An optical in situ strategy for the analysis of oxygen diffusion in ultrathin ceria layers with a thickness of 2−10 nm at temperatures between 50 and 200 °C is presented, which allows for the determination of diffusion coefficients. This method is based on the sensitivity of the photoluminescence (PL) intensity of InGaN nanowires to adsorbed oxygen. The oxygen diffusion through an ultrathin CeO2 coating deposited on the InGaN nanowires is monitored by analyzing the transient PL behavior of the InGaN nanowires, which responds to changes of the oxygen concentration in the environment when the corresponding oxygen concentration is established at the CeO2/InGaN interface due to diffusion through the coating. Quantitative evaluation of the oxygen diffusion in CeO2 based on a model considering Langmuir Adsorption and recombination yields a diffusion coefficient D of (2.55 ± 0.05) × 10−16 cm2 s−1 at a temperature of 100 °C. Temperature-dependent measurements reveal an Arrhenius type behavior of D with an activation energy of (0.28 ± 0.04) eV. In contrast, no oxygen diffusion is detected for an ultrathin layer (≥5 nm) of Al2O3, which is known as a poor oxygen ion conductor within the analyzed temperature regime.

1. Introduction

Understanding of the chemical diffusion processes and the knowledge of diffusion coefficients is essential for the design of ion-conducting layers in batteries,[1] catalysts,[2,3] or solid oxide fuel cells.[4,5] A material of high interest regarding the diffusion properties of oxygen is CeO2. It is known to exhibit a high oxygen diffusion coefficient, as oxygen vacancies are easily formed in its fluorite structure, which is the basis of the oxygen diffusion mechanism.[2,3] Typically, CeO2 is doped with rare earth materials (e.g., Y, Nd, Gd, Sm, Pr, La) or transition metals (mainly Zr) to enhance the oxygen storage and diffusion properties.[3,6,7] In this work we focus on the oxygen diffusion in nominally undoped ultrathin CeO2 layers grown by atomic layer deposition (ALD) to gain insight into basic material properties.

Oxygen self-diffusion coefficients in CeO2 are usually determined by experiments with isotope tracers, like O18 in combination with secondary ion mass spectrometry (SIMS)[7–9] or gas phase analysis[8] at elevated temperatures above 1000 K. Alternatively, self-diffusion coefficients are also estimated from conductivity measurements.[3,7,10] Reported literature values for the oxygen diffusion coefficient extracted from such methods range between 10−12 and 10−7 cm2 s−1 at 1000 K and exhibit activation energies between 0.4 eV and 2.3 eV.[3,8,9,11–13] The wide variation of the reported values mirrors the experimental difficulties involved in the determination of the oxygen self-diffusion coefficient. Furthermore, the methods reported so far are mainly applicable for bulk material. Hence, due to the small diffusion lengths involved, determination of the diffusion coefficients at room temperature or moderate temperatures below 200 °C has not been reported.

In this work we present an optical approach for the nonintrusive in situ monitoring of oxygen self-diffusion and the determination of oxygen diffusion coefficients in ultrathin CeO2 layers deposited by ALD on InGaN/GaN nanowire (NW) heterostructures. The latter serve as optical probes for the photoluminescence (PL) detection of interfacial oxygen adsorption, as their PL intensity is efficiently quenched upon adsorption of oxygen.[14,15] Here, the diffusion of oxygen through the CeO2 coating, i.e., the temporal evolution of the oxygen concentration at the InGaN/CeO2 interface, is monitored via detection of

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the time-dependent photoluminescence intensity. Investigation of different layer thicknesses and quantitative modeling of the extracted transients allows for quantitative estimation of the diffusion coefficients. This nondestructive in situ technique is applicable for ultrathin layers and for temperatures below 200 °C.

2. Results and Discussion

2.1. Sample Design and Concept

InGaN/GaN nanowire structures which feature a PL quenching response upon exposure to oxygen and other oxidizing gases\cite{14,15} were coated with a 2–10 nm thick homogeneous CeO2 layer by ALD as displayed in the schematic and in the high-resolution transmission electron microscopy (HRTEM) image in Figure 1.

The PL characteristics of the resulting nanocomposite in atmospheres with different oxygen concentration were recorded at temperatures of 50, 100, 150, and 200 °C. Due to the dense, homogeneous ALD coating, the InGaN core of the nanowire composite was not in direct contact with the surrounding gas atmosphere. To cause a PL quenching response to the oxygen-containing atmosphere, oxygen has to diffuse through the CeO2 coating until it reaches the CeO2/InGaN interface. The related time delay was detected in a transient PL measurement in direct comparison with the behavior of an uncoated InGaN/GaN reference. As the CeO2 coatings show 97% transparency for the PL excitation wavelength of 405 nm (Section S1, Supporting Information), electron–hole pairs were almost exclusively photogenerated in the InGaN core.

2.2. Influence of CeO2 Coatings on the Oxygen Response of InGaN Nanowires

Figure 2a shows PL spectra of uncoated InGaN/GaN NWs for different oxygen concentrations and temperatures. An increase of the respective entity results in quenching of the PL with the spectral shape remaining unchanged. In Figure 2b, similar PL spectra are shown for a 5 nm CeO2-coated sample. Also in this case, thermal and oxygen-induced quenching is observed, but the relative response to oxygen is reduced. The observation that oxygen has an influence on the InGaN PL intensity of 5 nm CeO2 coated samples indicates that oxygen passes the coating and reaches the CeO2/InGaN interface, where the PL quenching is induced due to interfacial oxygen adsorption.

Oxygen-induced relative PL intensity changes (responses) and their temporal evolution were investigated by a transient collection of PL spectra and evaluation of the PL intensities which were integrated over the spectral range between 400 and 700 nm.

In Figure 3a, the transient PL response for alternating intervals of pure nitrogen and 20.5% oxygen in nitrogen of the uncoated InGaN/GaN reference (black curve) and hybrid...
structures with CeO₂ coatings of different thickness (colors indicated in the figure) are compared. A detail of the transient measurements is shown in Figure 3b, which displays a magnification of the first 30 s during exposure to oxygen. Here, the transients are normalized to their maximum intensity at the end of the nitrogen-rich interval. In the magnified presentation of Figure 3b, it is seen that the time delay for the first measurable response to oxygen increases with increasing film thickness. However, similar to the uncoated sample, the sample with the 2 nm CeO₂ coating does not show any time delay and immediately responds to the oxygen exposure.

The PL intensity (Figure 3c) and the magnitude of the relative oxygen response (Figure 3d) are reduced and systematically decrease with increasing film thickness. The temperature dependence remains qualitatively comparable to that of uncoated nanowires.

In contrast, InGaN/GaN nanowires coated with ultrathin Al₂O₃ layers do only show a response to oxygen for an Al₂O₃ thickness of 2 nm. This response is qualitatively similar to that of samples coated with 2 nm of CeO₂, but already for a thickness of 5 nm the response of Al₂O₃-coated samples is completely suppressed (cf. inset in Figure 3a). As Al₂O₃ is known as a weak oxygen conductor with an oxygen self-diffusion coefficient of 5 × 10⁻¹⁷ cm² s⁻¹ at 1500 °C [16], which is by a factor of 10¹⁰ smaller than that of CeO₂ (5 × 10⁻⁷ cm² s⁻¹ at 1500 °C; approximated from ref. [8]), the absence of an oxygen response for the sample with the 5 nm coating is assigned to the fact that the oxygen diffusion proceeds too slow to cause a measurable decrease of the PL intensity at the temperatures applied here. This result further supports the interpretation that the delayed oxygen response of CeO₂-coated InGaN nanowires with a coating thickness of 5–10 nm indeed corresponds to the oxygen diffusion through the coating material. However, for a 2 nm Al₂O₃ coating a response to oxygen was observed, even though it is not expected due to the small diffusion coefficient.

As displayed in Figure 3b, the sample with 2 nm Al₂O₃ coating shows an immediate decrease in PL intensity upon oxygen exposure rather than a delayed response, and thus a comparable behavior as the 2 nm CeO₂ and the uncoated samples, indicating that the detection mechanism is different for 2 nm thin coatings and not induced by oxygen diffusion.

### 2.3. Application of the Langmuir Adsorption and Recombination Model

To explain the dependence of the PL quenching response of InGaN/GaN NW structures on the oxygen concentration for different temperatures, the LAR model was recently introduced [15]. According to that model the maximum oxygen response $R$ [%] is given by the maximum relative intensity change induced by a certain oxygen concentration and can be described by Equation (1)

$$ R = \frac{I_{\text{max}} - I_{\text{ref}}}{I_{\text{ref}}} \times 100 \% $$

where $I_{\text{max}}$ is the maximum PL intensity at the end of the nitrogen-rich interval, and $I_{\text{ref}}$ is the reference PL intensity. The $R$ value is separated from the gas environment by the CeO₂ coating, this result indicates that oxygen diffuses through the ceria film and causes quenching of the PL intensity when reaching the InGaN/CeO₂ interface. In the magnified presentation of Figure 3b, it is seen that the time delay for the first measurable response to oxygen increases with increasing film thickness. However, similar to the uncoated sample, the sample with the 2 nm CeO₂ coating does not show any time delay and immediately responds to the oxygen exposure.
The factor $\alpha(T)$ is the probability for nonradiative surface recombination according to the LAR model and depends on molecular properties of the adsorbate, the nanowire geometry, the potential barrier at the InGaN surface, the temperature, and the number of potential adsorption sites (cf. Section S2, Supporting Information). The term in square brackets is the oxygen surface coverage with values between 0 and 1, according to the Langmuir adsorption model. It depends on the oxygen partial pressure $p$, the thermal energy $k_B T$, and the effective adsorption energy $E_{\text{ads}}^{\text{eff}}$, given by the difference of the activation energies of adsorption and desorption. $p_0$ stands for the Langmuir desorption pressure, which is in turn dependent on temperature and the molecular mass of oxygen (for exact expressions see ref. [15] and Section S2, Supporting Information). The LAR model provides a phenomenological evidence for the temperature and concentration dependence of the oxygen response and quantitative results for $E_{\text{ads}}^{\text{eff}}$ and $\alpha(T)$ as temperature-dependent fitting parameters for the calibration curve in which $R$ is plotted as a function of the oxygen concentration or $p$. The application of the LAR model to the experimental results discussed here implies that the adsorption behavior can be described by a Langmuir isotherm. This is justified by the assumption that a defined number of oxygen adsorption sites is available at the InGaN/coating interface whose occupation probability between 0 and 1 by diffused oxygen follows the Langmuir isotherm. In that line the oxygen concentration in the solid film can be treated analogue to the partial pressure of a gas atmosphere. As for further evaluation only the interfacial oxygen concentration in saturation is taken into account, the deviation from ideal gas conditions can be overcome.

Quantitative evaluation based on the LAR model was carried out for the response curves of the hybrid nanostructures investigated here. In Figure 4a–d the PL responses of the uncoated reference and the coated nanowires are shown as a function of the oxygen concentration for different temperatures. The circles in Figure 4 indicate the experimental data while the solid lines represent the fits according to Equation (2).

All curves show the typical S-shape behavior, with zero response at very low concentrations, a quasi-logarithmic increase of response, which covers approximately three orders of magnitude in concentration, and a saturation regime with a maximum response at high concentrations. The concentration, where 50% of the maximum response is reached (turning point of the curve) is analyte- and temperature-dependent and directly linked to the effective adsorption energy $E_{\text{ads}}^{\text{eff}}$ in the LAR model.

**Figure 4.** Concentration-dependent response measurements fitted by the LAR model: a) uncoated, b) 2 nm CeO$_2$-coated, c) 5 nm CeO$_2$-coated, and d) 10 nm CeO$_2$-coated. Notice the change in scale of panels (c) and (d).
The observed increase of $E_{ads}^{eff}$ with temperature was previously attributed to a thermally activated transition of phys- to chemisorption on natively oxidized InGaN surfaces.\textsuperscript{[15]} For the experiments reported here this evolution could indicate a ther-
maIy activated modification of interfacial adsorption sites and thus a stabili-
zation of adsorbed oxygen.

The nonradiative surface recombination probability $\alpha(T)$ shows similar values and temperature dependence for uncoated and 2 nm CeO$_2$ coated samples, again indicating a similar detection me-
chanism for these samples. The observed temperature dependence is mainly determined by the potential barrier the carriers need to overcome, if they recombine nonradiatively over the adsorbed oxygen (cf. Section S2, Supporting Information).

However, for 5 and 10 nm CeO$_2$ coated samples, the absolute values of $\alpha(T)$ and the temperature dependence are both reduced. As $\alpha$ is linked to the number of surface states (cf. Section S2, Sup-
porting Information), the smaller values indicate that the number of adsorption sites at the InGaN/coating interface is reduced compared to an InGaN surface while it is not further influenced by the coating thickness. Consequently, full occupation of available adsorption sites is achieved at lower oxygen concentrations. The difference in temperature dependence can be assigned to a different potential barrier for coated and uncoated samples.

2.4. Determination of Diffusion Coefficients

Based on the quantitative relation between each PL response value and the respective oxygen concentration provided by the LAR-evaluation, the transient PL response measurements can serve as a base for modeling the oxygen diffusion applying the following strategy (exemplarily shown for a 10 nm CeO$_2$ coating measured at 150 °C in Figure 6):

(1) Figure 6a shows the time-dependent response to oxygen obtained by converting the measured PL($t$) to an $R(t)$-curve by Equation (1). $t = 0$ is the last point of the N$_2$ interval. The sub-
sequent increase in oxygen response is caused by the exposure to an atmosphere containing 20.5% of oxygen (synthetic air).

(2) The measured response is linked to the oxygen concentration at the InGaN/coating interface by the LAR model. By convert-
ing the $R(t)$ into a curve that displays the temporal evolu-
tion of the interfacial oxygen concentration, $c$ ($x = 10$ nm, $t$), represented by the data points in Figure 6b (cf. schematic in Figure 6b). As $\alpha(T)$ differs for uncoated and differently coated samples, the LAR fit result for the specific sample and tem-
perature must be used for this conversion. The error bars in Figure 6b are derived from the maximum deviation of experimental values from the LAR fit.

(3) The $c$ ($x = 10$ nm, $t$) data points in Figure 6b are fitted using Fick’s second law of diffusion (solid line in Figure 6b), expressed in detail in Equation (3), if an infinite reservoir of oxygen with a fixed surface concentration $c_s$ is assumed

$$c(x, t) = c_s \times \left[ 1 - \text{erf}\left( \frac{x}{2\sqrt{Dt}} \right) \right]$$  \hspace{1cm} (3)

Here, $x$ is the penetration depth and given by the thickness of CeO$_2$ coating, $c_s$ is given by the offered oxygen concentration
For the example shown in Figure 6 a diffusion coefficient of $D = (6.00 \pm 0.07) \times 10^{-16}$ cm$^2$ s$^{-1}$ is obtained for a 10 nm CeO$_2$-coated sample at a temperature of 150 °C. The error was derived by the standard error of the fit by Fick’s law, which was applied to the concentration values including their respective errors.

Following this procedure, diffusion coefficients for coatings with a thickness of 5 and 10 nm at temperatures of 50, 100, 150, and 200 °C were determined and are displayed in an Arrhenius plot in Figure 7. For comparison values for higher temperatures that are reported in literature are also shown. It is evident from the inset in Figure 7 that the 5 and 10 nm coated samples show similar diffusion coefficients independent of the film thickness, which increase with increasing temperature in an Arrhenius type behavior. A linear fit of these results is indicated in Figure 7 and its inset and reveals an activation energy of $E_{\text{act}} = (0.28 \pm 0.04)$ eV.

The comparison to existing literature values for the diffusion coefficient $D$, derived from different experimental and theoretical methods, indicated by the solid symbols in Figure 7, shows that our results fit into the range which is covered by the extrapolation to the investigated temperature regime of 50–200 °C, as indicated by the yellow area in Figure 7. Experimental literature values do only exist for elevated temperatures above 500 °C and were obtained for bulk material.

The related activation energies for the self-diffusion process can be assigned to two diffusion mechanisms, as suggested by Kamiya et al. High activation energies between 1.6 and 2.3 eV are attributed to the formation of vacancies at elevated temperatures above 1000 K and give rise to an intrinsic diffusion mechanism. Smaller activation energies between 0.4 and 0.6 eV are typically assigned to extrinsic diffusion mechanisms of 0.205 (synthetic air). Therefore, a fit of the $c(x,t)$ curve by Equation (3) provides the diffusion coefficient $D$ as fitting parameter.

This fitting procedure is applicable only for those samples where the time delay in the PL response is dominated by the diffusion process. For those samples with a fast PL response, the response time is determined by the exchange of the gas volume in the measurement chamber and hence a fit based in the law of diffusion is not meaningful (this is demonstrated in Section S3, Supporting Information).
processes observed for nonstoichiometric ceria already at lower temperatures.[8,11,13] This extrinsic diffusion process is dominated by impurity or defect diffusion, mainly assigned to the oxygen vacancy. These lower activation energies are similar to those obtained for Y- or Gd- doped CeO$_2$[8] which supports the assumption that the diffusion process observed in the present experiments is impurity-dominated.[8] The activation energy of $E_{\text{act}} = (0.28 \pm 0.04)$ eV extracted from our experiments agrees well with the values for extrinsic diffusion, as it is expected for the comparatively high density of oxygen vacancies due to high surface area and small film thickness. It has previously been shown that structural properties of the coating and particularly the presence of strain can influence the diffusion properties in oxide layers.[17] Figure 8 shows a detailed TEM analysis of the CeO$_2$ coating and the interfacial region to the GaN part of the nanowire, which is qualitatively similar to InGaN/ CeO$_2$ interface. The CeO$_2$ shell is composed of nanocrystals with ~5 nm diameter. Those nanocrystals are mainly epitaxially attached to the GaN surface with a good alignment between the (111) CeO$_2$ and the (0002) GaN planes. It should be noticed that the geometric phase analysis (GPA) dilatation maps show a mismatch relation of about 20.4% between the above mentioned families of planes, which is in good agreement with a perfect relaxation of the CeO$_2$ structure, implying the creation of misfit dislocations every five (111) CeO$_2$ planes and six (0002) GaN planes. This relaxation mechanism is complex as also the interaction of the nanocrystals with their closest neighbors has to be taken into account. This is the reason, why in some cases there is also a rotation observed in the (111) CeO$_2$ planes, implying an elastic deformation of the planes, in competition to the plastic deformation due to the formation of misfit dislocations. In sum, the influence of strain to the oxygen diffusion in the CeO$_2$ coatings can be neglected, but grain boundary diffusion has to be considered besides the bulk diffusion process in the CeO$_2$ grains. Also, the anelastic properties of ceria[18,19] might have influence on the oxygen penetration and diffusion properties in the ceria film and therefore on the determined diffusion coefficient and activation energy.

Due to the fast response time an extraction of the diffusion coefficients for the samples with an Al$_2$O$_3$ or CeO$_2$ coating thickness of 2 nm is not possible based on the existing experimental data. According to Figures 3 and 4 those samples show an almost instantaneous oxygen response with a similar magnitude, id est no time delay due to oxygen diffusion processes is observed for uncoated, 2 nm CeO$_2$ and 2 nm Al$_2$O$_3$ coated samples. In combination with the different extracted $\alpha(T)$ parameter of the 2 nm CeO$_2$ coating in comparison to the samples with a thicker coating, shown in Figure 5b, it can be concluded that a different detection mechanism has to be taken into account for samples with a coating thickness of 2 nm. In particular, oxygen diffusion does not determine PL response time for a coating thickness of 2 nm. The similarity of the extracted $\alpha(T)$-values and its temperature dependence for the samples with a 2 nm CeO$_2$ coating and the reference points toward a similar detection mechanism for those samples. Additionally, the observed oxygen response of 2 nm Al$_2$O$_3$-coated samples, even though oxygen diffusion is not likely to occur in Al$_2$O$_3$, supports this assumption.

A possible reason for the observed response characteristics of those structures could be that nonradiative recombination via oxygen atoms adsorbed at the surface that occurs via tunneling of photoexcited carriers through the oxide coating rather than the diffusion of oxygen determines the recombination process. The probability of this process is enhanced by the small oxide thickness and possibly further increased by monolayer thickness fluctuations. The strong temperature dependence of this process that rapidly decreases in probability for increasing coating thickness further supports this assignment.
3. Conclusion

We have presented a strategy for the in situ optical analysis of oxygen diffusion in ultrathin CeO₂ films with a thickness from 2–10 nm that were deposited on plasma-assisted molecular beam epitaxy (PAMBE)-grown InGaN nanowires by ALD. Employing the sensitivity of the InGaN nanowire photoluminescence to the adsorption of oxygen, oxygen diffusion coefficients in CeO₂ in the low temperature regime between 50 and 200 °C could be determined. A quantitative evaluation of PL transients upon exposure of the InGaN/CeO₂ hybrid nanostructures to oxygen was performed using a Langmuir Adsorption and Recombination model in combination with Fick’s second law of diffusion. The extracted diffusion coefficients range between 1.5 × 10⁻¹⁶ cm² s⁻¹ at 50 °C and 5.9 × 10⁻¹⁵ cm² s⁻¹ at 200 °C. The systematic increase with increasing temperature, exhibiting an activation energy of (0.28 ± 0.04) eV, suggests a dominant role of extrinsic impurities such as an initially high concentration of oxygen vacancies in the diffusion process. Although literature values in the investigated temperature regime are not available, the extension of reported data to the low-temperature regime agrees well with the results presented here.

Comparative analysis of Al₂O₃ as a poor oxygen conductor resulted in nonmeasurable oxygen diffusion down to a thickness of 5 nm. The high and fast oxygen response for CeO₂ and Al₂O₃ coatings with a thickness of 2 nm indicates that for those layer thicknesses the observed oxygen response is not due to oxygen diffusion through the coating but seems to be caused by tunneling of photoexcited carriers to the oxygen adsorbate. The presented method is applicable for conformal coatings with thicknesses of above 5 nm and is limited to the low-temperature regime up to ~300 °C due to thermal quenching of the PL intensity of InGaN nanowires. The determination of large diffusion coefficients is limited by the smallest required integration time for the PL analysis, i.e., by the PL efficiency of the nanowire samples. A reasonable value for the structures investigated here is 100 ms, allowing the determination of diffusion coefficients up to ~10⁻¹³ cm² s⁻¹ for a film thickness of 5 nm.

An extension of the proposed method to other oxygen ion conducting materials would allow for systematic analysis of diffusion processes and stabilization mechanisms in ultrathin layers and their dependence on incorporated defects and impurities.

4. Experimental Section

MBE Growth of InGaN/GaN NWs: The InGaN/GaN nanowire core of the nanohybrid structure was prepared by a self-assembled growth process using PAMBE[39] and consists of a GaN base with a height of 390 nm (730 nm for Al₂O₃-coated samples) and an InGaN top part with a height of 350 nm (370 nm for Al₂O₃ coated), the diameter varies between 50 and 100 nm over the substrate area. The position of InGaN PL emission indicates a band gap of ~2.4 eV (Al₂O₃-coated: 2.25 eV) at room temperature. From these values the indium content in the alloy was estimated to x = 0.28 for the CeO₂-coated and x = 0.33 for the Al₂O₃-coated samples by taking the literature values of E_GaN = 3.44 eV, E_InN = 0.76, and b = 1.4 eV[21] into account.

Atomic Layer Deposition of Oxide Films: After growth the nanowires were coated with thin films of CeO₂ using ALD. The initial nanowire sample was cut into four pieces, where one piece remained uncoated as reference sample and the other three were coated with 2, 5, and 10 nm ceria, respectively.

ALD of CeO₂ was carried out at a deposition temperature of 270 °C[22] using Ce(thd)₄ and ozone as precursors at a deposition rate of 80 cycles nm⁻¹ (thicknesses verified by HRTEM). The film is transparent for the excitation wavelength (405 nm) and PL emission wavelength of InGaN (517 nm). Optical transmission measurements are shown in Figure S1 of the Supporting Information.

Al₂O₃ coatings were prepared by thermal ALD at a growth temperature of 250 °C using trimethylaluminium and water as precursors and a deposition rate of 11 cycles nm⁻¹. The film thicknesses were verified by HRTEM.

Transmission Electron Microscopy: HRTEM was performed using a TECNAI F20 field emission gun microscope operated at 200 kV with a point-to-point resolution of 0.14 nm.

Transient Photoluminescence Measurements: For the PL measurements in atmosphere with controlled oxygen content the sample was mounted on a cell with a continuous gas flow of 200 sccm. A defined mixture of nitrogen and oxygen gas was led through the chamber; the oxygen concentration was controlled by mass flow controllers.

Temperature control between room temperature and 200 °C was possible by positioning the sample on top of a heated copper block. For photoexcitation of the InGaN, the light of a 405 nm laser diode was fiber-coupled through a quartz glass window on top of the chamber. The laser power on the sample was measured with a powermeter and was 29 mW, the spot size on the sample had a diameter of ~2 mm. For the photoluminescence measurement the light emitted by the nanowire was fiber-coupled into a QWave USB spectrometer from rgb lasersystems. Two pass filters at 435 and 425 nm in the detection path were used to cut off the laser wavelength. For recording of the photoluminescence transients the intensity of the PL spectrum was integrated in the wavelength interval between 400 and 700 nm with a temporal resolution of 4 s.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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