Influences of polarization effect and p-region doping concentration on the photocurrent response of solar-blind p–i–n avalanche photodiodes*

Li Xiao-Jing(李晓静)[a], Zhao De-Gang(赵德刚)[a]†, Jiang De-Sheng(江德生)[a], Liu Zong-Shun(刘宗顺)[a], Chen Ping(陈 平)[a], Wu Liang-Liang(吴亮亮)[a], Li Liang(李 亮)[a], Le Ling-Cong(乐伶聪)[a], Yang Jing(杨 静)[a], He Xiao-Guang(何晓光)[a], Wang Hui(王 辉)[b], Zhu Jian-Jun(朱建军)[b], Zhang Shu-Ming(张书明)[b], Zhang Bao-Shun(张宝顺)[b], and Yang Hui(杨 辉)[a,b]

[a] *State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*
[b] *Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou* 215123, *China*

(Received 20 March 2013; revised manuscript received 3 May 2013; published online 20 December 2013)

The influences of polarization and p-region doping concentration on the photocurrent response of $Al_{0.4}Ga_{0.6}N/Al_{0.4}Ga_{0.6}N$ /$Al_{0.65}Ga_{0.35}N$ p–i–n avalanche photodetector are studied in a wide range of reverse bias voltages. The simulation results indicate that the photocurrent under high inverse bias voltage decreases with the increase of polarization effect, but increases rapidly with the increase of effective doping concentration in p-type region. These phenomena are analyzed based on the calculations of the intensity and distribution of the electric field. A high p-region doping concentration in the p–i–n avalanche photodetector is shown to be important for the efficient compensation for the detrimental polarization-induced electrostatic field.

Keywords: nitride materials, photodetector, polarization

PACS: 85.60.Gz, 77.22.Ej, 74.72.Gh **DOI:** 10.1088/1674-1056/23/2/028503

1. Introduction

As one of the third generation semiconductors, III–V nitride materials have the advantages of wide-bandgap, high electron drift saturation rate, high breakdown electric field, and low dielectric constant. III–V nitride materials show great promise for a wide range of device applications, including blue and ultraviolet light-emitting diodes and lasers,[1–3] ultraviolet photodetectors,[4] high-temperature and high-power field-effect transistors,[5,6] etc. Investigations of AlGaN-based photodetectors are motivated by the need for ultraviolet (UV) detection in many civilian and military applications, including flame sensors, ultraviolet astronomy, early missile threat warning, etc. Many of these applications require high sensitivity, low-noise, and visible- or solar-blind detection. AlGaN is a promising material system for solar-blind device, because $A1_xGa_{l-x}N$ in its wurtzite form has a direct band gap tunable from 3.4 eV at $x = 0$ to 6.2 eV at $x = 1$, covering the whole range of solar-blind wavelengths.[7] We can regulate the composition of Al to make AlGaN-based p–i–n photodetectors operate in the solar blind spectral region.[8] Avalanche photodiodes (APDs) using internal avalanche multiplication as the most effective gain mechanism bring hope for realizing high photocurrent gain UV photodetectors. APD is one of the most promising photodetectors[9] because it does not require complicated external amplification equipment and can reduce the noise resulting from amplification equipment. The p–i–n APD normally shows an internal current gain due to impact ionization (avalanche effect) when a high reverse bias voltage is applied to the photodiode. However, the material growth and device design of GaN-based heterostructure APD have encountered a lot of challenges. As is well known, III–V nitride materials have strong spontaneous polarization and piezoelectric effects, resulting in a large quantity of polarization charges distributed at the interfaces.[10] The influence of polarization effect on the operation of APD is an important research subject.

We use APSYS simulation program to calculate the photocurrent of AlGaN-based p–i–n avalanche photodetector in a wide range of reverse bias voltages from 40 V to 140 V. The photocurrent is defined as the difference between the light currents, that is, the total current produced under the light ($\lambda = 260$ nm, $P = 6$ W) illumination, and the dark current of the device. The light illuminates from the back direction of the device as schematically shown in Fig. 1, unless otherwise mentioned.

*Project supported by the National Science Fund for Distinguished Young Scholars, China (Grant No. 60925017), the National Natural Science Foundation of China (Grant Nos. 10990100, 60836003, 60976045, and 61176126), and the Tsinghua National Laboratory for Information Science and Technology Cross-discipline Foundation.

†Corresponding author. E-mail: dgzhao@red.semi.ac.cn

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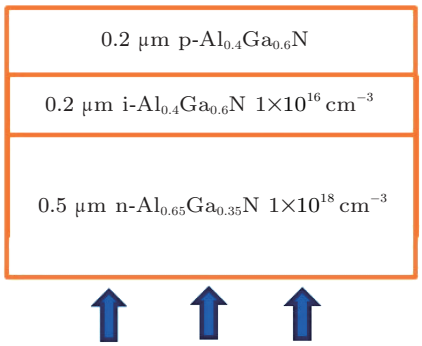


Fig. 1. (color online) Schematic diagram of the investigated AlGaN-based p–i–n APD.

Based on finite element analysis, APSYS includes physical models such as carrier transport, Schrödinger and Poisson equations, optical absorption model, and thermal analysis. Taking the polarization charge and two-dimensional (2D) electron gas into consideration, the Poisson equation is modified into

$$\frac{\mathrm{d}}{\mathrm{d}z}\left[\varepsilon_0\varepsilon_r(z)\frac{\mathrm{d}}{\mathrm{d}z}V(z)\right] = -\rho(z), \quad (1)$$

$$\rho(z) = q[N_{\mathrm{D}}^{+} - N_{\mathrm{A}}^{-} + p - n + p_{2\mathrm{D}} - n_{2\mathrm{D}} + \delta N], \quad (2)$$

where N_{D}^{+} is the donor doping concentration, N_{A}^{-} is the acceptor doping concentration, and δN is the polarization charge which is induced by spontaneous and piezoelectric polarization. The APSYS is used to calculate the photocurrent response of p–i–n photodetectors by jointly solving current continuity equation, carrier transmission equation, and photon rate equation. The electric field induced by the spontaneous and piezoelectric polarization in the device grown on [0001] oriented GaN template is considered in the simulation through a so-called screening factor P, which represents the percentage of polarization charges residing at the interfaces of nitrides.

We investigate the effects of polarization and p-region effective doping concentration on the photocurrent response of AlGaN-based p–i–n APD under high reverse bias voltage using APSYS simulation program, which is of practical significance for the design and application of AlGaN-based p–i–n solar-blind avalanche photodetector.

2. Simulation structure of APD device

Because of their convenience of integrating flip-chip bonded technology, back-illuminated solar-blind avalanche photodetectors have attracted considerable attention in the research field of APDs.[11] The schematic diagram of a back-illuminated AlGaN heterostructure is shown in Fig. 1. The $Al_{0.65}Ga_{0.35}N$ layer, with an absorption edge nearly at 220 nm is chosen to be the n-region material to form a suitable window layer. The i-region and p-region are both $Al_{0.4}Ga_{0.6}N$, with an absorption edge nearly at 280 nm. Thus, the p–i–n APD structure can operate in a solar-blind spectral region (280 nm $> \lambda >$ 220 nm). In order to obtain a high response of APD, we have tested the influence of the thickness parameter of GaN-based APD.[12] The thickness values of n-region, i-region, and p-region are reasonably chosen to be 0.5 μm, 0.2 μm, and 0.2 μm, respectively, in the simulation. The doping concentrations of the n-region and i-region are fixed to be 1×10^{18} cm^{-3} and 1×10^{16} cm^{-3}, respectively, and the p-region doping concentration is varied in a range from 1×10^{17} cm^{-3} to 1×10^{18} cm^{-3}.[13,14]

In the APSYS simulation process, the dark current and photocurrent of the p–i–n diodes are calculated, with an electric field-dependent impact ionization effect taken into consideration. Owing to the lack of data relevant to the ionization rate for AlGaN alloy, we take the ionization rate of GaN[15,16] as the first order approximation. At first, we keep the p-region effective doping concentration unchanged and study the effect of polarization on the photocurrent in a wide range of varying reverse bias voltages. Then, the polarization is fixed and the p-region doping concentration is changed.

3. Simulation results and discussion

Firstly, we study the photocurrent response under various values of polarization with a fixed p-region doping concentration. As shown in Fig. 2(a), the photocurrent response decreases obviously with screening factor (P) increasing from 0 to 0.8 while the p-region doping concentration is fixed at 1×10^{17} cm^{-3}. When the reverse bias voltage is 130 V, the photocurrents for $P = 0$, $P = 0.4$, and $P = 0.8$ are 1.17 A, 0.89 A, and 0.73 A, respectively. Similar diagrams of photocurrent response can also be found in those cases where p-region doping concentrations are 5×10^{17} cm^{-3} (Fig. 2(b)) and 1×10^{18} cm^{-3} (Fig. 2(c)), showing the differences between the magnitudes of photocurrent responses. If the reverse bias voltage is fixed at 130 V, the corresponding photocurrents for $P = 0$ are 1.86 A and 4.70 A, when the p-region doping concentration is 5×10^{17} cm^{-3} and 1×10^{18} cm^{-3}, respectively.

As is well known, photocurrent is an important parameter of APD performance. It is found that the screening factor (P) should be reduced as much as possible to achiev a larger photocurrent. To understand the effect of the polarization on photocurrent, the distribution of electric field strength is studied. Taking the case of Fig. 2(a), for example, when the p-region doping concentration is fixed at 1×10^{17} cm^{-3}, the distributions of electric field strength with various screening factors are shown in Fig. 3. It is found that the intensity of the electric field in the i-region decreases as the screening factor increases from 0 to 0.8. Actually, when significant interface charges induced by spontaneous and piezoelectric polarization are taken into consideration, the polarization-induced electrostatic field (in the order of 10^5 V/cm) whose direction is opposite to that of the reverse bias field will severely compensate for the reverse bias field in the i-region.[17,18]

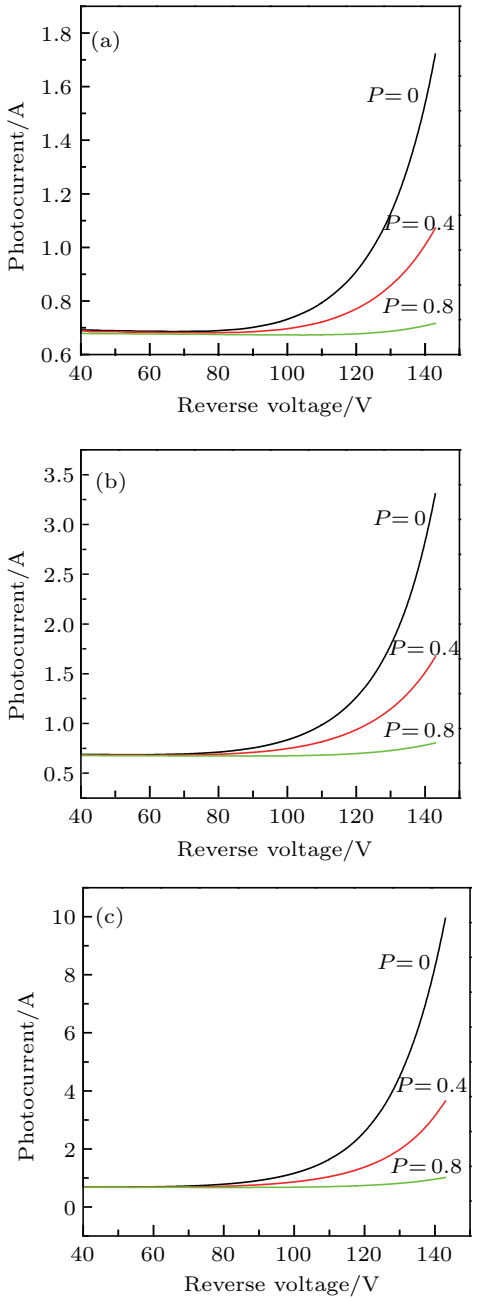


Fig. 2. (color online) Photocurrents under various screening factors with p-region doping concentrations fixed at (a) 1×10^{17} cm^{-3}, (b) 5×10^{17} cm^{-3}, and (c) 1×10^{18} cm^{-3}.

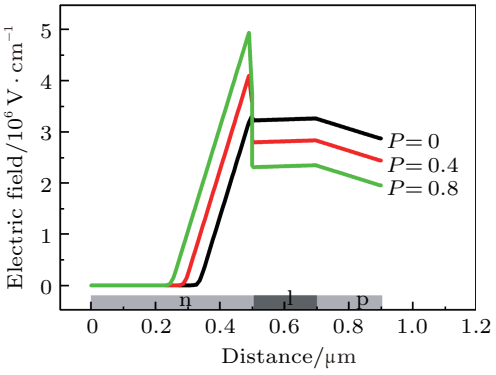


Fig. 3. (color online) Distributions of electric field under a reverse bias of 140 V with different screening factors when p-region doping concentration is 1×10^{17} cm^{-3}.

In APD the i-region is an active region where impact ionization multiplication of carriers happens under the condition of high reverse bias voltage. Next, we discuss the change of photocurrent dependent on the impact ionization effect. As is well known, the impact ionization rate is strongly dependent on the electric field in the i-region. The relationship between the impact ionization rate and the i-region electric field is presented with the following expression:[15,19]

$$\partial = A\mathrm{e}^{(-B/|E|)}, \tag{3}$$

where α is the impact ionization rate defined as the number of electron–hole pairs generated by a carrier travelling a unit distance, A and B are constants dependent on material, and $|E|$ is the absolute value of the intensity of i-region electric field.

With the increase of P, the polarization-induced field increases while the reverse bias field remains unchanged. As a result, the total electrostatic field in the i-region decreases, as shown in Fig. 3, which results in a reduced impact ionization rate. The impact ionization rate is a critical factor to affect the magnitude of photocurrent of APD under high reverse bias voltage conditions. Owing to the decrease of impact ionization rate, the number of electron–hole pairs generated in i-region reduces, resulting in a decrease of photocurrent under high reverse bias voltage.

It is clear that the polarization has a negative effect on the photocurrent response of AlGaN-based p–i–n solar-blind APD according to the above discussion. It is obvious that the reduction of polarization effect may improve the photocurrent response of APD under high reverse bias voltage. As is well known, the spontaneous polarization is unavoidable for III–V nitride materials grown in the [0001] orientation, but the piezoelectric polarization may be reduced through some structural modifications of the APD.[20] For example, n-AlInN can be used instead of n-AlGaN to reduce piezoelectric polarization by reducing the lattice mismatch. This may provide a guide line to the design of APDs with better characteristics.

Then, we study the photocurrent response at various p-region doping concentrations in the case of fixing polarization. The values of screening factor (P) are assumed to be 0, 0.4, and 0.8, respectively. As shown in Fig. 4(a), the photocurrent response increases obviously with p-region doping concentration increasing from 1×10^{17} cm^{-3} to 1×10^{18} cm^{-3} while the screening factor (P) is fixed at $P = 0$. If the reverse bias voltage is fixed at 130 V, the corresponding photocurrents are 1.17 A, 1.86 A, and 4.70 A, when p-region doping concentrations are 1×10^{17} cm^{-3}, 5×10^{17} cm^{-3}, and 1×10^{18} cm^{-3}, respectively. Similar diagrams can also be obtained in the cases of $P = 0.4$ and $P = 0.8$, which are shown in Figs. 4(b) and 4(c), respectively. In the case that the reverse bias voltage is 130 V, the photocurrents for $P = 0.4$ and $P = 0.8$ are 2.07 A

and 0.92 A, respectively, when the p-region doping concentration is 1×10^{18} cm^{-3}.

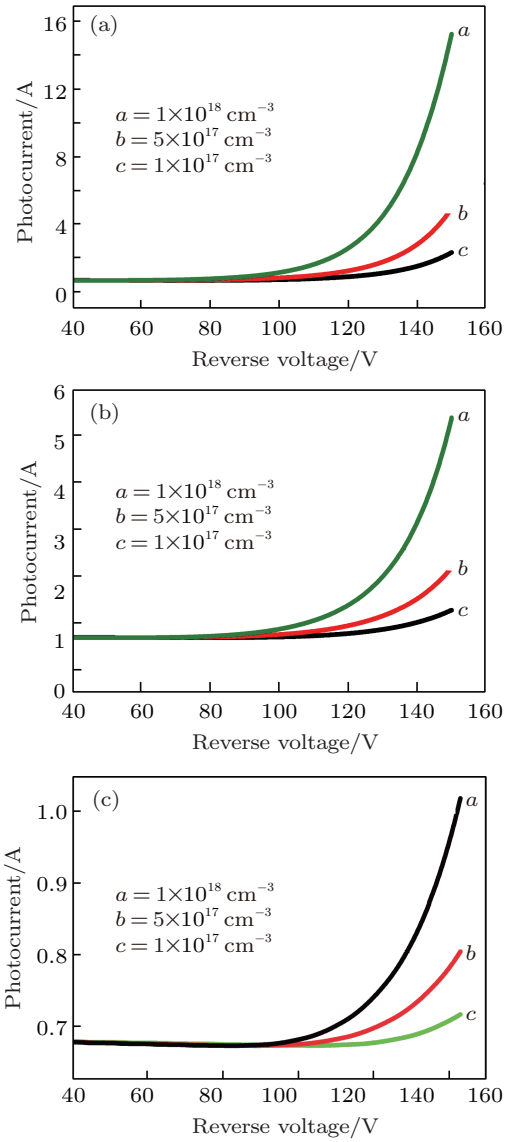


Fig. 4. (color online) Photocurrents with various p-region doping concentrations (in unit cm^{-3}) when the screening factors are (a) $P = 0$, (b) $P = 0.4$, and (c) $P = 0.8$.

It is concluded that elevating p-region doping concentration can improve the photocurrent response of AlGaN-based p–i–n solar-blind APD under a high reverse voltage condition. The mechanism of the effect of p-region doping concentration on the photocurrent of AlGaN-based APD under high reverse bias voltage can be analyzed by calculating the electric field. When the screening factor is set to 0.4, the distributions of electric field strength with various p-region doping concentrations are shown in Fig. 5. The electric field increases as the p-region doping concentration is elevated because a higher p-region doping concentration can effectively provide more free charges at interfaces and realize a better restriction on the polarization-induced electric field in the i-region, making the total electric field in the i-region stronger.[18,21] As a result, the impact ionization rate increases, resulting in an increase of photocurrent of APD under high reverse bias voltage condition.

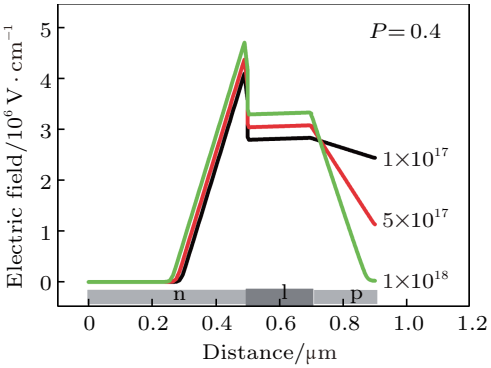


Fig. 5. (color online) Intensity distributions of electric field under 140 V reverse bias with different p-region doping concentrations (in unit cm^{-3}) when the screening factor is 0.4.

Based on the above calculations, we will check what will happen when the two parameters (i.e., the intensity of polarization and p-region doping concentration) are changed simultaneously. It is found that elevating p-region doping concentration can compensate for the negative effect of polarization. It is interesting to note that the photocurrents with different values of screening factor (P) and different p-region doping concentrations could almost be the same if these two parameters change in pairs in the opposite directions. As is well known, the photocurrent responses of $P = 0$ and $P = 0.4$ with the same p-region doping concentration cannot be the same. However, when we take different p-region doping concentrations (i.e., 1×10^{17} cm^{-3} and 5×10^{17}cm^{-3}), the photocurrent responses in the two cases will become almost the same (see line with squares and the line with triangles line in Fig. 6). A similar situation will occur for the other two groups of curves, as shown in Fig. 6, whose parameters are shown in Table 1.

From the above results, it can be seen that elevating p-region doping concentration can effectively compensate for the effect of increasing polarization on the photocurrent response of APD under high reverse bias voltage condition. According to the fore-mentioned discussion about the physical mechanism, the increase of screening factor (P) makes the i-region electric field decrease, while the increase of p-region doping concentration makes the i-region electric field increase. Their joint effect results in a compensation for the change of electric field in the i-region. Therefore, elevating p-region doping concentration can effectively compensate for the effect of increasing polarization on the impact ionization rate. The significance of a high p-region doping concentration in AlGaN-based p–i–n APD could be well understood because it can efficiently reduce the detrimental polarization-induced electrostatic field in the i-region.

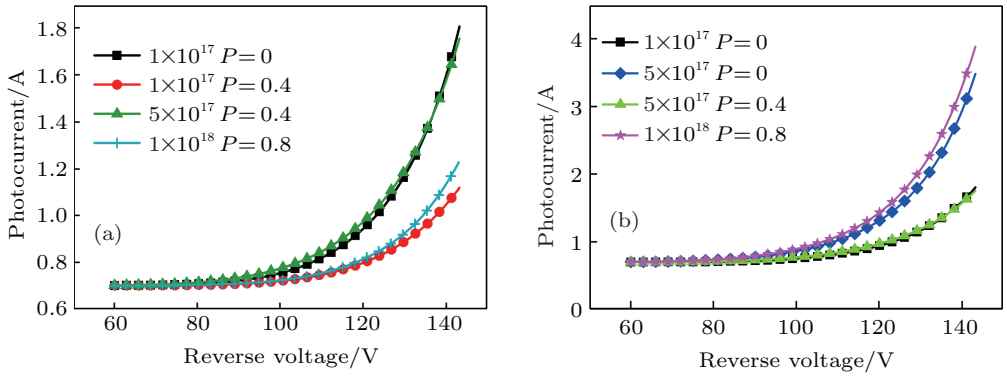


Fig. 6. (color online) The photocurrent responses of AlGaN-based p–i–n avalanche photodetector with different p-region doping concentrations (in unit cm^{-3}) and screening factors.

Table 1. Parameters of corresponding photocurrent in Fig. 6.

Screening factor (P)	Group 1		Group 2		Group 3	
	0	0.4	0	0.4	0.4	0.8
p-region doping concentration/cm^{-3}	1×10^{17}	5×10^{17}	5×10^{17}	1×10^{18}	1×10^{17}	1×10^{18}
Symbols of the curves in Fig. 6	—■—	–▲–	–◆–	–★–	–●–	–+–

4. Conclusions

The effects of polarization and the p-region doping concentration on the photocurrent response of $Al_{0.4}Ga_{0.6}N/Al_{0.4}Ga_{0.6}N/Al_{0.65}Ga_{0.35}N$ p–i–n APDs under high reverse bias voltage condition are theoretically investigated. The simulation results indicate that the photocurrent response under a high reverse bias voltage decreases with an increase of polarization intensity. Meanwhile, it increases effectively as p-region doping concentration is elevated. The physical mechanism is analyzed by calculating the distribution of electric field strength in the i-region. The increase of polarization intensity makes the i-region electric field decrease, while the increase of p-region doping concentration makes the i-region electric field increase, resulting in the changes of impact ionization rate and the photocurrent response under high reverse voltage.

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