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Study on the spectral response of the Schottky photodetector of GaN*

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The Schottky photodetector was fabricated on GaN epilayers grown by metalorganic chemical vapour deposition (MOCVD). The spectral response of the Schottky photodetector was characterized. A new model is proposed to interpret the characteristic of the spectral response curve of the Schottky photodetectors by introducing a penetrating distance of an incident light at a certain wavelength in the current continuity equation and the interface recombination at the metal–semiconductor rectifying contact. The expressions for the spectral response of the Schottky photodetector are deduced and used successfully to fit the experimental data.

Keywords: spectral response, Schottky photodetector, GaN
PACC: 7240, 8105E

1. Introduction

Gallium nitride (GaN) is one of the most promising materials for the fabrication of high-sensitive visible–blind UV photodetectors, since it has a large direct band gap and a high saturation electron drift velocity. The superior radiation hardness and high-temperature resistance of GaN also make it a suitable material for photodetectors working in extreme conditions.[1,2] The Schottky photodiode is attractive for high performance UV photodetector because it has the advantages of easy fabrication.[3] Although the performances of the Schottky photodetector made of GaN have been experimentally studied by many authors,[4−7] detailed studies about the characteristic of the spectral response curve of the Schottky photodetector are few.[8,9] Tang and Kao[10] studied the theoretical spectral response of photoconductivity of n-type germanium, but the expressions are not suitable for the Schottky photodetectors. Monroy *et al*[11] studied the characteristic of the spectral response curve of the Schottky photodetector. However, in their model they did not consider the loss of generated-current in the Schottky photodetectors due to defects in the interface between the metal and the semiconductor. So, there is the difference between experimental data and theoretical values. In this paper, a new model is proposed to interpret the characteristic of the spectral response curve of the Schottky photodetectors made of GaN and the calculated results are compared with our experimental data.

2. Experiments

The GaN samples used in this study were grown by metalorganic chemical vapour deposition (MOCVD) on sapphire substrate. A 50nm GaN buffer layer was initially grown at ∼500°C, then 2μm GaN film was grown at 1050°C. The electron concentration and the mobility of the unintentionally doped GaN film are about 5×10^{16}cm^{-3} and 400cm^2/V·s, respectively, measured by Hall-effect. Prior to metal deposition, the GaN samples were cleaned with organic solvents, followed by dipping in an aqua regia solution, and loaded in an ion beam sputtering systems. The conventional photolithographic lift-off technique was used to define the Schottky photodetectors as shown in Fig.1. A bilayer of In (200Å,top layer)Au (3000Å) was deposited on GaN film to form ohmic contacts. A 50Å of Au film was deposited on the samples as Schot-

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tky contacts. A thin Au layer (~3000Å) was deposited on top of the Au Schottky contact to facilitate Au wire bonding. A 350W xenon arc lamp served as UV source, and the illumination wavelengths were selected by a monochromator to test the spectral response of the photodetectors. The monochromator output was calibrated by using a UV-enhanced Si photodiode.

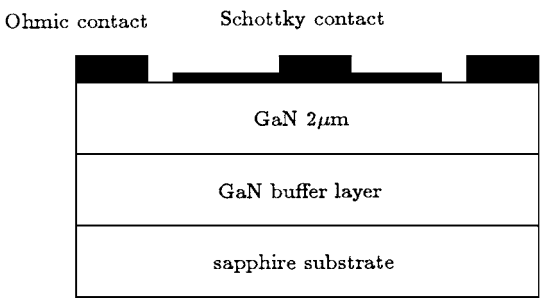


Fig.1. The structure of the Schottky photodetector of GaN.

3. Result and analysis

3.1. Experimental results

The spectral response characteristic of the Schottky photodetector made of GaN is shown in Fig.2. The inset of Fig.2. shows the current–voltage (I–V) curve of the Schottky photodetector made of GaN. We note that the sharp drop of the spectral response on the long wavelength side is unquestionably due to the rapid decrease of the number of photons absorbed by the specimen, and that the decrease of the spectral response on the short wavelength side is remarkable, which is similar to the experiment reported by Zhou *et al*[12] and Zhang *et al*,[13] since we know that absorption coefficients generally increase towards short wavelength side. This behaviour will be interpreted by the following model.

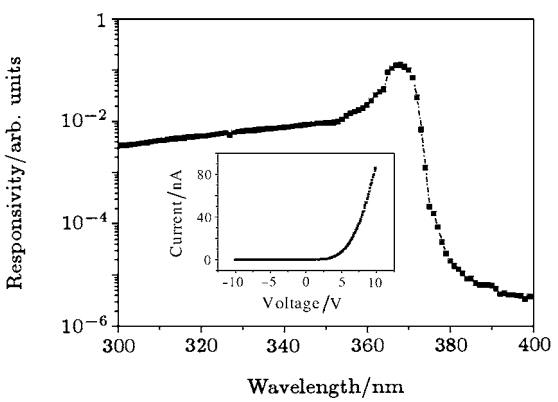


Fig.2. The spectral response characteristic of the Schottky photodetector of GaN.

3.2. Theoretical model

We believe that the phenomena outlined above can be interpreted by considering the recombination processes of the photo-generated carriers in the Schottky photodetector under illumination. There are three recombination processes: namely the interface recombination due to the surface state at the rectifying contact, the recombination in the depletion region and that in the diffusion region due to the other defects in the semiconductor, as shown in Fig.3. As is well known, the defects in the rectifying contact interface are much more than those in the body of the semiconductor, as a result, the interface recombination is the dominant process of the photo-generated carriers. Here, we only consider the interface recombination process in our model.

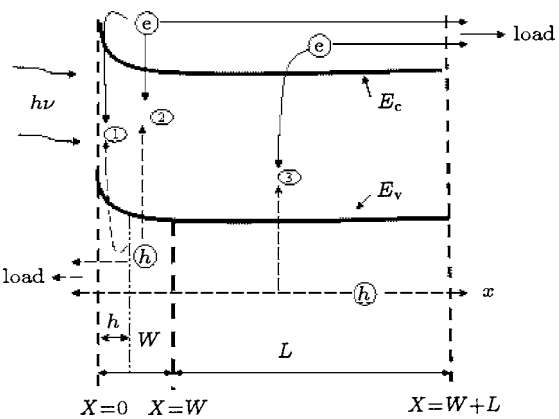


Fig.3. Schematic diagram of the recombination processes of the photo-generated carriers of the Schottky photodetector under illumination.

In the depletion region, part of the photo-generated electrons will flow towards the interface of the rectifying contact due to the gradient of the photo-generated electron concentration; others will flow into the diffusion region driven by the built-in electric field. Thus, there is a waste layer where the photo-generated carriers have been recombined, whose width is denoted by h in Fig.3. The width of the waste layer is associated with the interface conditions of the rectifying contact. The photocurrent density expressions of the Schottky photodetector will be deduced under the following conditions.

Considering that the intensity of the incident light decreases exponentially with the distance penetrating through the semiconductor material, we assumed that the incident light is absorbed completely in some distance (d), where the intensity of the light I_d equals 1/e of the initial incident light intensity I_0, that is

$$\frac{I_d}{I_0} = \frac{1}{e}, \tag{1}$$

where d is defined by the following equation

$$I_{\mathrm{d}} = I_0 \mathrm{e}^{-kd}. \tag{2}$$

with k being the absorption coefficient of the semiconductor with respect to the incoming monochromatic light.

By substituting Eq.(1) into Eq.(2), we obtain

$$d = 1/k. \tag{3}$$

For simplicity, we just consider the one-dimensional case and the intensity of the monochromatic incident light is I_0 (photons/s·cm^2) and perpendicular to the plane x=0, as shown in Fig.3. W is the depletion width and L is the diffusion length of holes. We discuss the spectral response of the Schottky photodetector under the following four different conditions.

3.2.1. $d \leq h$

According to the assumptions mentioned above, no effective photo-generated carriers exist in the Schottky photodetector. So, the photocurrent density is zero,

$$J = 0. \tag{4}$$

3.2.2. $h \leq d \leq W$

Photo-generated carriers are only generated in the part of the depletion region. According to the principle of current continuity, photocurrent density is given by

$$J = -J_{\mathrm{np}}(W), \tag{5}$$

where the minus sign means the electrons move towards positive x direction, $J_{\mathrm{np}}(W)$ is the photo-generated electron current density in the part of the depletion region, which passes through the $x = W$ plane. We can write $J_{\mathrm{np}}(W)$ as

$$J_{\mathrm{np}}(W) = -\int_h^{1/k} G_L(x)\mathrm{d}x, \tag{6}$$

where $G_L(x)$ is the generation rate of carriers and equals the number of photons absorbed per unit volume per unit time at x, because of unity quantum yield. Let the reflection coefficient at the surface of the metal be $R(\lambda)$, and we have

$$G_L(x) = (1-R)I_0 k \mathrm{e}^{-kx}. \tag{7}$$

Substituting Eq.(7) into Eq.(6), we have

$$J_{\mathrm{np}}(W) = q(1-R)I_0[\mathrm{e}^{-1} - \mathrm{e}^{-kh}]. \tag{8}$$

From Eqs.(8) and (5), we can rewrite Eq.(5) in the form

$$J = q(1-R)I_0[\mathrm{e}^{(-kh)} - \mathrm{e}^{(-1)}]. \tag{9}$$

3.2.3. $W \leq d \leq W + L$

Photo-generated carriers are generated not only in the entire depletion region but also in part of the diffusion region. The photocurrent density is given by

$$J = -[J_{\mathrm{n}}(W) + J_{\mathrm{pp}}(W)], \tag{10}$$

where $J_{\mathrm{pp}}(W)$ is the photo-generated hole current density in part of the diffusion region, which passes through the $x = W$ plane, and $J_{\mathrm{n}}(W)$ is the photo-generated electron current density in the entire depletion region, which passes through the $x = W$ plane.

In the entire depletion region, we can write $J_{\mathrm{n}}(W)$ as

$$J_{\mathrm{n}}(W) = -q\int_h^W G_L(x)\mathrm{d}x. \tag{11}$$

Substituting Eq.(7) into Eq.(11), we obtain

$$J_{\mathrm{n}}(W) = q(1-R)I_0[\mathrm{e}^{(-kW)} - \mathrm{e}^{(-kh)}]. \tag{12}$$

In the diffusion region, we have

$$J_{\mathrm{pp}}(W) = -qD_{\mathrm{p}}\frac{\mathrm{d}p}{\mathrm{d}x}\bigg|_{x=W}, \tag{13}$$

where p represents the hole concentration $p = p(x)$, and D_{p} is the diffusion coefficient of the holes.

Under steady-state conditions, we obtain the photo-generated hole current density by solving the well-known continuity equation in part of the diffusion region

$$\frac{\mathrm{d}^2 p}{\mathrm{d}x^2} - \frac{p - p_{\mathrm{n0}}}{L_{\mathrm{pp}}} + \frac{G_L(x)}{D_{\mathrm{p}}} = 0, \tag{14}$$

where P_{n0} is the equilibrium minority-carrier concentration. In the n-type semiconductor, P_{n0} is much smaller than the photo-generated hole concentration. So, we can omit P_{n0} in Eq.(14). $L_{\mathrm{pp}}$is the distance between x ($x = 1/k$) and the boundary of the depletion region, we can define it as

$$L_{\mathrm{pp}} = 1/k - W. \tag{15}$$

Substituting Eq.(15) and Eq.(7) into Eq.(14) yields

$$\frac{\mathrm{d}^2 p}{\mathrm{d}x^2} - \frac{p}{(1/k - W)^2} + \frac{I_0(1-R)k\mathrm{e}^{(-kx)}}{D_{\mathrm{p}}} = 0. \tag{16}$$

Once the holes diffuse to the boundary of the depletion region, they will be drawn away by the built–in electric field at once. And the carriers generated by light

at $x = \infty$ cannot be collected. Thus, the boundary conditions can be written as

$$x = W, \quad P(W) = 0;$$
$$x = \infty, \quad P(\infty) = 0. \tag{17}$$

By resolving Eq.(16) and using Eq.(17), we can rewrite Eq.(13) in the form

$$J_{\rm pp}(W) = -qI_0(1-R)\frac{1-kW}{2-kW}{\rm e}^{(-kW)}. \tag{18}$$

Substituting Eqs.(12) and (18) into Eq.(10), the total photocurrent density can be expressed as

$$\begin{aligned} J =& -(J_{\rm n} + J_{\rm pp}) \\ =& q(1-R)I_0[{\rm e}^{(-kh)} - {\rm e}^{(-kW)}/(2-kW)]. \end{aligned} \tag{19}$$

3.2.4. $W + L \leq d$

In this case, photo-generated carriers can be also generated beyond the depletion region and the diffusion region, but these photo-generated carriers are difficult to be collected by the built-in field to become effective photocurrent. Thus, effective photo-generated carriers can be calculated in the entire depletion region and also the entire diffusion region. The photocurrent density is given by

$$J = -[J_{\rm n}(W) + J_{\rm p}(W)], \tag{20}$$

where $J_{\rm p}(W)$ is the total hole diffusion current density generated in the diffusion region, which passes through the $x = W$ plane and is given by

$$J_{\rm pp}(W) = -qD_{\rm p}\frac{{\rm d}p}{{\rm d}x}\bigg|_{x=W}. \tag{21}$$

Under steady-state conditions, we obtain photo-generated hole current density by solving the well-known continuity equation in the diffusion region:

$$\frac{{\rm d}^2p}{{\rm d}x^2} - \frac{p}{L_{\rm p}^2} + \frac{I_0(1-\rho)\alpha{\rm e}^{-\alpha x}}{D_{\rm p}} = 0, \tag{22}$$

where $L_{\rm p}$ is the diffusion length of holes, $L_{\rm p} \equiv \sqrt{D_{\rm p}\tau_{\rm p}}$, $\tau_{\rm p}$ is the hole carrier lifetime. According to Eqs.(17), (21) and (22), we can obtain

$$J_{\rm p}(W) = -qI_0(1-R)\frac{kL}{1+kL}{\rm e}^{(-kW)}. \tag{23}$$

Substituting Eqs.(12) and (23) into Eq.(20), we obtain

$$\begin{aligned} J =& -(J_{\rm n} + J_{\rm p}) \\ =& q(1-R)I_0[{\rm e}^{(-kh)} - {\rm e}^{(-kW)}/(kL+1)]. \end{aligned} \tag{24}$$

The spectral response curves of the Schottky photodetector can be calculated by substituting the known values of $L_{\rm p}$, R, k and W into Eqs.(1), (9), (19) and (24). Using the absorption spectrum of Yu *et al*[14] and the reflection coefficients of Dingle *et al*,[15] we can obtain the spectral responses of the Schottky photodetector of GaN for different widths of the waste layer, as shown in Fig.4.

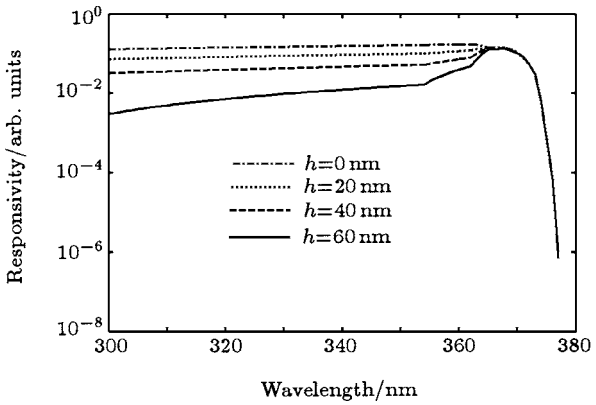


Fig.4. Theoretical spectral response curve of Schottky photodetector of GaN for different h values.

3.3. Fitting results

Figure 5 is the representative of the results obtained from comparison between the experimental data and the values of theoretical calculation. The symbols '◯' and '∇' represent experimental points of the samples treated with aqua regia and without aqua regia, respectively. The solid line represents theoretical fitting curve. Figure 5 shows that the theoretical curves agree satisfactorily with experimental data in the wavelength region from 300 to 375nm. Hence, we think that the characteristic of the spectral response curve of the GaN Schottky photodetector can be attributed to the interface recombination at the rectifying contact. And it also shows that the chemical surface treatment can reduce the interface recombination by decreasing the defects at the rectifying contact. In comparison with the theoretical curves, the experiment data fall more slowly when the wavelength is above 375nm. So we consider that other type of the photo-generated current may exist. Further experiments are needed to clarify this problem.

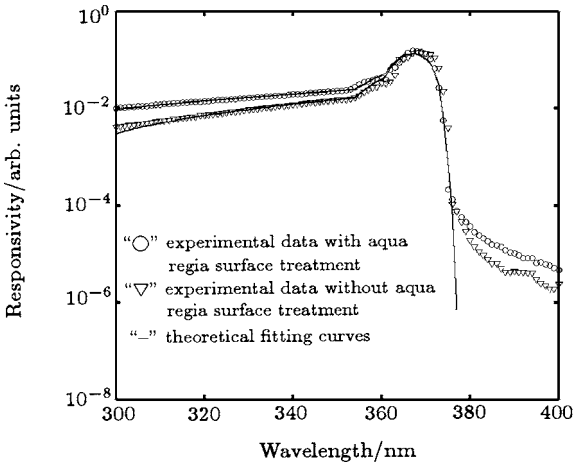


Fig.5. Comparison between experimental data and theoretical Schottky spectral response of GaN.

4. Conclusions

In this paper, we have fabricated the Schottky photodetector made of GaN and have investigated its characteristic of the spectral response curve. We have proposed a new model and deduced its expressions. The experimental data were fitted with these expressions and the fitting results show that the theoretical curves agree satisfactorily with experimental data in the wavelength region from 300 to 375nm and that the theoretical curves fall faster than the experimental data when the wavelength is above 375nm. This phenomenon may be attributed to some other types of the photo-generated current existing in the detector.

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