Density Controlled Growth of ZnO Nanowall–Nanowire 3D Networks

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ABSTRACT: This paper presents the synthesis of wafer scale 3D ZnO nanoarchitectures composed of an array of 1D nanowires (NWs) embedded in 2D nanowalls by the vapor–liquid–solid (VLS) method. The effects of oxygen concentration and growth temperature on the density of nanostructures were studied. The 3D ZnO nanostructures were synthesized on c-plane GaN-on-sapphire substrate utilizing high purity ZnO powder and oxygen (O2) as source materials, and argon (Ar) as carrier gas. ZnO materials were also grown on c-plane sapphire and Si (111) substrates for comparison. Transmission electron microscopy (TEM) diffraction pattern showed the nanostructures are high quality single crystals having wurtzite crystal structure. High resolution transmission electron microscopy (HRTEM) showed the growth direction of ZnO nanowires is along (0001) c-plane orientation. The growth mechanism of such 3D nanostructures was proposed. The understanding of the formation mechanism of the unique ZnO 3D nanostructures will provide guidance for controlled growth of other semiconductor-based nanostructures suitable for surface related applications such as sensing, energy harvesting, and catalyzing.

INTRODUCTION

Nanomaterials as building blocks have attracted significant interest due to their unique optical and electrical properties at nanometer scale. The bottom-up synthesis of semiconductor nanowires (NWs) with high aspect ratios have been developed since 1964.1 Various one-dimensional (1D) NW growth mechanisms have been explored and expanded from the originally proposed vapor–liquid–solid (VLS) growth mechanism.2−3 Expanding from the 1D NWs, semiconductor 2D nanowalls are novel nanostructures that contain networked morphologies,4−10 which offer opportunities for applications that require a high surface area such as solar cells, photodetectors, and gas sensors. Recently, a 3D architecture platform composed of vertically grown 1D nanowires and 2D nanowalls has been reported.11−13 This unique 3D nanostructure will provide new opportunities for advanced nanoelectronic and nano-optoelectronic device applications, in addition to the device applications mentioned above.

ZnO with wide direct bandgap (3.37 eV) and large exciton binding energy (60 meV)16−20 represents one of the most important semiconducting materials for applications related to ultraviolet (UV) optical devices,21 solar cells,22−24 sensors,25,26 photocatalysis,27 transparent field effect transistor,28 and acoustic wave devices.29 In addition, ZnO has been applied for mechanical energy harvesting devices due to its piezoelectric property.30−32 ZnO-based nanostructures such as nanowires,16−18,20−24,33−45 nanobelts,46,47 nanowalls,58−53 hierarchical nanostructures,54 nanobridges, and nanonails55 have been extensively explored in the past decades. Among them, aligned ZnO nanostructures have shown great potential for future nanodevice application due to their controlled morphology and growth direction.

The synthesis of 3D ZnO based nanostructure was first reported in ref 11, in which the ZnO NWs were grown at the junction of nanowalls by vapor–liquid–solid method using Au as catalyst.14 Highly oriented pyrolytic graphite (HOPG) and a-plane sapphire were used as substrates. The 3D ZnO nanoarchitectures were also synthesized via vapor–solid (VS) growth mechanism on GaN-on-sapphire substrate without catalyst,13 in which the Zn cluster drifting along the lattice stepping or dislocations over the substrate at high growth temperature was used to explain the VS growth mechanism. In another study, the control of the ZnO mesoporous film morphology was performed by controlling Zn vapor concentration and the amount of catalysts.14 Nevertheless, the synthesis of the 3D ZnO nanoarchitectures is a complex process and is not well understood.

Here, we study the synthesis of 3D ZnO nanoarchitecture composed of 1D nanowires and 2D nanowalls on c-plane GaN-on-sapphire substrate via VLS growth mechanism. The mixture of ZnO powder and graphite were used as precursors. The concentration of oxygen and growth temperature have a strong influence on the supersaturation of Zn vapor. The focus of this study is on the effects of oxygen concentration and growth temperature on the 3D ZnO nanoarchitecture morphology. Experimental studies indicate that both oxygen concentration and growth temperature have a strong effect on the supersaturation of Zn vapor. The focus of this study is on the effects of oxygen concentration and growth temperature on the 3D ZnO nanoarchitecture morphology. Experimental studies indicate that both oxygen concentration and growth temperature have a strong effect on the supersaturation of Zn vapor. 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The focus of this study is on the effects of oxygen concentration and growth temperature on the 3D ZnO nanoarchitecture morphology. Experimental studies indicate that both oxygen concentration
and growth temperature play important roles in controlling of the ZnO NW density embedded in the 3D nanoarchitecture.

## EXPERIMENTAL SECTION

A three-zone tube furnace with separate temperature controller for each zone was used for the synthesis of ZnO nanostructures. Si (111), c-plane sapphire and c-plane GaN-on-sapphire were used as substrates for the growth. Prior the VLS growth, the substrates were cleaned with acetone and isopropanol, rinsed by deionized water and dried with nitrogen flow. Au films of 5 nm thickness were deposited on top of the substrates via thermal evaporation. A mixture of equal amounts (by weight) of ZnO powder (Alfa Aesar, 99.99%) and graphite (Alfa Aesar, 200 mesh, 99.9995%) were used as source material. The mixture source was put inside a quartz tube of diameter 1 in. and length 46 in. in such a way that the source was located at zone 2 of the furnace. The substrates were placed horizontally at the downstream of the tube (zone 3) separated from the source by 6 in. Then the chamber was pumped down to a base pressure of ~1 mTorr. Prior to heating up the chamber to the desired growth temperature, the chamber was purged with nitrogen for 30 min. The chamber was then heated up to 950 °C at a rate of 20 °C/min under the flow of oxygen and argon and was held at that temperature for 1 h. The samples were taken out after cooling down to room temperature under argon flow. To understand the effects of oxygen concentration and substrate temperature on the density of the ZnO nanostructures, several experiments were conducted. All the parameters were kept the same during the experiments except substrate temperature (880 and 900 °C) and O₂ to Ar volume percentage (~14%–50%). The volume percentage was varied by keeping the oxygen flow rate fixed at 10 sccm and varying the argon flow rate from 10 to 60 sccm. The growth chamber pressures corresponding to 14%, 20%, 33% and 50% O₂ volume percentage are 2.2, 2.1, 1.8, and 1.6 Torr, respectively.

The structure and morphology of ZnO nanostructures were characterized by using scanning electron microscopy (SEM), field emission scanning electron microscopy (FESEM), and transmission electron microscopy (TEM). SEM images were taken with Tescan Vega-3 SBH and FESEM images were taken with Helios 650. High resolution transmission electron microscopy (HRTEM) images and selected-area electron diffraction (SAED) were taken with FEI Tecnai F30 at 300 kV. For the preparation of the TEM sample, the ZnO NWs were first dispersed in ethanol and then transferred to a Cu grid covered with carbon film. For photoluminescence study, a xenon lamp with an output power of 450 W and power density of 6000 W/cm² was used as the excitation source for the emission spectra. The excitation wavelength was 325 nm.

## RESULTS AND DISCUSSION

Our results indicate both growth substrate and growth condition are critical for 3D ZnO nanoarchitecture synthesis. Here, we have compared the growth of ZnO nanostructures on three different substrates: Si (111), sapphire (0001), and c-GaN-on-sapphire, all of which were deposited with Au film as catalyst prior the growth. Figure 1 shows the SEM images of the grown materials. The growth temperature was set at 900 °C with growth pressure of ~2 Torr. The oxygen and argon flow rates were 10 and 20 sccm, respectively. Under this growth condition, 3D ZnO nanostructures were formed on top of the GaN-on-sapphire substrate as shown in Figure 1(c). Vertical 1D ZnO NWs were embedded among the 2D ZnO nanowalls. The formation of such vertically oriented 3D nanostructures on the c-GaN-on-sapphire substrate is due to the good epitaxial lattice and crystal symmetry match between ZnO and GaN.11–15 Note that the in-plane lattice constants a for ZnO and GaN are 3.25 and 3.189 Å respectively.56 On the sapphire (0001) substrate, tilted pure ZnO NWs were grown without 2D nanowall structures. For the case of Si (111) substrate, there were no NWs grown due to high surface energy from the lattice differences between ZnO and Si substrate. The nanostructures that can be seen on top of the Si(111) substrate in Figure 1(a) are single crystalline ZnO. Note that the lattice mismatch between substrate and ZnO, and hence the surface energy determines the wettability on the surface. Due to the complex nature of interactions among the vapor, liquid, and solid phases during the VLS growth, not only the lattice match and crystal symmetry between the substrate and the nanostructure, but also the growth condition plays an important role for the heteroepitaxial growth of the nanostructures. Although we did not observe any nanowire growth on Si (111) substrate under this specific growth condition, with proper surface treatment and suitable growth condition, it is possible to grow ZnO nanowires on Si (111) substrates, which have been previously reported.56,42 This comparison study indicates the important effect of substrate lattice, crystal structure, and hence the surface energy, as well as the growth condition on the nanostructure VLS synthesis. Figure 2 shows the schematics of the proposed growth mechanism for the formation of 3D ZnO nanostructures on c-GaN-on-sapphire substrate. Au clusters formed by melting of thin Au film at high growth temperature act as the nucleation sites for ZnO nanostructure growth. Zn vapor generated from

![Figure 1. Top view SEM images of grown ZnO materials on (a) Si (111) substrate and (b) c-plane sapphire substrate. (c) Top view FESEM image of ZnO nanostructures on c-GaN-on-sapphire substrate. Inset shows the FESEM image of the ZnO nanostructures viewed at 20° from the surface normal.](image)
VS growth mechanism. Our unsuccessful synthesis of ZnO without the existence of Au catalyst, and thus it is based on a VLS growth mechanism. The nanowalls originate from the sidewalls of the nanowires. Due to the excellent symmetry and lattice match of the Au/Zn alloy droplets and led to the formation of ZnO nanowires. The oxygen then reacted with the Zn atoms precipitated out of the Au clusters due to the selective wetting of Zn on Au. The diffusion of these Zn atoms into the Au clusters led to the formation of Au/Zn alloy droplets. The subsequent Zn absorption then super-saturated the droplets and nucleation of the Zn phase occurred. The precursor material was adsorbed on the Au clusters due to their vapor—liquid—solid growth mechanism. The nanowalls originate from the sidewalls of the nanowires without the existence of Au catalyst, and thus it is based on a VS growth mechanism. Our unsuccessful synthesis of ZnO nanostructures on pure GaN substrate without the use of any catalyst under different growth conditions indicates the lack of wettablity on bare substrate. The use of Au film as catalyst, ZnO nanostructures were successfully synthesized on both GaN and sapphire substrates, which indicates that the NWs were grown based on the VLS mechanism. For the nanowall growth, we observed a tapered nanowall height when it extends away from the nanowires, as shown in Figure 2(f), which confirms that the nanowalls were grown from the sidewall of NWs. The overall growth rate of nanowalls is slower than that of the NWs. From these observations, we conclude that the nanowall growth is based on a VS mechanism. Similar observations were reported in ref 14. Note that the six side planes are not necessarily equivalent due to their different width which was also observed from previous study. This causes the nonsymmetry of the ZnO nanowall growth originating from the side planes. Due to the small distance (tens of nanometers) between the Au droplets, these nanowalls merge together and form a continuous network. It is well-known that the Au catalyst provides a suitable site for precursor deposition. As the growth progresses, the long NWs further hinder ZnO vapor from reaching the bottom nanowalls. Thus, the nanowalls' growth rate becomes even slower with the progression of growth.

Figure 2(c,f) shows the top view and tilted FESEM images of ZnO 3D nanostructures grown on c-GaN-on-sapphire substrate for different dwelling (total time at the growth temperature) times. The substrate temperature was 900 °C with flow of 10 sccm oxygen and 60 sccm argon. Figure 3 shows the top view and 20° tilted FESEM images of ZnO 3D nanostructures for different dwell times. Figure 3(a,b) shows the FESEM images of the nanostructures grown for a dwell time of 5 min. As can be seen from the images, both the NWs and the nanowalls have started to grow. With the increase of dwell time to 60 min (Figure 3(c,d), the height of both the NWs and the nanowalls increases, although the growth rate for the NWs are faster than the nanowalls due to their vapor—liquid—solid growth mechanism.

To confirm the crystal structure of the grown ZnO nanostructures, TEM was performed for a single nanowire, as shown in Figure 4. Note that the NW was part of the entire ZnO 3D nanostructure. The NW has a uniform diameter of ~55 nm. The inset of Figure 4(b) shows the SAED pattern of the NW taken along 01−10 zone axis. The pattern was taken at the edge of the NW. Different SAED patterns were taken at different positions along the NW and similar diffraction patterns were observed (not shown). The SAED pattern confirms that the synthesized materials are single crystalline wurtzite ZnO. The HRTEM images in Figure 4(b,c) clearly shows the lattice fringes. From Figure 4(c), the interplanar spacing measured for ZnO NW is 0.26 nm, which corresponds...
to wurtzite ZnO (0002) plane. The (0002) plane of ZnO is perpendicular to the NW growth direction which indicates that the NWs grew along the $\langle 0001 \rangle_c$ plane direction and the NWs are enclosed by $\{10\overline{1}0\}$ side planes.

To characterize the optical quality of the grown ZnO nanostructures, the room temperature PL spectrum was measured as shown in Figure 5. The sample was synthesized at an oxygen volume percentage of 33%. Strong UV emission at $\sim$380 nm corresponds to near band-edge emission and the green emission at $\sim$520 nm corresponds to deep level emission. The broad green emission may occur due to singly ionized oxygen vacancy in ZnO nanostructures. A photogenerated hole recombines radiatively with an electron occupying the oxygen vacancy and gives rise to the green emission. The narrow band-edge emission at 380 nm indicates the high optical quality of the as-grown 3D ZnO nanostructures. Note that the oxygen percentage may affect the vacancies of the grown ZnO nanostructures. The effect of oxygen percentage on the electrical and optical material properties will be part of our future studies.

Next, we investigated the effect of oxygen concentration on the ZnO nanostructure morphology. Four samples were grown on c-GaN-on-sapphire substrates with different oxygen volume percentages. The substrates were covered with 5 nm thick Au film deposited with thermal evaporation. For all the growths, the source and substrate temperatures were 950 and 880 °C, respectively. To vary the oxygen volume percentage, the oxygen flow rate was fixed at 10 sccm and the argon flow rate was varied from 60, 40, 20, to 10 sccm. Figure 6(a)–(d) shows the top view FESEM images for ZnO 3D nanostructures grown with oxygen volume percentage of 14%, 20%, 33%, and 50%, respectively. Figure 7(a)–(d) shows the corresponding FESEM images of the ZnO 3D nanostructures viewed at 20° from the surface normal.

As can be seen from the comparison of the images, the density of the ZnO NWs increases as the oxygen volume percentage increases from 14% up to 33% (Figure 6(a–c)). The density of the NWs decreases when the oxygen volume percentage increases from 14% up to 33% (Figure 6(a–c)). The density of the NWs decreases when the oxygen volume percentage increases from 14% up to 33% (Figure 6(a–c)).
phenomena can be explained as follows, which has been proposed in the ZnO NW synthesis.

In the carbothermal reduction process, the generation of the Zn vapor occurs by the following reaction at a temperature around 900 °C:

\[ \text{ZnO(s)} + \text{C(s)} \leftrightarrow \text{Zn(v)} + \text{CO(v)} \]  

Oxygen can be involved in the process through three possible reactions mentioned below:

\[ 2\text{C} + \text{O}_2 = 2\text{CO} \]  
\[ 2\text{CO} + \text{O}_2 = 2\text{CO}_2 \]  
\[ 2\text{Zn} + \text{O}_2 = 2\text{ZnO} \]

When a sufficient amount of oxygen is introduced into the reaction chamber, both reaction 2 and 3 can occur. Reaction 3 produces heat as well as reduces the concentration of CO. The produced heat and lower CO concentration help to expedite reaction 1. Thus, the Zn vapor can reach supersaturation leading to the growth of high quality vertical ZnO nanostructures. But when an excess amount of oxygen is introduced into the growth chamber, additional oxygen can react with the generated Zn vapor immediately. As a result, the amount of Zn vapor reaching the substrate decreases and consequently the density of the ZnO NWs drops. Thus, only moderate oxygen partial pressure leads to the growth of well aligned high density ZnO nanostructures.

Next, the effect of growth temperature on the density of ZnO nanostructures was also investigated by growing two samples on c-GaN-on-sapphire substrate with fixed oxygen volume percentage of 33%. For both growths, the source temperature was set at 950 °C. Two different substrate temperatures of 880 and 900 °C were used. Figure 9(a,b) shows the 20° tilted FESEM images for ZnO 3D nanostructures grown with growth temperatures of 880 and 900 °C, respectively. As can be seen from the figures, at a fixed oxygen volume percentage, the nanostructures are less dense for a higher growth temperature of 900 °C. This may be due to the fact that the amount of Zn vapor depends on the source temperature. With the increase of source temperature from 880 to 900 °C, the amount of Zn vapor has increased. But the partial pressure of oxygen might not be sufficient enough for this amount of Zn vapor to reach moderate supersaturation. Thus, there needs to be a balance between the amount of Zn vapor and oxygen partial pressure to achieve highly dense ZnO nanostructures. This density decrease could also be due to the dependence of Au wettability on the growth temperature.

**CONCLUSIONS**

In summary, we have synthesized ZnO 3D nanostructures composed of 1D nanowires and 2D nanowalls on c-GaN-on-sapphire substrate by VLS approach. SAED and HRTEM data show that the synthesized ZnO nanostructures are of high quality and have a single crystalline wurtzite structure. The growth temperature and oxygen concentration play an important role in controlling the density of the nanostructure morphology. The synthesis and proposed growth mechanism for this unique ZnO nanonetwork will provide a guideline for synthesizing other types of semiconductor nanonetwork structures. These 3D nanoarchitectures have great potential for device applications that require large surface to volume ratio.

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**Notes**

The authors declare no competing financial interest.

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**REFERENCES**


Gradeck, S. The Growth and Optical Properties of ZnO Nanowalls. J.
(49) Liang, Z.; Gao, R.; Lan, J.-L.; Wiranwetchayan, O.; Zhang, Q.;
Li, C.; Cao, G. Growth of Vertically Aligned ZnO Nanowalls for
34–40.
Chen, K.-J. Simple Fabrication Process for 2D ZnO Nanowalls and
Their Potential Application as a Methane Sensor. Sensors 2013, 13,
3941–3950.
Zhang, J. Y.; Lu, Y. M.; Shen, D. Z.; Fan, X. W. Structural Properties
and Photoluminescence of ZnO Nanowalls Prepared by Two-Step
Growth with Oxygen-Plasma-Assisted Molecular Beam Epitaxy. J.
Synthesis of ZnO Nanowall Networks on Si_N/Si Substrates by
Metalorganic Chemical Vapor Deposition. Appl. Phys. Lett. 2006, 88,
253114.
Danielsson, B. Chemically Fashioned ZnO Nanowalls and Their
Potential Application for Potentiometric Cholesterol Biosensor. Appl.
(54) Lao, J. Y.; Wen, J. G.; Ren, Z. F. Hierarchical ZnO
(55) Lao, J. Y.; Huang, J. Y.; Wang, D. Z.; Ren, Z. F. ZnO
(56) Hanada, T. Basic Properties of ZnO, GaN, and Related Materials;
(57) Xu, T.; Nys, J. P.; Addad, A.; Lebedev, O. I.; Urbietza, A.; Salhi,
B.; Berthe, M. Faceted Sidewalls of Silicon Nanowires: Au-Induced
2010, 81, 115403.
Voigt, J. A.; Gnade, B. E. Mechanisms Behind Green Photo-
(59) Wang, Y.-P.; Lee, W.-L.; Tseng, T.-Y. Degradation Phenomena
of Multilayer ZnO–Glass Varistors Studied by Deep Level Transient
(60) Lee, S.-D.; Park, H.-K.; Kim, S.-W. Controlled Growth of Two-
Dimensional ZnO Nanowalls by Thermal Chemical Vapor Deposition.