Excess Noise Factor in Avalanche Photodiodes with Dead Space Effect

Vignesh Reddy Angadi (vrangadi@gmail.com)

Case Report

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EXCESS NOISE FACTOR IN AVALANCHE PHOTODIODES WITH DEAD-SPACE EFFECT

Vignesh Reddy Angadi

Project Supervisor: Dr. J. S. Marsland

ABSTRACT

This project aims to develop a graphical user interface (GUI) for MATLAB programs written by J. S. Marsland as part of his research on the excess noise factor in avalanche photodiodes (APDs). The GUI will be developed using the GUIDE package supplied with MATLAB. The GUI will then be used to compare this research with other works—for example, the Monte Carlo calculations performed by the research group at the French Aerospace Laboratory (ONERA). A comparison with other works will require the digitisation of graphs, some of which have been published in academic journals.

INTRODUCTION

Avalanche photodiodes (APDs) amplify photo-generated currents by the process of impact ionisation; however, this is a random process which results in additional noise quantified by the excess noise factor. APDs with a low excess noise factor and high multiplication (amplification) have many applications in low-level light detection, such as medical imaging, astronomy, and such military applications as geodesy. Understanding the physics of APDs is crucial for the future improvement of photo-detectors.

Avalanche multiplication occurs when energetic carriers create additional carriers via impact ionisation. Typically, an electron produces random multiplications with impact ionisation.

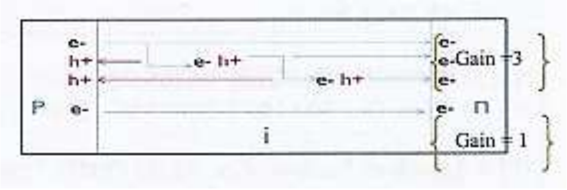


Figure 1: Avalanche multiplication

McINTYRE'S EQUATION

An ionisation coefficient k is defined by α divided by β; thus, an equation for the excess noise factor is given that relates the average multiplication M with k, as follows:

$$F(M) = kM + (1-k)\left\{2 - \frac{1}{M}\right\}; k = \frac{\alpha}{\beta} \qquad (\mathbf{1})$$

McIntyre [1] assumed that the ionisation coefficient depended only on the local electric field and did not consider the 'dead space effect'.

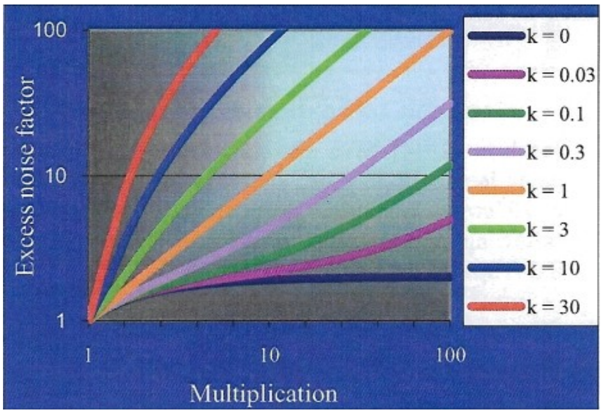


Figure 2: McIntyre's curves

NONLOCAL IONISATION COEFFICIENTS

Dead-space is a nonlocal effect. A nonlocal ionisation coefficient $\alpha(z)$ was defined by Marsland [2] such that $\alpha(z)dz$ is the probability that a carrier starting with no kinetic energy at $z = 0$ would impact ionisation in the interval $(z, z + dz)$. The ionisation path length PDF, $h_1(z)$, can be defined such that $h_1(z)dz$ is the probability that a carrier will impact ionisation for the first time in a given interval. The probability that a carrier will travel to z without ionising is called the survival probability $P_s(z)$.

The survival probability can be related to the ionisation path length PDF as follows:

$$P_s(z) = 1 - \int_0^z h_1(x)\,dx = \int_z^\infty h_1(x)\,dx \qquad (\mathbf{2})$$

The nonlocal ionisation coefficient *n(z)* is related to the PDF $h_1(z)$.

$$\alpha(z) = h_1(z) + \int_0^z \alpha(x) h_1(z-x)dx. \qquad (\mathbf{3})$$

MODEL FOR IONISATION PDF

This behaviour can be described by the following expression, where 1 is the length of the dead-space region and a and b are the constants governing the slope of the rise and fall of $h(z)$.

$$h(z) = \frac{ab}{b-a}\left\{\exp\left(-a(z-l)\right) - \exp\left(-b(z-l)\right)\right\}U(z-l)(\mathbf{4})$$

The above equation—fitted to $h(z)$—was computed using Monte Carlo techniques [4] for electrons in $GaAs$ at a field of $3 \, x \, 10^7 \, vm^{-1}$ using the following parameters.

$$a = 10\,\mu m^{-1};\ b = 1\mu m^{-1};\ l = 0.15\,\mu m^{-1}$$

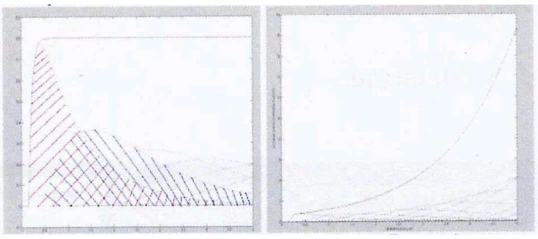


Figure 3: $GaAs\ at\ 3\ X\ 10^{7} vm^{-1}$

Jacob *et al*. [4] also calculated the ionisation path length PDF for electrons at a higher field of $10^{8} vm^{-1}$. Similarly, this result can be fitted using the following parameters:

$$a = b = 300\ \mu m^{-1};\ l = 0.0415\ \mu m^{-1}$$

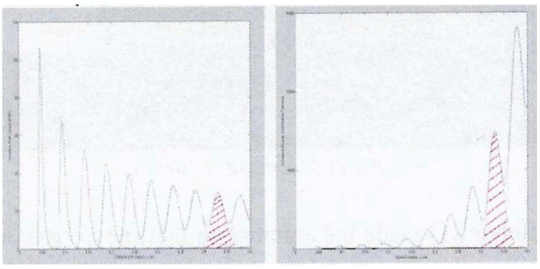
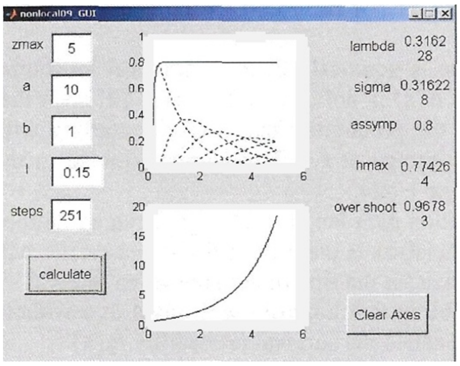


Figure 4: $GaAs\ at\ 10^{8} vm^{-1}$

MATLAB GUI



zmax 5

a 10

b 1

l 0.15

steps 251

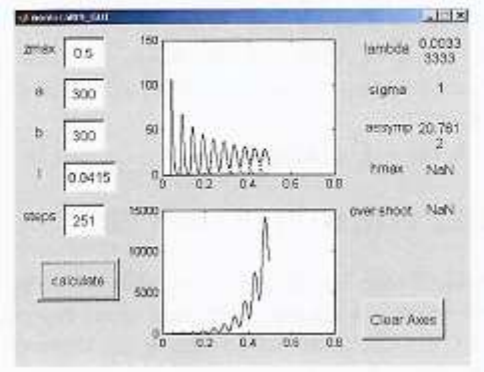
lambda 0.316228

sigma 0.316228

assymp 0.8

hmax 0.774264

over shoot 0.96783



zmax 0.5

a 300

b 300

l 0.0415

steps 251

lambda 0.00333333

sigma 1

assymp 20.7812

hmax NaN

over shoot NaN

The output graphs of the GUI obtained are as expected, although the dotted lines of axis component 2 is not displayed.

DIGITISATION

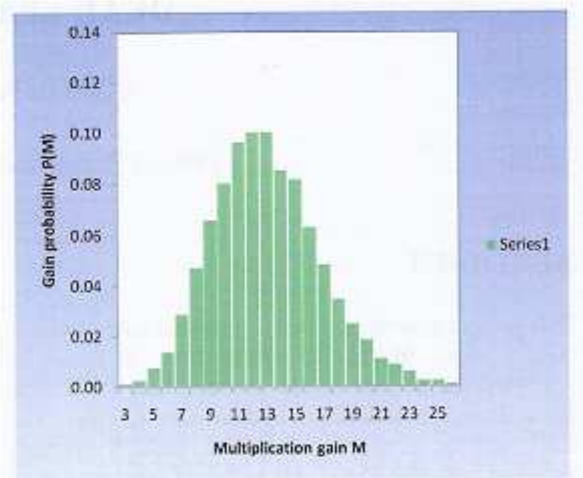


Figure 5: Digitised figure from Derelle et al. [3]

Probability, $\sum P(M) = 1$
Mean multiplication, $\sum MP(M) = \langle M \rangle = 12.02$
Mean square, $\langle M^{2} \rangle = \sum M^{2} P(M) = 168$

Excess noise factor, $\frac{\langle M^{2} \rangle}{\langle M \rangle^{2}} = 1.162$

Comparison of MJ03 with results from Derelle *et al.* [3]

MJ03	**Monte Carlo**
M = 12.02	M = 13.07
F = 1.162	F = 1.052

CONCLUSION

Ideally, the APD would be required to achieve maximum multiplication and less noise. This scenario is shown using nonlocal ionisation coefficients which provide stable multiplication and reduced noise. When dead space is included, noise is considerably reduced compared to the noise predicted by McIntyre's curves. Accordingly, a model for ionisation PDF was developed and reproduced using a GUI for the MATLAB program written by Marsland.

REFERENCES

[1] R.J. McIntyre, IEEE Trans. Electron Devices, ED-13, 164 (1966). Doi: 10.1109/T-ED.1966.1565I.

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Doi: 10.1049/ip-opt:20010089.

Figures

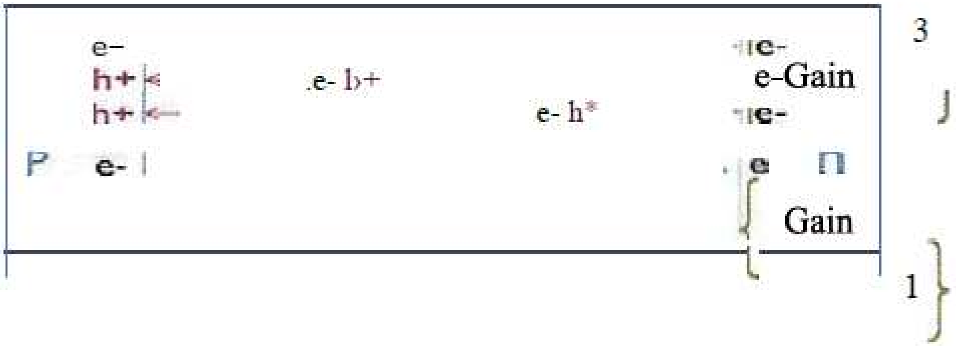


Figure 1

Avalanche multiplication

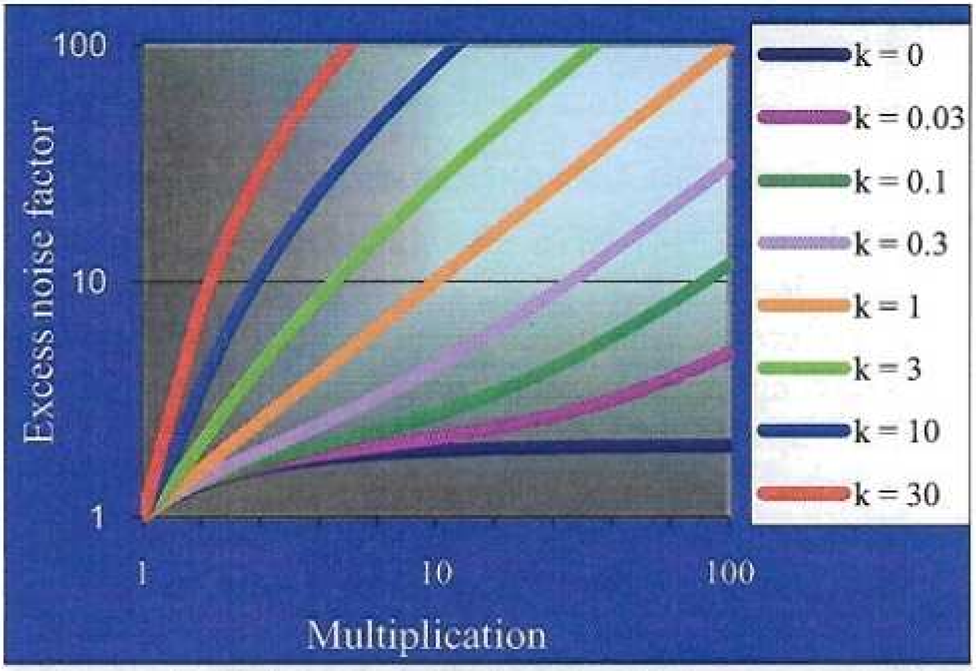


Figure 2

McIntyre’s curves

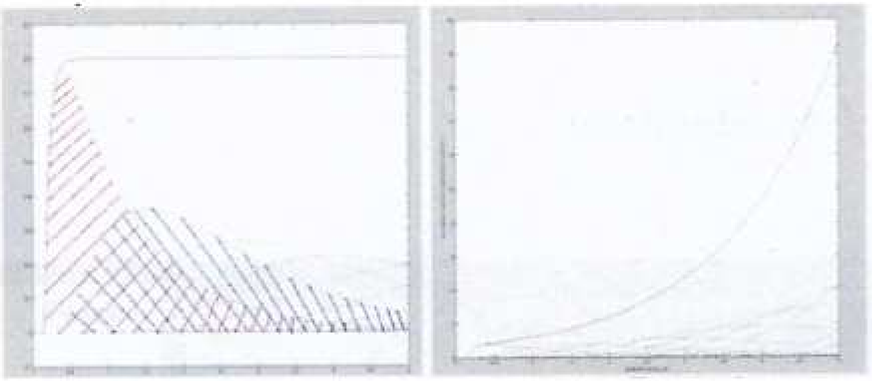


Figure 3

GaAS at 3 X 107 vm-1

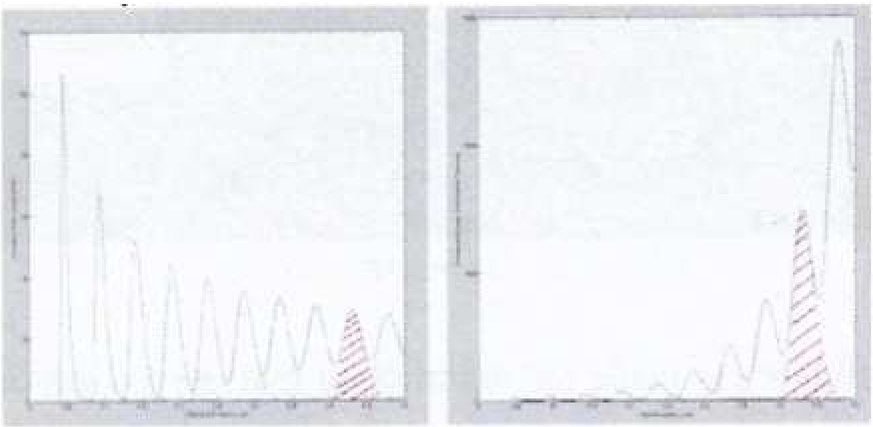


Figure 4

GaAs at 108 vm-1

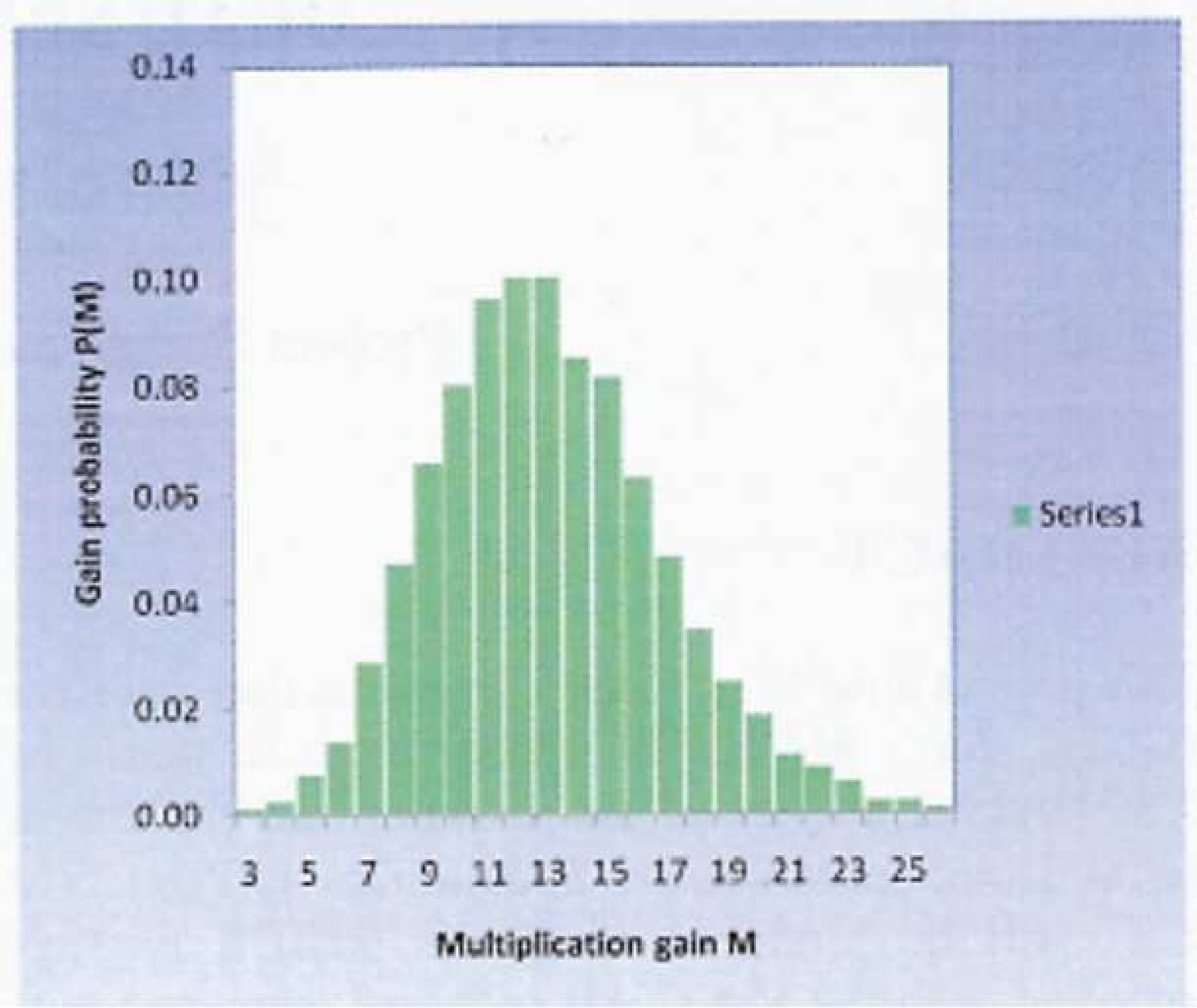
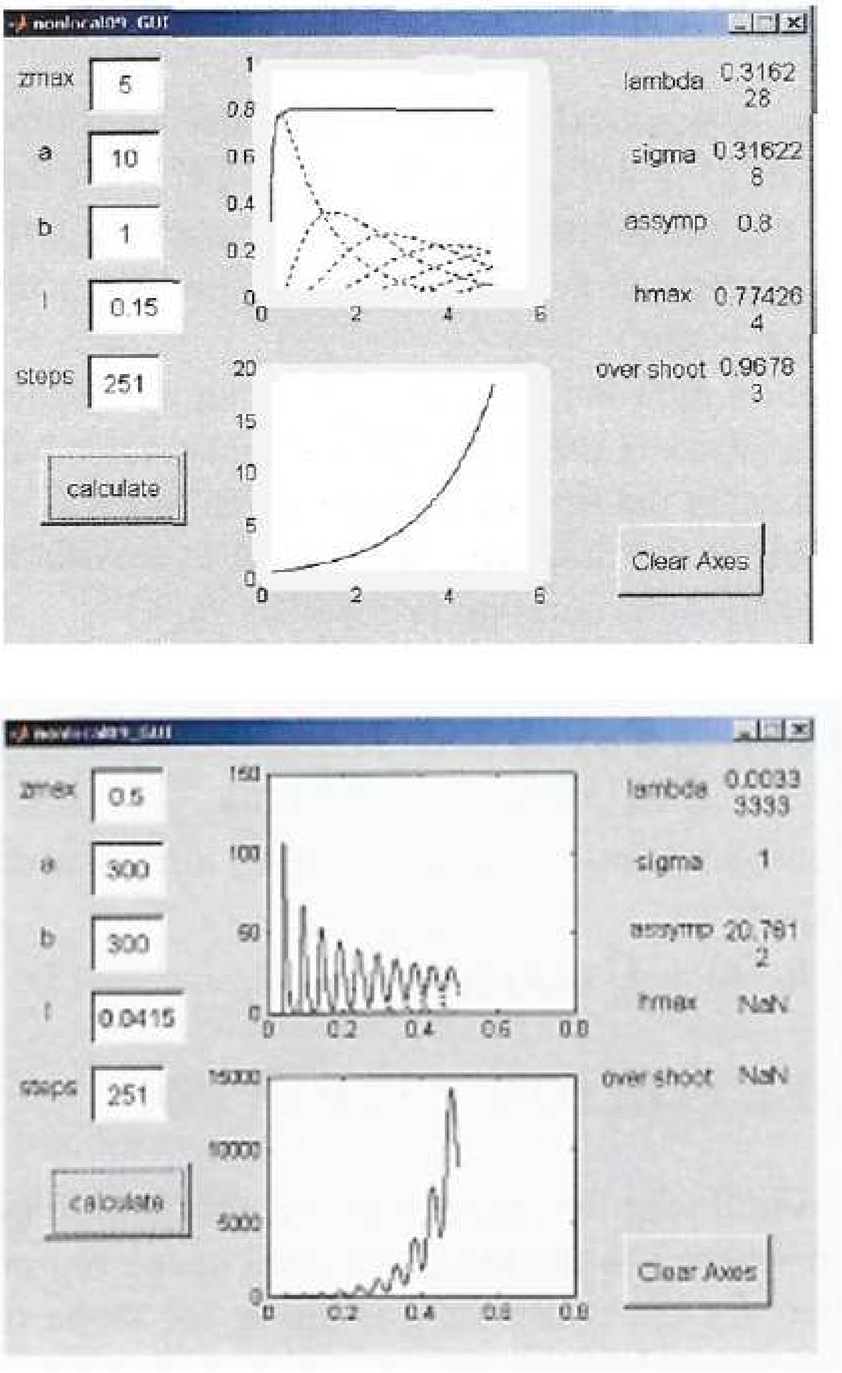


Figure 5

Digitised figure from Derelle et al. [3]



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lambda 0.00333333

sigma 1

assymp 20.7812

hmax NaN

over shoot NaN

Figure 6

Output graph of the GUI