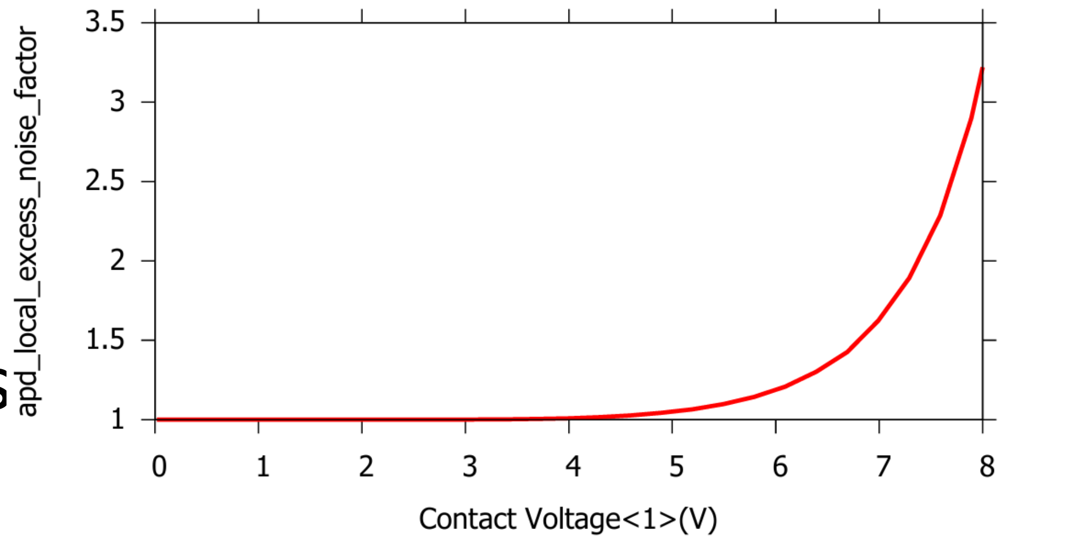


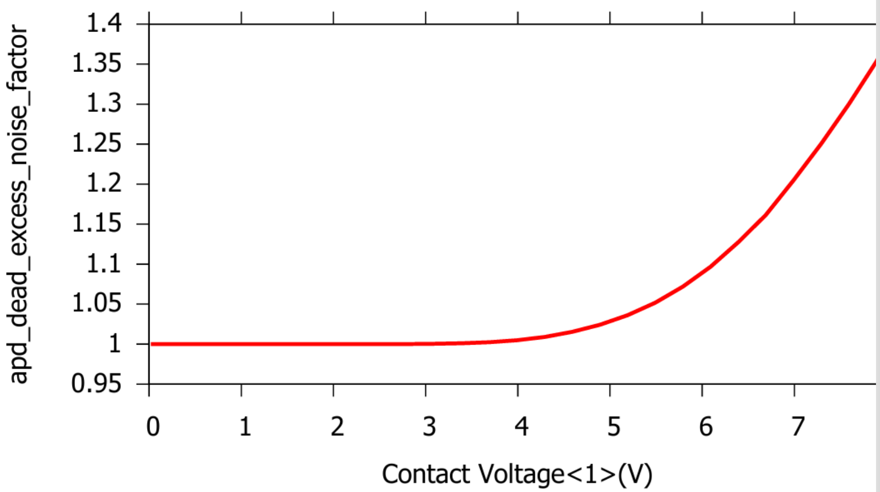


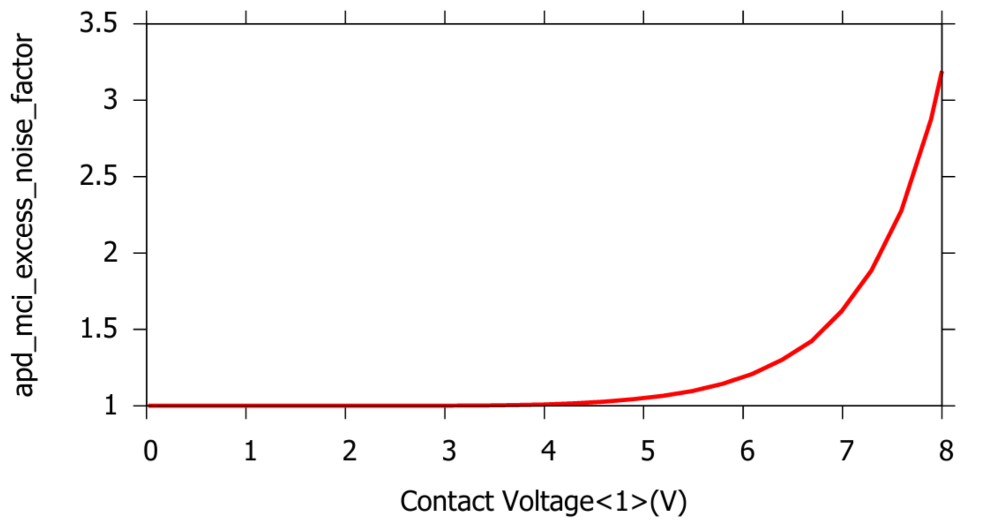


Excess Noise versus Bias

- F comparison
- With borrowed mean gain, the McIntyre model is similar

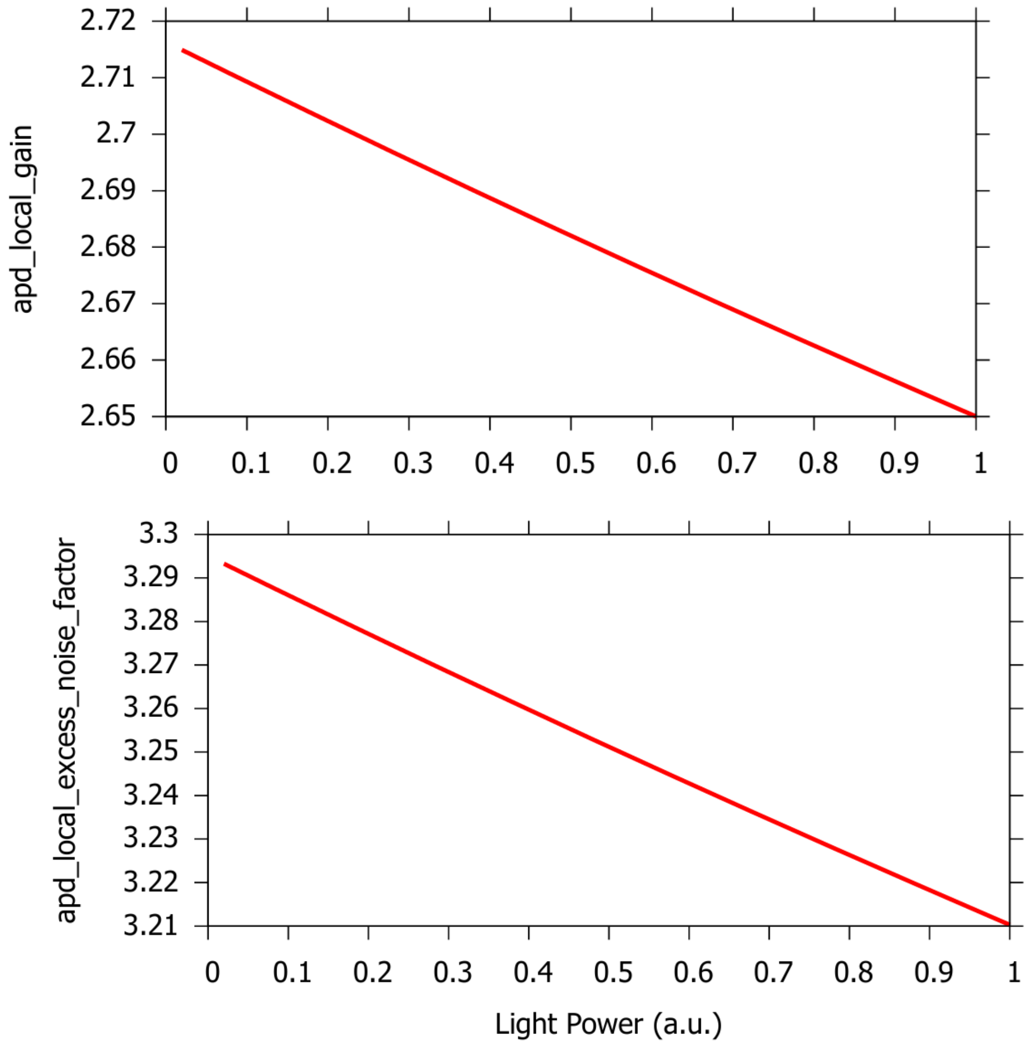






Optical Screening Effect

- APD is less noisy when light is on.



Conclusions

1. APSYS directly computes $\alpha(x)$, $\beta(x)$, $E(x)$, $Eg(x)$
2. Gain propagation extends McIntyre to non-uniform fields
3. Dead-space further reduces excess noise
4. Optical screening slightly reduces F
5. Framework applicable to APD and SPAD design