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p-GaN/n-Si HETEROJUNCTION PHOTODIODES

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PN photodiodes, as an alternative form of photodetectors, is based on carrier production in the high-field junction region, and it has a response time considerably faster than that of a photoconductor and is typically in the order of nanoseconds. Photodetectors operating in the short wavelength ultraviolet (UV) region are important devices that can be used in various commercial and military applications. In the present work, we fabricated the p-GaN/n-Si heterojunction photodiode to observe the photoelectric effects. From the results, the current–voltage characteristics of the device show the typical rectifying behavior of heterojunctions. The UV photocurrent measurement was performed using an Hg-lamp under a reverse bias.

Keywords: PN photodiodes; heterojunction; photoelectric effect; GaN; Si.

1. Introduction

Photodetectors operating in the UV and with a visible blind behavior have drawn great attention in recent years, with a number of applications in both civil and military industries which include missile plumes detection, flame sensing, engine control, solar UV monitoring, source calibration, UV astronomy, and secure space-to-space communications.[1,2] Moreover, the key advantage of *III–V* nitride detectors over competing devices based on semiconductors with smaller band gaps is the long wavelength response cut-off, which is directly related to the band gap of the material in the active region, and thus, does not require external filters. Unlike wide band gap photodetector, the front surface of a vacuum UV silicon photodiode is coated with filter materials to limit the sensitivity of the silicon to a much narrower band in the vacuum ultraviolet (VUV), because one significant shortcoming of Si photodiodes for certain VUV applications is the inherent broadband response extending from X-rays to the near infrared, which is undesirable.

In general, photodetectors can be classified according to the type of optical to electrical conversion effect. A photoelectric detector is based on the process of photon absorption by the material with the release of an electron–hole pair. In the case where the photo-generated electron is further emitted out of the material in which they become available for collection or multiplication, the device is called a photo-emissive detector which is based on the external photoelectric effect. Some examples of photo-emissive detectors are like photomultipliers, vacuum photodiodes, and image-intensifier tubes. However, if there is no emission taking place, but the photo-generated electron–hole pair is available for the current circulation in the external circuit, this is called an internal photoelectric effect detector which is the characteristic of all semiconductor photodetectors.

PN photodiodes, as an alternative form of photodetectors, is based on carrier production in the high-field junction region, and it has a response time considerably faster than that of a photoconductor, and is typically in the order of nanoseconds. Photoelectric effects from the photodiode will be well observed only if two important qualities in the photodiode are satisfied: a good interface (or p–n junction) quality for a low leakage current and a good film quality for the light transmission and carrier transport.

A p–n junction photodiode operates under reverse bias by the absorption of incident photons with energy greater than the energy gap, thus creating electron–hole pairs in the material on both sides of the junction. The electrons and holes generated within a diffusion length from the junction reach the depletion region by diffusion. There, the electron–hole pairs are separated by the strong electric field, and minority carriers are readily accelerated to become majority carriers on the other side, generating a photocurrent. However, the carrier diffusion step in this process is time-consuming and should be eliminated if possible. Therefore, it is desirable that the width of the depletion region be large enough so that most of the photons are absorbed within the depletion region rather than in the neutral p and n regions.

For metal–semiconductor contacts, ohmic contact is needed for connections to devices because of its linear current–voltage (I–V) characteristics in both biasing directions (with minimal resistance and no tendency to rectify signals). In the present work, we fabricated the p-GaN/n-Si heterojunction photodiode to observe the photoelectric effects.

2. Experiment

A heterojunction of Mg-doped p-type crystalline gallium nitride (GaN) were grown on n-type Si(111) by radio frequency nitrogen plasma-assisted MBE (PAMBE). Sample nominally consisted of 0.10 μm AlN as a buffer layer followed by 0.23 μm Mg-doped GaN with carrier concentration of $\sim 2 \times 10^{18}\,\text{cm}^{-3}$ as determined by Hall Effect measurement, and the electrical conduction of all the samples was p-type.

Metal contact was sputtered by a sputtering system onto the backside and front-side, respectively. Here, to provide a low contact resistance of electrode, Ni/Ag (250 nm/600 nm) dots (250 μm in diameter) were deposited on the Mg-doped GaN layer at a corner. In the same manner, a large area ohmic contact of Al/Ti (250 nm/600 nm) was also deposited on the backside of the Si substrate to form the second electrode of the p–n diode. A pair of contacts was made on the backside of a separate piece of the sample to check for ohmic contact formation.

After metallization, the samples were annealed in a tube furnace at 400°C under flowing argon gas environment for a duration of 10 min. The setup of the furnace is shown in Fig. 1. Nitrogen gas was purged into the tube during annealing to displace the room ambient inside the tube. Room ambient contains nitrogen molecules that may interfere with the ohmic contact formation. The gas was purged at a mass flow rate of approximately 4 L·min^{-1}.

The electrical behaviors of the contacts were analyzed by current–voltage (I–V) measurements. Keithley high-voltage-source-measure-unit model 237-semiconductor parameter analyzer measured the I–V characteristics of photodiodes. For the reverse bias configuration, negative bias was applied to the p-GaN film. The measurements were performed with or without an Hg-lamp onto the GaN surface. The Hg-lamp illumination was vertical and 3 cm away from the sample. The light beam size was large enough to barely cover the GaN surface.

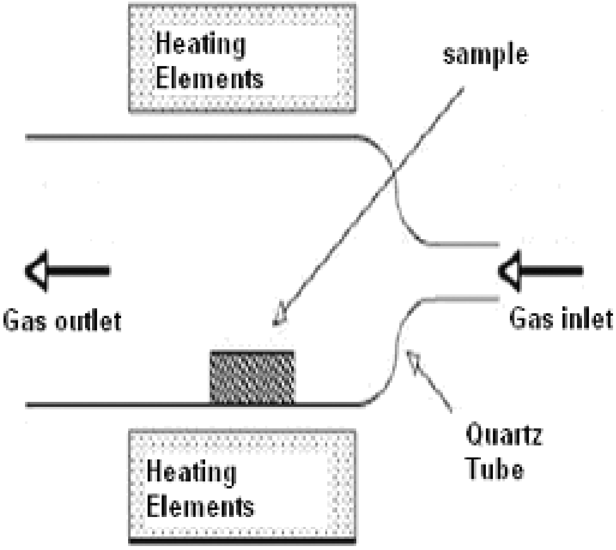

Fig. 1. Setup of tube furnace for thermal annealing.

3. Results and Discussion

In order to examine the quality of the films, ω scan of XRD rocking curves (RC) at (0002) plane were carried out. The corresponding symmetric curve of p-type GaN is depicted in Fig. 2. The GaN peak at about 17.33° correspond to the (0002) diffraction peaks of the sample. The FWHM of the RC for the p-GaN peak of sample is 22.96 arcmin.

The AFM studies on the surface morphology indicated that the films are reasonably smooth with uniform crystalline grain distribution as shown in Fig. 3. The images were acquired on different areas of the sample, and Fig. 3 is the representative selection of the captured images. The average roughness was about 15 nm for a scanning area of $10\,\mu\text{m} \times 10\,\mu\text{m}$. Hall effect measurements were carried out on the sample at room temperature with van der Pauw configuration. This heavily Mg-doped GaN sample exhibits a resistivity of $0.2\,\Omega\text{cm}$, and a mobility of $13.0\,\text{cm}^2/\text{Vs}$.

Studies of the I–V characteristics of the fabricated p-GaN/n-Si structure revealed a good p–n heterojunction as shown in Fig. 3. The I–V relationship for a heterojunction is given by[3]:

$$I = I_s\left[\exp\left(\frac{qV}{K_BT}\right) - 1\right], \tag{1}$$

where I is the current; I_s is the saturation current; V is the applied voltage across the heterojunction from p-side to n-side; K_B is the Boltzmann constant; and T is the absolute temperature. The typical I–V characteristic in the absence of light illumination at room temperature is observed in Fig. 4. A pronounced rectifying diode-like behavior with a threshold voltage of ~0.8 V is clearly observed. The forward current was as high as 0.012 A at 8 V forward bias.

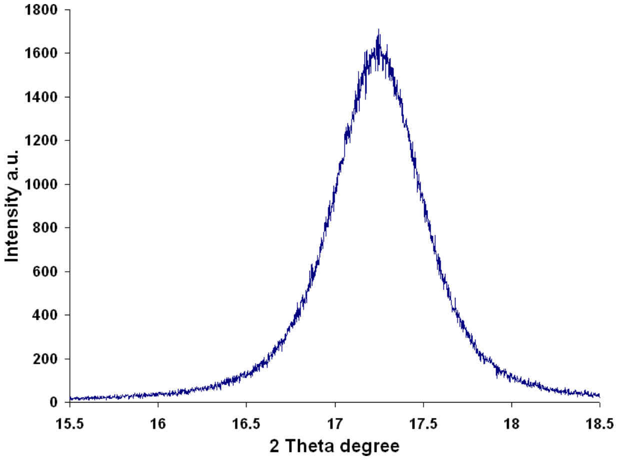

Fig. 2. X-ray diffraction (XRD) rocking curve (RC) of (0002) plane for p-type GaN grown on n-type Si substrate.

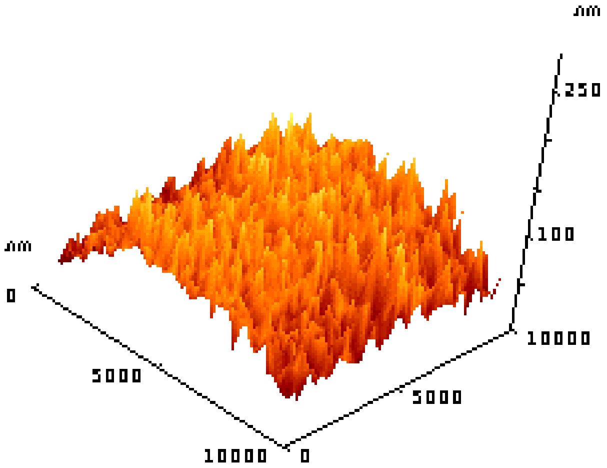

Fig. 3. Atomic force microscopy images of p-GaN grown on Si.

The mechanism of the crystalline-based p-GaN/n-Si diode is described as follows. Holes diffuse from the p-GaN side into the n-Si side, and electrons diffuse from n-Si into p-GaN. Although the electrons and holes can move to the opposite side of the junction, the donors and acceptors are fixed in space. When electrons diffuse from the n-Si to the p-GaN side, they leave behind uncompensated donor ions in the n-Si material, and holes leaving the p-GaN region create uncompensated acceptors. The diffusion of

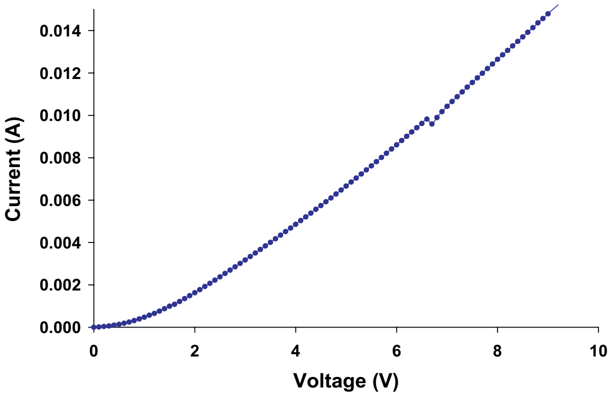

Fig. 4. I–V characteristics of the heterojunction in dark at room temperature.

electrons and holes from the vicinity of the junction establishes a region of positive space charge near the n-side of the junction and negative charge near the p-side. An electric field is built up at the interface. Photocurrents are consequently obtained.

At zero voltage bias, the energy gaps (E_g) for GaN and Si are 3.4 eV[4] and 1.12 eV,[5] respectively. The electron affinity for GaN is taken as 4.10 eV,[4] and the electron affinity for Si is 3.95 eV.[5] The energy barrier ΔE_c for electrons is $\Delta E_c = \chi_{\text{GaN}} - \chi_{\text{Si}} = (4.10 - 3.95)\,\text{eV} = 0.15\,\text{eV}$, while the energy barrier ΔE_v for holes is $\Delta E_v = E_{g,\text{GaN}} + \Delta E_c - E_{g,\text{Si}} = (3.4 + 0.15 - 1.12)\,\text{eV} = 2.43\,\text{eV}$. Thus, the energy barrier for holes (ΔE_v) is 16 times more than the barrier for electrons (ΔE_c).

When a reverse bias is applied, holes encounter ΔE_v, yielding a low current. In contrast, when a forward bias is applied, the electron only need to overcome a much smaller potential barrier (ΔE_c), thus giving rise to the rectifying effect. These arguments are for the ideal case, and direct measurements are required to determine the exact band structure of the heterojunction.

In addition, crystalline GaN photodiodes were designed to be responsive to optical input. The UV photocurrent measurement was performed using an Hg-lamp. Because the photon energy is higher than the bandgap of GaN (3.4 eV, ∼364 nm wavelength), UV light was absorbed by the crystalline GaN creating electron–hole pairs, which were further separated by the electric field inside GaN contributing to the increase of the external current. Since the bandgap of p-GaN layer is larger than that of the substrate, band-to-band photo excitation cannot take place in this layer.

In this work, reverse bias was used for the photodiode operation to maximize the depletion width, minimize the transit time and the carrier loss due to recombination process in the diffusion region. Photodiodes usually have extremely high resistance under reverse bias. This resistance is reduced when light of an appropriate frequency illuminates the junction to create additional free electron–hole pairs. Hence, a reverse-biased diode can be used as a detector by monitoring the current running through it.

The *I*–*V* characteristics are shown in Fig. 5, where clear rectifying behaviors can be observed both in the dark and under UV illumination conditions. Distinct response to UV illumination can be seen from Fig. 5 in the reverse-biased condition due to the photogeneration of additional electron–hole pairs. The magnitude of photocurrent increases with the increase of applied reverse bias due to enhanced carrier collection. The photocurrent is 2.0 mA with −3 V reverse bias. On the other hand, the dark leakage current for the GaN photodiodes is weak (0.8 mA in the −3 V reverse bias). This behavior indicates that GaN photodiodes can sensitively detect UV light to produce the measurable photocurrent response. The efficiency of the device is affected by several factors, including the existence of a thin native silicon dioxide barrier layer at the interface of the heterojunction that will reduce the photocurrent; and light loss by reflection and absorption of the top metal contact.

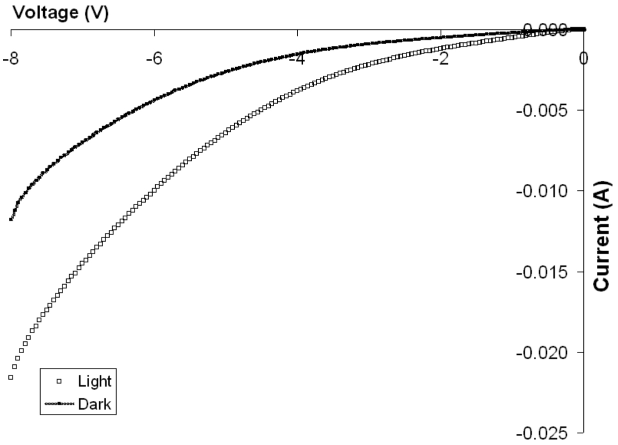

Fig. 5. The *I*–*V* characteristics of p-GaN/n-Si photodiodes. Photocurrents under illumination (light) are shown from the diodes. Dark current behavior is also indicated as a reference. Both curves revealed a strong rectifying behavior.

4. Conclusions

A heterojunction of Mg-doped p-type crystalline gallium nitride was grown on n-type Si (111) by radio frequency nitrogen plasma-assisted MBE. All the diodes show typical rectifying behaviors as characterized by the current–voltage measurements, and their photoelectric effects have been observed under illumination.

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