The improvements of GaN p–i–n UV sensor on 1° off-axis sapphire substrate

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Abstract

A thin gallium nitride (GaN) layer epitaxially grown on misorientation angles of a-plane 1° off-axis sapphire substrate by metal organic chemical vapor deposition (MOCVD) has exhibited excellent film qualities such as enhanced crystallinity, lower defect levels, and less etching pit density. Accordingly, the GaN p–i–n photodetector fabricated on 1° off-axis sapphire substrate the dark current density decreased from $2.4 \times 10^{-9}$ A/cm$^2$ to $1.82 \times 10^{-11}$ A/cm$^2$ at −3 V, the responsivity increased from 0.06 A/W to 0.105 A/W at 360 nm with no applied bias; the ultraviolet/visible (UV/vis) rejection ratio increased from $2.32 \times 10^3$ to $2.48 \times 10^4$ (comparing wavelength 360–450 nm). A superior device performance could be achieved, as device fabricated on 1° off-axis sapphire substrate.

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1. Introduction

Gallium nitride (GaN) and its alloys with aluminum and indium have been considered as the most promising materials for semiconductor photonic devices operating in blue and ultraviolet (UV) regions of the spectrum [1–3]. The transparency of high-quality GaN film to photons with wavelengths longer than 360 nm has made it an ideal material for photodetectors capable of retaining near unity quantum efficiency in the UV region of light spectrum while rejecting near infrared and visible light. Therefore, GaN-based photodetectors have been proposed for potentially possible applications such as UV astronomy, flame sensors, missile warning, and space communications [4,5].

It has been revealed that the quality of epitaxially grown GaN film is largely determined by its growth conditions such as substrate nitridation [6,7], buffered layer [8,9], and ramping conditions [10,11]. Nowadays, photodiodes grown on a low-defect lateral epitaxial overgrown (LEO) GaN layer [12], low temperature (LT) AlN interlayer [13], and strain-relief superlattice (SLs) interlayer [14] for the defect reduction have been proposed. Among various techniques that have been adopted for GaN film quality improvement, misorientate of the substrate by reducing threading or edge dislocations has been recognized as a promising technique [15–18]. However, very few devices results have been reported to verify the substrate misorientate effect on device performance. In this work, we experimentally focused on the electrical and physical character discussions as GaN p–i–n UV sensor grown on c-plane sapphire with misorientation angles of a-plane 1° off-axis substrate for defect reducing; samples were fabricated by metal organic chemical vapor deposition (MOCVD). The corresponding device grown on 0° on-axis has also been fabricated for comparisons.

2. Experiments

The GaN groups of samples utilized in this study were grown on 0° (sample 1) and misorientation angles of a-plane 1° off-axis (sample 2) sapphire substrate, respec...
3. Results and discussion

Fig. 1(b) shows the low temperature (17 K) PL intensity of GaN grown to a thickness of 2 μm on 0° (sample 1) and misorientation angles of a-plane 1° off-axis (sample 2) sapphire substrate, respectively. It was observed that at lower energy (∼3.1–3.6 eV) measurement, it was observed that near GaN bandedge (∼3.48 eV), the PL intensity of GaN grown on sample 2 is larger and presents a better film quality than sample 1. Misoriented slightly of a-plane 1° off-axis, possibly due to reduction of undesirable impurities and/or the reduction of nitrogen vacancies. Low-temperature PL reveals an unidentified peak, possibly related to an impurity or the substrate, which has great intensity on 0° on-axis sample than 1° off-sample at lower energy level. Regardless of the optical quality of the on-axis samples, the off-axis samples have a much yellow band emission, bright band edge emission; these factors lead to the possible conclusion that slight misorientation decreases the incorporation of unwanted impurities, such as silicon, carbon, or oxygen, and/or reduces the density of nitrogen vacancies [17].

To correlate with the electrical data, Fig. 2 shows the XRD rocking curves of GaN grown to a thickness of 2 μm on 0° (sample 1) and misorientation angles of a-plane 1° off-axis (sample 2) sapphire substrate, respectively. It was observed that sample 2 with a pure GaN free exciton peak intensity was observed and presented a narrow FWHM (240 s⁻¹) shown as Fig. 2(b) which presented a good film quality than sample 1 FWHM (266 s⁻¹) in Fig. 2(a), respectively. The contemporary studies also show that high-quality GaN films can be grown on sapphire substrate if the misorientation angle is chosen appropriately [15–18].

Fig. 3 shows the average dark current density (1 mm × 1 mm active region) of p–i–n UV sensors grown on 0° (sample 1) and misorientation angles of a-plane 1° off-axis (sample 2), respectively. Dark current is usually attributed to the hopping of charged carriers via localized defect-related states (traps) in the depletion region. Experimental results indicate that the dark current density of sample...
Fig. 2. XRD (0 0 4) analysis as GaN grown on (a) 0° sapphire (sample 1), FWHM = 266 s° and (b) 1° off-axis sapphire (sample 2), FWHM = 240 s°.

Fig. 3. Dark current analysis as GaN p–i–n UV sensor grown on 0° (sample 1) and 1° off-axis (sample 2) sapphire substrate, respectively.

Fig. 4. (a) Hall measurement of carrier concentration vs. temperature (K⁻¹) which shows the activation energy (Ea) as GaN grown on 0° (sample 1) and 1° off-axis (sample 2) sapphire substrate, respectively. (b) Interface state capacitance vs. frequency as GaN grown on 0° (sample 1) and 1° off-axis (sample 2) sapphire substrate, respectively.

Fig. 5. Spectrum responsivity analysis as GaN p–i–n UV sensor grown on 0° (sample 1) and 1° off-axis (sample 2) sapphire substrate, respectively.
2 is $1.82 \times 10^{-11}$ A/cm$^2$ which is about 2 orders of magnitude lower than sample 1 ($2.4 \times 10^{-9}$ A/cm$^2$) at reverse bias of $-3$ V. Although the dark currents do fluctuate, however, more than 90% of the p–i–n diodes retain their reverse currents between 10 pA/cm$^2$ and 20 pA/cm$^2$ at 0 V to $-3$ V, which are compatible with the results reported in GaN-based p–i–n diodes [19]. The turn-on voltages of samples 2 and 1 were 1.6 V and 2 V, the corresponding ideality factors were...
obtained by fitting the low-level injection region of dark current (Fig. 3) are 2.4 and 3.4, respectively. The lower turn-on voltage and lower ideality factor could be achieved on sample 2 which represents a lower defect density of the film. The corresponding electrical characteristics such as lower dark current in sample 2 can be attributed to the improvement of GaN film quality.

The crystal defects or impurities in the material may easily create energy levels within the bandgap and form recombination centers, which degrade the performance of UV photo detector. The improved analysis of defect level was characterized by Hall measurement (77–300 K) and interface state capacitance analysis, respectively. Fig. 4(a) shows the Hall measurement of carrier concentration with temperature (K$^{-1}$) as GaN grown to a thickness of 2 μm with the same silane (SiH4) flow on 0° (sample 1) and misorientation angles of a-plane 1° off-axis (sample 2) sapphire substrate, respectively. The slope of curve was calculated and defined as activation energy ($E_a$). It is observed that sample 1 presented two slope ($E_a = 19.3$ meV, $E_a = 30.5$ meV) of activation energy ($E_a$). The higher activation energy $E_a = 30.5$ meV could be recognized as deep-level behavior. On the other hand, sample 2 has only one slope and lowering of activation energy ($E_a = 16.5$ meV) was observed. Meanwhile, the mobility with temperature was carried out on both samples shown in inset of Fig. 4(a). It is observed that sample 2 has higher mobility than sample 1. The lower activation energy and higher mobility on sample 2 also show that the improvement of GaN film quality on 1° off-axis sapphire substrate.

Fig. 4(b) shows the C-V measurement on samples 1 and 2, respectively. It was observed that at lower frequency (100Hz), the related interfacial states capacitance, $C_p$ produced by defect extended into the surface of the bulk were measured about $8.5 \times 10^{-10}$ F and $2.1 \times 10^{-12}$ F on samples 1 and 2, respectively. The local defects or interface states hopping in the detector with bias, presented a higher dark current.

This effect was studied extensively in amorphous semiconductors and was found to be the dominant mechanism of the dark current flow. Fig. 5 shows the spectrum response of visible-blind UV photodiodes at zero bias; the average responsivity exhibits significantly larger during UV spectral response ranges during 280–360 nm visible-blind window as devices grown on 0° (sample 1) and misorientation angles of a-plane 1° off-axis (sample 2) sapphire substrate, respectively. Two devices roll off abruptly at wavelengths greater than 360 nm since they are transparent in this region. The decrease of responsivity at shorter wavelengths on samples 1 and 2, can be explained by the absorption in the p-layer. Sample 1 has lower responsivity as wavelength below 360 nm than sample 2 indicating that higher surface recombination since the carriers are created close to the surface and must diffuse to the junction in order to be collected. The response tail for photon energies below the band gap (wavelength > 360 nm) can be explained by the mechanisms of central photoionization in various defects such as dislocations during grain boundaries, or interface. These defect centers could generate energy levels in the semiconductor band gap and they can be ionized by photons with energies below the band gap. Meanwhile, high-energy photons could also ionize these centers and provoke band-to-band transition in the bulk, and a reduction of UV/vis rejection ratio is observed. Experiment shows that the maximum responsivity on sample 2 is 0.105 A/W at 360 nm with no applied bias, which corresponds to an internal quantum efficiency of 43% is due to the A- and B-exciton absorption [20]. The corresponding responsivity of sample 1 at the same condition is much lower ($\sim 0.06$ A/W). Moreover, the rejection ratio of sample 2 is about 2.48 $\times 10^3$ (comparing wavelength 360 nm and 450 nm) which is 1 order of magnitude higher than sample 1 ($\sim 2.32 \times 10^3$) at the same wavelength, respectively. Through PI spectrum, XRD FWHM, Hall measurement, and interface state capacitance analysis discussed in Figs. 1, 2 and 4, we confirm that the improved quality of GaN layers on sample 2 could be obtained, which induced a higher responsivity and rejection ratio on sample 2 was observed.

Fig. 6(a) and b) shows the SEM photograph of etching pit density (EPD) on top p-GaN film as devices grown on 0° (sample 1) and misorientation angles of a-plane 1° off-axis (sample 2) sapphire substrate, respectively. The EPD of sample 2 is 4.7 $\times 10^4$ cm$^{-2}$, which is about 2 order lower than sample 1 ($\sim 9.8 \times 10^5$ cm$^{-2}$); the possible reason is that slight misorientation decreases the incorporation of unwanted impurities (such as silicon, carbon, or oxygen) and/or reduces the density of nitrogen vacancies [17]. The improved grain alignment and lower EPD may be responsible for the superior electrical properties in sample 2. Through defect reduction, the efficiency of carrier collection can be increased and a higher response or rejection ratio on sample 2 is thus formed.

Fig. 6 (c and d) shows the AFM roughness analysis of p-GaN film on samples 1 and 2, respectively. The mean roughness of sample 2 is 4.7 $\times 10^{-8}$ cm, which is more than sample 1 (Rs = 0.156 nm). The reasons why such rougher surface morphology on 1° off-axis sample are not clear at present, but it is considered that the appropriate atomic steps of the substrate formed by the slight misorientation can relieve the lattice mismatch between sapphire and GaN, which is one of the reason why for the change rougher in surface morphology [21].

4. Conclusions

In conclusion, GaN p-i-n UV sensor grown on 0° and misorientation angles of a-plane 1° off-axis sapphire substrate have been fabricated and characterized, respectively. The GaN p-i-n UV sensor grown on 1° off-axis sapphire substrate has exhibited lower dark current, higher response sensitivity, and higher rejection ratio compared to that grown on 0° on-axis sapphire substrate, these results which are in accordance with the state-of-the-art of dislocation reduction technique as GaN p-i-n UV detector fabricated by using LT
inter layer, superlattice (SLs), or epitaxial lateral overgrowth (ELOG) technique. Through the electrical and physical characteristic analysis by LT-PL, XRD, Hall measurement, interface state capacitance, and EPD analysis in our experiments, the truly improvements of data on 1° off-axis were obtained. Meanwhile, the effects of GaN p–i–n UV detectors fabricated on different misorientation angles are under developed in our laboratory, and will be characterized and discussed in the future.

References