Polarization control in GaN nanowire lasers

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Abstract: We demonstrate polarization control in optically-pumped single GaN nanowire lasers fabricated by a top-down method. By placing the GaN nanowires onto gold substrates, the naturally occurring randomly orientated elliptical polarization of nanowire lasers is converted to a linear polarization that is oriented parallel to the substrate surface. Confirmed by simulation results, this polarization control is attributed to a polarization-dependent loss induced by the gold substrate, which breaks the mode degeneracy of the nanowire and forms two orthogonally polarized modes with largely different cavity losses.

OCIS codes: (220.4241) Nanostructure fabrication; (250.5960) Semiconductor lasers; (160.4236) Nanomaterials; (250.5590) Quantum-well, -wire and -dot devices; (250.5230) Photoluminescence.

References and links

1. M. H. Huang, S. Mao, H. Feick, H. Yan, Y. Wu, H. Kind, E. Weber, R. Russo, and P. Yang, "Room-temperature ultraviolet nanowire nanolasers," Science **292**(5523), 1897–1899 (2001).
2. J. C. Johnson, H.-J. Choi, K. P. Knutsen, R. D. Schaller, P. Yang, and R. J. Saykally, "Single gallium nitride nanowire lasers," Nat. Mater. **1**(2), 106–110 (2002).
3. X. Duan, Y. Huang, R. Agarwal, and C. M. Lieber, "Single-nanowire electrically driven lasers," Nature **421**(6920), 241–245 (2003).
4. Y. Ma and L. Tong, "Optically pumped semiconductor nanowire lasers," Frontiers Optoelectron. **5**(3), 239–247 (2012).
5. P. Yang, R. Yan, and M. Fardy, "Semiconductor nanowire: what's next?" Nano Lett. **10**(5), 1529–1536 (2010).
6. Q. Li, J. B. Wright, W. W. Chow, T. S. Luk, I. Brener, L. F. Lester, and G. T. Wang, "Single-mode GaN nanowire lasers," Opt. Express **20**(16), 17873–17879 (2012).
7. S. K. Lim, S. Crawford, G. Haberfehlner, and S. Gradečak, "Controlled modulation of diameter and composition along individual III-V nitride nanowires," Nano Lett. **13**(2), 331–336 (2013).
8. D. Wang, A. Pierre, M. G. Kibria, K. Cui, X. Han, K. H. Bevan, H. Guo, S. Paradis, A. R. Hakima, and Z. Mi, "Wafer-level photocatalytic water splitting on GaN nanowire arrays grown by molecular beam epitaxy," Nano Lett. **11**(6), 2353–2357 (2011).
9. K. A. Bertness, N. A. Sanford, and A. V. Davydov, "GaN nanowires grown by molecular beam epitaxy," IEEE J. Sel. Top. Quantum Electron. **17**(4), 847–858 (2011).
10. G. T. Wang, A. A. Talin, D. J. Werder, J. R. Creighton, E. Lai, R. J. Anderson, and I. Arslan, "Highly aligned, template-free growth and characterization of vertical GaN nanowires on sapphire by metal-organic chemical vapour deposition," Nanotechnology **17**(23), 5773–5780 (2006).
11. S. Arafin, X. Liu, and Z. Mi, "Review of recent progress of III-nitride nanowire lasers," J. Nanophoton. **7**(1), 074599 (2013).
12. H. Xu, J. B. Wright, T. S. Luk, J. J. Figiel, K. Cross, L. F. Lester, G. Balakrishnan, G. T. Wang, I. Brener, and Q. Li, "Single-mode lasing of GaN nanowire-pairs," Appl. Phys. Lett. **101**(11), 113106 (2012).
13. H. Gao, A. Fu, S. C. Andrews, and P. Yang, "Cleaved-coupled nanowire lasers," Proc. Natl. Acad. Sci. U.S.A. **110**(3), 865–869 (2013).
14. J. B. Wright, S. Campione, S. Liu, J. A. Martinez, H. Xu, T. S. Luk, Q. Li, G. T. Wang, B. S. Swartzentruber, L. F. Lester, and I. Brener, "Distributed feedback gallium nitride nanowire lasers," Appl. Phys. Lett. **104**(4), 041107 (2014).
15. H. Xu, J. B. Wright, A. Hurtado, Q. Li, T. S. Luk, J. J. Figiel, K. Cross, G. Balakrishnan, L. F. Lester, I. Brener, and G. T. Wang, "Gold substrate-induced single-mode lasing of GaN nanowires," Appl. Phys. Lett. **101**(22), 221114 (2012).

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16. A. Hurtado, H. Xu, J. B. Wright, S. Liu, Q. Li, G. T. Wang, T. S. Luk, J. J. Figiel, K. Cross, G. Balakrishnan, L. F. Lester, and I. Brener, "Polarization switching in GaN nanowire lasers," Appl. Phys. Lett. **103**, 251107 (2013).
17. S. Deshpande, J. Heo, A. Das, and P. Bhattacharya, "Electrically driven polarized single-photon emission from an InGaN quantum dot in a GaN nanowire," Nat. Commun. **4**, 1675 (2013).
18. Q. M. Li, K. R. Westlake, M. H. Crawford, S. R. Lee, D. D. Koleske, J. J. Figiel, K. C. Cross, S. Fathololoumi, Z. T. Mi, and G. T. Wang, "Optical performance of top-down fabricated InGaN/GaN nanorod light emitting diode arrays," Opt. Express **19**(25), 25528–25534 (2011).
19. J. B. Wright, S. Liu, G. T. Wang, Q. Li, A. Benz, D. D. Koleske, P. Lu, H. Xu, L. Lester, T. S. Luk, I. Brener, and G. Subramania, "Multi-colour nanowire photonic crystal laser pixels," Sci. Rep. **3**, 2982 (2013).
20. J. Zhang, L. D. Zhang, X. F. Wang, C. H. Liang, X. S. Peng, and Y. W. Wang, "Fabrication and photoluminescence of ordered GaN nanowire arrays," J. Chem. Phys. **115**(13), 5714–5717 (2001).
21. E. D. Palik, *Handbook of Optical Constants of Solids* (Academic, 1998), Vol. 3.
22. T. Yang, S. Goto, M. Kawata, K. Uchida, A. Niwa, and J. Gotoh, "Optical properties of GaN thin films on sapphire substrates characterized by variable-angle spectroscopic ellipsometry," Jpn. J. Appl. Phys. **37**(10A), L1105–L1108 (1998).

1. Introduction

Semiconductor nanowires are quasi-one-dimensional structures with unique optical properties such as wave-guiding, high photon confinement, and high index contrast [1–4]. Nanowire-based monochromic-coherent light sources may enable a number of groundbreaking applications, such as compact high resolution biochemical imaging and spectroscopy [5]. For III-nitride (GaN-based) nanowires, advances in synthesis techniques [6–10] have given rise to high material quality and controlled nanowire geometries needed for lasing [11]. Moreover, increasing efforts have been dedicated recently to manipulating the fundamental lasing properties of these nanowire lasers to make them more suitable for practical applications. For example, Li et al [6] demonstrated single-mode lasing of individual GaN nanowires by precisely controlling the nanowire diameter and length. Xu et al. [12] and Gao et al. [13] both demonstrated single-mode lasing behavior from coupled GaN nanowires, which individually exhibited multimode behavior. Wright et al. [14] achieved single-mode lasing using distributed feedback by coupling GaN nanowire lasers to an external dielectric grating. Moreover, single-mode lasing was recently demonstrated from single GaN nanowire lasers when coupled to a lossy metal substrate due to the suppression of the emission from higher order transverse modes [15]. However, the polarization, another key feature essential for many practical applications, apart from a couple of recent studies [16, 17] has rarely been studied in nanowire lasers. In this letter we demonstrate the effective control of the polarization of the light emitted by GaN nanowire lasers by coupling these devices to an underlying gold substrate.

2. Experimental details

The GaN nanowires investigated in this work are fabricated using a top-down dry plus wet-etch technique. A 5 μm thick c-plane GaN epilayer is grown on 2 inch sapphire substrates at 1050℃ using NH_3 and trimethylgallium as precursors in a MOCVD reactor. After the growth, a close-packed monolayer of 3 μm silica microspheres is assembled on the surface of the GaN epilayer using Langmuir-Blodgett techniques. This monolayer of silica microspheres functions as a mask layer for the subsequent inductively coupled plasma etch, which forms an array of tapered GaN micro-pillars. Subsequently an anisotropic wet etch is used to selectively etch the GaN pillar sidewalls to form cylindrical and non-tapered GaN nanowires with desired diameters and to remove the plasma etch-damaged sidewalls. Complete details of the fabrication process can be found elsewhere [6, 18, 19].

The GaN nanowires are dry-transferred onto target substrates for optical characterization. A cotton swab is used to rub the surface of the fabricated nanowire samples. As a result, GaN nanowires cleave at the sapphire/GaN interface and affix to the swab. The swab is then gently dabbed at the edge of the target substrates to transfer the nanowires onto them. In this work, a Si(100) wafer covered by a 200 nm thick gold film is used as the target substrate. After the dry transfer is performed, two types of nanowires are selected for analysis. As illustrated in Fig. 1, hanging nanowires hang over the edge of the substrate with minimal contact area to the substrate (held by electrostatic forces); on-gold nanowires contact the substrate along their

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entire length. Hanging and on-gold nanowires are subsequently characterized by means of a two-arm micro photoluminescence (PL) system. As seen in Fig. 1, the pump arm of the PL system consists of a pump laser, an attenuator, and a 50 × objective (0.4NA). The pump laser is a frequency-quadrupled Nd:YAG laser operating at 266 nm with a 400 ps pulse duration and a 10 kHz repetition rate. The pump spot size is approximately ~5 μm in diameter. A nanowire is optically excited from this pump arm and its light emission is collected by the other arm (end-facet collection arm), which includes a 20 × objective (0.4NA), a polarizer, and a 300 mm spectrometer with a 2400 groove/mm holographic grating. The collection arm is orientated perpendicularly to the pump arm. In this way, the nanowires can be pumped longitudinally along their entire length while their end-facet light emission can be collected simultaneously. Note that the end-facet collection technique reduces the effect of the substrate scattering that might depolarize the nanowire emission, ensuring the accuracy of the polarization measurements. The polarization of the nanowire laser is studied by adjusting the angle of the polarizer and measuring the light power after the polarizer.

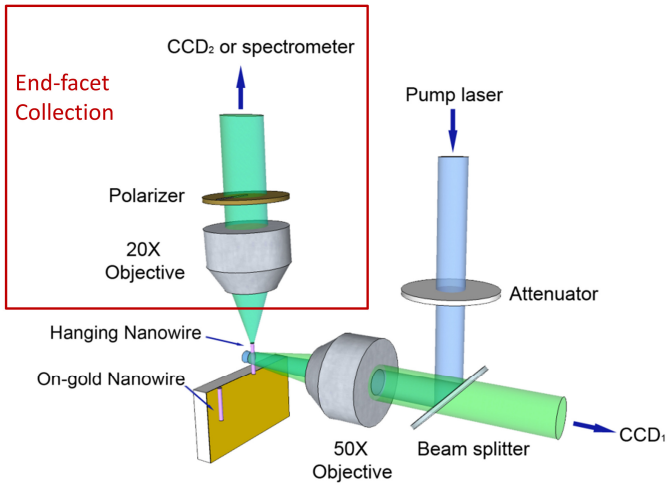

Fig. 1. Schematic of the two-arm micro-PL setup. In the pump arm (right), an incident laser beam pumps the GaN nanowires from the side. In the collection arm (left), the objective is aligned along the nanowire axis so that its polarization can be measured accurately.

3. Results and discussion

Figure 2(a) shows a scanning electron microscopic (SEM) image of a hanging nanowire. As seen in Fig. 2(a) the nanowire barely contacts the substrate surface, resulting in a negligible substrate effect. The nanowire is 5 μm long and has a diameter of 225 nm. By uniformly illuminating the nanowire and gradually increasing the pumping power, lasing behavior of the nanowire is observed with a threshold level of 246 kW/cm^2. The achievement of lasing threshold is experimentally evidenced by a sudden spectral narrowing, a transition from uniform body emission to a high contrast end-facet emission, and an interference pattern generation, as previously discussed [6]. Figure 2(b) shows a lasing spectrum from this nanowire obtained at 359 kW/cm^2, exhibiting single-mode lasing with a bandwidth of ~0.15 nm (limited by the resolution of the spectrometer). Our previous work has revealed that the single-wavelength lasing originates from the narrow material gain spectrum and the short nanowire cavity length, which leads to a strong mode competition [6]. Figure 2(c) shows a SEM image of an on-gold GaN nanowire with similar dimensions to those of the previously discussed hanging nanowire (5 μm long and diameter of 225 nm). Figure 2(d) shows the spectrum of the aforementioned on-gold nanowire obtained at a pump level of 389 kW/cm^2, also showing single-wavelength lasing. The higher threshold is consistent with a previous publication [15] where we observed a 13% increase to the lasing threshold for on-gold

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nanowires due to the additional loss from the gold. From the comparison of the spectra and threshold values it can be concluded that both hanging and on-gold nanowires present roughly similar lasing features.

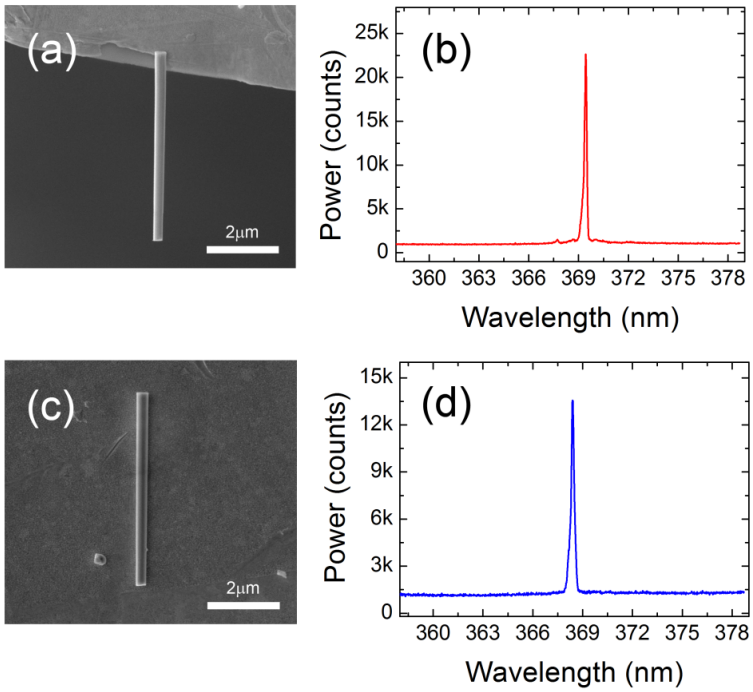

Fig. 2. (a) SEM image and (b) lasing spectrum of a GaN nanowire hanging over the substrate edge; (c) SEM image and (d) lasing spectrum of a nanowire lying on the gold substrate.

In contrast, the analysis of the polarization properties of the two types of nanowire lasers reveals significant differences. Figure 3(a) shows the measured lasing emission power of the hanging nanowire as a function of the polarizer rotation angle. A "peanut shaped" plot is obtained with clear major and minor axes at ~36° and ~126° respectively. Additionally, the measured cross-polarization suppression ratio (CPSR) was 2.7:1. These results show that this hanging nanowire's emission is elliptically polarized. In contrast, Fig. 3(b) shows that a highly linear polarized emission is obtained for the on-gold nanowire laser with a CPSR value as high as ~23:1. Moreover, its major polarization axis was ~0°, evidencing that the on-gold nanowire laser polarization is parallel to the substrate surface.

This experiment was further repeated on 10 more GaN nanowire lasers (5 hanging and 5 on-gold nanowires). The statistical analysis of the major polarization axes and the CPSRs of these nanowire lasers is summarized in Fig. 4. From Fig. 4(a), a mean axis of 63.6° is calculated with a standard deviation of 38.06° for hanging nanowires (black dots) a result that confirms a random polarization angle emission. In contrast, gold substrate nanowires (red dots in Fig. 4(a)) have a mean angle of 0.2° with a standard deviation of 4.96°, indicating a fixed polarization parallel to the substrate surface. Note that the uniformity of the nanowires, the substrate surface roughness, and the alignment of the nanowires with the collection arm all contribute to the deviation of polarization orientation. Moreover, Fig. 4(b) shows that gold substrate nanowires have in average a value of CPSR equal to 20 (red dots), which is 7 times larger than the average CPSR measured for hanging nanowires (black dots). These statistical results therefore demonstrate that the gold substrate leads to a linear polarization parallel to the substrate from GaN nanowire lasers.

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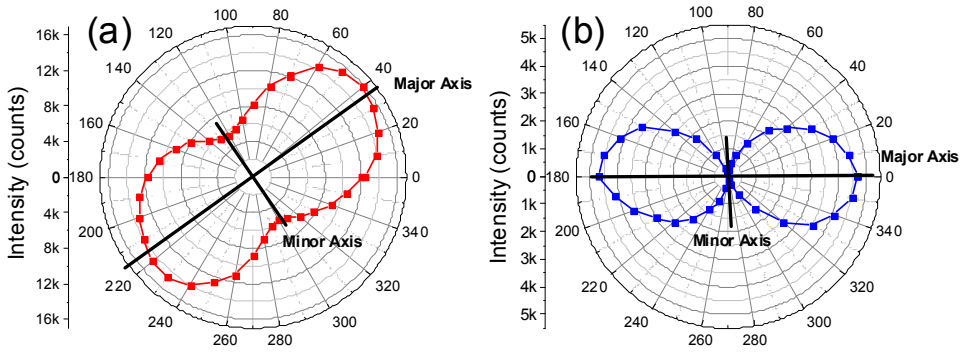

Fig. 3. Optical power versus polarizer rotation angle measured for (a) the hanging nanowire and (b) the on-gold nanowire. The 0°/90° indicates the orientation parallel/perpendicular to the substrate surface.

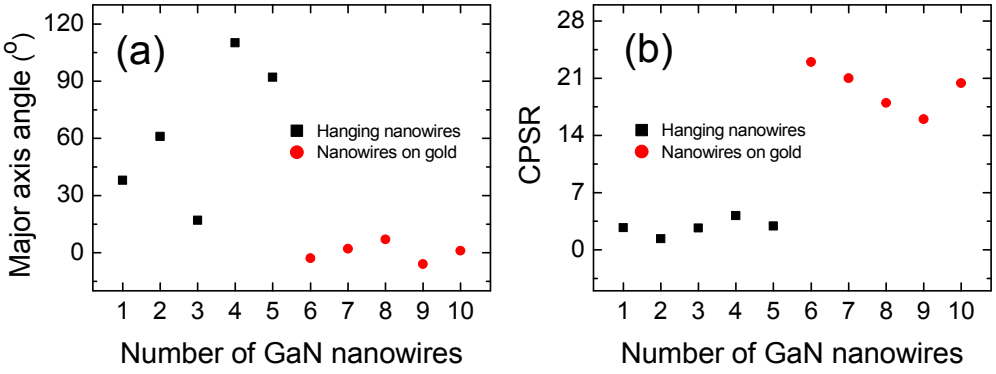

Fig. 4. Statistics of (a) polarization major axes and (b) CPSRs from 10 nanowires with similar geometry (5 hanging nanowires and 5 gold substrate nanowires).

This difference in the polarization properties of the nanowire-substrate configurations analyzed in this work can be attributed to a polarization-dependent loss generated by the gold substrate. Nanowires are axially symmetric and therefore, they simultaneously support degenerate modes with different polarization. Consequently, for the case of hanging nanowires, where the effect of the substrate is negligible, modes with different polarizations are excited simultaneously yielding the measured elliptically polarized lasing. In contrast, when the lossy gold substrate is present, the mode degeneracy is broken, leading to distinct cavity losses for differently polarized modes.

To clarify the gold substrate effect on the emitted light polarization, we carried out simulations to illustrate the modal properties of GaN nanowires when placed onto a gold substrate. The nanowire passive eigenmodes are determined using a fully vectorial commercial Eigenmode Solver from Lumerical Inc [20]. In the simulation, the operation wavelength is set to 367 nm, the real and imaginary parts of the gold's refractive index are set equal to 1.70 and 1.88 respectively [21], whereas the refractive index of GaN is set to 2.67 [22]. Figure 5 shows two orthogonally polarized HE_{11} modes supported by this nanowire/gold-substrate geometry. These two modes are polarized parallel (x polarized) and perpendicular (y polarized) to the substrate, respectively. In spite of the similar mode distributions, these two modes show, from simulation, a large difference in propagation loss, i.e., the propagation loss for the parallel polarized mode (Fig. 5(a)) is 0.36 dB/μm, which is significantly lower than 2.11 dB/μm for the perpendicularly polarized mode (Fig. 5(b)). The perpendicularly polarized mode, which is TM-like, readily couples to a surface plasmon, as seen in Fig. 5(b), and has a higher modal loss compared to the parallel polarized mode, which

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is TE-like, and does not couple to a surface plasmon. Hence, as a result of this optical cavity loss difference for the two orthogonal polarizations, the perpendicularly polarized mode is suppressed and the polarization of the light emitted by the on-gold nanowires is clamped parallel to the substrate.

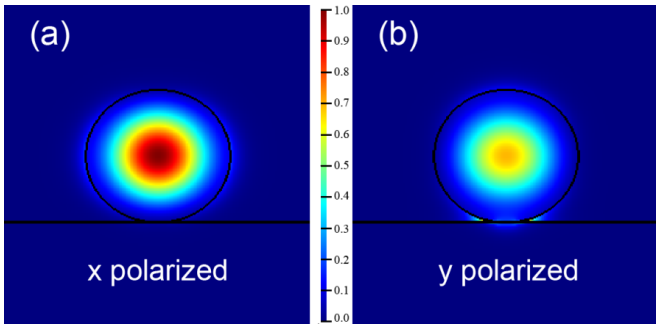

Fig. 5. Normalized mode intensity distributions calculated for a 230 nm diameter GaN nanowire placed on a gold substrate, i.e. distribution of the mode with polarization parallel (a) and perpendicular (b) to the substrate.

4. Conclusion

In conclusion, we have demonstrated polarization control of optically pumped individual GaN nanowires with the utilization of a gold substrate. The gold substrate breaks the mode degeneracy of a nanowire and forms two orthogonally polarized modes with a large difference in cavity loss. This polarization-dependent cavity loss suppresses the perpendicularly polarized mode, leading to a linearly polarized lasing with polarization orientation parallel to the substrate surface. These results represent a drastic contrast with the randomly oriented elliptical polarization laser emission observed from GaN nanowires without the loss mechanism. Our technique offers a simple methodology for controlling the polarization of individual nanowire lasers without drastically altering the performance of individual devices.

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