Transfer Printing of Roughened GaN-Based Light-Emitting Diodes into Reflective Trenches for Visible Light Communication

Zeinab Shaban,* Zhi Li,* Brendan Roycroft, Mehrdad Saei, Tanmay Mondal, and Brian Corbett

There is a great need to integrate dissimilar visible light components for the fabrication of thin, flexible, and 3D structures in the next generations of display and communication systems. Compared with monolithic integration, micro-transfer printing (µTP) of miniaturized devices allows the heterogeneous assembly of diverse devices in a scalable and cost-effective manner for expanded functionality. Here, advantages of µTP technology to boost the directional light output of light-emitting diodes (LEDs) are demonstrated with a remarkable sevenfold enhancement compared with devices on the original substrate. This is achieved using an original integrated approach to roughen the backside of the GaN-on-Si LEDs during their release together with their printing into 10 μm-deep reflective trenches formed in a new substrate. To address the bending of the 110 × 110 μm² LEDs due to the internal stress from the GaN layers, compensational stress with deposited SiNx, is engineered, which results in flat surfaces and successful transfer printing. Finally, the LEDs in trench are used in visible light communication (VLC), showing higher signal-to-noise ratio and lower bit-error rate compared with a flat platform due to higher power collected. This strategy could be used to integrate different colors of LEDs for enhanced VLC as well as in displays.

1. Introduction

Gallium nitride (GaN)-based light-emitting diodes (LEDs) have established themselves in a variety of applications, especially in delivering light at high brightness with low energy consumption and long lifetimes.[1–4] Due to the high efficiency and short response time of these materials, there has been intense interest from both academia and industry in devices at micrometer scales, that is, micro-LEDs (µLEDs), due to exciting opportunities for emerging applications in microdisplays,[5,6] visible light communication (VLC),[7–9] optogenetics,[10] and more. Particularly, GaN LEDs grown on Si have been broadly utilized within these applications due to their scalability, low manufacturing cost, and compatibility with existing Si (standard IC) manufacturing lines.[11,12] One critical step in these applications, however, involves how the LEDs are connected and combined with other components such as electronics in a precise and cost-effective manner.

Micro-transfer printing (µTP), as an emerging technology, has become a promising method to heterogeneously integrate components from different materials or fabrication platforms, hence achieving new functionality or applications. Compared with other techniques such as wafer bonding, which is extremely sensitive to wafer surface morphology and thermal expansion behaviors, and monolithic growth, which suffers from lattice mismatch between different layers, µTP is not only a more flexible process to combine different units together, but also is an efficient and highly accurate technique suitable for mass transfer of devices.[13,14] Various applications using µTP have been demonstrated such as photovoltaics,[15] optical communications,[16] optoelectronics,[17,18] and displays.[19] For example, active-matrix color displays were achieved by integrating red, green, and blue LEDs by transfer printing,[20] while GaN transistors were integrated with Si CMOS using this technology.[21] Printed µLED arrays used as VLC transmitters were also demonstrated in 2019.[22]

As Si can be selectively removed by wet chemical processes, it makes the releasing of GaN LEDs from Si substrates possible, allowing relatively easier assembly and exploitation in heterogeneous integration technologies.[23] Although good progress has been made, optimizing the GaN-on-Si LED fabrication process particularly for the transfer printing technique is still challenging. For instance, one needs to release the LED epilayers from the Si substrate while there is large residual stress in the epilayers due to the engineered flatness of the large-area wafers during epitaxial growth controlled by lattice and thermal expansion mismatch. Additional stress can also be introduced during device processing, which along with the former one results in bending

[The rest of the text is not visible in the image provided.]
of the released epilayers. This is particularly severe for large-sized devices, for example, ≥100 μm.24,25 Such issues will not only cause printing failures and hinder high yield, but also cause challenges in the postprint integration process. Another issue with GaN LEDs is that the majority of light can be trapped inside LEDs, resulting in low light extraction, which is due to the large refractive index contrast between GaN and air.26 Therefore, managing the stress to achieve flat devices as well as developing releasing processes to obtain high-performance LEDs are highly desired to advance transfer printing technologies.

In this article, we introduce several innovations to advance the performance of transfer-printed GaN-on-Si LEDs. To manage the intrinsic stress in GaN on Si, we proposed a stress compensation approach utilizing SiN layers based on COMSOL simulation. Control of the residual stress within the released devices is achieved by the engineered SiN layers, leading to a completely flat surface after transfer printing. In addition, we developed an integrated approach to roughen the backside of the released LEDs using aqueous tetramethylammonium hydroxide (TMAH) solution during the coupon preparation process for transfer printing. Measurements show that light output power collected into a numerical aperture of 0.5 from the roughened devices is enhanced by a factor of 2.14 when compared with the nonroughened LEDs, which is attributed to effective light scattering from the roughened surfaces where a high density of pyramids is formed. The combination of the roughening technique in conjunction with the silver reflector improved the light output power by a factor of 4.2 when compared with the device on the initial substrate. Using the unique property of transfer printing, the released LEDs are printed into silver coated trenches where a further improvement in optical power by a factor of 1.8 was achieved due to the light redirection effect by the trench. As a result, a net 7x increase in the forward-directed power is obtained. Finally, the potential of the fabricated devices was investigated for VLC. The >3 dB modulation bandwidth of the roughened blue LED with the size of 110 μm × 110 μm is 120 MHz at 60 mA. The roughened LEDs printed inside the reflective trench exhibited the lowest bit error rate (BER) and data rate of 270 Mbps due to enhanced light coupling into the collecting lens.

2. Results and Discussion

2.1. Stress Management

As GaN grown on Si generates high inbuilt stress during epitaxy, AlGaN/AlN buffer layers are normally used to compensate the differential thermal expansion between the Si substrate and GaN layers to avoid cracking and obtain flat wafers after growth. The residual stress within the epilayers was measured. To estimate the influence of processing on the additional deformation and curvature, COMSOL was used to simulate the thermal stress caused by plasma-enhanced chemical vapor deposition (PECVD) deposition of SiN layers on the devices. A simplified LED structure is assumed, as shown in Figure 1a, consisting of a 1 μm-thick AlGaN buffer layer and a 4 μm-thick GaN layer anchored with a 1 μm-thick SiN layer. The structure is 1.5 μm above the substrate. The stress within the epilayers originating from epitaxial growth is set to 70 MPa compressive stress to agree with the measured value in the LED wafers. The additional thermal stress of LED is simulated when the high temperature (i.e., 300 °C)-deposited SiN layer cools down to 20 °C, with the deformation on the device shown and analyzed. It can be seen from Figure 1b,c that the SiN layer with neutral stress and with 200 MPa tensile stress cause upward deformation at the edge of the released coupon of 1.4 and 2.5 μm, respectively, while the same thickness of SiN layer with 200 MPa compressive stress reduces the deformation value to 0.5 μm (Figure 1d).

Based on simulations, 1 μm of SiN layer with compressive and neutral stress was deposited by PECVD to compare the stress of the released coupon. Device deformation also was investigated by measuring the curvature using a profilometer and using white light interferometry of the transfer-printed devices. Note that the total thickness of transfer-printed devices including the epilayers and the SiN layer is now around 6.5 μm. As shown in Figure 2a, the profilometer measurement confirmed upward deformation of the device with neutral stress. Newton interference rings were observed due to the air gap between the substrate and device, as shown in the microscope images in Figure 2a. From Figure 2b, it is clear that the device with neutral stress in the deposited SiN layer suffers from net tensile stress and deforms upwards, which is in good agreement with simulation data. Simulation results and experimental data confirmed that by controlling the stress of the PECVD-deposited SiN layers, the residual stress within devices, when released from the substrate, could be compensated, resulting in a completely flat surface after undercut. It is worth noting that, while bowed devices can be printed, the process has large failure rate, whereas all compensated (i.e., flat) devices are printed successfully.

2.2. Performance of LEDs before and after Transfer Printing

To investigate how the roughening and the printing process affects the device performance, the current-voltage (I–V) characteristics of the LEDs before undercut and after transfer printing with the roughened backside (on Intervia-coated Si)27 are measured with the test devices with large bond pads, as shown in Figure 3a. It can be seen that the diode characteristic of the roughened LEDs is improved, with the voltage at the injected current of 10 mA reduced from 4.06 to 3.8 V, showing a reduction of the series resistance after the undercut. This result is confirmed by measuring a large number of devices. The voltage decrease could be attributed to the small bandgap shrinking due to self-heating resulting from the adhesive layer used for printing, whereas for devices before printing the Si substrate can dissipate the heat effectively. In addition, a current leakage is measured at reverse bias, inset of Figure 3a, where the leakage current is reduced from 3.7 × 10−4 A to nearly 4 × 10−6 A at −4 V. Similar results were also reported by other groups.28,29 One possible reason could be attributed to the undercut etching which removes the interfaces (mainly the one between the AlGaN buffer layers and n-GaN layer). Therefore, any possible leakage paths through the dislocations at the interface are eliminated.29,30

The electroluminescence (EL) spectra of different devices before and after printing are measured. As shown in Figure 3b, a marginal redshift of the peak wavelength is observed.
from 448 to 450 nm after printing. Similar to the voltage drop shown in Figure 3a, such a shift can also be attributed to the thermal impact of the adhesive layer (i.e., Intervia), which results in an increase in the device temperature. This thermal issue could be improved by reducing the thickness of adhesive layer. Along with the I–V curves, all of these indicate that transfer printing and undercut/roughening processes do not cause any issue for device quality.

### 2.3. Light Extraction Improvement

The effect of backside roughening and the integrated Ag reflector on the light output power are shown in Figure 4a. When compared with LEDs on the initial Si substrate, transfer printing these devices (non-roughened) onto a new Si substrate with the adhesion layer (i.e., Intervia) increases light output by a factor of 1.2, which is attributed to the low reflective index of Intervia.
while printing onto a Ag reflective layer leads to improvement by a factor of 2.0. The addition of backside roughening with the Ag reflector results in a remarkable improvement in light output by a factor of 4.2, which can be mainly attributed to the scattering effect of the pyramids formed on the backside. This is confirmed by fluorescence microscopy images of the three LEDs in Figure 4b where it is clear that the released LED with the roughened backside is the brightest image compared with the nonroughened LED. To investigate the effect of trench, the collected light output power of the device into the trench and flat platform is measured for multiple devices. As shown in Figure 4a, there is an approximate doubling (1.8x) of the collected power for roughened blue LEDs in the trench in comparison with that on the flat platform, which is attributed to the redirection of light, which means that the trench can effectively reduce the angle distribution of light, consequently converging.

Figure 3. a) Current–voltage (I–V) characteristics of the blue LED with size of 110 × 110 μm² before undercut and after transfer printing. The inset shows the I–V curves under reverse bias. b) EL spectra of nonroughened and roughened LEDs before undercut and after printing at 15 mA. The inset shows the EL spectra of the transfer-printed roughened LEDs operating under different currents.

Figure 4. a) Light output power collected into NA = 0.5 of LED before undercut, for nonroughened and roughened LED on silver-coated flat platform, and roughened LED on silver-coated trench. b) Fluorescent microscope images of printed LEDs and their corresponding optical images on the right. c) Optical image and SEM image of the printed roughened LED with size of 110 × 110 μm² into trench with depth of 10 μm.
higher optical power. In overall, the light output collected for the roughened LED in the trench is over seven times that of the device on the initial Si substrate (before undercut). An optical image and scanning electron microscope (SEM) image of the roughened LED in the 10 μm deep trench is shown in Figure 4c.

2.4. VLC with Printed LEDs

Figure 5a,b shows the frequency response and the extracted −3 dB bandwidth for the roughened LEDs in the trench at currents from 5 to 60 mA. It is seen that the frequency response and bandwidth increase with the injection current and the dependence can be related to the reduction of carrier lifetime. The maximum −3 dB bandwidth of sample is 120 MHz, which corresponded to an injected current of 60 mA. It can be seen from Figure 5c that the LEDs in the trench exhibit a higher signal-to-noise ratio (SNR) than that on a flat platform due to higher received optical power. In addition, the BER as a function of data rate for roughened LEDs and nonroughened LEDs on the flat platform and inside of the trench is shown in Figure 5d. A lower BER is observed for the device into the trench, which is in good agreement with the SNR data. The roughened LED in the trench, operating at 40 mA, can achieve a data rate of 270 Mbps with a BER of 9.6 × 10⁻⁴ before reaching the 3.8 × 10⁻³ forward-error-correction (FEC) threshold. The lower data rate for the nonroughened LED (220 Mbps) on a flat platform is likely due to its lower optical power. Finally, the eye diagram of the roughened LED and nonroughened LED on the flat platform and inside of the trench at the data rate of 100 Mbps and injection current of 40 mA are shown in Figure 5e. It can be seen that the eye diagram of the roughened LED into the trench is open and clear at 100 Mbps, which is related to the increased optical power, while the relatively noisy eye diagram for the nonroughened LED at this transmission speed is attributed to the lower SNR. Transmitting LEDs with a smaller divergence reduce spatial optical crosstalk.[31] Therefore, using the trench not only improves the light output power improving the SNR but also can be beneficial to reduce the optical crosstalk in VLC applications.

3. Conclusion

Transfer printing of released and roughened GaN-on-Si LEDs into structured and reflective trenches is demonstrated to increase the light output collected into a practical numerical aperture of 0.5 by over 7 times compared with the device on the initial Si substrate. The intrinsic deformation and curvature of the released LEDs was compensated by incorporating compressively stressed SiNx layers, leading to flat devices after releasing. We introduced an integrated backside roughening of the LEDs, which together with printing on the silver reflector improved the collected light output by a factor of 4.2. By printing the LEDs into a reflective trench, a further enhancement factor of 1.8 in the collected light is achieved. The potential of these devices for VLC was demonstrated where the results showed that the printed device in the trench improves the light output power and
consequently the SNR. Opportunities for further enhancement in the directionality can be obtained by depositing a polymeric lens. By incorporating quantum dots, effective downconversion of light to other colors can be achieved. Arrays of such devices in conjunction with detectors can act as a high-bandwidth multicolor transceiver for VLC.

4. Experimental Section

Fabrication of the LEDs for Undercut: Blue LED structures grown on (111) silicon from commercial vendors were used to fabricate the LEDs. The schematic of the device fabrication process is shown in Figure 6. The fabrication process began with the formation of a p-contact using a 40 nm Pd layer by lift-off lithography using photoresist (PR), followed by etching a mesa with the size of 100 μm × 100 μm by inductively coupled plasma (ICP) etching (Gas: Cl₂) to expose the n-GaN layer. After that, a 300 nm-thick SiO₂ insulation layer was deposited by PECVD. A window in the oxide was then patterned by lithography and opened by ICP etching (Gas: CHF₃/H₂) to expose areas above the p- and n-contacts. Subsequently, a Ti/Au (20/200 nm) layer was evaporated onto these open areas, serving as the n-contact as well as bond pads. Note that the commonly used Al-containing n-metal contact was avoided here as Al could be attacked by TMAH during the Si undercut process. LEDs with the size of 110 μm × 110 μm were defined by ICP etching (gas: BCl₃/Cl₂) through all the epilayers till the Si substrate. Then, a larger Si platform was defined by lithography and etched into the Si substrate (~1.5 μm deep) by ICP (gas: SF₆/C₄F₆) to assist the release. Finally, to prepare the LEDs for releasing and following transfer printing, 1 μm-thick SiNₓ was deposited by PECVD to passivate the sidewall of the device during wet etch. Then, SiNₓ was patterned using lithography and dry etch (gas: SF₆/C₄F₆/H₂) to form anchors along the Si [1–10] and tethers perpendicular to this direction. The anchor/tether system was used to support the suspended devices, preventing them from collapsing after releasing from the substrate. In addition to the LEDs with size of 110 × 110 μm², test devices with the same mesa size but large bond pads were also prepared for probe tests. It is noteworthy that the stress of the PECVD-deposited SiNₓ layers could be controlled by changing the plasma frequency. To be exact, deposition of SiNₓ with PECVD with low-frequency and high-frequency excitation resulted in films with compressive and tensile stress, respectively. To calculate the stress of the deposited thin film, the curvature of the

Figure 6. Fabrication process flow of blue GaN LEDs on Si. a) LED epistucture. b) Mesa etch, p–n metal evaporation. c) Coupon etch and Si etch. d) Defining tether and anchor using SiNₓ. e) Undercut etching of Si.
substrate was measured prior and after deposition of SiN, with a profilometer. A modified Stone equation was used to determine the stress of a thin layer. The residual stress within devices, when released from the substrate, could be compensated by the SiN layer, resulting in a completely flat surface after undercut, as explained in the Discussion.

**Undercut LEDs from the Original Substrate**: To enable the transfer printing process, devices were required to be separated from their original substrates and be properly anchored on the wafer. GaN-on-Si LEDs were released from the Si substrate by removing a thin layer of Si exposed by the etch from underneath the GaN epilayers using TMAH or KOH wet etching. The wet etching of Si with TMAH or KOH was highly anisotropic on (111)-oriented Si substrates, that is the etching rate of the (111) planes or their projections. As shown in Figure 7b, during the etching process, anchors oriented along the Si <1–10> direction were minimally etched while etching under the devices was fast. With 5% TMAH solution at 50 °C, 110 μm × 110 μm LEDs could be completely undercut in 2.5 h. The backside roughening of coupons was realized in this step; details will be explained in the next section.

**Backside Roughening to Improve Light Extraction**: As only a small fraction of light could be extracted from planar LEDs, proper light management was critical to achieving high device performance. An integrated approach to roughen the backside of GaN-on-Si LEDs was developed here. When the Si layer underneath the device was completely etched by the TMAH solution, the sample with suspended devices was dipped into the buffered oxide etchant to remove any native oxide and then immersed into the same aqueous 5% TMAH solution at 50 °C to form the pyramids. SEM images (not shown here) revealed that the AlN/AlGaN buffer layers were first etched by TMAH, after which the n-face GaN was exposed and pyramids were then formed on the bottom surface. As shown in Figure 8a, b, the roughening on the backside (seen as dark color in the optical microscope images) began from the edge of device and extended to the center. As the buffer layers at the edges were first exposed to TMAH etchant due to the anisotropic Si undercut etching, these areas were first roughened compared with the central areas, which explained why the roughening direction was the same as the Si undercut orientation, that is, along Si <1–10>. Figure 8c shows the completely roughened backside of the LEDs, where GaN pyramids with high density and various sizes were observed. It is worthwhile to note that the thickness of the etched GaN layers was around 1.2 μm (estimated from cross-sectional SEM of a cleaved device), which left enough n-GaN material for the contacts above.

**Fabrication of Reflective Trench and Micro-transfer Printing of Released LEDs**: To further enhance the collected optical power by redirecting the emission in the forward direction, the released LEDs were printed into silver-coated reflecting trenches formed in Si. To create the trenches in Si (100), first, SiN layer was deposited by PECVD. Then, an opening area with size of 220 × 220 μm² was defined, followed by dry etching of SiN. After that, the samples were immersed into hot TMAH for 9 min to create trenches into Si substrate with an angle of 54 and etch depth of 10 μm. Then, the patterned Ti/Ag (20/100 nm) was evaporated to serve as the reflector inside the trench, avoiding the location for subsequent metal tracks to avoid short circuit and capacitance effect after making interconnections.

The released LEDs with and without backside roughening were micro-transfer printed onto uncoated Si, Si with the reflective layer, and Si with the reflective trench to compare their light output. In the μTP process, an elastomeric transfer stamp was used to pick up the released LEDs from the original substrate and print into a new target. A layer of Intervia with thickness of 500 nm was used as an adhesive layer onto the target substrate. This technique picked up and printed devices by simply adjusting the speed of the PDMS stamp in accordance with peel rate-dependent adhesion in viscoelastic elastomers. It should be noted that when using an adhesion layer such as Intervia, the backside roughening of the device did not cause any issue in transfer printing. Finally, the LEDs into the trench were electrically interconnected using photolithography and evaporation of Ti/Ag/Au (20 nm/2000 nm/200 nm). A schematic diagram of the transfer printing into the Si trench is shown in Figure 9a–d.

**Figure 7.** Optical images of devices with size of 110 × 110 μm² a) before undercut, b) during undercut, and c) after being fully undercut. d) The SEM image of the array of released LEDs with details of an individual device.
Light Output Power and VLC Measurement: The light output power of LEDs before undercut and after printing was measured, where a lens was mounted 1 cm above the sample (numerical aperture of the setup was 0.5) to collect light into a large-area photodetector placed above the lens. The communication performance of the printed LEDs was measured using signals generated from a vector network analyzer (VNA; 8753ES) combined...
with a constant current source (Keithley 2400) via Bias-Tee (mini-circuit 15.542) to probe by a high-bandwidth ground-signal microprobe. The light output from the device was focused using an aspheric lens onto a high-speed photodetector (HSA-X-S-1G4-SI) and sent to a network analyzer to analyze the frequency response. The SNR was estimated by subtracting the noise level from the signal power. To capture the eye diagram, a digital data analyzer (MP1632A) was used to produce pseudorandom binary sequences (PRBS) pattern with peak-to-peak voltage ($V_{pp}$) of 2 V and the eye diagram was captured by an oscilloscope (DSO 80804A). The BER was estimated using the Q factor, which was obtained directly from the eye diagram at the different data rates. The printed blue LEDs on a flat reflective platform were compared with those printed into the trench by measuring the bandwidth modulation and eye diagram with on–off keying (OOK).

Acknowledgements

This work received funding through Science Foundation Ireland (12/RC/2276_P2 IPIC), Electronic Components, and Systems for European Leadership (737465, MICROPRINCE). The authors would like to acknowledge Vitaly Zubialevich, John Justice, and Fatih Atar for their help.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

GaN light-emitting diodes, light extraction, microtransfer printing, roughening, visible light communication

Received: October 13, 2021
Revised: January 25, 2022
Published online: March 22, 2022

[1] S. Nakamura, MRS Bull. 2009, 34, 101.
[2] G. Li, W. Wang, W. Yang, Y. Lin, H. Wang, Z. Lin, S. Zhou, Rep. Prog. Phys. 2016, 79, 056501.
[3] P. J. Parbrook, B. Corbett, J. Han, T. Y. Seong, H. Amano, Laser Photonics Rev. 2021, 15, 2000133.
[4] C.-L. Liao, Y.-F. Chang, C.-L. Ho, M.-C. Wu, Y.-T. Hsieh, C.-Y. Li, M.-P. Houng, C.-F. Yang, IWCMC. Light-Emitting Diodes for Visible Light Communication, Croatia, 2015, p. 665.
[5] J. Day, J. Li, D. Y. C. Lie, C. Bradford, J. Y. Lin, H. X. Jiang, Appl. Phys. Lett. 2011, 99, 031116.
[6] F. Templier, J. Soc. Inf. Disp. 2016, 24, 669.
[7] J. I. Hagger, Y. Cai, S. S. Ghataora, R. M. Smith, J. Bai, T. Wang, ACS Appl. Electron. Mater. 2020, 2, 2363.
[8] P. P. Maaskant, H. Shams, M. Akhter, W. Henry, M. J. Kappers, D. Zhu, C. J. Humphreys, B. Corbett, Appl. Phys. Express 2013, 6, 022102.
[9] P. Tian, J. J. D. McKendry, J. Herrnsdorf, S. Zhu, E. Gu, N. Laurand, M. D. Dawson, Micro-LED Based Optical Wireless Communications Systems, 2021, p. 81.
[10] H. S. Wasisto, J. D. Prades, J. Gölkin, A. Waag, Appl. Phys. Rev. 2019, 6, 041315.
[11] L. Zhang, W.-S. Tan, S. Westwater, A. Pujol, A. Pinos, S. Mezouari, K. Stibiley, J. Whitman, J. Shannon, K. Strickland, IEEE J. Electron Devices Soc. 2015, 3, 457.
[12] S. J. Kim, S. Oh, K. J. Lee, S. Kim, K. K. Kim, Micromachines 2021, 12, 399.
[13] B. Corbett, R. Loi, W. Zhou, D. Liu, Z. Ma, Prog. Quantum Electron. 2017, 52, 1.
[14] A. Carlson, A. M. Bowen, Y. Huang, R. C. Nuzzo, J. A. Rogers, Adv. Mater. 2012, 24, 5284.
[15] B. Furman, E. Menard, A. Gray, M. Meitl, S. Bonafe de, D. Kneeburg, K. Ghosal, R. Bukanov, W. Wagner, J. Gabriel, S. Seel, S. Burroughs, 35th IEEE Photovoltaic Specialists Conf., IEEE, Piscataway, NJ 2010, p. 475.
[16] K. Singh, Y. Huang, T. Ahmed, A. Liu, S. Chen, F. Liou, T. Wu, C. Lin, C. Chow, G. Lin, H. Kuo, Appl. Sci. 2020, 10, 7384.
[17] J. Yoon, S.-M. Lee, D. Kang, M. A. Meitl, C. A. Bower, J. A. Rogers, Adv. Opt. Mater. 2015, 3, 1313.
[18] B. Haq, S. Kumar, K. Van Gasse, J. Zhang, A. Gocalinska, E. Pelucchi, B. Corbett, G. Roelkens, Laser Photonics Rev. 2020, 14, 1900364.
[19] L. Li, G. Tang, Z. Shi, H. Ding, C. Liu, D. Cheng, Q. Zhang, L. Yin, Z. Yao, L. Duan, D. Zhang, C. Wang, M. Feng, Q. Sun, Q. Wang, Y. Han, L. Wang, Y. Luo, X. Sheng, Proc. Natl. Acad. Sci. USA 2021, 118, 2023436.
[20] C. A. Bower, M. A. Meitl, B. Raymond, E. Radauscher, R. Cok, S. Bonafe de, D. Gomez, T. Moore, C. Prevatte, B. Fisher, R. Rotzoll, G. A. Melnik, A. Fecioru, A. J. Trindade, Photonics Res. 2017, 5, A23.
[21] R. Lerner, S. Eisenbrandt, S. Bonafe de, M. A. Meitl, A. Fecioru, A. J. Trindade, R. Reiner, P. Walitre, C. A. Bower, IEEE 66th Electronic Components and Technology Conference (ECTC), IEEE, Piscataway, NJ 2016, p. 1186.
[22] J. F. C. Carreira, E. Xie, R. Bian, C. Chen, J. J. D. McKendry, B. Guilhabert, H. Haas, E. Gu, M. D. Dawson, Opt. Express 2019, 27, A1517.
[23] H. S. Kim, E. Brueckner, J. Song, Y. Li, S. Kim, C. Lu, J. Sulkin, K. Choquette, Y. Huang, R. C. Nuzzo, J. A. Rogers, Proc. Natl. Acad. Sci. USA 2011, 108, 10072.
[24] A. J. Trindade, B. Guilhabert, E. Y. Xie, R. Ferreira, J. J. McKendry, D. Zhu, N. Laurand, E. Gu, D. J. Wallis, I. M. Watson, C. J. Humphreys, M. D. Dawson, Opt. Express 2015, 23, 9329.
[25] B. F. Spiridon, M. Toon, A. Hinz, S. Ghosh, S. M. Fairclough, B. J. E. Guilhabert, M. J. Strain, I. M. Watson, M. D. Dawson, D. J. Wallis, R. A. Oliver, Opt. Mater. Express 2021, 11, 1643.
[26] C. D. Pynn, L. Chan, F. Lora Gonzalez, A. Berry, D. Hwang, H. Wu, T. Margalith, D. E. Morse, S. P. DenBaars, M. J. Gordon, Opt. Express 2017, 25, 15778.
[27] Rohm and Haas Electronic Materials, Intervia photodiodielectric 8023 series, https://kayakuam.com (accessed: January 2009).
[28] C. Youtsey, R. McCarthy, R. Reddy, K. Forghani, A. Xie, E. Beam, J. Wang, P. Fay, T. Ciarkowski, E. Carlson, L. Guido, Phys. Status Solidi B 2017, 254, 1600774.
[29] J. Wang, C. Youtsey, R. McCarthy, R. Reddy, N. Allen, L. Guido, J. Xie, E. Beam, P. Fay, Applied Physics Letters. 2017, 110, 173503.
[30] E. H. S. Besendörfer, E. Meissner, A. Lesnik, J. Friedrich, A. Dadgar, T. Erlbacher, J. Appl. Phys. 2019, 125, 095704.
[31] X. Liu, R. Lin, H. Chen, S. Zhang, Z. Qian, G. Zhou, X. Chen, X. Zhou, L. Zheng, R. Liu, P. Tian, ACS Photonics 2019, 6, 3186.
[32] F. Jiang, S. Chen, Y. Leng, N. Huang, J. Wuhan Univ. Technol. Mater. Sci. Ed. 2016, 31, 93.