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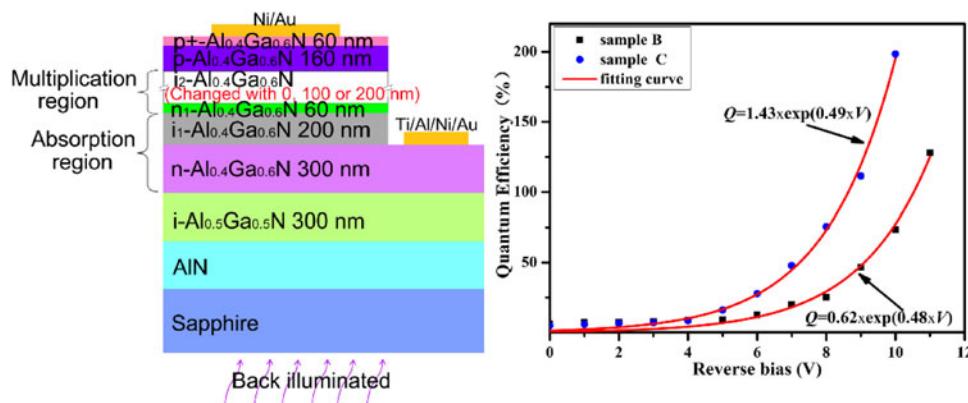
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Abstract: An experimental approach to evaluate the average energy required by holes for impact ionization in $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ alloys is presented. A series of back-illuminated separate absorption and multiplication structures with different thickness of multiplication layer are employed. With the measured quantum efficiency of devices and a consideration of energy conservation in ionization process, the average energy for electron-hole pair production by energetic holes is obtained and it qualitatively agrees with the bond energy of $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$, which is estimated from the Vegard's law.

Index Terms: Impact ionization, average energy, $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$.

1. Introduction

Solid-state avalanche photodiodes (APDs) based on $\text{Al}_x\text{Ga}_{1-x}\text{N}$ ternary alloy semiconductors have drawn great interest for the detection of very weak ultraviolet (UV) signals in the solar-blind range ($\lambda < 280$ nm), due to the intrinsic solar blind property of AlGaN material when Al composition exceeds 40% [1], [2]. In addition, the AlGaN UV-APDs have other outstanding advantages such as low power consumption, small size and no need for cooling. Thus, they could be a viable alternative to current bulky and fragile photomultiplier tubes (PMTs) and silicon-based APDs with extra filtering [3].

In previous works, several research groups have reported successful solar-blind operation with $\text{Al}_x\text{Ga}_{1-x}\text{N}$ APDs using Schottky, p-i-n and separate absorption and multiplication (SAM) structures [4]–[6]. However, the development of AlGaN solar-blind APDs has lagged far behind that of GaN APDs. In fact, there is a certain need for high performance AlGaN-based UV APDs. To design a high

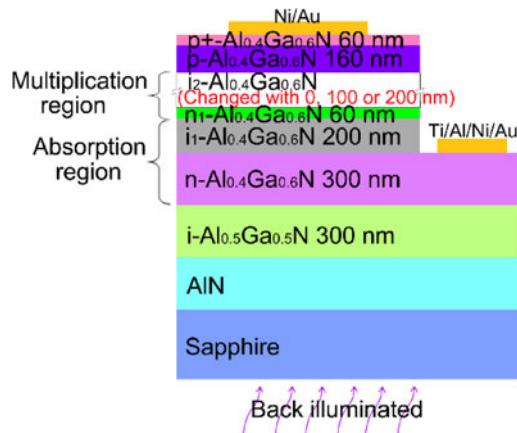


Fig. 1. Schematic cross-section showing the device structure of the back-illuminated.

performance APDs, it is not only related to the quality of material but also related to the knowledge of carrier behavior at high electric field. Although Bellotti and Bertazzi have computed the carrier impact ionization coefficients in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloy using a full-band Monte Carlo model [7], there has been no reports on the energy for impact ionization, which a carrier must have to create secondary electron-hole pair by collision. More detailed and complete understanding of the impact ionization is desirable both on fundamental scientific grounds and to design high performance solid-state UV avalanche detectors. Consequently, in the letter, we propose an experimental method to evaluate the average energy of impact ionization for the holes in $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ alloy.

2. Experimental Details

It is well known that a carrier must travel a finite distance which is generally referred to as the “dead length” before it can gain sufficient energy from the applied electric field to have a nonnegligible ionization probability [8]. It means that the ionization probability is not only a function of the intensity of electric field but also a function of the width of depletion region. Thus, a series of AlGaN-based APDs with a change in the width of the multiplication region were adopted. Meanwhile, a back-illuminated separate absorption and multiplication (SAM) structure was employed to realize hole-initiated multiplication due to the higher holes impact ionization coefficients [6].

The epitaxial structure of $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ APDs were grown on the AlN templates which were deposited on 2 in c-plane sapphire substrates using the method of two-step growth by low-pressure metal-organic chemical vapor deposition (LP-MOCVD) [9]. A 300 nm unintentionally doped $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ layer was firstly grown on the AlN template. Then, the growth continued with the different SAM structures. The 200 nm unintentionally doped $i_1\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer together with the 300 nm Si-doped $n\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer made up of the light absorption region. Subsequently, a 60 nm $n_1\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer as a charge layer was introduced. The thickness of the unintentionally doped $i_2\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer was varied to achieve a change in the width of the multiplication region with thickness of 0, 100, and 200 nm, corresponding to samples A, B, and C, respectively. On top of the Mg-doped $p\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer, a $p^+\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer was grown to improve the contact resistance of p-type ohmic electrode. A schematic diagram of the complete device structure is shown in Fig. 1 and the carrier concentrations are given in the accompanying Table 1. The carrier concentrations were determined by Hall-effect measurements.

For the device fabrication process, firstly, inductively coupled plasma (ICP) dry etching method was adopted to etch the material to the $n\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer and form a $500\text{-}\mu\text{m}$ -diameter mesa. Then, the samples were treated by a photo-electrochemical method to recover the damage made by ICP etching so as to reduce the leakage current [10]. The etching was followed by the electrodes deposition using electron-beam evaporation system. On top of the $p^+\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer, a Ni/Au

TABLE 1
Carrier Concentrations of the Various Layers Used in Device Structure

Layer	Composition	Doping
p+	Al _{0.4} Ga _{0.6} N Mg+	[Mg] = $\sim 1 \times 10^{20}$ cm ⁻³
p	Al _{0.4} Ga _{0.6} N Mg	p = 3×10^{17} cm ⁻³
I ₂	Al _{0.4} Ga _{0.6} N UD	n = 1×10^{16} cm ⁻³
n ₁	Al _{0.4} Ga _{0.6} N Si	n = 3×10^{17} cm ⁻³
I ₁	Al _{0.4} Ga _{0.6} N UD	n = 1×10^{16} cm ⁻³
n	Al _{0.4} Ga _{0.6} N Si	n = 8×10^{17} cm ⁻³

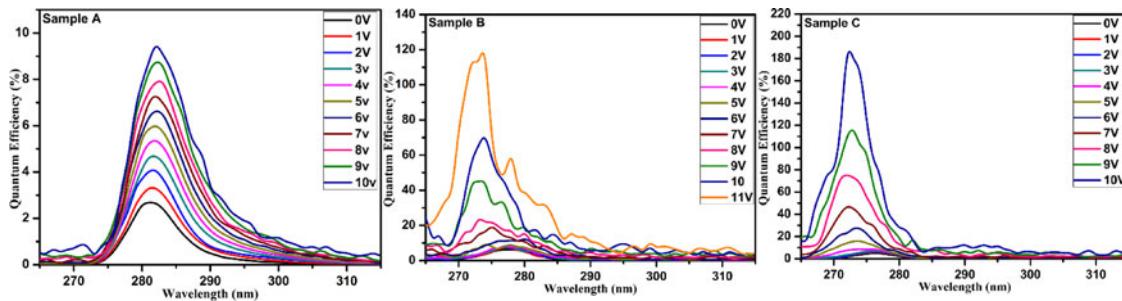


Fig. 2. Quantum efficiency of the samples of A, B, C under different reverse voltages.

(150/200 nm) circle electrode was deposited. Similarly, a Ti/Al/Ni/Au (30/100/150/200 nm) ring electrode was deposited onto the n-Al_{0.4}Ga_{0.6}N layer. Finally, the whole device was annealed by a rapid thermal annealing system in nitrogen ambient to form good ohmic contact.

3. Results

The experimental method was to determine the voltage at which one time impact ionization happened for the injected holes in statistical average. However, it is unreliable to obtain the voltage by the direct current measurement of the multiplication curve. Because, in general, the current avalanche gain is taken as the difference between the primary multiplied photocurrent and the multiplied dark current, normalized by the difference between the primary unmultiplied photocurrent and the unmultiplied dark current [11]. However, the difference between the multiplied and unmultiplied current is not obvious after one time impact ionization. In addition, one must account for the change of photocurrent in collected carrier as a function of bias. Small error in the determination of current causes error in the determination of voltage. Consequently, the method of measurement was designed to test the quantum efficiency (QE) of the APDs and a hypothesis was suggested by us that when the quantum efficiency reached 100%, the holes had just experienced one time impact ionization in statistical average before leaving the multiplication region.

During the measurement of the quantum efficiency (QE) of the APDs, a Xe arc lamp was used as the optical source. A mechanical chopper modulated the incident light, and a lock-in amplifier recorded the photocurrent from the photodetectors. The system was calibrated with an UV enhanced Si detector. All the measurements were carried out at room temperature. As shown in Fig. 2, the QE of the three samples were measured under different reverse voltages.

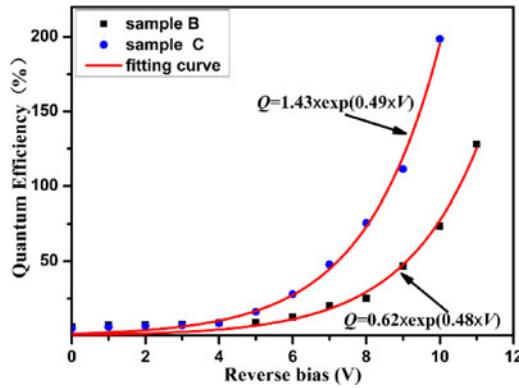


Fig. 3. Peak quantum efficiency under various reverse bias voltages for samples B and C.

It can be seen that the quantum efficiency of all samples increase with the reverse bias voltage. But the variation of peak values of the QE is different among each other and follows a sequence of $A < B < C$ when the reverse bias changes from 0 to 10 V. Comparing the main parameters of three samples, the width of multiplication region also follows the sequence $A < B < C$. These results suggest that the wider the multiplication region is, the higher the quantum efficiency is. This may be attributed to increasing the width of depletion region and strengthening the collection of carriers when increasing the bias. However, any increase in the quantum efficiency reached 100% must be due to avalanche multiplication. As shown in Fig. 3, the peak values of quantum efficiency exceed 100% when the reverse bias is greater than 10 V for sample B and 8 V for sample C respectively. In order to confirm the voltage at which the quantum efficiency is equal to 100%, we have fitted the peak value of quantum efficiency of samples B and C respectively under various reverse bias voltages. It can be seen that a good analytic description of the curve that fits the data is given by an exponential form, $Q = a \times \exp(b \times V)$, where Q is the peak quantum efficiency, a and b are constant, and V is the reverse bias voltage. Thus, the voltage is obtained by fitting and it is 10.5 V for sample B and 8.6 V for sample C respectively. In addition, a back-illuminated separate absorption and multiplication (SAM) structure is employed in this experiment, the effect of electron impact ionization on the quantum efficiency can be neglect. Because in the SAM-APD structure most of the incident photons are absorbed by the bottom $n\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ and $i_1\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layers. This results in nearly pure hole-injection into the multiplication region. Furthermore, the electric field and the thin $n_1\text{-AlGaN}$ charge layer between the two $i\text{-Al}_{0.4}\text{Ga}_{0.6}\text{N}$ regions also ensure that only holes initiate multiplication in the multiplication region.

Given E_0 is the average energy required for the holes to generate a secondary electron-hole pair by impact ionization. It is clear that, in general, the ionization will happen when a carrier has acquired energy E_0 . In the light of energy-conservation considerations, it can be written

$$q\varepsilon d = E_0 + qSd \quad (1)$$

where q is the charge of hole; ε is an effective electric field including the applied and built-in electric field; d is a distance while acquiring energy E_0 in travelling; S is the average effect of scatterings such as acoustic and optical phonons, ionized impurities, carriers-carriers, and alloy scattering; and it has an effect of retarding field acting on the holes while being accelerated up to the threshold energy. In the experiment, the same value of S was used for sample B and C and it was reasonable because of the fact that the parameters including doping concentration, the composition of aluminum and structures of devices were almost the same in samples B and C. Thus, the energy loss of the carrier was described by the forms of qSd , which is suggested by Chynoweth and McKay [12]. Then, the quantity required for the analysis of the function (1) is the effective electric field ε and the effective distance d when the voltages are applied to the devices.

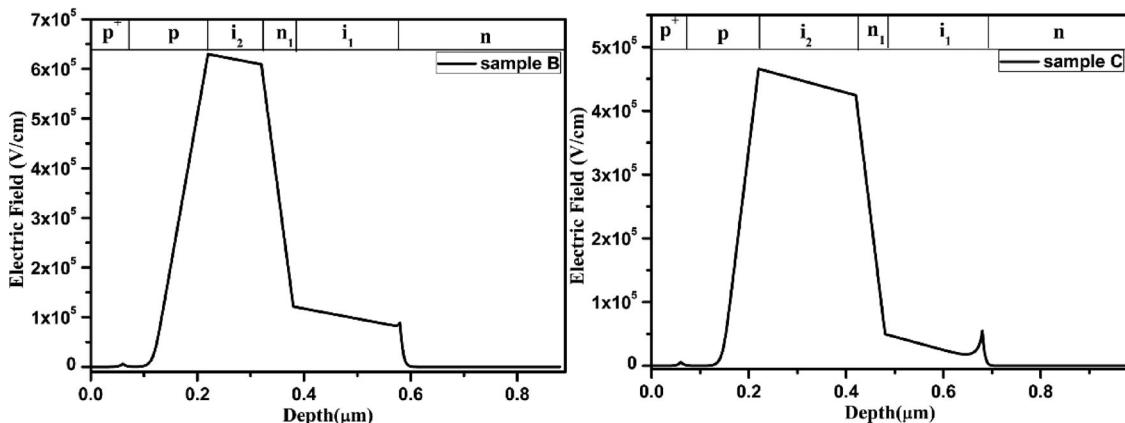


Fig. 4. Distribution of electric field in the AlGaN-based SAM APDs for sample B at 10.5 V and sample C at 8.6 V.

In order to facilitate intuitive analysis of the properties of samples B and C, the electric field profiles of samples B and C with doping levels in different layers were calculated using a commercial simulator, APSYS. Fig. 4 shows the distribution of electric field of the samples B and C when the reverse bias is at 10.5 V and 8.6 V, respectively. It is shown that the electric field intensity of multiplication region in sample B is larger than that in sample C. It implies that different critical electric field for impact ionization is required in different thickness of multiplication region and it would be expected that the electric field intensity would decrease as the thickness of the i_2 layer increases. In addition, the Fig. 4 also shows that the depletion region have extended into the i_1 layer in both samples, for ease analysis, an approximation is taken that essentially all of the impact ionization occurred before leaving the i_2 layer and neglecting the extent of the depletion region into the p and n layers, thus, the effective distance d is treated as the sum thickness of i_1 , n_1 and i_2 layers. Then, the total energy $q \epsilon d$ while acquiring energy E_0 could be obtained for samples B and C, respectively. Consequently, based on the function (1), the average energy E_0 for the holes could be calculated as 9.87 eV.

It is known that in impact ionization process, an energetic carrier needs to collide with an atom and break the lattice bonds so as to create the second electron-hole pair [13]. And the bond energy of GaN and AlN are 8.92 eV and 11.52 eV, respectively [14]. With the Vegard's law, the bond energy of $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ is estimated at 9.72 eV. Though there is a difference between the estimated value and experimental result, they do agree qualitatively and also prove that the hypothesis suggested is reasonable.

4. Conclusion

A series of back-illuminated $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ APDs based on separate absorption and multiplication structure with different multiplication width have been fabricated and measured. The average energy for impact ionization by holes was evaluated to be 9.87 eV. The experimental value provides a perspective from the energy to analyze quantitatively the impact ionization in $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ alloy.

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