Design challenges for mid-UV laser diodes

Qiang Guo
Department of Materials Science and Engineering
North Carolina State Univeristy
Raleigh NC, USA
qguo4@ncsu.edu

Ronny Kirste
Adroit Materials
Cary NC, USA

Pramod Reddy
Adroit Materials
Cary NC, USA

Seiji Mita
Adroit Materials
Cary NC, USA

Ramon Collazo
Department of Materials Science and Engineering
North Carolina State University
Raleigh NC, USA

Zlatko Sitar
Department of Materials Science and Engineering
North Carolina State University
Raleigh NC, USA

***Abstract*— An optimized 270 nm UV laser structure is proposed with a predicted turn-on current density of 5 kA/cm^2. The possible loss mechanisms are discussed, including p-GaN contact layer absorption, impact of a graded AlGaN layer on hole injection, and loss due to Mg doping.**

Keywords—UV laser design, p-GaN contact layer, graded AlGaN layer, Mg-doped AlGaN

I. Introduction

AlGaN-based optoelectronic devices have a wide range of applications, such as bio-sensing, air and water purification, and non-line-of-sight communication.[1]–[3] Recently, it was demonstrated that AlGaN multiple quantum well (MQW) lasers grown on low dislocation native substrates (bulk AlN, dislocation densities < 10^3 cm^{-2}) can achieve high internal quantum efficiencies (IQE=95%), lowest laser threshold (I_{Th}=6 kW/cm^2), as well as tunable lasing wavelength from 220 nm to 350 nm.[4]–[8] Despite significant efforts, no electrically injected lasing has been demonstrated below 320 nm. It is suspected that the main challenge in the realization of mid-UV laser diodes is related to Mg doping and hole injection.[9] However, UV laser diodes also have some unique device design challenges, which are not existent in e.g. InGaN- based laser diodes with light emission in the visible wavelength range.[10], [11] For example, in the current UV laser diode design, the hole injection is achieved via a GaN-based p-contact layer instead of AlGaN, due to a higher Mg ionization energy and poor conductivity in Al-rich AlGaN layer. However, p-GaN is not transparent to the generated UV laser light. Thus, using p-GaN as a contact layer may result in partial absorption of the generated UV (laser) light, which may increase the laser threshold or even prevent the device from lasing at all. This limitation can be overcome by reducing p-GaN layer thickness or increasing the p-cladding layer thickness which lies between the p-AlGaN waveguide and the p-GaN contact layer. However, thinner contact layer and thicker p-type cladding layer will induce worse contacts and higher resistance. Another result of using p-GaN contact layer is a high interfacial barrier for holes to overcome between the GaN and the p-AlGaN cladding layer because of the abrupt change of the Al-content from 0% to 75%. This difference in the Al-content accounts for a barrier of about 0.5 eV which can be detrimental for current injection. A solution for this is the insertion of a doped, graded AlGaN layer. Thickness of this graded layer needs to be thick enough to provide a low barrier for hole injection, but cannot be too thick because parts of it may become highly absorptive due to its low Al-content. Lastly, it is known that Mg doping can introduce absorption centers in GaN and AlGaN, which adds another loss mechanism for the laser diode. Identifying and assessing all these possible losses, and reducing them are crucial for the design of UV laser diodes as it may result in a significant reduction of the anticipated laser threshold. Due to the lack of available electrically injected diodes and related experimental data, simulation of the electrical and optical properties of UV lasers is currently the only pathway to optimize these devices.

In this work, we present a comprehensive study that assesses loss on the p-side of 270 nm AlGaN-based UV laser diodes grown on AlN single crystal substrates. Based on SILVACO simulation data, we show an optimized design of the p-GaN contact layer and p-AlGaN cladding layer. With implementation of a graded AlGaN layer, the carrier injection is improved by several orders of magnitude. Based on our optimized laser structure design, the optical loss is reduced to 30 cm^{-1}, and a low threshold current density of 5 kA/cm^2 is predicted.

II. Simulation

SILVACO simulation software was used to perform device simulation and find an optimized laser device design based on the predicted electrical and optical performance of the device. Figure 1 shows a schematic of electrically-pumped UV laser structure. The structure is to be grown on AlN substrates and consists of a n-cladding layer (500 nm, 75% Al), n-waveguide (60 nm, 65% Al), 3xMQW (AlGaN/AlGaN, 3 nm/3 nm), electron blocking layer (EBL, 10 nm, 80% Al), p-waveguide (60 nm, 65% Al), p-cladding (75% Al), and a p-GaN contact layer. The n-side of the laser device is well understood since highly conductive $Al_{0.75}Ga_{0.25}N$:Si with free carrier concentrations around 10^{19} cm^{-3} can be achieved and no significant losses are associated with Si-doping.[12] The design of the MQW and EBL is important, however, many

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design rules known from InGaN can be transferred to AlGaN-based devices.[13] In contrast, the design of the p-side of the laser diode is more challenging. Here, the influence of the p-cladding thickness, the insertion of a graded layer between the GaN and the AlGaN cladding layer, and the impact of Mg-doping related absorption loss is investigated.

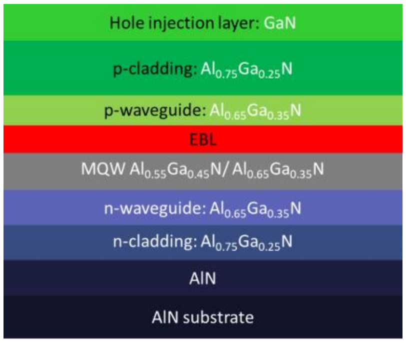

Figure 1: Schematic of the current UV laser diode design. Not shown is the graded layer between the thin p-GaN contact and the p-AlGaN cladding layer and the design of the active region which consists of 3 wells, 3 barriers, and an electron blocking layer.

III. Results

In Figure 1, hole injection is achieved via a GaN based p-contact layer. Since the energy of anticipated laser light of 270 nm is above the bandgap of GaN, this contact layer is absorbing the generated laser light. In addition, due to a higher refractive index in GaN compared to AlGaN, an anti-guiding effect is expected which, in the case of thicker GaN layers (>150 nm), can lead to a leakage of the laser mode into this layer. Both absorption and anti-guiding will add optical losses, increase the laser threshold and ultimately prevent the laser diode from lasing. The most convenient way to reduce the GaN related loss is a reduction of its layer thickness to a value around 20 nm. A thinner layer below 20 nm is significantly more challenging to achieve in MOCVD and also increases the contact resistance of Ni/Au-based contact. However, even for 20 nm layer thickness, a non-negligible part of the laser light may still penetrate into the p-GaN layer. Figure 2 shows light distribution of 270 nm AlGaN MQW laser structure based on SILVACO simulation. The maximum light intensity is achieved in the active region of the laser waveguide, which is consistent with the targeted design considerations. However, laser light also travels into the highly absorbing p-GaN contact layer. Although its thickness is only 20 nm, it is found that about 0.1 % of the wave intensity is in the absorbing p-GaN contact layer, which represents a considerable loss if the absorption coefficient of this layer is assumed to be 100,000 cm^{-1}.

In addition to reducing the p-GaN contact layer thickness, the p-cladding layer thickness can be increased. A thicker p-cladding layer thickness will reduce the light in the p-GaN layer and reduce the optical loss. Figure 3 shows simulation results for the laser threshold as a function of optical loss in the laser structure for the device design discussed above. The optical loss for different cladding thicknesses is indicated in Figure 3 as well. The data only considers optical loss in p-GaN with different cladding layer thickness, other losses such as defect absorption centers, facet losses, or scattering losses, are not considered. It is found that the calculated loss is around 5 cm^{-1} for a 500 nm thick p-cladding layer, which reduces the expected threshold to about 2 kA/cm^2. A reduction of p-cladding layer thickness increases the loss non-linearly and, for a cladding layer thickness below 60 nm, the absorption loss becomes dominant thus lasing cannot be achieved. It should also be noted that p-cladding thickness also plays an important role on the electrical properties of the laser device. Since the doping efficiency of AlGaN:Mg is very low due to compensation and high activation energy of the acceptor, the p-AlGaN cladding layer has a high series resistance. Too thick p-AlGaN layer is not favorable for hole transport. Thus, a 500 nm thick cladding layer is chosen as an optimized cladding thickness for the 270 nm laser structure to reduce absorption from p-GaN layer while keeping manageable resistance.

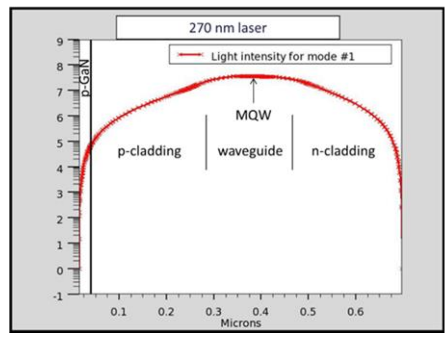

Figure 2: Light intensity distribution in a UV laser diode emitting at 270 nm as a function of the position based on SILVACO simulation data.

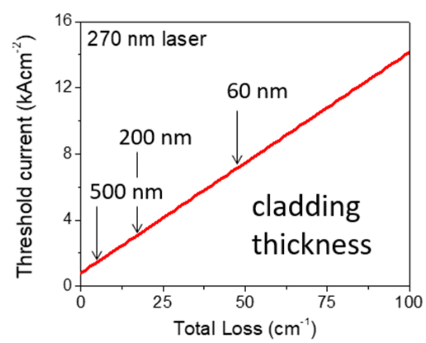

Figure 3: Simulated results of threshold current as a function of optical loss in the laser diode. The loss in p-GaN for different p-cladding layer thickness is indicated. For thin p-cladding layers, a higher loss and therefore a higher threshold are expected.

To achieve good optical confinement, the p-AlGaN cladding is designed with 75 % Al composition to allow for enough refractive index difference ($\Delta n \approx 0.1$) between the p-cladding and the p-waveguide. Since the p-GaN contact layer is grown on top of this Al-rich layer, injected holes have to overcome an interfacial barrier of about 0.5 eV. To overcome this limitation, a graded AlGaN layer is inserted between the p-GaN and the p-AlGaN. Figure 4 (a) shows the simulated current voltage curve of a UV laser with and without a graded layer between the p-GaN and the p-AlGaN layer. The data plotted in Figure 4 is based on SILVACO simulation. It is found that devices with a graded layer between the p-GaN and the p-AlGaN allow for about 3 orders of magnitude higher current density than devices grown without a graded layer. This is because of the reduction of the valence band barrier height that the holes need to overcome when a voltage is applied. As mentioned, without a graded layer, the holes need to overcome a barrier of approximately 0.5 eV from GaN to AlGaN. This energy is far beyond the thermal energy and presents a significant barrier to the holes that hinders efficient injection into the active region. Ultimately, for the laser structure without a graded layer, it is predicted that the maximum current density is still below the value needed to achieve population inversion. A graded layer, on the other hand, reduces this barrier height significantly, making current density high enough to achieve lasing. However, too thick graded AlGaN layer will also increase absorption in the laser since about 70% of the layer will have a bandgap smaller than the energy of the emitted UV laser light. This can be understood as the equivalent of an increased p-GaN layer thickness and the associated optical losses. Figure 4 (b) shows simulation results for the laser threshold current with different graded layer thicknesses. It is found that the laser threshold current is significantly increased when graded layer thickness increases from 20 nm to 60 nm. As a consequence, it is predicted that 20 nm of graded layer thickness is found to be sufficient to allow for high enough current densities while at the same time limiting the absorption loss to about 12 cm^{-1}.

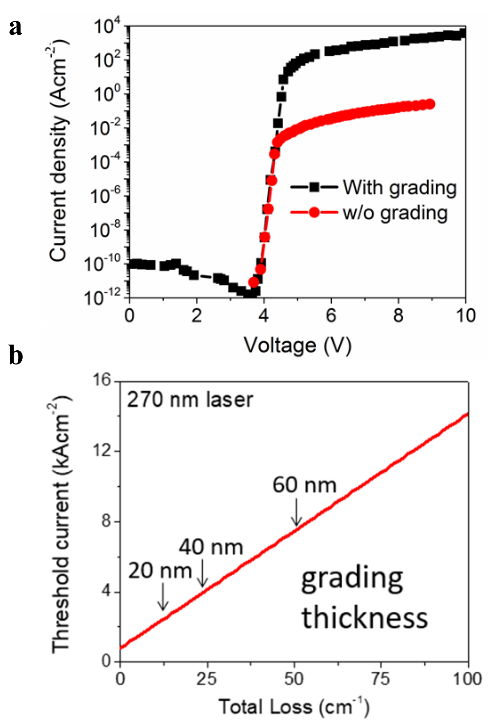

Figure 4: (a) Current voltage curve of a UV laser diode for a device with and without a graded layer (20 nm) between the p-contact layer and the p-cladding layer. (b) Threshold current as a function of optical loss in the laser diode. The loss is calculated from different grading layer thicknesses.

So far, we have only considered the absorption above the bandgap energy in GaN and graded AlGaN layer. For theses layers, the absorption is because the UV laser light energy is above the bandgap of the semiconductor. However, another major contribution for absorption losses on the p-side of the laser diode is Magnesium. Mg doping in GaN, InGaN, and AlGaN is known to introduce an absorption center as well. The strength of the absorption depends on the Mg doping concentration and the Al-content. Recent work from Martens et al. [11] indicated that Mg doped AlGaN layer may have a sub-bandgap defect center related absorption coefficient of around 30 cm^{-1}. Furthermore, it was claimed that depending on the confinement factor, this can introduce modal losses as high as 50 cm^{-1}. Figure 5 shows the laser threshold of the UV laser diode as a function of optical losses. Contributions from the p-GaN, the p-AlGaN cladding layer, and the Mg doping are indicated by arrows. Here a p-GaN thickness and a graded layer thickness of 20 nm are considered while a p-AlGaN cladding layer thickness of 500 nm is assumed. It is found the total loss is around 40 cm^{-1} , which results in a predicted laser threshold of 5 kA/cm^2. The predicted threshold is based on the output characteristic of the optimized laser structure as calculated via SILVACO. Other losses, such as decreased carrier injection efficiency (EBL design/ MQW design) or loss at the facets, are assumed to be negligible. The predicted laser threshold is found to agree with the best values achieved for electrically injected UV-B laser diode.

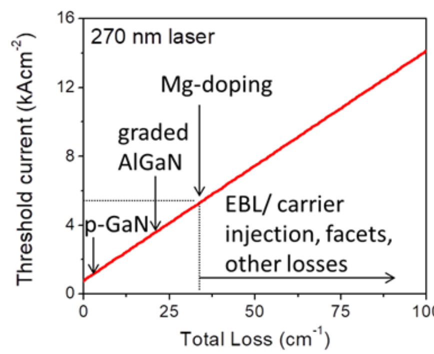

Figure 5: Threshold current as a function of optical loss with the indication of impact of the main losses related to the p-side of the laser diode. A laser threshold current density of 5 kA/cm^2 is predicted for an optimized laser emitting at 270 nm. The simulation assumes coated facet with reflectance > 95% to reduce these losses.

IV. CONCLUSIONS

In summary, our recent simulation data indicates that a low UV laser threshold current can be achieved if an optimized laser design is chosen. This includes implementation of 500 nm p-cladding layer and 20 nm graded layer between the p-GaN contact layer and the p-AlGaN cladding layer. A low threshold current density of 5 kA/cm^2 is predicted.

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