Towards electrically-driven semiconductor nanowire lasers

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Abstract

Semiconductor NanoWire (NW) lasers are highly promising for making new generation coherent light sources with the advantages of ultra-small size, high efficiency, easy integration and low cost. Over the past 15 years, this area of research has been developing rapidly, with extensive reports of optically pumped lasing in various inorganic and organic semiconductor NWs. Motivated by these developments, substantial efforts are being made to make NW lasers electrically pumped, which is necessary for their practical implementation. In this review, we first categorise the NW lasers according to the lasing wavelength and wavelength tunability. Then, we summarize the methods used for achieving single-mode lasing in NWs. After that, we review the reports on lasing threshold reduction and the realization of electrically-pumped NW lasers. Finally, we offer our perspective on future improvements and trends.

Keywords: nanowire, laser, wavelength, tunability, single mode lasing, threshold, electrical pumping

1. Introduction

Lasers are one of the greatest inventions and have become an integral part of our daily life. Lasers provide a source for coherent light, which has important applications in industry, engineering, information technology, medicine, defence and science. [1 , 2] Among the different types of lasers, semiconductor lasers are highly popular and have widespread applications, because of their smaller size, lower power consumption, and cheaper price compared with any other kind of lasers. Making lasers even smaller in size and more efficient in power consumption can promote device downscaling and enable wide-spread and more advanced applications, such as optical communication and data processing, medical imaging, sensing and consumer electronics. [3]

The semiconductor NanoWire (NW) has novel mechanical, optical and electronic properties that are not present in the

thin-film counterparts. [4]-[13] It is highly-promising nanomaterial for making new generation lasers with the advantages of ultra-small size, high efficiency, easy integration and low cost, which has great technological and commercial significance. The semiconductor NW laser has different optical cavity configurations from the conventional thin-film lasers. [14, 15] In thin-film lasers, the cavity is formed through a combination of epitaxial growth of layers with different refractive indexes and post-growth processing. [16] For the NW laser, the NW can function both as the gain medium and the optical cavity required for lasing. The refractive index difference between the NW (in the range of 2.5–3.5) and its embedding medium (usually free space or a low-refractive index dielectric material) is much larger compared with that of the cavity in thin-film lasers, allowing

to form a good cavity without complex post-growth processing. [17] Also due to the large refractive index contrast between the semiconductor and the embedding medium, the NW laser has strong optical modal confinement in the radial direction, which can reduce the laser diameter to a few hundred nanometers. Thus, the NW can use very small volume of materials (as little as a few cubic micrometers) to achieve lasing and the power required for NW to lase is much lower than macroscopic lasers. There have been some reports showing that the lasing threshold current of electrically-driven NW lasers was just a few microamps. [See section 6]

The NW can offer more freedom for lasers in material choice and band structure engineering compared with thin-film structures. Due to the small cross section, NWs have very good strain tolerance, [18]–[23] which can allow high-quality integration of materials with large lattice and thermal expansion coefficient mismatch that are not allowed in the thin-film growth. [7] Due to the unique 1-dimensional structure, the NW can offer new ways to grow some important structures. For example, quantum dots (QDs) can be grown within the NW by stacking different materials axially. [24,25] This is different from the traditional Stranski–Krastanow QDs that need the strain to assist the growth. [26] The NW structure can also help lasers to solve some big challenges in realizing some important applications. For example, one of the main challenges limiting the whole Si photonic industry is the lack of good lasers on Si, due to the huge difficulties in growing good planar III-V materials on Si. [27]–[31] However, the NW structure with III-V materials can be easily grown on Si platform with high quality due to good strain tolerance and small contact interface between the NW and the Si substrate. NW lasers can thus provide high-quality light sources for Si photonics with low cost and ultra-high integration density. [32]–[37]

In recent years, intensive research has been conducted in making NW lasers and this area is developing rapidly. Since the first observation of stimulated emission from ZnO in 2001, [38] hundreds of papers have been published on the subject. Although majority of them have achieved lasing by optical pumping, electrically-pumped NW lasers are essential for making practical devices. Here, we summarize the important progress in making NW lasers with special attention given to the development of electrically-pumped NW lasers. The other fundamentals can be found in some previous good reviews, such as Reference [39–43]

2. Wavelength range coverage

Various semiconductor materials, including metal oxides, II-VI or III-V semiconductor alloys, have been used for making NW lasers, which can cover the lasing wavelength across the ultraviolet (UV), visible, near-infrared and mid-infrared spectral regions (370 to 2200 nm).

UV lasers are particularly useful for sensing, water treatment, and biological applications. Semiconductors materials with large band gap can be used to make this type of NW lasers, including ZnO (385 nm) [44], ZnS (337 nm) [45], and GaN (375 nm) [46]. These materials commonly have a large Exciton Binding Energy (EBE) that is larger than the thermal energy at 300 K (25 meV). This is beneficial for combining carriers to form electron-hole pairs at room temperature and hence offering high optical gain by high-efficiency light emission. For example, the ZnO NW laser has a large EBE of 60 meV, which makes the external/internal Quantum efficiency (QE) as high as 60%/85%. [47] This could be one of the main reasons that the first lasing observations were from ZnO NWs and the second lasing demonstration was using GaN NW with a large EBE of ~26 meV. [46] Due to their small wavelengths, the NWs can achieve lasing with very small cavities. It has been reported that ZnO NWs can still lase when the diameter is 20 nm. [48]

NW lasers emitting in the visible range have widespread potential applications, including lighting, sensing, and biomedicine. More importantly, this wavelength range covers the green light region that is known as “green gap”: it is challenging to achieve efficient green light emission in thin-film structures due to limited material choices and the difficulties to grow high-quality materials that emit in this wavelength range. [49] The NW structure has more freedom in material growth and can produce high-quality materials that are not possible in the thin-film growth. For example, the growth of single-crystalline $\text{In}_x\text{Ga}_{1-x}\text{N}$ NWs across the entire compositional range ($x=0\sim1$) has been demonstrated. [50],[51] The NW structure can also turn in-direct bandgap materials, such as GaP, into direct band gap by changing the crystal structure from zinc blende into wurtzite. [52] The NW structure can therefore provide high-quality materials to cover the green wavelength and offer a promising solution to this “green gap” issue. Materials used for developing the visible-wavelength NW laser include CdS (490 nm), [53] InGaP (530 nm) [54], ZnSe (~460 nm) [55], and CdS_{Se} (530 and 637 nm) [56].

The NW laser working in infrared wavelengths is expected to be technologically important because it has many important potential applications in future telecommunication systems, chip-scale optical interconnects and integrated nanophotonic systems for detection, sensing, and information technology. For this spectral region, many materials have been investigated, including GaAs (870 nm) [28], InGaAs (900 nm) [57], CdSe (706–746 nm) [58], InP (~890 nm) [59], GaSb (1550 nm) [60], InGaAs/GaAs (~877 nm) [61], GaAs/GaAsP (815 nm) [62], InAsP/InP (~1340 nm) [63], and Cr^{2+} -doped ZnSe (2194 nm) [64]. Compared with UV and visible NW lasers, it is more challenging to realize infrared lasing. Firstly, because of the longer wavelengths, the infrared NW laser requires a relatively larger size to achieve decent waveguiding

effect. [65] For example, GaSb NW lasers reported to have large diameters in the range of 700–1500 nm and long lengths of 10–70 μm . [60] Secondly, non-radiative recombinations, such as Auger processes, become more severe in the infrared materials due to reduced bandgaps. Thirdly, materials with a small bandgap tend to have a small EBE. For example, GaAs has an EBE of ~ 5 meV and can easily be decomposed by the large thermal energy (25 meV at 300K). Therefore, it will need more complex structural design to achieve efficient radiative recombination. It could be due to all these reasons, there is still no report on lasing with InN, InAs, and InSb materials. Cr^{2+} -doped ZnSe NW lasers have demonstrated the longest emission wavelength so far as we know. However, their emission is from Cr^{2+} , rather than from the band-to-band recombination. Among these reported materials, GaAs is the most widely studied, because it is the foundation for a wide range of optoelectronic devices and GaAs-based lasers can

operate in the near infrared region, which is an important spectral region for short-distance optical data communication.

3. Wavelength tunability

Discrete colour tunability can be achieved by choosing different gain materials listed above. Here, we focus on the continuous wavelength tunability that can tailor accurately the emission of NW lasers for specific applications.

Controlling the composition of compound alloys, commonly ternary and quaternary alloys, is the most direct way to tune the emission wavelength, which has been well demonstrated using group-II/VI materials. Zapfen *et al.* [66] and Liu *et al.* [67] reported that the full composition tunability makes their $\text{CdS}_x\text{Se}_{1-x}$ ($0 < x < 1$) and $\text{Zn}_y\text{Cd}_{1-y}\text{S}$ ($0 < y < 1$) nanoribbon lasers continuously cover the whole wavelength ranges of 350–510 and 510–710 nm (Figure 1a), respectively. Later on, Pan *et al.* [68] and Luan *et al.* [69] showed that this

Figure 1. (a) Lasing from $\text{Zn}_y\text{Cd}_{1-y}\text{S}$ (spectra a–c) and $\text{CdS}_x\text{Se}_{1-x}$ (spectra d–f) nanoribbons covering near infrared to UV (710 to 340 nm). Reprinted from [66], with the permission of AIP Publishing. (b) Lasing from InGaN/GaN MQW NW lasers of different In composition. Inset is the schematic diagram of the MQW nanowire. Reprinted by permission from Springer Nature: Nature Materials [72], [COPYRIGHT] (2008). (c) Lasing emission spectra of the four CdS NWs of different length. The inset is optical images of the four individual NWs undergoing lasing. Reprinted (adapted) with permission from [74]. Copyright (2013) American Chemical Society. (d) Spectral shift of the lasing peak from 733.7 to 726.9 nm by changing the geometry of the loop in a CdSe NW. Reprinted (adapted) with permission from [76]. Copyright (2011) American Chemical Society. (e) The lasing peaks of four single CdS NWs on Au substrates covered with SiO₂ of different thickness. Inset is the schematic of the structure. Reprinted (adapted) with permission from [77]. Copyright (2011) American Chemical Society. (f) Lasing spectra of four InGaAs/GaAs photonic crystal lasers shown in the inset. Reprinted (adapted) with permission from [78]. Copyright (2013) American Chemical Society.

complete composition coverage can be achieved on a single wafer with one growth. Liu *et al.* [56] even realized two-color lasing (red and green) within a single CdSSe NW. By controlling the relative intensity of the two lasing peaks, they demonstrated the active dynamical color tuning between the two lasing colors with a separation of 107 nm in wavelength. Now, the ZnCdSSe quaternary alloy NWs can be synthesized with each wire being able to cover a wide wavelength range of 350–710 nm that is between the bandgap emission wavelengths of ZnS and CdSe. [70],[71] It would be interesting and very useful if such a broadly tunable lasing could be achieved on a single wire, but more systematic research is needed. Besides II–VI materials, there are also studies with III–V materials. Chen *et al.* [57] changed the In composition of InGaAs NWs between ~12 to 20% and realized a 50 nm control in the output laser wavelength. Apart from changing the composition of the bulk NWs, changing the composition in hetero-structures can also achieve good wavelength tunability. Qian *et al.* [72] changed the In composition of InGaN/GaN quantum wells from 5% to 23% and tuned the emission from 365 to 494 nm (Figure 1b). Lu *et al.* [73] demonstrated even larger wavelength tunability (474–627 nm) by changing the composition of InGaN NWs.

For NWs with fixed material composition, the wavelength tunability can be achieved through controlling the reabsorption of NWs. NWs with a broad Urbach tail can re-absorb generated photons and subsequently re-emit photons at lower energy, causing the redshift of emission wavelength. [58] This self-absorption can be reduced by shortening the NW length. Li *et al.* [58] tuned the lasing wavelength of the CdSe NW from 706 nm to 746 nm by shortening it from 289 μm to 8 μm . Liu *et al.* [74] also changed the lasing wavelength of CdS NWs from 520 nm to 489 nm as the length of the NWs decreased from 25 to 4 μm (Figure 1c). Alternatively, the tunability can be achieved by cavity design. Pauzauskis *et al.* [75] modified the shape of the NW from linear to pseudoring conformation and significant shifts, up to 10 nm, were observed. Xiao *et al.* [76] also observed this phenomenon. They decreased the size of the CdSe NW loop and observed a shift of the lasing peak from 733.7 nm to 726.9 nm due to the reduction in optical path of the lasing cavity (Figure 1d).

In the case of NWs with fixed material composition, wavelength tunability can still be realized. Liu *et al.* [77] demonstrated the use of the surface-plasmon-polariton-enhanced Burstein–Moss (BM) effect to tune the lasing wavelength of a single semiconductor NW. By decreasing the thickness of dielectric layer between CdS NW and Au film from 100 nm to 5 nm, the BM effect becomes stronger, leading to a larger blue shift of the lasing wavelength from 504 nm to 483 nm at room temperature (Figure 1e).

So far, we discussed reports on single NW lasers. Lasing has also been achieved in multiple NWs. In particular, for NWs that are arranged to form a photonic crystal type cavity,

spectral tuning can be achieved by suitably designing the cavity resonance. Scofield *et al.* [78] verified this method and varied the emission of InGaAs photonic crystal lasers from 960 nm to 989 nm (Figure 1f).

4. Single mode lasing

Monochromaticity in spectral emission is one of the key properties of lasers that is required for many applications, such as digitized communication and signal processing, since multiple lasing frequencies lead to both temporal pulse broadening and false signalling because of group-velocity dispersion. However, most NW lasers have multiple frequencies, due to the longitudinal modes native to simple Fabry–Pérot cavities and the large lengths (typically > 5 μm) required to obtain sufficient optical gain. [79]

Reducing the NW dimension and hence the number of cavity modes within the gain bandwidth is a straightforward method to achieve single-mode lasing. [80] Li *et al.* [80] achieved transverse mode selection by utilizing NW dimensions that supported a low number of transverse modes within the gain bandwidth. By significant reduction and precise control of NW dimensions to form strong mode competition and narrow gain bandwidth, they achieved stable single-mode lasing from a single GaN NW. Yang *et al.* [81] gave a more direct and detailed demonstration about this method. They cut short the 435- μm -long CdSSe NW and observed the mode change from multi-modes to single mode. However, this significant reduction of NW dimensions not only reduces the volume of gain material, but also leads to the high optical loss. Therefore, it requires more efficient scheme to achieve high material gain to compensate the reduced gain length. Surface plasmons with efficient optical confinement scheme can be used to improve the gain. With the assistance of surface plasmons, Lu *et al.* [73] achieved single mode lasing by reducing the InGaN NW size to 100–250 nm in length and 30–56 nm in diameter (Figure 2a). Chou *et al.* [82] reported a novel way to control the effective cavity length. They designed a novel planar surface plasmon polariton cavity by covering a Ag grating with 3 nm thick Al_2O_3 (Figure 2b). When the NW was in contact with the grating, the effective cavity length was determined by the contact length of the NW with the top edge of the notch. They demonstrated single-longitudinal-mode lasing from ZnO NWs with a short effective cavity length (approximately 50 nm).

Single-mode lasing can still be achieved without reducing the cavity size. However, a special cavity design is needed. The lasing mode can be controlled by changing the morphology of the NW. Röder *et al.* [83] showed that tapered NWs can filter out higher order transverse modes and achieve lasing from the fundamental transverse mode. Vernier effect can be used for cavity design, because it can select the modes which are sharing the same frequencies when two sets of Fabry–Pérot modes interact coherently with each other. [79]

Xiao *et al.* [76] formed self-coupled two loop cavities by bending single CdSe NW into “8” shape and achieved single-mode lasing. The cavity coupling can be achieved between NWs (Figure 2c). Xiao *et al.* [84] achieved single mode lasing by coupling two CdSe NWs into an X-shaped cavity (Figure 2d). Gao *et al.* [79] coupled two GaN NW Fabry-Pérot cavities axially via an air gap and demonstrated the single-wavelength room-temperature lasing (Figure 2e). Xu *et al.* [85] also demonstrated efficient single mode selection by coupling a pair of GaN NW cavities that were placed side-by-side and in contact with each other (Figure 2f). Except the coupling between NW cavities, single mode lasing can also be achieved by coupling NWs with their surroundings. Wei *et al.* [86] coupled core/shell GaAs/AlGaAs NWs to a microfiber with a diameter about 10 μm and achieved high-quality single-mode lasing. Wright *et al.* [87] coupled GaN NWs to a dielectric grating and achieved single mode emission by controlling the grating periodicity and the angular alignment between the NW and the grating (Figure 2g). Xu *et al.* [88,89] demonstrated a method for mode-selection by coupling a GaN NW laser to an underlying gold substrate. A mode-dependent loss is generated by the substrate absorption to suppress multiple transverse-mode operation. As a result, the multimode lasing of GaN NW is converted to single-mode behaviour with a concomitant increase in lasing threshold of only 13%. Takiguchi *et al.* [63] coupled InAsP/InP NWs to

silicon photonic crystal and achieved single-mode lasing at telecom-band wavelength (~ 1340 nm) with a sub-wavelength diameter of ~ 100 nm. Using this NW laser, they demonstrated a modulation speed of 10 Gb/s.

Moreover, NW lasers made of multi-NWs can still achieve single mode lasing. Scofield *et al.* [78] used InGaAs NWs to make photonic crystal lasers (Figure 1f). By coupling the NW emission to photonic bandgap of the photonic crystal cavity, they achieved single mode lasing at 960, 974, and 989 nm. Kim *et al.* [90,91] fabricated InGaAs/InGaP core/shell NW array with photonic crystal nanobeam cavities and achieved high-quality single mode lasing in the wavelength range of 1100–1440 nm (**Figure 2h**).

5. Threshold reduction

Reducing the threshold current of lasers is critical for lowering operation costs. For optically-pumped NW lasers, lowering threshold pumping power also means better suitability to fabricate high-performance electrically-pumped lasers. Here, we summarize the effective methods developed to reduce the threshold of NW lasers. We also review the enhancement of radiative recombination and the reduction of NW laser dimensions. It needs to be noted that due to the differences in material properties and the characterization methods, direct threshold comparison between different

Figure 2. (a) All-color single-mode lasing from InGaN NW. Reprinted (adapted) with permission from [73]. Copyright (2014) American Chemical Society. (b) Single-mode lasing from ZnO NW laser coupled to an Ag grating covered with 3-nm-thick Al_2O_3 . Reprinted (adapted) with permission from [82]. Copyright (2018) American Chemical Society. (c) SEM images and lasing spectra of single CdSe NW structures (A,B) without, (C,D) with one, and (E,F) with double loop mirrors. (d) Lasing spectra of single and X-coupled CdSe NW. Reprinted (adapted) with permission from [76]. Copyright (2011) American Chemical Society. (e) Lasing spectra of single GaN NWs and two GaN NWs coupled via an air gap. [79] Copyright (2013) National Academy of Sciences. (f) Lasing spectra of a single and parallelly-coupled GaN NWs. Reprinted from [85] with the permission of AIP Publishing. (g) Lasing spectrum of a GaN NW coupled to a grating with different angle alignments (90° , 45° , and 0°). Reprinted from [87] with the permission of AIP Publishing. (h) Single-mode lasing of a nanowire array. Reprinted (adapted) with permission from [91] Copyright (2017) American Chemical Society.

reports would be challenging, which is not our main focus here.

Changing NW properties can effectively reduce the threshold. Burgess *et al.* [92] reported that p-type doping can enhance the radiative recombination rate of GaAs NWs by a factor of several hundred times while also increase differential gain and reduce the transparency carrier density. Even without surface passivation, their GaAs NWs still show a room temperature lasing with a low threshold of $\sim 200 \mu\text{J}/\text{cm}^2$.

The NW has a large surface-to-volume ratio and hence high-density of surface states. The NWs with low surface recombination velocity can still realize a good performance. For example, InP NWs have a surface recombination velocity as low as 170 cm/s. Without surface passivation, they have an excellent quantum efficiency of $\sim 50\%$ that is on par with InP epilayer. [59] Room-temperature lasing is therefore observed from the bare InP NWs with a low threshold of $130 \mu\text{J}/\text{cm}^2$. However, NWs made of some other materials with high surface recombination velocities can lose a large number of carriers due to non-radiative surface recombination. For example, the surface recombination velocity of GaAs NWs is as high as 5.4×10^5 cm/s, which results in a very low carrier lifetime of 1–5 ps. [93] Surface passivation is thus critical for improving the performance of NW lasers made of this type of materials. [94] Saxena *et al.* [28] used a layer of AlGaAs to passivate the surface of GaAs NWs, which greatly improved the quantum efficiency from 1% [95] to 40% and the carrier life time to 440 ± 90 ps, leading to the demonstration of room-temperature lasing with a low threshold of $207 \mu\text{J}/\text{cm}^2$. Mayer *et al.* [96] also reported the effectiveness of AlGaAs surface passivation in improving the performance of self-catalyzed GaAs NW lasers and observed room temperature lasing with a low threshold of $\sim 16720 \text{ W}/\text{cm}^2$ (Figure 3a). Choi *et al.* [97] used AlGaN to passivate the GaN NWs and achieved lasing at $2\sim 3 \mu\text{J}/\text{cm}^2$. Some other passivation structures are also being used, including GaAs/GaNAs core/shell NW, [98] and GaAs/GaAsP core/shell NWs. [62]

The lasing threshold of NW lasers can be effectively reduced by introducing quantum confinement structures as the active regions. The quantum confinement structures can modify the density of states, which results in more condensed carriers and larger material gain compared to bulk semiconductors. This is in particular important for NWs made of materials with a small EBE. Quantum Wells (QWs) have been widely used in thin-film devices to enhance the carrier recombination and improve the light emission. [99]–[101] The core-shell QWs are even more attractive due to an additional advantage (Figure 3b). It wraps the whole NW conformably, which can greatly enlarge the area of active medium (well area) by hundreds of times compared with NW cross section and provide very large QW area-to-volume ratio. The population-inverted carriers in the QW can thus react sufficiently with the stimulating photons, leading to greatly

enhanced stimulated emission. The first successful demonstrations of QW NW lasers was reported by Qian *et al.* [72] They introduced InGaN/GaN multiple QWs into their NW lasers and presented a threshold $\sim 250 \text{ kW}/\text{cm}^2$. They also showed a 4–10-fold threshold reduction in 26 versus 13 MQW structures. Later on, QWs have been widely used in NW lasers, such as GaAs/AlGaAs QWs, [102]–[104] InGaAs/GaAs, [105] and InGaAs/InP QWs. [106] With the QW structure, the threshold of GaAs/AlGaAs MQW NW lasers has been reduced to $\sim 43 \mu\text{J}/\text{cm}^2$ at room temperature. [104] Quantum Dots (QD) can also achieve good carrier confinement. It could be due to the challenges in growing high-quality QDs with good uniformity, researchers used the stacked QW disks to improve the optical performances of the NWs at early stages. [107] Tatebayashi *et al.* [108] developed the technique to grow 50 high-quality $\text{In}_{0.22}\text{Ga}_{0.78}\text{As}$ QDs inside each GaAs NW and demonstrated infrared lasing at room temperature with a threshold of $\sim 179 \mu\text{J}/\text{cm}^2$ (Figure 3c).

The threshold of NW lasers can be achieved by optimizing the NW cavity configuration. NWs with Fabry–Pérot (FP) cavity use the end-facets of NWs as reflecting mirrors. However, the low reflectivity at the end-facets can induce considerable losses to the cavities, which prevents shorter wires from lasing. To solve this issue, ring cavity was developed, which allows for recirculation of light around the loop and increases optical feedback in the system. Hu *et al.* [109] bent CdS NWs to form rings (Figure 3d). The lasing threshold of the spliced-loop ring is much lower than that of the open-loop one. Xiao *et al.* [76] demonstrated the lasing threshold reduction by forming loop mirrors. The lasing threshold of a 200 nm CdSe NW decreased by almost half when one of the ends is looped compared to the case when both ends are open and decreased to about one-third when both ends are looped.

Coupling the NWs with external cavities can also reduce the lasing threshold. Kong *et al.* [110] put ZnO NWs on $\text{SiO}_2/\text{SiN}_x$ Distributed Bragg Reflector (DBR) and 20% lower threshold excitation power was achieved due to the lower cavity loss with the DBR structure. Heo *et al.* [111] cladded a GaN NW array by $\text{Si}_3\text{N}_4/\text{SiO}_2$ DBRs and demonstrated the lasing with a low threshold of $625 \text{ nJ}/\text{cm}^2$ (Figure 3e). Das *et al.* [112] coupled a single GaN NW to a large area dielectric microcavity sandwiched by a top and a bottom DBRs and achieved a record low threshold of $92.5 \text{ nJ}/\text{cm}^2$ at room temperature. The threshold carrier density is 3 orders of magnitude lower than that of photon lasing observed in the same device, and 2 orders of magnitude lower than any existing room temperature polariton devices at that period. Takiguchi *et al.* [63] coupled NW with silicon photonic crystal and achieved continuous-wave lasing with sub-wavelength diameter ($\sim 111 \text{ nm}$) but at cryogenic temperatures (Figure 3f). Gao *et al.* [79] coupled two Fabry–Pérot cavities axially

through an air gap and demonstrated the lowering of threshold due to the reduced number of lasing modes.

The modal confinement of NWs becomes too poor when the radius becomes too small. [65,113] Plasmonic resonators or cavities can support highly confined plasmon modes, which can greatly enhance the optical confinement, and increase radiative emission rate via Purcell effect. [114,115] This can help NWs to break the diffraction limit (half of the operating wavelength in the medium) and allow lasing with diameter in deep-subwavelength scales. [116] Till now, NW lasers with subwavelength diameter have been extensively reported, which is critical for the development of chip-integrated photonic and optoelectronic devices. Oulton *et al.* [117] showed that hybrid plasmonic CdS NWs as thin as 50 nm can still lase (Figure 3g, h), which is much smaller than the cut-off diameter of ~ 150 nm. Ho *et al.* [118] placed ~ 5 - μm -long GaAs/AlGaAs core-shell NWs with a sub-diffraction limit diameters of ~ 150 nm directly on a silver thin film and demonstrated plasmonic lasing with a low threshold of 1.0 kW/cm^2 at 8 K. After that, they [61] introduced InGaAs/GaAs QDs into GaAs plasmonic lasers and achieved lasing with the diameter below the cutoff limit of photonic modes (~ 180 nm) and the length in the order of the lasing wavelength ($\sim 2.3 \mu\text{m}$). The lasing threshold was as low as $\sim 120 \mu\text{J/cm}^2$ at 7 K, and the lasing was observed up to 125 K. Lu *et al.* [115] demonstrated lasing with InGaN/GaN core-shell NWs despite a length shorter than 500 nm, which benefited from surface plasmon

amplification by stimulated emission of radiation. Later on, they demonstrated InGaN/GaN core-shell NW lasing with even smaller dimensions (diameter ~ 50 nm and length ~ 200 nm). [73]

6. Achieving electrically-pumped lasing

Electrical injection is necessity for NW lasers to achieve compact applications, especially for applications in any nanophotonic integrated systems or on-chip systems. Theoretically, researchers have done careful design on the NW lasers and shown the possibility of achieving electrically-pumped NW lasers. For example, Fan *et al.* [119] presented a comprehensive theoretical study of the optical and thermal properties of an electrically-pumped semiconductor nanolaser with a metal coated GaN/(InGaN/GaN MQWs)/GaN core-shell NW structure. The threshold gain of the laser can be more than four times lower than the material gain calculated of thin-film structures in Reference [120] due to the large mode confinement in the active region. Such a low threshold gain indicates the possibility of achieving room temperature continuous wave operation of the NW lasers under electrical injection. Experimentally, the development of electrically-pumped NW lasers is motivated by the rapid evolution of optically-pumped NW lasers, as discussed above.

The first report on electrically-pumped single NW laser was by Duan *et al.* [121] using CdS NWs (Figure 4a, b). The NWs have an optically-pumped threshold $\sim 40 \text{ kW/cm}^2$ at

Figure 3. Illustration of (a) AlGaAs passivated GaAs NW lasers. Reprinted by permission from Springer Nature: Nature Materials [96], [COPYRIGHT] (2013). (b) GaAs/AlGaAs core-shell QW NW lasers. Reprinted from [102] with the permission of AIP Publishing. (c) InGaAs/GaAs QDs NW lasers. Reprinted by permission from Springer Nature: Nature Photonics [108], [COPYRIGHT] (2015). (d) CdS NW ring lasers in the forms of open-loop, closed-loop, and spliced-loop. Reprinted from [109] with the permission of AIP Publishing. (e) A GaN NW array laser sandwiched by $\text{Si}_3\text{N}_4/\text{SiO}_2$ DBRs. Reprinted (adapted) with permission from [111]. Copyright (2013) American Chemical Society. (f) A InAsP/InP NW laser coupled with a silicon photonic crystal. [63] (g) and (h) A CdS NW laser coupled with surface plasmon. Reprinted by permission from Springer Nature: Nature [117], [COPYRIGHT] (2009).

room temperature and $\sim 2 \text{ kW/cm}^2$ at low temperature. The electrically-pumped devices were fabricated by assembling CdS NWs on heavily doped p-Si on insulator substrates, followed by covering $\sim 60\text{--}80 \text{ nm}$ aluminium oxide, and then Ti/Au top contact. One end of the NW was left uncovered for emission output from the device. To pump the laser electrically, electrons and holes were injected into the CdS NW along the whole l

ength from the top metal layer and the bottom p-Si layer, respectively. This device showed lasing around 509 nm with a threshold of $\sim 200 \mu\text{A}$.

Since the first demonstration, there have been some reports on electrically-pumped random NW array lasers, in two different materials, ZnO and III-N. Firstly, Zhang *et al.* [122] fabricated ZnO NW lasers with p-ZnO:P NW array/n-Si heterojunction. The contacts were in top-bottom configuration made of transparent conductive indium Tin Oxide (ITO) films. The NW head facet and the epitaxial interface between the Si and ZnO served as good laser cavity mirrors. The electrically-driven ultraviolet lasing behavior was observed at $\sim 390 \text{ nm}$ with a threshold current of 24 mA . Chu *et al.* [123] also demonstrated electrically-pumped random ZnO NW array lasers (Figure 4c, d). Their p-n junction was formed by Sb-doped p-type ZnO NWs and n-type ZnO thin films. The n-type contact was made of Au/Ti on the n-type ZnO films besides the NW arrays; The p-contact was ITO on top of NW arrays. The Fabry-Perot chamber was formed between sapphire/ZnO interface and top PMMA/ITO interface. The diodes exhibited highly stable lasing at room temperature with a current threshold of $\sim 50 \text{ mA}$. Liu *et al.* [124] developed a Au-MgO-ZnO structure. A MgO layer was deposited onto

ZnO NWs but only partly covered the sample. A gold p-contact was made onto the MgO; the In n-contact was made on top of ZnO NWs next to the MgO covered area. The emission generated at the ZnO-MgO interface. When photons were emitted from the device, they were strongly scattered by the relatively large surface of the ZnO NWs because of the large refraction index of ZnO (2.45) compared to MgO (1.7). Due to this strong scattering, and coupling of the back-scattered photons with the NWs a random lasing type cavity was formed. When the optical gain in the loops was larger than the loss, random lasing occurred in the closed loops. With this structure, they achieved lasing with a threshold of $\sim 7.6 \text{ mA}$.

The other material that has been used for electrically-pumped NW laser arrays is III-N. Frost *et al.* [125] demonstrated the first edge-emitting random NW array laser on n-Si using the axial n-, i-, p-GaN NWs with axial InGaN disk inside as the active region (Figure 4e, f). It is a ridge waveguide structure with $\text{SiO}_2/\text{TiO}_2$ distributed Bragg reflectors (DBRs) at two ends to enhance facet reflectivity. Ni/Au/ITO and Al are deposited as the contacts to the p-GaN NW and n-Si substrate, respectively. The lasing output was measured from the low reflectivity DBR facet. This laser displayed excellent dc and dynamic characteristics with values of threshold current density, differential gain, T_0 and small signal modulation bandwidth equal to 1.76 kA/cm^2 , $3 \times 10^{-17} \text{ cm}^2$, 232 K , and 5.8 GHz respectively under continuous wave operation. The emission wavelength was 533 nm and could be tuned by varying the alloy composition in the quantum disks. Preliminary reliability measurements indicated a lifetime of 7000 h . Li *et al.* [126] grew disordered axial n-, i-, p-AlGaN NWs arrays on n-Si to form random resonance cavity using

Figure 4. Schematic diagram of electrically-pumped NW laser made of (a)(b) a single CdS. Reprinted by permission from Springer Nature: Nature [121], [COPYRIGHT] (2003). (c)(d) ZnO film and NWs. Reprinted by permission from Springer Nature: Nature nanotechnology [123], [COPYRIGHT] (2011). (e)(f) InGaN/GaN disk-in-NW array. Reprinted (adapted) with permission from [125]. Copyright (2014) American Chemical Society. (g) Simulation result showing the profile of the electric field of the AlGaN NW random cavity shown in (h). Inset in (g) is schematic diagram illustrating the formation of a closed-loop path inside AlGaN NW arrays. Reprinted by permission from Springer Nature: Nature nanotechnology [126], [COPYRIGHT] (2015).

Anderson localization effect. (Figure 4g, h) [127–130] A Ni/Au p-type and Ti/Au n-type contacts were deposited on the top of NWs and the backside of the substrate respectively. They demonstrated electrically-pumped lasers across the entire ultraviolet AII (UV-AII) band (~320–340 nm) at low temperatures with a low lasing threshold of ~12 A/cm². It needs to be mentioned that both the III-N NW lasers were monolithically built on Si substrate, which can therefore address wide-ranging applications associated with Si technologies, including Si photonics. More detailed review on electrically-pumped nitride NW lasers can be found in Reference [131].

7. Perspective on future improvements and trends.

Achieving electrical injection is critical for NW lasers to have practical applications. However, the majority of the NW lasers are still realized with optical pumping and there are only one/few demonstration of electrically-driven single/array NW lasers. Design, optimization, and fabrication of the most efficient electrical injection laser structures are critical to the next stage of development of NW lasers. There are some obstacles must be overcome to fully realize the potential of these lasers.

7a. Constructing high-quality p-i-n junctions

The doping mechanism of NWs are significantly different from the thin-film structures, because NWs have quite unique morphology, dimension, growth condition and growth modes. [132] This can significantly influence the dopant incorporation. In addition, the surface states can trap a large number of carriers, lowering the effective doping concentration.¹³³ More information is needed on how to control the doping to construct high-quality p-i-n junctions for NW lasers, especially the doping concentration and the thickness of each doped layers. Fiordaliso et al. [134] demonstrated a useful technology to characterize the quality of p-i-n junction of NWs. By using off-axis electron holography, the electrostatic potentials across the p-n junction can be mapped out, providing direct information on the built-in potential. This can greatly facilitate the development of high-quality junction.

7b. Fabricating High-quality contacts

It is relatively easy when we only need to contact the unstructured NWs. For example, Zhang et al. [135] optimized the NW doping and the annealing of AuZn contact, and achieved good Ohmic contact on GaAs NWs with a diameter as small as 50–60 nm. However, when it comes to devices, contact fabrication is more challenging. There are many factors that can affect the contact quality of NW lasers. First, the contact quality can largely be affected by the doping effect

of the contact layer and the pinning of the surface Fermi level by high-density surface states. The doping of contact layer needs to be studied and the effective surface passivation techniques need to be developed. Second, each layer on NWs is very thin and easy to be damaged. The traditional device fabrication technique needs significant modification before they can be used in the NW device fabrication, such as etching and annealing. Third, there will be strong absorption in the contact metal. Therefore, the NW contacts have to be appropriately designed to reduce the absorption loss by minimising the metal coverage on the NW and realize high-enough carrier injection efficiency. For axial devices, the contact fabrication is much easier and the NW array lasers listed in Section 6 are all in of this configuration. However, the optimization study is lacking and more effort is needed. For radial structure, there is still no report on making good electrically-pumped devices, let alone lasers. Only recently, Zhang et al. [135] fabricated the single GaAs NW solar cell with a world-record high fill factor of 80.5% and stable photo response, which demonstrated good contact fabrication technology in making radial devices. However, some effort is still needed in transferring the technology from photovoltaics to lasers. Especially, it is challenge to make the good contact on radial junction without affecting the quality of laser cavity.

7c. Heat sinking and Continuous wave operation at room temperature

Heating can significantly affect the performance of semiconductor devices even in thin-film structures. This is a more serious issue for NW lasers. The small volume makes NWs can be heat up easily. In most of the case, the majority part of NW lasers is in contact with surrounding medium of low thermal conductivity, such as low-index substrates and air. Their contact area with the substrate is small especially when they are standing vertically on the substrate, which makes the thermal dissipation very slow. For example, the thermal conductivity of single GaN NWs with different diameters was found in the unexpectedly-small range of 13–19 W/m-K at 300 K. [136–138] Because of this, most optically-pumped NW lasers were characterized by pulsed laser systems with femtosecond or nanosecond pulse durations that can generate high-enough instant carrier density and greatly reduce the thermal effect. Continuous wave lasing commonly need to put NWs in very low temperature environment. However, CW lasing is required for many applications, such as data transmission. To reduce heating in NW lasers and obtaining CW lasing at room temperature, effective heat-sinking is required.

7d. Vertical integration on Si substrates

One the major advantage of NWs is the ability to be monolithically integrated onto Si platform, which can bring

high-quality light emitters for Si photonics. This integration can bring two further advantages: Firstly, high-density integration due to the smaller footprint. Secondly, accurate NW position on the substrate. While NW lasers that are vertically standing on Si substrates have been demonstrated both optically and electrically, [90,91,139] further research is required for further increasing the performances and realize their integration with application system that will be mentioned in 7e.

7e. Integration into applicable system

Integrating NW lasers with other optoelectronic devices, such as detectors, waveguides, and modulators, is critical for realizing the practical applications of NW lasers, which is however still lack of study so far and needs to be seriously considered and researched. Especially, a significant amount of light from vertical NW lasers is coupled to the substrate, due to its higher refractive index than air. However, there is still lack of information on how to couple light from the vertically orientated NW lasers to waveguides that are integrated horizontally on the substrate. Besides, as the laser cavity is reduced in dimensions, the light emitted from the cavity becomes more divergent. Collimating the laser output from a NW needs to be carefully addressed and assisting components, e.g. nanoscale lenses and nanoscale gratings, needs to be developed with significant effort.

7f. Massive production

To reduce the fabrication cost, massive production is necessary. However, it is challenging to minimize the variations between each NWs. The variations can come from growth. There are billions of NWs grown on a wafer and there is usually a large variation in the threshold of NW lasers even if they are from the same growth. [104] Therefore, the growth of NWs needs to be optimised to minimise the variation in the

NW dimensions, morphology, material quality and composition across the sample. The growth on patterned substrates with highly-uniform pitch and layout can reduce this variation. The variation can also be generated when breaking NWs for transfer, as the cavity length and the quality of the broken NW end facets may vary. Therefore, more advanced NW transfer technique needs to be developed to achieve good NW selection and end facet refinement. Parkinson *et al* [104] developed a system to do large number (more than 10k) statistical analysis of NWs at the same time and can correlate geometrical and material parameters with lasing threshold. This system can be very helpful in the NW selection.

In conclusion, there are significant achievements in developing NW lasers with various material systems that can cover a wide lasing wave range, crossing the ultraviolet (UV), visible, near-infrared and mid-infrared spectral regions (370 to 2200 nm). This can allow NW lasers to have a wide range of applications. There are also great advances in achieving single mode lasing, which predicts good performance in the applications. The threshold of these NW lasers has been reduced greatly, which promotes the development of electrically-pumped NW lasers. Although there are many issues still to be addressed, with the rapid development of this area and the extensive literature reports, electrically-pumped NW lasers will be next generation coherent light sources with ultra-small size, high efficiency, easy integration and low cost, that can have extensive and important applications in lighting, biomedical, sensing, energy-harvesting applications, microanalysis, information storage, and optical computing.

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