Multi-Parameter Fluctuation Effects on InGaAsP/InP Geiger-Mode Avalanche Photodiodes

Qian Dai[1], Jie Deng[1], Zhu Shi[1], Li-Bo Yu1, and Hai-Zhi Song[1,2,a] *

[1]Southwest Institute of Technical Physics, Section 4-7, Renminnan Road, Chengdu, China

[2]Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Section 2-4, Jianshebei Road, Chengdu, Sichuan 610054, China

[a]hzsong1296@163.com

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Abstract. For Geiger-mode avalanche photodiodes, a statistical method is advanced to establish the quantitative correlation between the controllability of structure parameters and the homogeneity of device properties. Setting many parameters fluctuating independently and simultaneously, the collective effect of multi-parameters can be straightly obtained. For a typical InGaAsP/InP single-photon avalanche diode, it is seen that device homogeneity with excess bias fluctuation within 50% requires uncertainty in layer thickness and doping level better than ~3%.

Introduction

Single photon avalanche diodes (SPADs) [1] are widely investigated and developed for applications in many fields such as single photon imaging and quantum information processing, due to their advantageous features like small size, low bias, low power consumption and reliability, which are superior to other single photon detectors such as photomultiplier tubes and superconducting single photon detectors. InP-based Geiger-mode avalanche photodiode (APD) is an excellent SPAD for the near-infrared wavelength region (1.0-1.7 μm), especially as a focal plane array detector. Owing to the advanced epitaxial technology, InP-based SPADs are well developed and have been applied in recent years. However, there are still many critical problems to be resolved, one of which is the reproducibility and/or uniformity [2], which should be well-controlled by controlling the parameters in epitaxy and device process. Although one can estimate the influence of some individual parameters on the reproducibility/uniformity by an analytical method [3], it is difficult to clarify the collective effect from multiple parameters and impossible to quantitatively make tradeoff between various parameters. It is necessary to establish the quantitative correlation between the inhomogeneity in device characters and the fluctuation in all the epitaxy/process parameters. In this work, we perform a statistical analysis on device property by introducing random fluctuations in many structure parameters, and we give the control precisions of a few parameters required for good device reproducibility/uniformity for typical InGaAsP/InP SPADs.

Method

We design an InGaAsP/InP APD structure as an exampling object. As shown schematically in Fig.1(a), it has a hetero-structure consisting of separated absorption, charge, and multiplication layers. The InGaAsP absorption layer is designed to have band gap of 1.2 μm so as to get a peak response at 1.06 μm. Fig. 1(b) and (c) show the device characteristics of this structure, which are calculated using conventional APD theory [4] and recently advanced methods [5]. The simulated results of I-V characteristics without illumination is shown in Fig. 1(b), presenting individually the tunneling current, the generation/recombination current, and the total dark current with/without avalanche at 230K. The breakdown voltage V_b is defined as the value of applied reverse bias V corresponding to infinite avalanche current. The Geige-mode ($V > V_b$) dark current without

avalanche at 300K are contributed by both the generation/recombination and tunneling currents (not shown), while that at 230K are almost solely determined by the tunneling current. Figure 1(c) shows the dark count rate (DCR), the rate that an avalanche count occurs without any photon arrival, versus photon detection efficiency (PDE), the probability to record a count when there are incident photons (wavelength of 1.06 μm herewith). They are two most fundamental performance indices for a Geige-mode APD. Depending on the applied excess bias $V_{ex}=V-V_b$, DCR is getting worse while PDE is getting better. Operating at a middle excess bias $V_{ex0}=5$V, which will be taken as the reference point in the following simulation, is the optimal choice.

Taking the above structure parameters and the fundamental properties as a reference, we try studying the variation of device characters as a result of parameter fluctuations. In the application of SPAD arrays, thousands of pixels are generally biased by a common voltage V_0. If the individual pixels have structure fluctuation, the effective excess bias will be different from each other and then there occur inhomogeneity of device performance such as DCR and PDE. To study this effect, we randomly change the device structures in a way as, for any structure parameter t, allowed.

$$t_i = t_0(1+W\sigma_i),$$

(1)

where i=1, 2, 3…. denotes the cycle number of calculation trial, t_0 is the designed value of t as presented in Fig.1(a), W is an arbitrary constant determining the distribution width and σ_i is a series of random values normally distributed with full width at half maximum (FWHM) of 1. In this work,
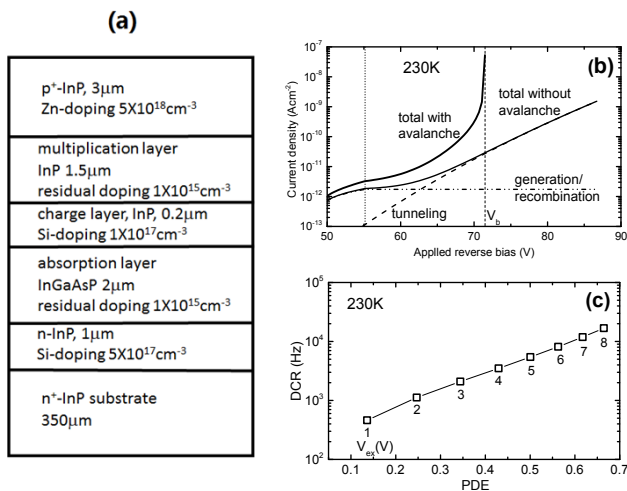

(a)

p+-InP, 3μm
Zn-doping 5X10^18 cm^-3

multiplication layer
InP 1.5μm
residual doping 1X10^15 cm^-3

charge layer, InP, 0.2μm
Si-doping 1X10^17 cm^-3

absorption layer
InGaAsP 2μm
residual doping 1X10^15 cm^-3

n-InP, 1μm
Si-doping 5X10^17 cm^-3

n+-InP substrate
350μm

Fig.1. (a) The epitaxial structure of a typical InGaAsP /InP Geige-mode APD used in this study; simulated (b) *I-V* characteristics and (c) DCR versus PDE of that device.

we use FWHM but not standard deviation to describe the fluctuation because FWHM encloses wider range of data than standard deviation for a normal distribution. The random variation in the way of Eq. 1 can be carried out simultaneously on many parameters, such as multiplication region width t_m, charge layer doping concentration n_c etc., *i.e.* $t_{mi} = t_{m0} (1 + Wt_m\sigma_{mi})$, $n_{ci} = n_{c0} (1 + W_{nc}\sigma_{nci})$ and so forth. Obviously the parameters are changing independently with their own distribution width. For every set of produced parameters (t_{mi}, n_{ci}….), device simulation gives a group of result for V_{bi}, $V_{exi}=V_0-V_{bi}$, DCRi and PDEi etc. With thousands of result data, statistics give the distributions of V_b, V_{ex}, DCR, and PDE, then the association between the fluctuations of device structure and device properties are figured out.

Since InP-based APD devices normally operate under cooled condition, we mainly focus on the device properties at 230K.

Results and Discussions

The simplest case is to study the fluctuation effect of a single parameter. By giving 1000 randomly varying values of absorption width ta normally distributed with FWHM of 3% ($W_{ta}=3\%$) while remaining other structure parameters invariable, we obtain the fluctuation distribution of excess bias V_{ex} as shown in Fig. 2(a). We see that the resulted V_{ex} fluctuation also exhibits a normal distribution, *i.e.* it can also be expressed by Eq. 1. Its distribution FWHM is 4.8%. By the same way, a 3% fluctuation in multiplication width t_m leads to a normal V_{ex} distribution with FWHM of 20%, as shown by Fig. 2(b). It implies that different parameters fluctuate the device properties to quite different degrees. More detailed and systematic simulations make clear how significant any

parameter is for a Gm-APD device. Figure 2(c) shows the V_{ex} distribution width as functions of the fluctuations of single parameters including the width/doping of the multiplication region t_m/n_m, absorption region t_a/n_a, and charge region t_c/n_c. We see that three parameters t_m, t_c and n_c, have strong effects, whereas other three n_a, t_a, n_m have weaker effects on excess bias V_{ex}. The strongest case is the doping concentration in the charge layer n_c. Fluctuation of only 3% in n_c may cause V_{ex} fluctuation of more than 30%. It suggests that the charge quantity should be considered most carefully in design and controlled most precisely in epitaxy process. The weakest case is the doping concentration in multiplication layer n_m. Fluctuation of 10% in n_m only brings about 5% fluctuation in V_{ex}. Besides, every parameter linearly generate V_{ex} fluctuation. As a reference, let us mark the parameter fluctuation FWHM leading to 10% of V_{ex} fluctuation as W_{-10}. From the data in the Fig. 2(c), we learn that the W_{-10} values of the absorption-region doping and width, the multiplication-region doping and width, and the charge-region doping and width are $W_{na-10}=19\%$, $W_{ta-10}=6.5\%$, $W_{nm-10}=23\%$, $W_{tm-10}=1.5\%$, $W_{nc-10}=0.5\%$, and $W_{tc-10}=0.9\%$, respectively.
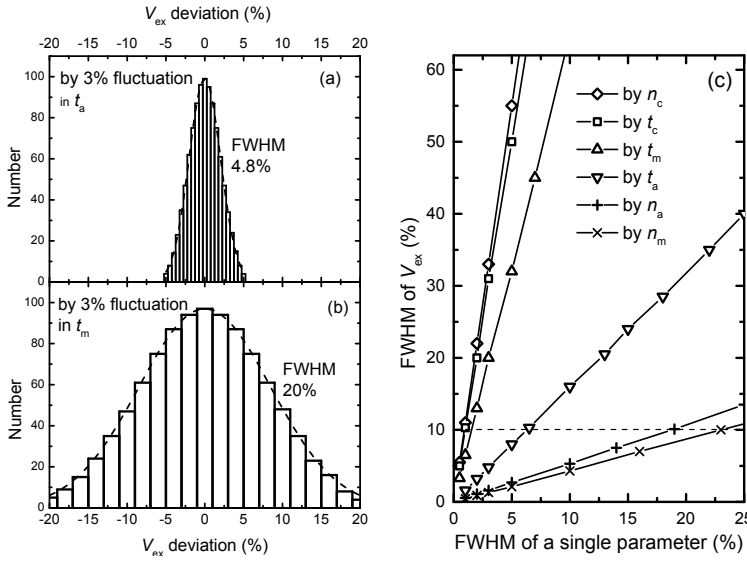

Fig. 2. Distribution of excess bias V_{ex} induced by a 3% normally fluctuated single parameter (a) absorption region width t_a, (b) multiplication-region width t_m; (c) V_{ex} fluctuation FWHM varying when a single parameter is changing.

It is more important to know several fluctuated parameters influence the precision of device properties. Firstly, let us consider the case of 2 parameters. Among the above six parameters, we choose arbitrarily two, e.g. (t_m, t_a). As a typical condition, we take 10% of V_{ex} fluctuation in the case of single varying parameters, corresponding to $W_{tm-10}=1.5\%$ of t_m fluctuation or $W_{ta-10}=6.5\%$ of t_a fluctuation as can be deduced from Fig 2(b), as a reference. In detail, we set $t_{mi}=t_{m0}(1 + W_{tm-10}\sigma_{tmi})$ and $t_{ai}= t_{a0}(1+W_{ta-10}\sigma_{tai})$ and keep other parameters invariable. Thousands of (σ_{tmi}, σ_{tai}) thus generate thousands of device character data sets (V_{exi}, DCR_i, PDE_i). Statistics over these results give the effect of simultaneously fluctuating t_m and t_a. The resulted V_{ex} fluctuation FWHM is 15%, less than a simple summation of single parameter effects 20%. Similarly changing other two arbitrary parameters, which have 14 choices such as (t_m, t_c), (t_c, n_c), (n_c, n_a) and so on, we get sets of device property data. Statistics on these data sets implies that the V_{ex} fluctuation generated by two parameters, normally and independently fluctuating with FWHM of W_{-10}, is $(15\pm2)\%$. Extending the above process to more parameters, we obtain the fluctuation of device property as a function of parameter numbers. The result for V_{ex} is shown in Fig. 3(a), where we see a sublinear change of V_{ex} fluctuation with increasing parameter number. As all of the six parameters are taken into accounted, the excess bias V_{ex} fluctuates with FWHM of 24%, far below a simple summation over single parameter effects. It suggests that the
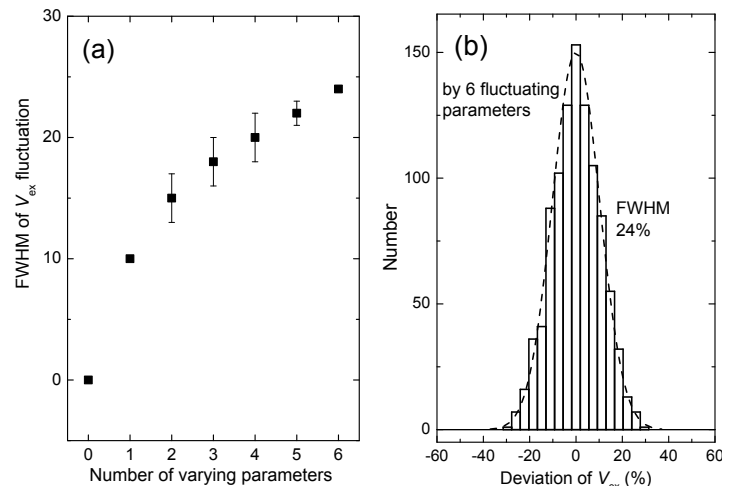

Fig.3. (a) Fluctuation of the excess bias V_{ex} as a function of the number of fluctuating parameters; (b) V_{ex} distribution caused by 6 fluctuating parameters

required limits in epitaxial condition may be greatly relaxed with respect to intuitive estimates. The V_{ex} distribution caused by six independently fluctuating parameters is shown in Fig. 3(b). Since the referred excess bias V_{ex0}=5V, the practical excess bias varies mainly within 4.4-5.6V, which looks tolerable in application. It is also important to know the effect on other device characters.

What is more meaningful, we shall see how the effect is if all the parameter fluctuations change. We check firstly a case where all parameters fluctuate with FWHM β times the above value W_{-10}. That is to set $n_{ai} = n_{a0}(1+ \beta W_{na-10}\sigma_{nai})$, $t_{ai} = t_{a0}(1+ \beta W_{ta-10}\sigma_{tai})$, $n_{mi} = n_{m0}(1+\beta W_{nm-10}\sigma_{nmi})$, $t_{mi} = t_{m0} (1+\beta W_{tm-10}\sigma_{tmi})$, $n_{ci} = n_{c0}(1+\beta W_{nc-10}\sigma_{nci})$, and $t_{ci} = t_{c0}(1+\beta W_{tc-10}\sigma_{tci})$. The result is presented in Fig. 4 by circles. It indicates that V_{ex} fluctuation increases proportionally with parameter fluctuation times β. When β=2, V_{ex} varies normally with FWHM of nearly 50%, which means V_{ex}~3.8-6.2V, acceptable in application. In this case, the fluctuations of n_a, t_a, n_m are respectively 38%, 13% and 46%, easy to realize in epitaxy; while those of t_m, n_c, and t_c should be better than 3%, 1.8% and 2%
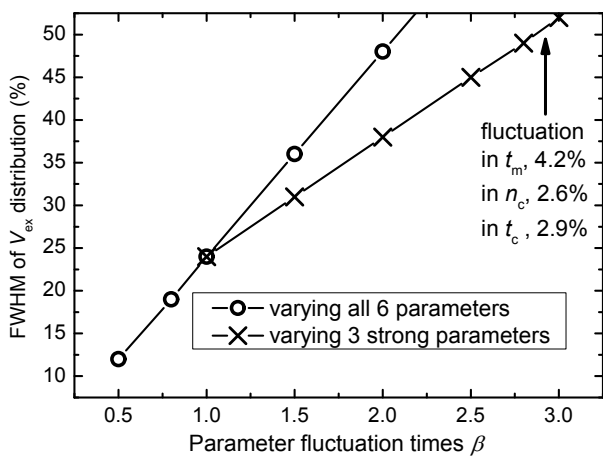

Fig. 4. V_{ex} fluctuation varying as all the six parameters or only 3 parameters t_m, n_c, t_c increase their fluctuations.

respectively, challenging for epitaxy growth. There may be some way to relax these strict requirements. Let us keep n_{ai}=$n_{a0}(1+ W_{na-10}\sigma_{nai})$, t_{ai}= $t_{a0}(1+ W_{ta-10}\sigma_{tai})$, n_{mi}= $n_{m0} (1+ W_{nm-10}\sigma_{nmi})$, i.e. remaining the fluctuations of weaker parameters at the reference level W_{-10}, while setting other parameters t_m, n_c, and t_c as the above, i.e. varying the stronger parameters with FWHM of βW_{-10}. The result shown by crosses in Fig. 4 indicates also a linear increase of V_{ex} fluctuation with β. More importantly, a V_{ex} fluctuation of ~50% corresponds to β~2.9, meaning that t_m, n_c, and t_c can vary within 4.2%, 2.6% and 2.9% respectively. A tradeoff among multiple parameters is thus practical for the design of SPAD arrays. If we set weaker parameters fluctuating less than W_{-01}, there will be more relaxation space in stronger parameters.

Summary

For Geiger-mode APDs, we propose a method to quantitatively correlate the controllability of structure parameters with the homogeneity of device properties. By setting many parameters fluctuating independently and simultaneously, the collective effect of multi-parameters can be obtained and a design tradeoff between different parameters becomes straightforward.

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