

Dark current characteristics of Ni contacts on porous AlGaIn-based UV photodetector

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The feasibility in reducing the dark current of the metal-semiconductor-metal (MSM) photodetector was investigated by the adoption of porous AlGaIn layer. High quality unintentionally doped n-type $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ films were grown on Si(111) with AlN as buffer layer using radio frequency (RF) nitrogen plasma-assisted molecular beam epitaxy (MBE). Porous AlGaIn in this work was generated by Pt assisted electroless etching. Two narrow stripes of Pt with thickness of about 300 nm were deposited on the AlGaIn sample by using sputtering system. The samples were then etched in a solution of 4:1:1 $\text{HF}:\text{CH}_3\text{OH}:\text{H}_2\text{O}_2$ under illumination of an UV lamp with 500 W power for 15 minutes. From the literature, the use of porous AlGaIn layer for dark current reduction has not been reported. In addition, the process involved in the fabrication of device was simple and required no expensive equipment. The I-V characteristics of as grown and porous Ni/AlGaIn MSM photodetectors under dark and Hg lamp illumination conditions were recorded. The porous sample showed a significantly low dark current at 3V as compared to as grown sample, the dark current of porous sample was about three orders of magnitudes smaller than as grown sample. When the sample was under Hg lamp illumination condition, the change of current was significant for porous sample as compared to the as grown sample.

(Received May 29, 2007; accepted August 22, 2007)

Keywords: AlGaIn, Porous, MSM, Si, UV-photodetector

1. Introduction

GaN-based materials (AlGaIn) are ideal for the fabrication of high-responsivity and visible-blind ultraviolet (UV) detectors due to its unique properties such as wide and direct band gap, high absorption coefficients, and sharper cutoff of the wavelength detection. Photodetectors operating in the UV and with a visible-blind behavior have received enormous attention in recent years, with a number of applications in both civil and military industries for instances missile plumes detection, flame sensing, engine control, solar UV monitoring, UV astronomy, and secure space-to-space communications.

The most common type of photodetectors fabricated based on III-V nitrides are the photoconductor, p-n junction or p-i-n photodiode, Schottky photodiode, and metal-semiconductor-metal (MSM) photodiode. Among the photodetectors, metal-semiconductor-metal (MSM) photodiode has drawn great deal of attention mainly due to reasons like fabrication simplicity, small capacitance, large active area for photodetection, fast response, large bandwidth, low noise, and the suitability for the monolithic integration of an optical receiver.

The structure of an MSM photodetector consists of two interdigitated Schottky contacts (Schottky barriers) connected back to back. When a bias is applied to the MSM structure, one of the Schottky contacts is forward biased and the other is reverse biased. Therefore, for characterization of MSM structure with current-voltage (I-V) measurement, only the reverse bias part of the detector can be measured. In addition, the interdigitated electrode structure of the planar MSM allows the detector to have a very low capacitance per unit area, making the RC

charging time not a limiting factor to the detector's speed of response.

$\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys are extremely important materials with widespread applications for optoelectronic devices because they have a direct wide energy bandgap, which ranges from 6.2 to 3.4 eV. Due to their wide band gap range, the alloys are very attractive materials for applications in ultraviolet (UV) laser diodes (LD's), light emitting diodes (LED's) and photodetectors [1-3].

The current interest in developing ultraviolet (UV) photodetectors is driven by applications in military counter measures, aerospace, automotive, petroleum, engine monitoring, flame detection and solar UV detection. Alloys of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ are ideal materials for developing UV photodetectors due to the relatively high mobility, sharp cut-off wavelength and high quantum efficiency [4-7]. Characteristics of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ photodetectors are degraded with increasing aluminum molar fraction because of the degradation of the crystal quality with increasing aluminum content.

Silicon substrate presents the obvious advantages of a well-known technology, availability of high-quality, large-area and low-cost wafers. However, its high lattice- and thermal-mismatch with III-nitrides and the high diffusion-coefficient of Si at growth temperatures have delayed the progress in the fabrication of efficient optoelectronic devices on this substrate. Thus, AlGaIn photodetectors are usually fabricated on sapphire substrates and grown by MOCVD. There are only a few reports on GaIn photodetectors on Si(111), which include photoconductors [8] and Schottky photodiodes [9].

To date, no approaches have been reported to fabricate the AlGaIn porous structures. Porous semiconductors have been widely studied in the last

decade, primarily due to the potential for intentional engineering of properties not readily obtained in the corresponding crystalline precursors as well as the potential applications in optoelectronics, chemical and biochemical sensing. The unique physical properties of the porous layer such as, high surface area, shift of bandgap and efficient luminescence are among the special features which show promise in some of the sensing applications [10-11].

The research in porous GaN is strongly driven by the superior physical properties such as the excellent thermal, mechanical and chemical stability, as well as the potential shift of the bandgap [12], moreover, it has been reported that porous GaN can be used as intermediate layer for the reduction of substrate induced strain [13-14]. Since bulk GaN in wafer size is not available, GaN thin film usually is grown on poor lattice and thermal mismatch foreign substrates which will result in high residual stress and eventually lead to high density of structural defects. Porous GaN shows promise as a growth template for epitaxial re-growth; this could reduce the density of structural defects significantly and allows the growth of residual-free epitaxial GaN layers. Comparatively, the study of porous GaN is still in the early stage, many fundamental properties are not well-established.

Similar to porous GaN, porous AlGaIn can be used as a buffer or intermediate layer to reduce substrate-induced stress. Such a regrowth method may reduce the defect density in the epitaxial layer leading to high quality stress free layer on porous template. In this paper, we have investigated growth of unintentionally doped n-type $\text{Al}_x\text{Ga}_{1-x}\text{N}$ epilayers grown on silicon (111) using Veeco model Gen II MBE system. Then, the investigation of porous AlGaIn prepared using Pt assisted electroless chemical etching for 15 minutes was carried out. The morphological of as grown and porous AlGaIn samples were characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM). Also reported is our attempt to fabricate and characterize metal-semiconductor-metal (MSM) photodetector based on these films.

2. Experimental details

The film growth has been performed in a MBE system, using standard effusion sources for evaporation of Al (6N5) and Ga (7N) and using a RF-source to supply activated nitrogen. Growth mode and surface superstructures have been monitored by a 15 kV RHEED system. The base pressure in the system was below 5×10^{-11} Torr. Prior to loading into the MBE chamber, the Si (111) wafers (resistivity < 0.02 ohm-cm, n-type) were ultrasonically degreased in solvents and etched in buffered HF. In the preparation chamber, the substrates were outgassed for 10 min at 400 °C prior to growth.

The plasma was operated at typical nitrogen pressure of 1.5×10^{-5} Torr under a discharge power of 300 Watts. In the growth chamber, Si substrate was heated at 750 °C, and a few monolayers of Ga was deposited on the substrate for the purpose of removing the SiO_2 by the

formation of GaO_2 . A RHEED reconstruction with prominent Kikuchi lines is then observed, that turns into clean Si (111) surfaces at 750 °C.

A way to avoid amorphous SixNy layer formation is to start the growth with an AlN buffer layer, because the bond formation between Al and N atoms prevails over the Si-N one. Due to the formation of SixNy , low temperature GaN is not a suitable buffer for GaN epitaxy. AlN deposition is started by opening both Al and N cell shutters and starting the N plasma simultaneously just before the growth of AlGaIn layer. The role of this layer is not only to improve the crystalline quality of the latter AlGaIn layer, but also to electrically insulate the epitaxial film from the conductive substrate. Sample nominally consisted of 0.20 μm AlN followed by 0.23 μm unintentionally doped n-type AlGaIn. The Al fraction of AlGaIn epilayer was determined by HRXRD simulation.

The wafer was then cleaved into few pieces. Prior to the metallization, the native oxide of the sample was removed in the 1:20 $\text{NH}_4\text{OH}:\text{H}_2\text{O}$ solution, followed by 1:50 $\text{HF}:\text{H}_2\text{O}$. Subsequently boiling aqua regia (3:1 $\text{HCl}:\text{HNO}_3$) was used to etch and clean the sample. Porous AlGaIn in this work was generated by Pt assisted electroless etching. Two narrow stripes of Pt with thickness of about 300 nm were deposited on the AlGaIn sample by using sputtering system. The samples were then etched in a solution of 4:1:1 $\text{HF}:\text{CH}_3\text{OH}:\text{H}_2\text{O}_2$ under illumination of an UV lamp with 500 W power for 15 minutes. After chemical treatment, the samples were removed from the solution and rinsed with distilled water; followed by the removal of the residual Pt by ultrasonic cleaning. The morphological of as grown and porous AlGaIn samples was characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM).

For the MSM photodiodes, the structure consists of two interdigitated Schottky contacts with finger width of 230 μm , finger spacing of 400 μm , and the length of each electrode was about 3.3 mm. It consists of 4 fingers at each electrode as shown in Fig. 1. Nickel (Ni) is used as the Schottky contact metal for all the fabricated devices due to its high metal work function ($\phi_m = 5.15$ eV) and its availability in our lab. Thermal evaporation method is employed for all the Ni Schottky contact formation by using a metal mask. The I-V characteristics of the contacts were investigated. The effective Schottky barrier heights (SBHs) are deduced from I-V measurement assuming the results can be described by the standard thermionic-emission equation.

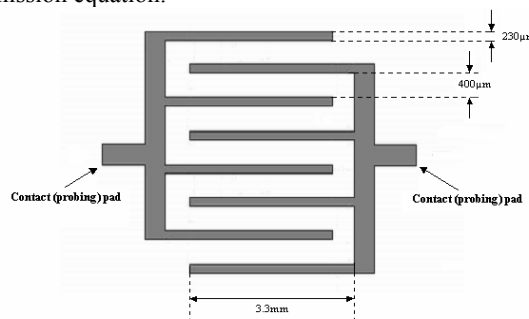
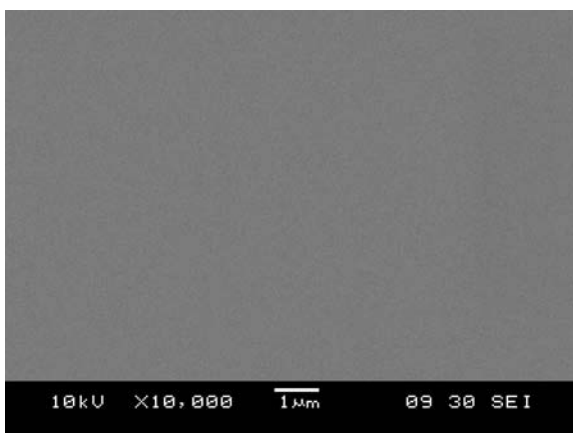


Fig. 1. Schematic diagram of the MSM structure.

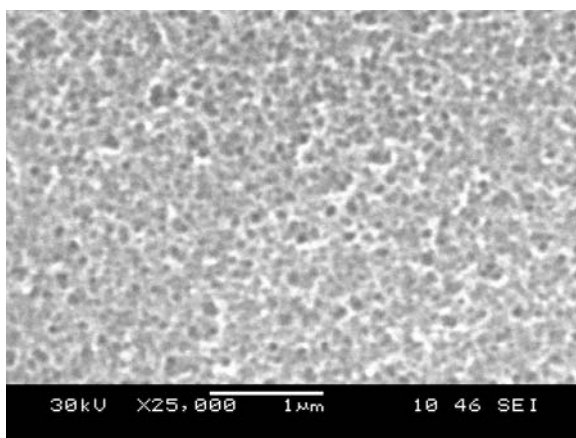
3. Results and discussion

Simulation of the diffraction process is the standard way of extracting details about the composition. Simulation of RC was performed, the simulation parameters for the Al-composition in the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer is 9.4 %.

The morphology of the as grown and porous AlGaIn films were characterized by plan-view scanning electron micrographs (SEM). As seen in Fig. 2, the porous area is very uniform, with pore diameter in the range of 100-110 nm. The surface roughness of as grown and porous AlGaIn samples measured by AFM (Fig. 3). The root-mean-square (RMS) roughness value of the surfaces as grown and porous AlGaIn are 6.55 nm and 10.00 nm, respectively on $5 \times 5 \mu\text{m}^2$. It was surprisingly to note that the surface roughness of the porous AlGaIn samples was relatively low despite high density of pores, however, the RMS of the porous samples were observed to be higher than as grown sample.



(a)



(b)

Fig. 2. SEM images of the samples. (a) As grown, (b) Etched for 15 min.

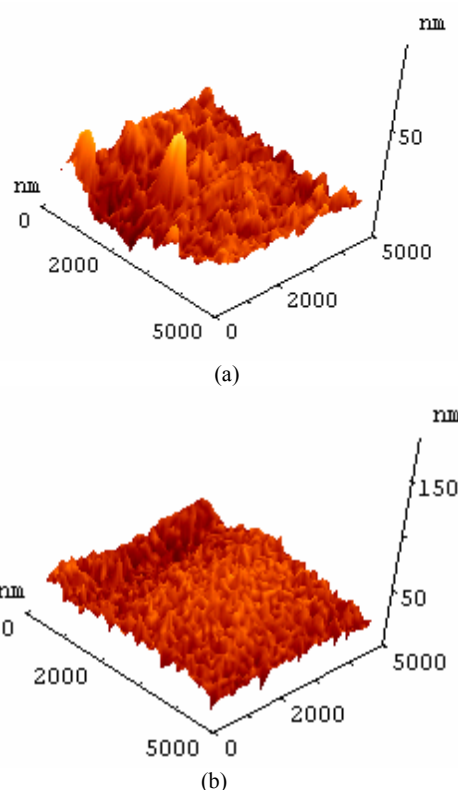


Fig. 3. AFM micrographs of the samples. (a) as grown, (b) etched for 15 min.

Fig. 4 shows the I-V characteristics of as-grown and porous Ni/AlGaIn photodetectors under dark and Hg lamp illumination conditions. The porous MSM photodetector showed a significantly low dark current at 3V as compared to as grown MSM photodetector, the dark current of porous sample was about three orders of magnitudes smaller than as grown sample. When the sample was under Hg lamp illumination condition, the change of current was significant for porous sample as compared to the as grown sample. Since both as grown and porous samples were originated from the same AlGaIn 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 AlGaIn thin film.

It can be seen that dark current rises slowly with the applied reverse bias and does not show any effect of saturation (Fig. 4). The lack of saturation for a Schottky contact under reverse bias can be commonly explained in terms of barrier height is dependent on the electric field strength in the barrier as a result of the existence of an interfacial layer between the metal and the semiconductor. The lack of saturation can also be caused by image force lowering of the barrier height and due to the generation of electron-hole pairs in the depletion region as generation current is more pronounced at low temperatures than high temperatures because it has lower activation energy than the thermionic-emission component.

$\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ is known to suffer from a high amount of defect densities due to reasons like the difference between the thermal expansion coefficient and large lattice mismatch between the substrates and the $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ material, especially of those grown on Si. During the reverse bias of the Schottky contact, the effect of the applied bias can be much greater when compared to the forward bias. Thus, tunneling current can also be seen in a semiconductor with a lower doping concentration during reverse bias which indicate that the tunnel current cannot be omitted when investigating Schottky contacts under reverse bias voltage.

Thus, apart from the usual thermionic emission current that exist within a metal-semiconductor contact, the high amount of dark current observed can be attributed to the tunneling of carriers across the barrier. This effect can be assisted by traps generated by defects (threading dislocation that reach the surface) and the interfacial layer to produce trap-assisted tunnel currents. Deep-level bulk states that are within a tunneling distance of the interface can be another kind of traps.

Another contribution to the high dark current in $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ is dominated by other current mechanism like leakage current generated by a high defect density present in $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ as well as the traps assisted tunnel current. The high defect density in $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ justifies the presence of inhomogeneity at Schottky contacts, that causes a local enhancement of the tunnel current. The rotation of the layer during the growth and the different positions of the III-element sources could produce alloy inhomogeneities, as already reported. However, in our sample, from XRD measurements, we have not seen any evidence of different alloy compositions.

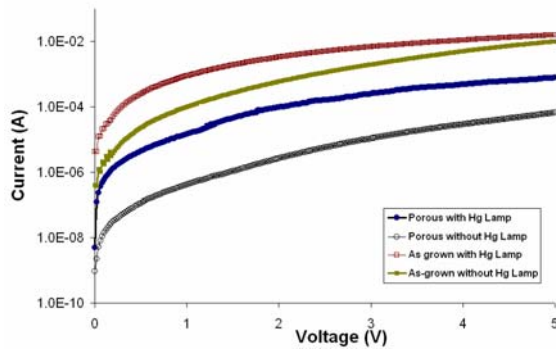


Fig. 4. The I-V characteristics of as-grown and porous AlGaIn photodetectors.

A Schottky contact behaviour can be more closely described by the equation which takes into account the barrier height lowering due to electric field, tunneling effects, the presence of an interfacial layer, and carrier recombination in the space charge region of the metal-semiconductor contact as given by [15-16]

$$I = I_0 \exp\left(\frac{eV}{nkT}\right) \left[1 - \exp\left(-\frac{eV}{kT}\right)\right] \quad (1)$$

where I is the current, I_0 is the saturation current, V is the bias voltage, and n is the ideality factor. The expression for the saturation current, I_0 is

$$I_0 = AA^* T^2 \exp\left(-\frac{q\Phi_b}{kT}\right) \quad (2)$$

where A is the Schottky contact area, the theoretical value [17] of A^* for GaN is $\sim 26.4 \text{ Acm}^{-2}\text{K}^{-2}$. Here, the theoretical value of A^* for $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ can be estimated by using the relation $A^* = 4\pi q m^* k^2 / h^3$ where h is Planck's constant and m^* is the effective electron mass for AlGaIn. As there has not been any references or reported experimental results of the effective mass of electron in AlGaIn, therefore m^* for $\text{Al}_x\text{Ga}_{1-x}\text{N}$ with different x is estimated by a linear interpolation from the theoretical value of $m^* = 0.35 m_0$ for AlN [18] and $m^* = 0.22 m_0$ for GaN [19]. Here, m_0 is the free electron mass. From the equation as being mentioned above, A^* for $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ is estimated to be $\sim 27.9 \text{ Acm}^{-2}\text{K}^{-2}$. However, it should be noted that a large variation in A^* does not have a significant influence on the Φ_B value that is to be determined [20]. Equation (1) can be written in the form of

$$\frac{I \exp(eV/kT)}{\exp(eV/kT) - 1} = I_0 \exp(eV/nkT) \quad (3)$$

At $T \leq 370 \text{ K}$ and when $V \leq -0.5 \text{ V}$, equation (3) can be simplified to [21]

$$I \exp\left(\frac{eV}{kT}\right) = I_0 \exp\left(\frac{eV}{nkT}\right) \quad (4)$$

$$\ln [I \exp(eV/kT)] = \ln I_0 + \frac{eV}{nkT} \quad (5)$$

The plot of $\ln [I \exp(eV/kT)]$ vs V should give a straight line with the slope = e/nkT and y-intercept at $\ln(I_0)$. Using Eq. (2), the ideality factor and Schottky barrier height (SBH) were determined by the I-V method.

Table 1 summarizes dark and photo-current measured at 3V, as well as the ideality factor and SBH of the as grown and porous samples determined from the I-V measurements (Fig. 4). 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. Under illumination condition, the SBHs of both as grown and porous samples became smaller, this translated to higher current of the photodetectors (measured at 3V). However, it should be noted that the change of SBH for porous sample was 0.06 eV as compared to 0.02 eV for as grown sample, the change of SBH was three times higher than as grown sample, this showed that porous AlGaIn sample was more sensitive to illumination. This finding was further confirmed by measuring the contrast ratio of photo-current and dark current at 3V. The contrast ratio for porous sample and as grown were found to be 23.8 and 3.4, respectively, this revealed that the sensitivity of the MSM photodetector fabricated based on porous AlGaIn was much higher than the as grown AlGaIn.

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

Sample	n	SBH (eV)	Current at 3V
As-grown with light	1.018	0.48	6.96×10^{-3}
As-grown without light	1.020	0.50	2.01×10^{-3}
Porous with light	1.022	0.55	2.57×10^{-4}
Porous without light	1.028	0.61	1.08×10^{-5}

The value of the ideality factor is quite near to unity, thus indicating the high quality Schottky contact under investigation and the absence of a thick interfacial layer. However, the existence of a thin interfacial layer cannot be ruled out unless the semiconductor is cleaved in an ultra-high vacuum condition [22]. The variation in barrier height values may be due to formation of alloy, different thickness of interfacial layer present on the film, variation in surface roughness of samples used, defects present in films, the presence of several transport mechanism, and the variations in the local stoichiometry [23].

Other than that, porous sample was found to have the lowest reverse-biased current at -3V among the samples. Obviously, the formation of porosity in the sample after chemical treatment was proven to be able to enhance the SBH and suppress the leakage current. There are several possible reasons for the increase of SBH in porous sample. For instances, the creation of deep surface levels during the preparation of material [24], and the inhomogeneous nature of the porous material which may have geometrical effects on the conductivity [25]. The enhancement of SBH could also be attributed to the roughening or damage of the sample surface which was introduced during chemical treatment. Surface roughening or damage may move the surface Fermi level downward to the valence band and thus increases the SBH, and eventually results in a decrease of the leakage current [26]. The change of the surface morphological of the sample has been confirmed by SEM.

4. Conclusion

In summary, the growth of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}/\text{AlN}$ on Si (111) substrate has been performed using plasma-assisted molecular beam epitaxy. $\text{Ni}/\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ MSM photodiode was achieved and characterized using I-V measurement. The SBHs of both under dark and illuminated conditions were observed to be higher for porous sample relative to the as grown sample. The contrast ratio for porous sample and as grown one were found to be 23.8 and 3.4, respectively. This revealed that the sensitivity of the MSM photodetector based on porous AlGaIn is much higher than the as grown AlGaIn.

Acknowledgments

The authors would like to acknowledge Universiti Sains Malaysia for financial support.

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