Photoresponse uniformity in planar InP/InGaAs avalanche photodiodes

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***Abstract*— Numerical simulation of the electric field distribution and photocurrent response of a planar InP/InGaAs avalanche photodiode is presented as a function of varying multiplication width. The Zn dopant diffusion front is obtained by numerically simulating the diffusion process. The simulation results indicate that while a local peak value of the electric field is observed near the device edge, it is not associated with a significant increase in the photocurrent response.**

Keywords—Avalanche photodetector, breakdown, numerical simulation, multiplication width, InP, InGaAs

I. Introduction

Planar InP/InGaAs avalanche photodiodes (APDs) are in wide use in linear mode in optical communication systems and for single photon detection, when operated in Geiger mode. A key design consideration is suppression of the edge breakdown effect, which leads to a lowering of the breakdown voltage and non-uniformity of the detector response both in linear mode [1] and in Geiger mode [2]. Experimental characterization of edge breakdown effects typically relies on raster scanning of the detector response in one or two dimensions with a focused beam [1-2]. Previous investigations using numerical simulation have revealed localized enhancement of the electric field near the device edge due to the junction curvature [3-4], but did not simulate the photocurrent response specifically. The observed enhancement of the photocurrent at the device edge has been generally attributed to the junction curvature effect in previous works [1-2]. However, we have recently shown experimentally that areas of enhanced photocurrent response are associated with increased Zn diffusion depth at the device edge in certain cases [5]. In this work, the electric field distribution and photocurrent distribution are simulated numerically for an InP/InGaAs avalanche photodiode without guard rings and with a single-step diffusion. The Zn dopant in-diffusion is simulated numerically in order to generate realistic values for the junction curvature and the dopant concentration gradient near the junction. The contributions of the junction curvature effect and possible diffusion depth variations across the active area are evaluated by comparing simulations with different values of the multiplication width (MW).

II. Numerical Model

A. Process Simulation

The epitaxial structure of the APD consists of a separate absorption, grading, charge sheet and multiplication (SAGCM) configuration similar to [4-5]. The simulated device radius is 30 microns with a Zn diffusion aperture of 15 microns, with a single diffusion and no guard rings; the simulation assumes cylindrical coordinates. Three multiplication widths are explored: 1.0, 1.05 and 1.1 microns. Note that the InP cap thickness is varied between 3.0 and 3.1 µm to maintain a constant diffusion depth for each MW explored; this ensures consistent edge field enhancement due to the curvature of the Zn diffusion front. The Athena module (v5.22.1.R) of Silvaco (Santa Clara, CA, USA) is adopted to simulate the diffusion of Zn through a SiN mask into the epitaxial structure. Note the edge of the Zn diffusion is ~50 nm shallower than the center in this diffusion model; in other words, there is no depth enhancement at the edges of the diffusion.

B. Device Simulation

Prior to device simulation using the Atlas module (v5.23.12.C), the DevEdit tool is used to refine the mesh according to the dopant diffusion profile. This improves numerical accuracy of the electric field near the edge of the diffusion profile. The Atlas simulation solves the partial differential equations that model semiconductor drift and diffusion. Recombination rates are modeled using radiative, Shockley-Read-Hall and Auger recombination, whereas the generation rate via impact ionization is modeled using the Zappa model for InP [6]. Carrier mobilities are modeled using the dopant dependent carrier mobilities from Sotoodeh [7]. Also included is a surface leakage mechanism enabled through traps at the InP/SiN interface to mimic experimental leakage currents.

III. Simulation Results

A. Electric Field Near Breakdown

The electric field of the structures corresponding to a MW=1 µm is illustrated in Fig. 1 for $V = 0.99 \times V_{BR}$, where V_{BR} is the breakdown voltage defined as the voltage when the dark current (I_D) reaches 10 µA. An enhancement of the electric field is observed where the junction curvature begins at the edge of the diffusion aperture, with a peak field magnitude that is 2.7% higher than the maximum value in the centre.

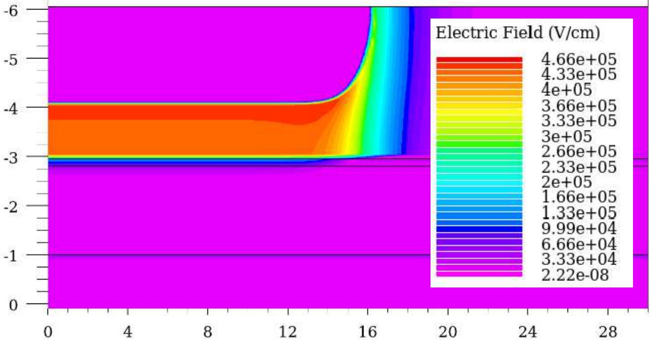

Fig. 1. Circularly symmetric APD simulation: Electric field strength plot at $V=0.99 \times V_{BR}$ breakdown.

Fig. 2 illustrates the electric field as a function of depth at the center and edge of the device at V = -50 V (~98% V_{BR}), which highlights the aforementioned peak electric field at the device edge. However, the integrated electric field across the MW is lower at the edge than at the center by ~3.6%. Note that the MW is effectively wider at 13 µm by ~20 nm.

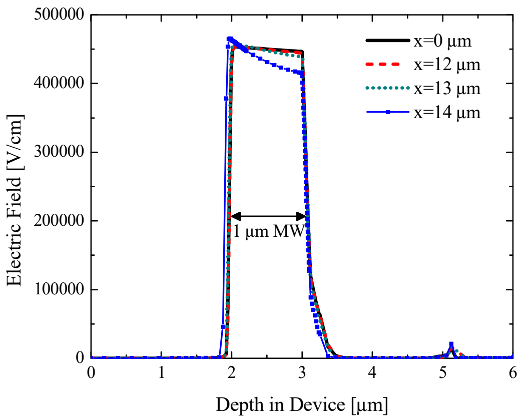

Fig. 2. Electric field as a function of depth at the center and near the edge (x=12, 13 & 14 um) of the diffusion aperture corresponding to V = -50 V.

B. Current – Voltage Simulation

The device is simulated both in the dark and illuminated by a beam that is scanned across the device. Due to the cylindrical coordinates, the beam width is reduced as a function of position to maintain a constant generation profile. A beam wavelength of 1.55 µm is used with an incident power of 5×10^{-2} W/cm^2. Fig. 3 illustrates the simulated current – voltage (*I-V*) of all three structures to compare the dark *I-V* and the light *I-V* corresponding to the centre beam. The primary impact of the increased MW is the larger breakdown voltage of ~1.8 V per 50 nm. The punch-through voltage has a similar trend for increasing MW.

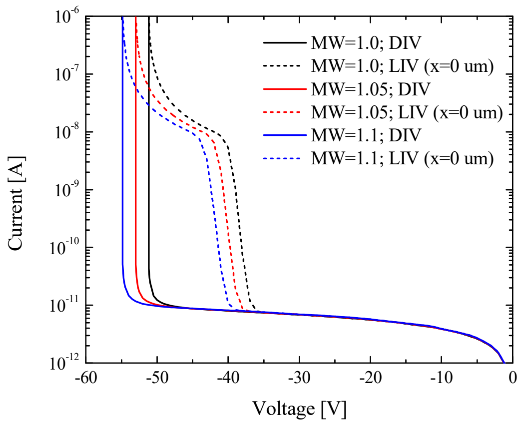

Fig. 3. Simulated dark and illuminated current-voltage curves with the illuminating beam incident at the center and edge of the diffusion aperture.

The photocurrent for V = -50 V is illustrated in Fig. 4 for the three MW values as a function of beam position. Beyond a beam position of ~ 12 µm, the photocurrent drops sharply, consistent with the expected reduction in gain for the lower average field values in this region noted above. It is worth noting that no increase in photocurrent occurs at the position $x = 14$ µm, where the local peak in the electric field magnitude occurs, as shown in Figs. 1 and 2. This is due to the gain being determined by the integrated, rather than peak, value of the electric field. The simulation results suggest that for reasonably large values of the diffusion depth, as typically used and as simulated here, the electric field enhancement due to the junction curvature is likely not the origin of observed photocurrent response increases near the edge, as reported for example in [1-2].

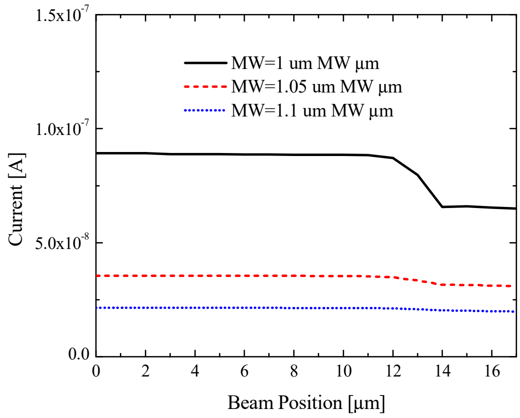

Fig. 4. Simulated photocurrent as a function of beam position corresponding to V = -50 V and for all three MW devices.

Rather, for a fixed bias near the breakdown voltage, a fairly small change in the multiplication width can strongly enhance the photocurrent. For example, assuming a target MW = 1.05 µm, the photocurrent at V = -50 V is enhanced by 250% when the MW is reduced by only 50 nm. The simulation results are in qualitative agreement with the observation in [5] of enhanced photocurrent in areas of APD devices where the Zn diffusion is driven deeper at the edges.

IV. Conclusions

An avalanche photodiode structure with a single diffusion was simulated numerically. The maximum electric field obtained in the multiplication region at the edge is 2.7% higher than at the center. However, the model does not predict a higher photocurrent response at the device edge due to the junction curvature. Simulations performed with variations of the diffusion depth imply that a diffusion depth enhancement of 50 nm at the device edge would result in a photocurrent enhancement of 250% at a bias of V = -50 V.

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