



Electronic transport properties in aluminum indium nitride nanorods grown by magnetron sputter epitaxy



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ABSTRACT

The electronic transport properties of the wide-bandgap aluminum indium nitride (AlInN) nanorods (NRs) grown by ultrahigh-vacuum magnetron sputter epitaxy (MSE) have been studied. The conductivities of the ternary compound nanostructure locates at the value of $15 \Omega^{-1} \text{cm}^{-1}$, which is respectively one and two orders of magnitude lower than the binary GaN and InN counterparts grown by chemical vapor deposition (CVD). The very shallow donor level/band with the activation energy at $11 \pm 2 \text{ meV}$ was obtained by the temperature-dependent measurement. In addition, the photoconductivity has also been investigated. The photoconductive (PC) gain of the NRs device can reach near 2400 under a low bias at 0.1 V and the light intensity at 100 W m^{-2} for ultraviolet response in vacuum. The power-insensitive gain and ambience-dependent photocurrent are also observed, which is attributed to the probable surface-controlled PC mechanism in this ternary nitride nanostructure.

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1. Introduction

The Group III-nitride semiconductors, including binary aluminum nitride (AlN), gallium nitride (GaN), and indium nitride (InN), and their ternary compounds have gain substantial attention due to their superior properties for the electronic and optoelectronic device development [1–3]. Among them, the ternary AlInN with the tunable bandgap, which spans near infrared (IR), visible, and deep ultraviolet (UV) ranges, is broader than the other ternary compound such as InGaN and AlGaIn. The tunable wide bandgap and lattice constant of AlInN have been utilized for device applications such as light emitting diodes (LEDs) [3], laser diodes (LDs) [4,5], solar-blind photodiodes [6,7], etc. The AlInN has also been used as an excellent barrier layer for optimizing the performance of the high-frequency and high-power high electron mobility transistors (HEMTs) [8–10].

Although the AlInN could offer broad application interest, it is still less studied due to the difficulty in preparing the high-quality crystal. Recently, growths of the AlInN epitaxial film and especially its quasi one-dimensional (1D) nanostructure have been achieved by the technique of magnetron sputter epitaxy (MSE) [11–13]. The achievement has allowed us to investigate the fundamental properties and the potential applications of the novel ternary compound

semiconductor. In this letter, we report on the electronic transport properties of the AlInN nanorods (NRs). The dark conductivity and photoconductivity have been investigated by the temperature, power, ambience-dependent measurements. The probable mechanisms for carrier transport in this wide-gap ternary nitride nanostructure are also discussed.

2. Experimental

The AlInN NRs were grown on *c*-plane sapphire substrates with and without a vanadium nitride (VN) seed layer at 650 °C and 800 °C, respectively, under 5-mtorr pure nitrogen working pressure by ultrahigh-vacuum magnetron sputter epitaxy. More growth details can be found in our previous publication [11]. The morphology, composition, and crystallinity of the as-grown AlInN NRs were characterized by the field-emission scanning electron microscopy (FESEM), X-ray diffractometry (XRD), and energy-dispersive X-ray spectroscopy (EDX), respectively. The electrical contact for the AlInN NRs devices which comprise of several or several tens NRs was fabricated by focused-ion beam (FIB) depositions using platinum (Pt) as the contact metal. Electrical measurements were carried out on an ultralow current leakage cryogenic probe station (LakeShore Cryotronics TTP4). A semiconductor characterization system (Keithley 4200-SCS) was utilized to source dc bias and measure current. The He–Cd laser with 325 nm wavelength was used as the UV excitation source for the PC measurements. The incident power of laser was measured by a calibrated power meter

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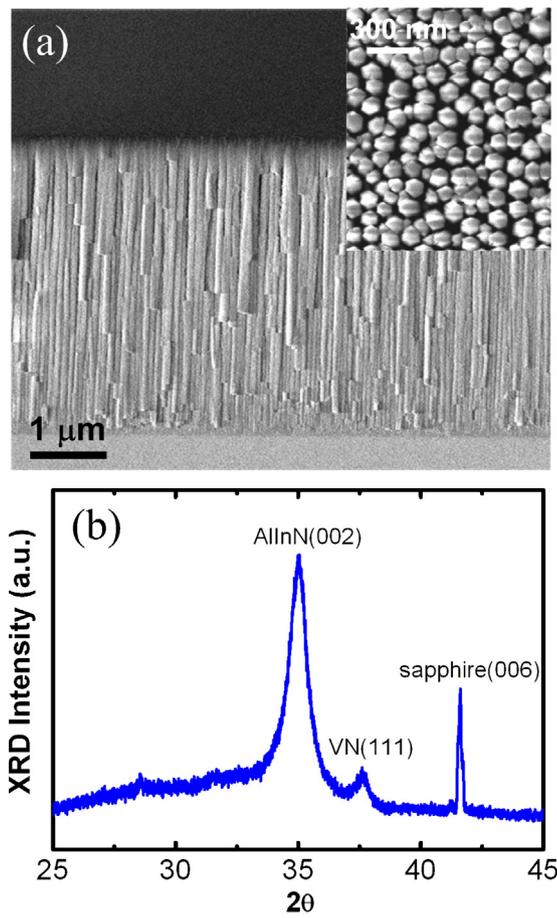


Fig. 1. (a) The typical cross-sectional view and top view (the inset) FESEM images of the vertically aligned AlInN NRs and (b) the XRD pattern of the as-grown AlInN NRs on VN(111)/sapphire(001) substrate.

(Ophir Nova II) with a silicon photodiode head (Ophir PD300-UV). An UV holographic diffuser was used to broaden laser beam size ($\sim 20 \text{ mm}^2$) to minimize the error of the power density calculation.

3. Results and discussion

The typical FESEM image of the MSE-grown high-density AlInN NRs with vertical alignment on the VN(111)/sapphire(001) substrate is shown in Fig. 1(a). The diameter range and the length of the as-grown NRs are 60–120 nm and 3.8 μm , respectively. The crystalline structure and aligned growth can be confirmed by the XRD measurement. Fig. 1(b) depicts the XRD pattern with single out-plane orientation of AlInN(001), indicating the NR ensembles with hexagonal structure and *c*-axial preferential growth. Upon the position of AlInN(002) diffraction peak (2θ at $\sim 35^\circ$) and the Vegard's law using bulk AlN and InN lattice constants [14], the indium composition (*x*) of the $\text{Al}_{1-x}\text{In}_x\text{N}$ NRs can be estimated to be $\sim 20\%$. The range of *x* was further confirmed by the EDX measurement.

The typical dark current versus applied bias (i_d -*V*) curves measured in the temperature range of 140–300 K for the AlInN NRs are illustrated in Fig. 2(a). The linear i_d -*V* behavior shows the stable ohmic contact condition of the NRs device at different temperature. The room temperature conductivity (σ) was estimated at $\sim 15 \Omega^{-1} \text{ cm}^{-1}$. While comparing with other III-nitride 1D nanostructures, the value is respectively one and two orders of magnitude lower than the GaN ($\sigma = 150 \pm 50 \Omega^{-1} \text{ cm}^{-1}$) [15] and InN ($\sigma = 2500 \Omega^{-1} \text{ cm}^{-1}$) [16] nanowires (NWs), and is higher than

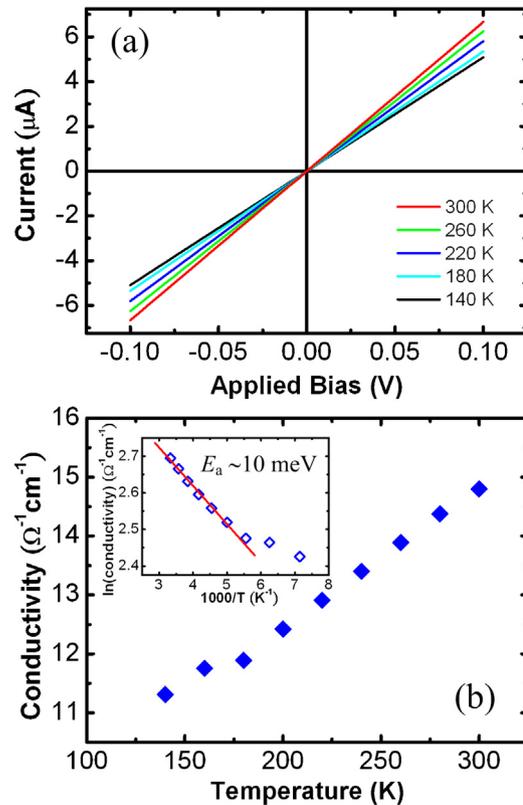


Fig. 2. (a) The selected dark current versus applied bias curves measured in the temperature range of 140–300 K and (b) the calculated conductivity versus temperature and its corresponding Arrhenius plot (the inset) for the AlInN NRs with $w = 300 \pm 60 \text{ nm}$ and $l = 2.0 \pm 0.2 \mu\text{m}$.

the AlN NWs ($\sigma = 1.6 \Omega^{-1} \text{ cm}^{-1}$) [17] grown by the chemical vapor deposition (CVD).

The temperature-dependent σ and its corresponding Arrhenius plot (the inset) are depicted in Fig. 2(b). According to the plot, the σ decreases slightly from 15 to $11 \Omega^{-1} \text{ cm}^{-1}$ with the decrease of temperature from 300 to 140 K. The thermal activation energy (E_a) of carrier was calculated by the Arrhenius slope to be $\sim 10 \text{ meV}$. The small E_a is consistent with other three NWs devices with E_a range at $11 \pm 2 \text{ meV}$. The AlInN NRs with the small E_a in common indicate the presence of shallow donor levels/bands in this MSE-grown nitride nanostructure. The shallow donor usually is attributed to the nitrogen vacancies in the Group III-nitride semiconductors [18]. The high-quality AlInN epitaxial films prepared by molecular beam epitaxy (MBE) with the similar shallow donors ($E_a = 5$ –70 meV) has also been observed by Lukitsch et al. [19] Accordingly, it is reasonable to infer that the shallow donors in the AlInN NRs could be originated from the nitrogen vacancies.

In addition to dark conductivities, photoconductivities of the AlInN NRs were also characterized. Fig. 3(a) depicts the typical photocurrent (i_p) responses to the 325 nm UV illumination under different light intensity (*I*) in vacuum for the AlInN NRs. The estimated i_p versus *I* curve is also plotted in Fig. 3(b). Overall, the i_p follows a near linear relationship with the excitation power. To investigate the performance of the NRs photodetector, the photoconductive gain (Γ), which is a physical quantity determining the efficiency of photocurrent generation or photocarrier collection of a photodetector, can be estimated according to the linear relationship with i_p

$$\Gamma = \frac{E}{e} \frac{i_p}{\eta P}, \quad (1)$$

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