Parameters study on the growth of GaAs nanowires on indium tin oxide by metal-organic chemical vapor deposition

Wu, Dan; Tang, Xiaohong; Wang, Kai; Olivier, Aurelien; Li, Xianqiang

2016

Wu, D., Tang, X., Wang, K., Olivier, A., & Li, X. (2016). Parameters study on the growth of GaAs nanowires on indium tin oxide by metal-organic chemical vapor deposition. *Journal of Applied Physics*, 119(9), 094305-.

<https://hdl.handle.net/10356/83610>

<https://doi.org/10.1063/1.4942864>

© 2016 American Institute of Physics (AIP). This paper was published in *Journal of Applied Physics* and is made available as an electronic reprint (preprint) with permission of American Institute of Physics (AIP). The published version is available at: [<http://dx.doi.org/10.1063/1.4942864>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 20:58:53 SGT

Parameters study on the growth of GaAs nanowires on indium tin oxide by metal-organic chemical vapor deposition

Dan Wu,¹ Xiaohong Tang,^{1,a)} Kai Wang,^{2,a)} Aurelien Olivier,³ and Xianqiang Li¹

¹OPTIMUS, Photonics Centre of Excellence, School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore

²Department of Electrical & Electronic Engineering, South University of Science and Technology of China, 1088 Xueyuan Avenue, Shenzhen 518055, China

³CINTRA UMI 3288, School of Electrical and Electronic Engineering, Nanyang Technological University, Research Techno Plaza, 50 Nanyang Drive, Border X Block, Level 6, 637553 Singapore

(Received 26 August 2015; accepted 15 February 2016; published online 2 March 2016)

After successful demonstration of GaAs nanowire (NW) epitaxial growth on indium tin oxide (ITO) by metal organic chemical vapor deposition, we systematically investigate the effect of growth parameters' effect on the GaAs NW, including temperature, precursor molar flow rates, growth time, and Au catalyst size. 40 nm induced GaAs NWs are observed with zinc-blende structure. Based on vapor-liquid-solid mechanism, a kinetic model is used to deepen our understanding of the incorporation of growth species and the role of various growth parameters in tuning the GaAs NW growth rate. Thermally activated behavior has been investigated by variation of growth temperature. Activation energies of 40 nm Au catalyst induced NWs are calculated at different trimethylgallium (TMGa) molar flow rates about 65 kJ/mol. The GaAs NWs growth rates increase with TMGa molar flow rates whereas the growth rates are almost independent of growth time. Due to Gibbs-Thomson effect, the GaAs NW growth rates increase with Au nanoparticle size at different temperatures. Critical radius is calculated as 2.14 nm at the growth condition of 430 °C and 1.36 $\mu\text{mol/s}$ TMGa flow rate. It is also proved experimentally that Au nanoparticle below the critical radius such as 2 nm cannot initiate the growth of NWs on ITO. This theoretical and experimental growth parameters investigation enables great controllability over GaAs NWs grown on transparent conductive substrate where the methodology can be expanded to other III–V material NWs and is critical for potential hybrid solar cell application. © 2016 AIP Publishing LLC.

[<http://dx.doi.org/10.1063/1.4942864>]

I. INTRODUCTION

Semiconductor nanowires (NWs) have demonstrated great potential applications in photonic and electronic devices such as solar cells,¹ light-emitting diode,² lasers,³ integrated microelectronics,⁴ bio-chemical sensors,⁵ etc., due to the advantages such as large aspect ratio, relaxation of lattice strain, and low material consumption.⁶ Vapor-liquid-Solid (VLS) growth mechanism is the most widely accepted NW growth mechanism proposed by Wagner and Ellis in 1964.⁷ The foreign nanoparticle (NP) such as Au is usually adopted as the catalyst to form a supersaturated liquid alloy with the growth precursors.⁸ The chemical potential difference drives the precipitation of semiconductor material to the liquid-solid interface and by continuous supply of the growth material, the eutectic alloy begins to crystallize and forms the NW.⁹ Metal organic chemical vapor deposition (MOCVD) is usually adopted in NW growth¹⁰ due to the capability of producing precise control over complex axial p-n junction,¹¹ core-shell¹² NWs structures, and potential large scale commercialization capability.

III–V group NWs such as GaAs possess the advantages such as direct band gap, high electron mobility, and potential

integration on low cost substrate such as Si^{13,14} and glass¹⁵ and have attracted much attention. Small diameter (below 10 nm) of the GaAs NWs with pure wurtzite structure has been demonstrated to grow on SiO₂ and integrated in field effect transistor (FET).¹⁶ GaAs NWs were also grown on unpolished float type glass with few crystal defects.¹⁵ However, the insulating nature of the substrate limits further applications after NWs integration. Deposition of a layer of transparent conductive oxide (TCO) on those low cost insulating substrates provides a feasible solution for such circumstances. Indium tin oxide (ITO) is the most widely used TCO due to the high conductivity and transmittance properties and thus a growing number of reports focus on synthesis of NWs on ITO. Most commonly, ZnO or TiO₂ NWs can be formed vertically standing on ITO by hydrothermal growth method.^{17,18} Si and InP NWs are also grown on ITO for polymer-inorganic hybrid solar cell application.^{19,20} Early this year, we have demonstrated successful growth of uniform and free-standing GaAs NWs on ITO.²¹

Nanowire physical dimensions such as length, diameter, density, orientation, and crystal quality control are vital to device fabrication and performance. Representative work includes that a systematic study on growth parameters of GaAs NWs on GaAs (111)B substrate in which an empirical expression of growth rate was derived as a function of temperature, precursor flow rates, and time.⁹ Two step growth

^{a)}Author to whom correspondence should be addressed. Electronic email: exhtang@ntu.edu.sg and wangk@sustc.edu.cn

has also been developed to obtain high crystal quality NWs.²² These important reports guarantee the precise control over physical dimension and crystal quality of the as grown NWs, which is also the foundation of future device fabrication. However, apart from metal oxides NWs, there have been few reports considering the growth parameters' effect on the NW growth on ITO. These can be attributed to the frequently observed kinks, worm-shaped defects, or crawling morphology of the III–V NWs grown on ITO and the length of the NWs cannot be measured. Based on our previous work, through surface functionalization of ITO, free-standing GaAs NWs are obtained with few morphological defects, and therefore, growth parameters study by MOCVD is feasible and highly desirable.

In this report, we present a systematic study of the effects of growth parameters, including temperature, precursor flow rates, growth time, as well as Au catalyst size on the GaAs NWs growth rate on ITO by MOCVD. The transmission electron microscopy (TEM) characterization show high crystal quality of the GaAs NWs. Based on the VLS mechanism, a kinetic model is used to calculate the tunable growth parameters and Au NP size effects on growth rate of NW. Thermally activated behavior of GaAs NWs growth is demonstrated by increasing the growth temperature. The GaAs NWs growth rate also increases with molar flow rates whereas the growth time has negligible effect. Gibbs-Thomson effect has also been proved theoretically and experimentally by varying Au NP size where larger catalyst induced NWs grows faster. These achieved results lay the foundation of future device fabrication of GaAs NWs based hybrid solar cell.

II. EXPERIMENT

The GaAs NWs were directly grown on ITO glass substrate by VLS mechanism using MOCVD. Au NPs were used as catalysts for the NWs growth. Commercial ITO glass with a 155 (± 20) nm-thick ITO layer (Xinyan Technology Co., LTD.) was used as the substrate. ITO substrates were cleaned by soaking them successively in an ultrasonic bath with acetone, isopropanol, and deionized water for 10 min each and dried with nitrogen. Then, they were functionalized by soaking in 1 wt. % polydiallyldimethylammonium chloride (PDDAC) solution (Polysciences, Inc.) for 60 min. After rinsing with deionized water for 30 s, the substrate was dried with nitrogen for 10 s. Au NPs solutions (Nanocs, Ltd.) with various NP diameters 5 nm, 10 nm, 20 nm, and 40 nm with the density of $\sim 1.8 \times 10^{14}$ NP/mL were dropped on ITO glass substrates for 3 h. Except for the Au NP size investigation, all the growths used 40 nm Au NPs as catalysts. Detailed research about optimization the PDDAC soaking time and Au NP deposition time as well as comparison with poly-L-lysine (PLL) can be found in our previous work.²¹ The samples were completely dried with nitrogen and then baked at 100 °C for 3 min. After that, the substrates were transferred into the MOCVD reactor (Aixtron 200) for growing the GaAs NWs. Precursors used for the MOCVD growth were trimethylgallium (TMGa) and tertiarybutylarsine (TBAs) and purified hydrogen gas was used as the carrier gas. The reactor chamber pressure was set as $P_{\text{chamber}} = 50$

mbar during the growth. TBAs were introduced into the reactor during the temperature ramping up. When the growth temperature T was reached, TMGa source was introduced into the reactor to start the GaAs NWs growth. The V/III ratio for all the growths was kept as 9.5. The TMGa molar flow rates Q_{TMGa} were changed for parameters study as 0.91, 1.36, and 1.81 $\mu\text{mol/s}$ whereas TBAs molar flow rates Q_{TBAs} varied accordingly for keeping the same V/III ratio. The NWs growth time was set as 30 s except for the study about time dependent growth when the time t was chosen as 30, 60, and 120 s. The growth temperature ranged from 410 to 480 °C. LEO 1550 Gemini field emission scanning electron microscopy (FESEM) was used to characterize the morphology of the GaAs NWs grown on ITO glass substrate whereas TEM (TEM: Philips Tecnai G2 F20 field-emission TEM, operated at 200 kV) was used for crystal quality inspection. Before detailed discussion about the dependence of NW growth rate and morphology on growth conditions, the NW growth rate is defined as the time dependent growth. Due to the various orientations of the GaAs NWs, the lengths of the NWs were obtained from a detailed zoom-in view to clearly display their three-dimensional contour as illustrated in the figures of our previous work.²¹

III. RESULTS AND DISCUSSION

A. GaAs nanowire morphology and crystal structure characterization

From Figs. 1(a) to 1(c), we can clearly observe the morphology of GaAs NWs grown at different growth temperatures and precursor molar flow rates. Compared with precursor molar flow rates, growth temperature affects the morphology of NWs strongly with uniform NWs growing at low temperatures. It has also been observed that at high

FIG. 1. FESEM images of 40 nm Au NPs induced GaAs NWs length change with TMGa molar flow rates of (a) 0.91, (b) 1.36, and (c) 1.81 $\mu\text{mol/s}$; (d) 40 nm Au NPs induced GaAs NWs length change with growth time at 460 °C with TMGa molar flow rates of 1.36 $\mu\text{mol/s}$.

growth temperatures of 460 and 480 °C with various precursor flow rates, the GaAs NWs become tapered, whereby the NWs exhibit shapes with wider bases and narrow Au NPs capped tips. Figure 1(d) displays that the NWs are almost linearly proportional to the growth time. Detailed analysis of growth parameters effect on the growth rate will be provided in later sections.

Crystal quality inspection of the as grown GaAs NWs is indispensable for hybrid solar cell application. 40 nm Au catalyst induced NWs grown at 430 °C with TMGa flow rate of 1.36 $\mu\text{mol/s}$ are examined using TEM along $\langle 110 \rangle$ zone axis. As illustrated in Fig. 2(a), straight, elongated NWs are observed, and there are few planar or twin defects along the 2 μm length NWs. Bright field image in Fig. 2(b) displays the zoom-in view of the tip of the GaAs NWs and high-resolution TEM (HRTEM) investigation in Fig. 2(c) shows details of the structural characteristics. According to the spacing between the crystal planes, the NWs were grown along $\langle 111 \rangle$ direction. Similar TEM results were found on three other GaAs NWs grown on ITO. Fourier transform of the NW crystal corresponds to zinc-blende structure, as shown in Fig. 2(d).

Due to polycrystalline nature of the ITO surface, the as grown GaAs NWs have various tilt angles with respect to the surface of the substrate.²¹ As mentioned in Ref. 23, variation of the NWs' growth direction may lead to different crystal structures of the NWs. In order to reveal the crystal structure of the as grown GaAs NWs from a larger area on the ITO substrate, X-ray diffraction (XRD) measurements using Cu K α radiation were performed. Figure 2(e) compares the measured $2\theta/\omega$ curves of the ITO substrate with that of the ITO glass with GaAs NWs grown on it. It shows that an additional diffraction peak was observed on the ITO glass with GaAs NWs at 2θ angle of 27.30°, which are indexed to the GaAs zinc-blende (111) plane. This supports the TEM results and implies that the majority of the GaAs NWs grown on the ITO were of zinc-blende phase. Dhaka *et al.*¹⁵ also reported that high quality GaAs NWs were grown on the non-crystalline soda lime glass with the majority of NWs along $\langle 111 \rangle$ direction.

B. Growth parameters effect on the GaAs nanowire growth

A kinetic model is used to investigate the GaAs NWs growth on ITO. As shown in Fig. 3, there are mainly four steps in the VLS GaAs NWs growth: step 1, pyrolysis reaction of the vapor precursors TMGa and TBAs and the mass transportation of the adatoms to Au catalysts where the liquid eutectic droplets are formed;¹⁰ step 2, chemical reaction

FIG. 3. Schematic of VLS growth mechanism of GaAs nanowire growth on ITO.

at the vapor-liquid interface where the Ga atom enters the droplet; step 3, Ga atom diffusion in the liquid phase to the liquid crystal interface;²⁴ step 4, GaAs crystallization at the liquid-solid interface.²⁵ In order to obtain analytical expressions for GaAs NWs growth rate on ITO, assumptions are usually made: (1) the growth species within the liquid Au droplet are in equilibrium state which denotes that the total number of adatoms enter into the liquid droplet equals to that crystallizes at the liquid-solid interface; (2) the GaAs NWs are cylinders with hemispherical Au catalysts riding on their tops, which are valid according to morphology observation from FESEM images, as shown in Fig. 1; (3) the behavior of vapor precursors can be governed by ideal gas law due to the high temperature and low MOCVD reactor pressure.

Detailed of derivations about the growth rate can be found in Refs. 9 and 24–26. The analytical expression of growth rate k_g of the NWs can be expressed as

$$k_g = 2 \times \frac{a^3}{n} \times \alpha \times \frac{P_\infty \exp(\Delta\mu_{gl}/k_B T) - P_\infty \exp(2\Omega_l \sigma_{lv}/Rk_B T)}{\sqrt{2\pi m k_B T}}. \quad (1)$$

For GaAs NWs, atomic volume in NW (solid phase) can be expressed as a^3/n , where a is the lattice constant and n is number of As or Ga atoms per unit cell. α is adsorption coefficient, which describes the probability of the available atoms being adsorbed into the NWs ranging from zero to one; α is set as 1 since all the adatoms incorporated unto the Au catalysts contributes the NW growth. R is the radius of the Au catalyst. P_∞ is the Ga vapor pressure in equilibrium with flat surface (radius is infinite), the chemical potential difference between vapor and liquid phase is $\Delta\mu_{gl}$. Ω_l is atom molar volume in liquid phase and σ_{lv} is the surface energy density at the liquid-vapor droplet interface.⁹ m is mass of Ga atom; k_B is Boltzmann constant; and T is the absolute temperature. In the following, we will analyze the

FIG. 2. (a) to (c) The TEM images of the 40 nm Au catalyst induced NWs whereas (d) gives the Fourier transform of the NW crystal; (e) the XRD measurements of ITO glass and the ITO with GaAs NWs grown on it.

FIG. 4. (a) 40 nm Au NPs induced GaAs NWs growth rate as a function of growth temperature and (b) logarithmic of NW growth rate as a function of reciprocal of growth temperature for various TMGa molar flow rates of 0.91, 1.36, and 1.18 $\mu\text{mol/s}$.

growth temperature, precursor flow rates, growth time, and catalyst size based on this kinetic model.

1. Temperature effect

In the following, each data point in the graphs represents the average growth rate calculated from 25 GaAs NWs, and the standard deviation is plotted as the error bar of that growth rate. Figure 4 shows the temperature dependence of the 40 nm Au NPs induced GaAs NW growth rate k_g at three precursor flow rates. The growth temperature rose from 410 to 480 °C. The TMGa flow rate was set as 0.91, 1.36, and 1.81 $\mu\text{mol/s}$, respectively, and TBAs' flow rates were varied proportionally. In general, the NW growth rates increase with growth temperature for various precursors' molar flow rates. This thermally activated behavior is mainly because the pyrolysis efficiencies of the precursors rise with the increase in growth temperature, which leads to more available adatoms for the NW growth. The highest growth rate is 51.48 nm/s at 480 °C. Based on the above kinetic analysis, 40 nm diameter catalyst induced NWs is large enough to neglect the Gibbs-Thompson effect, and similar conclusions have also been verified both theoretically and experimentally by other researchers.^{26,27} Therefore, growth rate of NWs can be simplified as

$$k_g = 2 \times a^3 / n \times \alpha \times P_{Ga} / \sqrt{2\pi m k_B T}, \quad (2)$$

where P_{Ga} is the effective Ga pressure responsible for supersaturation in vapor phase, which can be calculated by $P_{Ga} = \varepsilon_{pyro} P_{TMGa}$, where ε_{pyro} is pyrolysis efficiency and P_{TMGa} is the precursor metalorganic partial pressure and can be estimated as $P_{TMGa} = [Q_{TMGa} / (Q_{TMGa} + Q_{TBAs} + Q_{H_2})] \times P_{Chamber} \approx [Q_{TMGa} / Q_{H_2}] \times P_{Chamber}$. With the parameters of $a = 0.565 \text{ nm}$, $n = 4$, and $m = 1.158 \times 10^{-25} \text{ kg}$ and the pyrolysis efficiency extracted from Ref. 9, the calculated growth rate of GaAs NW with different diameter changes with temperature agrees well with the experiment results, as shown in Fig. 4.

As shown in Fig. 4(b), the thermally activated behavior can also be described by Arrhenius equation in which the

NW growth rate k_g is proportional to $\exp(-E_A/k_B T)$. Molar activation energy E_A is used to evaluate the minimum energy required for starting the NW growth, and in our case, it measures the energy of crystallization at the liquid-solid interface.¹⁹ Therefore, E_A can be easily obtained from the slope of the curve, $\ln k_g = f(1/T)$. It has been calculated that the activation energy, E_A , are 65.86, 65.53, and 63.59 kJ mol^{-1} for the 40 nm Au NP induced GaAs NWs at Q_{TMGa} of 0.91, 1.36, and 1.81 $\mu\text{mol/s}$, respectively, which is similar to that of the $E_A \sim 67\text{--}75 \text{ kJ/mol}$ for GaAs NWs growth on GaAs (111)B substrate.^{17,20} This indicates that ITO substrates do not increase the kinetic barrier for GaAs NWs growth.

2. Precursor flow rates effect

Precursor molar flow rates effect on GaAs NWs growth is summarized in Fig. 5. For a constant V/III ratio, the NW growth rates are almost linearly dependent on Q_{TMGa} at all growth temperatures from 410 to 480 °C. Interestingly, the morphology of NWs is less affected by the Q_{TMGa} as shown in Figs. 1(a)–1(c). Since the molar flow of Q_{TBAs} is always

FIG. 5. GaAs NW growth rate as a function of TMGa molar flow rate at various growth temperatures of 410, 430, 460, and 480 °C.

redundant compared to Q_{TMGa} , the molar flow of Q_{TMGa} is the limiting factor to the growth rate, and thus, the rates will increase as the TMGa partial pressure rises. At the same time, according to Eq. (2), with the same growth temperature T , we have the same ε_{pyro} , and by increasing molar flow of Q_{TMGa} , we raised P_{Ga} . Therefore, an increased net precursor flux as well as higher growth rate can be obtained. The fitting curves match well with the experimental data.

3. Growth time effect

Figure 6 shows the time dependence of the NW growth rate at two growth temperatures of 430 and 460 °C and morphology of NWs grown for various time is shown in Fig. 1(d) where Q_{TMGa} is kept constant at 1.36 mol/s. It is found that the NW growth rates are almost unchanged with prolonged growth time. This implies that the growth rate is independent of growth time and NW length is proportional to growth time. Therefore, we can synthesize the desired length of NWs by variation of growth time.

4. Catalyst size effect

Catalyst is critical to the NW growth according to the VLS mechanism. Indeed, the Au NPs distribution on the ITO glass determines the position and area density of the grown GaAs NWs. Tuning the size of the catalyst will also result in the dimension change of the NWs, which is desirable since the band gap of semiconductor NWs can be tuned by varying the diameters.²⁸ Figure 7 shows the dependence of the NW growth rate as a function of Au NP size when the molar flow rate of TMGa is kept constant at 1.36 $\mu\text{mol/s}$ with various temperatures of 410, 430, 460, and 480 °C. At the growth temperature of 480 °C, the highest growth rate of the 40 nm diameter NWs is 35.27 nm s⁻¹, whereas for the 5 nm diameter NWs, the growth rate is only 23.29 nm/s. The NW growth rate increases with NP size, which has been commonly attributed to the Gibbs-Thompson effect. This is because reaction rates of the precursors are proportional to the pressure difference between the reactants surrounding the NWs and the pressure inside the catalyst. According to Gibbs-

FIG. 6. GaAs NW growth rate as a function of growth time at two growth temperatures of 430 and 460 °C.

FIG. 7. GaAs NW growth rate as a function of Au NP diameter at various growth temperatures where the TMGa molar flow rate fixed at 1.36 $\mu\text{mol/s}$.

Thompson effect, at a given temperature, T , the reactant pressure inside the Au catalyst is higher when the Au NP diameter is smaller. Therefore, larger diameter NWs grow faster than the GaAs NWs grown with smaller diameter NP catalysts.^{17,18}

Using the above kinetic model, critical radius R_c is defined as $R_c = 2\sigma_{lv}\Omega_l/\Delta\mu_{gl}$ when the growth rate is reduced to zero. We use experimentally obtained growth rates of 10 nm and 20 nm induced NWs at 430 °C and TMGa molar flow rates of 1.36 $\mu\text{mol/s}$ with atomic volume Ω_l is 10.20 cm³/mol and surface tension σ_{lv} is 1.237 J/m².⁹ The calculated R_c is 2.14 nm. At the same time, we also found experimentally that there were no NWs grown with 2 nm Au NPs as catalysts. The fitting curves for GaAs NWs growth rate with various catalyst diameters are calculated, and for each curve, one experimental data are used for rectifying the proportional constant determined from experiment.

IV. CONCLUSION

In this study, uniform and free-standing GaAs NWs are successfully grown on ITO glass substrate by MOCVD based on VLS growth using Au NP as the catalysts. The NW growth rates change with the growth temperature, precursor molar flow rate, time, and Au NPs catalyst sizes have been investigated. As expected, the growth rates show thermally activated behavior. The activation energy of GaAs NWs induced by 40 nm Au NPs as catalysts is around 65 kJ/mol. At high growth temperature (480 °C), tapering of the grown GaAs NWs is observed since precursors diffuse from the substrate and nucleate on the side facets of NWs. As TMGa molar flow rate rises, the NWs growth rate increases almost linearly when the V/III ratio is kept as 9.5. Changing of precursor flow rates has less effect on the NW morphology. Moreover, the GaAs NWs growth rate is almost the same as time prolongs. Thus, it indicates the length of NWs can be controlled by variation of the growth time. As Au NP size dependence of NW growth rate, we find that the growth rate increases with diameter of the catalyst, which is attributed to the Gibbs-Thomson effect. Theoretical analysis is carried out for in depth understanding of the NWs growth and critical

radius is calculated as 2.14 nm using experimental data at 430 °C and TMGa molar flow rate of 1.36 $\mu\text{mol/s}$. It is also proved experimentally that 2 nm Au NPs cannot initiate NWs growth on ITO at the above growth condition. Straight elongated and GaAs NWs with 40 nm diameter are also demonstrated via TEM characterization. These results demonstrate great potential of GaAs NWs to be integrated in ITO substrate for device fabrication for high efficiency hybrid solar cell application.

- ¹M. Law, L. E. Greene, J. C. Johnson, R. Saykally, and P. Yang, *Nat. Mater.* **4**, 455 (2005).
- ²H. Sekiguchi, K. Kishino, and A. Kikuchi, *Appl. Phys. Lett.* **96**, 231104 (2010).
- ³X. Duan, Y. Huang, R. Agarwal, and C. M. Lieber, *Nature* **421**, 241 (2003).
- ⁴C. Thelander, L. E. Fröberg, C. Rehnstedt, L. Samuelson, and L.-E. Wernersson, *IEEE Electron Device Lett.* **29**, 206 (2008).
- ⁵Y. Cui, Q. Q. Wei, H. K. Park, and C. M. Lieber, *Science* **293**, 1289 (2001).
- ⁶N. P. Dasgupta, J. Sun, C. Liu, S. Brittman, S. C. Andrews, J. Lim, H. Gao, R. Yan, and P. Yang, *Adv. Mater.* **26**, 2137 (2014).
- ⁷R. S. Wagner and W. C. Ellis, *Appl. Phys. Lett.* **4**, 89 (1964).
- ⁸M. E. Messing, K. Hillerich, J. Johansson, K. Deppert, and K. A. Dick, *Gold Bull.* **42**, 172 (2009).
- ⁹C. Soci, X.-Y. Bao, D. P. R. Aplin, and D. Wang, *Nano Lett.* **8**, 4275 (2008).
- ¹⁰J. J. Coleman, *Proc. IEEE* **85**, 1715 (1997).
- ¹¹J.-H. Park, M.-H. Kim, S. Kissinger, and C.-R. Lee, *Nanoscale* **5**, 2959 (2013).
- ¹²B. Hua, J. Motohisa, Y. Kobayashi, S. Hara, and T. Fukui, *Nano Lett.* **9**, 112 (2009).
- ¹³K. Ikejiri, F. Ishizaka, K. Tomioka, and T. Fukui, *Nanotechnology* **24**, 115304 (2013).
- ¹⁴J. H. Kang, Q. Gao, H. J. Joyce, H. H. Tan, C. Jagadish, Y. Kim, D. Y. Choi, Y. Guo, H. Xu, J. Zou, M. A. Fickenscher, L. M. Smith, H. E. Jackson, and J. M. Yarrison-Rice, *Nanotechnology* **21**, 035604 (2010).
- ¹⁵V. Dhaka, T. Haggren, H. Jussila, H. Jiang, E. Kauppinen, T. Huhtio, M. Sopanen, and H. Lipsanen, *Nano Lett.* **12**, 1912 (2012).
- ¹⁶N. Han, J. J. Hou, F. Y. Wang, S. Yip, H. Lin, M. Fang, F. Xiu, X. L. Shi, T. F. Hung, and J. C. Ho, *Nanoscale Res. Lett.* **7**, 632 (2012).
- ¹⁷P. A. Sedach, T. J. Gordon, S. Y. Sayed, T. Fürstenhaupt, R. Sui, T. Baumgartner, and C. P. Berlinguette, *J. Mater. Chem.* **20**, 5063 (2010).
- ¹⁸L. E. Greene, M. Law, D. H. Tan, M. Montano, J. Goldberger, G. Somorjai, and P. Yang, *Nano Lett.* **5**, 1231 (2005).
- ¹⁹C. J. Novotny, E. T. Yu, and P. K. L. Yu, *Nano Lett.* **8**, 775 (2008).
- ²⁰C. Y. Kuo and C. Gau, *Appl. Phys. Lett.* **95**, 053302 (2009).
- ²¹D. Wu, X. H. Tang, A. Olivier, and X. Q. Li, *Mater. Res. Express* **2**, 045002 (2015).
- ²²H. J. Joyce, Q. Gao, H. H. Tan, C. Jagadish, Y. Kim, X. Zhang, Y. Guo, and J. Zou, *Nano Lett.* **7**, 921 (2007).
- ²³H. A. Fonseka, P. Caroff, J. Wong-Leung, A. S. Ameruddin, H. H. Tan, and C. Jagadish, *ACS Nano* **8**, 6945 (2014).
- ²⁴P. Kratzer, S. Sakong, and V. Pankoke, *Nano Lett.* **12**, 943 (2012).
- ²⁵Z. Chen and C. Cao, *Appl. Phys. Lett.* **88**, 143118 (2006).
- ²⁶W. Seifert, M. Borgström, K. Deppert, K. A. Dick, J. Johansson, M. W. Larsson, T. Mårtensson, N. Sköld, C. Patrik, T. Svensson, B. A. Wacaser, L. Reine Wallenberg, and L. Samuelson, *J. Cryst. Growth* **272**, 211 (2004).
- ²⁷J. Johansson, B. A. Wacaser, K. A. Dick, and W. Seifert, *Nanotechnology* **17**, S355 (2006).
- ²⁸N. Han, Z. Yang, F. Wang, S. Yip, G. Dong, X. Liang, T. Hung, Y. Chen, and J. C. Ho, *ACS Appl. Mater. Interfaces* **7**, 5591 (2015).