Low-Noise Silicon APD with Enhanced Blue-Violet Sensitivity

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Summary: A theoretical two-carrier formalism for the calculation of the optoelectrical properties of APDs is established based on the independent Bernouilli trial and generating function method. The gain and excess noise factor can be calculated for any doping profile under any bias and illumination wavelength. This is applied to the design of a CMOS compatible low-noise silicon avalanche photodiode. The doping profile and antireflection layer are optimized to achieve enhanced blue-violet sensitivity and low-noise, while keeping the operating bias at a moderate level. The properties of the fabricated APDs are in good agreement with the theoretical analysis.

Keywords: Silicon, APD, gain, excess noise factor, blue-violet enhanced

Introduction

For PET and high-energy physics applications, gamma photons are converted to blue or violet photons with scintillators and detected by an APD or photomultiplier [1]. Therefore, it would be advantageous if the APD used has low noise and enhanced blue-violet sensitivity [2]. Since sensitivity and noise are strongly dependent on the device doping profile, the operating bias, and the wavelength of the incident photons, design and optimization using conventional TCAD simulation would be very time-consuming. To this end, we have derived a formalism to calculate the gain and excess noise factor from a given doping profile at any bias and for any wavelength of incident photons. This formalism is based on the independent Bernouilli trial and generating function method, which applies the impact ionization rate for electrons and holes. It is shown that the theoretical results are in good agreement with the TCAD simulation. Therefore, for the design of APDs, it is only necessary to perform a process simulation to realize the obtained doping profile and to design an appropriate layout edge structure. Using this procedure, we developed a low-noise silicon APD with enhanced blue-violet sensitivity.

The opto electrical properties of APD

Due to the impact ionization the accelerated charge carriers in an electric field generate further generations of charge carriers according to the ionization rate of electrons and holes. The initial carriers can be the light-generated or thermally excited electron-hole pairs. We divide the one dimensional multiplication zone into N sections. The section i has a length of $l_i = \frac{e_a}{q|E(x_i)|}$, where $E(x_i)$ is the electric field strength at x_i, e_a is the ionization energy of charge carriers. Therefore, in section i, the electron has an impact ionization probability of $\alpha_n(x_i)l_i$, the hole has an impact ionization probability of $\alpha_p(x_i)l_i$, where the α_n and α_p are the impact ionization rates of electrons and holes, respectively. For photon of wavelength λ, the light generation probability in section i is $\gamma(\lambda)l_i \exp(-\gamma(\lambda)x_i)$, where γ is the absorption coefficient of photon. This random process can be well described by the N independent Bernoulli trial [3]. If we take the generating function as $\phi_i(t)$ for section i, we get the gain as

$$G_i = \phi_i'(1) \tag{1}$$

and its variance as

$$Var(G_i) = \phi_i''(1) - \phi_i'^2(1) + \phi_i'(1) \tag{2}$$

The excess noise factor is

$$F_i = 1 + \frac{Var(G_i)}{G_i^2} \tag{3}$$

For pn junctions formed in n-type silicon of doping concentration $1.3 \times 10^{15} cm^{-3}$ under a bias voltage of 202V, the calculated spectral gain and excess noise factor are shown in Fig. 1 and Fig. 2, respectively. It is shown that shorter wavelengths have higher gain and lower noise than those of longer wavelengths.

Low noise APD design and manufacture

To reduce the noise of the APD, it is important to achieve a lower ratio of hole to electron ionization rate, which means a lower electric field strength for silicon. Combined with the requirement of low leakage current and high blue-violet sensitivity, n-type 3ohmcm (100) silicon wafers are used. A shallow trench technology is introduced to reduce possible edge breakdown and to achieve better surface isolation. Furthermore, the top layers are designed to realize antireflection and passivation at the same time. The active

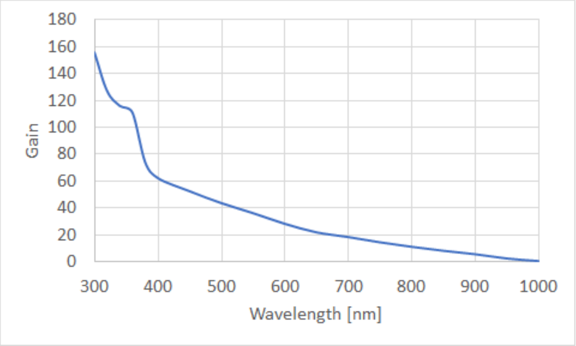

Fig. 1: The spectral gain characteristics of APD for a bias voltage of 202V.

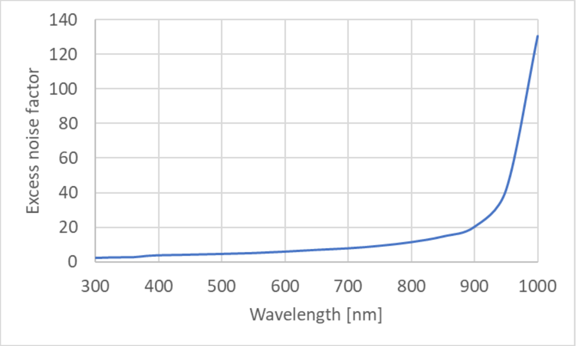

Fig. 2: The spectral excess noise factor characteristics of APD for a bias voltage of 202V.

area of the APD is $4.5mm \times 4.5mm$. Shallow pn junctions are formed through ion implantation.

Characterisation

After prototyping, the APD devices are systematically characterized. At low bias (20V), the dark current is between 0.3 and 0.5nA at room temperature. The gain voltage relations for illumination under red and blue LEDs are shown in Fig. 3. The spectral responses measured at bias voltages of 186V and 191V are shown in Fig. 4. The results showed that the sensitivity in the blue-violet region is increased. The peak sensitivity is at a wavelength of 400nm, where the gain is 42 for a bias voltage of 210V. The noise spectra under red and blue LED illumination are measured at a bias of 202V. The gain and excess noise factor are summerised in Tab.1. The excess noise factor for blue light is 7.9. Compared with Fig. 1 and Fig. 2, the agreement is good. Small deviations may be due to the doping concentration applied and the spectral profile of the LEDs.

Summary

A theoretical formalism for the optoelectrical properties of APDs is developed, which can effectively support the design and optimization of customer-specific APDs. A prototype of low-noise APD with enhanced blue-violet sensitivity is developed. The APDs have potential uses in the PET of nuclear medicine and electromagnetic calorimeter of high-energy physics experiment.

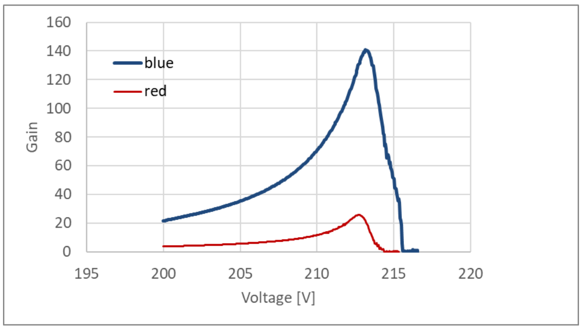

Fig. 3: The gain voltage characteristics of APD for two different LEDs with centre wavelengths of 405nm and 850nm.

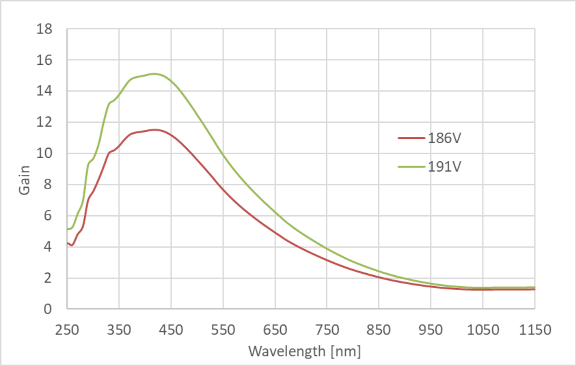

Fig. 4: The gain spectral response characteristics of APD for two bias voltages, 186V and 191V.

Tab. 1: The gain and excess noise factor measured at 202V

LED	Gain	Excess noise factor
red	4.4	31.5
blue	26.2	7.9

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