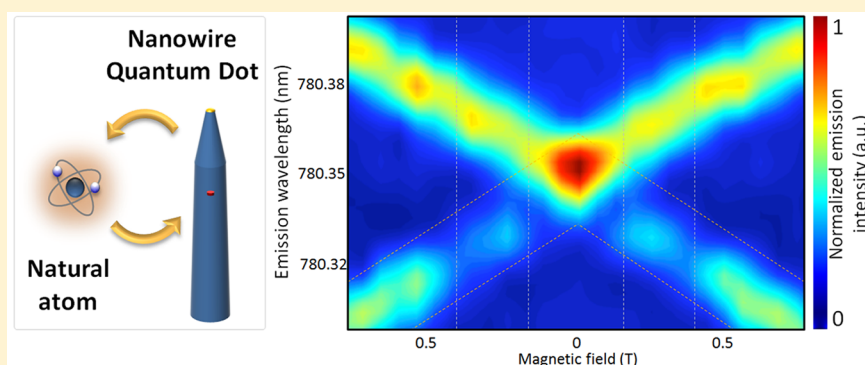


Nanowire Quantum Dots Tuned to Atomic Resonances

Lorenzo Leandro,[†] Christine P. Gunnarsson,[†] Rodion Reznik,^{‡,§} Klaus D. Jöns,^{||} Igor Shtrom,[‡] Artem Khrebtov,[§] Takeshi Kasama,[†] Valery Zwiller,^{||,⊥} George Cirlin,^{‡,§} and Nika Akopian^{*,†}[†]DTU Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark[‡]St. Petersburg Academic University, RAS, St. Petersburg 194021, Russia[§]ITMO University, Kronverkskiy pr. 49, 197101 St. Petersburg, Russia^{||}Department of Applied Physics, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden[⊥]Kavli Institute of Nanoscience, TU Delft, 2628CJ Delft, Netherlands

Supporting Information



ABSTRACT: Quantum dots tuned to atomic resonances represent an emerging field of hybrid quantum systems where the advantages of quantum dots and natural atoms can be combined. Embedding quantum dots in nanowires boosts these systems with a set of powerful possibilities, such as precise positioning of the emitters, excellent photon extraction efficiency and direct electrical contacting of quantum dots. Notably, nanowire structures can be grown on silicon substrates, allowing for a straightforward integration with silicon-based photonic devices. In this work we show controlled growth of nanowire-quantum-dot structures on silicon, frequency tuned to atomic transitions. We grow GaAs quantum dots in AlGaAs nanowires with a nearly pure crystal structure and excellent optical properties. We precisely control the dimensions of quantum dots and their position inside nanowires and demonstrate that the emission wavelength can be engineered over the range of at least 30 nm around 765 nm. By applying an external magnetic field, we are able to fine-tune the emission frequency of our nanowire quantum dots to the D₂ transition of ⁸⁷Rb. We use the Rb transitions to precisely measure the actual spectral line width of the photons emitted from a nanowire quantum dot to be $9.4 \pm 0.7 \mu\text{eV}$, under nonresonant excitation. Our work brings highly desirable functionalities to quantum technologies, enabling, for instance, a realization of a quantum network, based on an arbitrary number of nanowire single-photon sources, all operating at the same frequency of an atomic transition.

KEYWORDS: Nanowires, quantum dots, hybrid systems, VLS growth, GaAs/AlGaAs

Exploiting the advantages of atomic and semiconducting systems opens new possibilities and research directions. For instance, quantum dots have been frequency tuned and locked to atomic resonances to provide a single photon source with stable emission frequency.^{1–3} Such hybrid systems enable multiple emitters working at the exact same wavelength, which is one of the major challenges in quantum communication and quantum information processing. Recently, a different material system has been used to tune InGaAs quantum dots to Cs atoms, optically with a laser⁴ and by electrically induced strain.^{5,6} Furthermore, electrically pumped quantum dots were developed to make the first quantum-LED tuned to atomic lines,⁷ paving the way to on-chip electrically controlled tunable single and entangled photon sources. In addition, coupling

between a single quantum dot and a single ion has been shown,⁸ allowing for direct transfer of quantum information from a single quantum dot to a single atom.

Nevertheless, all previous works have used quantum dots in materials grown in bulk, while embedding the quantum dots in nanowires provide additional important functionalities to the system, making them one of the most promising systems for numerous applications in quantum nanophotonics.^{9–13} Over the past few years several groups have successfully demon-

Received: August 20, 2018

Revised: October 10, 2018

Published: October 15, 2018

strated nanowire quantum dots in various material systems.^{14,15} Recently, the exciton energy of single nanowire quantum dots on piezo crystals was tuned into resonance by applying strain,¹⁶ and Bell's inequality violation¹⁷ and entanglement^{18,19} have been also demonstrated. The advantages of the nanowire structure are, among others, high extraction efficiency,^{10,11,20,21} the possibility of maximizing the coupling to optical fibers,^{10,22,23} the positioning of nanowires in highly uniform arrays with higher uniformity than what is achievable with self-assembled quantum dots,^{24–28} and the deterministic and scalable integration with photonic nanostructures that can lead to on-chip photonic circuits.^{16,29,30}

GaAs quantum dots in AlGaAs structures are our preferred material system; their emission energy can be engineered close to the D_2 transitions of ^{87}Rb ,¹ they are the most pure single photon sources reported to date,³¹ and they show the highest degree of polarization entanglement of photons³² generated from semiconductor quantum dots. Furthermore, GaAs quantum dots grown in AlGaAs nanowires are expected to have much sharper interfaces between the two materials, since aluminum crystallizes at least 100 times faster than gallium,^{33,34} quickly leaving the droplet without aluminum once the source is closed. This allows for a higher control of the quantum dot shape, compared to the case of other material systems. The first works have already shown the growth of GaAs quantum dots in AlGaAs nanowires.^{35,36} However, the optical properties were not yet optimal to address quantum applications, for instance, the emission line width spans from $95\ \mu\text{eV}$ ³⁵ to $2\ \text{meV}$.³⁶ As of today, realization of a controlled growth of high optical quality nanowire quantum dots working at atomic frequencies requires development of the material system. Here, we demonstrate precisely engineered GaAs quantum dots in AlGaAs nanowires with nearly pure crystal structure, high optical quality, and frequency-tuned to the optical transition of Rb atoms.

We grow our GaAs quantum dots in AlGaAs nanowires on a Si wafer using the vapor liquid solid technique in a Molecular Beam Epitaxy reactor, using a gold particle as catalyst. The growth takes place just below the catalyst particle, where the atoms from the vapor crystallize, forming the nanowire. To grow a quantum dot, we stop the Al source for a few seconds (e.g., 5, 7, or 15 s). This brief growth of only GaAs creates a quantum dot confined between AlGaAs segments of the nanowire. We set the growth parameters to allow for a simultaneous axial and radial growth, resulting in tapered nanowires (for details see [Methods](#) section). The radial growth results in an essential shell that protects the quantum dot from the environment outside the nanowire. We grow several sets of nanowires, with heights in the range of $3\text{--}6\ \mu\text{m}$ and with diameters (core plus shell) in the range of $150\text{--}200\ \text{nm}$ at the position of a quantum dot, depending on the growth conditions. The quantum dots have diameters defined by the size of the gold catalysts, which is about $20\ \text{nm}$.

In [Figure 1a](#) we present a schematics showing the quantum dot and the core–shell structure of the nanowire. Parts b and c of [Figure 1](#) depict 2D energy-dispersive X-ray spectroscopy (EDS) elemental maps for Ga and Al, respectively. As expected, we observe an increase in the Ga content with a corresponding decrease of Al content at the quantum dot position. To clearly show the quantum dot, in [Figure 1d](#) we present 1D EDS scans along the nanowire core. We note that the expected sharp interfaces are not observed here due to the small concentration difference between GaAs and AlGaAs and

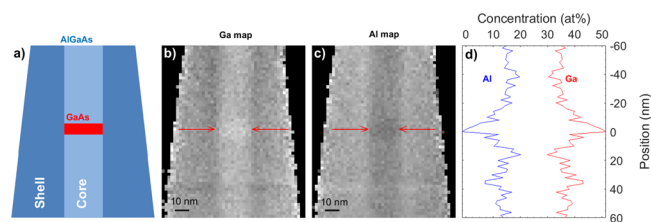


Figure 1. GaAs quantum dots in AlGaAs nanowires. (a) Schematics of a GaAs quantum dot (red) in an AlGaAs nanowire (blue), composed of a core surrounded by a shell. (b) and (c) Concentration maps of Ga and Al in a nanowire measured using STEM-EDS, respectively. The quantum dot is seen as an increase in Ga concentration and a corresponding decrease in Al concentration. (d) Concentrations of Ga (red) and Al (blue) in the nanowire core along its length, corrected for imperfect measurement technique and low material contrast (see [Supporting Information section 1](#)). All measurement in this figure are done on a sample specifically grown to have the quantum dot closer to the top of the nanowire to reduce the effect of the shell on the measurements (see [Supporting Information section 1](#)).

a beam broadening inside the material which reduces the sensitivity and the spatial resolution of the measurement.

In [Figure 2a](#) we show the photoluminescence (PL) spectra at $4.2\ \text{K}$ from three quantum dots, grown for different times: 5,

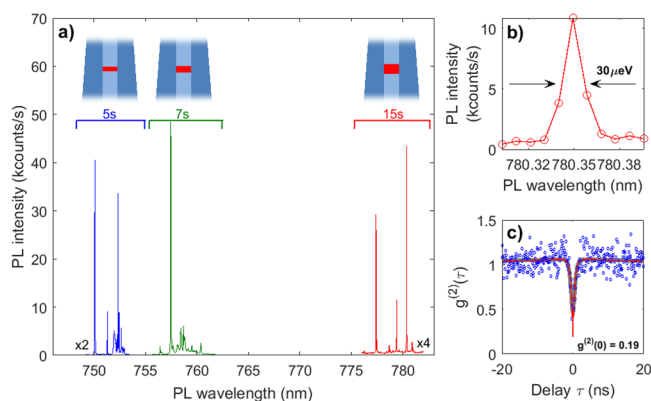


Figure 2. Optical characterization of nanowire quantum dots. (a) Photoluminescence (PL) spectra at $4.2\ \text{K}$ of three samples with different growth times of the quantum dot: 5, 7, and 15 s (for more details see [Supporting Information section 3](#)). A schematic of the quantum dot in nanowire structure is shown above each corresponding spectra. (b) Spectral zoom on the exciton line at $\sim 780\ \text{nm}$ (D_2 line of ^{87}Rb). (c) Autocorrelation measurements of an exciton ($750\ \text{nm}$) in a nanowire quantum dot (5 s). The blue circles are the measured data and the gray line is the fit, which takes into account the finite time resolution of our detectors. The red line shows how the measurement would appear for an ideal system response (for more details see [Supporting Information section 4](#)).

7 and 15 s. As we expect, increase in the growth time increases the height of the quantum dot, which decreases the emission energy (increases the emission wavelength) of the quantum dot. As we show in [Figure 2b](#), the PL spectra of our nanowire quantum dots has narrow line width, limited by the resolution of our spectrometer ($30\ \mu\text{eV}$). In [Figure 2c](#) we plot an autocorrelation measurements of the exciton emission of a quantum dot, showing antibunching with a fitted $g^{(2)}(\tau=0) = 0.19$ (see [Supporting Information section 4](#)). Our results show that we can engineer the wavelength of the emission from our nanowire quantum dots over a range of 30

nm around 765 nm, by selecting the growth time from 5 s (emission at 750 nm) to 15 s (emission at 780 nm). Our nanowire quantum dots are spectrally narrow and bright sources of single photons, with rates of 2.2 Mcounts/s under continuous wave excitation (see [Supporting Information section 3](#)), even without any intentional cavity integration. The count rates can be further increased, for instance, by implementing mirrors at the bottom of the nanowires^{37,38} and by optimizing the waveguide design of the nanowire.^{11,39} The narrow and intense lines also suggest that our nanowires are defect free and of a very high crystal purity, in some cases down to only 10 stacking faults per micrometer (see [Supporting Information section 1](#)). We note, however, that not all of our nanowires are free from defects, and not all quantum dots have excellent optical properties.

Even if one can precisely control the dimensions of quantum dots, no growth method allows obtaining systematically identical heterostructure quantum dots. In virtually all cases, the emission frequency is slightly different from one quantum dot to the other, not allowing for exchange of photons between distant quantum dots. Therefore, a reliable postgrowth technique is necessary to fine-tune each quantum dot to a frequency reference provided, for instance, by an atomic transition line. To demonstrate such tuning with our nanowire quantum dots, we interface them with a vapor of Rb atoms, similarly to our earlier work on quantum dots grown in a multistep self-assembly process in bulk.¹ In the absence of strong electric or magnetic fields, these atomic transition energies are the same, independently on time, location and number of emitters.

We use the D₂ optical transition of ⁸⁷Rb atoms as established frequency references to which we fine-tune the emission from our nanowire quantum dots, using an external magnetic field. This is done by means of the Zeeman effect and diamagnetic shift. During the experiment, we excite the nanowire quantum dot with a laser and then direct its emission through a cell with a vapor of ⁸⁷Rb (see [Figure S11](#) for schematics). Varying the applied magnetic field, we change the frequency of the emitted photons. The photons propagate through the Rb cell and as their frequency matches the atomic transitions, they get absorbed or scattered. The transmission of photons through the Rb cell is then measured.

In [Figure 3](#), we show the results of our experiment. We scan the magnetic field from 0.7 to 0 T and then back to 0.7 T for reproducibility. We then trace the short-wavelength branch of the Zeeman-split lines (highlighted by dashed lines in [Figure 3a](#)) and analyze the transmitted intensity, shown on [Figure 3b](#). We clearly resolve two transmission dips due to the hyperfine structure of the D₂ lines of ⁸⁷Rb. Since the experiment is repeated twice (from 0.7 to 0 T and from 0 to 0.7 T), [Figure 3b](#) shows four dips. We then fit the data to our model¹ (see [Supporting Information section 6](#)) and take advantage of our hybrid system to perform high-resolution spectroscopy of our nanowire quantum dot, similarly to laser spectroscopy.³ The fit, which has only one fitting parameter (the spectral line width of the emission) reveals a narrow exciton line of 9.4 μ eV. To the best of our knowledge, this is the narrowest line width reported for GaAs nanowire quantum dots^{15,40,41} and can be further improved by exciting the quantum dots resonantly.

In summary, we developed a technique for controlled growth of GaAs quantum dots in AlGaAs nanowires on Si substrates, where we precisely engineer the size and position of the dots inside the nanowire. Our nanowires are nearly defect

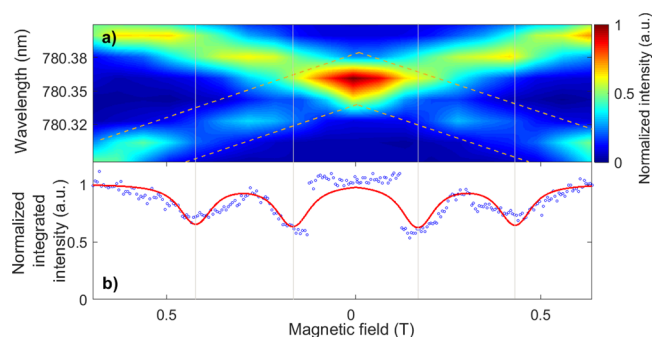


Figure 3. Transmission through Rb vapor. (a) PL spectra of an exciton in a nanowire quantum dot scanned through the atomic transitions. The experiment is done by swiping the magnetic field from 0.7 to 0 T and then back to 0.7 T. Colors represent the normalized PL intensity. The data are then interpolated for clarity (see raw data in [Figure S12](#)). (b) Transmission of the exciton line through the Rb vapor, obtained by tracing the short wavelength branch of the Zeeman-split exciton in the raw data, marked by dashed lines in (a). Blue points refer to the experimental data, while the red line represents the fit to our model. The fit reveals a very narrow emission line width of $9.4 \pm 0.7 \mu\text{eV}$.

free, and we can design the quantum dot to emit single photons anywhere in the range of 30 nm around 765 nm. These nanowire quantum dots are bright emitters with very narrow spectral line width, down to 9.4 μ eV. We demonstrated the tuning of their emission to the D₂ lines of ⁸⁷Rb, enabling operation of our nanowire quantum dots at a stable and precise reference frequency. The hybrid system we present in this work combines the reliability and stability of natural atoms with a variety of functional advantages of nanowire quantum dots. Nanowire quantum dots tuned to atomic resonances could be one of the key elements in quantum information networks, on-chip photonic circuits, and in generation of multidimensional photonic cluster states.⁴²

Methods. We grow our nanowires on a Si(111) wafer. The wafer is first outgassed at 850 °C and then the Au is deposited with total thickness of 0.1 nm at 550 °C. After deposition, the Au layer will form droplets of about 20 nm in diameter, as this formation minimizes the potential energy. In order to improve the homogeneity of the Au droplet size, the substrate is kept for 1 min at 550 °C; this time is long enough to ensure that the droplets become similar in size. Afterward the substrate is cooled to room temperature and transferred to the growth chamber with no vacuum brake. During the nanowire growth the substrate temperature is set at 510 °C, the V/III flux ratio is 3, and the total AlGaAs growth rate is fixed at 0.3 nm/s, for all samples in this work. The AlGaAs part of the nanowire is grown for 20 or 25 min, depending on the desired height of the final nanowire, and then the Al source is closed for 5, 7, or 15 s in order to form the GaAs quantum dots. Afterward, the supply of Al is opened again for 5 min to continue the nanowire growth. The growth method results in tapered core-shell nanowires (see [Figure 1a](#)). The Au droplet diameter will determine the nanowire core diameter, and hence the quantum dot diameter. As the distribution of the size of the Au droplets is ensured to be homogeneous, the nanowire core and the quantum dot for all samples will have a diameter close to 20 nm. The diameter of the total (core+shell) nanowire is in the range 150–200 nm at the position of the quantum dot, depending on the total AlGaAs growth time. The height of the quantum dot inside the nanowire is given by the time in which

the Al shutter is closed (5, 7, or 15 s in these samples). The Al shutter closing time is 0.3 s and thus allows accurate control the quantum dot height. The density of the nanowires was kept low during growth (see Figure S1), in order to be able to distinguish individual nanowire quantum dots.

■ ASSOCIATED CONTENT

■ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.nanolett.8b03363.

Electron microscopy images of the samples, EDS line scan corrections, further optical characterization measurements, magneto-luminescence data, fitting procedures and details on data interpolation used in the main text (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*N. Akopian. E-mail: nikaak@fotonik.dtu.dk.

ORCID

Lorenzo Leandro: 0000-0002-5259-3114

Klaus D. Jöns: 0000-0002-5814-7510

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We gratefully acknowledge the support of Villum Fonden (Project no. VKR023444). The nanowire samples were grown under the support of the Russian Science Foundation (Project no 14-12-00393). We gratefully acknowledge CryoVac GmbH (www.cryovac.de) for developing a cryogenic system used in some of the experiments reported here.

■ REFERENCES

- (1) Akopian, N.; Wang, L.; Rastelli, A.; Schmidt, O. G.; Zwiller, V. Hybrid Semiconductor-Atomic Interface: Slowing down Single Photons from a Quantum Dot. *Nat. Photonics* **2011**, *5* (4), 230.
- (2) Akopian, N.; Trotta, R.; Zallo, E.; Kumar, S.; Atkinson, P.; Rastelli, A.; Schmidt, O. G.; Zwiller, V. An Artificial Atom Locked to Natural Atoms. *arXiv*: 1302.2005, **2013**.
- (3) Jahn, J.-P.; Munsch, M.; Béguin, L.; Kuhlmann, A. V.; Renggli, M.; Huo, Y.; Ding, F.; Trotta, R.; Reindl, M.; Schmidt, O. G.; et al. An Artificial Rb Atom in a Semiconductor with Lifetime-Limited Linewidth. *Phys. Rev. B: Condens. Matter Mater. Phys.* **2015**, *92* (24), 245439.
- (4) Ulrich, S. M.; Weiler, S.; Oster, M.; Jetter, M.; Urvoy, A.; Löw, R.; Michler, P. Spectroscopy of the D1 Transition of Cesium by Dressed-State Resonance Fluorescence from a Single (In,Ga)As/GaAs Quantum Dot. *Phys. Rev. B: Condens. Matter Mater. Phys.* **2014**, *90* (12), 125310.
- (5) Trotta, R.; Martín-Sánchez, J.; Wildmann, J. S.; Piredda, G.; Reindl, M.; Schimpf, C.; Zallo, E.; Stroj, S.; Edlinger, J.; Rastelli, A. Wavelength-Tunable Sources of Entangled Photons Interfaced with Atomic Vapours. *Nat. Commun.* **2016**, *7*, 10375.
- (6) Vural, H.; Portalupi, S. L.; Maisch, J.; Kern, S.; Weber, J. H.; Jetter, M.; Wrachtrup, J.; Löw, R.; Gerhardt, I.; Michler, P. Two-Photon Interference in an Atom–quantum Dot Hybrid System. *Optica, OPTICA* **2018**, *5* (4), 367–373.
- (7) Huang, H.; Trotta, R.; Huo, Y.; Lettner, T.; Wildmann, J. S.; Martín-Sánchez, J.; Huber, D.; Reindl, M.; Zhang, J.; Zallo, E.; et al. Electrically-Pumped Wavelength-Tunable GaAs Quantum Dots Interfaced with Rubidium Atoms. *ACS Photonics* **2017**, *4* (4), 868–872.
- (8) Meyer, H. M.; Stockill, R.; Steiner, M.; Le Gall, C.; Matthiesen, C.; Clarke, E.; Ludwig, A.; Reichel, J.; Atatüre, M.; Köhl, M. Direct Photonic Coupling of a Semiconductor Quantum Dot and a Trapped Ion. *Phys. Rev. Lett.* **2015**, *114* (12), 123001.
- (9) Tatebayashi, J.; Ota, Y.; Ishida, S.; Nishioka, M.; Iwamoto, S.; Arakawa, Y. Highly Uniform, Multi-Stacked InGaAs/GaAs Quantum Dots Embedded in a GaAs Nanowire. *Appl. Phys. Lett.* **2014**, *105* (10), 103104.
- (10) Claudon, J.; Bleuse, J.; Malik, N. S.; Bazin, M.; Jaffrennou, P.; Gregersen, N.; Sauvan, C.; Lalanne, P.; Gérard, J.-M. A Highly Efficient Single-Photon Source Based on a Quantum Dot in a Photonic Nanowire. *Nat. Photonics* **2010**, *1* (3), 215.
- (11) Reimer, M. E.; Bulgarini, G.; Akopian, N.; Hocevar, M.; Bavinck, M. B.; Verheijen, M. A.; Bakkers, E. P. A. M.; Kouwenhoven, L. P.; Zwiller, V. Bright Single-Photon Sources in Bottom-up Tailored Nanowires. *Nat. Commun.* **2012**, *3*, 737.
- (12) Minot, E. D.; Kelkensberg, F.; van Kouwen, M.; van Dam, J. A.; Kouwenhoven, L. P.; Zwiller, V.; Borgström, M. T.; Wunnicke, O.; Verheijen, M. A.; Bakkers, E. P. A. M. Single Quantum Dot Nanowire LEDs. *Nano Lett.* **2007**, *7* (2), 367–371.
- (13) Pribyl, V. S.; Nadj-Perge, S.; Frolov, S. M.; van den Berg, J. W. G.; van Weperen, I.; Plissard, S. R.; Bakkers, E. P. A. M.; Kouwenhoven, L. P. Electrical Control of Single Hole Spins in Nanowire Quantum Dots. *Nat. Nanotechnol.* **2013**, *8* (3), 170–174.
- (14) Dalacu, D.; Mnaymneh, K.; Lapointe, J.; Wu, X.; Poole, P. J.; Bulgarini, G.; Zwiller, V.; Reimer, M. E. Ultraclean Emission from InAsP Quantum Dots in Defect-Free Wurtzite InP Nanowires. *Nano Lett.* **2012**, *12* (11), 5919–5923.
- (15) Heiss, M.; Fontana, Y.; Gustafsson, A.; Wüst, G.; Magen, C.; O'Regan, D. D.; Luo, J. W.; Ketterer, B.; Conesa-Boj, S.; Kuhlmann, A. V.; et al. Self-Assembled Quantum Dots in a Nanowire System for Quantum Photonics. *Nat. Mater.* **2013**, *12* (5), 439–444.
- (16) Chen, Y.; Zadeh, I. E.; Jöns, K. D.; Fognini, A.; Reimer, M. E.; Zhang, J.; Dalacu, D.; Poole, P. J.; Ding, F.; Zwiller, V.; et al. Controlling the Exciton Energy of a Nanowire Quantum Dot by Strain Fields. *Appl. Phys. Lett.* **2016**, *108* (18), 182103.
- (17) Jöns, K. D.; Schweickert, L.; Versteegh, M. A. M.; Dalacu, D.; Poole, P. J.; Gulinatti, A.; Giudice, A.; Zwiller, V.; Reimer, M. E. Bright Nanoscale Source of Deterministic Entangled Photon Pairs Violating Bell's Inequality. *Sci. Rep.* **2017**, *7* (1), 1700.
- (18) Versteegh, M. A. M.; Reimer, M. E.; Jöns, K. D.; Dalacu, D.; Poole, P. J.; Gulinatti, A.; Giudice, A.; Zwiller, V. Observation of Strongly Entangled Photon Pairs from a Nanowire Quantum Dot. *Nat. Commun.* **2014**, *5*, 5298.
- (19) Huber, T.; Predojević, A.; Khoshnegar, M.; Dalacu, D.; Poole, P. J.; Majedi, H.; Weihs, G. Polarization Entangled Photons from Quantum Dots Embedded in Nanowires. *Nano Lett.* **2014**, *14* (12), 7107–7114.
- (20) Bulgarini, G.; Reimer, M. E.; Zehender, T.; Hocevar, M.; Bakkers, E. P. A. M.; Kouwenhoven, L. P.; Zwiller, V. Spontaneous Emission Control of Single Quantum Dots in Bottom-up Nanowire Waveguides. *Appl. Phys. Lett.* **2012**, *100* (12), 121106.
- (21) Friedler, I.; Sauvan, C.; Hugonin, J. P.; Lalanne, P.; Claudon, J.; Gérard, J. M. Solid-State Single Photon Sources: The Nanowire Antenna. *Opt. Express* **2009**, *17* (4), 2095–2110.
- (22) Bulgarini, G.; Reimer, M. E.; Bouwes Bavinck, M.; Jöns, K. D.; Dalacu, D.; Poole, P. J.; Bakkers, E. P. A. M.; Zwiller, V. Nanowire Waveguides Launching Single Photons in a Gaussian Mode for Ideal Fiber Coupling. *Nano Lett.* **2014**, *14* (7), 4102–4106.
- (23) Munsch, M.; Malik, N. S.; Dupuy, E.; Delga, A.; Bleuse, J.; Gérard, J.-M.; Claudon, J.; Gregersen, N.; Mørk, J. Dielectric GaAs Antenna Ensuring an Efficient Broadband Coupling between an InAs Quantum Dot and a Gaussian Optical Beam. *Phys. Rev. Lett.* **2013**, *110* (17), 177402.
- (24) Tseng, C.-H.; Tambe, M. J.; Lim, S. K.; Smith, M. J.; Gradecak, S. Position Controlled Nanowire Growth through Au Nanoparticles Synthesized by Galvanic Reaction. *Nanotechnology* **2010**, *21* (16), 165605.

- (25) Dalacu, D.; Mnaymneh, K.; Wu, X.; Lapointe, J.; Aers, G. C.; Poole, P. J.; Williams, R. L. Selective-Area Vapor-Liquid-Solid Growth of Tunable InAsP Quantum Dots in Nanowires. *Appl. Phys. Lett.* **2011**, *98* (25), 251101.
- (26) Subannajui, K.; Güder, F.; Zacharias, M. Bringing Order to the World of Nanowire Devices by Phase Shift Lithography. *Nano Lett.* **2011**, *11* (9), 3513–3518.
- (27) Fan, H. J.; Werner, P.; Zacharias, M. Semiconductor Nanowires: From Self-organization to Patterned Growth. *Small* **2006**, *2*, 700.
- (28) Heiss, M.; Russo-Averchi, E.; Dalmau-Mallorquí, A.; Tütüncüoğlu, G.; Matteini, F.; Rüffer, D.; Conesa-Boj, S.; Demichel, O.; Alarcon-Lladó, E.; Fontcuberta i Morral, A., III Nanowire Arrays: Growth and Light Interaction. *Nanotechnology* **2014**, *25* (1), 014015.
- (29) Elshaari, A. W.; Zadeh, I. E.; Fognini, A.; Reimer, M. E.; Dalacu, D.; Poole, P. J.; Zwiller, V.; Jöns, K. D. On-Chip Single Photon Filtering and Multiplexing in Hybrid Quantum Photonic Circuits. *Nat. Commun.* **2017**, *8* (1), 379.
- (30) Zadeh, I. E.; Elshaari, A. W.; Jöns, K. D.; Fognini, A.; Dalacu, D.; Poole, P. J.; Reimer, M. E.; Zwiller, V. Deterministic Integration of Single Photon Sources in Silicon Based Photonic Circuits. *Nano Lett.* **2016**, *16* (4), 2289–2294.
- (31) Schweickert, L.; Jöns, K. D.; Zeuner, K. D.; Covre da Silva, S. F.; Huang, H.; Lettner, T.; Reindl, M.; Zichi, J.; Trotta, R.; Rastelli, A.; et al. On-Demand Generation of Background-Free Single Photons from a Solid-State Source. *Appl. Phys. Lett.* **2018**, *112* (9), 093106.
- (32) Huber, D.; Reindl, M.; Huo, Y.; Huang, H.; Wildmann, J. S.; Schmidt, O. G.; Rastelli, A.; Trotta, R. Highly Indistinguishable and Strongly Entangled Photons from Symmetric GaAs Quantum Dots. *Nat. Commun.* **2017**, *8*, 15506.
- (33) Dubrovskii, V. G.; Shtrom, I. V.; Reznik, R. R.; Samsonenko, Y. B.; Khrebtov, A. I.; Soshnikov, I. P.; Rouvimov, S.; Akopian, N.; Kasama, T.; Cirilin, G. E. Origin of Spontaneous Core–Shell AlGaAs Nanowires Grown by Molecular Beam Epitaxy. *Cryst. Growth Des.* **2016**, *16* (12), 7251–7255.
- (34) Priante, G.; Glas, F.; Patriarche, G.; Pantzas, K.; Oehler, F.; Harmand, J.-C. Sharpening the Interfaces of Axial Heterostructures in Self-Catalyzed AlGaAs Nanowires: Experiment and Theory. *Nano Lett.* **2016**, *16* (3), 1917–1924.
- (35) Heinrich, J.; Huggenberger, A.; Heindel, T.; Reitzenstein, S.; Höfling, S.; Worschech, L.; Forchel, A. Single Photon Emission from Positioned GaAs/AlGaAs Photonic Nanowires. *Appl. Phys. Lett.* **2010**, *96* (21), 211117.
- (36) Kats, V. N.; Kochereshko, V. P.; Platonov, A. V.; Chizhova, T. V.; Cirilin, G. E.; Bouravleuv, A. D.; Samsonenko, Y. B.; Soshnikov, I. P.; Ubyyovk, E. V.; Bleuse, J.; et al. Optical Study of GaAs Quantum Dots Embedded into AlGaAs Nanowires. *Semicond. Sci. Technol.* **2012**, *27* (1), 015009.
- (37) Friedler, I.; Lalanne, P.; Hugonin, J. P.; Claudon, J.; Gérard, J. M.; Beveratos, A.; Robert-Philip, I. Efficient Photonic Mirrors for Semiconductor Nanowires. *Opt. Lett.* **2008**, *33* (22), 2635–2637.
- (38) Somaschi, N.; Giesz, V.; De Santis, L.; Lored, J. C.; Almeida, M. P.; Hornecker, G.; Portalupi, S. L.; Grange, T.; Antón, C.; Demory, J.; et al. Near-Optimal Single-Photon Sources in the Solid State. *Nat. Photonics* **2016**, *10* (5), 340.
- (39) Gregersen, N.; Nielsen, T. R.; Claudon, J.; Gérard, J.-M.; Mørk, J. Controlling the Emission Profile of a Nanowire with a Conical Taper. *Opt. Lett.* **2008**, *33* (15), 1693–1695.
- (40) Yang, S.; Ding, K.; Dou, X.; Wu, X.; Yu, Y.; Ni, H.; Niu, Z.; Jiang, D.; Li, S.-S.; Luo, J.-W.; et al. Zinc-Blende and Wurtzite GaAs Quantum Dots in Nanowires Studied Using Hydrostatic Pressure. *Phys. Rev. B: Condens. Matter Mater. Phys.* **2015**, *92* (16), 174.
- (41) Wu, J.; Ramsay, A.; Sanchez, A.; Zhang, Y.; Kim, D.; Brossard, F.; Hu, X.; Benamara, M.; Ware, M. E.; Mazur, Y. I.; et al. Defect-Free Self-Catalyzed GaAs/GaAsP Nanowire Quantum Dots Grown on Silicon Substrate. *Nano Lett.* **2016**, *16* (1), 504–511.
- (42) Schwartz, I.; Cogan, D.; Schmidgall, E. R.; Don, Y.; Gantz, L.; Kenneth, O.; Lindner, N. H.; Gershoni, D. Deterministic Generation of a Cluster State of Entangled Photons. *Science* **2016**, *354* (6311), 434–437.