REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 30-08-2015	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 15-Sep-2012 - 14-Sep-2015

4. TITLE AND SUBTITLE Final Report: Ultrahigh-Speed Electrically Injected 1.55 um Quantum Dot Microtube and Nanowire Lasers on Si	5a. CONTRACT NUMBER W911NF-12-1-0477
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 1D10BA
6. AUTHORS Zetian Mi	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES McGill University 845 Sherbrooke Street West, 2nd Floor	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 62606-EL.13

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

In this report, we describe the progress made in rolled-up InP-based tube lasers and in the growth and characterization of III-nitride nanowire structures on Si. We report on the demonstration of electrically injected rolled-up InP-based tube lasers, which exhibit a threshold current ~ 1.05 mA. We also describe the achievements of electrically injected AlGaN nanowire lasers that can operate in the UV-AII (315-340 nm), UV-B (280-315nm), and UV-C (200-280 nm).

15. SUBJECT TERMS

rolled-up tube, nanowire, laser, Si photonics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Zetian Mi
UU	UU	UU	UU		19b. TELEPHONE NUMBER 514-398-7114

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: Ultrahigh-Speed Electrically Injected 1.55 um Quantum Dot Microtube and Nanowire Lasers on Si

ABSTRACT

In this report, we describe the progress made in rolled-up InP-based tube lasers and in the growth and characterization of III-nitride nanowire structures on Si. We report on the demonstration of electrically injected rolled-up InP-based tube lasers, which exhibit a threshold current ~ 1.05 mA. We also describe the achievements of electrically injected AlGaN nanowire lasers that can operate in the UV-AII (315-340 nm), UV-B (280-315nm), and UV-C (200-280 nm).

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/30/2015	7.00	S. Zhao, X. Liu, S. Y. Woo, J. Kang, G. A. Botton, Z. Mi. An electrically injected AlGaN nanowire laser operating in the ultraviolet-C band, Applied Physics Letters, (07 2015): 43101. doi: 10.1063/1.4927602
08/30/2015	10.00	M. Djavid, Z. Mi, M. H. T. Dastjerdi. An electrically injected rolled-up semiconductor tube laser, Applied Physics Letters, (01 2015): 21114. doi: 10.1063/1.4906238
08/30/2015	9.00	K. H. Li, X. Liu, Q. Wang, S. Zhao, Z. Mi. Ultralow-threshold electrically injected AlGaN nanowire ultraviolet lasers on Si operating at low temperature, Nature Nanotechnology, (01 2015): 140. doi: 10.1038/nnano.2014.308
08/30/2015	8.00	S. Zhao, A. T. Connie, M. H. T. Dastjerdi, X. H. Kong, Q. Wang, M. Djavid, S. Sadaf, X. D. Liu, I. Shih, H. Guo, Z. Mi. Aluminum nitride nanowire light emitting diodes: Breaking the fundamental bottleneck of deep ultraviolet light sources, Scientific Reports, (02 2015): 8332. doi: 10.1038/srep08332
09/01/2014	3.00	B. H. Le, S. Zhao, D. P. Liu, X. D. Liu, M. G. Kibria, T. Szkopek, H. Guo, Z. Mi. p-Type InN Nanowires, Nano Letters, (11 2013): 0. doi: 10.1021/nl4030819
09/01/2014	4.00	Songrui Zhao, Xuedong Liu, Zetian Mi. Photoluminescence properties of Mg-doped InN nanowires, Applied Physics Letters, (11 2013): 0. doi: 10.1063/1.4831895
09/01/2014	5.00	Qiuhang Zhong, Zhaobing Tian, Venkat Veerasubramanian, M. Hadi Tavakoli Dastjerdi, Zetian Mi, David V. Plant. Thermally controlled coupling of a rolled-up microtube integrated with a waveguide on a silicon electronic-photonic integrated circuit, Optics Letters, (04 2014): 0. doi: 10.1364/OL.39.002699
09/01/2014	2.00	S. Zhao, O. Salehzadeh, S. Alagha, K. L. Kavanagh, S. P. Watkins, Z. Mi. Probing the electrical transport properties of intrinsic InN nanowires, Applied Physics Letters, (02 2013): 0. doi: 10.1063/1.4792699
09/01/2014	1.00	M H T Dastjerdi, M Djavid, S Arafin, X Liu, P Bianucci, Z Mi, P J Poole. Optically pumped rolled-up InAs/InGaAsP quantum dash lasers at room temperature, Semiconductor Science and Technology, (09 2013): 0. doi: 10.1088/0268-1242/28/9/094007

TOTAL: **9**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Zetian Mi received the Young Scientist Award at the International Symposium on Compound Semiconductors in 2015

Zetian Mi received the Innovation Award, Faculty of Engineering, McGill University

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Mohammad Hadi Tavakoli Dastjer	0.00	
Songrui Zhao	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Songrui Zhao	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Zetian Mi	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME	
Mohammad Hadi Tavakoli Dastjerdi	
Songrui Zhao	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

N/A

Project Report

1. Statement of the Problem Studied

It is of immense interest to replace electrical interconnects with optical counterparts for both intra- and inter-chip connections. However, the realization of such optical interconnect systems on CMOS chips poses stringent requirements, in terms of the energy, density, bandwidth, and CMOS-compatibility for the constituting optical and optoelectronic devices. For example, to meet the global on-chip interconnect demands in 2022, device energies of ~ 10-20 fJ/bit and 2-10 fJ/bit are required for off-chip and on-chip interconnects, respectively [1, 2]. In this regard, it is critical to develop micro/nanoscale lasers with significantly reduced energy budget for electrical-to-optical signal conversion. In this project, we propose to develop electrically injected self-organized quantum dot tube and nanowire lasers on a Si platform. We have studied the growth and characterization of InAs/InP quantum dot tube and AlGaN nanowire heterostructures on Si. We have further investigated the design, fabrication, and characterization of such nanoscale lasers, with the objective to achieve both ultralow threshold and ultrahigh-speed operation.

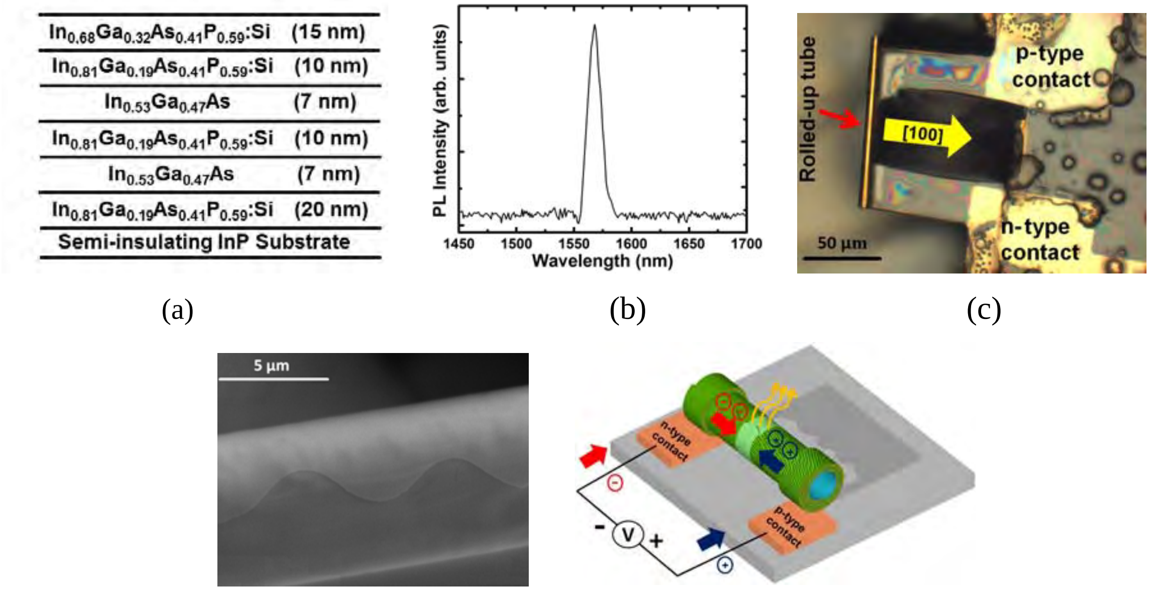
We have recently demonstrated electrically injected rolled-up InAs quantum well (or dot) tube lasers using a lateral injection scheme. In parallel, we have demonstrated, for the first time, electrically injected AlGaN nanowire lasers that can operate in the UV-B and UV-C bands. These achievements are summarized below.

2. Summary of the Most Important Results

2.1. Electrically injected rolled-up microtube lasers

Rolled-up microtubes [3-6], formed upon selective release of coherently strained semiconducting nanomembranes have been intensively studied. They offer many extraordinary advantages, including tunable optical emission properties by changing the diameter, layer thickness and surface geometry of the tube devices through standard photolithography [7, 8]. Moreover, they present polarized and directional emission and have extremely high Q-factors [6-8]. Previously, microtube coherent light sources/lasers have been demonstrated under optical pumping. For example InGaAs/GaAs [9] and InP/InGaAsP lasing at room temperature [10] have been demonstrated under 632 nm optical excitation. However, practical on-chip and integrated solutions will require electrically-driven devices to directly inject carriers rather than using an extra light source for pumping.

In this context, we have designed and fabricated InP/InGaAsP electrically injected rolled-up tube laser devices with the incorporation of InGaAs quantum wells as the gain medium. The devices operate at telecom wavelength range and show lasing at 80 K [11]. The device layer structure is shown in Figure 1(a). The material layer structure was grown using molecular beam epitaxy (MBE) on semi-insulating InP substrate. Two layers of 7 nm $In_{0.532}Ga_{0.468}As$ quantum wells were grown in between three layers of $In_{0.81}Ga_{0.19}As_{0.41}P_{0.59}$ with silicon doping. There exists a lattice mismatch between layers of $In_{0.81}Ga_{0.19}As_{0.41}P_{0.59}$ and $In_{0.68}Ga_{0.32}As_{0.41}P_{0.59}$. Therefore by selectively releasing this strained bilayer from the host substrate, the strained bilayer nanomembrane is rolled into tubular structures, due to the minimization of strain. The rolling, depending on the mesa shape, generally takes place along <100> crystal directions. The quantum well heterostructure shows strong photoluminescence emission, with the peak position at ~1.57 µm as shown in Figure 1(b).



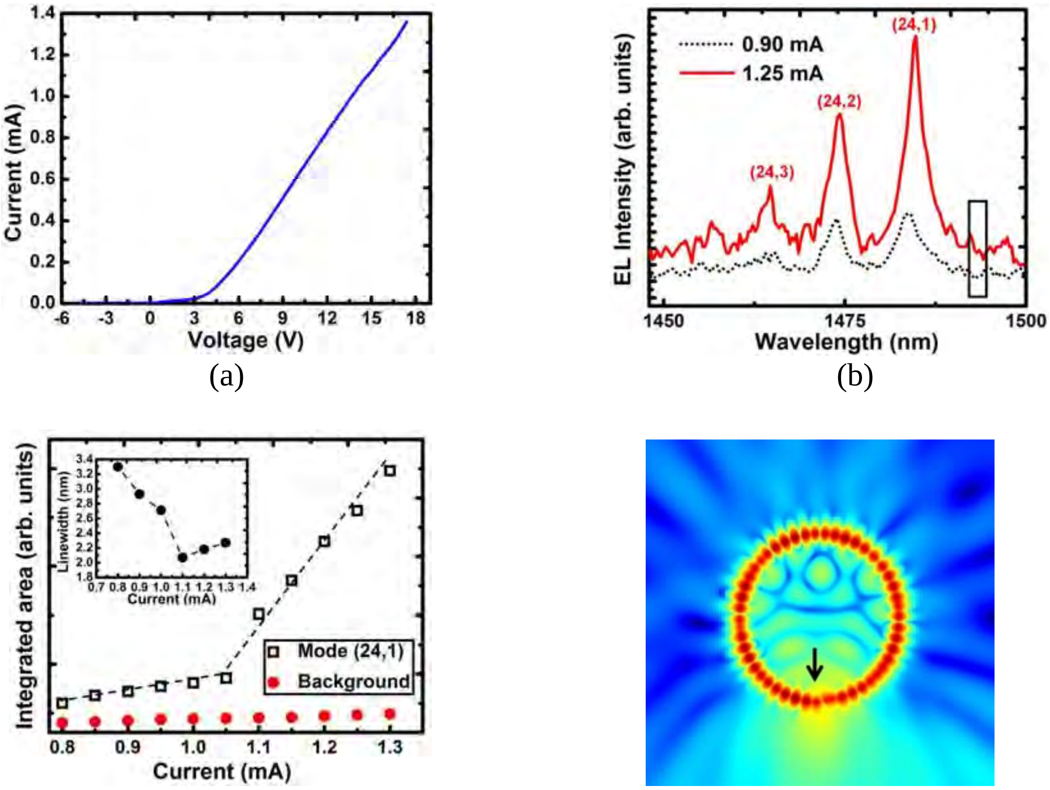
(a) (b) (c)

(d) (e)

Figure 1. (a) Schematic of the InGaAs/InGaAsP quantum well heterostructures grown on semi-insulating InP substrate. (b) Photoluminescence spectrum measured at room temperature. (c) Optical microscopy image of the free-standing rolled-up tube device with metal contacts. The green arrow shows the rolling direction of the tube device. (d) SEM image of the free-standing part of the tube device showing surface corrugations for axial mode confinement. (e) Schematic of the lateral carrier injection scheme during electrical pumping.

As described above, the entire wafer is doped n-type. Prior to the device fabrication, a single step ion-implantation of Be was done to selectively p-dope part of the tube device. The implanted dopant was activated by a post-implant annealing of the sample at 600 °C for 35 sec. Ni/Ge/Au and Pd/Ti/Pd/Au were e-beam evaporated and thermally annealed as the n- and p-metal contacts, respectively. Photolithography and wet etching in $HCl:HNO_3:H_2O$ (1:2:10) were performed to etch the U-shaped mesas deep into the InP substrate. Then another photolithography step was performed to cover the bottom part of the U-shaped mesa with photoresist to avoid side-rolling of the mesas during the sacrificial etching step and also to protect the metallic contacts during etching. The sample was then put in $HCl:H_2O$ (2:1) solution for about 15 minutes during which, by etching the underlying InP substrate layer, the coherently strained InGaAsP bilayer is rolled up to form the tube device, shown in figure 1(c). The tube devices have diameters of about 5-6 µm and the rolling takes place along the <100> crystal direction. The SEM image of the center part of the rolled-up tube device is shown in Figure 1(d). The presence of surface corrugations can be clearly identified, which provide strong optical confinement along the tube axial direction. The schematic of the carrier injection and light emission for the tube device is shown in Figure 1(e).

The device was measured under pulsed-bias conditions (1 KHz, 8% duty cycle) at 80 K. An optical fiber was used to collect the light emission which was then guided to a spectrometer and detected by a liquid nitrogen cooled InGaAs detector with lock-in amplification. The devices exhibit relatively good current-voltage characteristics, shown in Figure 2(a). The current-voltage characteristics can be further improved by optimizing the growth, doping, and annealing conditions. The output spectra measured at 0.9 mA and 1.25 mA are shown in Figure 2(b). The corresponding azimuthal and axial mode numbers are identified.



(a) (b)

(c) (d)

Figure 2. (a) Measured current-voltage characteristic at room temperature. (b) Electroluminescence spectra of the rolled-up tube device measured at 0.9 mA (below threshold) and 1.25 mA (above threshold). (c) Integrated intensity versus current for the mode (24,1) and for the background emission extracted from the box shown in (b). Inset: Full-width-at-half-maximum of the mode (24,1) vs. current. (d) Resonance mode distribution in a rolled-up InGaAsP tube with a wall thickness of 140 nm and diameter of 5 µm calculated by the two-dimensional FDTD method. The presence of inside notch is shown by the arrow.

With the use of a Lorentzian function method to analyze the optical modes measured at various injection currents, the corresponding integrated area and the full-width-at-half-maximum (FWHM) parameters were derived. Figure 2(c) shows the integrated intensity vs. current for the mode (24,1) (~1485 nm) which exhibits a clear threshold at ~1.05 mA. Variations of the FWHM of this lasing mode with current are shown in the inset of Figure 2(c). A clear reduction of the spectral linewidth from ~3.3 nm to ~2 nm at the same current value is measured, further confirming the achievement of lasing. In addition, due to the presence of doublet modes related to the spiral symmetry of the tube cavity, the intrinsic linewidth of the lasing mode can be significantly smaller [12].

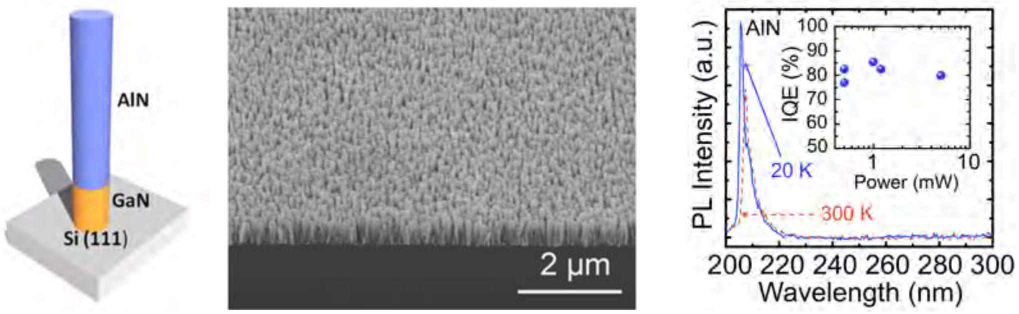
In order to evaluate the behavior of background emission at different currents, we have calculated the integrated area of a spectral width of 4 nm separated from the mode (24,1) by 8 nm. This spectral area is shown as the square box in Figure 2(b). Compared to the intensity of the lasing mode, the background emission shows a negligible increase at or above the threshold current. This provides further evidence for the observed lasing behavior, as the carrier concentration is clamped at the threshold value. By further increasing the current, a small increase in the background emission is observed which can be described by hot carrier effect [13].

The distribution of the stimulated optical resonance azimuthal mode for a rolled-up tube with a wall thickness of 140 nm by the two-dimensional finite-difference time-domain (FDTD) method is shown in Figure 2(d). The scattered light by the inside notch is clearly seen, which can be used as the useful output of such devices, leading to controlled directional emission. For the lasing mode (24,1), the Q factor is estimated to be ~ 800, and V_{eff} and n_{eff} are estimated to be ~ 4μm^3 and ~2.26, respectively. The Purcell factor is then calculated to be ~ 4.3.

2.2. Al(Ga)N nanowire light emitting diodes (LEDs) on silicon

AlN and Al-rich AlGaN alloys have attracted significant attention for deep ultraviolet (DUV) optoelectronic devices, including light emitting diodes (LEDs) and lasers, and are positioned to replace conventional mercury DUV light sources. However, the performance of AlGaN based DUV light sources reduces drastically due to the intrinsic electrical and optical properties of the end compound – AlN [14-16]. In this report, we demonstrate that these challenges can be largely addressed by nitrogen polar Al(Ga)N nanowires. With a careful control of the growth process, an IQE of ~ 80% can be realized in the end compound – AlN at room-temperature. Furthermore, strong band edge (~ 210 nm) electroluminescence (EL) can be measured from AlN nanowire LEDs. The turn on voltage is only ~ 6 V, significantly lower compared to previously reported planar AlN LEDs. With the incorporation of Ga, high performance AlGaN nanowire deep UV LEDs can also be demonstrated.

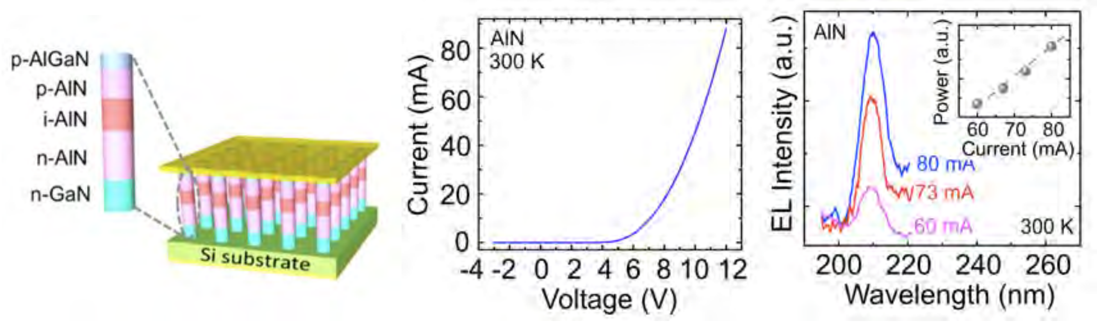
The AlN nanowire structure is schematically shown in Figure 3(a). In this structure, to promote the formation of AlN nanowires, GaN nanowire template was grown first. The SEM image is shown in Figure 3(b). It is seen that highly uniform, vertically aligned AlN nanowires can be formed, which is well suited for the fabrication of large area devices. Detailed TEM studies further indicate that such AlN nanowires have N-polarity and are free of stacking faults and misfit dislocations [17]. Temperature dependent photoluminescence (PL) experiments were formed subsequently. The PL spectra measured at 20 K and room temperature are shown in Figure 3(c). It is seen that strong band edge emission can be measured. The internal quantum efficiency (IQE) can be further estimated by the ratio of integrated PL intensity at room temperature vs. the integrated PL intensity at 20 K, assuming the IQE at 20 K being unity. Shown in the inset of Figure 3(c), it is seen that the IQE is around 80 % with an excitation power varying more than 10 times. It is further noted that this high IQE is naturally expected from nearly defect free AlN nanowires, due to the large exciton binding energy in AlN (~ 60 meV).



(a) (b) (c)

Figure 3. (a) Schematic of AlN nanowires. (b) SEM image of AlN nanowires. (c) The PL spectra measured at 20 K and 300 K, with the inset showing the derived IQE vs. excitation power.

The electrically injected devices, which consist of n- and p-GaN contact layers, and AlN p-i-n junctions, were fabricated subsequently. The structure of the device is schematically shown in Figure 4(a). In this fabrication, to avoid any deep UV light absorption, no polymer passivation was used. Instead, a direct metal deposition was used for p-contact. The I-V characteristics of AlN nanowire LEDs with a size of 0.3 mm by 0.3 mm are shown in Figure 4(b). It is seen that at a forward current of 20 mA (~ 20 A/cm^2), the forward voltage is only ~ 8 V, which corresponds to an electrical efficiency of ~ 74 % for an emission wavelength of ~ 210 nm (shown in Figure 4(c)) if using 20 A/cm^2 as the operation point. The EL spectra measured under different injection currents are shown in Figure 4(c). It is seen that as the injection current increases, the EL intensity increases linearly (illustrated by the integrated EL intensity in the inset of Figure 4(c)). With further incorporating Ga, AlGaN nanowire deep UV LEDs emitting at ~ 290 nm were realized [17].



(a) (b) (c)

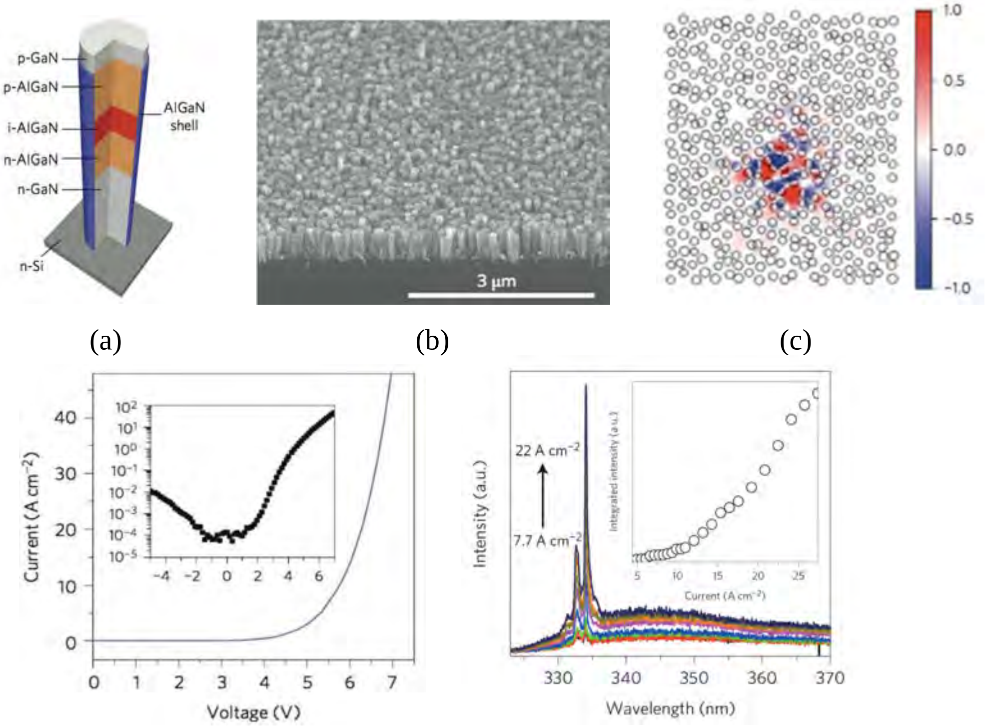
Figure 4. (a) Schematic of the fabricated AlN nanowire LEDs. (b) I-V characteristics of AlN nanowire LEDs measured at 300 K. (c) The EL spectra measured at 300 K, with the inset showing the integrated EL intensity vs. the injection current.

The significantly improved electrical performance compared to AlN planar LEDs [18, 19] can be ascribed to the enhanced Mg-dopant incorporation in nanowires, due to the reduced formation energy for Al-substitutional Mg in the near-surface region and the reduced growth rate of AlN nanowires [17, 20]. The resulting efficient hole hopping conduction leads to relatively low device resistance.

2.3. Ultralow threshold, electrically injected nanowire lasers on Si

Deep ultraviolet (UV) lasers are important light sources for a wide range of applications including disinfection, water purification, and bio/chemical sensing. To date, however, the currently reported electrically injected semiconductor lasers with conventional AlGaN multiple quantum well structures are limited to the UV-AI band (~ 340-400 nm) [21]. In this work, we demonstrate the use of nearly defect-free AlGaN core-shell nanowires as a solution to bridge the gap in the deep UV spectral range. We have discovered that the randomly distributed AlGaN nanowire arrays can function as a high Q optical cavity, due to the Anderson localization of light. We have further demonstrated electrically injected AlGaN nanowire lasers that can operate in the entire UV-AII, UV-B, and UV-C bands [22-24].

The realization of electrically injected AlGaN nanowire lasers in the UV-AII band (~ 315-340 nm) is first described. The nanowire structure is schematically shown in Figure 5(a), which consists AlGaN *p-i-n* layers and *n-* and *p*-GaN contact layers [22]. An Al-rich AlGaN shell was spontaneously formed during the nanowire growth process, which can largely suppress nonradiative surface recombination. The SEM image of AlGaN nanowires is shown in Figure 5(b). In such randomly distributed AlGaN nanowire arrays, strong light confinement can be realized due to the Anderson localization, shown in Figure 5(c). The I-V characteristics measured at low temperature are shown in Figure 5(d). The EL spectra are shown in Figure 5(e). It is seen that as the injection current increases, a sharp peak centered ~ 334 nm appears, with a spectral linewidth of 0.2 nm. The corresponding light output vs. current (L-I) curve is shown in the inset of Figure 5(e). The threshold current density is only ~ 12 A/cm^2 at low temperature (6 K), which is orders of magnitude lower compared to the previously reported AlGaN quantum well lasers in the similar wavelength range at room-temperature [25, 26]



(a) (b) (c)

(d) (e)

Figure 5. (a) The layer-by-layer schematic of AlGaN nanowire laser structure. (b) SEM image of AlGaN nanowires. (c) The simulated electrical field distribution. (d) I-V characteristics of AlGaN nanowire lasers. (e) EL spectra of AlGaN nanowire lasers, with the inset showing the L-I curve. [22]

By further optimizing the nanowire diameter and fill factor as well as Al content, electrically injected AlGaN nanowire lasers in the deep UV spectral range can be realized. The EL emission was measured under continuous-wave biasing conditions at 77 K. Illustrated in Figure 6(a), as the injection current increases, a sharp peak centered around 262.1 nm appears. Above threshold, the spectral linewidth is ~ 0.3 nm. The laser threshold is ~ 200 A/cm^2, illustrated in Figure 6(b), which is about two orders of magnitude smaller than that (20 kA/cm^2) measured from electrically injected AlGaN quantum well lasers at 336 nm [26]. The L-I curve for the background emission is also shown in Figure 6(b). It is seen that above threshold the intensity of the background emission only increases slightly. The inset of Figure 6(b) shows the L-I curve of the lasing peak in a logarithmic scale, and a clear S-shape curve, corresponding to spontaneous emission, amplified spontaneous emission, and lasing, can be observed. This provided unambiguous evidence for the achievement of lasing. Figure 6(c) shows the linewidth reduction from 1.2 nm to 0.3 nm near the threshold, and Figure 6(d) shows that the lasing peak remains highly stable above the threshold without any measureable wavelength shift. Such a low threshold deep ultraviolet laser is made possible due to the nearly defect-free AlGaN nanowires, the presence of quantum dot like nanostructures, and the high Q optical cavity.

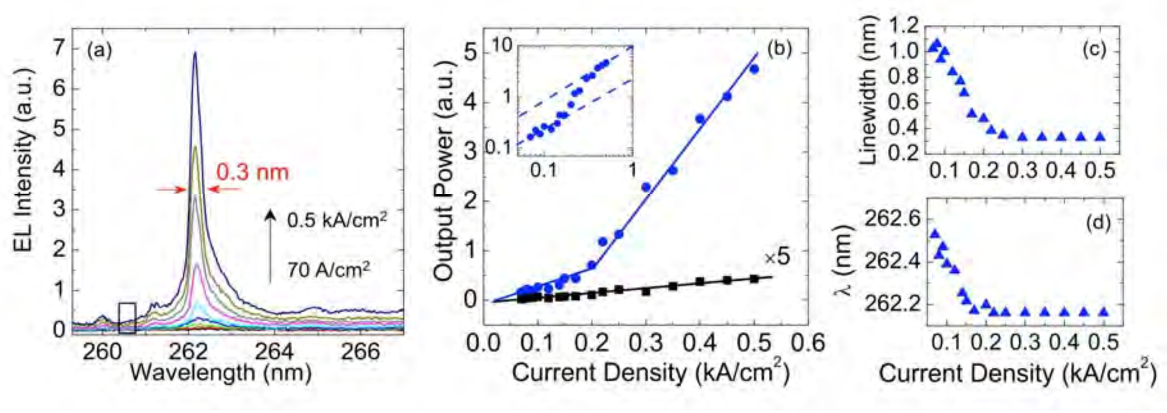


Figure 6. UV-C lasing characteristics measured at 77 K [23]. (a) The EL spectra under different injection currents. (b) The L-I curve. The solid blue circles are for the 262.1 nm lasing peak, while the solid black squares are from the boxed region in (a). The inset shows the L-I curve of the 262.1 nm peak in a logarithmic scale. The solid lines are guide-for-eye. (c) and (d) The EL spectral linewidth and the variation of the lasing wavelength as a function of the injection current density, respectively.

3. Publications

__Journal Papers:__

1. M. H. T. Dastjerdi, M. Djavid and Z. Mi, "An electrically injected rolled-up semiconductor tube laser," *Appl. Phys. Lett*. 106, 021114 (2015).
2. S. Zhao, X. Liu, S. Woo, J. J. Kang, G. Botton, and Z. Mi, “An electrically injected AlGaN nanowire laser operating in the UV-C band”, *Appl. Phys. Lett.* 107, 043101 (2015).
3. S. Zhao, A. T. Connie, M. H. T. Dastjerdi, X. H. Kong, Q. Wang, M. Djavid, S. Sadaf, X. D. Liu, I. Shih, H. Guo, and Z. Mi, “Aluminum nitride nanowire light emitting diodes: Breaking the fundamental bottleneck of deep ultraviolet light sources”, *Nature Sci. Rep.* 5, 8332 (2015).
4. K. H. Li, X. Liu, Q. Wang, S. Zhao, and Z. Mi, “Ultralow threshold, electrically injected AlGaN nanowire ultraviolet lasers on Si”, *Nature Nanotechnol.* 10, 140 (2015).
5. M. H. T. Dastjerdi, M. Djavid, S. Arafin, X. Liu, P. Bianucci, Z. Mi, and P. J. Poole, “Optically pumped rolled-up InAs/InGaAsP quantum dash lasers at room temperature,” *Semicond. Sci. Technol.*, vol. 28, no. 9, p. 094007, 2013.
6. Q. Zhong, Z. Tian, V. Veerasubramanian, M. H. T. Dastjerdi, Z. Mi, D. Plant, “Thermally controlled coupling of a rolled-up microtube integrated with a waveguide on a silicon electronic-photonic integrated circuit,” *Opt. Lett.*, vol. 39, no. 9, 2699, 2014.
7. S. Zhao, B. H. Le, D. P. Liu, X. D. Liu, M. G. Kibria, T. Szkopek, H. Guo, and Z. Mi, "p-Type InN nanowires," *Nano Letters*, vol. 13, pp. 5509-13, 2013
8. S. Zhao, X. D. Liu, and Z. Mi, “Photoluminescence properties of Mg-doped InN nanowires”, *Applied Physics Letters*, vol. 103, p. 203113, 2013.

9. S. Zhao, O. Salehzadeh, S. Alagha, K. L. Kavanagh, S. P. Watkins, and Z. Mi, “Probing the electrical transport properties of intrinsic InN nanowires,” *Appl. Phys. Lett.*, vol. 102, 073102, 2013.
10. **Invited:** M. H. T. Dasterjdi, M. Djavid, S. Arafin, X. Liu, P. Bianucci, and Z. Mi, “Optically pumped rolled-up InAs/InGaAsP quantum dash lasers at room-temperature,” *Semicond. Sci. Technol.*, vol. 28, 094007, 2013.

Conferences:

1. **(Invited)** Z. Mi, S. Zhao, X. H. Liu, B. H. Le, J. J. Kang, K. H. Li, Q. Wang, “Electrically injected AlGaN nanowire deep ultraviolet lasers on Si,” *11th International Conference on Nitride Semiconductors*, Beijing, China, Aug. 30-Sept.4, 2015.
2. **(Invited)** Z. Mi, S. Zhao, and X. Liu, “Electrically injected AlGaN nanowire deep ultraviolet lasers,” *SPIE Optics and Photonics*, San Diego, Aug. 9-13, 2015.
3. **(Invited)** Z. Mi, M. Djavid, and O. Salehzadeh, “Rolled-up semiconductor tube lasers and lasers based two-dimensional atomic crystals,” *2015 IEEE Summer Topical Meeting on On-chip Optical Interconnects*, Nassau, Bahamas, July 13 -15, 2015.
4. **(Invited)** Z. Mi, S. Zhao, X. Liu, A. T. Connie, K. H. Li, and Q. Wang, “High efficiency AlGaN deep ultraviolet nanowire LEDs and lasers on Si,” *SPIE Photonics West*, San Francisco, Feb. 7-12, 2015.
5. **(Invited)** Z. Mi and D. Plant, “Rolled-up quantum dot optoelectronics and integrated nanophotonic circuits on Si,” *SPIE Photonics West*, San Francisco, Feb. 7-12, 2015.
6. **(Invited)** Z. Mi, S. Zhao, H. P. T. Nguyen, B. Le, Q. Wang, and X. Liu, “High performance III-nitride nanowire light emitting diodes from the deep ultraviolet to the near infrared,” *The 10th International Symposium on Semiconductor Light Emitting Devices (ISSLED)*, National Sun Yat-Sen University, Kaohsiung, Taiwan, Dec. 14-19, 2014.
7. M. H. T. Dastjerdi, M. Djavid, P. Bianucci and Z. Mi, "Coherent emission from electrically-injected InP/InGaAsP rolled up quantum well microtubes" ***IEEE Photonics Conference***, San Diego, California, Oct. 2014.
8. S. Zhao, A. T. Connie, B. H. Le, I. Shih, and Z. Mi, “Molecular beam epitaxial growth and characterization of AlN nanowire LEDs: Breaking the bottleneck of deep UV light sources,” ***2015 Compound Semiconductor Week***, University of California, Santa Barbara, California, United States, Jul. 2015.
9. S. Zhao, X. Liu, B. H. Le, J. J. Kang, K. H. Li, Q. Wang, and Z. Mi, “Electrically injected deep ultraviolet lasers based on AlGaN nanostructures,” ***2015 Compound Semiconductor Week***, University of California, Santa Barbara, California, United States, Jul. 2015.
10. S. Zhao, X. Liu, J. J. Kang, K. H. Li, Q. Wang, and Z. Mi, “Electrically injected AlGaN nanowire ultraviolet lasers,” ***57th Electronic Materials Conference***, The Ohio State University, Columbus, Ohio, Jun. 2015.
11. S. Zhao, A. T. Connie, M. H. T. Dasterjdi, S. Sadaf, I. Shih, and Z. Mi, “Molecular beam epitaxial growth and characterization of AlN nanowire LEDs on Si,” ***57th Electronic Materials Conference***, The Ohio State University, Columbus, Ohio, Jun. 2015.
12. Z. Mi, S. Zhao, X. Liu, A. T. Connie, K. H. Li, and Q. Wang, “High efficiency AlGaN deep ultraviolet nanowire LEDs and lasers on Si,” ***SPIE Photonics West***, San Francisco, California, United States, Feb. 2015.

13. S. Zhao, A. T. Connie, Q. Wang, M. H. T. Dasterjdi, and Z. Mi, “Molecular beam epitaxial growth and characterization of superior quality AlN nanowires on Si,” ***18th International Conference on Molecular Beam Epitaxy***, Flagstaff, Arizona, United States, Sept. 2014.
14. **(Invited)** Z. Mi, S. Zhao, and B. H. Le “p-Type InN nanowires,” *The International Workshop on Nitride Semiconductors*, Wrocław, Poland, Aug. 2014.
15. **(Invited)** Z. Mi, S. Zhao, and H. P. T. Nguyen, “p-Type III-nitride nanowires: Epitaxial growth, surface charge properties, and novel device applications,” *SPIE Optics and Photonics Meeting*, San Diego, California, United States, Aug. 2014.
16. S. Zhao, H. P. T. Nguyen, and Z. Mi, “Near-infrared InN nanowire optoelectronic devices on Si,” *2014 IEEE Summer Topical Meeting on Nanowire Materials and Integrated Photonics*, Montreal, Quebec, Canada, Jul. 2014.
17. B. H. Le, S. Zhao, N. H. Tran, T. Szkopek, and Z. Mi, “p-Type conduction and ambipolar characteristics of Mg-doped InN nanowires”, *56th Electronic Materials Conference*, University of California, Santa Barbara, California, United States, Jun. 2014.
18. S. Zhao, B. L. Huy, D. P. Liu, X. D. Liu, M. G. Kibria, T. Szkopek, H. Guo, and Z. Mi, “p-Type InN nanowires: Towards ultrahigh speed nanoelectronics and nanophotonics”, *SPIE Photonics West*, San Francisco, California, United States, Feb. 2014.
19. **(Invited)** Z. Mi, S. Zhao, B. L. Huy, D. P. Liu, X. D. Liu, M. G. Kibria, T. Szkopek, and H. Guo, “Molecular beam epitaxial growth and characterization of intrinsic and p-type InN nanowires”, *SPIE Photonics West*, San Francisco, California, United States, Feb. 2014.
20. S. Zhao and Z. Mi, “Tuning the surface charge properties of InN nanowires: From n-type degenerate to nearly p-type degenerate”, *The 30th North American Molecular Beam Epitaxy Conference*, Banff, Alberta, Canada, Oct. 2013.
21. **Invited:** Z. Mi, H. P. T. Nguyen, S. Zhao, Q. Wang, B. H. Le, and K. H. Li, “High performance III-nitride nanowire LEDs and lasers on Si,” *The 16th Canadian Semiconductor Science and Technology Conference*, Thunder Bay, ON, Canada, Aug. 12-16, 2013.
22. **Invited:** Z. Mi, H. T. Dastjerdi, P. Bianucci, Z. Tian, Q. Zhong, V. Veerasubramanian, P. J. Poole, A. G. Kirk, and D. V. Plant, “Rolled-up 1.5 μm quantum dot tube lasers and integrated nanophotonic circuits on Si,” *IEEE Photonics 2013 Summer Topical Meetings on Micro- and Nano-Cavity Integrated Photonics*, Hilton Waikoloa Village, Waikoloa, HI, USA, July 8-10, 2013.
23. Q. Zhong, Z. Tian, M. H. T. Dastjerdi, Z. Mi, and D. V. Plant, “Counter-propagating whispering-gallery-modes of InGaAs/GaAs microtubes,” *Conference on Lasers and Electro-Optics*, San Jose, CA, June 9-14, 2013.

4. Report of Inventions

None.

5. List of Scientific Personnel Supported, Degrees, Awards and Honors

Songrui Zhao (Postdoctoral researcher) and Mohammad Hadi Tavakoli Dastjerdi (PhD student)

Mohammad Hadi Tavakoli Dastjerdi received the PhD degree in Aug. 2015.

Songrui Zhao received the PhD degree in May 2013.

Zetian Mi received the Young Scientist Award at the International Symposium on Compound Semiconductors in 2015

Zetian Mi received the Innovation Award, Faculty of Engineering, McGill University

Songrui Zhao received the Outstanding Student Paper Award from the North American Molecular Beam Epitaxy Conference in 2012.

6. Technology Transition

None.

Bibliography:

[1] D. A. B. Miller, "Optical interconnects to electronic chips," *Appl. Opt.* , vol. 49, p. F59, 2010.

[2] D. A. B. Miller, "Device Requirements for Optical Interconnects to Silicon Chips," *Proc. IEEE,* vol. 97, p. 1166, 2009.

[3] V. Y. Prinz, V. A. Seleznev, A. K. Gutakovsky, A. V. Chehovskiy, V. V. Preobrazhenskii, M. A. Putyato, *et al.*, "Freestanding and overgrown InGaAs/GaAs nanotubes, nanohelices and their arrays," *Phys. E,* vol. 6, p. 828, 2000.

[4] S. Vicknesh, F. Li, and Z. Mi, "Optical microcavities on Si formed by self-assembled InGaAs/GaAs quantum dot microtubes," *Appl. Phys. Lett.,* vol. 94, p. 081101, 2009.

[5] O. G. Schmidt and K. Eberl, "Thin solid films roll up into nanotubes," *Nature,* vol. 410, p. 168, 2001.

[6] T. Kipp, H. Welsch, C. Strelow, C. Heyn, and D. Heitmann, "Optical modes in semiconductor microtube ring resonators," *Physical Review Letters,* vol. 96, p. 077403, 2006.

[7] Z. Tian, V. Veerasubramanian, P. Bianucci, S. Mukherjee, Z. Mi, A. G. Kirk, *et al.*, "Single rolled-up InGaAs/GaAs quantum dot microtubes integrated with silicon-on-insulator waveguides," *Optics Express,* vol. 19, p. 12164, 2011.

[8] C. Strelow, H. Rehberg, C. M. Schultz, H. Welsch, C. Heyn, D. Heitmann, *et al.*, "Optical Microcavities Formed by Semiconductor Microtubes Using a Bottlelike Geometry," *Phys. Rev. Lett.,* vol. 101, p. 127403, 2008.

[9] F. Li and Z. Mi, "Optically pumped rolled-up InGaAs/GaAs quantum dot microtube lasers," *Opt. Express,* vol. 17, p. 19933, 2009.

[10] M. H. T. Dastjerdi, M. Djavid, S. Arafin, X. Liu, P. Bianucci, Z. Mi, *et al.*, "Optically pumped rolled-up InAs/InGaAsP quantum dash lasers at room temperature," *Semicond. Sci. Technol.,* vol. 28, p. 094007, 2013.

[11] M. H. T. Dastjerdi, M. Djavid, and Z. Mi, "An electrically injected rolled-up semiconductor tube laser," *Appl. Phys. Lett.,* vol. 106, p. 021114, 2015.

[12] M. Hosoda and T. Shigaki, "Degeneracy breaking of optical resonance modes in rolled-up spiral microtubes," *Applied physics letters,*, vol. 90, p. 181107, 2007.

[13] P. Bhattacharya and Z. Mi, "Quantum-dot optoelectronic devices," *Proceedings of the IEEE,* vol. 95, p. 1723, 2007.

[14] A. Khan, K. Balakrishnan, and T. Katona, "Ultraviolet light-emitting diodes based on group three nitrides," *Nature Photonics,* vol. 2, p. 77, 2008.

[15] H. Hirayama, N. Maeda, S. Fujikawa, S. Toyoda, and N. Kamata, "Recent progress and future prospects of AlGaN-based high-efficiency deep-ultraviolet light-emitting diodes," *Japanese Journal of Applied Physics,* vol. 53, p. 100209, 2014.

[16] Y. Muramoto, M. Kimura, and S. Nouda, "Development and future of ultraviolet light-emitting diodes: UV-LED will replace the UV lamp," *Semiconductor Science and Technology,* vol. 29, p. 084004, 2014.

[17] S. Zhao, A. T. Connie, M. H. Dastjerdi, X. H. Kong, Q. Wang, M. Djavid, *et al.*, "Aluminum nitride nanowire light emitting diodes: Breaking the fundamental bottleneck of deep ultraviolet light sources," *Sci Rep,* vol. 5, p. 8332, 2015.

[18] Y. Taniyasu and M. Kasu, "Surface 210 nm light emission from an AlN p–n junction light-emitting diode enhanced by A-plane growth orientation," *Applied Physics Letters,* vol. 96, p. 221110, 2010.

[19] Y. Taniyasu, M. Kasu, and T. Makimoto, "An aluminium nitride light-emitting diode with a wavelength of 210 nanometres," *Nature,* vol. 441, pp. 325-8, May 18 2006.

[20] A. T. Connie, S. Zhao, S. M. Sadaf, I. Shih, Z. Mi, X. Du, *et al.*, "Optical and electrical properties of Mg-doped AlN nanowires grown by molecular beam epitaxy," *Applied Physics Letters,* vol. 106, p. 213105, 2015.

[21] H. Yoshida, M. Kuwabara, Y. Yamashita, K. Uchiyama, and H. Kan, "The current status of ultraviolet laser diodes," *physica status solidi (a),* vol. 208, pp. 1586-1589, 2011.

[22] K. H. Li, X. Liu, Q. Wang, S. Zhao, and Z. Mi, "Ultralow-threshold electrically injected AlGaN nanowire ultraviolet lasers on Si operating at low temperature," *Nat Nanotechnol,* vol. 10, p. 140, Jan 19 2015.

[23] S. Zhao, X. Liu, S. Y. Woo, J. Kang, G. A. Botton, and Z. Mi, "An electrically injected AlGaN nanowire laser operating in the ultraviolet-C band," *Applied Physics Letters,* vol. 107, p. 043101, 2015.

[24] S. Zhao, S. Y. Woo, M. Bugnet, X. Liu, J. Kang, G. A. Botton, *et al.*, "Three-dimensional quantum confinement of charge carriers in self-organized AlGaN nanowires: A viable route to electrically injected deep ultraviolet lasers," *Nano Lett.,* under review.

[25] H. Yoshida, Y. Yamashita, M. Kuwabara, and H. Kan, "A 342-nm ultraviolet AlGaN multiple-quantum-well laser diode," *Nature Photonics,* vol. 2, pp. 551-554, 2008.

[26] H. Yoshida, Y. Yamashita, M. Kuwabara, and H. Kan, "Demonstration of an ultraviolet 336 nm AlGaN multiple-quantum-well laser diode," *Applied Physics Letters,* vol. 93, p. 241106, 2008.