Optik 148 (2017) 268–274

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Reduction of dark current and gain increase in InAs avalanche photodiode with AlGaAs blocking layer

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ARTICLE INFO

Article history:
Received 16 May 2017
Accepted 5 September 2017

Keywords:
Dark current
Avalanche gain
Blocking layer
Excess noise factor

ABSTRACT

This article presents a new method to reduce the dark current and increase the avalanche gain in InAs avalanche photodiode (APD) by adding $Al_{0.84}Ga_{0.16}As$ blocking layer. This photodiode has displayed a high avalanche gain around 400 in 8 V bias voltage. Furthermore, a very low dark current and low excess noise factor between 0.1 and 1.9 in a temperature of 180 K to 300 K is observed. Finally, in comparison with other devices, a considerable increase of the gain along with decrease in dark current is observed.

1. Introduction

Having an internal gain, the APDs have a number of applications including near wavelength, mid wavelength and infrared such as fiber optic communication, gas sensors, laser radar and thermal imaging [1]. Function of the APDs is based on multiplication of the carriers originated from avalanche processes during the impact ionization process. Since the impact ionization is a stochastic process, we will always have an increase in dark current noise along with increase of gain in APDs [2].

Since the low excess noise in structure of APDs widely depends on properties of the materials used, thus there is a great interest to identify semiconductor materials with ideal and desirable properties in the structures [3]. To minimize the excess noise and increase the gain in structure of APD, there must be a significant difference between electron ionization coefficient (α) and hole ionization coefficient (β). Ideally, α & β should be close to zero and ionization coefficient ratio (K) must also be close to zero [4]. The low excess noise in function of APDs is independent of the avalanche gain. A feature of the impact ionization exclusively obtained by the electron in APDs is that, carrier transit time is not more than avalanche process time. InAs with an energy bandgap of 0.35 eV, provides the best light detection for the wavelengths in the range of 1550 nm to 3500 nm [5]. The electron ionization coefficient in InAs is considerably greater than hole ionization coefficient, thus multiplication region of InAs has some properties such as low dark current noise and gain-dependent low excess noise coefficient [4].

In previous works, Pin Jern Ker [3] has used an InAs photodiode p-i-n structure which includes the intrinsic region with a thickness of 3.5 μm and p & n layers respectively with thicknesses of 1 μm & 2 μm and a doping of 2×10^{18} cm^{-3}. For high gains, InAs APD with an intrinsic region of 3.5 μm has a low excess noise of 1.45–1.6. Analysis and measurement of avalanche gain and excess noise of InAs electron APD and its dependence on temperature within range of 77 K to 250 K

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http://dx.doi.org/10.1016/j.ijleo.2017.09.010
0030-4026/

Table 1
Concentration of Carriers and Thickness of proposed Structure.

i region		p region		n region	
Thickness	Doping	Thickness	Doping	Thickness	Doping
12 μm	4×10^{16} cm^{-3}	2.4 μm	5×10^{18} cm^{-3}	2 μm	2×10^{18} cm^{-3}

was studied. Avalanche gain has started with pure electron injection. Decrease in electron avalanche gain has been shown with temperature reduction in a constant bias voltage. This has led to increase in ionization threshold energy too. Thus it has been shown in the proposed model that a high gain can be produced along with low excess noise. Wenlu Sun[6] has employed a p-i-n photodiode structure with a 6 μm thick intrinsic region and p & n layers respectively with thicknesses of 1.6 μm & 1 μm. Using a 0.05 μm thick AlAsSb blocking layer in region p, he showed that the dark current can be reduced in room temperature to a great value. In the introduced structure, the wide intrinsic area has caused an avalanche gain around 300 in a voltage bias of 15 V to be obtained in room temperature. Wenlu Sun et al. [7], have studied and analyzed the charge-compensated InAs APDs with a multiplication region of 6 μm. P region includes a p^+ & p layers respectively with a thickness of 0.1 μm & 0.9 μm and doping of 1×10^{19} cm^{-3} & 5×10^{18} cm^{-3}.In this structure, n^+ layer has a thickness of 1 μm and doping 1×10^{18} cm^{-3}.This device produces a low dark current for a gain around 100 in room temperature and a voltage of 10 V. A layer with grading doping with a thickness of 2 μm has been used in region p in this structure. It is noteworthy that amount of measured dark current is high compared to the [6]. Akma Roslan et al. [8], have simulated the p-i-n structure of InAs photodiode with an intrinsic region of 3.5 μm and a doping concentration of 2×10^{14} cm^{-3}, n and p layers respectively with thicknesses of 1.9 μm & 1 μm and doping concentrations of 2×10^{18} cm^{-3} and 6×10^{18} cm^{-3}. Because of narrow bandgap energy in InAs the electrons are easily transmitted from valence band to conduction band and they ultimately need a low-threshold energy for impact ionization. Dark current density has been measured in a voltage of 0 V to 1 V and has shown an approximate of $0.12 \frac{A}{cm^2}$ in a voltage of 0.1 V.

To obtain the low dark current, we used an AlGaAs blocking layer with a thickness of 0.3 μm in p region in the structure to suppresses the electron diffusion current and the predominant dark current in the room temperature. By biasing the device, the ionized carriers easily penetrate the high-field region and start the impact ionization process. In InAs, the photons are completely absorbed in p region and finally lead to pure electron injection inside the depletion region. In this work, the minimum avalanche gain in low voltage has been estimated about 1 V and the desired avalanche gain is obtained in bias voltages under 16 V. On the other hand, the gain-dependent excess noise coefficient under 2 has been shown.

2. Device structure and the model

Since the impact ionization is a random process, the gain faces some fluctuations. Therefore, a high level of noise usually called the excess noise or multiplication noise is produced which with excess noise coefficient, its rate is identified and shown with (F). F is a derivation of avalanche gain caused by exclusively electron ionization and follows the relationship mentioned below [10].

$$F_e(M_e) = KM_e + \left(2 - \frac{1}{M_e}\right)(1 - K) \tag{1}$$

The noise initiated from impact ionization process is created in two ways. First, through the random situation of the secondary carriers produced in avalanche region, second, from number of the produced carriers depending on impact ionization inside the avalanche region. Obviously, producing a low amount of (F) in APDs is conditional on maintaining the high difference among α and β coefficients in a way that one of them is close to zero. To obtain the lowest level of (F) in a specific APD type, a carrier type with a greater ionization coefficient must be injected, and then the impact ionization process is started.Recently, APDs that have cut-off wavelengths of about 3 μm have been shown with excess noise coefficient of F(M)~1 which have a rather low dark current in room temperature [6]. Increase in thickness of multiplication region brings increase of gain in low bias [5]. In our proposed structure, i layer has a low background doping but a large depletion region width. The bias voltage rate and the uniform electric filed created in intrinsic region is very important to have high gain of the device. Thickness and doping of the layers have been designed according to Table 1.

Designing high-gain InAs APD often requires a thick multiplication region. In this article we managed to obtain a high gain in InAs APD having a 12 μm intrinsic region and a low doping of cm^{-3}. Structure of the proposed device has been drawn in Fig. 1.

Region P in this structure include a layer with a thickness of 0.1 μm of InAs substance and a doping of 10^{18} cm^{-3}. Metals such as Ti/Au (titanium/gold) respectively with thicknesses of 20/200 nm are used for InAs APD designed structure contacts, because strength of these metals for all photodiode structures is 5 ohm to 12 ohm in room temperature.

InAs is an absorption layer and AlGaAs is a barrier layer used in the structure. There exist composition, (X), of $Al_xGa_{1-x}As$ that lattice matches InAs. The $Al_xGa_{1-x}As$ combination has a large conduction band and an energy band a little more different with InAs. Any combination of $Al_xGa_{1-x}As$ has a great energy of conduction band compared to InAs. The great difference among energies of conduction band effectively covers the thermionic emission effect above the barrier. Because it passes under the barrier layer by tunnelling and creates an effective barrier against electron majority carrier currents in detectors.