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Growth of InGaN layers on (1 1 1) silicon substrates by reactive sputtering

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ABSTRACT

InGaN films were grown on (1 1 1) silicon substrates by reactive magnetron sputtering. It was demonstrated that the indium composition in the InGaN films can be controlled by varying the ratio of the applied radio-frequency power of the indium target to that of the GaAs target. Optical investigation showed that the bandgap energy of the InGaN films can be tailored in wide range to obtain maximal absorption of solar energy for improving the efficiency of a solar cell. Raman scattering analysis revealed that A_1(LO) phonon in InGaN wurtzite structure obeys a one-mode behavior. The results indicates that the reactive sputtering is a promising growth technique for obtaining InGaN layers on silicon substrates with low cost and good compatibility with silicon based devices.

1. Introduction

Ternary InGaN continues to receive considerable attention owing to its applications in light-emitting diodes, laser diodes, photodetectors, and high-power and high-speed electronic devices [1–2]. Recently, InGaN has been extensively investigated as an excellent candidate for high-efficiency photovoltaic devices because its wide bandgap energy variation and superior high energy radiation resistance for space-based photovoltaic applications [3–8]. The conversion efficiency of a four-junction solar cell based on InGaN has been predicted to be as high as 63%, which is much higher than those of solar cells based on other material systems [9]. Neufel et al. [5] have observed external quantum efficiency as high as 63% from InGaN/GaN double heterojunction solar cells grown on (0001) sapphire substrates. However, the growth of these InGaN films was fabricated by metalorganic chemical vapor deposition (MOCVD) with high growth temperature, resulting in a high cost for mass production in the photovoltaic industry. Moreover, MOCVD growth technique faces big challenges in the epitaxial growth of a high-indium-content InGaN films owing to the low thermal stability of InN. Reactive sputtering, however, has the advantage of using a simple apparatus and a low growth temperature for obtaining III–V nitrides [10–12]. We have demonstrated that the feasibility of InGaN films grown on sapphire substrates by reactive sputtering technique using a GaAs target and a pure indium target in nitrogen plasma and have succeeded in tailoring the band gap energy of the InGaN films in a wide range [13–15]. From the perspective of device technology, however, sapphire possesses severe problems as a substrate material because it is difficult to cleave. Moreover, since the sapphire substrate is not conductive, it is impossible to create optical devices which operate between the films and the substrates. Silicon is a desirable substrate because of the attractive advantages with availability of large size wafers at very low cost. Therefore, it is highly desirable to deposit the InGaN films on silicon substrates, which also has the potential for integrating InGaN electronic and optoelectronic devices with well-developed silicon microelectronic circuits. In this article, we report on the growth of InGaN films on (1 1 1) silicon substrates by using reactive sputtering technique.

2. Experiments

InGaN films were prepared on (1 1 1) silicon substrates by reactive radio-frequency (rf) magnetron sputtering in nitrogen ambient. Polished (1 1 1) silicon substrates were chemically cleaned, decreased in organic solvents, etched in an acid solutions, and then rinsed in deionized water. The sputtering chamber was evacuated to a pressure of 10^{-7} Torr using a turbomolecular pump before introducing the sputtering gas. During the growth, the gas flow rate and pressure were maintained at 4 sccm and 5 mTorr, respectively. The substrate temperature was monitored using a thermocouple and controlled at 550 °C. The indium and GaAs were separately mounted onto the targets and were simultaneously sputtered at different rf power, while the substrate holder was rotated at constant rate of 36 rpm. The growth conditions for InGaN films were summarized in Table 1. After the growth, the film thickness was determined by a surface step profile analyzer. Chemical

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Table 1
Growth conditions of InGaN films.

Targets	Indium, GaAs
Substrates	(1 1 1) Silicon
Residual pressure	<5 × 10^{-7} Torr
Substrate temperature	550 °C
RF power	
Indium	20–150 W
GaAs	20–150 W
N_2 gas flow rate	4 sccm
Sputtering pressure	5 mTorr
Substrate holder rotation speed	36 rpm

compositions of the obtained films were measured by energy-dispersive X-ray (EDX) spectroscopy. Optical reflectance measurements were carried out using a double-beam spectrophotometer at room temperature. Raman measurements were performed on a micro-Raman system with a conventional charge-coupled device detector. The surface morphology of the films was observed by atomic force microscopy (AFM). The root mean square (RMS) surface roughness of the films was determined over a 1 × 1 μm^2 area.

3. Results and discussion

Fig. 1 shows the EDX spectra of the InGaN films grown at different ratio of the applied rf powers on indium target to those on indium and GaAs targets. The peaks corresponding to indium (In), gallium (Ga) and nitrogen (N) elements are clearly observed in EDX spectra of InGaN samples. We note that no arsenic (As) element in the EDX spectra was observed as shown in Fig. 1 because the arsenic atoms in the grown layer were completely desorbed at a substrate temperature of 550 °C, which agrees with the results of InGaN films grown on sapphire substrates [13]. From Fig. 1 it is clear that the In/Ga peak height ratio in the EDX spectra increases while the intensity of N peak remains almost constant when the rf power ratio increases. The indium composition x in InGaN obtained from the EDX spectra by quantitative analysis after calibration using a cobalt standard specimen is shown in Fig. 2 as a function of rf power ratio. The indium composition x increases almost linearly with the increase of the rf power ratio, suggesting that the InGaN with the desired indium composition x can be designed by varying the ratio of the rf power of the indium target to that of the GaAs target easily.

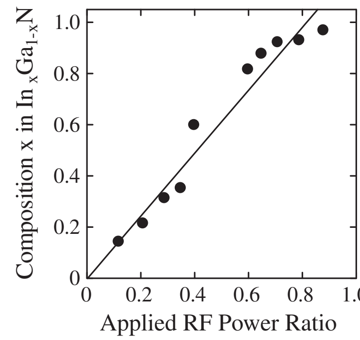
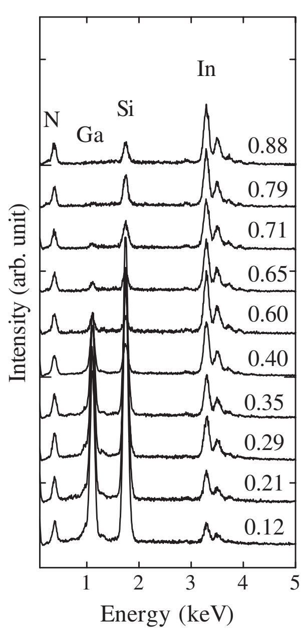


Fig. 2. Dependence of indium composition x in InGaN films on ratio of the applied rf powers on indium target to those on indium and GaAs targets.

Fig. 3 shows the wavelength dependence of optical reflectance spectra of the InGaN films with different indium compositions x at wavelength ranges of 250–850 nm using a dual-beam spectrometer at room temperature. Prominent Fabry–Perot interference fringes due to multiple-layer-substrate reflections are observed at a long wavelength for all samples. Since the interference fringe begins to vanish in the vicinity of the wavelength related to the optical bandgap energy, the results in Fig. 3 clearly show that the optical bandgap energy of the InGaN films increases with an decrease in the indium composition x. This indicates that the bandgap of InGaN films grown on silicon can be controlled in wide range by changing the ratio of the rf power of the indium target to that of the GaAs target in order to obtain maximal absorption of solar energy for improving the efficiency of a solar cell.

Fig. 4 shows AFM images of the InGaN films with different indium compositions x, where the scan area is 1 × 1 μm^2. The InGaN films with indium composition of 0.14 exhibits a very smooth surface with roughness of 1.8 nm. The surface roughness of the InGaN films is essentially independent of the indium composition x in the range above 0.35 as shown in Fig. 5. Kajikawa and coworkers [16] investigated the correlation between process conditions and film



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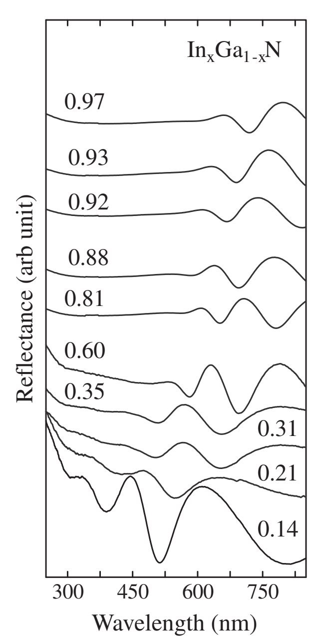

Fig. 3. Reflectance spectra of InGaN at different indium composition x.