Dynamical Tuning of Nanowire Lasing Spectra

Maximilian Zapf, Robert Röder, Karl Winkler, Lisa Kaden, Johannes Greil, Marcel Wille, Marius Grundmann, Rüdiger Schmidt-Grund, Alois Lugstein and Carsten Ronning

1Institute for Solid State Physics, University of Jena, Max-Wien-Platz 1, 07743 Jena, Germany
2Institute for Solid State Electronics, Vienna University of Technology, Floragasse 7, 1040 Vienna, Austria
3Felix Bloch Institute for Solid State Physics, University of Leipzig, Linnéstraße 5, 04103 Leipzig, Germany

Supporting Information

ABSTRACT: Realizing visionary concepts of integrated photonic circuits, nanospectroscopy, and nanosensing will tremendously benefit from dynamically tunable coherent light sources with lateral dimensions on the subwavelength scale. Therefore, we demonstrate an individual nanowire laser based device which can be gradually tuned by reversible length changes of the nanowire such that uniaxial tensile stress is applied to the respective semiconductor gain material. By straining the device, the spontaneous excitonic emission of the nanowire shifts to lower energies caused by the bandgap reduction of the semiconductor. Moreover, the optical gain spectrum of the nanolaser can be precisely strain-tuned in the high excitation regime. The tuning of the emission does not affect the laser threshold of the device, which is very beneficial for practical applications. The applied length change furthermore adjusts the laser resonances inducing a redshift of the longitudinal modes. Thus, this concept of gradually and dynamically tunable nanolasers enables controlling and modulating the coherent emission on the nanoscale without changing macroscopic ambient conditions. This concept holds therefore huge impact on nanophotonic switches and photonic circuit technology.

KEYWORDS: Nanowire, lasing, strain, emission tuning, bandgap modification

Nanoscale photonic devices with increasing functionality, such as photonic chips or lab-on-a-chip devices are a promising driving force for the future technological progress. In contrast to the common way to achieve technological progress, as by pure miniaturization of electronic devices, a high degree of variability and an increased functionality of such nanoscale devices might prove advantageous for future applications in biology, chemistry, or medicine. Particularly remarkable fields of research in integrated nanoscale devices are nanospectroscopy. High spatial resolution and on-chip compatibility should hereby be combined with the wavelength-resolution information gained by optical spectroscopy. The variety of photonic nanoscale building blocks required for these devices include light detectors, waveguides, active optical switches, and light-emitting devices. In particular, coherent nanoscale light sources which allow for wavelength tunability are urgently needed for these applications.

Remarkable progress has been made using semiconductor nanowire (NWs) lasers as nanoscale coherent light sources suited for such applications. Coherent emission has been realized in NWs for a vast number of materials. Furthermore, detailed characterizations regarding the temporal and modal emission dynamics enabled a profound understanding of nanolasers. Additionally, emission tuning was achieved by varying the material composition, NW length or by using core–shell structures. Yet, all current approaches for tuning the laser emission lack a dynamical tunability, that is, the ability to reversibly tune the emission in a ready-made single NW device. However, in the spontaneous emission regime, besides static emission tuning such dynamic tunability of the excitonic NW emission has been demonstrated by applying strain. What is of further particular interest using NWs is the elastic limit surpassing the bulk value. The elastic limit for semiconductor NWs has been reported to be in the range of 2%–15%. The huge elastic limit leads to a significant enlargement of the linear strain tuning range; NWs are therefore particularly suited for straining applications. In this work, a controlled bandgap modification and the subsequent shift of the emission wavelength is achieved by straining individual CdS NW devices by applying uniaxial stress. This enables a controlled dynamical modification of the optical emission and allows transferring the principle of strain-tuning from the spontaneous to the stimulated emission regime. The CdS material is a highly advantageous model system for our proof of principle experiments, as it emits in the important green spectral range while providing extraordinarily high gain values. We prove dynamical tuning of the NW laser spectra by exploiting the inherent resonator morphology of the NW in combination with the strain induced bandgap modification of the semiconductor material.

Received: June 19, 2017
Revised: September 19, 2017
Published: September 29, 2017

DOI: 10.1021/acs.nanolett.7b02589
Nano Lett. 2017, 17, 6637–6643
Results and Discussion. Figure 1a schematically depicts the tunable NW laser device with a CdS NW bridging the gap between two isolated Si pads covered by 300 nm thermal oxide. Additionally, the NW is fixed to the substrate with sputtered SiO\textsubscript{2} pads on both sides of the gap. By moving the Si/SiO\textsubscript{2} substrate areas apart, tensile stress is applied to the NW between the fixation pads (lower drawing). The enlarged excitation laser spot homogeneously illuminating the NW is visualized in purple. (b) Near-band edge emission (NBE) central wavelength depicted as a line scan along the NW axis around the gap region. The relative NBE peak shift in the tensioned regions of the NW with respect to the tension-free NW yields the strain-induced shift of the spontaneous emission around the gap region. In order to take into account uncertainties in overlapping both line scans, error bars are added to the relative shift values. The NW ends are outside of the range of the line scan with the left end located at \(~4\,\mu m\) and the right and at \(~28\,\mu m\). Furthermore, the left fixation pad ranges from \(~6\,\mu m\) to \(~10\,\mu m\), and thus might explain the negative relative shift around \(~10\,\mu m\). The right pad is outside of the range of the line scan around \(~21\,\mu m\).

Microphotoluminescence (\(\mu\text{PL}\)) maps were acquired in the spontaneous emission regime in order to examine the tension-dependent optical properties of the device. Therefore, the sample was mounted onto a piezo-driven stage and scanned with a focused laser spot (diameter \(~1\,\mu m\)), such that a \(\mu\text{PL}\) spectrum was acquired for each excitation position. The maximum peak position of the near band edge (NBE) losses out of the NW and thus ensures efficient wave guiding within it. Furthermore, the large contact area with the supporting substrate allows effective dissipation of the heat load deposited in the NW by the excitation laser. All following graphs are color-coded in the same way: Measurements for the unstrained NW are plotted in blue, while measurements for the maximally strained NW are plotted in red; data recorded at moderate strain values in between are drawn in green. The inset shows the broad spontaneous emission subtracted as baseline and the clearly shifted individual longitudinal modes, as indicated by the colored lines. (b) The respective \(\mu\text{PL}\) spectra around the laser threshold value. In addition to the mode shift, a distinct spectral broadening for increasing tensile stress becomes evident and is indicated by the mode envelopes. (c) Double logarithmic power dependence of the output intensity as a function of the gain/loss ratio. The solid lines result from a multimode lasing fit,\textsuperscript{34} which yielded threshold values around 55 kW/cm\textsuperscript{2} and \(x_0\)-parameters of \(~0.08\). The inset shows a SEM picture of the NW straining sample (scale bar 10 \(\mu m\)).

Figure 2. (a) Microphotoluminescence spectrum of the first modes, which evolve superimposed to the spontaneous emission at sufficiently high pump powers of \(~30\,\text{kW/cm}^2\) for three different stress values (increasing values from blue to red). The inset shows the broad spontaneous emission subtracted as baseline and the clearly shifted individual longitudinal modes, as indicated by the colored lines. (b) The respective \(\mu\text{PL}\) spectra around the laser threshold value. In addition to the mode shift, a distinct spectral broadening for increasing tensile stress becomes evident and is indicated by the mode envelopes. (c) Double logarithmic power dependence of the output intensity as a function of the gain/loss ratio. The solid lines result from a multimode lasing fit,\textsuperscript{34} which yielded threshold values around 55 kW/cm\textsuperscript{2} and \(x_0\)-parameters of \(~0.08\). The inset shows a SEM picture of the NW straining sample (scale bar 10 \(\mu m\)).

Nano Letters

DOI: 10.1021/acs.nanolett.7b02589
Nano Lett. 2017, 17, 6637−6643
Furthermore, for increasing excitation powers the lasing spectra exhibit a blueshift and a broadening of their mode envelope (colored Gaussian curves). These effects occur for all strain situations (blue, green, and red). The dashed, colored lines indicate the shift of the mode envelope maximum with increasing power for the respective strain situation. Note that the blue line for the unstrained laser spectra is drawn for comparison again in the right graph. Comparing the individual mode positions at a fixed excitation power reveals a redshift for each respective mode caused by the change of the resonator length. Additionally, a strain-induced redshift and spectral broadening of the mode envelope (colored Gaussian curves) becomes evident at all excitation powers. (b) Spectral position of one particular mode (upper diagram, traced mode is marked by the gray arrow in (a)) and envelope maximum position (lower diagram) as a function of excitation power. The spectral blueshift due to a refractive index reduction due to the applied tensile stress.23 Hence, the stress in our NW as shown in Figure 1b, due to a bandgap reduction by uniaxial tensile stress along the NW.24 Hence, the stress in our NW sample can be adjusted and is distributed around the gap region between the fixation pads, which is additionally confirmed by Raman measurements (see Figures S2 and S3 in the Supporting Information). Using the bulk deformation potentials, we estimated a good agreement between the theoretical bandgap shift and the experimentally obtained values (compare Supporting Information).

In order to induce lasing in the strain-tunable NW device, high excitation densities were applied using a pulsed (≈7 ns) 355 nm excitation source. Using an enlarged laser spot enabled homogeneous pumping of the entire NW and collecting emission from the entire NW volume. Sharp, equidistant Fabry-Pérot (FP) resonator modes become perceptible on the low-energy side of the near band edge emission for these excitation conditions and sufficiently high pump powers (see Figure 2a), indicating amplified spontaneous emission (ASE).31 The occurrence of these longitudinal resonator modes is almost independent of the applied stress. Upon higher pump powers these modes started to dominate the spectra while the spontaneous NBE becomes negligible; this is attributed to lasing.7 The coherent emission is dominated by the transverse $TE_{01}$ mode.14,32,33 However, the ASE and lasing spectra reveal two different strain-dependent effects: (i) A redshift of the individual resonator modes becomes apparent with increasing tensile stress, which is particularly apparent for the first modes of the ASE (Figure 2a) by comparing the peak positions of the unstrained (blue line) to the strained (green and red lines) NW laser. The inset depicts the emission of the longitudinal resonator modes after subtracting the broad, spontaneous emission as baseline. As indicated by the colored lines, the individual resonator modes show a clear shift of ≈0.8 nm toward longer wavelengths for the strained NW. (ii) Additional effects become apparent by increasing the pump power further (Figure 2b). The Gaussian lasing mode envelopes, indicating the underlying gain profile marked in Figure 2b, show an unambiguous redshift with increasing stress at pump powers around the threshold value. Additionally, these mode envelopes clearly visualize a broadening of the gain spectrum as a function of increasing stress. (The notation of using (i) and (ii) to distinguish both strain-induced effects will be maintained in this article.)

Despite this spectral changes, however, the NW laser characteristics by means of the laser output intensity is not changed discernibly. This pump power dependency of the NW laser output intensity is plotted in Figure 2c on a double logarithmic scale for the different strain values. A multimode laser oscillation14 was applied to these data (solid lines). Astonishingly, the nanolaser device reveals almost strain-independent threshold values of around 55 kW/cm² and $x_\text{crit}$-parameters of ≈0.1. For low excitation power densities, the linear slope of the output intensity (Figure 2c) indicates the spontaneous emission regime. The slope changes to superlinear for higher excitation powers, when the longitudinal modes evolve in the spectrum (compare Figure 2a), indicating the ASE regime. For even higher pump power, the slope changes back to linear, which proves stable laser oscillations in the NW device.
for all strain configurations. Hence, the three well-known operation modes of the NW laser device are clearly distinguishable for all strain values. In agreement with these observations, time-resolved μPL measurements confirm that the excitonic properties are nearly unaltered by applying strain to the NW (see Figure S4 in the Supporting Information).

Since the spontaneous decay rate does not change with strain significantly, the laser inversion built up kinetics eventually is also similar in all cases, which leads to a roughly maintained lasing threshold value (see caption of Figure S4 in the Supporting Information). It is therefore very beneficial in particular for practical applications that we can tune the nanolaser emission wavelength (see Figure 2a,b) while keeping the optical excitation power constant (Figure 2c).

In order to gain further insights into the strain-induced origin of both aforementioned spectral changes and the strain-dependent lasing properties, an exemplary selection of PL spectra from the power series acquired at each tension value is depicted in Figure 3a. The excitation power was always limited to about twice the lasing threshold, such that sample destruction is avoided. The respective adjacent spectra were always acquired at similar pump powers. The unstrained spectra (blue lines) reveal a spectral blueshift of the mode positions with increasing excitation power. This originates from an increase in the mean charge carrier density with increasing excitation power in the electron hole plasma (EHP),\(^\text{12}\) which is the gain mechanism in our NWs. This increasing carrier density ultimately leads to an increase in the screening and thus a refractive index reduction. Since \(\lambda_{\text{mode}}/n\) must remain constant for the respective mode to fulfill the FP mode condition, a refractive index decrease leads to a decrease in the mode emission wavelength.

The spectral blueshift of all FP mode positions with increasing excitation power is also clearly apparent in the spectra of the strained NW (green and red lines). Additionally the strain-tuned NW laser exhibits both aforementioned strain-dependent effects, (i) the mode redshift and (ii) the gain envelope broadening and redshift with increasing tensile stress for all respective excitation powers. Indeed, lasing spectra with similar excitation powers need to be compared in order to distinguish strain-related effects from power- and heat-related ones. This FP mode position redshift is plotted for the mode marked by the gray arrow as a function of the pump power in Figure 3b (upper graph). Additionally, as indicated by the colored, dashed lines, the central wavelength of the gain envelope redshifts with increasing stress. This redshift is also plotted for a wider variety of powers in Figure 3b (lower graph). Likewise, the broadening of the gain envelope is clearly present for all excitation powers. Note that changes in the NW emission spectrum can, however, also result from a varying absorption on the high energy side of the emission for different excitation conditions.\(^\text{35}\) Yet, since the excitation conditions in our experiments were kept constant and the observed redshift of individual resonator modes cannot be explained by absorption changes, we can rule out this explanation for our data. We can unambiguously distinguish strain-related from non-strain-related (such as power dependent) spectral changes by this thorough analysis. Temperature or heat-induced effects can also be ruled out, as shown in the Supporting Information (Figure S5). Strain induces (i) the redshift of all FP modes and (ii) the redshift and broadening of the mode envelope. These observations are attributed to (i) the elongation of the optical resonator and (ii) the alteration of the properties of the semiconductor gain material, respectively.

Stressing the NW leads to a strained/elongated region between both SiO₂ fixation pads (marked red in Figure 4a) and unstrained parts of the NW between the respective pad and the end facet. (i) The resonator elongation leads to a shift of the individual lasing modes. Their spectral position is not material- but resonator geometry-related: The wavelength of the \(N\)th mode is given by \(\lambda = 2n_{\text{eff}}L/N\), where \(n_{\text{eff}}\) is the effective refractive index of the transverse mode and \(L\) the resonator length. By elongating the middle section of the NW (\(L_i\) marked in light red in Figure 4a), \(L_i\) is increased causing the redshift of the respective \(N\)th mode, assuming \(n_{\text{eff}}\) remains almost unchanged. In addition, using the mode positions of the unstrained resonator (solid blue curve in Figure 4b), we modeled the mode positions of the strained resonator analytically (red, vertical, dash-dotted lines). The calculated mode positions match the observed ones (solid red curve) for using a length change value of 0.6% for the calculations (compare Supporting Information). This length change is roughly confirmed by SEM measurements. However, note that a strain-induced refractive index reduction\(^\text{36}\) might lead to a slight overestimation of strain in the NW. (ii) At the same time, the strained regions experience a decrease of the bandgap. This coincides with the results of the spontaneous PL and the Raman measurements (see Figure 1 and Figures S2 and S3 in the Supporting Information). Additionally, wave-guiding experiments support this observation, as the light, that has

---

**Figure 4.** (a) Schematic illustration of the resonator elongation of the fixed CdS NW. The NW is elongated between both fixation pads (marked in red in the lower sketch) by a certain length \(\Delta L\). Thus, the FP resonator is equally elongated by \(\Delta L\) which explains the strain dependent individual mode shift. (b) Mode spectrum of the unstrained and the strained NW for the investigation of the mode shift due to the elongation of the NW resonator. The modeled mode positions for the mode numbers \(N = 191...195\) are indicated by the dashed lines. By including the strain-induced elongation into the calculation of the Fabry-Pérot mode positions, the mode positions for the strained NW were determined.
been guided through the NW exhibits a redshift, which depends on the applied stress (see Figure S6 in the Supporting Information). Thus, homogeneously pumping of the strained region with decreased bandgap and the unstrained regions with unaltered bandgap leads to the superposition of the red-shifted and original gain spectra. This composite gain spectrum provides amplification for the resonator modes in the NW. Therefore, the broadening and redshift of the mode envelope is observed in the experiment.

The observed strain-dependent effects are summarized in the schematics of the gain spectra in Figure 5. Figure 5a shows the initial gain spectrum in the unstrained case centered at $\lambda_{\text{max}}$, which results from the formation of an electron–hole plasma (EHP) in the CdS NW at high pump powers. The gray vertical lines mark all resonant FP mode positions from the NW cavity. Amplification is reserved for FP resonator modes, which experience gain values above the threshold (TH, horizontal, black, dashed line). Consequently, only these modes (sketched as bold, black lines) become apparent in the lasing spectrum. Both material and resonator-dependent properties are altered when stress is applied to the NW by moving the Si/SiO$_2$ substrate areas apart (Figure 1a). (i) Figure 5c shows the consequences of the FP resonator elongation, solely. All FP mode positions are red-shifted when stress is applied, as indicated by the red, thin, vertical lines. Again, only those modes within the gain spectrum with gain exceeding the threshold value are amplified and detectable in the experiment (bold red lines in Figure 5c). (ii) Apart from this, Figure 5b depicts the changes, which result only from the bandgap decrease in the strained region of the NW (marked in red in Figures 1a and 4a). In this NW volume, the gain spectrum is red-shifted and thus centered at $\lambda_{\text{max}}$ as indicated by the dashed red line in Figure 5b. Superposing this gain spectrum with the initial gain spectrum from the unstrained NW tails under and beyond the fixation pads yields the broadened gain spectrum drawn in red. Finally, both effects (Figure 5b,c) are considered in the composite Figure 5d. The resulting shifted and broadened gain spectrum and the shifted resonator modes are drawn in red. Additionally, the initial gain spectrum as well as the initial FP mode positions are drawn for comparison. Thus, this model concept is fully suitable for explaining the experimental observations. Furthermore, our nanolaser device concept shows strong benefits in comparison to previously demonstrated (static) strain tuning in buckled CdS microribbon lasers, as it avoids a possible diffusion of the photoexcited carriers out of the cavity and gain medium.

**Conclusion.** We fabricated dynamically strainable NW laser devices using CdS NWs in order to establish a proof of principle design for tunable nanolasers. Micro-PL measurements in the spontaneous emission regime revealed a bandgap reduction in the NW, which can be controlled by uniaxial tensile stress. Furthermore, our study shows unambiguous proof for coherent emission wavelength tuning in NW lasers. We distinguished two different strain-related effects: (i) the resonator elongation caused by the uniaxial stress which gives rise to a redshift of the individual resonator modes, and (ii) the bandgap reduction in strained parts of the NW which leads to a broadening and a redshift of the gain spectrum and thus the lasing mode envelope. Hence, our work provides a proof of principle for dynamical strain-tuning in semiconductor nanowires, whose fundamentals could be extended toward electrically driven devices such as LEDs. In addition, already these devices can have practical impact by adding further nanophotonic components such as filters or waveguides. Uniaxial stress is a powerful tool for the dynamical emission control in NW laser devices which might pave the way for novel highly functional nanoscale spectroscopic devices in combination with MEMS architectures. Indeed, for evolving strain values of up to $(3-4)$ % in such tunable nanolasers designs, a shift of the gain envelope of over $\pm 10$ nm should be achievable. Additionally, beyond the spectral emission control, this concept might enforce research on nanosensing (see concept Figure S7a in the
Supporting Information), nanoscale signal tuning devices such as periodic emission modulators (Supporting Information Figure 57b), tunable waveguides, and tunable absorbers.

**Experimental Methods. NW Growth.** CdS NWs were grown by a vapor transport method using the vapor–liquid–solid (VLS) mechanism.38 In a tube furnace, the source material consisting of CdS powder was placed in an alumina boat, evaporated at 700 °C and transported downstream by an argon carrier gas toward the Si growth substrate with a 10 nm layer of sputtered gold on top. The pressure within the tube during growth was kept between 10–100 mbar resulting in CdS NW batches with NW diameters between 100–700 nm and NW length of several μm.

**Fabrication.** NWs were subsequently transferred by droplet utilizing isopropyl onto a structured low refractive index substrates consisting of 300 nm of SiO₂ (n ~ 1.4) on an SOI wafer. By optical lithography and sputtering, NWs were fixed with SiO₂ pads to the supporting substrate. Uniaxial stress was applied by a micromechanical 3-point bending device. More detail can be found in the Supporting Information of ref 39.

**Optical Setup.** The optical excitation for the lasing experiments was always set to 355 nm. Spontaneous PL measurements were performed with an excitation wavelength of 325 nm. All spectra were acquired at room temperature.

**ASSOCIATED CONTENT**

* Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.nanolett.7b02589.

Reversible stress-dependent emission tuning, stress-dependent Raman spectroscopy, time-resolved photoluminescence as a function of stress, excitation power-dependent near-band edge emission, stress-dependent wave guiding, calculation of stress-dependent Fabry–Pérot mode positions, conceptual drawings of nanophotonic/-sensing using the tunable NW laser (PDF)

**AUTHOR INFORMATION**

Corresponding Authors
* E-mail: maximilian.zapf@uni-jena.de.
* E-mail: robert.roeder@uni-jena.de.
* E-mail: carsten.ronning@uni-jena.de.

ORCID
Maximilian Zapf: 0000-0002-7600-6340
Robert Röder: 0000-0002-1338-8548
Alois Lugstein: 0000-0001-5693-4775

Present Address
Solid State Physics, Lund University, Box 118, 22100 Lund, Sweden

Author Contributions
M.Z. and M.W. carried out the nanowire growth. The device was fabricated by K.W. Raman measurements were conducted by M.Z. and J.G. Photoluminescence and lasing were measured by M.Z. and L.K. Time-resolved photoluminescence measurements were performed by M.Z. and M.W. This manuscript was written by M.Z. and R.R. with feedback from all coauthors.

**AUTHOR INFORMATION**

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The authors gratefully acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG) within the research unit FOR1616 and financial support by the Austrian Science Fund (FWF): project No. P 28175-N27.

**REFERENCES**

(1) Liu, W.; Li, M.; Guzzon, R. S.; Norberg, E. J.; Parker, J. S.; Lu, M.; Coldren, L. A.; Yao, J. Nat. Photonics 2016, 10, 190–195.
(2) Craighead, H. Nature 2006, 442, 387–393.
(3) Schwarz, B.; Reininger, P.; Ristic, D.; Dets, H.; Andrews, A. M.; Schrenk, W.; Strasser, G. Nat. Commun. 2014, 5, 4085.
(4) Yang, P.; Yan, R.; Fardy, M. Nano Lett. 2010, 10, 1529–1536.
(5) Sibbuly, D. J.; Law, M.; Pauzauskie, P.; Yan, H.; Maslow, A. V.; Knutsen, K.; Ning, C.-Z.; Saykally, R. J.; Yang, P. Proc. Natl. Acad. Sci. U. S. A. 2005, 102, 7800–7805.
(6) Rodriguez-Ruiz, I.; Ackermann, T. N.; Munoz-Berbel, X.; Lobera, A. Anal. Chem. 2016, 88, 6630–6637.
(7) Qian, F.; Li, Y.; Gradecak, S.; Park, H.-G.; Dong, Y.; Wang, Z. L.; Lieber, C. M. Nat. Mater. 2008, 7, 701–706.
(8) Zimmler, M. A.; Capasso, F.; Müller, S.; Ronning, C. Semicond. Sci. Technol. 2010, 25, 024001.
(9) Geburt, S.; Thielmann, A.; Röder, R.; Borschel, C.; McDonnell, A.; Kozlik, M.; Kühnel, J.; Sunter, K. A.; Capasso, F.; Ronning, C. Nanotechnology 2012, 23, 365204.
(10) Sidiropoulos, T. P. H.; Röder, R.; Geburt, S.; Hess, O.; Maier, S. A.; Ronning, C.; Oulton, R. F. Nat. Phys. 2014, 10, 870–876.
(11) Röder, R.; Sidiropoulos, T. P. H.; Tessarek, C.; Christiansen, S.; Oulton, R. F. Nat. Lett. 2015, 15, 4637–4643.
(12) Wille, M.; Sturm, C.; Michalsky, T.; Röder, R.; Ronning, C.; Schmidt-Grund, R.; Grundmann, M. Nanotechnology 2016, 27, 225702.
(13) Karras, C.; Röder, R.; Paa, W.; Ronning, C.; Stafast, H. ACS Photonics 2017, 4, 1067.
(14) Röder, R.; Sidiropoulos, T. P. H.; Buschinger, R.; Riediger, M.; Peschel, U.; Oulton, R. F.; Ronning, C. Nano Lett. 2016, 16, 2878–2884.
(15) Saxena, D.; Wang, F.; Gao, Q.; Mokkapati, S.; Tan, H. H.; Jagadish, C. Nano Lett. 2015, 15, 5342–5348.
(16) Lu, Y.; Gu, F.; Meng, C.; Yu, P.; Ma, Y.; Fang, W.; Tong, L. Opt. Express 2013, 21, 22314–22319.
(17) Li, J.; Meng, C.; Liu, Y.; Wu, X.; Lu, Y.; Ye, Y.; Dai, L.; Tong, L.; Liu, X.; Yang, Q. Adv. Mater. 2013, 25, 833–837.
(18) Xu, X.; Zhao, Y.; Sie, E. J.; Lu, B.; Ekahana, S. A.; Ju, X.; Jiang, Q.; Wang, J.; Sun, H.; et al. ACS Nano 2011, 5, 3660–3669.
(19) Dietrich, C. P.; Lange, M.; Klüpfel, F. J.; von Wencelstern, H.; Schmidt-Grund, R.; Grundmann, M. Appl. Phys. Lett. 2011, 98, 031105.
(20) Fu, Q.; Zhang, Z. Y.; Kou, L.; Wu, P.; Han, X.; Zhu, X.; Gao, J.; Xu, J.; Zhao, Q.; Guo, W.; et al. Nano Res. 2011, 4, 308–314.
(21) Fu, X.; Jacobin, G.; Shahrhammad, M.; Liu, R.; Benenauer, M.; Ganière, J.-D.; Feng, J.; Guo, W.; Liao, Z.-M.; Deveaud, B.; et al. ACS Nano 2014, 8, 3412–3420.
(22) Sun, L.; Kim, D. H.; Oh, K. H.; Agarwal, R. Nano Lett. 2013, 13, 3836–3842.
(23) Fu, X.; Liao, Z.-M.; Liu, R.; Lin, F.; Xu, J.; Zhu, R.; Zhong, W.; Liu, Y.; Guo, W.; Yu, D. ACS Nano 2015, 9, 11960–11967.
(24) Wei, B.; Zheng, K.; Ji, Y.; Zhang, Y.; Zhang, Z.; Han, X. Nano Lett. 2012, 12, 4595–4599.
(25) Hoffmann, S.; Östlund, F.; Michler, J.; Fan, H. J.; Zacharias, M.; Christiansen, S. H.; Ballif, C. Nanotechnology 2007, 18, 205503.
(26) Wang, J.; Shen, Y.; Song, F.; Ke, F.; Liao, X.; Lu, C. Nanotechnology 2017, 28, 165705.
(27) Sturm, C.; Wille, M.; Lenzner, J.; Khujanov, S.; Grundmann, M. Appl. Phys. Lett. 2017, 110, 062103.
(28) Bohnert, K.; Schmieder, G.; El-Dessouki, S.; Klingshirn, C. Solid State Commun. 1978, 27, 295–299.
(29) Zapf, M.; Ronning, C.; Röder, R. Appl. Phys. Lett. 2017, 110, 173103.
(30) Maslov, A. V.; Ning, C. Z. Appl. Phys. Lett. 2003, 83, 1237–1239.
(31) Zimmler, M. A.; Bao, J.; Capasso, F.; Müller, S.; Ronning, C. Appl. Phys. Lett. 2008, 93, 051101.
(32) Röder, R.; Ploss, D.; Kriesch, A.; Buschlinger, R.; Geburt, S.; Peschel, U.; Ronning, C. J. Phys. D: Appl. Phys. 2014, 47, 394012.
(33) Röder, R.; Ploss, D.; Kriesch, A.; Buschlinger, R.; Geburt, S.; Peschel, U.; Ronning, C. J. Phys. D: Appl. Phys. 2015, 48, 239501.
(34) Casperson, L. W. J. Appl. Phys. 1975, 46, 5194–5201.
(35) Wille, M.; Michalsky, T.; Krüger, E.; Grundmann, M.; Schmidt-Grund, R. Appl. Phys. Lett. 2016, 109, 061102.
(36) Cai, J.; Ishikawa, Y.; Wada, K. Opt. Express 2013, 21, 7162–7170.
(37) Wang, Q.; Sun, L.; Lu, J.; Ren, M.-L.; Zhang, T.; Huang, Y.; Zhou, X.; Sun, Y.; Zhang, B.; Chen, C.; et al. Sci. Rep. 2016, 6, 26607.
(38) Wagner, R. S.; Ellis, W. C. Appl. Phys. Lett. 1964, 4, 89.
(39) Greil, J.; Lugstein, A.; Zeiner, C.; Strasser, G.; Bertagnolli, E. Nano Lett. 2012, 12, 6230–6234.
(40) Geburt, S. Lasing and ion beam doping of semiconductor nanowires. Ph.D. thesis, Friedrich-Schiller-Universität, Jena, 2012.