The synthesis of hybrid nanostructure comprising star-shaped GaN nanowires and Si nanoworms

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1. Introduction

Recently, oriented one-dimensional (1-D) nanostructures, such as nanowires (NWs) and nanorods, have attracted significant research interest due to their potential application as building blocks in many opto-electronic devices, such as photovoltaics,1–4 light-emitting diodes (LEDs),5–8 field effect transistors (FETs),9–12 nanolasers,13–15 and electric generators.16,17 Moreover, the carrier diffusion coefficient and electron recombination time of the ordered 1D nanostructure were found to be larger than those for polycrystalline films, which in turn remarkably increased the diffusion length of the minority carrier.18–20 It has been reported in studies that the electron transport in crystalline nanowires is several orders of magnitude faster than that in the polycrystalline material, which may remarkably reduce the recombination loss and enhance the photocurrent.21 Additionally, nanowires (NWs), due to their high surface-to-volume ratio compared to that of their bulk material, show a significant reduction in the defect and dislocation densities. However, despite these prolific advantages, the nanostructured devices made of these homogeneous material arrangements often suffer from low efficiency and poor performance. Thus, many researchers have studied nanostructured devices fabricated with a heterogeneous material assembly. The III-nitrides family, with attractive properties such as a direct energy band gap, high thermal stability, and high electron mobility, comprises one of the most investigated materials paired with the most common semiconductor material silicon (Si).22–26 Y. B. Tang et al. investigated a photovoltaic device containing p-GaN nanowires grown on a n-Si substrate and reported a relatively high Jsc value around 7.6 mA cm–2.27 A demonstration of a III-nitride/Si tandem solar cell was reported by L. Reichertz et al. in 2009.28 K. M. A. Saron et al. fabricated another hybrid photovoltaic device comprising GaN and n-Si.29 Although these tandem structures are very interesting to study, the high cost and complexity of the fabrication techniques often hinder their further development. In this background, we studied unique star-shaped GaN NWs, which may offer a greater surface to volume ratio than the conventional hexagonal-shaped materials along with simultaneously grown Si nanoworms bearing Au nanoparticles inside.

Herein, we report the growth and characterization of novel star-shaped GaN NWs along with Si nanoworms bearing Au nanoparticles. Both the nanostructures were simultaneously grown to achieve a hybrid structure by designing a favorable experimental environment. In addition, extensive characterization

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methods were used to study the structural and optical properties of the grown hybrid structure, comprising the star-shaped GaN NWs and Si nanoworms with Au nanoparticles inside. The respective growth mechanisms were also systematically investigated and reported.

2. Experimental procedure

All the samples studied in this report were grown on a Si (111) substrate using a home-designed horizontal MOCVD system. Trimethylgallium (TMGa) and ammonia (NH3) were used as the gallium (Ga) and nitrogen (N2) sources, respectively. For the n-type doping, silane (SiH4) was used as the source. Hydrogen (H2) was supplied as the carrier gas. All the chemicals were used without any further purification. Before the deposition, the Si (111) substrate was cleaned in an ultrasonic bath with organic solvents including acetone (CH3COCH3) and methanol (CH3OH). The same substrate was then subjected to solutions containing DI water : H2O2 : H2SO4 (1 : 1 : 3) and H2O : HF (50 : 1) to etch out any inorganic impurities and the native oxide layer. The etching time for both the solutions was 5 minutes. Lastly, the substrate was dried under a flow of N2.

After the cleaning steps, the Si substrate was subjected to a DC magnetron sputtering system for 10 s to deposit the Au nanoparticles. Then, at 720 °C, 12 pairs of GaN seed layers were prepared using a MOCVD system operating in the pulse growth mode. TMGa and NH3 were used as the precursors for Ga and N, respectively. The TMGa flow rate was kept constant at 0.3 sccm throughout the process, whereas the NH3 flow rate was 3 SLM. For the carrier gas, H2 was supplied at the rate of 1 SLM. During the growth process, 100 ppm SiH4 gas was utilized for the n-type doping. The flow rate for SiH4 was maintained at 10 sccm and 5 sccm for the simultaneous growth of the star-shaped GaN nanowires (NWs) with Si nanoworms and star-shaped GaN nanowires (NWs) only, respectively. The total growth time was 1 hour. During the entire growth time, the chamber pressure was kept at the constant value of 600 Torr. Finally, the Au : Ni (8 : 2) metal contacts were formed to measure the photocurrent, employing a DC magnetron sputtering system. The entire growth process is schematically presented in Fig. 1.

The surface morphology of the grown nanowires was characterized by employing a Hitachi S-7400 field effect scanning electron microscope (FE-SEM), operated at 15 kV. X-ray diffraction (XRD) measurements were carried out utilizing a PANalytical EMPYREAN instrument. The crystallinity was examined using a JEM-ARM-200F Cs-corrected-field emission transmission electron microscopy (Cs-corrected- FE-TEM) instrument equipped with an EDX facility at the accelerating voltage of 200 kV. The optical properties were investigated via carrying out photoluminescence (PL) experiments at room temperature. A He–Cd 325 nm laser was used as the photon source. The detector used for photoluminescence investigation was a InGaAs detector. The photocurrent of the fabricated devices was measured by employing a solar simulator (McScience Lab 100) as the light source. This light source generated white light at the maximum power density 100 mW cm–2.

3. Results and discussion

To study the surface morphology and structures of the grown GaN NWs and Si nanoworms, we employed the FE-SEM technique. Fig. 2(a, b, and c) show the obtained FE-SEM images. In Fig. 2(a), only the star-shaped GaN NWs can be seen. Highly dense star-shaped GaN NWs showing growth in the (002) direction or vertical direction can be predominantly observed in Fig. 2(a and b). The top-view of a single NW exposing the 12 facets clearly showing the star shape is shown in the inset of Fig. 2(a). In Fig. 2(b), along with the star-shaped GaN NWs, the Si nanoworms were observed. The Si nanoworms form a highly dense structure similar to a fishing net. The bright spots seen inside the Si nanoworms in Fig. 2(b) are the Au nanoparticles. In Fig. 2(c), a single star-shaped GaN NW is displayed, exposing the sharp edges. The base of the NW was an undoped GaN seed, which was hexagonal in shape. However, the introduction of SiH4 at a high flow rate restrains the lateral growth, which in

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Fig. 1  A schematic of the simultaneous growth process for the star-shaped GaN NWs along with Si nanoworms.
turn results in the final star-shaped structure. This phenomenon has been discussed later in this study. Furthermore, the crystallinity and optical characterization were carried out using XRD and PL characterization techniques, respectively.

Additionally, XRD measurements were performed on the grown structures to investigate the induced stress. In Fig. 3(a), the obtained XRD patterns for both structures are presented. Clearly, the dominant peak was (002), appearing at $2\theta = 34.2^\circ$. However, the stress free $c$-axis directional growth of the GaN NWs shows a peak value of 34.562°. This shift in the XRD $2\theta$ value was attributed to the tensile stain in the $z$-direction, which suppressed the lateral growth of the NWs to retain the final star shape. Similar findings have been reported by B. G. Park et al.\textsuperscript{31} The other three minor peaks represent the (100), (101), and (102) semi-polar planes. The XRD diffractograms for both structures are similar in nature. Thus, it can be concluded that the Si nanoworms do not induce any additional stress in the final hybrid structure. The residual strain in the $z$-direction and in-plane strain were estimated to be 0.0029 and −0.042, respectively, for the star-shaped GaN NWs only.\textsuperscript{31,32} However, the same stain values for the hybrid nanostructure comprising star-shaped GaN NWs and Si nanoworms were found to be 0.0043 and −0.0054.\textsuperscript{31,32} This enhancement in compressive strain in the in-plane was attributed to the increased Si doping, which in turn modifies the shape of the synthesized GaN NWs. The PL spectra of both structures are shown in Fig. 3(b). In the spectrum representing the star-shaped GaN NWs only, the peak position at 365.66 nm displays the band edge emission. While a yellow luminescence (YL) at 559.64 nm is associated with the native Ga vacancy defects ($V_{Ga}$) and surface defects.\textsuperscript{33} However, in the hybrid structure comprising star-shaped GaN NWs and Si nanoworms, the dominant GaN peak position was at the wavelength value of 363.67 nm. This blue shift in the hybrid structure was caused by compressive stress, which confirmed the XRD findings. In the case of the hybrid structure, the YL peak was suppressed, which was due to the excessive doping effect. E. R. Glaser et al. reported the same phenomenon in their report while investigating a GaN system doped with shallow acceptors.\textsuperscript{34} A longitudinal phonon recombination peak was also observed in the hybrid structure at 401.45 nm.\textsuperscript{33,34} Next, the crystallinity of the grown structures was examined by Cs-corrected-FE-TEM.

The Cs-corrected-FE-TEM images and EDX mapping data of the grown structures are shown in Fig. 4(a–i). The Cs-corrected-FE-TEM dark field image of a star-shaped GaN NW is displayed. The hexagonal GaN seed can be seen at the bottom of the NW.
In the 1st stage of growth, an hexagonal GaN seed was formed and the nanostructures are schematically shown. In Fig. 5(a), the nanoworm growth mechanism of the star-shaped GaN NW’s is explained. In Fig. 5, a plausible growth mechanisms for both bamboo-shaped Si nanoworms and hexagonal GaN NW’s along the top r-plane direction presenting all the desired elements. (f) A Cs-corrected-FE-TEM image of a single Si nanoworm showing the Au nanoparticles inside. (g) A high magnification Cs-corrected-FE-TEM image of a single Si nanoworm taken at in the designated area (Ø) shown in the previous figure clearly displaying the bamboo shape inside. (h) A high magnification Cs-corrected-FE-TEM image of a single Si nanoworm clearly showing the Au nanoparticles inside. The inset displays a single Au nanoparticle with lattice fringes. (i) EDX mapping data of a single Si nanoworm, revealing all the desired elements.

No threading dislocation defect was detected in the star-shaped GaN NWs. The EDX mapping data for the star-shaped GaN NWs is displayed in Fig. 4(b), presenting all the desired materials. Fig. 4(c and d) represent the inverse fast Fourier transform (IFFT) image and the transferred image of the star-shaped GaN NWs showing no dislocation defects. (d) The transferred image of the star-shaped GaN NWs revealing the wurtzite structure. (e) EDX mapping data of the star-shaped GaN NWs along the top r-plane direction presenting all the desired elements. (f) A Cs-corrected-FE-TEM image of a single Si nanoworm showing the Au nanoparticles inside. The inset clearly displaying the bamboo shape inside. (h) A high magnification Cs-corrected-FE-TEM image of a single Si nanoworm clearly showing the Au nanoparticles inside. The inset displays a single Au nanoparticle with lattice fringes. (i) EDX mapping data of a single Si nanoworm, revealing all the desired elements.

As evident from Fig. 4(e), all the vertices of the star-shaped GaN NWs have a higher concentration of the n-type dopant Si, which acts as a shape breaker of the conventional hexagonal GaN NWs structure. Previously, many researchers have reported that Si dopants help towards vertical growth and suppress the lateral growth in the GaN NWs. Therefore, it can be concluded that the high concentration of Si dopants employed in this current investigation stopped the lateral growth process and broke the conventional hexagonal shape.
Fig. 5  (a) A schematic of the growth mechanism to realize the star-shaped GaN NWs. (b) A schematic of the growth mechanism to realize the Si nanoworms, following a base-growth mechanism.

Fig. 6  (a) An FE-SEM image of the island-like seed formation of the Au–Si solid solution. (b) An FE-SEM image at the beginning of the Si nanoworms following the base-growth mechanism. (c) An FE-SEM image of the Si nanoworms showing the drifted Au nanoparticles at the top. (d) An FE-SEM image of the final Si nanoworms structure after 1 h of growth. (e) An FE-SEM image of various Si nanoworms with drifted Au nanoparticles.
base-growth mechanism for carbon nanotubes in detail. However, in the presence of an excess of \( \text{H}_2 \) and \( \text{SiH}_4 \), the Au nanoparticles began to decompose from the base and due to the pressure difference inside the nanoworm, because of the size variation from base to top, they started to drift upwards. During this instant drifting, the Au nanoparticles expedited inside the hollow shape of the Si nanoworms. K. Yadav et al. have observed and reported a similar phenomenon in 2014. This stage is schematically represented as the 3\textsuperscript{rd} stage in Fig. 5(b). However, although the shape of the Au nanoparticles remained spherical, the size of the nanoparticles continuously decreased, depending on the Si nanoworm diameter.

The FE-SEM images obtained during different stages of the Si nanoworm growth without the Ga and N sources are shown in Fig. 6(a–e). The 1\textsuperscript{st} stage of growth or the formation of the Au–Si solid solution as small islands on the Si substrate can be seen in Fig. 6(a). After the eutectic melting, the Si nanoworm growth begins from the island-like seeds, which can be observed in Fig. 6(b). The growth of Si nanoworms following the base-growth mechanism with drifting Au nanoparticles from base to top is represented in Fig. 6(c). The complete structure of the Si nanoworms after 1 hour is displayed in Fig. 6(d), where the drifted Au nanoparticles can be found at the top of the Si nanoworms. Fig. 6(e) reveals different Si nanoworms containing the drifted Au nanoparticles at various locations inside the nanoworm structure. All the FE-SEM images shown in Fig. 6(a–e) are in accordance with the aforementioned growth mechanism.

Furthermore, the opto-electronic applicability of both nanostructures was tested via photocurrent measurements. Fig. 7(a) shows the obtained photocurrent measurement results in comparison with those of the conventional hexagonal-shaped GaN NWs. At the positive bias value of 1.5 V, the star-shaped GaN NWs displayed a photocurrent of 4.04 mA, whereas the photocurrent of the hybrid structure comprising the star-shaped GaN NWs and Si nanoworms bearing Au nanoparticles inside was measured to be up to 7.1 mA. On the other hand, the photocurrent observed for the conventional hexagonal-shaped GaN NWs was measured to be 1.447 mA at 1.5 V, which was previously reported by our group elsewhere. This enhancement in the photocurrent can be attributed to the embedded Au nanoparticles, which mediate the charge transport and enhance the light absorption. The improved photoresponsivity of the hybrid structure can be attributed to the reduced density of the trap levels in the photoconductive channel, as shown in Fig. 7(b). The power law dependence of the photocurrent on the optical power density is shown in Fig. 7(c), with an exponent of approximately 0.87. This measurement was performed with the bias fixed at 1.5 V.
nanoparticles, which increase the photosensitivity of the Si nanoworms by generating hot electrons, which in turn enhance the photocurrent of the final hybrid nanostructure. A similar phenomenon has been reported by M.-S. Hu et al.\(^4\) The photoresponsivity was estimated by the \(I_{\text{photo}}/(\text{illuminated area} \times \text{power density of light})\).\(^5\) The maximum light power density value \(i.e.\) 100 mW cm\(^{-2}\) was used in the current investigation. At a bias of 1.5 V, the absolute photoresponsivity of the hybrid structure comprising the star-shaped GaN NWs and Si nanoworms bearing Au nanoparticles inside was calculated to be 71 mA W\(^{-1}\), and the same for the star-shaped GaN NWs only was obtained to be 40.4 mA W\(^{-1}\). The reduced empty spaces between the individual NWs and the larger photoconductive area due to the presence of the Si nanoworms are the noteworthy causes for the enhancement in the photoresponsivity of the hybrid structure. Photoresponsivity analysis further proves that the hybrid structure was superior in terms of the opto-electronic applications when compared to the star-shaped GaN NWs only. The photocurrent of the hybrid structure at various light power densities is shown in Fig. 7(c). In the inset of the same figure, the photocurrent evolution of the star-shaped GaN NWs only with variable light power density is shown. The photocurrent was observed to be enhanced with an increasing incident optical power density, as expected. The photocurrent values at a bias of 1.5 V are plotted against the optical power density and fitted by the simple power law, \(I_{\text{photo}} \propto P^x\), where \(P\) is the incident optical power of the white light source and the exponent \(X\) determines the density of trap levels between the Fermi level and the conduction band of the hybrid structure.\(^4\)\(^6\) These trap levels absorb the photogenerated carrier and significantly reduce the photocurrent. Even at a lower optical power density, the photogenerated carriers should not be absorbed by these trap levels and contribute to the photocurrent. Therefore, upon increasing the optical or light power density, the photocurrent should linearly increase in a defect-free structure. The same plot of the synthesized hybrid structure is shown in Fig. 7(d). The value of the exponent \(X\) should be considerably smaller than 1 for a structure containing a higher density of traps. However, when the photocurrent values are fitted in Fig. 7(d), the photocurrent shows \(X\) to be approximately 0.87. While the same for the star-shaped GaN NWs only was found to be 0.75 (the inset in Fig. 7(d)). The evidence of the minimal defects or trap states in the synthesized hybrid structure reveals that these MOCVD grown hybrid structure comprising star-shaped GaN NWs and Si nanoworms bearing Au nanoparticles inside can be a prolific alternative for efficient opto-electronic devices.

4. Conclusion

In summary, a unique novel star-shaped GaN NW structure was grown on a Si substrate. Additionally, with the help of an excess n-type dopants (SiH\(_4\)), Si nanoworms could be simultaneously realized with the star-shaped GaN NWs. Various characterization techniques were employed to study the crystalline and optical properties of both grown novel nanostructures. The Si nanoworms were found to be unique in the sense of their growth mechanism, which was investigated in detail. The Si nanoworms were found to grow according to a base-growth mechanism, whereas the star-shaped GaN NWs were realized by suppressing the lateral growth by the high concentration of SiH\(_4\). In other words, intentional strain was induced to design the growth of the star-shaped GaN NWs. Moreover, it was found that the drifted Au nanoparticles assisted the formation of the bamboo shape of the Si nanoworms. Both nanostructures were found to be photoresponsive. The photocurrent for the hybrid structure comprising star-shaped GaN NWs and Si nanoworms with drifted Au nanoparticles was higher than that of the star-shaped GaN NWs only. Therefore, it was concluded that the unique hybrid nanostructure has the potential of mixing III–V materials and Si for the next generation high power-high efficient photoelectronic devices.

Conflict of interest

The authors declare no competing financial interest.

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