Enhanced Gain-Bandwidth Product and Performance in Thin Heterostructure Avalanche Photodiodes

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It is well known that the excess noise factor of an avalanche photodiode (APD), which is a measure of its gain fluctuation, can be reduced by decreasing the thickness of the avalanche multiplication region. This noise reduction is attributable to the increased importance of the dead-space effect in thin layers, which prevents a carrier from impact ionizing before it travels a sufficient distance enabling it to acquire a minimum ionization threshold energy. Recently, it has been observed that there are yet two dead-space related mechanisms that can further reduce the excess noise factor. They are: 1) the initial-energy effect and 2) the bandgap-boundary effect, which is observed in heterostructure APDs [1]. The initial energy is referred to the energy that an injected carrier acquires just before entering the multiplication layer, which can be due to the presence of a strong electric-field gradient in a doped region just before the multiplication layer. This initial energy reduces the first dead space of the parent carrier, resulting in the localization of the first impact ionization. On the other hand, the bandgap-boundary effect occurs when the initial-energy effect is deliberately incurred by means of using two (or more) bandgap engineered intrinsic layers in the multiplication region. For example, in a heterostructure APD with a two-layer side-by-side $Al_{0.6}Ga_{0.4}As$/GaAs multiplication regions, as shown in Fig. 1, the high bandgap intrinsic $Al_{0.6}Ga_{0.4}As$ layer, termed the energy-buildup layer, is used to energize the carriers that are injected into it while the low-bandgap GaAs layer is used as the primary layer for hosting the ionization events. Moreover, the width of the energy-buildup layer can be optimized to maximize the benefit of the initial-energy effect, thus minimizing the excess noise.

The optimization strategy for minimizing the excess noise factor using an $Al_{0.6}Ga_{0.4}As$/GaAs heterostructure APD has been developed in [2] demonstrating a significant theoretical reduction in the excess noise factor. The performance advantages rendered by the bandgap-boundary effect have been demonstrated in the class of heterostructure devices termed "impact-ionization-engineered" APDs [3]. In this paper, the initial-energy and bandgap-boundary mechanisms are shown to improve the gain-bandwidth product (GBP) beyond the limits previously known. We will use the rationale of the modified dead-space multiplication theory (MDSMT) [1] for gain noise, which captures both the initial-energy and the bandgap-boundary effects in heterostructure APDs, to extend our recursive technique [4] for the prediction of the mean impulse response to arbitrary heterostructure APDs.

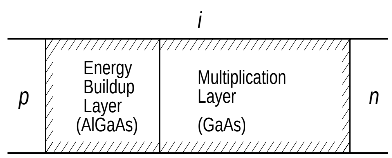

Figure 1. Schematic of a heterostructure APD which is used exploit the bandgap-boundary effect.

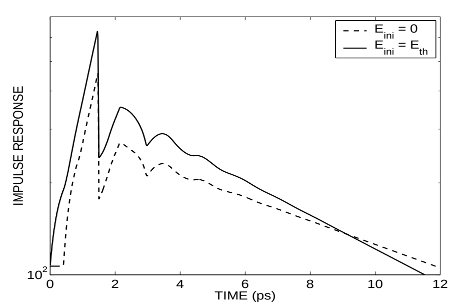

Figure 2. Mean impulse response of a 100-nm homojunction GaAs APD with no initial energy ($E_{\rm ini} = 0$, dashed curve) and with maximal initial energy ($E_{\rm ini} = E_{\rm th} = 1.9$ eV, solid curve).

Figure 2 shows the impulse response of a 100-nm homojunction GaAs APD in two cases. In the first case, the injected carrier is assumed to have zero initial energy (dashed curve) while in the second case, the initial energy is assumed to be equivalent to the 1.9 eV electron ionization-threshold energy of GaAs (solid curve). It is observed that in the presence of the initial energy, the impulse response decays at a faster rate suggesting an increase in the bandwidth. The ability to calculate the impulse response response allows us to calculate the GBP as a function of the multiplication-layer width, in the two cases of the initial energy described above, as shown in Fig. 3. The improvement in the GBP due to the initial-energy effect is clearly evident. It is also observed that the initial-energy effect becomes more significant as the width of the multiplication layer decreases.

An optimized structure (see Fig. 1) is designed such that an injected carrier from the *p*-layer builds up the ionization threshold energy (for GaAs) in the $Al_{0.6}Ga_{0.4}As$ layer and thus becomes capable of impact ionization as soon as it enters the GaAs layer. (This requirement also prevents any premature ionizations in the $Al_{0.6}Ga_{0.4}As$-layer.) Figure 4 shows the GBP as a function of the width of the energy-buildup ($Al_{0.6}Ga_{0.4}As$) layer for different multiplication-layer (GaAs) widths. With a 100-nm multiplication-layer width, the highest GBP is achieved when the energy-buildup layer is 30 nm, exhibiting a 15% improvement over a homostructure APD. Generally, the optimum width of an APD of the form shown in Fig. 1 is determined by its multiplication-layer width and the types of materials used. Interestingly, our calculations show that the width that maximizes the GBP is the same as that which minimizes the excess noise factor [2]. Finally, our calculations (not shown) prove that the optimal width of the energy-buildup layer is independent of the operational gain of the device.

Finally, to assess the performance of high-speed APD-based receivers, the traditional formula for shot noise must be revised to capture the stochastic nature of the APD's impulse response function. This is because the traditional formula ignores the strong correlation between the random gain and the duration of the random impulse response. Thus, the traditional bandwidth considered so far can be used only as an approximation to the shot-noise-equivalent bandwidth, and its use would result in underestimating the true APD-driven shot noise (e.g., up to a factor of 1.5 for an 100-nm GaAs APD with mean gain of 10). To have a more accurate assessment of the shot noise, we will present an "effective" bandwidth that captures the correlation between the gain and bandwidth. This is done by parameterizing the stochastic impulse response function by the random gain and random response time while utilizing a new recurrence theory that characterizes the joint distribution of the gain and response time.

In conclusion, it is clear that maximizing the beneficial effect of dead space through either the initial-energy or the bandgap-boundary effects is crucial in improving the GBP characteristics of thin APDs beyond conventional limits. Notably, a heterostructure APD of the type shown in Fig. 1 can be simultaneously optimized for lowest excess noise and highest GBP uniformly in its operational gain. Moreover, the traditional formula for the assessment of shot noise in high-speed APD-based receivers must be revised to capture the stochastic nature of the APD's impulse response function. This work was supported by the National Science Foundation.

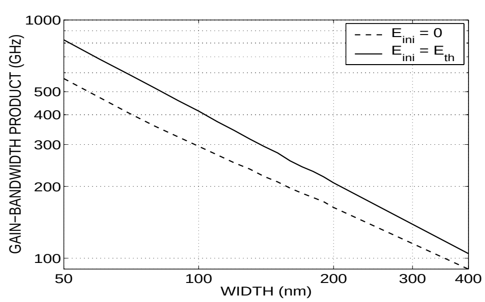

Figure 3. GBP of a 100-nm homojunction GaAs APD showing the effect of the absence (dashed curve) and presence (solid curve) of the initial energy.

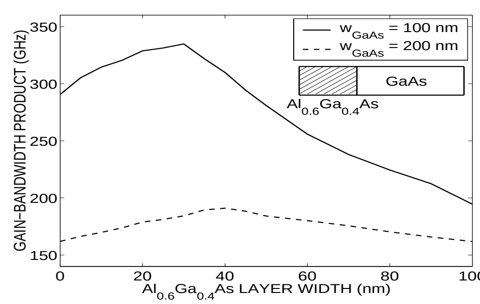

Figure 4. Dependence of the gain-bandwidth product in a heterostructure APD on the width of the $Al_{0.6}Ga_{0.4}As$ energy-buildup layer.

References

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