Impact of Fabrication Variabilities on Performance of Avalanche Photodetectors

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I. INTRODUCTION

Avalanche photodetectors (APDs) are a crucial technology for detection of weak optical signals. These devices operate on internal gain, meaning only the device currents, including the optical signal, are amplified [1]. This allows high performance APDs to maximize their signal-to-noise ratio as long as the excess noise due to the amplification process remains low. In this work, we investigate how slight geometric changes to a device design due to variabilities in the fabrication process can affect the performance of an APD. The performance metrics considered are gain, excess noise factor, and bandwidth.

The mechanism behind gain in APDs is impact ionization (ImI), which refers to the generation of an electron-hole pair due to scattering between a high energy carrier and an electron in the valence band. In order for ImI to occur, the ionizing carrier must have an energy greater than the bandgap of the material, which means ImI requires high electric fields that will accelerate particles to the required energies. The ionization coefficient, which refers to the inverse of the mean free path between ionization events, increases exponentially with increasing electric field strength [1]. This means that carriers in an APD will mostly ionize in the highest field regions of an APD. Thus, the proper design of an APD requires appropriate geometries and doping profiles so that the resulting electric field profiles are conducive for maximum performance. Conversely, designs that result in extremely non-uniform electric field profiles may reduce performance and can be deleterious for the APD [2].

II. METHODOLOGY

Monte Carlo is a well-established method for accurate simulations of APDs due to its capability of simulating non-equilibrium transport and capturing effects that other simulation methods cannot, such as dead-space. Simulations are performed using the 3-D Monte Carlo code developed at Boston University [3]. The simple *p-i-n* diode geometry is shown in Figure 1, and has been used in previous works [2], [4], [5]. This design and was chosen for this work due the many degrees of freedom it provides, such as its pitch, bevel angle, and non-planarity of the layers. Each of these designs result in different electric field profiles within the device.

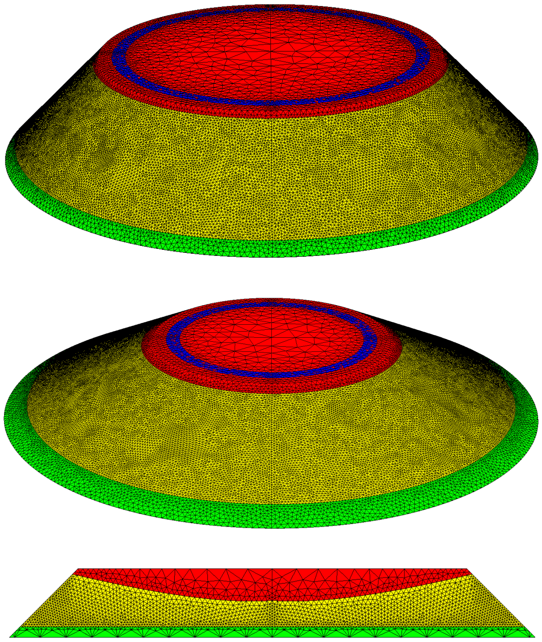

Fig. 1: Examples of varying geometries of a simple beveled diode. The bevel angle and instrinc region thicknesses are altered in the top and middle 3-D devices. The bottom device shows non-planarity of the p^+/n^- interface

The material chosen for this work is silicon due to its well-known material properties and widespread use as an APD material. Its bandstructure and scattering rates, including impact ionization, is computed through empirical pseudopotential (EPM) or density function theory (DFT) methods [3]. Relevant transport and ionization parameters used in this work are presented in Figure 2 and compared against experimental and other Monte Carlo values [6]–[8].

Gain, excess noise, and bandwidth of the APD is simulated by injecting electron hole pairs near the surface of the *p-i-n* diode, simulating the absorption of a photon. The position of the electron is sampled across the surface so that the spatial dependence of the performance metrics can be understood. This is intended to mimic the experimental procedure for spatial sampling of gain.

III. RESULTS

Sample results are shown in Figure 3. The computed electric field profile for a 35V bias of the mesa with the 45 degree bevel angle and 1.5 μm thick intrinsic region shows electric

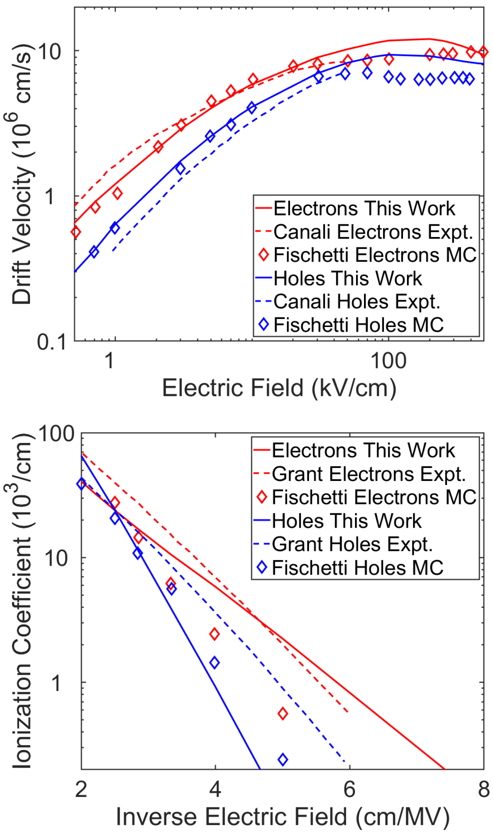

Fig. 2: Saturation velocity and impact ionization coefficients obtained from full-band calculations of silicon

field crowing at the top corners of the device. The electric field vectors presented in the same figure show the expected trajectory of electrons and holes absorbed within the device. The peak electric field magnitude of 500 kV/cm in the device corresponds to a regime where the ionization coefficient ratio (k-ratio) is nearly 1, which promotes high gain, but also induces high multiplication noise and reduced bandwidth. The k-ratio decreases dramatically in the lower field regions of the device.

To compute a gain profile, electron-hole pairs are injected along the top surface of the APD. For the cylindrically symmetric device shown, a 1-D sample was taken in one radial direction. The resulting gain profile is shown in Figure 4, and shows the highest gain occurs when carriers are injected on the mesa sidewall and at the peak electric field region. This exercise is repeated for excess noise factor and bandwidth and for varied geometries and biases and absorption depths.

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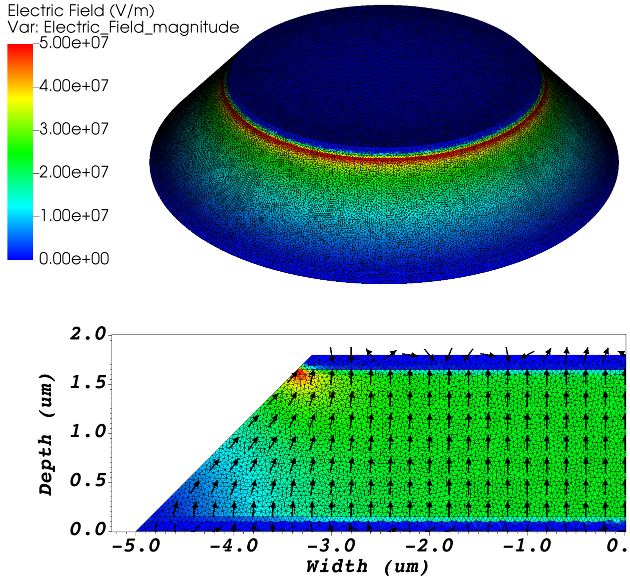

Fig. 3: Electric field profile computed with FBMC3D at 35V. Top panel shows the electric field on the 3-D device. Bottom panel shows a cross-section of the 3-D device with electric field vectors.

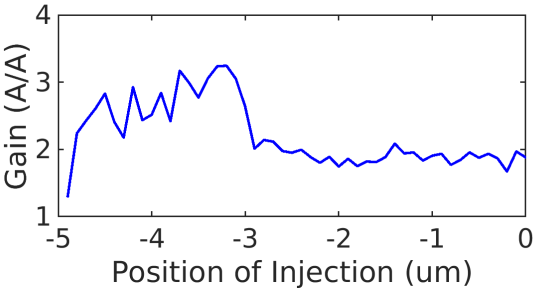

Fig. 4: Gain of electron-hole pairs injected along the top surface of the device

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