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Computational Modeling of Nonlinearity in a PIN Photodetector

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Photodetector nonlinearity plays an important role in limiting the overall performance of RF-photonic links [1]. There are numerous potential sources of nonlinearity in photodetectors, including the electric field dependence of the carrier velocity, external loading, nonlinear capacitance, impact ionization, and the Franz-Keldysh effect [2]–[4].

Determining which mechanisms limit the performance can be difficult experimentally, and simulation can play a valuable role in sorting that out. Since geometric effects are often important, it is useful in many cases to keep at least two dimensions in the simulation, instead of just one as is the case in many photodetector simulations [2], [5].

In this work, we use a variant of the drift-diffusion equations to investigate nonlinearity of a cylindrical *p-i-n* heterojunction photodetector made from InP and InGaAs [2]. Earlier work has shown that this model can accurately reproduce the principal features of experiments even with simple one-dimensional (1D) simulations if the effective radius of the current flow is properly chosen [2]. An advantage of the cylindrically symmetric two-dimensional (2D) simulations that we present here is that there is no need to assume an effective radius.

Device Structure and Model

The device is composed of a highly-doped transparent *n*-InP substrate of length $w_{\mathrm{n}} = 0.1\ \mu$m ($N_A = 2\times10^{17}$ cm^{-3}), an intrinsic layer of *n*-InGaAs of length $w_{\mathrm{i}} = 0.95\ \mu$m ($N_B = 5 \times 10^{15}$ cm^{-3}), and a degenerately doped *p*-InGaAs of length $w_{\mathrm{p}} = 1\ \mu$m ($N_D = 7 \times 10^{18}$ cm^{-3}). The total length of the photodetector is W = 2.05 μm. The diameter of the device is 30 μm. The structure of the device is described in [2], [6]. In the simulation, we set $N_A = 2 \times 10^{17}$ cm^{-3}, $N_D = 2 \times 10^{18}$ cm^{-3}, $N_B = 5 \times 10^{15}$ cm^{-3}. The incident light is assumed to pass through an aperture on the n-side ohmic contact of the device.

The drift-diffusion equations that we use may be written as

$$\frac{\partial n}{\partial t} = G_{\mathrm{opt}} + G_{\mathrm{ii}} - R(n,p) + \frac{\nabla \cdot \mathbf{J}_n}{q},$$
$$\frac{\partial p}{\partial t} = G_{\mathrm{opt}} + G_{\mathrm{ii}} - R(n,p) - \frac{\nabla \cdot \mathbf{J}_p}{q},$$
$$\nabla \cdot \boldsymbol{E} = \frac{q}{\epsilon}\left(N_D^+ + p - n - N_A^-\right),$$

where q is the unit of charge (here positive), while n and p are the electron and hole densities, and N_D^+ and N_A^- are the ionized donor and acceptor doping density in the crystal. The parameters G_{opt}, G_{ii}, and R denote respectively the optical generation, generation due to impact ionization, and the recombination rate due to the Shockley-Read-Hall (SRH) effect. The parameter ϵ is the permittivity of the semiconductor material. The variables $\mathbf{J}_n$ and $\mathbf{J}_p$ are the current densities for the electrons and holes. Assuming that there are no reflections, the generation rate as a function of position in the device is expressed as

$$G_{opt}(r,z,t) = G_0(r,t)\exp\left[-\alpha\left(w_p + w_i - z\right)\right],$$

where α is the absorption coefficient in the InGaAs. For the harmonic analysis, G_0(r, t) is a time harmonic function. We will assume that the beam is a Gaussian with a shape given by

$$G_0(r,t) = G_0(t)\exp\left[-2\left(\frac{r}{r_0}\right)^2\right],$$

where G_0(t) is the time-dependent generation rate, r_0 is the spot size of the light.

The impact ionization generation rate is defined as

$$G_{ii} = \alpha_n \frac{|\mathbf{J}_n|}{q} + \alpha_p \frac{|\mathbf{J}_p|}{q},$$

where α_n and α_p are the impact ionization coefficients of electrons and holes [7], respectively.

Simulation Results and Conclusion

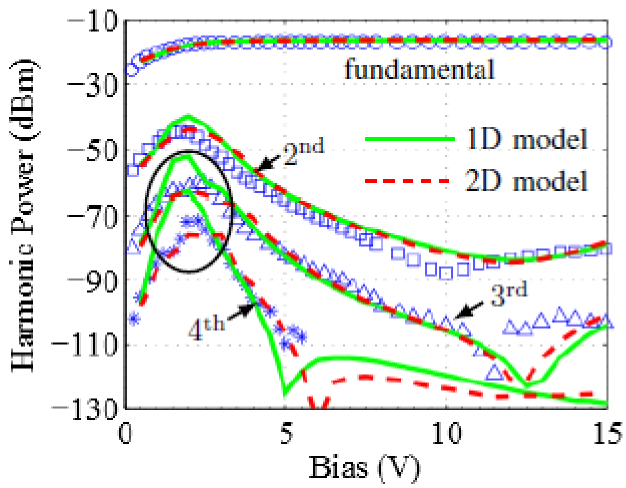

Figure 1 Measured (symbols) and calculated harmonic power. The red dash and green solid curves represent the results of the 1D and 2D models, respectively. The light diameter in the 1D model is 8 μm, and r_0 = 4 μm in the 2D model. The oval surrounds the portion of the 3rd and 4th harmonics in which the 1D and 2D simulations differ significantly.

The 1D model and 2D model are compared in Fig. 2. We see that both the 1D and 2D models agree qualitatively with the experimental data. The harmonic power first increases, then decreases, and finally stays the same or even increases a little as the reverse bias voltage increases. The 1D model disagrees quantitatively with the 2D model and experiments at low reverse biases. The 1D model predicts third and fourth harmonic powers that are too large. This discrepancy occurs because the 1D model assumes that the optical generation rate is constant and neglects the radial motion of the charges. The radial motion is particularly important at low reverse biases because the longitudinal motion becomes small enough that the radial motion can significantly affect the overall motion.

We have developed one-dimensional and two-dimensional simulation models of a cylindrically symmetric *p-i-n* photodetector, and we have used them to study the nonlinearity in the photodetector. We find that both models agree well with the experimental data when the reverse bias is large, but the 1D model overestimates the harmonic power when the reverse bias is small. To achieve good agreement with experiments at all biases, we have found that it is necessary to do 2D simulations.

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