# Qucs

## A Report

### Compact Verilog-A pn junction photodiode model

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# Introduction

Optoelectronic devices are not included in Qucs version 0.0.14 or earlier releases of the software. With the growing importance of these devices, and indeed the fact that they are present in an increasing number of electronic systems, this is a significant omission. This report presents the structure and physical details of a Qucs implementation of a pn junction photodiode model. The photodiode model is the first in a planned series of Verilog-a compact device models for optoelectronic components. The report also introduces the concept of a light bus and shows how light paths can be added to Qucs simulation schematics. A number of example schematics are also included in the report to demonstrate the performance of the new Verilog-A pn junction photodiode model. The background to the work outlined in this report was first published in the International Journal of Numerical Modelling: Electronic Networks, Devices and Fields in September 2008[1].

# pn junction photodiode effects modelled

The Qucs pn junction photodiode model includes the following features:

- Diode photocurrent response characteristics expressed as a function of light power and wavelength.

- Diode DC I-V characteristics in the forward and reverse bias regions including avalanche breakdown in reverse bias.

- Diode bias dependent capacitance.

- Diode shunt resistance.

- Diode package series resistance.

- Device noise, including thermal, shot, flicker and quantum contributions.

# The Qucs pn junction photodiode model

The schematic capture symbol and equivalent electrical circuit for the Qucs pn junction photodiode is shown in Fig. 1. In this model the DC properties and capacitance of the photodiode are represented by a semiconductor diode with a parallel shunt resistance Rsh. Device lead resistance is represented by series resistance Rseries_area. A voltage-controlled current source models the diode photocurrent. The gain of the controlled source is set as the responsivity of the photodiode. The equivalent circuit shown in Fig. 1(c) presents the

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[1]Brinson M.E. and Jahn S., Qucs: A GPL software package for circuit simulation, compact device modelling and circuit macromodelling from DC to RF and beyond, published online, 5 September 2008, http://www3.interscience.wiley.com/journal/121397825/abstract.

complete photodiode model with thermal, shot and flicker noise sources included. One interesting, and unusual, feature of the Qucs photodiode noise model is the inclusion of quantum shot noise, modelled by noise current source *Ilightn*. Photocurrent *Ilight* is given by

$$Ilight = Light \cdot Responsivity \tag{1}$$

where *Light* is the optical signal in W and *Responsivity* is the the spectral responsivity in A/W. Responsivity can also be written in terms of the photodiode quantum efficiency given by.

$$Responsivity = \frac{QE \cdot q \cdot \lambda}{h \cdot c} = \frac{QE_{percent} \cdot \lambda}{1.2398e5} \tag{2}$$

where QE is the photodiode quantum efficiency, $\lambda$ is the light wavelength in nm, $h$ is Plank's constant, c is the speed of light in a vacuum, and $QE_{percent}$ is the quantum efficiency given in percentage. In Fig. 1 the optical signal path is shown as a green line connected at the side of the photodiode symbol. In Qucs simulations optical signals are modelled as voltage quantities expressed as real numbers, even though they represent a power quantity, and are shown on a schematic as green connecting lines between components. This has the effect of clearly identifying optical signal paths on a schematic, when compared to the blue lines which indicate connecting wires characterised by conventional current and voltage signals. Similarly, signal sources which input light to a circuit are coloured green, see later example simulations.
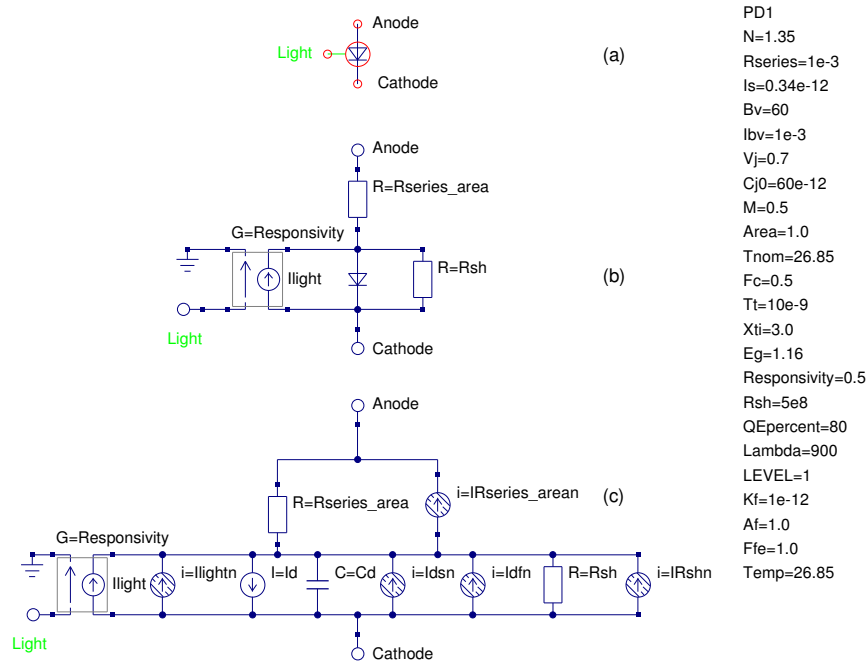


Figure 1: Qucs pn junction photodiode model: (a) schematic capture symbol, (b) basic model circuit, (c) full equivalent circuit, including noise

# Photodiode parameters

| Name | Symbol | Description | Unit | Default |
|------|--------|-------------|------|---------|
| N | $N$ | photodiode emission coefficient | | 1.35 |
| Rseries | $Rseries$ | series lead resistance | $\Omega$ | $1e-3$ |
| Is | $Is$ | diode dark current | A | $0.34e-12$ |
| Bv | $Bv$ | reverse breakdown voltage | V | 60.0 |
| Ibv | $Ns$ | current at reverse breakdown voltage | A | $1e-3$ |
| Vj | $Vj$ | junction potential | V | 0.7 |
| Cj0 | $Cj0$ | zero bias junction capacitance | F | $60e-12$ |
| M | $M$ | grading coefficient | | 0.5 |
| Area | $Area$ | diode relative area | | 1 |
| Tnom | $Tnom$ | parameter measurement temperature | $^\circ$C | 26.85 |
| Fc | $Fc$ | forward-bias depletion capacitance coefficient | | 0.5 |
| Tt | $Tt$ | transit time | s | $10e-9$ |
| Xti | $Xti$ | saturation current temperature exponent | | 3.0 |
| Eg | $Eg$ | energy gap | eV | 1.16 |
| Responsivity | $Responsivity$ | responsivity | A/W | 0.5 |
| Rsh | $Rsh$ | shunt resistance | $\Omega$ | $5e8$ |
| QEpercent | $QEpercent$ | quantum efficiency | % | 80.0 |
| Lambda | $Lambda$ | light wavelength | nm | 900.0 |
| LEVEL | | responsivity calculator selector* | | 1 |
| Kf | $KF$ | flicker noise coefficient | | $1e-12$ |
| Af | $Af$ | flicker noise exponent | | 1.0 |
| Ffe | $Ffe$ | flicker noise frequency exponent | | 1.0 |
| Temp | $Temp$ | device temperature | $^\circ$C | 26.85 |

* Parameter LEVEL is used to select how the photodiode *Responsivity* is determined: with LEVEL = 1 the model uses the listed value of parameter *Responsivity* or calculates it's value if QEpercent is not equal to zero; with LEVEL = 2 *Responsivity* is always calculated using QEpercent.

# pn junction photodiode model equations

- Basic semiconductor DC characteristics

$$Id = I1 + I2 + I3 + I4 \tag{3}$$

Where

1. $I1 = Area \cdot Is(T2) \cdot \left[ limexp \left( \dfrac{Vd}{N \cdot Vt(T2)} \right) - 1 \right] + Vd \cdot GMIN \quad \forall \, (Vd > -5 \cdot N \cdot Vt)$

2. $I2 = -Area \cdot Is(T2) + Vd \cdot GMIN \quad \forall \, (-Bv < Vd) \text{ and } (Vd > -5 \cdot N \cdot Vt)$

3. $I3 = -Ibv \quad \forall \, (Vd == -Bv)$

4. $I4 = -Area \cdot Is(T2) \cdot \left[ limexp \left( \dfrac{-(Bv + Vd)}{Vt(T2)} \right) - 1 + \dfrac{Bv}{Vt} \right] \quad \forall \, (Vd < -Bv)$

- photodiode capacitance

$$Cd = Cdiff + Cdep \tag{4}$$

Where

1. $Cdiff = \dfrac{dQdiff}{dVd} = Tt \cdot \dfrac{dId}{dVd}$

2. $Cdep = \dfrac{dQdep}{dVd} = Area \cdot Cj0 \cdot \left(1 - \dfrac{Vd}{Vj}\right)^{-M}$

where $Qd = Qdep + Qdiff$, and

$$Qd = Tt \cdot Id + \dfrac{Area \cdot Cj0 \cdot Vj}{1 - M} \cdot \left\{1 - \left(1 - \dfrac{Vd}{Vj}\right)^{1-M}\right\} \qquad \forall\,(Vd < Fc \cdot Vj)$$

$$Qd = Tt \cdot Id + Area \cdot Cj0 \cdot \left\{F1 + \dfrac{1}{F2} \cdot \left(F3 \cdot (Vd - Fc \cdot Vj) + \left[\dfrac{M}{2 \cdot Vj}\right] \cdot \left[Vd^2 - (Fc \cdot Vj)^2\right]\right)\right\}$$

$$\forall\,(Vd >= Fc \cdot Vj)$$

Where

$F1 = \dfrac{Vj}{1 - M} \cdot \left[1 - (1 - Fc)^{1-M}\right]$

$F2 = [1 - Fc]^{1+M}$

$F3 = 1 - Fc \cdot (1 + M)$

and GMIN = 1e-12S.

- Diode area factors

  1. $Is\_area = Is \cdot Area$

  2. $Cjo\_area = Cj0 \cdot Area$

  3. $Rseries\_area = \dfrac{Rseries}{Area}$

- Diode temperature factors

  1. $Is(T2) = Is \cdot \left\{\dfrac{T2}{T1}\right\}^{\frac{Xti}{N}} \cdot limexp \left\{\dfrac{-Eg(T1)}{Vt(T2)} \cdot \left[1 - \dfrac{T2}{T1}\right]\right\}$

  2. $Vj(T2) = \dfrac{T2}{T1} \cdot Vj - 2 \cdot Vt(T2) \cdot ln \left(\dfrac{T2}{T1}\right)^{1.5} - \left\{\dfrac{T2}{T1} \cdot Eg(T1) - Eg(T2)\right\}$

  3. $Cj0(T2) = Cj0 \cdot \left\{1 + M \cdot \left[400e - 6 \cdot (T2 - T1) - \dfrac{Vj(T2)}{Vj}\right]\right\}$

     Where

     $T1 = Tnom + 273.15, \quad T2 = Temp + 273.15$

     $Eg(T) = EG(0) - \dfrac{7.02e - 4 \cdot T^2}{1108 + T}$

     $Vt = \dfrac{K \cdot T1}{q}, \quad Vt(T2) = \dfrac{K \cdot T2}{q}$ and $K$ and $q$ have their usual meaning.

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- Diode photocurrent

$$Ilight = Light \cdot Responsivity \tag{5}$$

Where $Responsivity = \dfrac{QE \cdot q \cdot \lambda}{h \cdot c} = \dfrac{QEpercent \cdot \lambda}{1.2398e55}$

- photodiode noise

$$Ipd\_noise^2 = IRshn^2 \cdot \Delta f + Idsn^2 \cdot \Delta f + Idfn^2 \cdot \Delta f + Ilightn^2 \cdot \Delta f \tag{6}$$

Where $IRshn^2 = \dfrac{4 \cdot K \cdot T}{Rsh}, \;\; Idsn^2 = 2 \cdot q \cdot Id, \;\; Idfn^2 = \dfrac{Kf \cdot Id^{Af}}{f^{Ffe}},$

$Ilight^2 = 2 \cdot q \cdot Ilight$, and $\Delta f$ is the noise frequency bandwidth in Hz.

## Verilog-A model code

```
//    Qucs compact photodiode model
//    The structure and theoretical background to the photodiode
//    Verilog-a model are presented in the Qucs photodiode report.
//
//    This is free software; you can redistribute it and/or modify
//    it under the terms of the GNU General Public License as published by
//    the Free Software Foundation; either version 2, or (at your option)
//    any later version.
//
//    Copyright (C), Mike Brinson, mbrin72043@yahoo.co.uk, October 2008.
//
`include "disciplines.vams"
`include "constants.vams"
module photodiode (Anode, Cathode, Light);
 inout Anode, Cathode, Light;
 electrical Anode, Cathode, Light;
 electrical n1;
 `define attr(txt) (*txt*)
//
 parameter real N=1.35 from [1e-6:inf]
          `attr(info="photodiode_emission_coefficient");
 parameter real Rseries=1e-3 from [1e-6:inf]
          `attr(info="series_lead_resistance" unit = "Ohm");
 parameter real Is=0.34e-12 from [1e-20:inf]
          `attr(info="diode_dark_current" unit="A" );
 parameter real Bv=60 from [1e-6:inf]
          `attr(info="reverse_breakdown_voltage" unit="V");
 parameter real Ibv=1e-3 from [1e-6:inf]
          `attr(info="current_at_reverse_breakdown_voltage" unit="A");
 parameter real Vj=0.7 from [1e-6:inf]
          `attr(info="junction_potential" unit="V");
 parameter real Cj0=60e-12 from [0:inf]
          `attr(info="zero-bias_junction_capacitance" unit="F");
 parameter real M=0.5 from [1e-6:inf]
          `attr(info="grading_coefficient");
 parameter real Area=1.0 from [1.0:inf]
          `attr(info="diode_relative_area");
```

```verilog
  parameter real Tnom=26.85 from [−273:inf]
          'attr(info="parameter_measurement_temperature" unit="Celsius");
  parameter real Fc=0.5 from [1e−6:inf]
          'attr(info="forward−bias_depletion_capcitance_coefficient");
  parameter real Tt=10e−9 from [1e−20:inf]
          'attr(info="transit_time" unit="s" );
  parameter real Xti=3.0 from [1e−6:inf]
          'attr(info="saturation_current_temperature_exponent");
  parameter real Eg= 1.16 from [1e−6:inf]
          'attr(info="energy_gap" unit="eV");
  parameter real Responsivity=0.5 from [1e−6:inf]
          'attr(info="responsivity" unit="A/W");
  parameter real Rsh=5e8 from [1e−6:inf]
          'attr(info="shunt_resistance" unit="Ohm");
  parameter real QEpercent=80 from [0:100]
          'attr(info="quantum_efficiency" unit="%");
  parameter real Lambda=900 from [100:2000]
          'attr(info="light_wavelength" unit="nm");
  parameter integer LEVEL=1 from [1:2]
          'attr(info="responsivity_calculator_selector");
  parameter real Kf=1e−12 from [0:inf]
          'attr(info="flicker_noise_coefficient");
  parameter real Af=1.0 from [0:inf]
          'attr(info="flicker_noise_exponent");
  parameter real Ffe=1.0 from [0:inf]
          'attr(info="flicker_noise_frequency_exponent");
//
real A, B, T1, T2, F1, F2, F3, Rseries_Area, Eg_T1, Eg_T2,
real Vt_T2, Vj_T2, Cj0_T2, Is_T2, GMIN;
real I1, I2, I3, I4, I5, Id, V1, Q1, Q2, fourkt, TwoQ, Res1,
real Res2, Res, Vt, I_flicker;
real con1, con2, con3, con4, con5, con6;
// Model branches
branch (Anode, n1) b6;
branch (n1, Cathode) b1;
//
analog begin
// Model equations
@(initial_step)
  begin
    Rseries_Area=(Rseries+1e−10)/Area;
    A=7.02e−4;
    B=1108.0;
    T1=Tnom+273.15;
    T2=$temperature;
    Vt='P_K*300.0/'P_Q;
    Vt_T2='P_K*T2/'P_Q;
    F1=(Vj/(1−M))*(1−pow((1−Fc),(1−M)));
    F2=pow((1−Fc), (1+M));
    F3=1−Fc*(1+M);
    Eg_T1=Eg−A*T1*T1/(B+T1);
    Eg_T2=Eg−A*T2*T2/(B+T2);
    Vj_T2=(T2/T1)*Vj−2*$vt*ln(pow((T2/T1),1.5))−((T2/T1)*Eg_T1−Eg_T2);
    GMIN=1e−12;
    Cj0_T2=Cj0*(1+M*(400e−6*(T2−T1)−(Vj_T2−Vj)/Vj));
    Is_T2=Is*pow( (T2/T1), (Xti/N))*limexp(−(Eg_T1)/$vt*(1−T2/T1));
    Res1=(QEpercent != 0) ? QEpercent*Lambda/1.2398e5:Responsivity;
    Res2=QEpercent*Lambda/1.2938e5;
    Res=(LEVEL==1) ? Res1 : Res2;
    con1=−5.0*N*Vt;
    con2=Area*Is_T2;
    con3=Area*Cj0_T2;
    con4=Fc*Vj;
    con5=Fc*Vj_T2;
    con6=Bv/Vt_T2;
```

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```verilog
    end;
    // Current contributions
    V1=V(b1);
    I1=(V1 > con1) ? con2*(limexp(V1/(N*Vt_T2))-1.0)+GMIN*V1: 0;
    I2=(V1 <=   con1) ? -con2+GMIN*V1 :0;
    I3=(V1 == -Bv)?-Ibv:  0;
    I4=(V1<-Bv)?-con2*(limexp(-(Bv+V1)/Vt_T2)-1.0+con6):0;
    Q1=(V1<con4)   ? Tt*I1 + con3*(Vj_T2/(1-M))*(1-pow((1-V1/Vj_T2),(1-M))):0;
    Q2=(V1>=con4)  ? Tt*I1 + con3*(F1+(1/F2)*(F3*(V1-con5)+
                       (M/(2.0*Vj_T2))*(V1*V1-con5*con5))):0;
    I5=V(Light)*Res;
    Id=I1+I2+I3+I4;
    I(b1)  <+ -I5;
    I(b1)  <+ V(b1)/Rsh;
    I(b6)<+V(b6)/Rseries_Area;
    I(b1)<+Id;
    I(b1)<+ddt(Q1+Q2);
    I(Light)<+V(Light)/1e10;
    // Noise contributions
    fourkt=4.0*`P_K*$temperature;
    TwoQ=2.0*`P_Q;
    I_flicker=pow(Id, Af);
    I(b6)<+white_noise(fourkt/Rseries_Area, "thermal");
    I(b1)<+white_noise(fourkt/Rsh, "thermal");
    I(b1)<+white_noise(TwoQ*Id, "shot");
    I(b1)<+flicker_noise(Kf*I_flicker, Ffe, "flicker");
    I(b1)<+white_noise(TwoQ*I5, "shot");
    //
    end
    endmodule
```

# Example photodiode circuits

PD1
QEpercent=0

Light_Const1
Light_Power=PLS

Ipd

+ V1
− U=Vpd

**dc simulation**

DC1

**Parameter sweep**

SW1
Sim=DC1
Type=lin
Param=Vpd
Start=-5
Stop=0.85
Points=121

**Parameter sweep**

SW2
Sim=SW1
Type=lin
Param=PLS
Start=0
Stop=40m
Points=10

P_light1

+ V2
− U=Light_Power

Light_Const2
Light_Power=1m
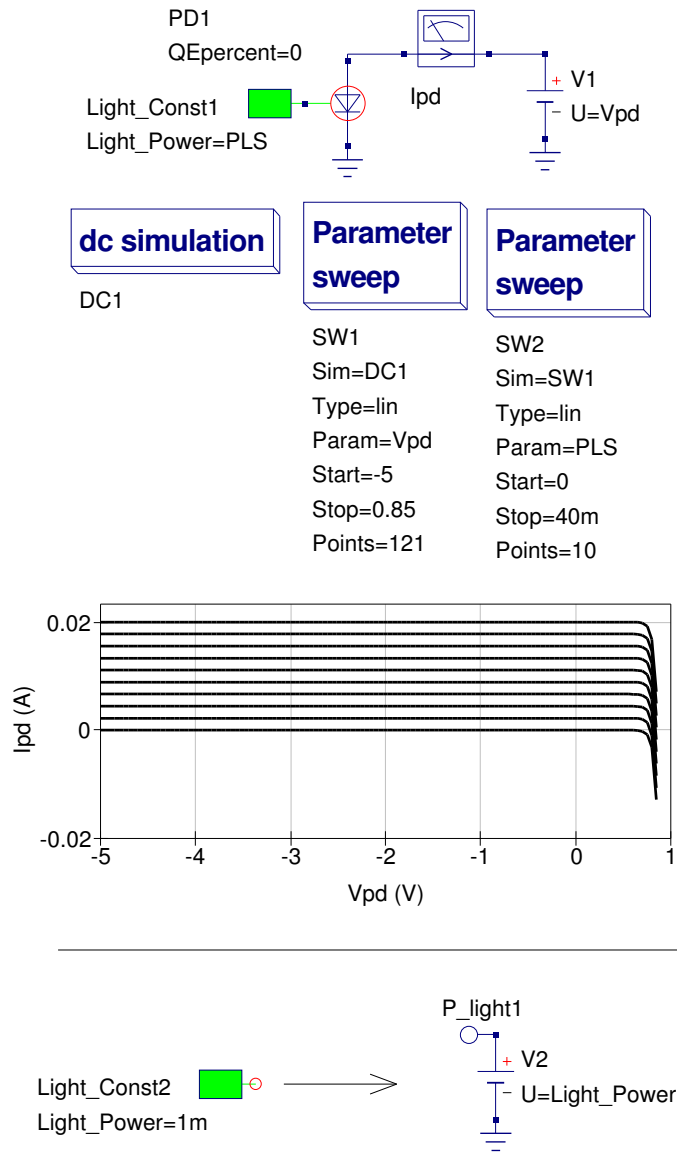
Figure 2: Basic photodiode test circuit for simulating device output current as a function of light input level and applied DC bias

PD1

Light_Const1
Light_Power=PLS

X1 V1
U=Vpd

P1
Num=1
Z=50 Ohm

**dc simulation**

DC1

Equation

Eqn1

PLS=5m

**Parameter sweep**

SW1
Sim=SP1
Type=lin
Param=Vpd
Start=-5
Stop=1
Points=61

Equation

Eqn2

Omega=2*pi*frequency
y=stoy(S)
RD=PlotVs(1/(real(y[1,1])),Vpd)
CD=PlotVs(imag(y[1,1])/Omega,Vpd)

**S parameter simulation**

SP1
Type=const
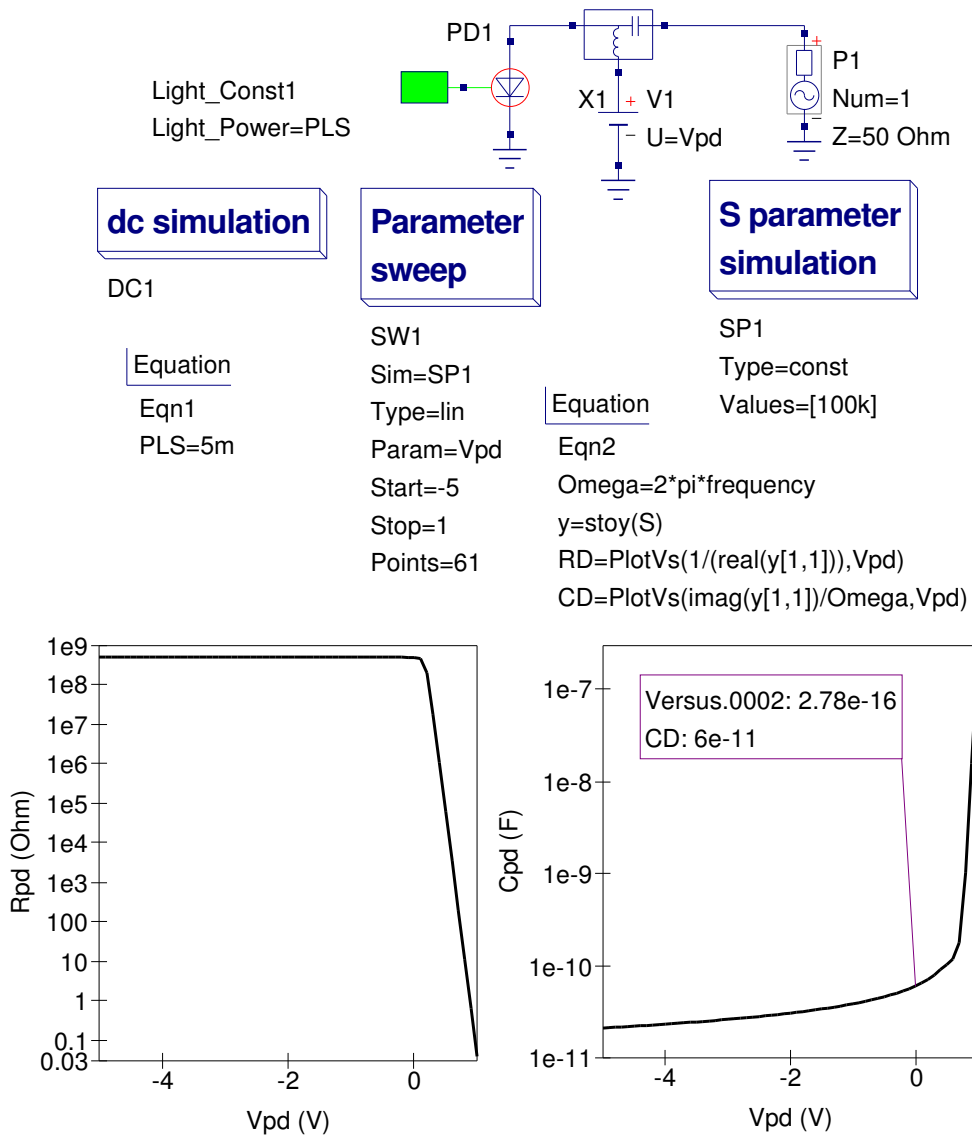Values=[100k]

Versus.0002: 2.78e-16
CD: 6e-11

Figure 3: Photodiode test circuit for extracting device capacitance and resistance as a function of applied DC bias

VL2    PD2

Light_pulse
Power_Const=1u
Power_PL=0.1u
Power_PH=200m
Stime=1m
Ftime=4m
TR=10u
TF=10u

PD1

Light1
Light_Power=1u

Vout

**transient simulation**

**dc simulation**

DC1

LA1
Kv=1.0
Dk=0.3
M=5
Vosout=3e-3
Ro=10

TR1
Type=lin
Start=0
Stop=10ms
Points=2000
IntegrationMethod=Gear
Order=6



Light_source21
Power_Const=1m
Power_PL=0
Power_PH=1m
Stime=0.1m
Ftime=1m
TR=1u
TF=1u

V1
U=Power_Const

P_Light1

SRC2
G=1

V2
U1=Power_PL
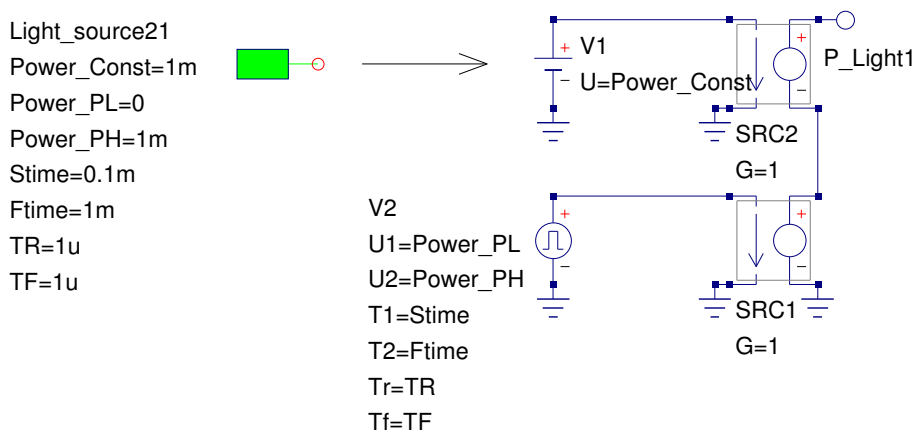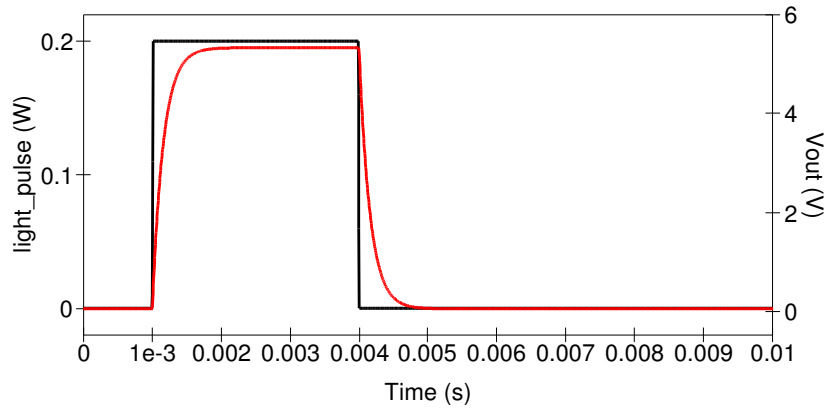U2=Power_PH
T1=Stime
T2=Ftime
Tr=TR
Tf=TF

SRC1
G=1

Figure 4: Pulsed light power comparator circuit using two photodiodes and a logarithmic amplifier

Light_source
Light_Power=Light

Ipd

+ V1
− U=Vbias

Equation

Eqn1
Ipd_noise=PlotVs(Ipd.in, Light, Vbias)

**Parameter sweep**

SW1
Sim=SW2
Type=lin
Param=Light
Start=1m
Stop=10m
Points=10

**Parameter sweep**

SW2
Sim=AC1
Type=lin
Param=Vbias
Start=-0.5
Stop=0.8
Points=100

**ac simulation**

AC1
Type=const
Values=[10k]

**dc simulation**

DC1

PD1
N=1.35
Rseries=1e-3
Is=0.34e-12
Bv=60
Ibv=1e-3
Vj=0.7
Cj0=60e-12
M=0.5
Area=1.0
Tnom=26.85
Fc=0.5
Tt=10e-9
Xti=3.0
Eg=1.16
Responsivity=0.5
Rsh=5e8
QEpercent=0
Lambda=900
LEVEL=1
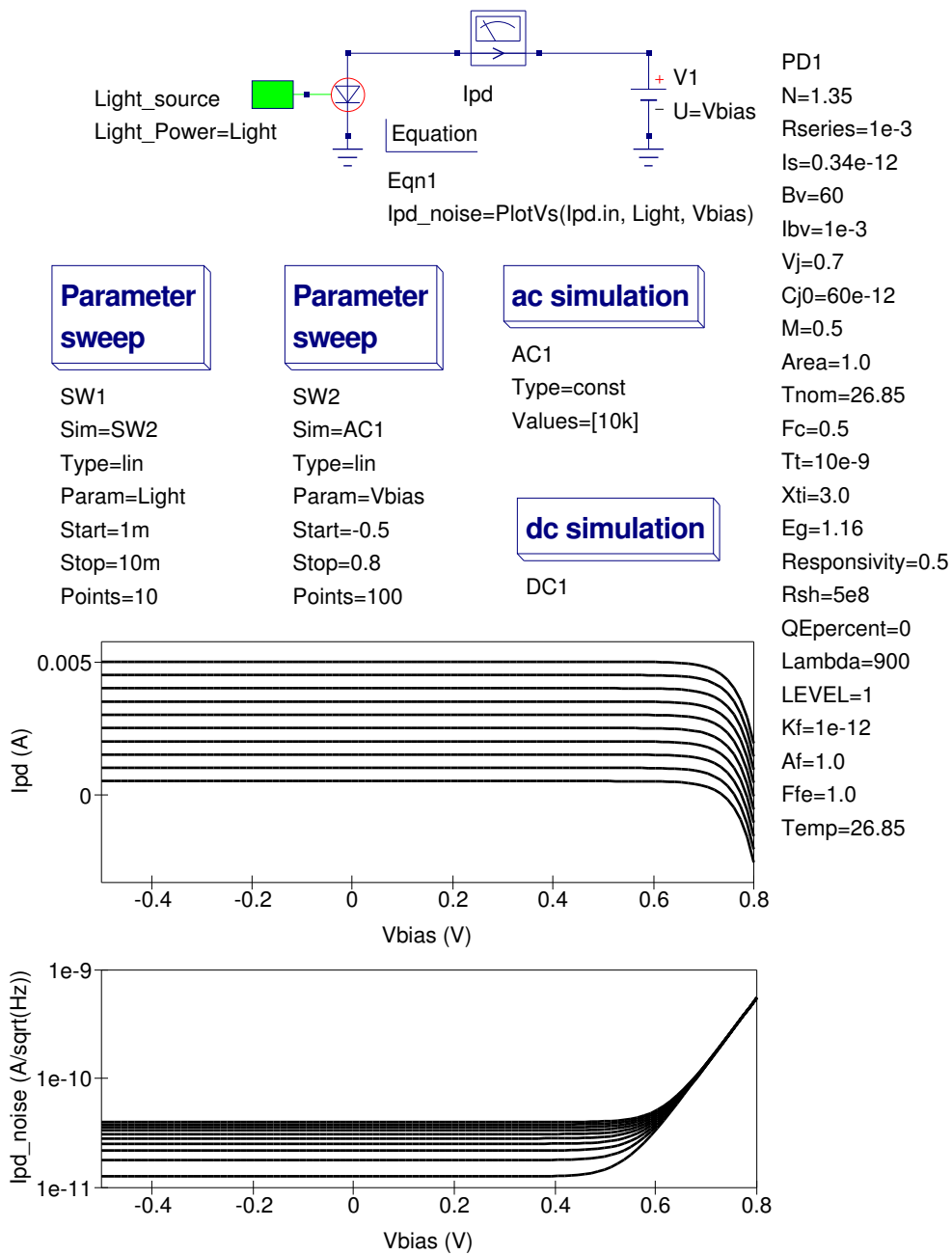Kf=1e-12
Af=1.0
Ffe=1.0
Temp=26.85

Figure 5: Photodiode noise test circuit and simulated noise characteristics

# End Note

Optoelectronic devices are an important group of electronic components and as such deserve more attention than has been given to them in the past by the Qucs development team. This situation should improve over the coming year. The pn junction photodiode model is the first in a planned series of optoelectronic models, including models for transimpedance amplifiers, optical actuators and optical media. Given time it should be possible to significantly improve Qucs optoelectronic capabilities. The photodiode model reported here is an interesting model in that it is one of the first Verilog-A models to fully utilize the recent changes to the ADMS/Qucs interface which allow proper initialisation of model parameters. A new procedure for combining Verilog-A generated models also introduces for the first time the initial stages towards a fully modularized approach to linking complex models with the main body of the Qucs code. Once again my thanks to Stefan Jahn for all his encouragement and help during the period I worked on the photodiode model.