High Speed Heterostructure Avalanche Photodiodes

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ABSTRACT

It has been shown recently that the noise and speed characteristics of avalanche photodiodes (APDs) can greatly benefit from the presence of moderate amounts of an initial energy stored in the injected carriers that initiate the avalanche multiplication process. The benefits range from reduced excess noise factor, increased abruptness in the breakdown probability, as well as an increase in the bandwidth. The key mechanism for the improved performance is the significant reduction of the first dead space in the ionization process. The dead space is the minimum distance a carrier must travel before acquiring sufficient kinetic energy enabling it to impact ionize. The reduction of the first dead space has the effect of localizing the first impact ionization and forcing it to occur quickly near the edge of the multiplication region. This, in turn, will have the effect of nearly inducing two avalanche processes which run in parallel and whose combination will yield the total gain. In this paper, a theoretical model for the avalanche multiplication is utilized to examine the fundamental limits of the gain-bandwidth product in light of the initial-energy effect in practical APD structures.

Keywords: Thin avalanche photodiodes, gain-bandwidth product, frequency response, impact ionization, dead space, ionization threshold energy, excess noise factor, heterostructure APDs, initial-energy effect.

1. INTRODUCTION

Avalanche photodiodes (APDs) are the detector of choice in many high-speed lightwave systems mainly due to their internal optoelectronic gain, which results in significant improvement in the receiver sensitivity in comparison to the traditional PIN-based receivers. The APD gain results from a cascade (or avalanche) of carrier impact ionizations in a high-field depletion region, called the APD's multiplication region. In fact, as long as their speeds can meet the required transmission rates (including 2.5 Gbps transmission), APDs can provide a cost-effective alternative to the costly PIN-based receiver modules that employ Erbium-doped optical amplifiers (EDFAs), which perform the optical pre-amplification necessary for boosting the otherwise poor performance of PIN photodetectors. However, the performance of APDs at ultra-high transmission speeds (i.e., 10 Gbps and beyond) is generally plagued by their limited bandwidth. This is due to their notorious and inherent avalanche buildup time, which is the time required for all the carrier impact ionizations to complete. Since the ionizations do not occur simultaneously (in fact they almost occur sequentially, due to what is known as the dead-space effect, in most modern thin APDs that are designed for high speed applications), the very avalanche multiplication gain that is sought to boost the photocurrent's signal-to-noise ratio limits the APD's operable speed. This is because the APD's impulse response, which is the response to a single photo-excitation event, is a stochastic process with a random shape (whose total area is proportional to the random gain) and random duration.[1] Generally, the duration of the impulse response, or the avalanche buildup time, increases with the gain. In many of today's state-of-the-art high-speed APDs,[2–5] the avalanche buildup time starts to dominate the RC effects at moderate gains (e.g., > 10). Unfortunately, the buildup time has limited the wide-spread utilization of APDs in 10 Gbps receivers to some extent and prohibited their use entirely in 40 Gbps lightwave systems.

In this paper, we will discuss some of the main factors that dominate the performance of APDs and show strategies for optimizing the performance that may possibly pave the way for their utility in ultrafast systems. The strategies described here will focus on the structure of the multiplication region of the APD. In particular, we will address the effect of the thickness of the APD's multiplication region, the dead-space effect, the so-called

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initial energy effect, and bandgap engineered heterostructures on enhancing the gain-bandwidth-product (GBP) characteristics and noise.

This paper is organized as follows. In Section 2 we describe some of the key factors that control the gain uncertainty and speed in modern APDs. In Section 3, we show the potential benefits of heterostructures and the initial-energy effect on the gain-bandwidth product. The conclusions are included in Section 4.

2. KEY FACTORS CONTROLLING THE NOISE AND SPEED IN APDS

2.1. Thickness of the Multiplication Region

By now it is evident that the excess noise factor (which is a measure of the gain fluctuations) and the avalanche buildup time can be simultaneously reduced by using APDs with thin (e.g., < 200) multiplication layers.[2–17] The reason for the reduction of the avalanche buildup time in thin APDs is relatively straightforward, as a reduction in the depletion width results in a reduced transit time per carrier, leading to a reduced overall buildup time. In contrast, the reason for the reduction of the excess noise factor is more subtle. This reduction is now known to be primarily due to the dead-space effect, which prohibits a carrier from immediately impact ionizing after its generation for a certain distance. As the thickness of the multiplication region is reduced, the dead space begins to occupy a larger fraction of the multiplication region's width.[10,12,13] At the same time, the dead space regularizes (or localizes) the locations of impact ionizations, as it inhibits ionization within a dead space of each new carrier generation.[18] The conventional avalanche multiplication model, first developed by McIntyre,[19] does not account for the dead-space effect, nor does it predict a reduction in the excess noise factor in thin APDs. The effect of dead space on the gain and excess noise factor has been extensively studied and more sophisticated multiplication models that take carrier history into account have been developed and tested against experimental measurements.[7–14,18,20–26]

As for the buildup time in thin APDs, recent advances in the design and fabrication of APDs have allowed these devices to achieve levels of gain-bandwidth products in excess of 300 GHz.[2,3,5] However, the difficulties for reliably and consistently producing ultrafast APDs is far from over. Moreover, due to the lack of efficient techniques for coupling the light into thin absorption layers, achieving acceptable levels low quantum efficiency has also been a challenge.

2.2. Heterostructure APDs and the Initial-Energy Effect

To further enhance the excess-noise characteristics of APDs beyond thin homojunction APDs, a number of bandgap-engineered heterostructure APDs[27,28] have been demonstrated exhibiting excess noise factors that are well below the predictions of the dead-space-inclusive multiplication models for thin homojunction APDs. For example, Yuan *et al.*[27] introduced APDs with an "impact-ionization-engineered" (or I^2E) multiplication region and showed a minimum excess noise factor of approximately 2.5 at a gain of 20. The corresponding APD had a multiplication region consisting of three layers: 50-nm-GaAs, 85-nm-$Al_{0.6}Ga_{0.4}As$, and 50-nm-GaAs layers. To see the extent of the noise reduction, we recall that theoretical models predict an excess noise factor of approximately 6.5 (at a gain of 20) for a 100-nm homojunction GaAs APD.[29] The idea is to sandwich a layer with a high ionization threshold energy, between two thin layers with a low ionization threshold energy. Low multiplication noise is achieved by means of localizing the location of impact ionizations as electron ionizations are forced to occur in one of the low-threshold layers while hole ionizations occur in the opposite low-threshold layer.[27] Other forms of I^2E APDs were subsequently introduced and demonstrated. The localization of impact ionization in I^2E structures has been recently confirmed by Monte-Carlo studies.[30,31]

Similar trends in noise reduction (beyond the traditional dead-space-based limit) was also attributed to a related mechanism called the initial-energy effect.[29,32] In certain structures (including certain I^2E structures), injected carriers enter the multiplication region with substantial kinetic energy. This energy buildup may occur, for example, when an injected carrier experiences a sharp electric-field gradient in the doped region just before the multiplication layer.[29] Figure 1 schematically depicts the initial-energy phenomenon. We next show the effect of the initial energy on the excess noise factor.

Figure 2 shows the prediction of the modified dead-space multiplication model (MDSMT)[29] of the excess noise factor for a GaAs APD with a 153-nm multiplication region. The MDSMT is a recursive technique

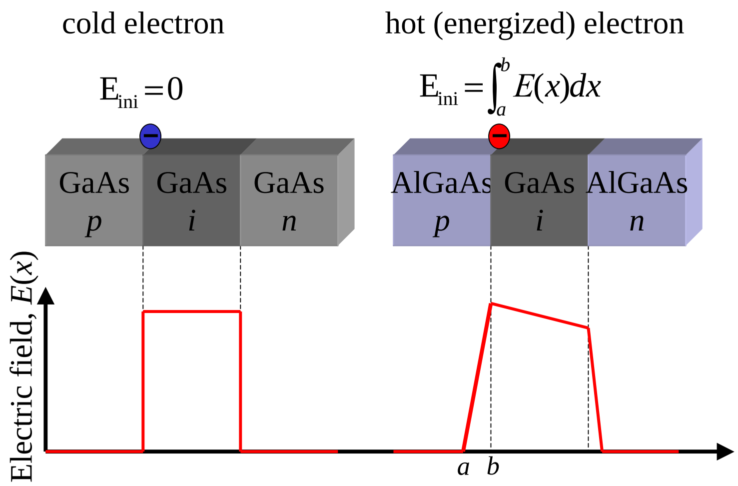

Figure 1. The device on the left does not exhibit the initial-energy effect since electrons are injected into the i multiplication layer without substantial energy (cold-electron injection). The device on the right exhibits a narrow high-field region (from a to b) where electrons can build up a substantial energy E_{ini} prior to entering the i layer. The electrons are therefore injected hot in the latter case.

similar to its predecessor, the DSMT,[18] but it allows specifying an arbitrary amount of initial energy for injected carriers. It is shown in the figure that when the injected electron's initial energy is $0.3E_{th}$, where E_{th} is the ionization threshold energy for GaAs (taken as 1.9 eV, according to Saleh *et al.*[8]), the best match with experimental measurement for this device is obtained.[28] (The fabrication and testing of all the device considered in this paper was performed at the Microelectronics Research Center at the University of Texas at Austin.) Since the actual initial energy is unknown in this case, we infer from the noise-versus-multiplication data and the theoretical predictions that $E_{ini} = 0.3E_{th}$. This value of the initial energy is realistic and has been observed in other devices (for example in Device II in Hayat *et al.*[29]). This figure clearly demonstrates the need for including the initial-energy effect in the multiplication model.

We also applied the MDSMT to an InAlAs APD (with a 200-nm multiplication region), which was fabricated and tested by Lenox *et al.*[3] The results of the MDSMT predictions of the excess noise factor are shown in Fig. 3. It is seen that with an initial energy of $E_{ini} = E_{th} = 2.15eV$ (according to Saleh *et al.*), good agreement with experiment is obtained.

2.3. Controlled Initial-Energy Effect in a Two-Layer Multiplication Region Heterostructure APD

Despite its appeal, the initial-energy effect, as described above, may not be a practical means for noise reduction. This is because it is difficult to precisely craft doping profiles that can precisely yield the desired electric-field profiles. As a result, the initial-energy effect may vary significantly from one sample to another, making reliable production of such low-noise APDs difficult. Fortunately, an alternate method has been recently proposed to bring about the initial-energy effect[30, 32, 37] without relying on the presence of a sharp field gradient in the doped region just before the multiplication region. The alternative technique relies on the use of a two-layer heterostructure multiplication region for which a high-field and high-bandgap intrinsic layer, called the energy-buildup layer, is dedicated to elevating the energy of carriers without incurring significant ionization within the layer itself. At the same time, an adjacent high-field and low-bandgap intrinsic layer is used to host the bulk of the impact ionizations. In this way, *energized* carriers are injected into the low-ionization-threshold layer with a high probability of ionizing at the boundary.[37]

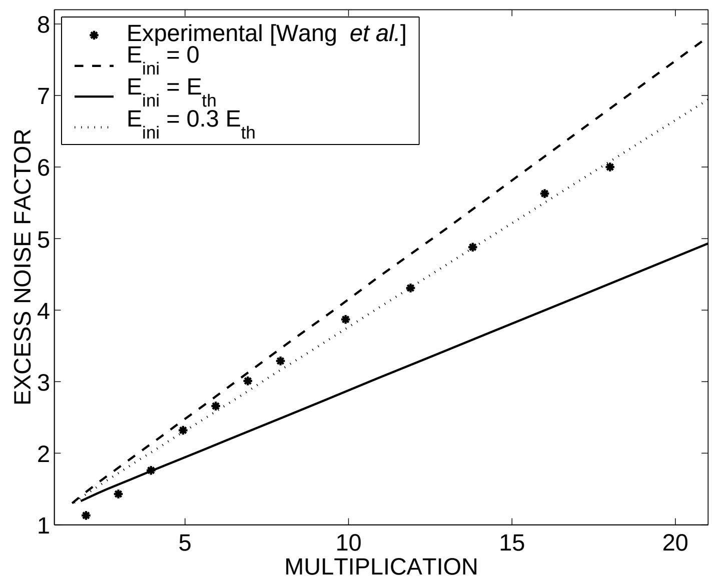

Figure 2. The calculated excess noise factor, as a function of the mean multiplication (gain), for a GaAs APD with a 153-nm multiplication layer. The calculations are parameterized by the initial energy for three cases: $E_{ini} = 0$, $E_{ini} = 0.3E_{th}$, and $E_{ini} = E_{th}$. The case $E_{ini} = 0.3E_{th}$ produces the best match with the experimental results (symbols) reported by Wang *et al.*[28]

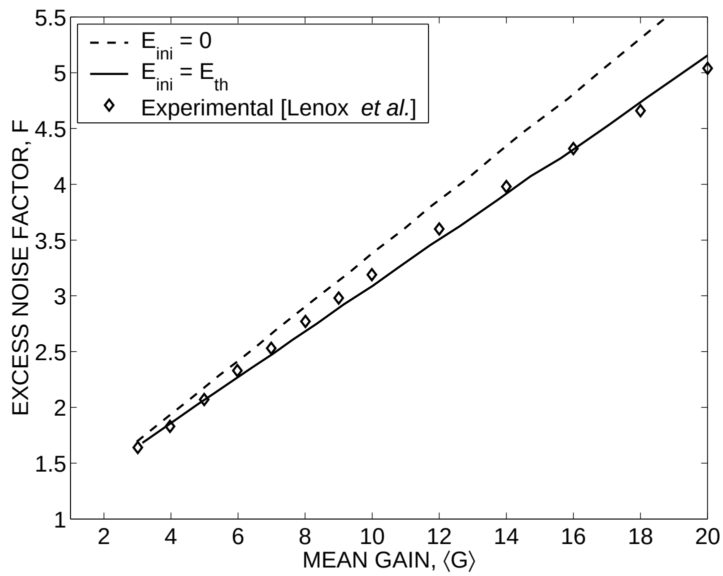

Figure 3. The calculated excess noise factor, as a function of the mean multiplication (gain), for a InAlAs APD with a 200-nm multiplication layer. The calculations are parameterized by the initial energy for two cases: $E_{ini} = 0$ and $E_{ini} = E_{th}$. The case $E_{ini} = E_{th}$ produces the best match with the experimental results (symbols) reported by Lenox *et al.*[3]

3. EFFECT OF THE INITIAL ENERGY ON THE GAIN-BANDWIDTH PRODUCT

As in the case of the excess noise factor, it turns out that the initial-energy effect has a positive impact on the GBP as well. [illegible] calculating the mean impulse [illegible] ılse response is shown in Fig. 4 [illegible] the ionization threshold energ[illegible] in the absence of initial energ[illegible]nt in the decay rate of the tail [illegible]cay rate of the

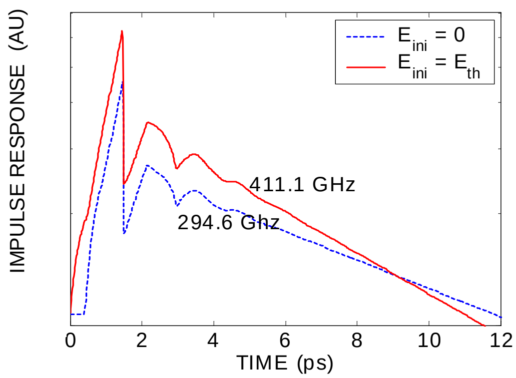

Figure 4. The calculated mean impulse response function of a GaAs APD with a 100-nm multiplication region. The solid curve represents the case when the initial energy of injected carriers is equal to the ionization energy and the dashed curve corresponds to the case where zero-initial energy is present. The mean gain in both cases is 10.

tail of the impulse response results in a n enhanced bandwidth, as shown by the frequency response in Fig. 5.

Figure 6 shows the calculated GBP as a function of the width of the multiplication region for homojunction GaAs APDs. For example, when the width of the multiplication region is 100 nm, the results show that an improvement in the GBP from 300 GHz up to 400 GHz may be possible if the initial energy effect is maximally exploited.

We also applied the modified recursive technique for the impulse response function to a waveguide APD developed by Kinsey *et al.*[5] First, we used the excess noise data[5] related to the waveguide APD and back calculated the amount of the initial energy. This was done by fitting the MDSMT model to the excess-noise versus mean gain data. The results are shown in Fig. 7. It is found that the best fit is obtained when $E_{ini} = 0.33E_{th}$. Now, we used the estimated initial energy to calculate the GBP, as shown in Fig. 7. Indeed, the predicted GBP is 317 GHz, which is in good agreement with the measured value of 320 GHz.[5] Note that when no initial energy is assumed, then the predicted GBP is 353 GHz, which badly underestimates the true GBP. On the other hand, when the initial energy is at its maximum value of the ionization threshold energy, then the GBP 374 GHz.

Finally, we wish to emphasize that the noise-reduction and bandwidth-enhancement mechanism described in this paper is *not the same as* that proposed by Williams *et al.*[34] in the eighties. In the latter, an enhancement in the ionization coefficients was assumed at the interface between a high bandgap and low bandgap layers. In contrast, we do not assume any enhancement in the ionization probability as a result of the band-edge discontinuity at the hetero-interface, but instead consider the dead-space effect at the boundary. In fact, several Monte-Carlo studies on $Al_{0.6}Ga_{0.4}As$/GaAs multilayers showed that band-edge discontinuities in multilayer structures appeared to offer no ionization-coefficient enhancement due to carrier energy losses brought about by phonon scattering.[35,36]

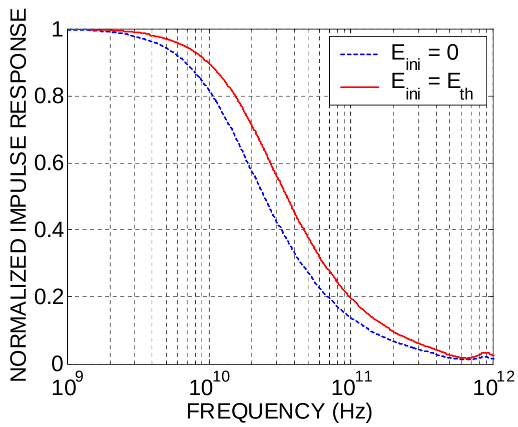

Figure 5. The calculated frequency response of a GaAs APD with a 100-nm multiplication region showing the bandwidth enhancement due to the initial-energy effect. The solid curve (top) represents the case when the initial energy of injected carriers is equal to the ionization energy and the dashed curve (bottom) corresponds to the case where zero-initial energy is present. The mean gain in both cases is 10.

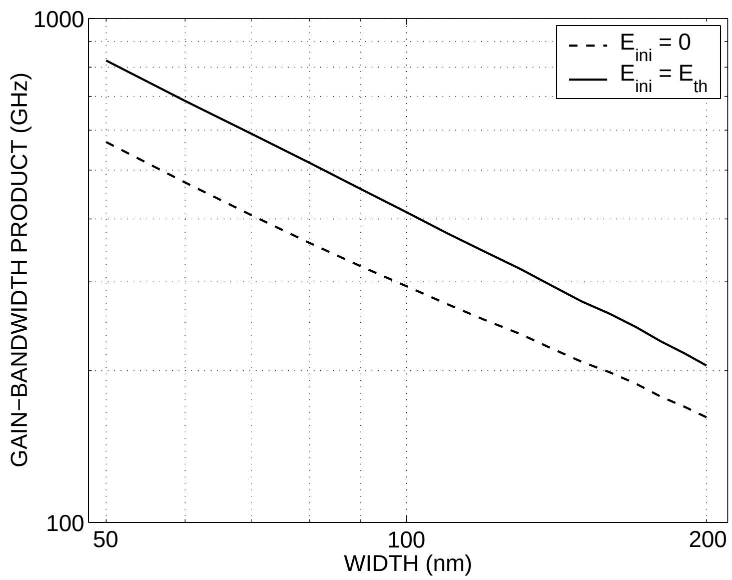

Figure 6. Gain-bandwidth product as a function of the width of the multiplication region for GaAs APDs. The top curve assumes maximal initial energy, equal to the ionization threshold energy, and the bottom curve assumes zero initial energy.

4. CONCLUSIONS

The initial energy-effect is an important phenomenon that occurs in heterostructure APDs where the injected carrier enters the multiplication region with a moderate initial energy comparable to the ionization threshold energy. This initial energy serves to reduce the first dead space, associated with the injected carrier, and leads to improved performance in two regards: 1) It reduces the excess noise factor and 2) it enhances the gain-bandwidth product. We have pointed out a method for calculating the excess noise factor and the gain-bandwidth product and shown good agreement with experimental results. It is noted that without the inclusion of the initial-energy

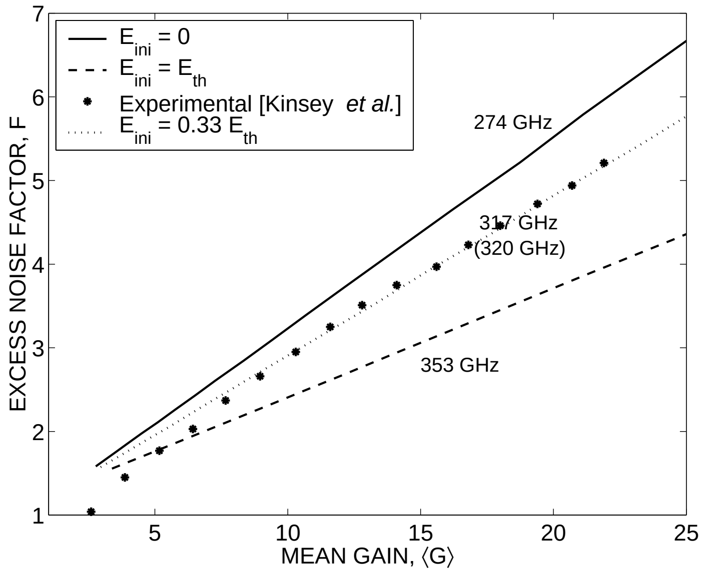

Figure 7. Excess noise factor as a function of the mean gain for a waveguide InAlAs APD developed by Kinsey *et al.*[2,5] The case $E_{ini} = 0.33E_{th}$ yields the best noise-gain fit to data. The calculated GBP for this case is 317 GHz, which is in close agreement with the measured GBP of 320 GHz. The cases of $E_{ini} = 0$ and $E_{ini} = E_{th}$, respectively, yield theoretical GBPs of 353 GHz and 274 GHz.

effect, theoretical models fail to explain the performance of many of the state-of-the-art heterostructure APDs.

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