Charge-Compensated High Gain InAs Avalanche Photodiodes

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***Abstract*—We report an InAs avalanche photodiode with graded p-doping to compensate the n-type background doping in the depletion region. The measured gain, excess noise, and bandwidth are consistent with Monte Carlo simulation.**

***Index Terms*—Avalanche photodiode, Monte Carlo simulation, excess noise, gain-bandwidth product.**

INTRODUCTION

Avalanche photodiodes (APDs) can improve receiver sensitivity and detect weak photon flux owing to their internal gain. They have been widely used in short-wave and mid-wave infrared detection systems, such as imaging, LIDAR detection, and communications. The low bandgap of $Hg_{0.7}Cd_{0.3}Te$ (~ 0.29 eV) renders it appropriate for long-wavelength applications. A particularly attractive feature of $Hg_{0.7}Cd_{0.3}Te$ is that the ionization coefficients ratio, k, is ~ 0 since only electrons can initiate impact ionization. Hence the excess noise factor is < 2 independent of gain. On the other hand, the low bandgap also results in relatively high dark current at room temperature. Recently, InAs APDs have been shown to exhibit the same k = 0 property and moderately low dark current has been demonstrated at room temperature [1]. InAs APDs with thick multiplication regions have also exhibited high gain at low bias [1], which is beneficial for integration with Readout-Integrated Circuits (ROICs). To design a high-gain InAs APD with a thick gain region, low background doping is essential in order to realize complete depletion and uniform electric field. In this paper, Monte Carlo simulation is employed to study the impact ionization properties of InAs APDs. The simulated results agree well with experimental data obtained on an InAs APD with a 6 µm-thick charge compensated gain region.

MONTE CARLO SIMULATION AND MEASUREMENT

The Monte Carlo simulation in this work is similar to the model in [2,3]. The scattering parameters were determined by simulating the p-i-n structures with different i-region thicknesses that are grown and measured inreported in Ref. [1]. Pure electron injection is assumed for simulation with i-region thicknesses of 0.9 µm, 1.9 µm, and 3.5 µm. Simulated gain and excess noise factor agree quite well with experimental data for all three thicknesses, as shown in Fig. 1(a). The excess noise simulations (Fig. 1(b)) are consistent with previous measurements on InAs APDs. By calculating the occupancy percentage of electrons and holes in different valleys of the band structure, we find that a significant fraction of electrons populate the satellite valleys (L and X valleys) at low gain, which implies indicates that electrons in InAs can gain energy very fast and initiate inter-valley scattering or impact ionization. While for holes, most of them will stayOn the other hand few holes occupy states outside thein heavy hole valance band and their energy get increases marginally even at high electric fields. It follows that the ionization coefficient for holes is much lower than that of electrons, therefore the k = 0 property is expected for InAs, which is consistent with the observation of very low excess noise in InAs APDs. Our simulations also reveal that the gain is highest for the p-i-n structure with 3.5 µm i-region. We project that thicker i-regions and lower background doping will yield significantly higher gain. Therefore, in order to investigate the properties of InAs APDs experimentally, we have grown an InAs APD structure, shown in Fig. 2, with i-region as thick as 6 µm using molecular beam epitaxy. As shown in Fig. 2, the n-type background doping concentration inside i-region is demonstrated to be as low as $\sim 7\times10^{14}$ cm^{-3}. To increase the thickness of the depletion layer and achieve a relatively flat, uniform field profile in the multiplication layer, a graded p-doping was introduced in the first 2 µm of the depletion region to compensate the n-type background doping.

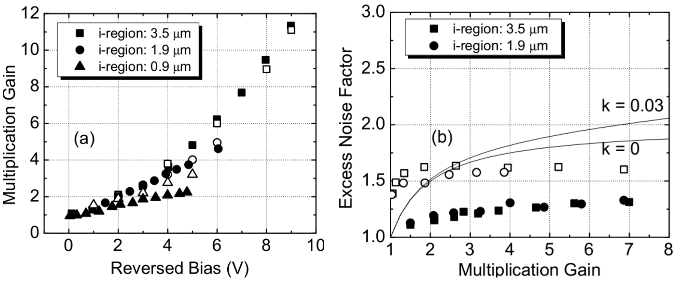

Figure 1. Measured in [1] (open symbol) and simulated (closed symbol) (a) gain and (b) excess noise factor of InAs p-i-n structures with i-region thicknesses of 0.9 µm, 1.9 µm, and 3.5 µm.

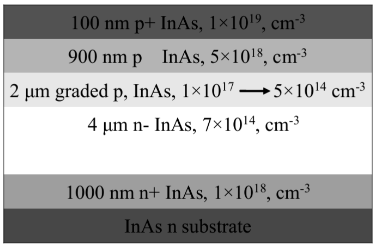

Figure 2. Layer structure of the p-i-n InAs APD with p-type graded doping inside i layer.

Figure 3 shows the measured dark current of a 100 µm-diameter InAs APD; the dark current is comparable to that reported in [5]. By measuring devices with different diameters, it was found that the dark current scales with the area, which attests to the efficacy of the SU-8 surface passivation that was employed. The gain and excess noise factor were measured using the set-up described in [4], Figure 4(a) shows the measured and Monte Carlo simulated gain of the charge compensated InAs APD. The gain increases exponentially with bias, showing no sign of breakdown, which is consistent with the k = 0 property of InAs. A gain of 100 was achieved at 10 V bias. In Ref. [6] 15 V was required to obtain the same gain, an indication of enhanced gain in the charge-compensated 6 µm depletion region. Figure 4(b) shows the measured and simulated excess noise factor. These results are consistent with a k value close to 0. The bandwidth was measured using a HP 20 GHz lightwave component analyzer. Figure 5 shows the measured bandwidth versus gain. The measured and simulated bandwidths are in the range 2 GHz to 3 GHz, which is consistent with gain-bandwidth measurements in [6]. The bandwidth of these APDs is limited by carrier transit time. Although this bandwidth may be too restrictive for telecommunication applications, it may be sufficient for imaging systems, where bandwidths of several GHz are widely used. More importantly, as demonstrated in Fig. 5, the bandwidth of the charge-compensated InAs APD does not decrease at higher gain, and very high gain-bandwidth product is expected due to the low k value for InAs.

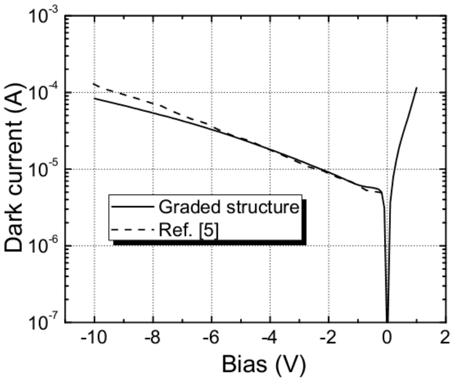

Figure 3. Measured dark current with 100 µm size for the Graded InAs APD structure, compared to data in [5].

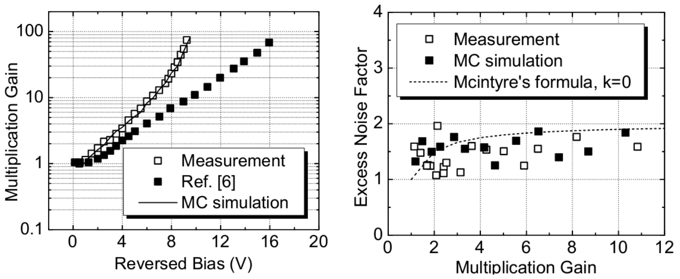

Figure 4. Measured and Simulated (left) gain of Graded InAs APD, compared to data in [6], and (right) excess noise factor.

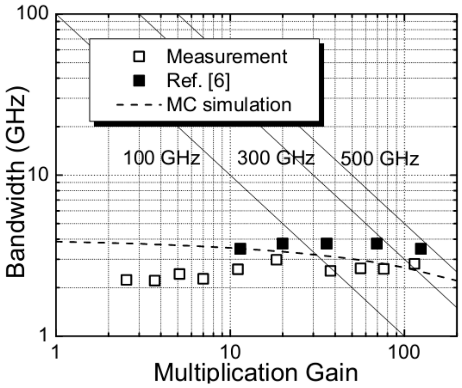

Figure 5. Measured and simulated bandwidth of the Graded InAs APD in this work, compared to data in Ref. [6].

CONCLUSION

In this paper, we report a charge-compensated InAs APD with 6 µm-thick multiplication region. Monte Carlo simulation tool for InAs APDs. These APDs exhibit low dark current and gain of 100 at room temperature and 10 V bias. The bandwidth is 2 to 3 GHz independent of gain. The performance has also been with a Monte Carlo model. Good agreement between measurements and simulations has been achieved.

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