Noise Reduction and Simulation in Avalanche Photodiodes

F. Emami and M. Frdosiyan Tehrani

***Abstract*—**One of the most important devices used in optical communication systems are Avalanche Photo Diodes (APDs). APDs are the proper devices in signal detection because of their wide bandwidth, low noise operation and sensitive detection respect to other detectors. In this paper, an overview of the noise specification is presented for them. Some structures such as thin multiplication layer APDs, impact ionization engineering, ultra-low noise APD with a centered-well multiplication region and some theories such as dead space multiplication theory (DSMT) and modified DSMT (MDSMT) are studied. The numerical simulation of nonlocal ionization and dead space effects in homojunction APDs are reviewed based on the history dependent multiplication theory (HDMT). Finally, we discussed the low noise CMOS APDs.

***Keywords*—**Avalanche photodiodes, simulation, low noise operation, dead space, noise equivalent power.

I. Introduction

It has become evident in recent years that progresses in avalanche photodiodes (APDs) are caused to achieve the higher gain-bandwidth products which is proper for high bit rate long haul fiber optical communications and these devices have some advantages respect to other detectors, such as PIN diodes [1]. APD bandwidths and noises could be described by the electron, α, and the hole, β, multiplication factors in the multiplication layer [2]-[4]. It is shown that, for very large or very small values of α/β, defined by k, the APD has better efficiency. In fact, k is a material dependent factor. The value of $k=0.15$ or less is reported for AlGaAs APDs [5]-[12]. There are smaller values for k in other structures such as $Hg_{1-x}Cd_x$. Beck *et al.* are studied an APD made by $Hg_{0.7}Cd_{0.3}Te$ [13]. This is a low noise APD [i.e. its excess noise factor, $F(M)$, is about 1] so we expect a very small value for k. Contrary to III-V compounds; $Hg_{0.7}Cd_{0.3}Te$ has a very low band gap for Γ valley ($\approx 0.29eV$) and a relatively large gap for L and X valleys

($\approx 1.5eV$ $\approx 2.50eV$, respectively) [14]. To decrease the noise effects, a lot of methods are reported. Generally, low excess noises and high gain bandwidth products are the main purposes. They can be classified on different materials: InP [15]-[18], GaAs [19]-[23], $Al_xIn_{1-x}As$ [17], [18], [24], Si [25], [26], $Al_xGa_{1-x}As$ [17], [18], [27]-[29], SiC [30] and finally GaInP [31].

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II. Lowering The Width Of Multiplication Layer

Detecting applications for APDs are a lot. This is due to the high gain characteristic of these devices. But, because of this gain and random occurrences of avalanche process, there is an excess noise in the device [32]-[34]. The multiplication layer in an APD has a very important role in the noise and the gain bandwidth product considerations. So, to diminish the noise effects, we can use a thin multiplication layer say less than 1μm [17], [35]. By use of this multiplication layer in an appropriate structure such as resonant cavity enhanced APD (RCE-APD), it is possible to achieve a high quantum efficiency (>70%) and large gain bandwidth product (>290 GHz) [12], [36], [37]. Theoretically, and based on a Monte-Carlo simulation, it is shown that the excess noise factor is decreased when the multiplication layer thickness is reduced [16], [21], [24], [38], [39]. In all of the APD structures, noise decreasing can be achieved by using a thin multiplication layer, apart from the k value. In fact, the multiplication of an APD plays an important role in determining the gain and the noise. The main reason of this phenomenon is the non-local impact ionization, which is known as dead space in the APD literature [40]-[43]. This layer is the minimum distance for the carriers to acquire the necessary energy of impact ionization. The dead space can degrade the excess noise as shown in Fig. 1. The gain distributions for two types of $Al_{0.48}In_{0.52}As$ APD structures with two thicknesses of 1.0 and 0.1 μm are studied (shown by dashed and solid curves in the figure). Both APDs have almost identical average gains ($M \approx 20$) and different excess noises (6.9 for thick and 4 for thin APD). There is a larger gain distribution for thicker APD and this is due to the more multiplication noise of the former device.

The figure shows that in a device with a wider multiplication region, there is a high ionization probability for large ($M > 80$) and small ($M \approx 1$) gains. For an intermediate gains ($2 < M < 80$) this probability is higher for the thinner device. Another interesting point from the figure is, for thick APD there is a maximum for $M = 1$ but for thin APD it is in $M = 2$.

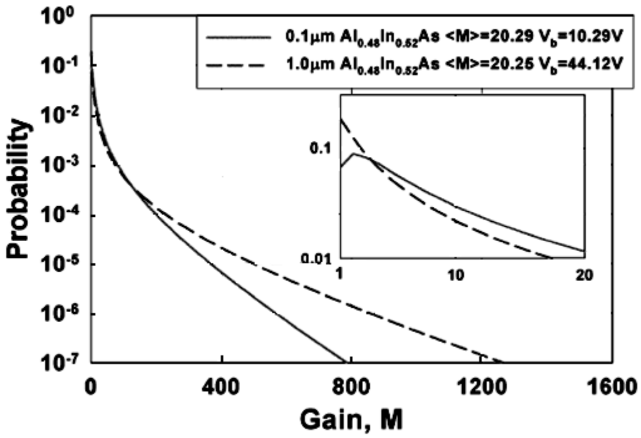

Fig. 1. Comparison of the gain distribution curves for $Al_{0.48}In_{0.52}As$ APDs with different multiplication region widths of 1.0 (dashed line) and 0.1 µm (solid line). The average gain for both APDs is M ~ 20 but the excess noise factors for the 1.0 µm APD is 6.9 and for the 0.1 µm APD is 4

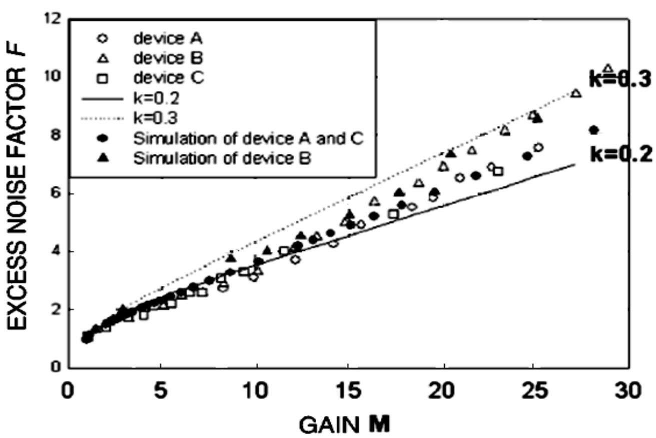

Fig. 2. Experimental and simulated excess noise factor versus gain for three devices A, B, and C

This phenomenon shows, for the thinner devices, maybe with the same gains, the initial carriers will emerge from the i-region (multiplication layer) without ionization [22]. The impact ionization effects in the absorbing layer of an APD is reported too [44]. Using a tunable laser as an optical source at 1.55µm, the measurement of *F(M)* is done for three devices named *A*, *B* and *C* as shown in Fig. 2. The effective value for *k* is estimated about *0.2* for *A* and *C* (based on the typical values [45]). The bold circles are the results of the theoretical calculations [46]. It is evident the excess noise factor for device *B* is deviated from *k=0.2* for $M > 15$. This is a confirmation of impact ionization existence in the absorption layer. By use of the Monte-Carlo simulation, it is proved that the impact ionization phenomenon is important in the absorbing layer of InGaAs devices (shown by solid triangles in Fig. 5) [47].

III. Using The Impact Ionization Engineering

One way to reducing the noise is utilizing the impact ionization engineering (I^2E) [44]. In a heterostructures there is a large space for impact ionization respect to the homostructures. At first, the works done on the heterostructures are based on the efficiency improvement for the $GaAs/Al_xGa_{1-x}As$ structures [9], [11], [44], [48], [49]. Recently, a better efficiency respect to the previous structures is reported for InGaAlAs/InP semiconductors [50].

The main idea for I^2E is the fact that, a thin layer with a narrow band gap and relatively low threshold energy lies next to a wide band gap and higher threshold energy. The carrier energies in wider band gap layer are increased and because of the higher threshold energy, the ionization process in these regions is low. This structure is shown in Fig. 3. The two separated regions seen in the figure, demonstrated the multiplication region.

The excess noise factor, *F(M)*, versus gain are shown in the Fig. 4 for three different APD types of InGaAlAs which are grown on InP substrate.

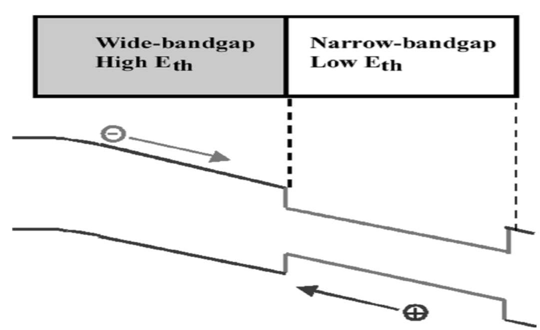

Fig. 3. Experimental and simulated excess noise factor versus gain for three devices A, B, and C

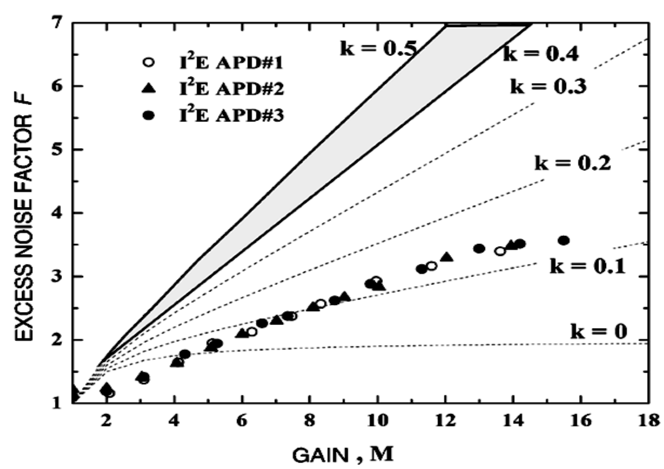

Fig. 4. Excess noise factor as a function of mean gain

The multiplication layer contains an $In_{0.52}Al_{0.48}As$ layer with thickness of *100nm* and a *100nm* quaternary compound $In_{0.52}Ga_{0.15}Al_{0.33}As$ layer which is inserted between two layers; a layer of n-type $In_{0.52}Al_{0.48}As$ with a thickness of $0.5\mu m$ and

doping of $5 \times 10^{18}\,/cm^3$ and a layer of p-type $In_{0.52}Al_{0.48}As$ with a thickness of $0.8\mu m$ and doping of $3 \times 10^{18}\,/cm^3$. There is a high doped $In_{0.53}Ga_{0.47}As$ layer at the top of all layers too.
The existence of an $In_{0.52}Ga_{0.15}Al_{0.33}As$ layer with a lower band gap ($E_g \approx 1.25eV$) respect to an $In_{0.52}Al_{0.48}As$ layer (with $E_g \approx 1.51eV$) causes the ionization threshold energy of carriers is decreased. There is a small amount of ionization processes in the $In_{0.52}Al_{0.48}As$ region and this is due to the effects of dead space and higher threshold energy in the $In_{0.52}Al_{0.48}As$ layer. The dotted lines in Fig. 4 show *F(M)* for *k=0.0* to *0.5*. These curves are derived from the local field model [2] and [3]. If the effects of the excess noise are considered, the value of *k* will increased. Comparing the local field model with I^2E procedure, we found that for $M \le 4$ the local field model is not proper for the multiplication layer. At the higher gains the excess noise is equivalent to the curve of *k* value of about *0.12*. This is the lowest reported noise for APDs which are used in the low loss fiber optical communication wavelengths ($\lambda \approx 1.3$ and $1.55\,\mu m$). As a reference, the related commercial $InP/In_{0.53}Ga_{0.47}As$ APDs curves, which have large usage in optical fibers, are settled between two lines *k=0.4* and *k=0.5*.
There are many practical works on excess noise factor [44], [51]. To measure this factor, a semiconductor laser works at $1.55\mu m$ is used as an optical source in Ref. [44]. In the experiment a value of *F(M)=1.41* is achieved for a gain of *3.2*. The reported results, for the higher gains, are shown in Fig. 5.

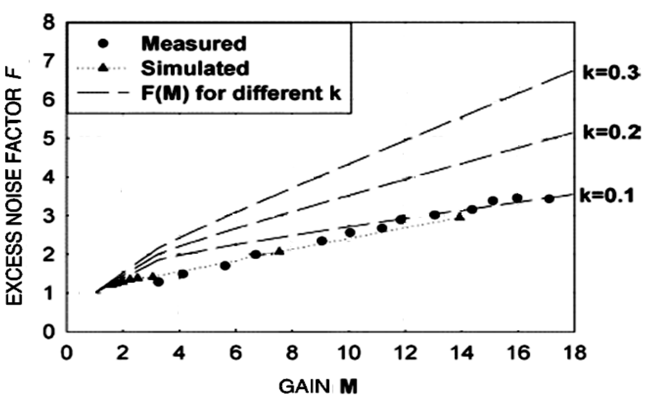

Fig. 5. Measured and simulated excess noise factor versus gain

There is a comparison between the experimental and theoretical results in this figure. From the figure, it can be estimated the effective value of *k* to have the gain values higher than *15*, is about *0.1*. Decreasing the effects of dead space on the carriers, injected from the higher band gap and larger threshold energy regions to the lower band gap and smaller threshold energy layers, causes the device has low noise behavior [49], [8]. From the above discussions, we conclude the reduced noise in the I^2E structure is due to a space model describing the probability distribution of impact ionization [52] and generally there is a lower noise for heterostructures. Note also that, application of a large field in the multiplication layer has an important role in the noise lowering [53].

IV. Using a Centered-Well Layer

To diminish the noise in an APD, we can use a centered-well (CW) structure in the multiplication layer. As shown in Fig. 6, in a CW structure the multiplication region contains an $Al_{0.6}Ga_{0.4}As$ layer with a thickness of almost *20nm*, an $Al_{0.6}Ga_{0.4}As$ layer with a thickness of about *10nm* and a well at the middle of them made by an *80nm* $Al_{0.2}Ga_{0.8}As$ [9].

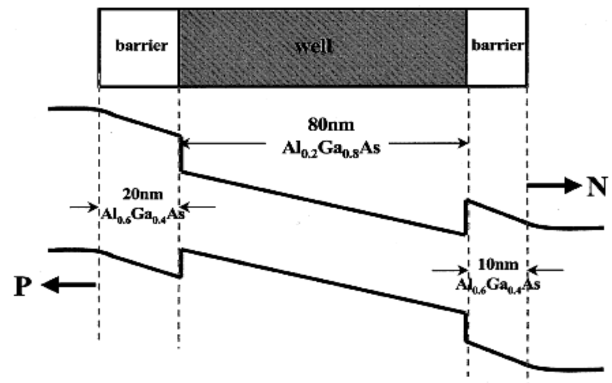

Fig. 6. The structure and the energy band diagram of the centered-well (CW) configuration

All of the layers are n-doped with the concentration about $2 \times 10^{15}\,/cm^3$. Sometimes this structure is made in mesa form [44]. In Fig. 7 the excess noise factor curves versus different values of gains are plotted for the CW and homogeneous $Al_{0.6}Ga_{0.4}As$ structures at the room temperature.

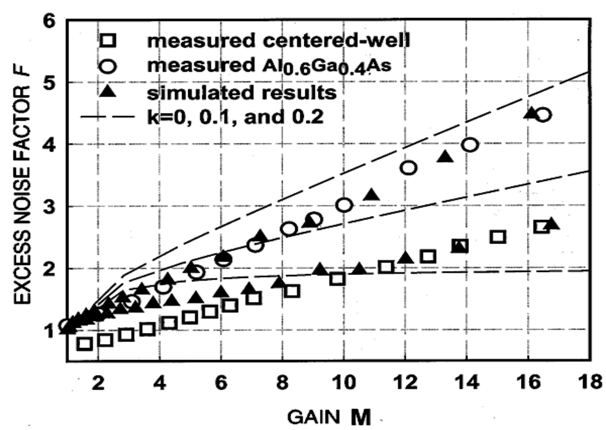

Fig. 7. Measured excess noise factors for the CW structure (squares) and the ~140 nm $Al_{0.6}Ga_{0.4}As$ homostructure (circles) with the same UV laser as in Fig. 6. Solid triangles: Monte Carlo calculation results. Dashed lines: plots for k_{eff} =0, 0.1, and 0.2 based on local field theory [2] (After [9])

The bold triangles are the results of the Monte-Carlo model and the dashed lines are the consequences of local-field model, for k_{eff}*=0.01* and *0.02* [2]. The values of *F(M)* for k_{eff}*=0.0* for CW structure is shown in this plot too. As seen,

the noise level is less than a homogeneous $Al_{0.6}Ga_{0.4}As$. It is shown that this noise is less than that a homogeneous $Al_{0.2}Ga_{0.8}As$ structure which is used in the same conditions, temperature and thickness [6].
For a homogeneous $Al_{0.6}Ga_{0.4}As$ there is a good compatibility between the simulated and the reported empirical results. In fact, based on the figure it is evident that for low gains (especially for $M<8$) the simulated results are a little less than the measured values. Indeed, for $M<4$ in a CW structure this model is useless since there is an incompatibility between the measured values and theoretical modeling. This point is mentioned in almost all the experiments. In this case, for a pure electron injection and to noise measurements, an argon laser is used (with *351* and *365 nm*) [54], [55].

V. Using Different Materials

At the beginning of 1990, Hayat *et al.* formulate the dead space multiplication theory (DSMT) [56]-[58]. Dead space is a feature of the avalanche-multiplication process because band to band impact ionization can take place only after an electron or hole has acquired sufficient kinetic energy to collide with the lattice and ionized the other electron-hole pair [65]. Generally, the dead space can reduce the excess noise factor and it is important when the ratio of the dead space to the multiplication width is increased. Recently, it is reported that for a thin APD the relatively large portion of the multiplication layer belongs to the dead space (up to *25%* for the devices with widths less than $100\mu m$), so it is concluded the dead space has an important effect on noise reduction for all types of APDs [20], [22], [12].
The predictions of the dead space effects on avalanche multiplication are not exact always, even by use of the DSMT. So, an appropriate way to describe the ionization phenomenon in the dead space is needed. This is based on the McIntyre multiplication theory [59]. He and Yuan *et al.* worked on the DSMT to improve it [54]. They worked on the low excess noise factor APDs. The DSMT requires the charge activated ionization coefficients. Based on the Li *et al.* researches [20] and the McIntyre theory, the ionization coefficients are combined to a mean free path formulation, to describing the ionization effects [60], [61]. Using these results in DSMT, the excess noise specifications in thin APDs are predictable. The results have some degrees of approximations [62].
Recently, Saleh *et al.* [12] uses the DSMT for GaAs and AlGaAs and present a model for ionization coefficients. In this model, these coefficients are related to the width of the multiplication layer. They used only the field, the ionization threshold energy for each carrier, and the measured gain-noise information. For each carrier and material, there are presented models for ionization coefficients of different devices. A good method is described for calculation of the carrier's ionization coefficient which travels the distances larger than the dead space length. This procedure is distinguished [67] from the other methods for DSMT [20], [35], [54].
Combining this model, which is independent of the width; with DSMT for calculation of the excess noise, have a good coincidence with the practical results [12]. Unfortunately, the presented values of the ionization threshold energy is correct only for limited classes of materials (for example the electrons in GaAs and InP semiconductors) [63]. So, one of the noise reduction mechanisms in APDs, is selecting an appropriate material.
To increase the gain-bandwidth product of APDs we can use the InP semiconductor together with InAlAs, GaAs and AlGaAs [42]. The noise calculations in APDs can be modeled by use of DSMT [60]-[66]. To do this, consider four types of materials with different multiplication layer thicknesses as shown in Table I [65]. Using the data reported in the literature [35], [39] and application of DSMT [12], [57], [59], the excess noise factor versus gain for the above materials are shown in Fig. 8 to 11.

Table I Typical thickness of different materials

InP	**281nm**	**317nm**	**582nm**	**1110nm**
$In_{0.52}Al_{0.48}As$	**190nm**	**363nm**	**566nm**	**799nm**
GaAs	**100nm**	**200nm**	**500nm**	**800nm**
$In_{0.52}Al_{0.48}As$	**200nm**	**1400nm**	**800nm**	

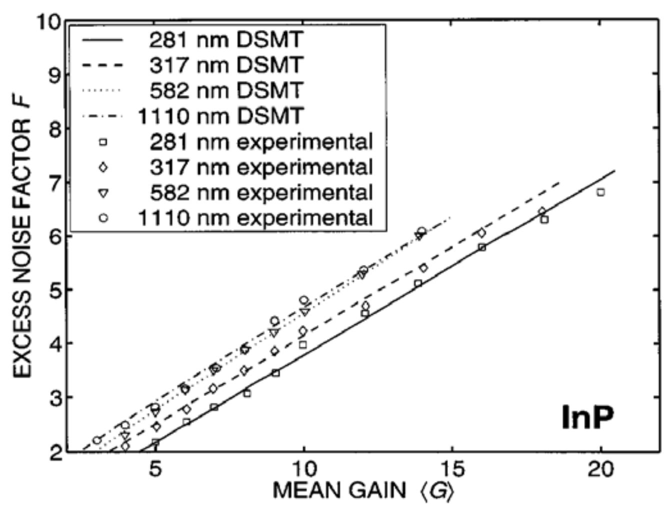

Fig. 8. DSMT-prediction and the experimental excess noise factor F versus mean gain G for thin InP APDs in Table 1. Symbols represent experimental data and curves represent predictions using the DSMT

Optimizing of the ionization threshold energy is the reason for this theoretical and experimental coincidence. Fig. 10 and 11 show the similar results for GaAs and $Al_{0.2}Ga_{0.8}As$ APDs [48], [64].

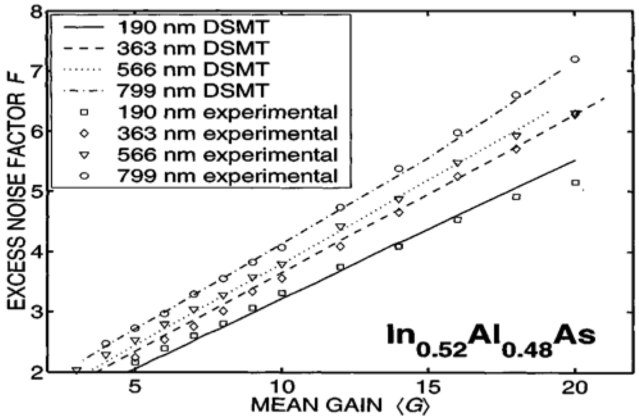

Fig. 9. DSMT-prediction and the experimental excess noise factor F versus mean gain G for thin $In_{0.52}Al_{0.48}As$ APDs in Table 1. Symbols represent experimental data and curves represent predictions using the DSMT

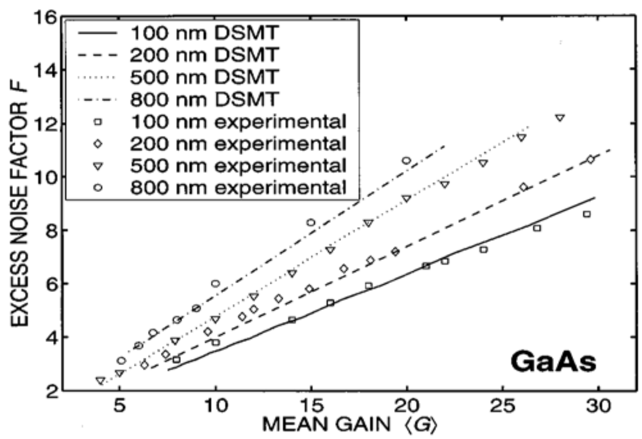

Fig. 10. DSMT-prediction and the experimental excess noise factor F versus mean gain G for thin GaAs APDs in Table 1. Symbols represent experimental data and curves represent predictions using the DSMT

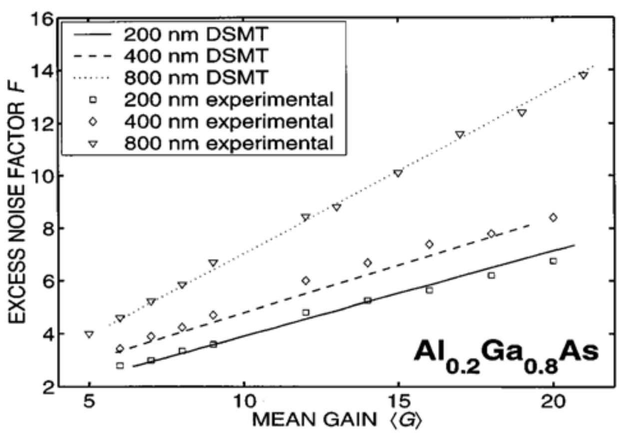

Fig. 11. DSMT-prediction and the experimental excess noise factor F versus mean gain G for thin $Al_{0.2}Ga_{0.8}As$ APDs in Table 1. Symbols represent experimental data and curves represent predictions using the DSMT

VI. Modified DSMT

As said in the previous section, the noise characteristics of APDs can be modeled by DSMT. This theory along with the effects of the initial energy is improved and a new theory named modified DSMT or MDSMT is presented [11], [48].

The required key parameters for this theory are:

- the ionization coefficients of the electron and holes for the used material which are independent of the width of the multiplication layer,
- the hole and the electron ionization threshold energy and
- the initial energy of the injected carriers.

These ionization coefficients are related to the dead space characteristics. The ionization coefficients and the threshold energies for GaAs and $Al_{0.6}Ga_{0.4}As$ are reported [8], [51], [69]. It is shown that the MDSMT has the ability for predicting the specifications of a low noise APD, for which injected carriers have a finite initial energy. Consider an $Al_{0.6}Ga_{0.4}As$ homostructure APD which has a multiplication layer of *140nm* thickness. The field in this device is shown in Fig. 12. The field slope near the edge of i-layer (multiplication layer), is sharp. The initial energy configuration can be calculated from the field distribution in p-layer. For example at gain of about *20* the high energy electrons start the multiplication process with the initial energy of almost *0.9*. This is in the range of $\approx 26\%$ of the ionization threshold energy for $Al_{0.6}Ga_{0.4}As$ [66].

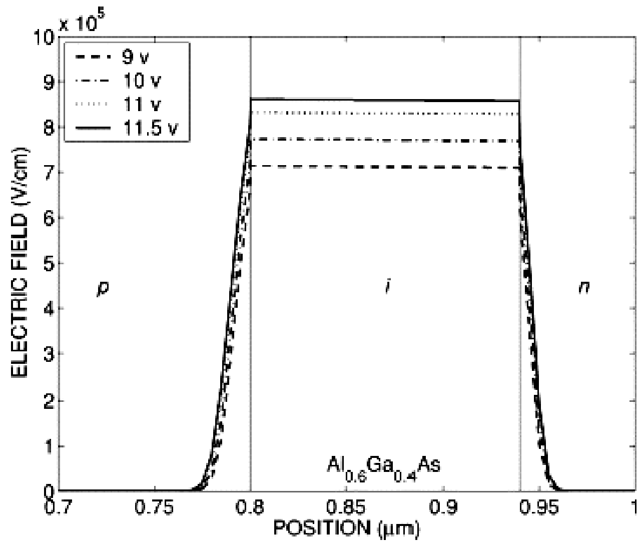

Fig. 12. Electric-field distribution for an $Al_{0.6}Ga_{0.4}As$ homojunction APD with a 140-nm multiplication layer

The solid curve in Fig. 13 is an estimation of the excess noise with the initial energy calculations. There is a good agreement between the theoretical and practical results. The computations show if the electrons have *100%* of their threshold energies before entrance to the multiplication layer, there is a $\approx 35\%$ noise reduction at the gain of about *20*.

This is shown in the figure by dashed lines. When the initial energy of the injected carriers is not considered, the exact noise is in the form of the dotted line in the figure.

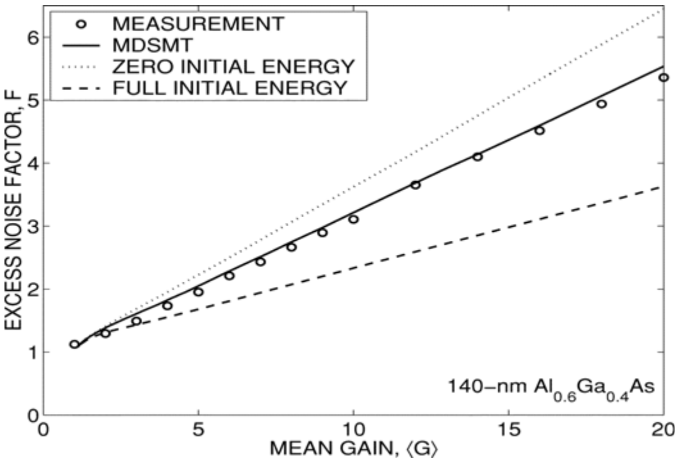

Fig. 13. Excess noise factor F versus the mean gain G for different initial-energy scenarios. There is a very good coincidence between the theoretical (MDSMT) predictions which includes the actual initial energy with experiment

Finally, we survey a heterostructure with two intrinsic layers, $Al_{0.6}Ga_{0.4}As$ and GaAs when the carrier injection is in the $Al_{0.6}Ga_{0.4}As$ layer. For different thicknesses of the $Al_{0.6}Ga_{0.4}As$ layer, for a fixed multiplication layer of 140nm and for a constant gain of 20, the results are shown in Fig. 14.

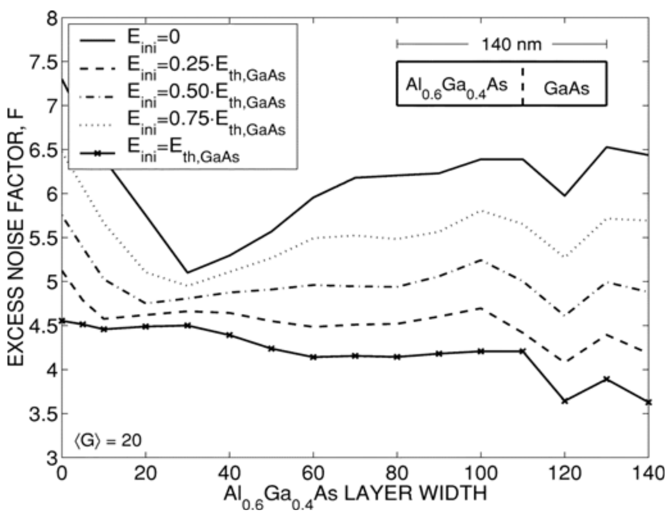

Fig. 14. Dependence of the excess noise factor in $Al_{0.6}$ $Ga_{0.4}$ As/GaAs heterostructure APDs on the width of the $Al_{0.6}$ $Ga_{0.4}$ As energy-buildup layer. The plots are parameterized by different initial-energy levels of the carriers that are injected into the $Al_{0.6}$ $Ga_{0.4}$ As layer. The initial-energy values are taken relative to the ionization threshold energy of GaAs

The curves are plotted for different initial energies of entered carriers to the $Al_{0.6}Ga_{0.4}As$ layer. The solid curves are the theoretical excess noise factor with zero initial energy. The connected lines (shown by $\times$) are the excess noise factor with complete initial energy. Note that, there is a minimum noise for zero initial energy when the $Al_{0.6}Ga_{0.4}As$ layer has a thickness of *30nm*.

VII. History Dependent Multiplication Theory (HDMT)

A model that has an excellent agreement on gain and noise measurement of InAs and GaAs APDs is history-dependent ionization coefficients called history-dependent multiplication theory (HDMT) [67], [68]. Recently, this theory is used to calculate the noise, the gain and the carrier injection breakdown probability simulations in homojunction InAs and GaAs APDs [69], [70].

As mentioned, the *k* parameter has an important role to determine the gain and noise of an APD. This is local field (or McIntyre) theory [2] which assumes continuous ionization (it is also assumed that there is no interaction between any of the carriers in the multiplication region except at the moment of impact ionization and the carriers contribute to noise independently which are quite reasonable for low level injection).

In HDMT it is assumed the ionization probability has a dependent process and relates to the history of carriers at previous points. So, when the carrier starts impact ionization, it loses all of its energy relative to the band edge. Therefore α and β or equivalently *k* parameters at each point are related to the corresponding values in the previous points. It means we have an ionization probability which can be used to the noise calculations and these coefficients are defined to represent the local ionization probability density at a determined point related to the previous point.

Finally, an iterative technique can be used to compute the APD noise and gain. Based on the ensemble average of the carriers, the noise power spectral density can be calculated too. As said, the dead space thickness has considerable effects on noise performance of an APD. Mokari *et al.* [69] showed these effects for two types of APDs; GaAs APD, Fig. 15, and InAs APD, Fig. 16.

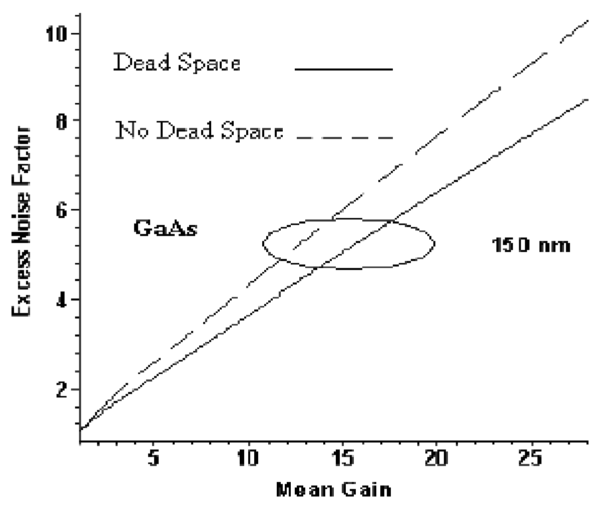

Fig. 15. Excess noise factor calculations with local field theory (dashed lines) and HDTM (solid lines) for GaAs APD

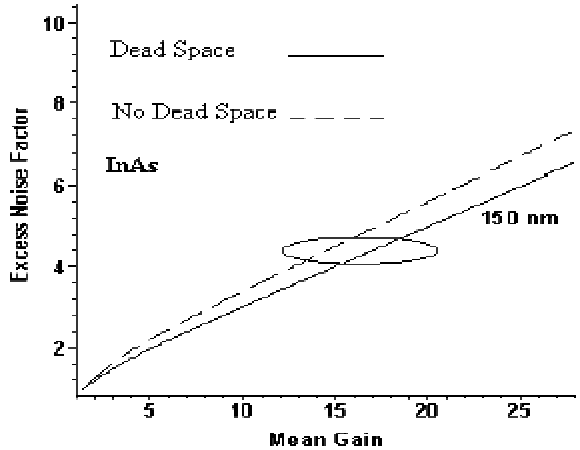

Fig. 16. Excess noise factor calculations with local field theory (dashed lines) and HDTM (solid lines) for InAs APD

They proved that the dead space reduces the excess noise factor and this effect is more significant for thin APDs. The results are true for InAs APDs too.

VIII. CMOS APDs

CMOS APDs has been reported by several researchers [71], [72], [73]. An APD in a standard 0.35µm CMOS technology is fabricated [73] with a cross section shown in Fig. 17.

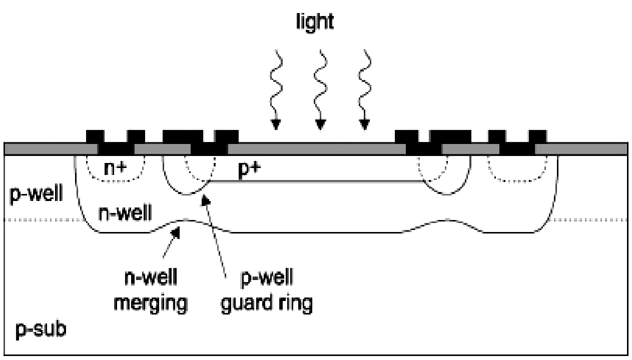

Fig. 17. Schematic cross section of a standard 0.35µm CMOS APD

A p^+ region implanted in an n-well area to made the active area medium. Next to the central n-well area another n-well ring has been formed and between the two n-wells there is a p-well diffused region. This p-well region is separated from the p-substrate during the fabrication process. Pancheri *et al.* [73] simulated the device and tested it under different situations. Based on their reports, the multiplication gain and the reverse current voltage curve are shown in Fig. 18. They attained a higher dark current respect to the reported structures and the same gain [74]. Because of the higher doping concentration of the multiplication region, a tunneling effect is occurred in the above device (Fig. 17).

They also measured the noise factor of the proposed device by LEDs at different wavelengths, excited with a stabilized current source. The noise factor as a function of the multiplication gain measured at 560 and 380 nm is plotted in Fig. 19. As shown, the proposed device has much lower noise factor than computed by McIntyre theory.

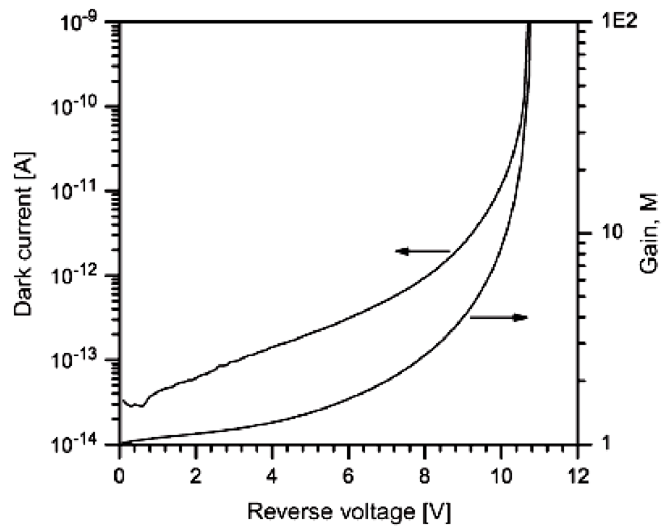

Fig. 18. Measured reverse current-voltage curve and multiplication gain of the proposed device

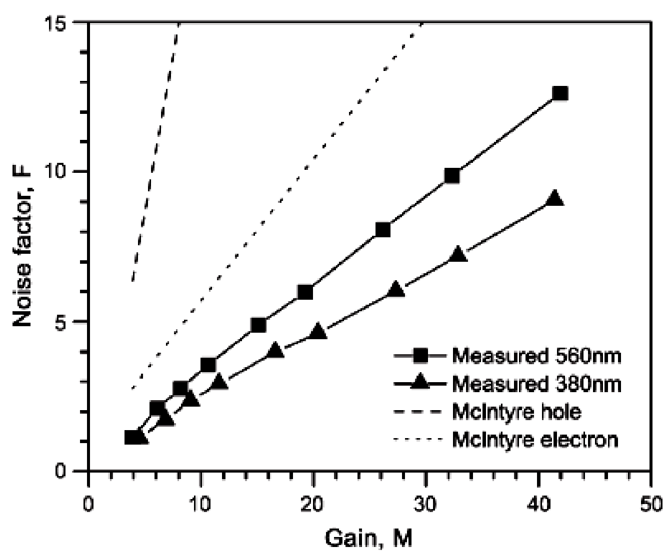

Fig. 19. Theoretical (based on McIntyre theory with the *k*-value of ≈ 0.47) and measured noise factor of the proposed device

The curves for higher wavelengths are almost in the form of 560nm curves [73]. Again, the effects of the dead space region, which has been chosen a substantial fraction of multiplication region, can explain the low noise behavior of this device. It is related to the distance traveled by newly generated carriers before it acquires sufficient energy to become capable of causing impact ionization [73]. Due to application of a thinner high field region, this device behaves a low noise operation.

Sometimes, it is possible to compare the noise of an APD with a standard photodiode [73]. To do this, we should define the noise equivalent power (NEP) of a detector as the optical power at which the signal to noise ratio is unity. This parameter is a function of avalanche gain and wavelength. Pancheri *et al.* [73] simulated the NEP and their results are redrawn in Fig. 20. As shown, there is a minimum NEP at a determined gain for every wavelength.

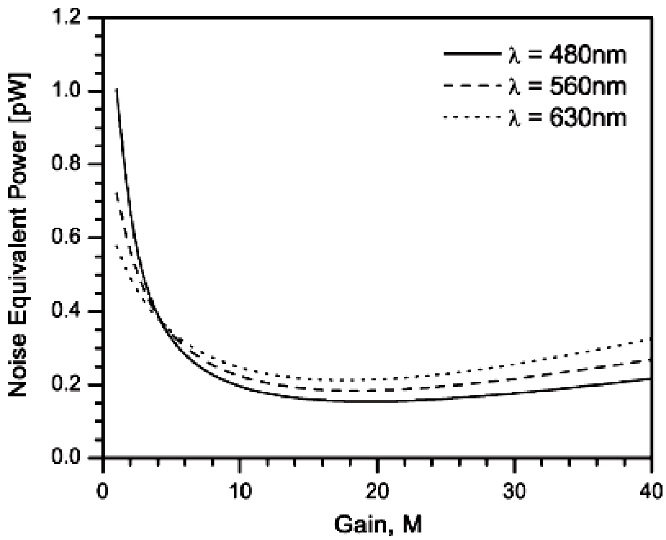

Fig. 20. Simulated NEP versus gain for different wavelength and in a finite time domain (≈ 100μs)

To compare the noise performance of APDs, define a performance factor *P* as the ratio between the NEP of a standard photodiode (NEP of APD at *M=1*) and the minimum NEP. It was shown that the highest values of *P* are achieved in the blue spectral region. At higher wavelengths this factor decreases.

IX. Final Remarks

In writing this article, we have not to cover every topic in the field of the noise in APDs. We hope our subjective selection of the above discussions along with the references reported here can present a general guideline in this area.

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