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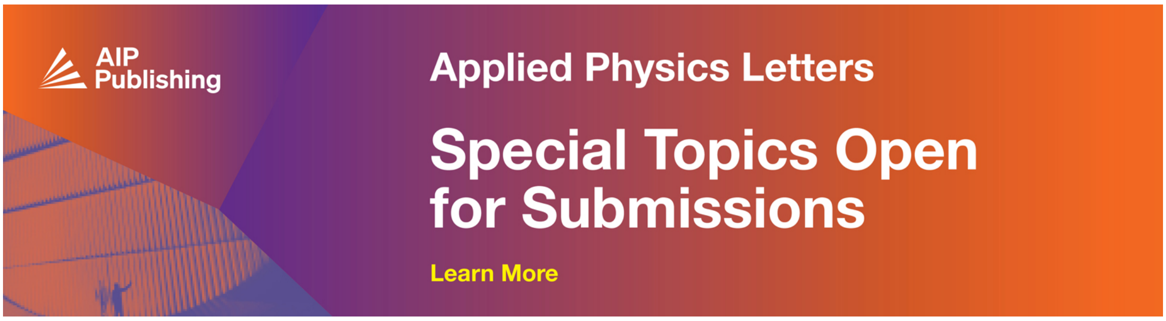

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ABSTRACT

MicroLEDs, particularly when integrated with CMOS microelectronics, represent a significant advancement in nitride technology. While large-area, high-power LEDs for solid-state lighting have seen extensive optimization, microLEDs present unique fabrication and characterization challenges. Utilizing standard CMOS design and foundry services for silicon driver electronics, a new hybrid interconnect technology must be developed for chip–chip or wafer–wafer integration, necessitating much higher lateral resolution than current bonding technologies. Beyond display technology, microLED integration opens avenues for groundbreaking applications such as highly efficient nanosensors, miniaturized optical neuromorphic networks, and robust chip-based microscopy. This paper explores recent advancements in nitride/CMOS hybrid modules, providing an overview of current technologies and future possibilities in this dynamic field.

I. INTRODUCTION

Nitride technology, being the basis for devices from the GaN/InN/AlN material system, has originally been invented for realizing blue laser diodes, increasing the information density of optical DVDs. The breakthrough in nitride technology in the 90s, for which the Noble Prize in physics has been awarded in 2014, was the starting signal for an amazing development. Since a wavelength of 405 nm was a sweet spot with highest quality laser diodes, this happened to be the wavelength for the BlueRay DVD standard. Only then was it seriously considered to use blue light-emitting diodes and combine them with a fluorescent wavelength converter to realize LEDs emitting white light. Initially used as backlight illumination for small LCD screens in mobile phones and later for larger displays, this technology today has developed as a key technology for general lighting, with amazingly high efficiency.[1,2] Parallel to this revolution in lighting technology, first electronic devices have also been developed, after it was realized that a two-dimensional electron gas forms at the AlGaN–GaN interface, supported by internal electric fields in this piezo-electric material. High electron mobility transistors today are used as high-frequency devices in mobile communication as well as for power electronics for highly efficient voltage converters.[3–5]

Today, nitride-based electronics and light-emitting devices are conquering ever increasing markets, even though both areas of applications have been largely followed independently from each other. Although electronic GaN devices are preferably grown on silicon wafers, light-emitting GaN devices are almost always grown on (smaller) sapphire wafers. Compared to their silicon counterparts, sapphire substrates are slightly more expensive, feature less thermal conductivity, but enable less crystal defects and also higher crystal quality of epitaxially grown GaN layers. Sapphire is also transparent in the visible spectral range, allowing more freedom in the design of optical devices (i.e., top and bottom emitters) and more flexibility in the manufacturing process (i.e., using laser lift-off to remove the substrate for improved light extraction). Until recently, all these applications relied on individual components, like single LEDs, single laser diodes, or single FETs. Meanwhile, however, there is an increasing trend toward integration. In the electronic realm, integrated nitride circuits have already been designed and fabricated, offering even higher efficiency for electric inverters.[4] In the photonic realm, the market pull toward highly efficient, bright, and miniaturized micro-displays calls for the integration of microLEDs with silicon CMOS backplanes delivering the driver electronics. The reason for this is the fact that millions of microLEDs need to be controlled separately, which can only be achieved in a chip-chip configuration with a silicon CMOS backplane directly connected to the GaN microLED chip. The significance of this development cannot be overestimated. The impact of nitride/CMOS integration, which is presently needed for micro-displays, is reaching out far beyond displays into many other interesting applications of high relevance.

Therefore, beyond micro-displays, we are now at the dawn of a full photonic–electronic integration, including light emitters, waveguides, electro-optical elements, and detectors. A key element for this photonic–electronic integration, meaning nitride/CMOS integration, is the fact that nitride light emitters can be miniaturized down to 100 nm and below, still efficiently emitting light.[6,7] This is a consequence of the small wavelength in the blue-UV range in vacuum, and even smaller inside the device, and the relatively slow surface recombination velocities of carriers in GaN in comparison to other semiconductors.

Although large-area, high-power LEDs for solid-state lighting have been optimized for many years, microLEDs have their own challenges, both related to fabrication and characterization. Standard CMOS design and foundry services can be used for the silicon chip, but a totally new technology for hybrid interconnect needs to be developed, either on a chip–chip or wafer–wafer basis, with a much better lateral resolution in comparison to existing bonding technology and a resilience against the challenges brought about by two different wafer materials—silicon and sapphire—including omnipresent strain issues. Integrated microLED/CMOS displays will pave the way not only to next generation micro-displays for augmented reality devices but also have the potential to fully replace LCD and OLED technology in the long term. The integration of microLEDs enables many exciting new applications, like highly efficient nanosensors, miniaturized optical neuromorphic networks, or robust chip-based microscopy. This paper will dive into the novel developments described above and give an overview on state-of-the-art as well as future possibilities of this exciting technology of nitride/CMOS hybrid modules.

II. TECHNOLOGY OF STATE-OF-THE-ART MICROLEDS

A. GaN chip processing

The production of solid-state LEDs always begins with the epitaxial growth of the layer stack, which can typically be achieved with MOCVD,[8] MBE,[9] or similar growth techniques. However, the MOCVD process has proven to be more robust and cost-effective, which is why it is now the gold standard for the industrial production of microLEDs. In recent decades, a series of groundbreaking inventions [Fig. 1(a)] have refined MOCVD growth in the polar c-direction to produce high-quality crystal layers with low defect density.[10]

Therefore, microLED technology is based on thin film stacks fabricated by MOCVD on sapphire substrates.[11,12] Subsequent dry etching techniques are required to shape the epitaxial GaN into individual pixels and to gain access to the n-type GaN layer buried by the active region and p-GaN for electrical contacts. Since the optical transmission of the p- and n-sides is sufficiently high for the photons generated in the MQW, the light can be coupled out via both the top and bottom of the LED stack. However, the bottom emitter configuration is the preferred choice as it enables a higher external quantum efficiency.[13]

Figure 1(b) shows a possible process flow for producing a microLED in the bottom emitter design. For this purpose, the p-GaN side is typically fully metalized, which improves the injection of holes into the MQW and increases the reflection of the generated photons toward the n-GaN side. The p-GaN side is protected by an etch mask during dry etching. Anisotropic etching recipes are often taken into account to create sloped sidewalls (e.g., inclination angle of 30° to the vertical) and adding a thin passivation/insulation layer (e.g., 40 nm SiO_2) helps to improve light extraction toward the bottom and reduce leakage currents along the sidewalls, respectively.[14] Modifying the shape of this mesa for an optimized photon extraction is an ongoing area of research. Additionally, intermediate steps (e.g., HCl cleaning of the surface before metallization, KOH cleaning of the sidewalls, different materials for sidewall passivation, thermal annealing of metal contacts/sidewall passivation, among others) can further reduce undesired

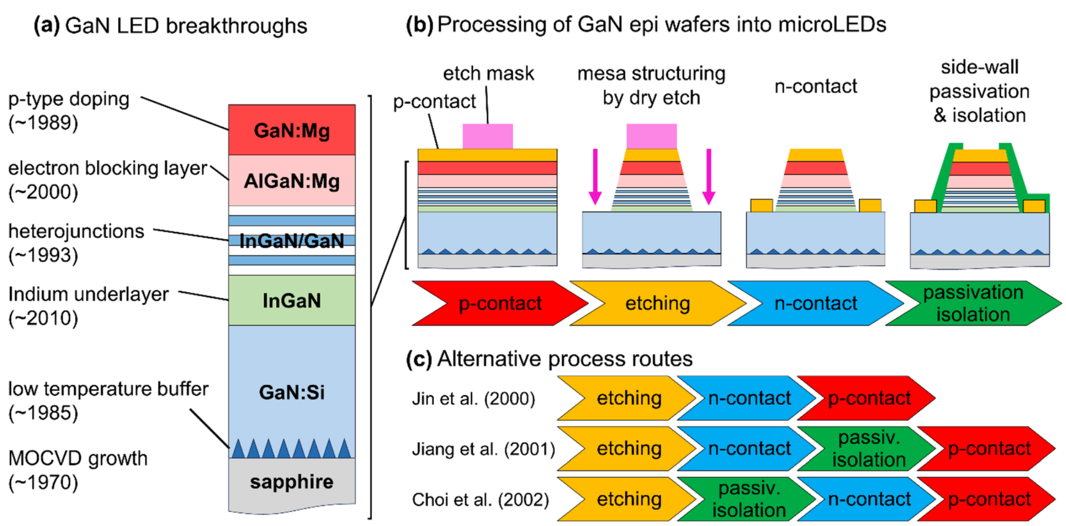

FIG. 1. (a) Schematic of GaN-based blue LEDs and the technological breakthroughs. (b) Possible process flow for pixelation and metallization of a conventional vertical microLED stack based on dry etching. (c) Further process flows as described in literature by Jin *et al.*,[11] Jiang *et al.*,[25] and Choi *et al.*[14]

non-radiative recombination and help to optimize EQE. In contrast to dry etching, efficient pixelation of LEDs can also be realized by ion implantation, resulting in crystal defects within the active zone and/or p-GaN layer without completely etching the material.[15–19]

Depending on the design and application, numerous possible process sequences for microLED production can be described [Fig. 1(c)]. Since an intensive discussion would go beyond the scope of this article, we would like to refer the interested reader to the review by Parbrook *et al.*,[20] who provided a tabular overview along with a comprehensive discussion of the size-dependent electrical and optical power output for various microLED processing routes.

A fundamentally different approach for lateral pixel structuring is selective area growth (SAG), which uses predefined masks (typically made of SiO_2) to constrain lateral dimensions of the LED stack already during the epitaxial growth by MOCVD. Although SAG was in the past often considered for the fabrication of 3D core-shell LED architectures,[21,22] it is also applicable for microLEDs based on the conventional vertical LED stacks.[23] Since subsequent dry etching become basically redundant, SAG could possibly avoid some of the size-dependent efficiency issues, especially when microLED arrays with small-sized pixels (e.g., $<1\,\mu$m) and high pixel density ($>10^4$ PPI) are targeted.[24]

B. CMOS driving and control

Powering and control of the LEDs is usually done with CMOS integrated circuits (ICs). The integration of GaN with CMOS provides flexibility to new functionalities and applications. Different methods have been proposed for such a combination. Conventionally it is performed by flip-chip bonding of the individual LEDs onto the driver circuit.[26,27] More recently, to allow for large-area and higher density microLED displays, wafer-level bonding of the epiwafer GaN with the LED array to the CMOS substrate with the backplane design has been used,[28,29] where every LED is connected to the corresponding underlying driver [Fig. 2(a)]. The trend followed by industry such as Mojo Vision or JBD is to use ultra-deep sub-micrometer CMOS processes on 300 mm wafers.[30] The structure for driving each microLED is composed of two transistors and one capacitor [2T1C in Fig. 2(b)] and variants of it.[31,32] It is used for pulse amplitude modulation (PAM) as well as by pulse width modulation (PWM). The basic circuit drawn in Fig. 2(b) works by shortly opening the transistor M_s to store the signal V_{data} on the holding capacitance C_s. Activating/deactivating the transistor M_d allows to start/stop current flow through the LED. A traditional control panel includes interfaces, control logic, processing electronics like gamma correction, digital to analog converters, and synchronization, calibration, and biasing circuits. For applications like AR/MR (Augmented/Mixed Reality), high brightness LEDs and a high density of pixels are required. The maximum current that the CMOS backplane can afford imposes limits to the number of "simultaneously on" LEDs and brightness. Losses due to power and ground-resistances limit the illumination uniformity of the micro-display. The flexibility that CMOS offers provides novel applications, like displays including smart optical sensing,[33,34] where the backplane can not only integrate the sensors but also the CMOS pixel and the integrating or time resolving electronics or any additional circuitry providing display management, authentication processing, or any function to control environment light.[35] For ultra-high brightness and speed applications, high driving current drivers[36–39] need to be integrated to be able to switch LEDs at unusually fast rates. It includes, e.g., high speed communications,[40,41] raster chip-sized microscopy,[42] optogenetic control,[43] and DNA manufacturing.

C. Hybrid integration

One of the bottlenecks that still hampers the industrial mass production of microLED displays is the mass transfer of LED pixels onto the electronic backplane or driver IC. High placement accuracy ($<1\,\mu$m), high transfer rate ($>$100 M/h), and especially high transfer yield of functional pixels ($>$99.999%) are actual requirements that must be met in display applications but are indeed especially challenging for the hybrid integration of GaN-based microLEDs due to the intrinsic different material properties. In particular, the temperature dependent mismatch of the coefficient of thermal expansion (CTE) of GaN and Si, the strong wafer bow of GaN on sapphire caused be residual strain and the topographic surfaces of the patterned microLED arrays all strongly contribute to challenges during hybrid bonding. Therefore, in addition to the actual transfer technology, efficient inspection and repair of defective pixels is also very important. During the past years, researchers have dedicated tremendous effort to the hybrid integration and mass transfer technologies, as can also be seen by the high number of publications dedicated to this topic.[24,44–50] While the industrial race for cost-effective commercial production of microLED displays is still ongoing, it is worth to take a closer look at some of the most promising transfer technologies described in the literature.

Elastomeric stamps [Fig. 3(a)] for transfer printing are a widely used method for integrating various optoelectronic materials[51,52] and

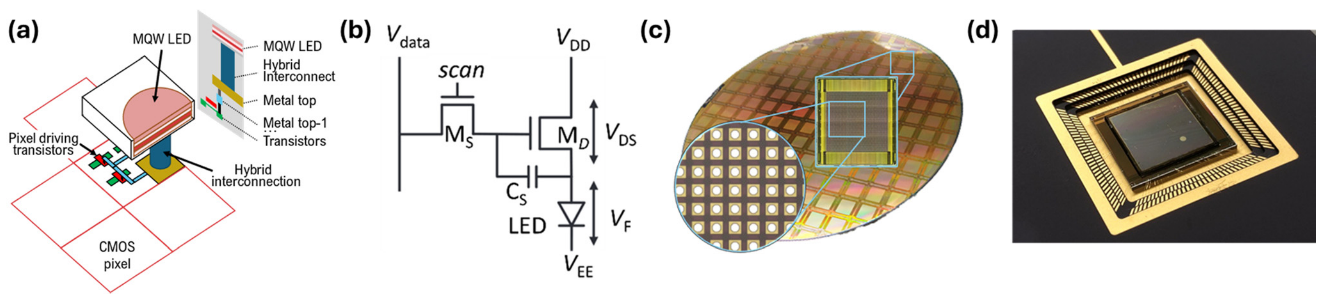

FIG. 2. (a) Scheme of a hybrid interconnection of the CMOS backplane and GaN LED array. (b) The 2T1C (two transistors and one capacitor) circuits are common designs for driving microLED. (c) CMOS backplane. (d) LED microdisplay achieved through hybrid interconnection of wafers with the CMOS backplane and GaN microLED array chips.

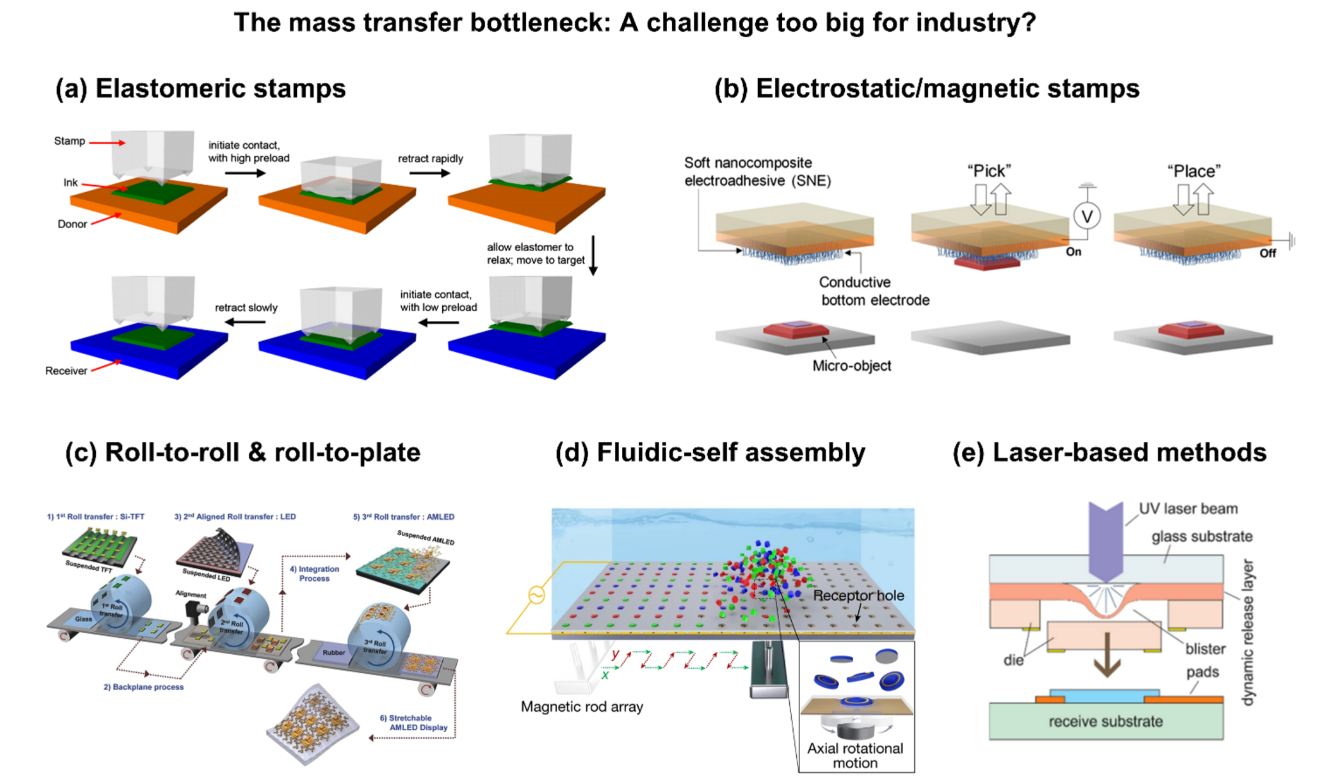

FIG. 3. Overview of mass transfer technologies employed for hybrid integration of microLEDs on CMOS backplanes. Image in (a) reproduced with permission from Kim *et al.*, Proc. Natl. Acad. Sci. **107**, 17095–17100 (2010).[53] Image in (b) reproduced with permission from Kim *et al.*, Sci. Adv. **5**, eaax4790 (2019).[61] Copyright 2010 Science/AAAS. Image in (c) reproduced with permission from Choi *et al.*, Adv. Funct. Mater. **27**, 1606005 (2017).[66] Copyright 2017 John Wiley and Sons. Image in (d) reproduced with permission from Chang *et al.*, Nature **617**, 287–291 (2023).[72] Copyright 2023 Springer Nature Limited. Image in (e) reproduced with permission from Marinov, SID Symp. Dig. Tech. Papers **49**, 692–695 (2018).[80] Copyright 2018 John Wiley and Sons.

are also employed for assembling microLEDs.[53,54] The stamps are typically made of a soft polymer such as poly(dimethylsiloxane) (PDMS), which often contain relief embossed surface features (e.g., pyramidal microtips[51]) in order to selectively pick entire microLED arrays and subsequently place them onto the receiving ICs. During pickup, the stamps are mechanically pressed against the donor substrate, and the devices (i.e., the microLED) adhere to the polymer surface by means of nonspecific van der Waals forces. Since microLEDs are strongly attached to their native growth substrate (e.g., sapphire in the case of nitride LEDs), additional steps (e.g., implementation of sacrificial release layers[55] or use of laser liftoff tools[56]) are necessary to employ elastomeric transfer stamps for hybrid integration. However, once the interfacial adhesion strength between the stamp and the microLED is larger than the adhesion between the device and the native donor substrate, the device can be lifted and transferred to the receiver substrate. PDMS is optically transparent and vertically compliant, which simplifies alignment and placement on topographic surfaces, such as metal contact pads, respectively.[57] In order to place the LED onto the receiver substrate, the adhesion between the stamp and the LED must be reduced, which can be realized by controlling the peel velocity and temperature and introducing adhesive bond materials, among others. To gain high retrieval and delivery yields, reversibly switching between low and high adhesion strength is therefore an important characteristic of the elastomeric stamps. Electrostatic and (electro-)magnetic transfer stamps [Fig. 3(b)] are another group of dry transfer methods that typically rely on patterned electrodes, which enable switchable adhesion for pick-and-place operations of micrometer-sized objects,[58–60] such as microLEDs.[61–63] Roll-to-roll and roll-to-plate [Fig. 3(c)] techniques also possess huge potential transfer rates for mass transfer and are applicable both for rigid and soft substrates, respectively.[64,65] Based on the spinning motion of rolls, this method combines multiple operations (e.g., pick, separate, align, and place) in a continuous single assembly line for microLEDs, which was demonstrated for dry conveyer belts[66] as well as liquid environment.[67,68] Fluidic self-assembly [Fig. 3(d)] is typically carried out inside a liquid and relies on various driving forces such as gravity,[69] capillary force,[70] directed surface tension,[67,68] agitation,[71] magnetic/dielectrophoretic forces,[72] van der Waals forces,[73] among other mechanism.[74] Combining multiple of these forces is indeed an appealing approach for simultaneous RGB pixel transfer, as was recently demonstrated by Chang *et al.*[72] Laser-based methods [Fig. 3(e)] are widely employed in manufacturing of LEDs and possess great potential for microLED assembly. Removing the sapphire substrate from the MOVPE-LED stack by laser lift-off (LLO) is a common approach to improve light extraction, optimize heat transfer, and transfer LEDs to foreign flexible substrates.[75–79] Laser-induced forward transfer (LIFT) is a more elaborate process, in

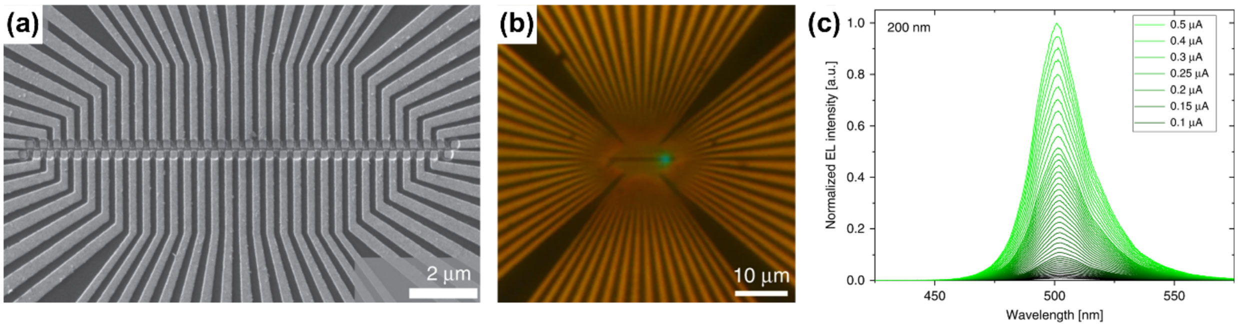

FIG. 4. (a) SEM image of 2 × 32 nanoLED array with a pixel size of 200 nm. (b) Microscope image of electroluminescence and (c) emission spectra at different forward currents. Images (a)–(c) are reproduced with permission from Bezshlyakh *et al.*, Microsyst. Nanoeng. **6**, 88 (2020).[82] Copyright 2020 Authors, licensed under a Creative Commons CC BY license.

which the chip/pixel is pushed from an intermediate donor substrate (typically a polymer-based dynamic release layer) toward the receiver substrate. Here, selective single or massively parallel LIFT are both described and developed for microLED display manufacturing with pixel transfer rates as high as 500 M/h.[45,80]

Despite the remarkable efforts and creative developments of the past decade, there is currently no technology that perfectly meets all the requirements for a reliable and cost-effective hybrid integration of microLEDs. It is this complexity which presently makes the industry assume that mass-market launch is shifting backward. This statement can be underlined by Apple's recent decision of postponing their microLED smartwatch project, which hit experts in the display industry quite by surprise.[81] It is quite clear that this is only a temporary shift of the road map, which has been too optimistic concerning a quick market entry. Therefore, it is very important to understand that there are many additional, highly relevant applications which can be addressed by GaN microLEDs, with requirements concerning reproducibility and yield being more relaxed. Some of these applications are already around the corner, and some of them are addressing topics with a relevance possibly even higher than display applications, like efficient optical neuromorphic compute systems, which need further intense research. We, therefore, focus here on applications beyond display technology.

Finally, a remark concerning the minimum feasible size of a single LED die. This certainly depends on the type of display and the desired application. Compact AR displays require the smallest pixel sizes (∼1–10 μm), smart watch/phone displays have medium sizes (∼10–50 μm), and large screen TVs typically feature bigger pixels (∼50–100 μm). Since handling small pixels is only possible with a correspondingly high level of precision, the production of small color displays in particular is significantly more complex. The single microLED dies to be transferred will then issue a very high aspect ratio. A typical thickness of the thin film structure of a microLED is about 5 μm. Therefore, dies with dimensions of 1 μm are already very difficult to process by, e.g., laser-induced forward transfer.

III. APPLICATIONS BEYOND DISPLAYS

In the last few years, microLED arrays have already been proven as an enabling technology for several applications like structured illumination (even with super resolution), optogenetics, holographic chip-sized microscopy, and sensing.

A. Super resolution structured illumination

Structured illumination can be used for a totally different type of microscopy: chip microscopy. For that, the object is directly attached to the light-emitting array. In contrast to conventional microscopes, the object is not illuminated all at once, but stepwise, switching on and off each single nanoLED of an array. The approach is shown in Fig. 4 in more detail. The concept draws from the fact that the position of illumination is known at any point in time. Therefore, the detector (top) must not deliver spatial resolution, as is the case in conventional microscopy. The concept comes without any optical parts, like lenses, and focusing is not necessary. In principle, this approach can deliver images with resolutions which are given by the pitch of the nanoLEDs, which can be below the conventional diffraction limit of about 400 nm. NanoLEDs with diameters as low as 200 nm have already been demonstrated.[82] However, to translate that into spatial image resolution, the object must be in the near-field of the nanoLED array, with a distance smaller than 400 nm. This, unfortunately, is difficult to achieve, because the active InGaN quantum well in nitride LEDs needs to be covered with an electron blocking layer, p-type GaN, and a current spreading layer. Overall, that sums up to at least 0.5 μm in conventional device architectures used today.

When the size of a nanoLEDs is small, its absolute output power is of course also small, even though it can still operate at relatively high efficiencies. As a rule of thumb, a high-power nitride LED with 1 mm^2 for solid-state lighting is emitting about 1 W of visible light, with a wall plug efficiency of more than 50%. A nanoLED with dimensions as low as 100 nm would emit only 1 pW, but with the same power density of 100 W/cm^2. When higher power densities are needed, another way to excite samples or objects with high spatial resolution can be used: "optical downscaling." This approach has been demonstrated in Ref. 82. Power levels as high as 10^6 W/cm^2 can be achieved by this.

Figure 5 shows a setup where the emission from a microLED array with 10 μm pixel pitch is optically miniaturized by a factor of 100, leading to a pixel pitch in the image of the array of only 100 nm, which is below the diffraction limit. Consequently, single pixels can no longer be seen when the array is emitting light at the same time. However, when operated pixel by pixel, the position of the image of the pixel can be shifted by 100 nm and less, which—by using deconvolution techniques—can, e.g., be used to measure the position of certain characteristics, like an edge between metal and transparent material, with a precision of about 5 nm. For general imaging, however, this

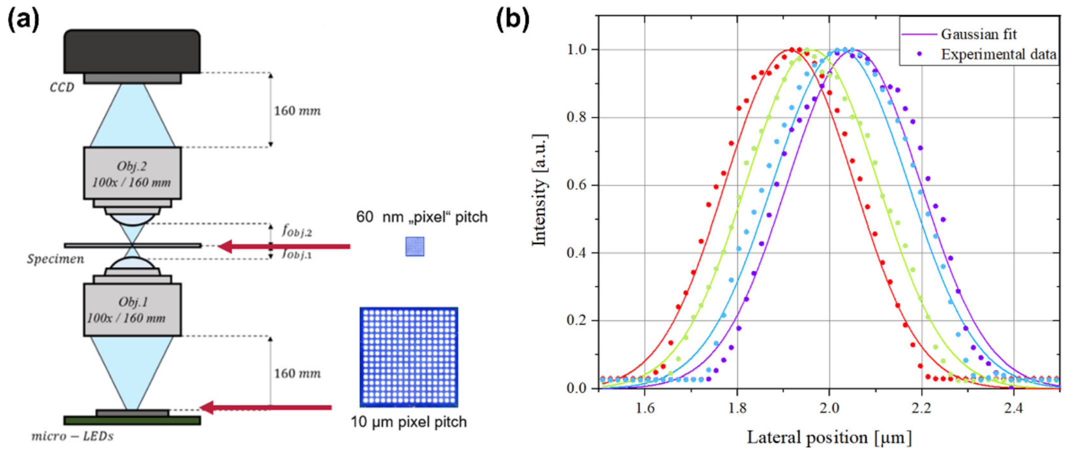

FIG. 5. (a) Sketch of the experimental optical downscaling system based on an inverse microscope for obtaining a demagnified image of the original microLED array in the image plane. (b) Spatially intensity profiles of four different demagnified pixels (indicated by different colors) in the optical downscaling system generated by a microLED array with 10 μm pixel pitch and a 160$\times$ microscope objective lens. Experimental data (symbols) are fitted to Gaussian distributions (solid lines). The x axis displays the measured pixel positions along one line in the focal plane of the downscaling optical system recorded by a CCD camera. Images in (a) and (b) are reproduced with permission from Bezshlyakh, Ph.D. thesis (TU Braunschweig, 2020).[83] Copyright 2020 TU Braunschweig.

approach cannot be used since a single pixel is still diffraction limited, with linewidths of about 400 nm.

B. Visible light communication

The field of visible light communications (VLC) has gained significant interest over the last decade, both for fiber and free-space communications. In free-space applications, the availability of large spectrum spaces (hundreds of THz) makes VLC attractive for wireless communications. Gallium nitride (GaN) light-emitting diodes (LEDs) are considered for transmitters due to their high average efficiency.[105,106] LED arrays can be used for classical illumination, then information transmission with photo-diode (PD) receptors, and finally, it could be also used for power transfer using, e.g., indoor transmission scenario with LED array at the ceiling. The LED arrays serve a number of users simultaneously by individual data and energy transfer while the requested illumination level is varied. The work shows how to maximize the data rate by transmit beamforming, LED selection, and rate splitting multiple access (RSMA) rate adaption. The problem is transformed into a Markov decision process and an algorithm based on proximal policy optimization is developed. A similar model and algorithmic approach can also be applied in an outdoor scenario, where drones carry the LED arrays. A joint multi-objective optimization problem is solved by a multi-agent deep deterministic policy gradient.

C. Optogenetics

Illumination by an arbitrary light pattern is particularly interesting in optogenetics, and an important branch of cardiac research. In optogenetics, certain chemicals, e.g., channelrhodopsins, are converting light into the electric excitation of neurons. To optically excite neurons, laser scanners are used until now, which is limited to the excitation of a single spot of a neural network in time. It has already been shown that nitride-based microLEDs excite ChR2 molecules with an intensity above a certain threshold for firing, to excite patterned response from a neural network[43] using a 450 nm central wavelength, which is adapted to the absorption of ChR2. Absolute numbers of intensity are difficult to derive from such experiments, since they depend on many unknown variables, and where hence not given. Being part of a regular fluorescence microscope setup, these microLED arrays have been focused onto the neural network and do reach the required excitation intensities, which is an exciting new experimental possibility for optogenetic cardiac research to study, e.g., contraction behavior of bioartificial cardiac tissue. In addition, calcium waves could be excited with predefined light patterns by dynamically controlling different groups of microLEDs, with arbitrary geometries, including lines and spirals. MicroLEDs allow switching at high frequencies, which is much faster than the response time of the neural excitation. Like other applications, the highest achievable intensity of microLEDs is also a key parameter in optogenetics. In these experiments, the pixel width in the sample plane has been chosen to be between 12.5 and 62.5 μm, while the maximum power at the sample plane (per pixel) has been set to a range between 90 and 149 μW.[43] An important issue of the experiment is that the microLEDs can be aligned so that they always cover the whole field of view of the fluorescence microscope.

D. Holographic, chip-sized illumination sources for microscopy

Light microscopy is one of the most used tools in modern cell biology and other fields. It has evolved with many different techniques available today.[84] In digital lens-free holographic microscopy images are obtained by directly sampling the light transmitted through a specimen located close to a photodetector without the use of any imaging lens. It has the advantage of being small and low cost, presents a large field of view (FOV) and no need to focus.[85,86] Usually, a laser and more recently a LED are used to illuminate the sample through a small pinhole to decrease the size of resolvable details.[87] Resolution relies on the pixel size of CMOS cameras. However, by using a microLED arrays for illumination, the resolution of this type of imaging can be increased by combining the LED array and the CMOS camera and switching some LEDs to get different holograms of the sample and performing stitching of the images.[88] It has been demonstrated that for smaller LED pitches, better resolution is obtained and is independent of the optical sensor size.[88] Chip-sized microscopes can be very small, hence allowing operation in incubators. Living tissue like cells can be monitored in their normal environment of an incubator, over long timescales, without taking the samples out periodically. The development of mass production of microLED arrays in combination with CMOS integration, leading to high-frequency operation, would massively push this field. Considering point-of-care usage and the possibility to replace existing microscope technology, this application can be expected to target large markets.

E. LED arrays for sensing

LEDs have emerged as crucial components in sensing applications due to their multiple functionalities across different polarization points [refer to Fig. 6(a)].[33] When miniaturized and organized in arrays, they offer unprecedented spatial localization capabilities for sensing, enabling multiplexing of measurements and spatial mapping with exceptional precision.

In forward bias and beyond the light emission threshold [I. in Fig. 6(a)], these LEDs serve as efficient light sources for optical sensing. They facilitate a spectrum of sensing methods, ranging from direct optical transmission approaches such as colorimetry[89] and absorbance spectroscopy to acting as excitation sources for secondary emissions like photoluminescence and fluorescence.[90] These techniques predominantly rely on an optical detector and an optically active material that translates the presence of a target molecule, bio-entity, or physical property into localized changes in optical properties.[91] Although there are instances of utilizing microLEDs as light excitation sources for non-optical sensors (e.g., photoexcited chemo-resistors[92,93]) that require direct electrical interrogation, the complexity arising from the high number of in-pixel interconnects renders their integration into large sensor arrays yet unfeasible,[94] but possibly at reach for the upcoming nitride/CMOS hybrid integration methods.

Furthermore, in the sub-threshold regime, when the LEDs behave as a non-emitting diode [II. in Fig. 6(a)], reports highlight the mapping capabilities of local physical properties such as temperature, strain, or stress.[95] This is made possible by the interplay between these magnitudes and the electron-transport properties of the diode. Liu *et al.* demonstrated this principle by directly examining the current–voltage characteristics of the microLED array pixels.[33]

Under external illumination, the p–n junction within LEDs can generate photocurrent, converting a portion of incident light into electrical signals at each pixel [III. and IV. in Fig. 6(a)]. This property enables repurposing microLED arrays as convenient photodetector arrays, eliminating the need for external, dedicated photodetectors in certain applications.

Moreover, the energy collected at each pixel can power localized sensor elements, such as electrochemical reactions [Fig. 6(b)]. Red-emitting AlInGaP LEDs exhibit the capability to produce luminescence signals following optical excitation with an appropriate wavelength, that depends on the impedance of the element loading the diode. Leveraging this photon-recycling mechanism,[96] luminescence patterns modulated by the sensing state of chemosensors within each pixel can be recorded without direct contact with the microLED array (remote optical excitation and remote luminescence observation).

Finally, novel integration methods for microLED arrays open doors to additional sensing possibilities. For instance, arrays transferred onto flexible/stretchable surfaces enable direct visualization of deformation patterns [Fig. 6(c)].[97]

The future adoption of these foundational research concepts hinges on the scalable and reliable integration of these complex in-pixel sensor elements.

IV. FUTURE PERSPECTIVES

The light engines described until now are based on microLEDs, which emit incoherent light by nature. Their small dimensions, however, establish a certain degree of partial coherence, coming from the spatial coherence of the light source. Photons emitted by a microLED are uncorrelated in phase and time, but give rise to the exact same optical wave pattern in real space.

One exciting development is to move on from microLEDs to coherent microLaser light sources. Vertically emitting laser diodes are required for that, which rely on a vertical optical cavity formed by, e.g., distributed Bragg reflectors (DBR). This cavity can be built by conventional dielectrics like oxides or nitrides. However, using this conventional approach, the DBRs are non-conductive, which poses challenges on the current guiding in such structures. As an alternative, AlGaN/GaN DBRs can be fabricated *in situ* during the growth of the epitaxial

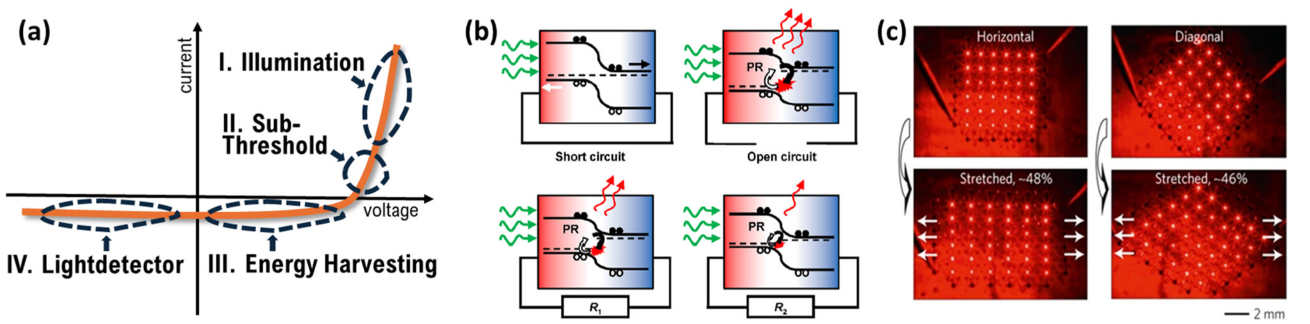

FIG. 6. (a) Current–voltage characteristic of a LED, highlighting the three operation ranges relevant for sensing. (b) Principle of photon-recycling and an example of a remote luminescence sensor array based on AlInGaP. Reproduced with permission from Ding *et al.*, Nano Res. **14**, 3208–3213 (2021).[96] Copyright 2022 Tsinghua University Press and Springer-Verlag GmbH Germany, part of Springer Nature. (c) Flexible AlInGaP microLED array for deformation mapping. Reproduced with permission from Kim *et al.*, Nat. Mater. **9**, 929–937 (2010).[98] Copyright 2010 Springer Nature Limited.

structure, but impose addition challenges concerning doping and strain relaxation. This is why such DBRs today can only be used as bottom mirrors in the n-type region of the device. Another approach for developing bottom DBRs relies on porous GaN, which can be fabricated in a monolithic fashion based on a recently developed dopant-dependent electrochemical etching process.[99] Since the etched channels are filled with air, porous GaN is an ideal low-refractive index material for DBRs with peak reflectivity of > 99%. Although porous GaN DBRs have already been implemented in first resonant cavity LEDs[100] and VCSELs,[101] it is still unclear to what extent scattering losses impair the performance of such devices. If successful, this approach leads to a much higher flexibility in VCSEL architectures as compared to devices with conventional dielectric DBR mirrors.

It will be very interesting to follow up the development of single VCSEL devices into VCSEL arrays. Since VCSEL is quite similar to microLEDs in external architecture and dimensions, nitride/CMOS hybrid integration can directly be transferred from microLEDs to VCSEL arrays, which has even more exciting potential applications. Coherent emission is very advantageous for light guiding needed for many applications, including optical neuromorphic processing cores. In addition, when the phase of neighbored VCSEL devices can be controlled separately, one might even use these arrays for beam steering, similar to radar arrays. For that to become reality, however, GaN devices must be integrated with light guiding and light controlling elements, like electro-optic materials. AlN itself offers electro-optic activity, meaning that the index of refraction can be controlled in certain limits by an external gate voltage.

In this case, vertically emitting VCSEL diodes can be combined with optical feedback, e.g., from a ring oscillator, they might even be used for controlling single ions in ion-trap quantum computing, where extremely small linewidths are needed to address concrete atomic transitions properly. The field of photonic integrated circuits (PICs), which is already quite developed in the silicon area, will be another area of interest for future nitrides. Here, 3D nanoporous GaN fabricated by electrochemical etching of ion-implanted nitride layers[102,103] could become the technological tool box for monolithic integration of new on-chip devices.

All the light engines mentioned above are opening interesting market opportunities. One application, however, might be of even much higher impact: micro-arrays for optical neuromorphic computing. The main advantage of optical systems is their naturally given parallel way of communication. One single microLED can easily communicate with millions of detectors in parallel. This is very similar to our human brain, where this massively parallel interconnect is realized by biological neurons. Recently, such optical neuromorphic processing cores with artificial neurons based on microLED arrays have been investigated in more detail.[104] It turned out that the efficiency and compute power of such optical systems is extremely high. Floating point operations can be achieved with less than one photon on average. Since GaN microLEDs are very efficient, this might lead to a compute power of more than 10^2 TOPS/W, which is about 2 orders of magnitude better than today's NVIDIA H100 processor used for realizing large language models and AI in general.

V. CONCLUSIONS

All the applications mentioned above are based on the ability of GaN-based light-emitting devices to be still efficient, even at very low dimensions. In addition, GaN is a robust material allowing various laser techniques to be used for material processing. This facilitates hybrid integration with silicon electronic circuits, merging the power of CMOS electronics with the power of GaN photonics. Overall, this sets the scene for an exciting research field heading toward many new applications of GaN, even more than 30 years after its "invention." Since the fabrication of GaN homo-substrates is difficult, such substrates are still expensive, limiting their widespread use. Therefore, material development and the reduction of defect densities is of continuous concern. One limiting factor for the development of GaN technology is the fact that GaN foundries are basically not available. This is very different to the field of silicon electronics, where access to high-end chip processes is possible by foundry services, and even small-scale fabrication or research has access to high-end technology. We, therefore, suggest that the establishment of an ecosystem of GaN foundries would massively help to push this technology further, and to address the interesting challenges even more efficiently.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

J. D. Prades: Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **F. Meierhofer:** Data curation (equal); Formal analysis (equal); Investigation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Á. Diéguez:** Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **A. Waag:** Conceptualization (equal); Funding acquisition (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

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