The investigation of dark current reduction in MSM photodetector based on porous GaN

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In this article, we investigate the use of porous GaN layer for the reduction of dark current in the metal-semiconductor-metal (MSM) photodetector. For comparative study, a standard MSM photodetector was also prepared based on the as-grown GaN wafer. The initial study revealed that the porous GaN layer was able to reduce the dark current of the MSM photodetector by two orders of magnitude as compared to MSM photodetector fabricated on the as-grown GaN.

1. Introduction

Galium nitride (GaN), a wide and direct band gap semiconductor is a largely studied semiconductor material due to its potential as an excellent candidate for the application in optoelectronic and high power/temperature electronic devices [1]. Great attention has been paid in recent years to the development of visible-blind ultraviolet (UV) photodetectors based on III–V nitride which have application in both civil and military industries such as engine control, flame sensing, source calibration, solar UV monitoring, UV astronomy, secure space-to-space communications, and missile plume detection [2].

To date, various types of GaN-based photodetectors with different structures have been reported [3-6]. Among them, metal-semiconductor-metal (MSM) photodetectors have attracted much attention due to ease of fabrication, small intrinsic capacitance, high speed, and suitability for integration in an optical receiver. However, leakage currents in GaN-based MSM photodetectors are often large due to high structural defect density in the GaN epitaxial layers [7]. Therefore efforts have been channeled to further reduce the dark current of the MSM photodetector. Low dark current in the range of 10^{-10}A has been reported [7, 8], however, a relative complicated process is required for the fabrication of the device. For instance, the introduction of a SiO_2 as a current suppressing layer underneath the contact [7], or a special treatment using photo-chemical annealing system [8], all these involved extra processes as well as expensive equipment.

Recently porous semiconductors have been studied extensively mainly due to the potential for intentional engineering of properties not readily obtained in the corresponding crystalline precursors. Among porous semiconductors, porous silicon has been investigated intensively; however the instability of physical properties has prevented it from large scale application [9]. This leads to the development of other porous semiconductors, for instance, the conventional III-V compounds i.e. GaAs, GaP and InP. However, the study of wide bandgap porous semiconductors such as GaN is still in its infancy stage, the fundamental properties of porous GaN are rarely reported in the literature [10-12]. Therefore, there is a room to further explore the potential of this material.

Most recently, we have reported the use of porous GaN for hydrogen gas sensing application and a significant result was obtained [13,14]. From the literature, the use of porous GaN layer for dark current reduction has not been reported. In addition, the processes involved in the fabrication of porous GaN and MSM photodetector were relatively simple and required no expensive equipment. In this work, the feasibility in reducing the dark current of the MSM photodetector was investigated by the adoption of porous GaN layer. The initial study showed that the result was very encouraging.

2. Experimental Method

2.1 Generation of porous GaN layer

The unintentionally doped n-type GaN film grown on sapphire substrate was used in this study. The native oxide of the wafer was removed in the $NH_4OH:H_2O =1:20$ solution, followed by $HF:H2O =1:50$, subsequently boiling aqua regia ($HCl:HNO_3 = 3:1$) was used to etch and clean the wafer.

Porous GaN in this work was generated by Pt assisted electroless chemical etching. Two narrow stripes of Pt were first deposited on both sides of the sample by using sputtering system. The sample was then etched in a solution of $HF:CH_3OH:H_2O_2 = 4:1:1$ under illumination of an UV lamp with 500 W power. After one hour etching, the sample was removed from the solution and rinsed with distilled water, followed with the removal of the residual Pt by ultrasonic cleaning. Fig. 1 shows the scanning electron microscopy (SEM) images of porous GaN and as-grown GaN samples.
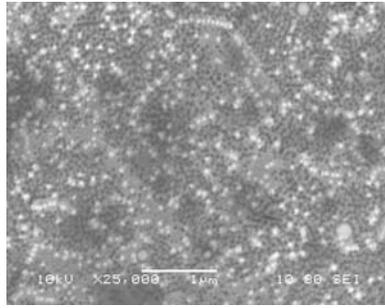
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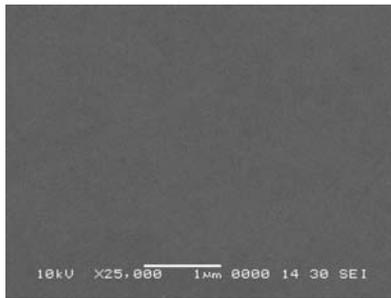
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Fig. 1. The SEM images for (a) porous GaN,
(b) as-grown GaN.

2.2 Fabrication of MSM photodetectors

The MSM photodetector was fabricated by sputtering the Pt with thickness about 150 nm onto the thin film via a metal mask. For comparative study, two photodetectors have been fabricated by using porous GaN and as-grown GaN wafer. Both samples were from from the same wafer.

Pt is used as Schottky contact since Pt has the highest metal work function. The structure of MSM photodetector consists of two interdigitated Schottky contact (electrode) with finger width of 230µm, finger spacing of 400 µm and the length of each electrode is about 3.3 mm. Each electrode has four fingers as schematically shown in Fig. 2.
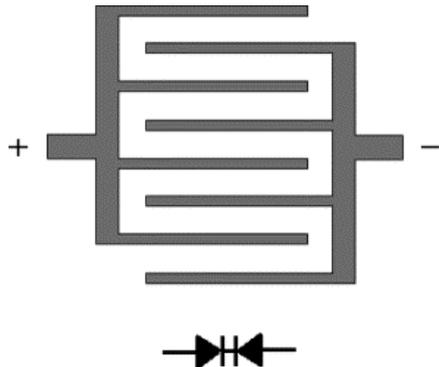

Fig. 2. The schematic diagram of the photodetector.

Normally the structure of an MSM photodiode consists of two interdigitated Schottky contacts connected back to back as shown in Fig. 1. When a bias is applied to the MSM structure, one of the Schottky contacts is forward biased and the other is reverse biased. So, for characterization of MSM structure with I–V measurement, we can only measure the reverse bias part of the detector [15].

3. Results and discussion

Fig. 3 shows the I-V characteristics of as-grown and porous GaN photodetectors under dark and light illumination conditions.
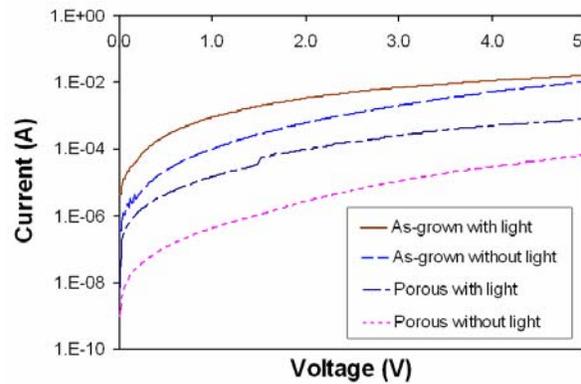

Fig. 3. The I-V characteristics of the as-grown and porous GaN photodetectors under different illumination conditions.

Schottky barrier heights, SBH, can be determined by I-V measurements. For thermionic emission and V>3kT/q, the general diode equations are [16]:

$$I = I_o \, exp\{qV/(nkT)\} \tag{1}$$

$$I_o = A^* A T^2 \, exp\{-q \, \Phi_B/(kT)\} \tag{2}$$

As usual, I_o is the saturation current, n is the ideality factor, k is the Boltzmann's constant, T is the absolute temperature, Φ_B is the barrier height, A is area of the Schottky contact and A^* is the effective Richardson coefficient. The theoretical value of A^* can be calculated using

$$A^* = 4\pi m^* q k^2/h^3 \tag{3}$$

where h is Planck's constant and $m^* = 0.22m_o$ is the effective electron mass for n-type GaN [11]. The value of A^* is determined to be *26.4 $Acm^{-2}K^{-2}$*.

For samples involving two Schottky contacts, representing two diodes connected back-to-back, the *I-V* characteristics of the Schottky contact are more appropriate to be analyzed in the more general form of equation, where it can be used under reverse bias conditions [15,18]

$$I = I_o \, exp(qV/\{nkT\})[1-exp(-qV/\{kT\})] \qquad (4)$$

The equation can be written as

$$\frac{I \exp(qV/\{kT\})}{\exp(qV/\{kT\})-1} = I_o \exp(qV/\{nkT\}) \quad (5)$$

Based on equation (5), the plot of *In{I exp(qV/{kT})/[exp(qV/{kT})-1]} against V* will give a straight line, similarly, I_o is derived from the intercept with y-axis, in which SBH, Φ_B can be calculated using Eq. (2). The SBHs of porous GaN and as-grown GaN samples under different conditions, i.e. illumination and without illumination were deduced and summarized in Table 1.

From Fig. 3, the porous sample showed a significantly low dark current at 5V as compared to as-grown sample, the dark current of porous sample was about 2 orders of magnitudes smaller than as-grown sample. When the sample was under illumination condition, (i.e. shined with white light) the change of current was quite significant for porous sample as compared to the as-grown sample.

Since both as-grown and porous samples were originated from the same GaN wafer, both of the devices were fabricated using same processing tools and under identical parameters, however, significant difference in dark current was observed. High dark current in the as-grown sample could be attributed to the low barrier height of the metal contact with the GaN thin film [8]. On the other hand, low dark current in porous GaN sample could be due to the enhancement of SBH which was ascribed to the roughening of the sample surface. Etched-induced damage may move the surface Fermi level downward to the valence band and thus increases the SBH, and eventually results in a reduction of the leakage current [19].

Table 1 summarizes dark and photo-current measured at 5V, as well as the ideality factor and SBH of the as-grown and porous samples determined from the I-V measurements. SBH was found to be influenced by both illumination and porosity. The SBHs of both under dark and illuminated conditions were observed to be higher for porous sample relative to the as-grown sample.

Table 1. The ideality factor, SBH and dark and photo-current of as-grown and porous samples.

Sample	n	SBH (eV)	Current at 5V (A)
As-grown with light	1.014	0.492	1.610×10^{-2}
As-grown without light	1.017	0.514	1.026×10^{-2}
Porous with light	1.020	0.593	7.859×10^{-4}
Porous without light	1.026	0.638	6.741×10^{-5}

Under illumination condition, the SBHs of both as-grown and porous samples became smaller, this translated to higher current of the photodetectors (measured at 5V). However, it should be noted that the change of SBH for porous sample was 0.045 eV as compared to 0.022 eV for as-grown sample, the change of SBH was two times higher than as-grown sample, this showed that porous GaN sample was more sensitive to illumination. This finding was further confirmed by measuring the contrast ratio of photo-current and dark current at 5V. The contrast ratio for porous sample and as-grown were found to be 11.66 and 1.57, respectively, this revealed that the sensitivity of the MSM photodetector fabricated based on porous GaN was much higher than the as-grown GaN.

4. Conclusion

In summary, MSM photodetectors have been fabricated and investigated based on porous GaN and as-grown GaN samples. The porous GaN sample was found to be capable of reducing the dark current due to the inherent higher SBH. Smaller dark current means lower noise of the photodetector. The initial study showed that the porous GaN sample has a higher photo-current to dark current ratio as compared to the as-grown sample. This revealed that the porous GaN is potentially used for the enhancement of the sensitivity of the photodetector.

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