electron and hole are created in the Γ valley and heavy hole respectively [15].

The Cloud-In-Cell (CIC) scheme and successive linear over relaxation (SLOR) method are employed for charge assignment and solution of the Poisson equation, respectively. In our simulation, potential distribution is updated every 20fs [13].

To calculate the impact ionization coefficients, we inject a carrier to the multiplication region with an applied electric field. Due to electric force, it moves (drifts) and scatters consecutively until II is occurred. Trajectory of carrier and distance of between two ionization events (ionization length) are recorded. We progress this process for 10^4 injected carriers and calculate the mean of ionization lengths. For the applied electric field, impact ionization coefficient is defined to inverse of this mean.

Also, we enter an initial carrier to the multiplication region and follow trajectory of the carrier and generated carriers until they exit from the multiplication region. Total number of the exited carriers is assumed as the multiplication number. We repeat this process for 10^4 initial carriers and define the mean of the multiplication numbers as the multiplication factor.

Breakdown phenomenon is occurred when the number of carriers is increased to infinity. In our MC model, we assume this case as the avalanche breakdown. For an applied reverse bias, we enter an initial carrier to the multiplication region and calculate the multiplication number. Uniformly, the reverse voltage is increased with a 0.1V step until the multiplication number is limited to infinite. The final voltage is known as the breakdown voltage.

III. Results

According to the MC model, Fig. 1 compares our simulated ionization coefficients for electron (α) and hole (β) with results obtained from experiment [6]. Symbols and lines present MC simulation and experimental results respectively.

Fig. 1 shows our calculations are good agreement with experimental results [6]. One can see the higher electric field results in more ionization coefficients. Drift mechanism increases the carrier energy while the scattering mechanism decreases it usually. Electric field dominates the first mechanism effect and causes the mean energy of carrier increases with electric field monotonically. This issue reduces the mean ionization length, hence, increases the ionization coefficients.

The model is capable of presenting the microscopic view of the device. For example, the distribution of ionization length for both electrons and holes with electric fields 700 and 900 $kV.cm^{-1}$ are shown in Fig.2.

One can see the decreasing of electric field broadens the distribution of ionization length. The high electric field results in shrinkage of the distributions. In Fig.2, the mean ionization lengths are given as the Table I.

Using the MC model, we simulate a fabricated InAlAs APD and calculate the multiplication factor (*M*) for electron and hole initiated multiplication regimes with different multiplication lengths *w*=100 and 200nm. Fig. 3 compares our calculated results with the experimental results [6].

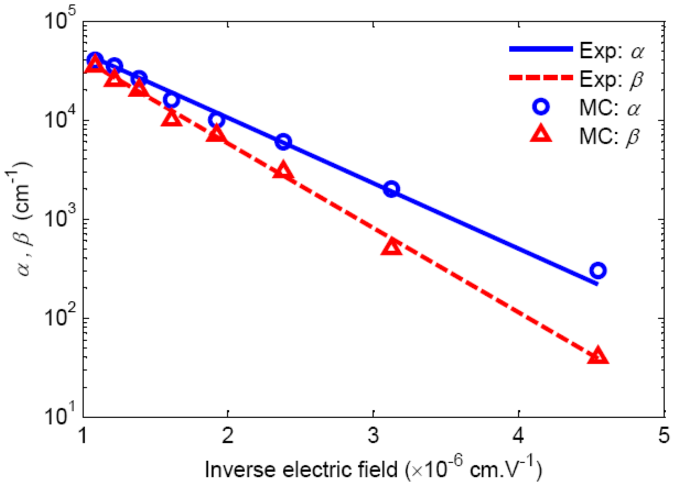
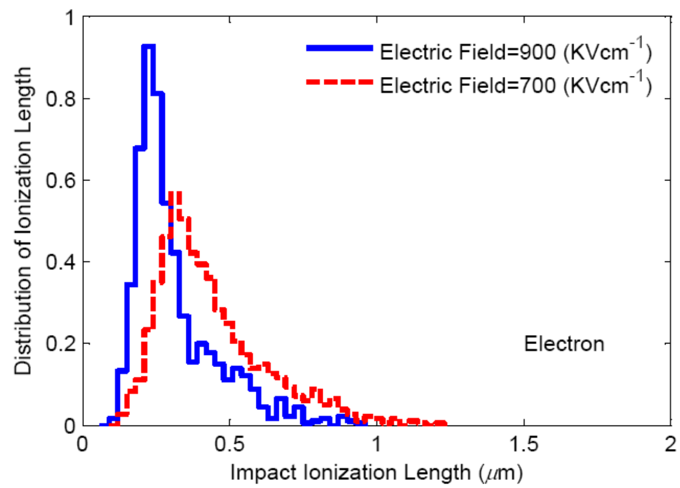
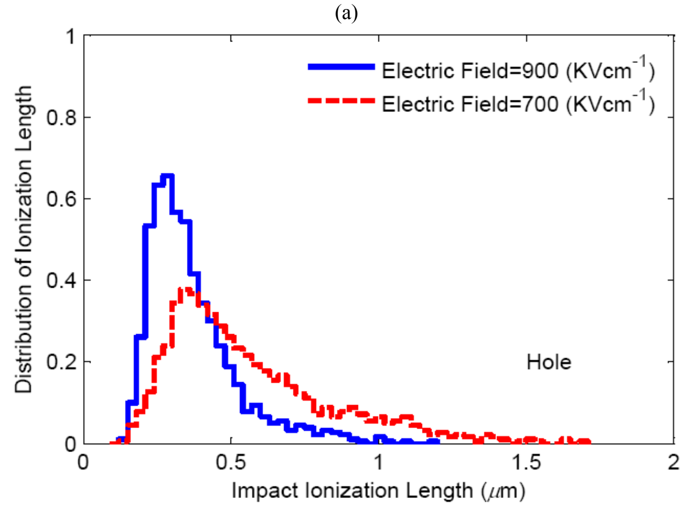


Fig.1. Calculated ionization coefficients for electron (open circle) and hole (open triangle) versus inverse electric field. Lines present experimental results [6].



(a)

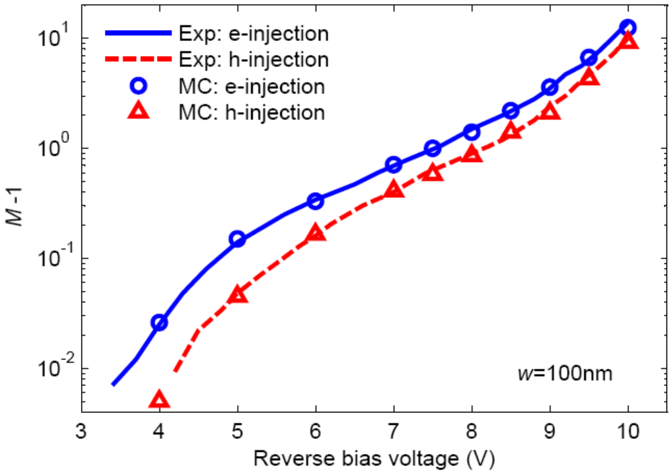


(b)

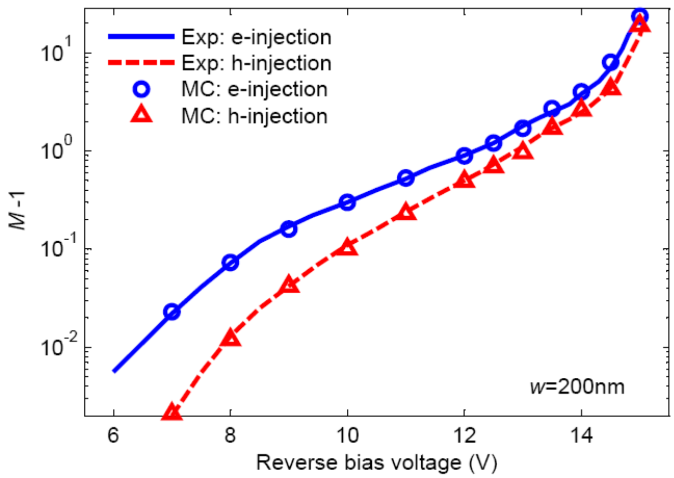
Fig.2. Calculated distribution of ionization length for (a) electron and (b) hole with different electric fields 700 and 900 $kVcm^{-1}$.

TABLE I
CALCULATED MEAN IONIZATION LENGTH IN FIG.2

Electric Field (kV.cm^{-1})	Mean Ionization Length (×10^{-5} cm)	
	Electron	Hole
700	4.22	5.45
900	2.97	3.53



(a)



(b)

Fig.3. Calculated *M*-1 for electron (open circle) and hole (open triangle) injection with *w*=100nm (a) and 200nm (b). Lines are measured results [6].

As the reverse bias is stronger, the electric field in multiplication region is higher too. Consequently, the probability of ionization events is increased and more electron-hole pairs are generated. This issue means the total number of carriers is increased via ionization events. Now, one can see the multiplication factor (or gain) is directly related to reverse voltage (see Fig.3).

The type of carrier that initiates multiplication process is a main issue for APDs, because it can reduce excess noise in photodetection. Therefore, one selects a type of carrier to initiate multiplication that has more ionization coefficient than another type. According to Fig.1, impact ionization coefficient for electron is more than hole in InAlAs. This causes the electron initiation case is preferred to hole initiation. At the same time, the electron initiation process results in more multiplication factor than another process for the same applied biases (see Fig.3).

Although increasing of the multiplication factor is desirable, the breakdown phenomenon restricts it. The breakdown is an important phenomenon that is occurred in high electric fields. Fig. 4 presents the MC simulated results for breakdown voltage (V_{bd}) and compares with the calculated results in [6].

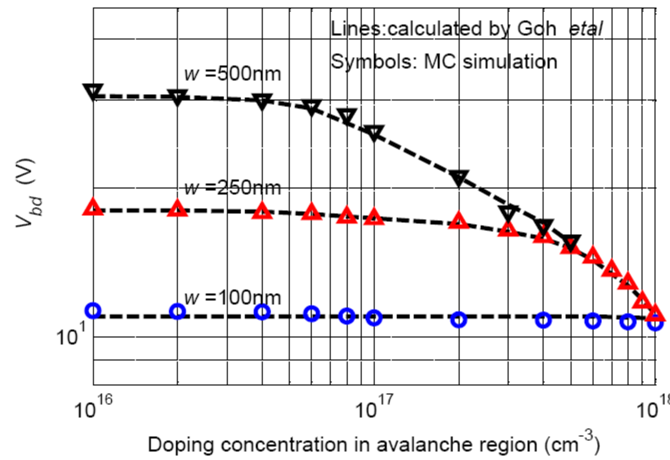


Fig.4. Breakdown voltage versus doping concentration in avalanche region with *w*=100, 250 and 500nm. Symbols and lines are our MC results and calculated results in [6] respectively.

In our calculations, breakdown event is occurred when the number of carriers is increased to infinitely.

Previous figures demonstrate the presented MC model is capable of calculating ionization coefficients (Fig.1) and multiplication factor (Fig.3) for InAlAs PIN-APDs. Also, it can predict the breakdown voltage (Fig.4).

We used a PC whose CPU and RAM were 3.2GHz and 2GB respectively. Also, we used the sparse matrixes and shortcut programs in MATLAB to reduce the simulation time. Although we included the mentioned issues, our calculations were time consuming. For example, Fig.1 was calculated in 138 minutes.

In this study, we experienced and used the MC method to simulate an InAlAs APD. Although this method is almost complex and takes a lot of time, we recommend this method to simulate semiconductor devices, because it gives a microscopic image of carriers in space and time domains. One can use the model to calculate different parameters such as excess noise factor, bandwidth and time response, and different materials for APDs. Also, one can extend this efficient model to simulate other structures for APD such as separate absorption, charge and multiplication region (SACM) avalanche photodiode.

IV. CONCLUSION

We presented a Monte Carlo model to simulate an InAlAs avalanche photodiode. The model involved two bands and valleys for holes and electrons respectively. Also, it included POP, non-POP, acoustic and impurity as the most important scattering mechanisms. The Keldysh approximation was assumed to ionization rate. Using the injection of carriers, we calculated the impact ionization coefficients, multiplication factor and breakdown voltage. Comparison of our results with experimental results confirmed the validity of our simulation. One can extend this model to different materials and structures for APDs.

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