Temperature-dependent Photon Detection Efficiency model for InGaAs/InP SPAD

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***Abstract*— We present a comprehensive model to estimate photon detection efficiency (PDE) of InGaAs/InP single photon avalanche diodes (SPADs) through bidimensional simulations, including the temperature dependence of both optical and electrical properties, aimed at assisting the design of enhanced-PDE detectors.**

***Keywords*— InGaAs/InP, Single-Photon Avalanche Diode, SPAD, TCAD simulation, Photon Detection Efficiency, Photon Counting**

I. Introduction

InGaAs/InP single-photon avalanche diodes (SPADs) [1] are among the best performing sensors for single-photon detection in the near-infrared (NIR) wavelength range, a common ground for many quantum information applications [2] and other technologies, such as eye-safe light LiDAR [3]. The separate absorption, grading, and multiplication (SAGM) heterostructure of the detector is finely tailored, with the aid of TCAD simulations, to confine carrier multiplication within the high energy-gap InP multiplication layer [4] thus reducing Dark Count Rate (DCR) ensuing from high electric field. However, there are no complete simulation models to estimate the PDE of an InGaAs/InP SPAD at low temperature. Here, we present the first comprehensive and reliable model to compute such PDE at different temperature and bias conditions, over the entire wavelength range of interest. Our model is a powerful tool to support the design of next-generation high efficiency InGaAs/InP SPADs.

II. Methods

In our model, we compute the PDE as the product of: i) the probability that a photon at a given wavelength is absorbed inside the device (P_{abs}); ii) the probability that a free carrier triggers an avalanche (P_{ava}).

A. *Photon absorption probability*

As an example, the absorbed photon density of a front-illuminated SPAD at 1550 nm, resulting from a finite-difference time-domain (FDTD) optical simulation performed with Synopsis Sentaurus, is reported in Fig. 1 (top). The P_{abs} is computed as the absorbed photon density normalized by the impinging optical power. The complex refractive indexes ($n^* = n + jk$) of $In_{0.53}Ga_{0.47}As$ and InP at room temperature are available in the literature [5],[6]. To simulate P_{abs} at typical operational temperatures (200 K ~ 230 K), we considered the measurements of the absorption coefficient ($\alpha = 4\pi \cdot k/\lambda$) of InP and InGaAs around their cut-off

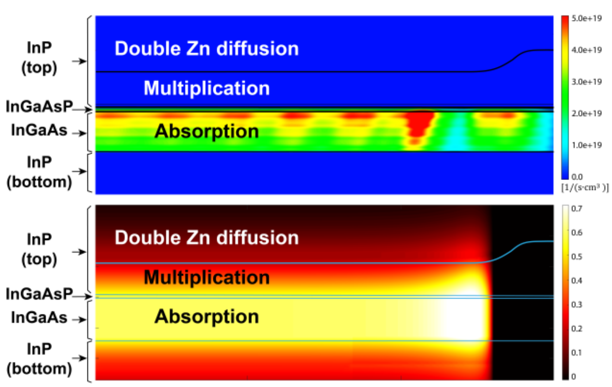

Fig. 1. Top: bidimensional distribution of absorbed photon density at $\lambda = 1550$ nm with 1 mW/cm^2 illumination. Bottom: avalanche triggering probability at 225 K with $V_{EX} = 5$ V, including the triggering probability of carriers diffusing from low electric field regions (i.e.: from Zn diffusion region and from InP bottom layer).

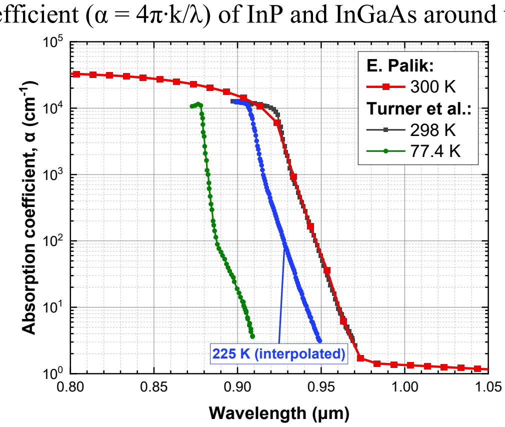

Fig. 2. Starting from complete room temperature values of the InP absorption coefficient and from partial values at low temperatures, the temperature dependence of the InP absorption coefficient is estimated. The same approach was used for InGaAs. The cutoff at the temperature of interest (225 K in this figure) is estimated by interpolating the data reported in [7], and then the full spectrum of α is updated.

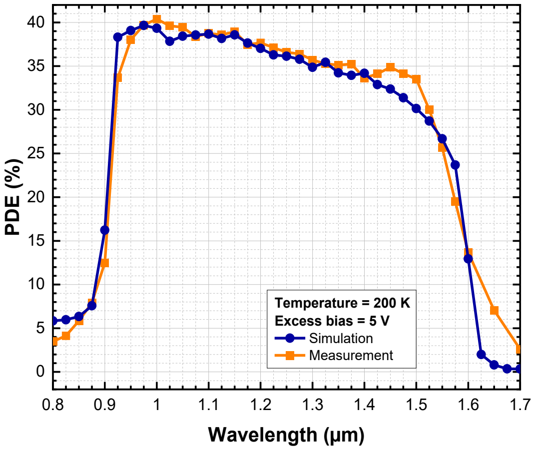

Fig. 3. Comparison between the PDE at 200 K of a SPAD illuminated at different wavelengths, obtained from experimental measurement (blue line), and our simulation (orange line). Despite some minor discrepancies, the PDE model successfully predicts the main trends and critical values of the measured PDE.

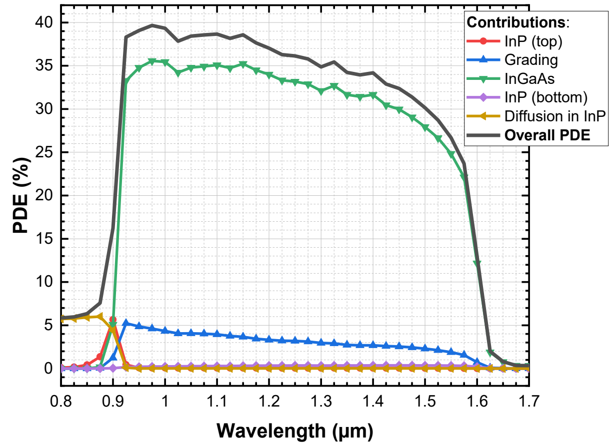

Fig. 4. PDE curve estimated using our model (black line) split into the individual contributions from each region: the diffusion from the top InP region is dominant at short wavelengths; the central part of the curve is mainly due to photons absorbed in the InGaAs absorption layer, as expected; the quaternary InGaAsP grading layer contribute to roughly 10% of the final curve for the central wavelengths.

wavelength at different temperatures, presented in [7] and [8], respectively. Since the effect of temperature variations on the absorption coefficient spectrum is effectively represented by a horizontal shift of the cut-off wavelength of α, we used these data to adjust the wavelength dependence of α at different temperatures, as shown in Fig. 2.

B. Avalanche triggering probability

Exploiting Synopsys Sentaurus simulator, we calculated the probability that a carrier, photogenerated in the depleted region, may trigger a self-sustaining avalanche, when the device is biased at a given excess bias (V_{EX}) above its breakdown voltage. Additionally, short-wavelength photons can also be absorbed in the top InP quasi-neutral region: such photogenerated carriers might diffuse towards the multiplication region and trigger an avalanche as well. Starting from the InP minority carrier lifetime values reported in [9], we implemented a custom algorithm for estimating the diffusion contribution to PDE. An example of the avalanche triggering probability distribution inside a SPAD biased at V_{EX} = 5 V at 225 K is shown in Fig. 1 (bottom).

C. Photon Detection Efficiency

The photon detection efficiency is calculated as a normalized surface integral of the product $P_{abs}{\cdot}P_{ava}$ in each point of the device. Fig. 3 shows a comparison between simulated and measured PDE as a function of wavelength performed on the SPAD described in [1]. The simulation result is in good agreement with the experimental measurement, accurately representing the main trends of the spectrum. In Fig. 4, we highlight the main contributions to PDE: at short wavelengths (below 900 nm), carrier diffusion is dominant; between 900 nm and 1600 nm, absorption and grading layers provide the main contributions.

III. Conclusions

We developed the first comprehensive model for the estimation of the photon detection efficiency of InGaAs/InP SPAD detectors at different temperatures and wavelengths. Our model relies on experimental data taken from the literature and shows excellent agreement with measured values.

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