Absorption and Light Scattering in InGaN-on-Sapphire- and AlGaInP-Based Light-Emitting Diodes

Sven-Silvius Schad, Barbara Neubert, Christoph Eichler, Marcus Scherer, Frank Habel, Matthias Seyboth, Ferdinand Scholz, Daniel Hofstetter, Peter Unger, Member, IEEE, Wolfgang Schmid, Christian Karnutsch, and Klaus Streubel

Abstract—Different experimental and simulation techniques aiming at a better understanding of lateral mode absorption in light-emitting diodes (LEDs) are presented in this paper. A measurement of transmitted power versus propagation distance allows us to derive the absorption losses of LED layer structures at their emission wavelength. Two models for the observed intensity distribution are presented: one is based on scattering, whereas the other relies on selective absorption. Both models were applied to InGaN-on-sapphire-based LED structures. Material absorption losses of 7 cm\(^{-1}\) for the scattering model and 4 cm\(^{-1}\) for the absorbing-layer model were obtained. Furthermore, these values are independent of the emission wavelength of the layer structure in the 403–433-nm range. The losses are mostly likely caused by a thin highly absorbing layer at the interface to the substrate. In a second step, interference of the modal field profile with the absorbing layer can be used to determine its thickness (d = 75 nm) and its absorption coefficient (\(\alpha \approx 3900\) cm\(^{-1}\)). This method has also been tested and applied on AlGaInP-based layer structures emitting at 650 nm. In this case, the intensity decay of \(\alpha = 30\) cm\(^{-1}\) includes a contribution from the absorbing substrate.

Index Terms—Absorption, AlGaInP, buffer absorption, buffer scattering, InGaN, light-emitting diodes (LEDs), nucleation.

I. INTRODUCTION

THE HIGH PERFORMANCE of state-of-the-art light-emitting diodes (LEDs) has opened a whole range of new applications such as traffic signals, automotive rear lights, and large-area full-color outdoor displays. Besides improvement of epitaxial methods and device processing, the problem of light extraction became a further important field of research. The occurrence of total internal reflection and absorption causes a significant fraction of light to remain trapped in the semiconductor and become lost. In order to overcome the problem of total internal reflection, different strategies leading to novel chip designs were proposed.

In resonant-cavity (RC) LEDs, the internal radiation pattern is changed by coupling to a resonator. An improvement of light extraction is achieved by increasing the fraction of light propagating perpendicular to the surface. Further improvement could be obtained by outcoupling of remaining guided modes using photonic crystals [1]. Scattering at the semiconductor surface is aimed in surface-textured thin-film LEDs [2]. The extraction enhancement is achieved by scattering of the internally reflected light at the textured surface. These scattering processes change the propagation angle of nonescaping photons. Together with a highly reflective mirrorlike bottom surface, multiple scattering events are possible, and extraction gets more likely every time the surface is hit.

Besides modification of the spontaneous emission behavior and statistical light extraction approaches, a change in chip geometry is another promising strategy. The most efficient one regarding extraction is the use of truncated inverted pyramids (TIPs) [3], [4]. It uses a structured thick window layer that serves as reflector. Most of the light is extracted through the top surface, whereas the reflected part escapes through the sidewalls. Yet another chip design is implemented in the tapered LED. The light is generated in the center of a circularly symmetric device and is guided to a tapered region. Within the latter, the angle of incidence is reduced at every reflection until extraction of the guided modes takes place.

Losses can significantly reduce the device efficiency, therefore they have a major impact on the success of an extraction approach. For optimization, the different loss mechanisms have to be identified and quantified. Thus, the scope of this paper is to address light scattering, absorption, and its distribution.

II. MEASUREMENT METHOD

As opposed to established measurement methods, we employ a fully integrated optical waveguide experiment that is fabricated using standard processing techniques (see Fig. 1). For the determination of absorption losses, intensity versus propagation distance in the material is measured. This is achieved by an arrangement of an electrically passive waveguide (100-\(\mu\)m width) and two electrically active rectangular LED structures (20 \(\times\) 100 \(\mu\)m\(^2\)) in a unit. The aim of the two rectangular LEDs
is to serve as an excitation source and as a detector, respectively. The active LED structures are located at the front and back end of the waveguide region. Electrical isolation between active and passive sections is accomplished by etching 2-μm-deep grooves across the waveguide. The LED structure for excitation is driven at forward current, whereas at the detecting structure, a negative bias is applied, and the photocurrent is measured. Thus, the method is named the photocurrent measurement method (PMM). To obtain an intensity distribution as a function of distance, different units having waveguide lengths between 200 and 3000 μm are necessary. Each unit provides one data point for a specific distance as explained subsequently. The mesa formation is accomplished by a dry-etching process. Thus, steep sidewalls down to the substrate enable a lateral guiding by the semiconductor–air interface over the whole epitaxial stack.

For each unit, the same current is applied to the emitting LED structure, and the photocurrent is measured at the dedicated detecting LED structure. One advantage of an integrated optical structure, and the photocurrent is measured at the dedicated detector for each unit. The relatively large groove of 4 μm width between the emitter, waveguide, and detector will introduce large coupling losses. However, because of the much larger lateral dimension, enough light remains in the system to obtain a sufficient photocurrent.

Thus, the intensity distribution in an undisturbed waveguide can be determined. Furthermore, a sufficiently homogeneous epitaxy regarding the emission wavelength and the output power of the emitters is assumed. Since the structure is used for detection, a spectrally resolved behavior cannot be obtained. In addition, a spectral weighting due to the sensitivity of the LED detector possibly has to be accepted. Since coupling of spontaneous emitted light into a single-mode waveguide is inefficient, a multimode waveguide has to be used for this kind of experiment, and therefore, waveguide dispersion is considered for the evaluation of the intensity distribution (see Section IV-A).

The wave guiding in the vertical direction depends on the investigated material system and the layer structure itself. Regarding group III nitrides grown on sapphire, total internal reflection at the GaN–air interface and the GaN–sapphire interface occur for modes with effective index between the refractive index of GaN and the refractive index of the substrate. For AlGaN-based devices grown on GaAs, no total internal reflection exists at the substrate–epi interface. However, the large extinction coefficient causes an exponential intensity decay, which can be regarded as a weak node for the electric and magnetic field. Thus, a contribution of the substrate absorption to the overall lateral intensity decay is given.

III. EXPERIMENTAL

The measurements are done using a HP4145 semiconductor parameter analyzer. I–V curves of the detector LED structures are shown in the inset of Fig. 2 with and without illumination for InGaN-on-sapphire structures. First, we discuss the dark current I–V curves of the detector structures without illumination. Toward large negative voltages, the current arises. This behavior can be modeled by a resistor in parallel to an ideal p–n–junction. Since we have observed a clear dependence on the length of the mesa edge from the analysis of different geometries (not shown), we assume that etching-induced defects are the origin of this anomalous current increase. Between −5 and 1.7 V, the current wiggles because of the noise limit of the semiconductor parameter analyzer.

Applying an emitter forward current of 10 mA causes a significant increase in the detector current. The induced photocurrent acts as a current source in the detecting LED structure and a self-biasing occurs. Thus, a virtual increase in forward voltage $V_f$ is observed. To get rid of the parasitic leakage current and the noise current, a subtraction of both curves is performed. Thus, Fig. 2 depicts the absolute value of the net photocurrent. However, for low currents and large reverse biases, an influence of leakage current remains. Furthermore, the photocurrent is a function of voltage, since a band alignment due to the quantum-confined Stark effect occurs. Around $V = 0$, however, the I–V curves are alike for different excitations, and the photocurrent is free of parasitic effects.

We investigated three InGaN-on-sapphire samples (S1–S3). They have been grown using the same growth parameters with respect to the nucleation, recrystallization, and the further
the emission wavelength $\lambda = 400$ nm. This value is larger than $210$ nm, the intensity decay is exponential. A linear relationship is obtained on the first 500 nm of the samples. The inset depicts the net photocurrent.

The inset of Fig. 4 shows an intensity distribution for AlGaN-based LED structures with an emission wavelength of $\lambda = 650$ nm. Data is fit by an exponential law with $\alpha = 30 \text{ cm}^{-1}$. The inset depicts the net photocurrent.

The active region consists of three compressively strained InGaN/AlGaN quantum wells, which are sandwiched between two InAlP confinement layers. On the n-side of the p-n-junction, a $3.1-\mu \text{m} \ AlO_{3.5}Ga_{0.5}As$ layer follows, whereas on the p-side, a $420$-nm-thick $AlO_{0.6}Ga_{0.4}As$ layer is grown. The inset of Fig. 4 shows the photocurrent versus bias for the sample K1 emitting at 650 nm. A current of 5 mA was applied to the emitting structure. In contrast to the nitride samples, no voltage dependence is obtained. A similar evaluation of the IV curves yields the intensity distribution, which is depicted in Fig. 4. Apart from the first 900 $\mu \text{m}$, the intensity decay is exponential. A linear fit leads to an intensity decay of $\alpha = 30 \text{ cm}^{-1}$. This value is larger than typical values of AlGaN-based laser diodes [6], [7]. We show below that the observed intensity distribution is a result of the contribution from the absorbing GaAs substrate.

**IV. THEORETICAL CONSIDERATIONS**

**A. Waveguide Dispersion**

To get insight into the interaction of waveguide dispersion, scattering, and material absorption, we performed some theoretical modeling. At first, an analytical model is presented that is based on the absorption properties at the emission wavelength. The absorption properties of bulk GaN are governing higher energies with respect to the emission photon energy [5]. Thus, absorption properties of bulk GaN are governing the absorption properties at the emission wavelength. The intensity distribution is caused by a complex interplay between waveguide dispersion, scattering, and material absorption and will be discussed subsequently.

A similar intensity distribution can be observed on AlGaN-based LED structures. We will briefly outline the layer structure of an AlGaN-based sample, show the experimental intensity distribution, and discuss the results.

**TABLE I**

Layer Structure Used for the Calculation of Modal Absorption Coefficients for a Homogeneous Layer Absorption Distribution (See Fig. 1). The Refractive Index Was Taken From Literature [8] for a Wavelength of $\lambda = 400$ nm

<table>
<thead>
<tr>
<th>thickness (nm)</th>
<th>material</th>
<th>$n$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>p-GaN:Mg</td>
<td>2.5410</td>
<td>$\alpha_1$</td>
</tr>
<tr>
<td>20</td>
<td>Al$<em>{0.3}$Ga$</em>{0.7}$N:Mg</td>
<td>2.3847</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>GaN</td>
<td>2.5410</td>
<td></td>
</tr>
<tr>
<td>5x${5,4}$</td>
<td>n-GaN</td>
<td>2.5410</td>
<td></td>
</tr>
<tr>
<td>$d = d_1 = 1500$</td>
<td>n-GaN:Si</td>
<td>2.5410</td>
<td></td>
</tr>
<tr>
<td>300000</td>
<td>sapphire</td>
<td>1.7866</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE II**

Layer Structure Used for the Calculation of Modal Absorption Coefficients if a Bottom-Layer Absorption Is Assumed (See Fig. 1). $d_2$ Denotes the Thickness of the Absorbing Layer, and $d_1 + d_2 = 1500$

<table>
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<tr>
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<td>2.5410</td>
<td>$\alpha_1$</td>
</tr>
<tr>
<td>300000</td>
<td>$d_2$</td>
<td>1.7866</td>
<td>0</td>
</tr>
</tbody>
</table>

The obtained intensity versus distance behavior is depicted in Fig. 3. The dependence is clearly nonexponential, and despite different emission wavelengths, the samples exhibit nearly the same distance dependence. As reported previously, the intensity distribution is not affected by the common rough backsurface of the sapphire substrate [5]. Due to the quantum-confined Stark effect, the absorption edge of the wells is detuned toward higher energies with respect to the emission photon energy [5]. Thus, absorption properties of bulk GaN are governing the absorption properties at the emission wavelength. The intensity distribution is caused by a complex interplay between waveguide dispersion, scattering, and material absorption and will be discussed subsequently.

**TABLE III**

Layer Structure Used for the Calculation of Modal Absorption Coefficients if a Bottom-Layer Absorption Is Assumed (See Fig. 1). $d_2$ Denotes the Thickness of the Absorbing Layer, and $d_1 + d_2 = 1500$

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A similar intensity distribution can be observed on AlGaN-based LED structures. We will briefly outline the layer structure of an AlGaN-based sample, show the experimental intensity distribution, and discuss the results.
used to study the consequences of waveguide dispersion on the intensity distribution. Since the complex layer structure of LEDs impedes a practical description, a simplified two-layer model consisting of a waveguide on top of a substrate is investigated. If no scattering is present, the intensity distribution can be calculated by an analytical ray-based transfer function \( f(\theta, \phi, y) \) between emitter and detector. An isotropic emission of a point source and also an isotropic absorption behavior of the detector LED structure is assumed. Moreover, the physical size of the source has to be small compared with the propagation length. In this case, the calculation of subsequent incidence angles succeeds since all interfaces are perpendicular to each other. Thus, it is possible to describe the whole propagation process in terms of the initial ray direction \( \theta \) and \( \phi \). Choosing the \( x \) axis as lateral direction and the \( y \) axis as propagation direction, the transfer function is (see Appendix I)

\[
\begin{align*}
    f(\theta, \phi, y) &= (r_{z,1}r_{z,2})^\mu_z(r_x)_{x}^\mu_x \exp \left( -\frac{\alpha_y y}{\sin \theta \sin \phi} \right) \\
    \mu_z &= \frac{y}{h \sin \phi \tan \theta} \\
    \mu_x &= \frac{y}{w \tan \phi}.
\end{align*}
\]

(1)

\( r_{z,1}(\theta) \) and \( r_{z,2}(\theta) \) denote the reflection coefficients at the waveguide–air and waveguide–substrate interface, respectively, and \( r_x(\theta, \phi) \) is the waveguide–air reflection coefficient in the lateral direction. It differs in its incident angle from \( r_{z,1} \). The geometry is accounted for by the waveguide width \( w \) and the height \( h \). The numbers of reflections in the \( z \) and \( x \) direction are \( \mu_z \) and \( \mu_x \), respectively. \( \alpha \) denotes the material absorption.

The waveguide dispersion effect enlarges the propagation distance, which is accounted by the exponential term in (1). Therefore, the observed intensity decay is larger than calculated by a pure exponential law and the associated waveguide length. Initially, no polarization is assumed; thus, 50% of the power is transverse electric (TE) and transverse magnetic (TM) polarized. The TE-polarized light with respect to the upper and lower interface is TM-like on the sidewalls, and vice versa. Each initial polarization is considered separately for the whole propagation. The photocurrent of the detector LED is obtained by integration of \( f(\theta, \phi, y) \) with respect to \( \theta \) and \( \phi \) for each initial polarization and added up.

In a first example, we calculated the intensity distribution function for a nitride-based sample, which is illustrated in Fig. 5. Within the first 40 \( \mu \)m, losses from leaky modes dominate the intensity decay. Afterwards, the behavior is almost exponential. As expected, the observed intensity decay is larger than the material absorption caused by waveguide dispersion, which is accounted for by \( \sin \theta \sin \phi \) in the exponential term in (1). However, after a short distance, the decay is almost exponential, and there the waveguide dispersion alone cannot explain the measured intensity distribution. Thus, further effects have to be taken into account.

B. Light Propagation in the Presence of a Dominating Scattering Effect

Nitride-based LEDs typically exhibit a large defect density in the buffer layer. Therefore, one possibility for the observed deviations might be scattering at the almost amorphous crystal structure at the interface between substrate and GaN layer. The presence of scattering yields additional optical losses in the waveguide since part of the light will be extracted. To study surface scattering, a ray tracer is employed. It calculates the complete trajectory for each ray and allows a summation of power at different distances to the emitter. Scattering is described by a statistical change in the propagation direction (see Appendix II). The scattered direction is calculated by a Gaussian distribution function with width \( \sigma \) centered about the specular ray for each reflection. A small \( \sigma \) causes a narrow scattering distribution and an almost undisturbed propagation. For the simulation, the same geometry and refractive indexes as those used for the undisturbed waveguide are taken. In Fig. 6, the obtained intensity distribution is depicted. The presence of scattering causes a bending of the intensity distribution curve with increasing \( \sigma \). If \( \sigma \) is chosen between 0.4 and 2.0, the intensity behavior gets more and more independent from the absolute value of \( \sigma \).
In contrast, a strong dependence on the absorption coefficient remains (Fig. 7).

Surface scattering losses combined with the waveguide dispersion effect lead to mode-dependent absorption losses. A mode with a high effective index propagates in a nearly straight way through the waveguide without significant interaction with the surface. Modes with small effective indexes, on the other hand, will experience more surface reflections, leading to increased scattering losses. Thus, the modal losses depend strongly on the effective index. This dependence leads to the measured nonexponential intensity distributions. However, modal-dependent losses can also be the result of an inhomogeneous absorption distribution.

C. Light Propagation in the Presence of Inhomogeneous Absorption

The poor material quality at the substrate–GaN interface can lead to a significant band tail. Thus, we believe that the interface and part of the buffer layer can be regarded as a highly absorbing layer, and therefore, an inhomogeneous absorption distribution may be present. In this case, however, the dominant loss mechanism is absorption, not scattering.

For this model, we assume that no scattering is present in the structure. The solution of the electric field $E_y$ of the Helmholtz equation is then independent of the propagation direction $x$ and can be calculated based on the transfer matrix approach. A plane wave

$$E_y = (E_y^{(+)} \exp{ik_z z} + E_y^{(-)} \exp{-ik_z z}) \exp{ik_x x}$$

(2)

with complex $k_z$ and $k_x$, is a solution of the Helmholtz equation

$$\Delta E_y + k_0^2 E_y = 0.$$  

(3)

The application of the boundary conditions leads to a finite number of modes with a complex effective refractive index

$$n_{\text{eff}} = \frac{k_x}{k_0}.$$  

(4)

$k_0$ denotes the vacuum wave vector. The imaginary part of the effective index contains the extinction from which the modal absorption is calculated.

In the following, we compare homogeneous and inhomogeneous absorption according to Tables I and II (see Fig. 1 for explanation of the abbreviations). We focus on the nitride samples containing a highly absorbing layer at the substrate–GaN-layer interface. The remaining layers of the structure are of high material quality and will thus show low absorption. For the AlGaN-based samples, the highly absorbing GaAs substrate causes a similar effect at 650 nm.

For homogeneous absorption, one expects to observe the bare waveguide dispersion effect. The increase in path length should therefore depend only on the effective index and not on the value of the material absorption $\alpha_1$. This behavior is found for absorption coefficients of $\alpha_1 = 1 \text{ cm}^{-1}$, 10 cm$^{-1}$, and 100 cm$^{-1}$. Thus, a plot of $\alpha_{\text{mod}}/\alpha_1$ results in the same curve (Fig. 8).

The situation is different for inhomogeneous absorption. In the following example, we assume an absorbing bottom layer with an absorption coefficient of $\alpha_2 = 3000 \text{ cm}^{-1}$ and a thickness $d_2 = 300 \text{ nm}$ in order to study the effect (see Fig. 9). The sinusoidal behavior of the absorption coefficient versus the refractive index is caused by the overlap of the mode profile with the absorbing layer. Moreover, for large refractive indexes, a sudden drop of the modal absorption is observed. For those modes, the penetration depth into the absorbing layer is weak.

The range of the obtainable modal absorption coefficients are much larger than for a homogeneous absorbing structure. It is shown subsequently that the intensity distribution obtained by PMM can only be described if such a large spreading in the modal absorption is present.

For the further application of the model, it is necessary to estimate suitable modal absorption coefficients to describe the intensity distribution. The asymptotic behavior of the intensity decay depicted in Fig. 3 can be used to determine the order of magnitude of the modal absorption.
Furthermore, the amount of absorbed power must be known. This cannot be calculated from the lateral measurement data; thus, an additional measurement by a different method is required. For this purpose, another series of samples has been investigated using both the transmission method and the photothermal deflection spectroscopy (PDS) [9]. Three samples T1, T2, and T3 have been investigated which consist only of a single GaN layer with different film thicknesses ranging from 0.62 to 2.53 μm grown on double-sided polished sapphire substrates.

The obtained transmission curves are depicted in Fig. 10. For layers without absorption, the transmission should achieve the value of sapphire whenever the optical thickness of GaN is a multiple of λ/2. As can be seen in the range between 2.0 and 3.3 eV, the envelope transmission is noticeably reduced independently of the thickness. Thus, we conclude that the reduction is not caused by a bulk absorption but by a thin highly absorbing part of the layer. By numerical simulation of the transmission [9], only an amount of absorbed power (absorbance value) αd = 0.030 can be determined since neither the transmission measurement nor the PDS can be used to determine the absorbing-layer thickness. α denotes the absorption, and d the thickness of the absorbing layer.

In order to eliminate this ambiguity, we investigated which modes were necessary to describe the measured intensity distribution. Modes with a large absorption coefficient decay quickly and no longer show up in the observed range. Thus, only modes with slopes lying between the two tangents shown in Fig. 3 are of interest. The limiting absorption coefficients are αmin = 10.5 cm⁻¹ and αmax = 80.5 cm⁻¹. The product αd can be distributed into the bottom layer d1 and a remaining GaN layer d2 according to

\[ αd = α1d1 + α2d2. \]  

Besides the thickness degree of freedom, the relative composition of absorption can be changed. One possibility is

\[ α2d2 = p \cdot αd \]  

with 0 ≤ p ≤ 1. p denotes the relative absorbed power for normal incidence on the sample, which is the fraction of power absorbed in the bottom layer for the transmission measurement. Due to the overlap of the modal-field profile with the two layers, the values of d1 and d2 are important for the intensity decay of the PMM. Both parameters p and d1 of the buffer layer have been varied for αd = 0.030. In Fig. 11, the modal absorption coefficient versus buffer thickness is shown for a representative subset of modes. The absorbance distribution factor was set to p = 0.9. To get low absorption coefficients of about αmin, it is obviously necessary to have a thin absorbing bottom layer. The dependence of p is shown in Fig. 12 for the first six modes. As can be seen, the modal absorption coefficient drops below αmin for a thickness of d2max = 130 nm. This can be regarded as the maximum layer thickness since αmin has been the minimal observed absorption of the lateral intensity decay. Finally, the intensity distribution can be described by

\[ I = I_0 \sum b_i \exp \{-α_i x\} \]
where $b_i$ denotes the modal excitation factor for the mode $i$, and $\alpha_k$ the corresponding modal absorption coefficient. $x$ is the propagation distance. The theoretical modeling of the modal excitation factors is subject to further investigations; in this paper, we used them only as fitting parameters.

V. RESULTS

A. InGaN-on-Sapphire-Based LED Structures

The two simulation models were utilized to fit the measurement data. The simulation model is fitted at the experimental measurement data according to (7) using the Levenberg–Marquardt algorithm. During the fit, the eigenmodes of the layer structure and thus the modal absorption coefficients have been calculated. Thus, besides the modal excitation factors $b_i$, the important parameters $p$ and $d_2$ were the only fitting parameters. We observed a weak dependence on the modal excitation factors, but the fit was strongly influenced by the parameters $p$ and $d_2$. This behavior results in a small error in $d_2$ and $p$ and can be explained by an overlap effect of the mode profile with the absorbing layer. We obtained $d_2 = 75$ nm and $p = 0.98$. Using (5) and (6), the bottom-layer absorption $\alpha_2 \approx 3900$ cm$^{-1}$ and the absorption of the remaining LED structure $\alpha_1 = 4$ cm$^{-1}$ can be calculated.

When starting with the scattering model, the simulation curves fit the data best for an absorption coefficient of $\alpha = 7$ cm$^{-1}$ and a scattering parameter $\sigma = 0.8$. While the scattering model describes the data fairly well (see inset of Fig. 13), a perfect agreement even in logarithmic scale and across three orders of magnitude is achieved for the absorbing-layer model (Fig. 13). Both models however, predict similar values for the absorption coefficient. Although either of them allows a correct extraction of the absorption coefficient from the measured intensity distribution, it should be emphasized that photothermal deflection spectroscopy measurements based on the absorbing substrate model.

[9] clearly lead to the conclusion that the physical origin for the nonexponential decay is absorption and not scattering.

B. AlGaInP-Based LED Structures

For AlGaInP-based devices, the confinement of the optical waves is based on an absorbing substrate. This is very different from a dielectric waveguide; and therefore, the scattering model is not applicable. In contrast, the absorbing-layer model should by definition describe the experimental facts very well. In Fig. 14, a similar least-square fit, as in Fig. 13, is presented. As can be seen, the data is very well represented by the simulation curve. However, since the guidance is based on absorbance, no comparable interference effect exists. For a highly absorbing cladding layer, the modal absorption coefficients in AlGaInP-based devices increase continuously with decreasing effective index. Therefore, many more modes may contribute to the intensity distribution than for InGaN-based samples. No value for the material absorption coefficient can be calculated from the experimental data without further modeling of the mode excitation.
VI. CONCLUSION

The lateral intensity distribution in InGaN-on-sapphire-based LEDs and AlGaNp-based LEDs has been investigated. The nitride-based samples exhibit a nonexponential intensity decay that is nearly independent of the emission wavelength of the investigated samples (404–433 nm). Likewise, the 650-nm-emitting AlGaNp sample shows a region where the behavior is strictly exponential. However, a similar nonexponential intensity decay is observed for short distances. Furthermore, a theoretical model is presented and the effect of waveguide dispersion and emission from leaky modes is studied. It is found that the emission from leaky modes is not the dominating factor for the observed intensity distribution. Especially for short propagation lengths, the dispersion effect leads to a curve of intensity versus distance, which decreases considerably faster than what is expected from Lambert–Beers law and the normal material absorption. Ray-tracing simulations reveal that scattering causes a nonexponential intensity decrease. However, in the presence of significant absorption, it is still possible to derive the absorption coefficient of laterally guided modes. Moreover, the nonexponential intensity distributions can only be obtained if modal-dependent absorption losses are present. For this reason, an absorption model is developed that introduces modal-dependent absorption losses based on the overlap of the mode profile with a highly absorbing layer close to the substrate and allows a much better representation of the experimental data. Surface scattering and the absorbing layer have a similar influence on the intensity distribution of propagating light. While the scattering model leads to an absorption coefficient of $\alpha = 7 \text{ cm}^{-1}$ for the high-quality GaN layer, the absorption model leads to $4 \text{ cm}^{-1}$. The modal losses in the scattering model is described by the scattering parameter $\sigma = 0.8$. For the absorbing-layer model, the losses are caused by a thin absorbing layer with a thickness of $d_2 = 75 \text{ nm}$ and an absorption coefficient $\alpha_2 \approx 3900 \text{ cm}^{-1}$. The thickness $d_2$ is larger than the nucleation layer thickness of 40 nm. However, since part of the reduction of dislocation takes place in the beginning of the buffer layer, the larger thickness is reasonable.

By photothermal deflection spectroscopy [9], one can clearly identify the detrimental effects of such a highly absorbing layer, which is most likely the reason for the nonexponential intensity decay.

The presented techniques allow the optimization of LEDs by identification of the dominant loss mechanism. The small thickness of the highly absorbing layer indicates a poor material quality of the nucleation layer and the lowest part of the GaN-buffer layer. Due to the large amount of absorption, this layer becomes one of the major optical loss mechanisms of InGaN-LEDs grown on sapphire. Since a reduction of the absorption coefficient increases the output power exponentially, a marked improvement of efficiency and output power should be achievable. This can be done by a removal of both substrate and absorbing layer.

APPENDIX I

If no scattering is present, the intensity distribution can be analytically calculated. The fraction of detectable power to emitted power is described by the transfer function that is deduced in the following. The $x$ axis is chosen in the lateral direction, and it is assumed that the $y$ axis is the propagation direction, as shown schematically in Fig. 15. At first, waveguide dispersion is considered. As depicted, the propagation path within the waveguide can be folded out of the waveguide into a straight propagation. The increase in propagation path is obtained by

$$y_{\text{eff}} = \frac{y}{\sin \theta \sin \phi}.$$  

The number of intersections $\mu_z$ in the $z$ direction is calculated by modulo of the propagation distance in $z$ direction and the height $h$

$$\mu_z = \frac{y}{h \sin \phi \tan \theta}.$$  

For the lateral direction, $\mu_x$ is

$$\mu_x = \frac{y}{w \tan \phi},$$  

with width $w$. Furthermore, the effective reflection coefficient for the whole propagation $r_{\text{eff}}$ is

$$r_{\text{eff}} = (r_{z,1} r_{z,2})^{\mu_z} r_{x}^{\mu_x},$$

where $r_{z,1}$ denotes the reflectivity at the waveguide–air interface in $z$ direction, $r_{z,2}$ the reflectivity at the waveguide–substrate interface, and $r_x$ the reflectivity at the waveguide–air interface in $x$ direction. The square of $r_{\text{eff}}$ is the intensity reflection coefficient $R_{\text{eff}}$.

$$R_{\text{eff}} = (r_{z,1} r_{z,2})^{\mu_z} (r_x)^{2 \mu_x}.$$  

Thus, the transfer function for one polarization is

$$f(\theta, \phi, y) = (r_{z,1} r_{z,2})^{\mu_z} (r_x)^{2 \mu_x} \exp \left( \frac{\alpha y}{\sin \theta \sin \phi} \right)$$

$$\mu_z = \frac{y}{h \sin \phi \tan \theta},$$

$$\mu_x = \frac{y}{w \tan \phi}.$$  

The photocurrent is obtained by numerical integration with respect to $\theta$ and $\phi$, for both, initially, TE-like and TM-like modes.
APPENDIX II

If scattering is taken into account, a ray tracer is applied. For the simulation, a statistical description of surface scattering is used; the direction of the specular reflection is modified by a Gaussian distribution function. For that purpose, the direction cosines $l = \cos \alpha$ and $m = \cos \beta$ of the specular ray are calculated. The angle $\alpha (\beta)$ lies in between the $x$ axis ($y$ axis) and the specular ray direction of a local coordinate system. The scattering distribution function then modifies these values according to

$$f_{lm}(l, m) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{r^2}{2\sigma^2} \right)$$

where

$$l = l_{\text{scattered}} - l_{\text{specular}}$$
$$m = m_{\text{scattered}} - m_{\text{specular}}$$
$$r = \sqrt{l^2 + m^2}.$$ 

$\sigma$ is the standard deviation of the rotationally symmetric Gaussian scattering distribution.

REFERENCES


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