



HAL
open science

Perspectives for III-Nitride photonic platforms

Philippe Boucaud, Nagesh Bhat, Maksym Gromovyi, Moustafa El Kurdi,
Antoine Reserbat-Plantey, Minh Tuan Dau, Mohamed Al Khalfioui, Blandine
Alloing, Benjamin Damilano, Fabrice Semond

► **To cite this version:**

Philippe Boucaud, Nagesh Bhat, Maksym Gromovyi, Moustafa El Kurdi, Antoine Reserbat-Plantey, et al.. Perspectives for III-Nitride photonic platforms. Nano Futures, 2024, 8 (2), pp.022001. 10.1088/2399-1984/ad41aa . hal-04560375

HAL Id: hal-04560375

<https://hal.science/hal-04560375v1>

Submitted on 6 May 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Perspectives for III-Nitride photonic platforms

Philippe Boucaud¹, Nagesh Bhat,¹ Maksym Gromovyi,²
Moustafa El Kurdi,² Antoine Reserbat-Plantey,¹ Minh Tuan
Dau,¹ Mohamed Al Khalfioui,¹ Blandine Alloing,¹ Benjamin
Damilano,¹ and Fabrice Semond¹

¹ Université Côte d'Azur, CNRS, CRHEA, Rue Bernard Grégory, 06905
Sophia-Antipolis, France

² Université Paris-Saclay, CNRS, C2N, 10 boulevard Thomas Gobert, 91120
Palaiseau, France

E-mail: philippe.boucaud@crhea.cnrs.fr

March 2024

Abstract. The development of photonic platforms for the visible or ultra-violet spectral range represents a major challenge. In this article, we present an overview of the technological solutions available on the market. We discuss the pros and cons associated with heterogeneous or monolithic integration. We specifically focus on the III-nitride platform for integrated photonics. The III-nitrides offer every building block needed for a universal platform. We discuss the additional opportunities offered by combining III-nitride semiconductors with other materials such as two-dimensional materials.

1. Introduction

The first concepts of integrated optics have been pioneered at the end of the 1960s with the proposal by Stewart Miller of a miniature laser beam circuitry and the simultaneous construction of complex circuitry patterns [1]. As stated in the conclusion of this seminal work, "Work is just beginning in the direction indicated and we have identified goals rather than accomplishments. We recognize these are difficult goals; but we believe they are worth the serious efforts required to achieve them". Since then, serious efforts have indeed been undertaken in the field by a very large scientific community. The first major traction came from the development of fibre optic communication for which integrated optics or integrated photonics presented key advantages. A first integrated photonic circuit consisting of a laser and a modulator was reported in 1987 by Suzuki [2]. One of the first decisive steps to promote this concept was the invention of planar devices such as Arrayed Waveguide Gratings multiplexers/demultiplexers in 1988 [3] followed by the introduction of MultiMode Interference couplers [4, 5]. The initial efforts were devoted to demonstrating the key building blocks with the vision that an equivalent

of the Moore's law, similar to the one for electronic circuits, could be achieved with integrated photonics [6].

Once the key components of integrated photonics have been demonstrated, the focus has switched to the most suitable platforms to integrate the circuits. The most versatile platforms are probably those based on indium phosphide (InP) [6] and silicon [7]. The indium phosphide (InP) based photonic circuits can combine both active and passive components with efficient active lasers integrated with routing, amplification, modulation and detection functionalities. Their key success was reported in the field of optical communications in the 1.1 – 1.6 micrometer spectral window.

In the early stage of their development, silicon-based photonic circuits lacked an efficient integrated laser source. However, it did not prevent the success of the silicon-on-insulator platform since this platform provides ultra-low losses passive components like waveguides and the possibility to achieve a high density photonic integration due to the strong index contrast between silicon and silicon oxide [8]. Si is transparent to infrared light for wavelengths above about 1.1 micrometers making it fully compatible with fiber optic telecommunication and datacom systems operating around the 1.55 micrometer wavelength. The compatibility with Complementary Metal Oxide Semiconductor foundries also represents a key advantage.

The range of applications that integrated photonic circuits can address is impressive. While the first developments of photonic circuits were clearly addressing the telecommunication and datacom markets in connection with the fiber optics ecosystem, the diversity of usage has increased steadily. The main advantages of the integrated photonic circuits as compared to their electronic counterparts delivering the same functionality are their compactness, low power consumption, reconfigurability, and enhanced performances. The high level of integration enables the engineering of multiple functions on chips or on separate high-performance chiplets with dedicated tasks. The scalability offered by photonic circuits is as well a key advantage. This scalability can be both defined in terms of dense integration of functions on chips and in terms of the capacity to be manufactured on large size wafers, up to 300 mm in the case of silicon substrate. The integrated photonic circuits are also particularly suited for emerging applications since new engineering solutions can be built based on their specific properties. In 2023, the photonic integrated circuit market size is estimated at more than 10 Billion US dollars, and the growth rate continues to be significant with a predicted annual growth rate higher than 10% for the next decade [9]. On its own, the silicon photonics is expected to reach a \$5 Billion market for datacom in 2027 [10].

A solid-state solution like integrated photonics offers numerous advantages in terms of reliability as compared to systems where mechanical and moving parts are present. Consequently, the implementation of integrated photonics solutions might be a game-changer for the development of optical comb sources with applications in metrology, telecommunication [11], sensing or optical clocks [12]. On-chip Light Detection and Ranging (Lidars) with small footprints, like those dedicated to automotive applications represent a very active domain [13]. Optical beam scanning can be achieved through

the combination of tunable laser diodes, semiconductor optical amplifier, phase shifter and antenna arrays. This approach is also highly relevant for augmented reality and virtual reality technologies with precise control of red, green and blue projector beams. Wearable retinal projection technologies are as well being developed.

Applications in life science and bio-sensing are numerous. Photonic biosensors have been implemented on compact chips for the detection of multiple types of biological agents, such as DNA, proteins and cells along with environmental pollutants and food contaminants. Optical coherence tomography is also gaining significant interest.

More recently, quantum photonic circuits have attracted a significant traction for on-chip generation, processing, and detection of quantum states of light. A scheme for universal quantum computation using photons in linear optics was presented in 2001 [14]. One of the key features of nanofabricated devices is the ability to combine on chip all basic features for light generation and detection along with linear optical elements like beamsplitters, nonlinear optical frequency conversion elements, tunability etc. The combination of integrated photonics and quantum features offers unprecedented functionalities. Discrete variables, continuous variables, squeezed states of light and single photons can be handled on chip. The first integrated photonic quantum logic gate was demonstrated in 2008 [15]. Since then, the complexity of quantum photonic circuits has steadily increased and the progresses in this field such as quantum key distribution, quantum computing, quantum sensing and quantum optics on chip are staggering. A review of recent progress in integrated photonic quantum technologies and material platforms for integrated quantum photonics can be found in Refs. [16, 17, 18]. A specific review of material platforms for spin-based photonic quantum technologies has been discussed in Ref. [19]. While integrated photonic quantum circuits will remain a hot topic for the coming years, novel architectures for classical computing, such as neuromorphic computing, are under development as well. Addressing the optical transitions of specific atoms including ytterbium (Yb^{171+}) at 369.5 nm, nitrogen vacancy centers in diamond at 637 nm, and rubidium (Rb^{85}) at 778.1 nm, in the near-UV or visible spectral range, is also a significant challenge for on-chip quantum computing [20] and precision optical clocks.

2. Photonic platforms for the visible and ultra-violet

As the major photonic platforms are based on indium phosphide and silicon, numerous demonstrations were reported in the near-infrared spectral range. While some developments are ongoing in the mid-infrared spectral range, the major novel area of development is related to platforms at shorter wavelengths, i.e. those that can be operated in the visible and ultra-violet spectral range. One of the main driving force is to address new applications for example in life science, metrology, virtual reality and any other fields where the combination with optoelectronics devices is foreseen. A further advantage of short wavelengths and the use of transparent or wide band gap materials is the quenching of multi-photon absorption which usually drastically limits

the power that can be manipulated on chip. The nonlinear processes become much more efficient and very specific demonstrations can be achieved, not available on any other platforms. One can find in the literature many different approaches where each material can provide key advantages in one specific subfield. One should be aware that beyond academic demonstrations, the transfer to industry requires all key components to be available within one specific platform, a form of compatibility with the existing environment dominated by CMOS production lines, a reasonable cost and high-volume wafer-scale production capability. The platform that fulfills all these requirements will certainly dominate the market. We discuss below the most promising ones.

2.1. Si_3N_4 photonic platform

Si_3N_4 is by far the dominant platform for the visible. This material has a very wide transparency window from 400 to 4000 nm. Si_3N_4 is usually deposited by low pressure chemical vapor deposition and the waveguides are obtained with thermal oxide claddings. One of the main advantages is the ultra-low losses that can be obtained with this approach leading to outstanding quality factors in resonators. Quality factors up to 55 M have been reported in ring resonators operating at 674 nm along with waveguide losses in the dB/m range [21]. It is all the more impressive that low losses are much more challenging to achieve in the visible spectrum as compared to longer visible wavelengths since Rayleigh-like scattering increases as λ^{-4} . One strong interest of the Si_3N_4 platform is its compatibility with a wafer-scale CMOS environment. Demonstration of quality factors up to 6 M at 453 nm has been recently achieved in the environment of a 200 mm foundry [22]. Losses below 1dB/cm have been obtained even in the violet range. As discussed in Ref. [23], the performance of photonic-integrated components based on Si_3N_4 goes beyond those reported in other integrated platforms, either for ultra-high quality factor resonators, optical filters, highly coherent lasers, optical signal processing circuits, nonlinear optical devices, frequency comb generators, and biophotonic system-on-chip. Commercial foundry platforms such as those offered by e.g. Lionix or Ligentec provide chip-based solutions based on Si_3N_4 .

One of the drawbacks of the Si_3N_4 environment is the lack of a monolithically-integrated laser source and the additional difficulty to integrate active components. The optical source for the Si_3N_4 chips is usually provided with an external cavity laser thus adding some complexity in the manufacturing process. As demonstrated for silicon photonics, the heterogeneous integration of efficient III-V lasers can be implemented on chip but the process flow remains challenging [24]. Alternatively, optically-pumped rare earth ions or quantum dots can provide the gain material incorporated into the Si_3N_4 waveguiding layers [25]. The Si_3N_4 platform is highly attractive for on-chip quantum processing with photons. The coupling of single photon emitters like semiconductor quantum dots and entangled photon sources to photonic circuits represents a powerful technological approach for quantum processing. While high-performance integrated nonlinear optics can be achieved through third-order processes, including frequency

comb generation, with an n_2 parameter ten times higher than the one of silica [26], this platform lacks efficient second-order nonlinear processes with this material, posing another drawback.

2.2. Lithium Niobate photonic platform

Lithium niobate is a ferroelectric material characterized by a large transparency window, from 350 nm to the mid-infrared. The lithium niobate platform offers several advantages as it exhibits simultaneously large second-order nonlinear susceptibilities ($d_{33} \simeq 27$ pm/V around 1550 nm as well as a large electro-optic coefficient) and third-order ($\chi^{(3)}$) Kerr nonlinearities along with low optical losses. Quality factors up to 100 M, close to the intrinsic losses of the bulk material (0,0034 dB/cm), have been recently reported with thin films lithium niobate on insulator [27, 28]. Very efficient modulation can be achieved with monolithic lithium niobate photonic circuits as well as the generation of Kerr frequency combs [29]. Flip-chip laser integration has been reported [30] along with on-chip optical isolators [31], underlining the flexibility of design for engineering.

The high second-order nonlinearity is commonly used to produce correlated photon pairs and entanglement through parametric down-conversion. The first demonstration of a high-efficiency source of photon pairs for engineering quantum entanglement took place in 2001 [32]. Since then, the use of optimized periodically poled structures has greatly increased the efficiency of the spontaneous parametric generation process. Multiple protocols and manipulation of quantum states have been demonstrated [33]. One severe drawback of the thin film lithium niobate platform is that lithium is considered a contaminant for CMOS processing. It might severely limit the platform's industrial scale adoption. Similarly to Si_3N_4 , there are no monolithically-integrated optical sources with lithium niobate.

2.3. Wide band gap semiconductors: SiC, diamond

The alternative approach to Si_3N_4 or lithium niobate for visible photonic circuits is the use of wide band gap semiconductors. We will discuss specifically below the interest of the III-nitride semiconductors. The III-nitride semiconductors are not the sole wide band gap semiconductors of interest. In particular, silicon carbide, diamond and gallium phosphide [34] are gaining a lot of traction.

Silicon carbide (SiC) is a wide band gap group IV semiconductor material that is one of the mainstream semiconductor for power electronics. Different polytypes exist with silicon carbide, mostly 4H and 3C-SiC. There is as well an interest of this semiconductor for integrated photonics as this material exhibits a wide variety of color centers that can be implemented for quantum photonics. The color centers can be either used for bright and stable single photon sources [35] and their spin qubits with long coherence times can be optically addressable [19]. The recent development of silicon carbide on insulator through wafer bonding offers new perspectives for integrated nanophotonic devices [36]. One can combine on the same platform quantum emitters and nonlinear

devices since silicon carbide is non centrosymmetric and exhibits second-order nonlinear susceptibilities. Moreover, silicon carbide is compatible with the foundry industry standards and a whole ecosystem has already been demonstrated for power devices. Scalable quantum photonic circuits based on solid-state spins in silicon carbide can be envisioned [37].

One should emphasize the strong similarity between silicon carbide and diamond. The nitrogen-vacancy centers in diamond were among the first ones to be investigated for quantum applications either as single photon emitters or spin qubits [38]. Diamond is as well an engineer best friend thanks to its remarkable properties like its high thermal conductivity of 2000 W/mK, its ultra-wide band gap (5.5 eV) and negligible multi-photon absorption. Diamond is biocompatible and chemically robust. Specific processing techniques have been developed in order to confine light in diamond and numerous photonic circuits have been demonstrated with diamond or nano and microcrystalline diamond [39, 40, 41]. An integrated diamond nanophotonics platform for quantum-optical networks has been demonstrated [42]. One of diamond's drawbacks is the lack of availability of the material in large substrate sizes.

3. Specificities of the III-nitride photonics platform

As wide band gap semiconductors, the III-nitride semiconductors represent a major platform for integrated photonics in the visible and in the ultra-violet range. When referring to III-Nitrides, we usually refer to gallium nitride (GaN), aluminum nitride (AlN) and the alloys made of Al, Ga, In, and N. There are as well other III-nitrides like boron nitride (BN), niobium nitride (NbN), scandium-based nitride (ScAlN). The variety of the compound materials and their combination is significant from the start and represents distinctive features as compared to the other platforms previously discussed. Figure 1 summarizes some of the main features of III-nitrides for photonic platforms, as discussed below.

Different deposition techniques have been developed to grow III-nitride semiconductors [43]. The first report of aluminum nitride synthesis from liquid aluminum and N_2 gas can be traced back to 1862 [44], emphasizing the interest in III-nitrides over time. Among the techniques that are still in use, one can mention sputtering, pulsed laser deposition, metalorganic vapor phase epitaxy, hydride vapor phase epitaxy and molecular beam epitaxy (plasma-assisted or ammonia). Each technique comes with specific advantages. Metalorganic chemical vapor deposition has become a standard for industrial applications, particularly for optoelectronics and electronics devices. As emphasized in Ref. [45], the MOCVD technology has imposed itself as the Swiss army knife for the epitaxial growth of compound semiconductors. It applies as well for III-nitrides. The pioneer reports related to III-nitrides started in 1971 with Manasevit and coworkers [46]. It was later followed by the seminal works of Amano, Akasaki and Nakamura who established the conditions for obtaining high-quality materials and p-doping [47, 48, 49, 50, 51, 52]. While MOCVD is a mainstream



Figure 1. Summary of the main opportunities offered by the III-nitride materials for a photonic platform.

technology, it does not rule out the interest of other methods, like molecular beam epitaxy, depending on the targeted applications.

The main application domains of III-nitride semiconductors are in optoelectronics and microelectronics. The main driving field in optoelectronics is associated with LEDs for lighting applications, and more recently, for automotive applications which represents a significant share of the market [53]. The overall LED chips market is estimated to be around 27 Billion US\$ in 2024 [54]. The compound annual growth rate of this market is around 12 %. The initial developments of LEDs in the blue have been extended to the ultra-violet wavelengths [55] and to the red spectral range [56, 57]. In the latter case, different approaches are investigated in order to increase the In content and to achieve efficient LEDs with III-nitrides: relaxed pseudo-substrates following transfer on an oxide layer [58] or porosification of the buffer layer [59]. External quantum efficiencies of around 4.5% have been recently demonstrated in the red [60, 61]. This quest for efficient red emission is undertaken in parallel with the development of micro-LEDs and microdisplays with III-nitride heterostructures that represent a huge field of interest [62, 63, 64].

A similar dynamic is present as well for microelectronics devices, either for power and Radio Frequency applications. This market is partly driven by the development of the 5G network infrastructure, the adaptation of the electric grid to intermittent power sources, and the dissemination of high-power devices for multi-purposes, including electric vehicles and autonomous vehicles. Gallium nitride exhibits a large critical field and a high saturation velocity, along with its wide band gap. It offers excellent performance for high-voltage components. It can moreover exhibit low switching losses and enables high-frequency operation which is a key for miniaturization [65]. Meanwhile

the development of high-linearity power amplifiers is a workhorse for 5G and beyond 5G networks [66, 67].

To address these markets, numerous foundries integrating III-nitride materials have been developed. III-nitrides are very cost-effective and represent the second semiconductor market after silicon. This ecosystem which includes growth and processing is a second key feature to seriously consider the III-nitrides for other applications with integrated photonics.

The III-nitrides can be epitaxially-grown on large wafer sizes. Figure 2 shows an example of a III-nitride layer for integrated photonics and photonic crystal fabrication grown on a 200 mm diameter silicon substrate. The most standard wafers are sapphire and silicon but homoepitaxy on GaN substrate is also available, in particular when the dislocation density is a critical parameter. In the case of silicon(111), growth on 300 mm substrates has been demonstrated. Wafer-scale manufacturability is not an issue with these materials.



Figure 2. GaN-based heterostructure for integrated photonics grown by molecular beam epitaxy with a Riber R49 reactor on a Si 200 mm diameter substrate. The uniform color indicates an excellent thickness uniformity (below $\pm 1\%$). The surface roughness (rms) is 0.7 nm.

Beyond LEDs, the III-nitrides are particularly interesting for photonics since they can provide monolithic integration of lasers. As it is the case for indium phosphide or gallium arsenide compound semiconductors, the III-nitrides are direct band gap semiconductors and are particularly well suited for laser integration. Monolithically-grown ridge lasers on sapphire, GaN and silicon substrates operating between 400 and 500 nm have been demonstrated [68, 69, 70, 71]. More recently microdisk lasers have been demonstrated as single devices operating under electrical injection fabricated on sapphire substrate [72] or silicon substrate [29]. Numerous demonstrations of individual microdisk lasers operating at room temperature under optical pumping from the UV-C to the green spectral range were reported [73, 74, 75, 76, 77, 78, 79, 80, 81, 82]. Microdisk lasers operating under optical pumping and integrated into photonic circuits have also

been demonstrated on silicon substrates [83, 84, 85]. Microdisk lasers under electrical injection were further demonstrated on Si(111) substrate [86] or on Si(100) substrate [87]. As compared to the other platforms, monolithic integration is a key advantage in terms of manufacturing simplicity and, ultimately costs. Complete active-passive photonic integration based on a GaN-on-silicon platform has been recently reported [88]. In the latter case, multi-quantum well light sources, modulators, photodiodes, waveguides and splitters were integrated on the same chip and did operate in the near-UV spectral range. The III-nitride platform is the only platform for the visible/UV spectral range where efficient monolithic lasers can be integrated and operated at room temperature. It is thus a key and a distinctive advantage as compared to the other platforms.

LEDs or lasers are not the only available devices in terms of light sources. Quantum dots can provide single photon emitters for quantum photonic application [89]. These quantum dots can operate up to room temperature even if the purity of the source is significantly decreased at this temperature. Extensive studies have been performed on III-nitride quantum dots [90]. Emitters analogous to color centers are as well present in III-nitrides, see e.g. what has been reported for GaN [91, 92], AlN [93] and BN [94] for example. There is, thus, a large variety of single photon sources in III-nitride semiconductors which, once again, make them ideal candidates for integrated photonics with the prospect of a large variety of applications.

As compound semiconductors, the III-nitrides are non-centrosymmetric and they can provide second-order nonlinearities. There is some dispersion in the values reported in the literature [95] but typically, AlN has an absolute $\chi^{(2)}$ value in the 6-8 pm/V range in the near-infrared [96, 97] while $\chi^{(2)}$ absolute values for GaN between 10 to 23 pm/V have been reported [98, 99]. More interestingly, the values of second-order coefficient between GaN and AlN have opposite signs [100] thus opening engineering opportunities to achieve efficient phase matching for second-order nonlinear processes with as-grown materials without requiring any bonding procedure [101]. The III-nitride platform offers more opportunities for nonlinear interactions and wavelengths conversion as compared to silicon nitride or diamond platforms.

Detection is as well directly available on-chip with III-nitride materials. Niobium nitride can be epitaxially-grown on gallium nitride. At low temperature, niobium nitride is a superconductor. Niobium nitride and related materials (NbTiN) are the best materials for single photon detection in the near-infrared with time resolution below the nanosecond range [102]. Niobium nitride is usually deposited by sputtering but it can be, as well, epitaxially-grown on aluminum nitride [103]. Large arrays of on-chip superconductor nanowire single photon detectors can thus be integrated with AlN-based photonic circuits [104].

The opportunities offered by the III-nitride compounds are thus astonishing and encompass anything that is required for high performance photonic platforms. It is unique for the visible spectral range and even for the ultra-violet. The materials are available on large wafer sizes, up to 300 mm, and are compatible with industry

Table 1. Comparison of different material for photonic platforms. The \checkmark sign indicates the compatibility and potential in the field or that outstanding results have been reported.

Material platform	UV range	Visible range	Ultra-high Q resonators	Si Integration	Monolithic laser	Second-order non-linear processes	Quantum technologies	Hetero-integration with 2D materials
Si ₃ N ₄		\checkmark	\checkmark	\checkmark			\checkmark	
Lithium Niobate		\checkmark	\checkmark			\checkmark	\checkmark	
SiC		\checkmark	\checkmark	\checkmark		\checkmark	\checkmark	\checkmark
Diamond	\checkmark	\checkmark	\checkmark				\checkmark	
III-Nitrides	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark

standards. LEDs, lasers, single photon emitters can be integrated monolithically on-chip. The compatibility with CMOS technology enables the co-integration of devices like emitters with a CMOS-based driving electronics, as demonstrated for microdisplays [105] or visible light communication [106]. Efficient photodetectors can even be directly integrated. Devices based on second-order nonlinearities can be developed in addition to those based on third-order nonlinearities. As discussed below, low-loss waveguides and resonators can be fabricated. The III-nitrides are probably the most universal platform for designing high performance photonic circuits for the visible range.

Table 1 summarizes some of the main specificities of different materials for photonic platforms in the visible or ultra-violet range. One can clearly see that the III-nitrides are the most versatile materials to address multiple challenges.

4. III-nitride photonic platform: what has been achieved so far

Numerous demonstrations have been reported in the literature on III-nitride photonic platforms. One of the first priority for integrated nanophotonic devices is the ability to fabricate photonic cavities with high quality factors. Numerous developments were dedicated to photonic crystal cavities as they can provide small mode volumes and a testbed for cavity quantum electrodynamics [107]. Despite the efforts provided by the community, the quality factors of two-dimensional photonic crystal cavities or one-dimensional nanobeam cavities have remained below their theoretical values [108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120]. It did not prevent reporting the demonstration of high-performance single devices from vertical-emitting photonic crystal lasers [121, 122], watt-class photonic crystal lasers [123] or high- β values nanobeam lasers [124].

Simultaneously, one of the most popular system in terms of photonic cavities

is the microring resonators. First demonstrations of high quality microresonators were obtained with sputtered aluminum nitride on oxide [125, 126]. It was later acknowledged that epitaxial materials can lead to higher quality factors [127], in the near-infrared spectral range and more importantly at short wavelengths where defect-related absorption can limit the intrinsic values. Intrinsic quality factors in the Million range have been reported by several groups, either with aluminum nitride or gallium nitride as the waveguiding layer [127, 128]. The demonstrations were either achieved on sapphire substrates [129, 130] or on silicon substrate after a bonding step [131]. The proof of concepts was first reported in the near-infrared telecom spectral range as precise characterization tools are easily available. These demonstrations were later extended at shorter wavelengths [132]. Quality factors up to 2.1×10^5 , corresponding to 8 dB/cm, were demonstrated at 390 nm on single-crystalline AlN microrings. These values are significantly higher than the intrinsic values reported earlier [133] or those reported with microdisk resonators in the same spectral range [134, 119].

The number of demonstration of nonlinear devices based on a III-nitride photonic platform is staggering and illustrates the versatility provided by these materials. To cite a few, we can mention the demonstration of second-harmonic generation in aluminum nitride microrings with a remarkable conversion efficiency of 2500%/W [135] that was further extended to 17000%/W [96]. Engineering of the susceptibility for epitaxial materials allows one to enhance the conversion efficiency of second-order nonlinear processes with very simple structures [101]. Optical frequency comb generation was demonstrated in 2013 [136]. A parametric down-conversion process was used to generate on-chip a source of photon pairs based on second-order nonlinearity in an aluminum nitride microring resonator [104]. This nonlinear process was further extended with the development of on-chip $\chi^{(2)}$ microring optical parametric oscillator achieved around the telecom wavelength [137]. Kerr frequency combs based on a $\chi^{(3)}$ third-order nonlinear process were demonstrated with a GaN platform on sapphire [128].

The integration of monolithic optical sources has been investigated by several groups. Mode locking in monolithic two-section InGaN blue-violet semiconductor lasers was reported in 2013 and prefigures what can be achieved with blue lasers for the generation of optical frequency combs [138]. Microdisk resonators were embedded in air-suspended waveguiding layers on silicon [83, 84, 85].

Room temperature microdisk lasers have been demonstrated under electrical injection with Si(100) substrate [87], thus indicating that laser integration is not limited to sapphire substrates. A GaN-based Fabry-Perot laser diode butt-coupled to a crystalline III-N photonic integrated circuit chip with either AlN, AlGaIn, or GaN waveguide core was reported very recently [139]. It highlights the potential of hybrid integration with, in the latter case, the demonstration of laser self-injection locking and single-frequency operation.

5. III-nitride photonic platform: some future directions

As mentioned earlier, wurtzite-type III-nitrides offer opportunities for hybrid integration. Fig. 3 (a) shows an example of a superconducting nanowire single photon detector fabricated from a NbN thin film epitaxially grown by molecular beam epitaxy. Fig. 3 (b) shows a transmission electron microscopy image of the niobium nitride film and its interface with aluminum nitride. The AlN/NbN interface is atomically abrupt and the NbN surface morphology is smooth (rms lower than 0.5 nm). We did mention earlier the interest of integrating epitaxial niobium nitride on chip for single photon detection. This integration can be used for developing single photon devices on large scale wafers. It can also be integrated as the detection module for complex photonic circuits for quantum information processing [104]. All nitride superconducting qubits can also be obtained with NbN [140]. The coupling between a superconducting hardware platform and photonic circuits could be considered. Further developments are expected in this area.

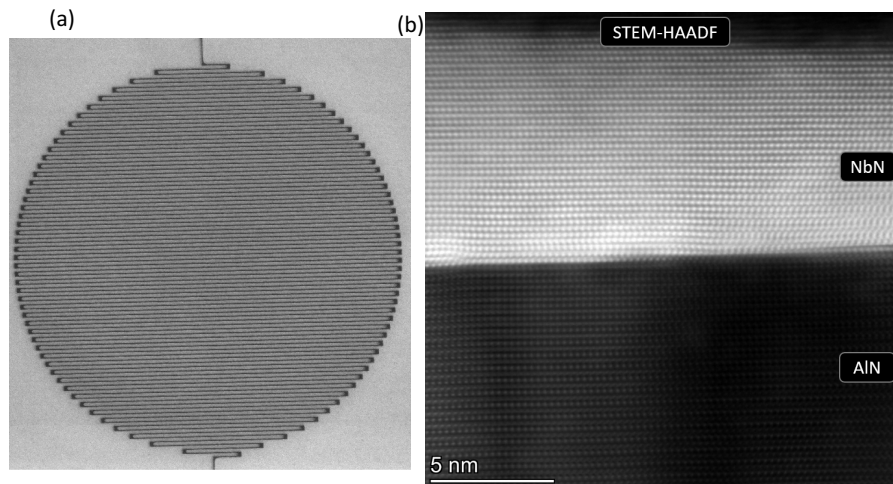


Figure 3. (a) Superconducting nanowire single photon detector (SNSPD) fabricated at KTH Royal Institute of Technology (Sweden) on a NbN thin layer epitaxially grown at CRHEA by molecular beam epitaxy on a silicon substrate using an AlN buffer layer. (Courtesy of KTH). (b) Scanning transmission electron microscopy - High angle annular dark field (STEM-HAADF) picture of a NbN epitaxial layer on AlN on silicon.

Another interest of the III-nitrides is the ability to overgrow new materials on top of them. Among these new materials are the two-dimensional materials. So far, the most standard approach for integrating 2D materials has been the material exfoliation followed by their transfer on an appropriate platform. Numerous demonstrations were reported with this technique [141]. More interestingly for heterogeneous integration, the direct or *in situ* epitaxial growth of 2D materials offers much more simplicity and opportunities [142]. These 2D materials can be either h-BN, graphene or transition metal dichalcogenides (TMDs)[143] but many more materials can be envisioned. Epitaxially-

aligned MoS₂ on GaN has been reported for example in Ref. [144] and in Ref. [145] with epitaxial growth by chemical vapor deposition. Figure 4 shows an example of a monolayer of a transition metal dichalcogenide (MoS₂) grown by molecular beam epitaxy on a GaN buffer layer on sapphire.

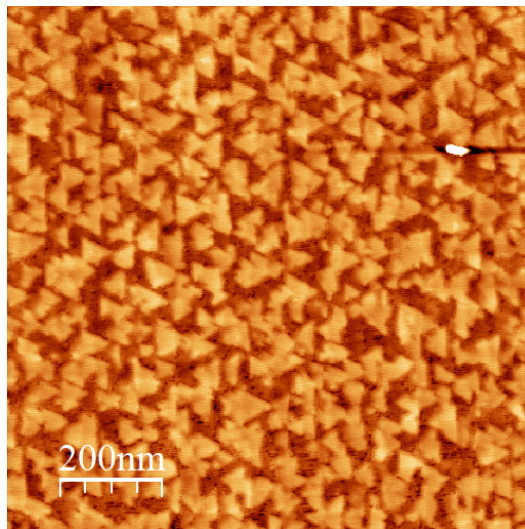


Figure 4. Transition metal dichalcogenide (MoS₂) grown on GaN on sapphire by molecular beam epitaxy as observed by atomic force microscopy. The flakes of MoS₂ monolayer appear as triangles. A surface coverage around 65% is achieved in this case. The surface is mostly covered by a monolayer of TMDs except at some interfaces.

The fusion of III-Nitride photonic architectures with 2D crystals holds great promise for advancing the capabilities of optoelectronic and photonic devices. This potential arises from the inherent characteristics of 2D materials, characterized by their small volume footprint, suitability for stacking into van der Waals (vdW) heterostructures with embedded control features like electrical gates, and the capacity to finely adjust electronic properties at the monolayer level. This adaptability enables the integration of various materials, including metals, semiconductors, insulators, and ferroelectrics. Moreover, many 2D materials possess a relatively smaller band gap, endowing them with exceptional light absorption properties, and rendering them suitable for optoelectronic and photovoltaic devices. Notably, 2D layered materials lack dangling bonds, simplifying their integration with three-dimensional semiconductors to form van der Waals heterostructures.

Looking at the TMD/GaN heterojunction, GaN poses challenges due to its wide band gap, particularly in achieving p-type doping. Integrating narrow band gap semiconductors with GaN has the potential to create high-performance devices and the performances of TMD/III-nitrides heterostructures remain dependent of the interface quality affected by lattice mismatch [146], or transfer technique [147]. The two main methodologies to achieve such integration involve either transfer or non-transfer of

2D crystals on a target substrate. In the transferless approach, monolayers or vdW heterostructures are directly epitaxially grown on the surface of a III-nitride substrate. It is worth noting that, in certain instances, III-nitrides have been grown directly on 2D crystals [148] like graphene to create UV photodetectors, using GaN as the active material. Conversely, the transferable approach involves the deliberate transfer of 2D materials onto a III-nitride substrate using either wet or dry transfer techniques. In the latter case, 2D crystals can be obtained through large-area synthesis or flakes exfoliation, thereby enabling the creation of 2D/III-nitride hybrid structures without introducing complications arising from lattice mismatches.

TMD/III-nitride heterostructures have led to type-II band alignment structures [149, 150], exemplified by MoS₂/GaN photodiodes. These structures exhibit remarkable sensitivity to 405 nm laser light and demonstrate outstanding optoelectronic performance, boasting an ultrahigh photoresponsivity of 10⁵ A/W [151]. This achievement has been reported using both epitaxially grown MoS₂ [149] and exfoliated flakes [150]. The MoS₂/GaN heterojunction notably improves absorption properties across the UV-visible region – even for thin multilayer MoS₂–, expanding the absorption spectra over hundreds of nanometers [152]. This extension encompasses the UV to visible spectrum, potentially leading to a broadband photodetection capability. In recent experiments [153], the successful creation of a MoS₂/n-doped GaN heterojunction photodiode has been achieved, revealing an even higher photoresponsivity in the UV range at 365 nm, reaching up to 10⁶ A/W. Although the responsivity diminishes as the wavelength increases, this photodiode maintains functionality up to the near-infrared (NiR) range at 900 nm [153]. This performance makes it a promising candidate for broadband photodetection applications, covering a wide spectrum from UV to NiR. These heterojunctions have also found alternative applications in gas sensing. Studies have demonstrated that MoS₂/GaN exhibits notable selectivity for detecting NO₂ gas when compared to pristine p-GaN film under UV illumination [154]. Advanced vdW heterostructures involving GaN, such as ReS₂/WS₂/p-GaN, have resulted in dual heterojunctions [155]. These structures combine fast photoresponse at the p-GaN interface with prolonged photocarrier lifetimes at the TMD interface. This combination yields highly sensitive and rapid photodetectors, akin to the concept initially introduced in TMD/Graphene-based ultra-fast photodetectors [156].

For 2D crystals and van der Waals (vdW) heterostructure physics, the quality of the interface plays a pivotal role in determining the functionality and overall properties of the structure. Special attention has been directed towards understanding the influence of interfacial phonons in MoS₂-GaN heterojunctions and their impact on excitons which can lead to alterations in carrier relaxation rates [157] explored through transient optical pump-probe spectroscopy. Similar experimental techniques have been employed to uncover the transport of out-of-plane acoustic phonons through mono- and bi-layer MoS₂/GaN structures [158]. This understanding is essential for elucidating the nanothermics of vdW heterostructures and optimizing thermal transfer in functional devices.

When integrated into more intricate III-nitride-based photonic structures, 2D crystals introduce novel device functionalities and give rise to emergent physical phenomena. As an example, GaN microdisk resonators coupled to MoS₂ showcase a robust nonlinear response (four-wave mixing)[159]. Furthermore, structures composed of GaN/AlGaIn quantum wells with graphene acting as a semi-transparent gate electrode have enabled precise control of surface potentials and inherent electric fields across the structure [160]. This capability unlocks the potential for electrostatic modulation of indirect exciton densities.

While hexagonal boron nitride (h-BN) is commonly used to encapsulate TMDs enhancing their excitonic and electronic properties [161, 162], wide band gap semiconductors like GaN hold promise for spatially manipulating the dielectric environment surrounding 2D TMDs. One could anticipate intriguing possibilities in TMD exciton engineering by utilizing GaN as a patterned substrate [163]. All these examples illustrate how combining 2D materials with 3D semiconductors can enable an advanced integration creating multifunctional heterostructures for integrated photonics.

Another future mainstream development will certainly be associated with the development of photonic circuits operating at very short wavelengths in the deep UV-range. Materials like AlN or BN are perfectly appropriate to address these issues. Applications in the domain of life science and quantum information are expected. The III-nitride platform can indeed be well suited for hybrid photon-atom integrated circuits. Low-power atom trapping on a GaN-on-sapphire chip has been proposed in Ref. [164].

We are convinced that the III-nitrides provide exceptional opportunities for integrated photonic circuits in the visible and ultra-violet range. The III-nitride semiconductors offer all functionalities in terms of passive and active devices along with state-of-the-art performances. We should nonetheless be aware that the strategy based on "one size fits all" is not the sole approach available for integration. It might happen that the future of integrated photonics might be based on hybrid multifunctional platforms where each chiplet provides specific functionalities with enhanced performances.

6. Conclusion

Integrated photonics is becoming a mainstream technology and an essential element in the available toolbox to build complex multifunctional systems. Integrated photonics has recently evolved with the development of platforms in the visible and ultra-violet spectral range. From this perspective, the platform based on III-nitride materials is particularly exciting because it combines all key features necessary for becoming a universal platform, including scalability for industrial production. One of the key advantage of the III-nitride platform is the monolithic integration of a laser source and we can be confident that numerous developments will be proposed in the coming years with monolithic sources associated to active and passive devices. Another key feature of the III-nitrides is their capability to be complemented by epitaxy with other materials, either other

III-Nitrides like niobium nitride or two-dimensional materials. The perspectives in this domain are truly exciting and will undoubtedly be a major driving force in promoting this platform.

7. Acknowledgments

This work was supported by the French National Research Agency (Agence Nationale de la Recherche, ANR) through funding of the OPOINT project (ANR-19-CE24-0024). Nagesh Bhat is partly funded by Labex GANEX (ANR-11-LABX-0014). GANEX belongs to the public funded ‘Investissements d’Avenir’ program managed by the French ANR agency.

This work benefits from a France 2030 government grant PEPR Electronique “ADICT” managed by the French National Research Agency (ANR-22-PEEL-00011). The authors acknowledge the financial support from NANOFUTUR project handled by ANR in the framework of Programme d’Investissement d’Avenir (ANR-21-ESRE-0012).

We thank Antoine Pedèches for the growth of NbN films on GaN and Val Zwiller for providing the image of the SNSPD. The TEM image of the NbN film was obtained by H el ene Rotella and we acknowledge her contribution. We thank Yvon Cordier for useful discussions.

8. Conflict of interest

The authors declare no conflict of interest.

9. Data access

The data presented in this work might be accessible upon reasonable requests to the authors.

References

- [1] Miller S E 1969 *The Bell System Technical Journal* **48** 2059–2069
- [2] Suzuki M, Noda Y, Tanaka H, Akiba S, Kushiro Y and Isshiki H 1987 *Journal of Lightwave Technology* **5** 1277–1285
- [3] Smit M 1988 *Electronics Letters* **24**(7) 385–386(1) ISSN 0013-5194 URL <https://digital-library.theiet.org/content/journals/10.1049/e1.19880260>
- [4] Bryngdahl O 1973 *J. Opt. Soc. Am.* **63** 416–419 URL <https://opg.optica.org/abstract.cfm?URI=josa-63-4-416>
- [5] Soldano L and Pennings E 1995 *Journal of Lightwave Technology* **13** 615–627
- [6] Smit M, Williams K and van der Tol J 2019 *APL Photonics* **4** 050901 ISSN 2378-0967 (Preprint https://pubs.aip.org/aip/app/article-pdf/doi/10.1063/1.5087862/14010749/050901_1.onlin) URL <https://doi.org/10.1063/1.5087862>
- [7] Reed G 2004 *Index* (John Wiley & Sons, Ltd) pp 251–255 ISBN 9780470014189 (Preprint <https://onlinelibrary.wiley.com/doi/pdf/10.1002/0470014180.index>) URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/0470014180.index>

- [8] Sun J, Timurdogan E, Yaacobi A, Hosseini E S and Watts M R 2013 *Nature* **493** 195–199 URL <https://doi.org/10.1038/nature11727>
- [9] <https://www.mordorintelligence.com/industry-reports/hybrid-photonic-integrated-circuit-market>
- [10] <https://www.yolegroup.com/product/report/silicon-photonics-2022/>
- [11] Hermans A, Van Gasse K and Kuyken B 2022 *APL Photonics* **7** 100901 ISSN 2378-0967 (Preprint <https://pubs.aip.org/aip/app/article-pdf/doi/10.1063/5.0105164/16493114/100901.1.onlin>) URL <https://doi.org/10.1063/5.0105164>
- [12] Papp S B, Beha K, Del’Haye P, Quinlan F, Lee H, Vahala K J and Diddams S A 2014 *Optica* **1** 10–14 URL <https://opg.optica.org/optica/abstract.cfm?URI=optica-1-1-10>
- [13] Kim I, Martins R J, Jang J, Badloe T, Khadir S, Jung H Y, Kim H, Kim J, Genevet P and Rho J 2021 *Nature Nanotechnology* **16** 508–524 URL <https://doi.org/10.1038/s41565-021-00895-3>
- [14] Knill E, Laflamme R and Milburn G J 2001 *Nature* **409** 46–52 URL <https://doi.org/10.1038/35051009>
- [15] Politi A, Cryan M J, Rarity J G, Yu S and O’Brien J L 2008 *Science* **320** 646–649 (Preprint <https://www.science.org/doi/pdf/10.1126/science.1155441>) URL <https://www.science.org/doi/abs/10.1126/science.1155441>
- [16] Wang J, Sciarrino F, Laing A and Thompson M G 2020 *Nature Photonics* **14** 273–284 URL <https://doi.org/10.1038/s41566-019-0532-1>
- [17] Bogdanov S, Shalaginov M Y, Boltasseva A and Shalaev V M 2017 *Opt. Mater. Express* **7** 111–132 URL <https://opg.optica.org/ome/abstract.cfm?URI=ome-7-1-111>
- [18] Moody G, Sorger V J, Blumenthal D J, Juodawlkis P W, Loh W, Sorace-Agaskar C, Jones A E, Balram K C, Matthews J C F, Laing A, Davanco M, Chang L, Bowers J E, Quack N, Galland C, Aharonovich I, Wolff M A, Schuck C, Sinclair N, Lončar M, Komljenovic T, Weld D, Mookherjee S, Buckley S, Radulaski M, Reitzenstein S, Pingault B, Machielse B, Mukhopadhyay D, Akimov A, Zheltikov A, Agarwal G S, Srinivasan K, Lu J, Tang H X, Jiang W, McKenna T P, Safavi-Naeini A H, Steinhauer S, Elshaari A W, Zwiller V, Davids P S, Martinez N, Gehl M, Chiaverini J, Mehta K K, Romero J, Lingaraju N B, Weiner A M, Peace D, Cernansky R, Lobino M, Diamanti E, Vidarte L T and Camacho R M 2022 *Journal of Physics: Photonics* **4** 012501 URL <https://dx.doi.org/10.1088/2515-7647/ac1ef4>
- [19] Atatüre M, Englund D, Vamivakas N, Lee S Y and Wrachtrup J 2018 *Nature Reviews Materials* **3** 38–51 URL <https://doi.org/10.1038/s41578-018-0008-9>
- [20] Monroe C and Kim J 2013 *Science* **339** 1164–1169 (Preprint <https://www.science.org/doi/pdf/10.1126/science.1231298>) URL <https://www.science.org/doi/abs/10.1126/science.1231298>
- [21] Chauhan N, Isichenko A, Liu K, Wang J, Zhao Q, Behunin R O, Rakich P T, Jayich A M, Fertig C, Hoyt C W and Blumenthal D J 2021 *Nature Communications* **12** 4685 URL <https://doi.org/10.1038/s41467-021-24926-8>
- [22] Morin T J, Chang L, Jin W, Li C, Guo J, Park H, Tran M A, Komljenovic T and Bowers J E 2021 *Optica* **8** 755–756 URL <https://opg.optica.org/optica/abstract.cfm?URI=optica-8-5-755>
- [23] Blumenthal D J, Heideman R, Geuzebroek D, Leinse A and Roeloffzen C 2018 *Proceedings of the IEEE* **106** 2209–2231
- [24] Xiang C, Guo J, Jin W, Wu L, Peters J, Xie W, Chang L, Shen B, Wang H, Yang Q F, Kinghorn D, Panizza M, Vahala K J, Morton P A and Bowers J E 2021 *Nature Communications* **12** 6650 URL <https://doi.org/10.1038/s41467-021-26804-9>
- [25] Hosseini E S, Purnawirman, Bradley J D B, Sun J, Leake G, Adam T N, Coolbaugh D D and Watts M R 2014 *Opt. Lett.* **39** 3106–3109 URL <https://opg.optica.org/ol/abstract.cfm?URI=ol-39-11-3106>
- [26] Moss D J, Morandotti R, Gaeta A L and Lipson M 2013 *Nature Photonics* **7** 597–607 URL <https://doi.org/10.1038/nphoton.2013.183>

- [27] Gao R, Yao N, Guan J, Deng L, Lin J, Wang M, Qiao L, Fang W and Cheng Y 2022 *Chin. Opt. Lett.* **20** 011902 URL <https://opg.optica.org/col/abstract.cfm?URI=col-20-1-011902>
- [28] Zhuang R, He J, Qi Y and Li Y 2023 *Advanced Materials* **35** 2208113 (Preprint <https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202208113>) URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.202208113>
- [29] Wang C, Zhang M, Yu M, Zhu R, Hu H and Lončar M 2019 *Nature Communications* **10** 978 URL <https://doi.org/10.1038/s41467-019-08969-6>
- [30] Shams-Ansari A, Renaud D, Cheng R, Shao L, He L, Zhu D, Yu M, Grant H R, Johansson L, Zhang M and Lončar M 2022 *Optica* **9** 408–411 URL <https://opg.optica.org/optica/abstract.cfm?URI=optica-9-4-408>
- [31] Yu M, Cheng R, Reimer C, He L, Luke K, Puma E, Shao L, Shams-Ansari A, Grant H R, Johansson L, Zhang M and Lončar M 2023 *Nature Photonics* URL <https://www-nature-com.ezp-prod1.hul.harvard.edu/articles/s41566-023-01227-8>
- [32] Sanaka K, Kawahara K and Kuga T 2001 *Phys. Rev. Lett.* **86**(24) 5620–5623 URL <https://link.aps.org/doi/10.1103/PhysRevLett.86.5620>
- [33] Alibart O, D’Auria V, Micheli M D, Doutre F, Kaiser F, Labonté L, Lunghi T, Picholle E and Tanzilli S 2016 *Journal of Optics* **18** 104001 URL <https://dx.doi.org/10.1088/2040-8978/18/10/104001>
- [34] Pantzas K, Combré S, Bailly M, Mandouze R, Talenti F R, Harouri A, Gérard B, Beaudoin G, Le Gratiet L, Patriarche G, De Rossi A, Léger Y, Sagnes I and Grisard A 2022 *ACS Photonics* **9** 2032–2039 URL <https://doi.org/10.1021/acsphotonics.2c00156>
- [35] Wang J, Zhou Y, Wang Z, Rasmita A, Yang J, Li X, von Bardeleben H J and Gao W 2018 *Nature Communications* **9** 4106 URL <https://doi.org/10.1038/s41467-018-06605-3>
- [36] Lukin D M, Dory C, Guidry M A, Yang K Y, Mishra S D, Trivedi R, Radulaski M, Sun S, Vercauteren D, Ahn G H and Vučković J 2020 *Nature Photonics* **14** 330–334 URL <https://doi.org/10.1038/s41566-019-0556-6>
- [37] Lukin D M, Guidry M A and Vučković J 2020 *PRX Quantum* **1**(2) 020102 URL <https://link.aps.org/doi/10.1103/PRXQuantum.1.020102>
- [38] Aharonovich I, Greentree A D and Prawer S 2011 *Nature Photonics* **5** 397–405 URL <https://doi.org/10.1038/nphoton.2011.54>
- [39] Checoury X, Néel D, Boucaud P, Gesset C, Girard H, Saada S and Bergonzo P 2012 *Applied Physics Letters* **101** 171115 ISSN 0003-6951 (Preprint <https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4764548/14256854/171115.1.online.pdf>) URL <https://doi.org/10.1063/1.4764548>
- [40] Hausmann B J M, Bulu I B, Deotare P B, McCutcheon M, Venkataraman V, Markham M L, Twitchen D J and Lončar M 2013 *Nano Letters* **13** 1898–1902 URL <https://doi.org/10.1021/nl3037454>
- [41] Burek M J, Chu Y, Liddy M S Z, Patel P, Rochman J, Meesala S, Hong W, Quan Q, Lukin M D and Lončar M 2014 *Nature Communications* **5** 5718 URL <https://doi.org/10.1038/ncomms6718>
- [42] Sipahigil A, Evans R E, Sukachev D D, Burek M J, Borregaard J, Bhaskar M K, Nguyen C T, Pacheco J L, Atikian H A, Meuwly C, Camacho R M, Jelezko F, Bielejec E, Park H, Lončar M and Lukin M D 2016 *Science* **354** 847–850 (Preprint <https://www.science.org/doi/pdf/10.1126/science.aah6875>) URL <https://www.science.org/doi/abs/10.1126/science.aah6875>
- [43] Ambacher O 1998 *Journal of Physics D: Applied Physics* **31** 2653 URL <https://dx.doi.org/10.1088/0022-3727/31/20/001>
- [44] Briegleb F and Geuther A 1862 *Justus Liebigs Annalen der Chemie* **123** 228–241 (Preprint <https://chemistry-europe.onlinelibrary.wiley.com/doi/pdf/10.1002/jlac.18621230212>) URL <https://chemistry-europe.onlinelibrary.wiley.com/doi/abs/10.1002/jlac.18621230212>

- [45] Dupuis R D 2023 *Journal of Vacuum Science & Technology B* **41** 060803 ISSN 2166-2746 (Preprint https://pubs.aip.org/avs/jvb/article-pdf/doi/10.1116/6.0003062/18192243/060803_1.6.0003062) URL <https://doi.org/10.1116/6.0003062>
- [46] Manasevit H M, Erdmann F M and Simpson W I 1971 *Journal of The Electrochemical Society* **118** 1864 URL <https://dx.doi.org/10.1149/1.2407853>
- [47] Amano H, Sawaki N, Akasaki I and Toyoda Y 1986 *Applied Physics Letters* **48** 353–355 ISSN 0003-6951 (Preprint https://pubs.aip.org/aip/apl/article-pdf/48/5/353/18456282/353_1_online.pdf) URL <https://doi.org/10.1063/1.96549>
- [48] Amano H, Kito M, Hiramatsu K and Akasaki I 1989 *Japanese Journal of Applied Physics* **28** L2112 URL <https://dx.doi.org/10.1143/JJAP.28.L2112>
- [49] Amano H, Asahi T and Akasaki I 1990 *Japanese Journal of Applied Physics* **29** L205 URL <https://dx.doi.org/10.1143/JJAP.29.L205>
- [50] Nakamura S, Senoh M S M and Mukai T M T 1991 *Japanese Journal of Applied Physics* **30** L1708 URL <https://dx.doi.org/10.1143/JJAP.30.L1708>
- [51] Nakamura S, Mukai T M T and Senoh M S M 1991 *Japanese Journal of Applied Physics* **30** L1998 URL <https://dx.doi.org/10.1143/JJAP.30.L1998>
- [52] Nakamura S, Mukai T, Senoh M S M and Iwasa N I N 1992 *Japanese Journal of Applied Physics* **31** L139 URL <https://dx.doi.org/10.1143/JJAP.31.L139>
- [53] <https://www.osram.com/am/light-for/led-lighting/index.jsp>
- [54] <https://www.mordorintelligence.com/fr/industry-reports/led-chips-market>
- [55] Kneissl M, Seong T Y, Han J and Amano H 2019 *Nature Photonics* **13** 233–244 URL <https://doi.org/10.1038/s41566-019-0359-9>
- [56] Damilano B and Gil B 2015 *Journal of Physics D: Applied Physics* **48** 403001 URL <https://dx.doi.org/10.1088/0022-3727/48/40/403001>
- [57] Iida D and Ohkawa K 2021 *Semiconductor Science and Technology* **37** 013001 URL <https://dx.doi.org/10.1088/1361-6641/ac3962>
- [58] Dussaigne A, Maitre P L, Haas H, Pillet J C, Barbier F, Grenier A, Michit N, Jannaud A, Templier R, Vaufrey D, Rol F, Ledoux O and Sotta D 2021 *Applied Physics Express* **14** 092011 URL <https://dx.doi.org/10.35848/1882-0786/ac1b3e>
- [59] Pasayat S S, Gupta C, Wong M S, Ley R, Gordon M J, DenBaars S P, Nakamura S, Keller S and Mishra U K 2020 *Applied Physics Express* **14** 011004 URL <https://dx.doi.org/10.35848/1882-0786/abd06f>
- [60] Li P, Li H, Zhang H, Yang Y, Wong M S, Lynsky C, Iza M, Gordon M J, Speck J S, Nakamura S and DenBaars S P 2022 *Applied Physics Letters* **120** 121102 ISSN 0003-6951 (Preprint https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/5.0086912/16444828/121102_1_online.pdf) URL <https://doi.org/10.1063/5.0086912>
- [61] Iida D, Kirilenko P, Velazquez-Rizo M, Zhuang Z, Najmi M A and Ohkawa K 2022 *AIP Advances* **12** 065125 ISSN 2158-3226 (Preprint https://pubs.aip.org/aip/adv/article-pdf/doi/10.1063/5.0097761/16464226/065125_1_online.pdf) URL <https://doi.org/10.1063/5.0097761>
- [62] Day J, Li J, Lie D Y C, Bradford C, Lin J Y and Jiang H X 2011 *Applied Physics Letters* **99** 031116 ISSN 0003-6951 (Preprint https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.3615679/14453135/031116_1_online.pdf) URL <https://doi.org/10.1063/1.3615679>
- [63] Jiang H X and Lin J Y 2013 *Opt. Express* **21** A475–A484 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-21-103-A475>
- [64] Wong M S, Nakamura S and DenBaars S P 2019 *ECS Journal of Solid State Science and Technology* **9** 015012 URL <https://dx.doi.org/10.1149/2.0302001JSS>
- [65] Meneghini M, De Santi C, Abid I, Buffolo M, Cioni M, Khadar R A, Nela L, Zagni N, Chini A, Medjdoub F, Meneghesso G, Verzellesi G, Zanoni E and Ma-

- tioli E 2021 *Journal of Applied Physics* **130** 181101 ISSN 0021-8979 (*Preprint* https://pubs.aip.org/aip/jap/article-pdf/doi/10.1063/5.0061354/15270763/181101.1_online.pdf) URL <https://doi.org/10.1063/5.0061354>
- [66] Lu H, Zhang M, Yang L, Hou B, Martinez R P, Mi M, Du J, Deng L, Wu M, Chowdhury S, Ma X and Hao Y 2023 *Fundamental Research* ISSN 2667-3258 URL <https://www.sciencedirect.com/science/article/pii/S2667325823003023>
- [67] Zanoni E, De Santi C, Gao Z, Buffolo M, Fornasier M, Saro M, De Pieri F, Rampazzo F, Meneghesso G, Meneghini M, Zagni N, Chini A and Verzellesi G 2024 *IEEE Transactions on Electron Devices* **71** 1396–1407
- [68] Nakamura S, Senoh M, ichi Nagahama S, Iwasa N, Yamada T, Matsushita T, Kiyoku H K H and Sugimoto Y S Y 1996 *Japanese Journal of Applied Physics* **35** L74 URL <https://dx.doi.org/10.1143/JJAP.35.L74>
- [69] ichi Nagahama S, Iwasa N, Senoh M, Matsushita T, Sugimoto Y, Kiyoku H, Kozaki T, Sano M, Matsumura H, Umemoto H, Chocho K and Mukai T 2000 *Japanese Journal of Applied Physics* **39** L647 URL <https://dx.doi.org/10.1143/JJAP.39.L647>
- [70] Sun Y, Zhou K, Sun Q, Liu J, Feng M, Li Z, Zhou Y, Zhang L, Li D, Zhang S, Ikeda M, Liu S and Yang H 2016 *Nature Photonics* **10** 595–599 URL <https://doi.org/10.1038/nphoton.2016.158>
- [71] Feng M, Li Z, Wang J, Zhou R, Sun Q, Sun X, Li D, Gao H, Zhou Y, Zhang S, Li D, Zhang L, Liu J, Wang H, Ikeda M, Zheng X and Yang H 2018 *ACS Photonics* **5** 699–704 (*Preprint* <https://doi.org/10.1021/acsphotonics.7b01215>) URL <https://doi.org/10.1021/acsphotonics.7b01215>
- [72] Kneissl M, Teepe M, Miyashita N, Johnson N M, Chern G D and Chang R K 2004 *Applied Physics Letters* **84** 2485–2487 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/84/14/2485/10203757/2485.1_online.pdf) URL <https://doi.org/10.1063/1.1691494>
- [73] Haberer E D, Sharma R, Meier C, Stonas A R, Nakamura S, DenBaars S P and Hu E L 2004 *Applied Physics Letters* **85** 5179–5181 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/85/22/5179/18601727/5179.1_online.pdf) URL <https://doi.org/10.1063/1.1829167>
- [74] Choi H W, Hui K N, Lai P T, Chen P, Zhang X H, Tripathy S, Teng J H and Chua S J 2006 *Applied Physics Letters* **89** 211101 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.2392673/14363084/211101.1_online.pdf) URL <https://doi.org/10.1063/1.2392673>
- [75] Tamboli A C, Haberer E D, Sharma R, Lee K H, Nakamura S and Hu E L 2007 *Nature Photonics* **1** 61–64 URL <https://doi.org/10.1038/nphoton.2006.52>
- [76] Simeonov D, Feltin E, Bühlmann H J, Zhu T, Castiglia A, Mosca M, Carlin J F, Butté R and Grandjean N 2007 *Applied Physics Letters* **90** 061106 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.2460234/14365818/061106.1_online.pdf) URL <https://doi.org/10.1063/1.2460234>
- [77] Simeonov D, Feltin E, Altoukhov A, Castiglia A, Carlin J F, Butté R and Grandjean N 2008 *Applied Physics Letters* **92** 171102 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.2917452/14392879/171102.1_online.pdf) URL <https://doi.org/10.1063/1.2917452>
- [78] Aharonovich I, Woolf A, Russell K J, Zhu T, Niu N, Kappers M J, Oliver R A and Hu E L 2013 *Applied Physics Letters* **103** 021112 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4813471/13023074/021112.1_online.pdf) URL <https://doi.org/10.1063/1.4813471>
- [79] Sellés J, Brimont C, Cassabois G, Valvin P, Guillet T, Roland I, Zeng Y, Checoury X, Boucaud P, Mexis M, Semond F and Gayral B 2016 *Scientific Reports* **6** 21650 URL <https://doi.org/10.1038/srep21650>

- [80] Sellés J, Crepel V, Roland I, El Kurdi M, Checoury X, Boucaud P, Mexis M, Leroux M, Damilano B, Rennesson S, Semond F, Gayral B, Brimont C and Guillet T 2016 *Applied Physics Letters* **109** 231101 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4971357/13138862/231101.1_online.pdf) URL <https://doi.org/10.1063/1.4971357>
- [81] Tabataba-Vakili F, Brimont C, Alloing B, Damilano B, Doyennette L, Guillet T, El Kurdi M, Chenot S, Brändli V, Frayssinet E, Duboz J Y, Semond F, Gayral B and Boucaud P 2020 *Applied Physics Letters* **117** 121103 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/5.0015252/14537220/121103.1_online.pdf) URL <https://doi.org/10.1063/5.0015252>
- [82] Zhu G, Li J, Zhang N, Li X, Dai J, Cui Q, Song Q, Xu C and Wang Y 2020 *Scientific Reports* **10** 253 URL <https://doi.org/10.1038/s41598-019-57118-y>
- [83] Tabataba-Vakili F, Doyennette L, Brimont C, Guillet T, Rennesson S, Frayssinet E, Damilano B, Duboz J Y, Semond F, Roland I, El Kurdi M, Checoury X, Sauvage S, Gayral B and Boucaud P 2018 *ACS Photonics* **5** 3643–3648 (*Preprint* <https://doi.org/10.1021/acsp Photonics.8b00542>) URL <https://doi.org/10.1021/acsp Photonics.8b00542>
- [84] Tabataba-Vakili F, Doyennette L, Brimont C, Guillet T, Rennesson S, Damilano B, Frayssinet E, Duboz J Y, Checoury X, Sauvage S, El Kurdi M, Semond F, Gayral B and Boucaud P 2019 *Scientific Reports* **9** 18095 URL <https://doi.org/10.1038/s41598-019-54416-3>
- [85] Tabataba-Vakili F, Alloing B, Damilano B, Souissi H, Brimont C, Doyennette L, Guillet T, Checoury X, Kurdi M E, Chenot S, Frayssinet E, Duboz J Y, Semond F, Gayral B and Boucaud P 2020 *Opt. Lett.* **45** 4276–4279 URL <https://opg.optica.org/ol/abstract.cfm?URI=ol-45-15-4276>
- [86] Wang J, Feng M, Zhou R, Sun Q, Liu J, Sun X, Zheng X, Ikeda M, Sheng X and Yang H 2020 *Opt. Express* **28** 12201–12208 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-28-8-12201>
- [87] Feng M, Zhao H, Zhou R, Tang Y, Liu J, Sun X, Sun Q and Yang H 2023 *ACS Photonics* **10** 2208–2215 (*Preprint* <https://doi.org/10.1021/acsp Photonics.2c01046>) URL <https://doi.org/10.1021/acsp Photonics.2c01046>
- [88] Yan J, Fang L, Sun Z, Zhang H, Yuan J, Jiang Y and Wang Y 2023 *Advanced Photonics Nexus* **2** 046003 URL <https://doi.org/10.1117/1.APN.2.4.046003>
- [89] Holmes M J, Choi K, Kako S, Arita M and Arakawa Y 2014 *Nano Letters* **14** 982–986 pMID: 24422516 (*Preprint* <https://doi.org/10.1021/nl404400d>) URL <https://doi.org/10.1021/nl404400d>
- [90] Holmes M J, Arita M and Arakawa Y 2019 *Semiconductor Science and Technology* **34** 033001 URL <https://dx.doi.org/10.1088/1361-6641/ab02c8>
- [91] Zhou Y, Wang Z, Rasmita A, Kim S, Berhane A, Bodrog Z, Adamo G, Gali A, Aharonovich I and Gao W 2018 *Science Advances* **4** eaar3580 (*Preprint* <https://www.science.org/doi/pdf/10.1126/sciadv.aar3580>) URL <https://www.science.org/doi/abs/10.1126/sciadv.aar3580>
- [92] Meunier M, Eng J J H, Mu Z, Chenot S, Brändli V, de Mierry P, Gao W and Zúñiga-Pérez J 2023 *Nanophotonics* **12** 1405–1419 URL <https://doi.org/10.1515/nanoph-2022-0659>
- [93] Bishop S G, Hadden J P, Alzahrani F D, Hekmati R, Huffaker D L, Langbein W W and Bennett A J 2020 *ACS Photonics* **7** 1636–1641 pMID: 32905301 (*Preprint* <https://doi.org/10.1021/acsp Photonics.0c00528>) URL <https://doi.org/10.1021/acsp Photonics.0c00528>
- [94] Grosso G, Moon H, Lienhard B, Ali S, Efetov D K, Furchi M M, Jarillo-Herrero P, Ford M J, Aharonovich I and Englund D 2017 *Nature Communications* **8** 705 URL <https://doi.org/10.1038/s41467-017-00810-2>
- [95] Vermeulen N, Espinosa D, Ball A, Ballato J, Boucaud P, Boudebs G, Campos C L A V,

- Dragic P, Gomes A S L, Huttunen M J, Kinsey N, Mildren R, Neshev D, Padilha L A, Pu M, Secondo R, Tokunaga E, Turchinovich D, Yan J, Yvind K, Dolgaleva K and Stryland E W V 2023 *Journal of Physics: Photonics* **5** 035001 URL <https://dx.doi.org/10.1088/2515-7647/ac9e2f>
- [96] Bruch A W, Liu X, Guo X, Surya J B, Gong Z, Zhang L, Wang J, Yan J and Tang H X 2018 *Applied Physics Letters* **113** 131102 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.5042506/14516365/131102.1_online.pdf) URL <https://doi.org/10.1063/1.5042506>
- [97] Majkić A, Franke A, Kirste R, Schlessner R, Collazo R, Sitar Z and Zgonik M 2017 *physica status solidi (b)* **254** 1700077 URL <https://doi.org/10.1002/pssb.201700077>
- [98] Larciprete M C, Centini M, Belardini A, Sciscione L, Bertolotti M, Sibilica C, Scalora M, Passaseo A and Potì B 2006 *Applied Physics Letters* **89** 131105 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.2357022/13522338/131105.1_online.pdf) URL <https://doi.org/10.1063/1.2357022>
- [99] Kravetsky I V, Tiginyanu I M, Hildebrandt R, Marowsky G, Pavlidis D, Eisenbach A and Hartnagel H L 2000 *Applied Physics Letters* **76** 810–812 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/76/7/810/10184423/810.1_online.pdf) URL <https://doi.org/10.1063/1.125592>
- [100] Sanford N A, Davydov A V, Tsvetkov D V, Dmitriev A V, Keller S, Mishra U K, DenBaars S P, Park S S, Han J Y and Molnar R J 2005 *Journal of Applied Physics* **97** 053512 ISSN 0021-8979 (*Preprint* https://pubs.aip.org/aip/jap/article-pdf/doi/10.1063/1.1852695/14941515/053512.1_online.pdf) URL <https://doi.org/10.1063/1.1852695>
- [101] Gromovyi M, Bhat N, Tronche H, Baldi P, El Kurdi M, Checoury X, Damilano B and Boucaud P 2023 *Opt. Express* **31** 31397–31409 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-31-19-31397>
- [102] Goltsman G N, Okunev O, Chulkova G, Lipatov A, Semenov A, Smirnov K, Voronov B, Dzardanov A, Williams C and Sobolewski R 2001 *Applied Physics Letters* **79** 705–707 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/79/6/705/8782545/705.1_online.pdf) URL <https://doi.org/10.1063/1.1388868>
- [103] Cheng R, Wright J, Xing H G, Jena D and Tang H X 2020 *Applied Physics Letters* **117** 132601 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/5.0018818/14539879/132601.1_online.pdf) URL <https://doi.org/10.1063/5.0018818>
- [104] Guo X, Zou C I, Schuck C, Jung H, Cheng R and Tang H X 2017 *Light: Science & Applications* **6** e16249–e16249 URL <https://doi.org/10.1038/lsa.2016.249>
- [105] Templier F 2016 *Journal of the Society for Information Display* **24** 669–675 (*Preprint* <https://sid.onlinelibrary.wiley.com/doi/pdf/10.1002/jsid.516>) URL <https://sid.onlinelibrary.wiley.com/doi/abs/10.1002/jsid.516>
- [106] Griffiths A D, Islim M S, Herrnsdorf J, McKendry J J D, Henderson R, Haas H, Gu E and Dawson M D 2017 *Opt. Express* **25** A338–A345 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-25-8-A338>
- [107] Butté R and Grandjean N 2020 *Nanophotonics* **9** 569–598 URL <https://doi.org/10.1515/nanoph-2019-0442>
- [108] Néel D, Sergent S, Mexis M, Sam-Giao D, Guillet T, Brimont C, Bretagnon T, Semond F, Gayral B, David S, Checoury X and Boucaud P 2011 *Applied Physics Letters* **98** 261106 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.3605592/14059477/261106.1_online.pdf) URL <https://doi.org/10.1063/1.3605592>
- [109] Sergent S, Arita M, Kako S, Tanabe K, Iwamoto S and Arakawa Y

- 2012 *Applied Physics Letters* **101** 101106 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4751336/14254029/101106.1_online.pdf) URL <https://doi.org/10.1063/1.4751336>
- [110] Sam-Giao D, Néel D, Sergent S, Gayral B, Rashid M J, Semond F, Duboz J Y, Mexis M, Guillet T, Brimont C, David S, Checoury X and Boucaud P 2012 *Applied Physics Letters* **100** 191104 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4712590/13983342/191104.1_online.pdf) URL <https://doi.org/10.1063/1.4712590>
- [111] Pernice W H P, Xiong C, Schuck C and Tang H X 2012 *Applied Physics Letters* **100** 091105 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.3690888/13968353/091105.1_online.pdf) URL <https://doi.org/10.1063/1.3690888>
- [112] Roland I, Zeng Y, Han Z, Checoury X, Blin C, El Kurdi M, Ghrib A, Sauvage S, Gayral B, Brimont C, Guillet T, Semond F and Boucaud P 2014 *Applied Physics Letters* **105** 011104 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4887065/13898810/011104.1_online.pdf) URL <https://doi.org/10.1063/1.4887065>
- [113] Vico Triviño N, Minkov M, Urbinati G, Galli M, Carlin J F, Butté R, Savona V and Grandjean N 2014 *Applied Physics Letters* **105** 231119 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4903861/13673031/231119.1_online.pdf) URL <https://doi.org/10.1063/1.4903861>
- [114] Zeng Y, Roland I, Checoury X, Han Z, El Kurdi M, Sauvage S, Gayral B, Brimont C, Guillet T, Mexis M, Semond F and Boucaud P 2015 *Applied Physics Letters* **106** 081105 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4913679/13591986/081105.1_online.pdf) URL <https://doi.org/10.1063/1.4913679>
- [115] Zeng Y, Roland I, Checoury X, Han Z, El Kurdi M, Sauvage S, Gayral B, Brimont C, Guillet T, Semond F and Boucaud P 2016 *ACS Photonics* **3** 1240–1247 URL <https://doi.org/10.1021/acsp Photonics.6b00236>
- [116] Mohamed M S, Simbula A, Carlin J F, Minkov M, Gerace D, Savona V, Grandjean N, Galli M and Houdré R 2017 *APL Photonics* **2** 031301 ISSN 2378-0967 (*Preprint* https://pubs.aip.org/aip/app/article-pdf/doi/10.1063/1.4974311/14567573/031301.1_online.pdf) URL <https://doi.org/10.1063/1.4974311>
- [117] Tabataba-Vakili F, Roland I, Tran T M, Checoury X, El Kurdi M, Sauvage S, Brimont C, Guillet T, Rennesson S, Duboz J Y, Semond F, Gayral B and Boucaud P 2017 *Applied Physics Letters* **111** 131103 ISSN 0003-6951 (*Preprint* https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4997124/14502780/131103.1_online.pdf) URL <https://doi.org/10.1063/1.4997124>
- [118] Rousseau I, Sánchez-Arribas I, Shojiki K, Carlin J F, Butté R and Grandjean N 2017 *Phys. Rev. B* **95**(12) 125313 URL <https://link.aps.org/doi/10.1103/PhysRevB.95.125313>
- [119] Rousseau I, Callsen G, Jacopin G, Carlin J F, Butté R and Grandjean N 2018 *Journal of Applied Physics* **123** 113103 ISSN 0021-8979 (*Preprint* https://pubs.aip.org/aip/jap/article-pdf/doi/10.1063/1.5022150/9237835/113103.1_online.pdf) URL <https://doi.org/10.1063/1.5022150>
- [120] Iwaya T, Ichikawa S, Timmerman D, Tatebayashi J and Fujiwara Y 2022 *Opt. Express* **30** 28853–28864 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-30-16-28853>
- [121] Matsubara H, Yoshimoto S, Saito H, Jianglin Y, Tanaka Y and Noda S 2008 *Science* **319** 445–447 (*Preprint* <https://www.science.org/doi/pdf/10.1126/science.1150413>) URL <https://www.science.org/doi/abs/10.1126/science.1150413>
- [122] Taguchi N, Iwai A, Noguchi M, Takahashi H, Michiue A, Zoysa M D, Inoue T, Ishizaki K and Noda S 2024 *Applied Physics Express* **17** 012002 URL

- <https://dx.doi.org/10.35848/1882-0786/ad126f>
- [123] Emoto K, Koizumi T, Hirose M, Jutori M, Inoue T, Ishizaki K, De Zoysa M, Togawa H and Noda S 2022 *Communications Materials* **3** 72 URL <https://doi.org/10.1038/s43246-022-00288-6>
- [124] Triviño N V, Butté R, Carlin J F and Grandjean N 2015 *Nano Lett* **15** 1259–1263 ISSN 1530-6992 (Electronic); 1530-6984 (Linking)
- [125] Xiong C, Pernice W H P and Tang H X 2012 *Nano Letters* **12** 3562–3568 PMID: 22663299 (*Preprint* <https://doi.org/10.1021/nl3011885>) URL <https://doi.org/10.1021/nl3011885>
- [126] Pernice W H, Xiong C and Tang H X 2012 *Opt. Express* **20** 12261–12269 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-20-11-12261>
- [127] Liu X, Sun C, Xiong B, Wang L, Wang J, Han Y, Hao Z, Li H, Luo Y, Yan J, Wei T, Zhang Y and Wang J 2017 *Opt. Express* **25** 587–594 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-25-2-587>
- [128] Zheng Y, Sun C, Xiong B, Wang L, Hao Z, Wang J, Han Y, Li H, Yu J and Luo Y 2022 *Laser & Photonics Reviews* **16** 2100071 (*Preprint* <https://onlinelibrary.wiley.com/doi/pdf/10.1002/lpor.202100071>) URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/lpor.202100071>
- [129] Cai Y, Wu K, Ma Z, Zhao S and Zhang Y 2023 *Opt. Express* **31** 42795–42806 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-31-26-42795>
- [130] Bhat N, Gromovyi M, El Kurdi M, Checoury X, Damilano B and Boucaud P 2024 *Opt. Mater. Express* **14** 792–800 URL <https://opg.optica.org/ome/abstract.cfm?URI=ome-14-3-792>
- [131] Gromovyi M, El Kurdi M, Checoury X, Herth E, Tabataba-Vakili F, Bhat N, Courville A, Semond F and Boucaud P 2022 *Opt. Express* **30** 20737–20749 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-30-12-20737>
- [132] Liu X, Bruch A W, Gong Z, Lu J, Surya J B, Zhang L, Wang J, Yan J and Tang H X 2018 *Optica* **5** 1279–1282 URL <https://opg.optica.org/optica/abstract.cfm?URI=optica-5-10-1279>
- [133] Lu T J, Fanto M, Choi H, Thomas P, Steidle J, Mouradian S, Kong W, Zhu D, Moon H, Berggren K, Kim J, Soltani M, Preble S and Englund D 2018 *Opt. Express* **26** 11147–11160 URL <https://opg.optica.org/oe/abstract.cfm?URI=oe-26-9-11147>
- [134] Mexis M, Sergent S, Guillet T, Brimont C, Bretagnon T, Gil B, Semond F, Leroux M, Néel D, David S, Chécoury X and Boucaud P 2011 *Opt. Lett.* **36** 2203–2205 URL <https://opg.optica.org/ol/abstract.cfm?URI=ol-36-12-2203>
- [135] Guo X, Zou C L and Tang H X 2016 *Optica* **3** 1126–1131 URL <https://opg.optica.org/optica/abstract.cfm?URI=optica-3-10-1126>
- [136] Jung H, Xiong C, Fong K Y, Zhang X and Tang H X 2013 *Opt. Lett.* **38** 2810–2813 URL <https://opg.optica.org/ol/abstract.cfm?URI=ol-38-15-2810>
- [137] Bruch A W, Liu X, Surya J B, Zou C L and Tang H X 2019 *Optica* **6** 1361–1366 URL <https://opg.optica.org/optica/abstract.cfm?URI=optica-6-10-1361>
- [138] Vasil'ev P P, Sergeev A B, Smetanin I V, Weig T, Schwarz U T, Sulmoni L, Dorsaz J, Lamy J M, Carlin J F, Grandjean N, Zeng X, Stadelmann T, Grossmann S, Hoogerwerf A C and Boiko D L 2013 *Applied Physics Letters* **102** 121115 ISSN 0003-6951 (*Preprint* <https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.4798264/13220437/121115.1.online.pdf>) URL <https://doi.org/10.1063/1.4798264>
- [139] Wunderer T, Siddharth A, Johnson N M, Chua C L, Teepe M, Yang Z, Batres M, Maeda P, Lihachev G and Kippenberg T J 2023 *Opt. Lett.* **48** 2781–2784 URL <https://opg.optica.org/ol/abstract.cfm?URI=ol-48-11-2781>
- [140] Kim S, Terai H, Yamashita T, Qiu W, Fuse T, Yoshihara F, Ashhab S, Inomata K and Semba K 2021 *Communications Materials* **2** 98 URL

- <https://doi.org/10.1038/s43246-021-00204-4>
- [141] Cai X, Luo Y, Liu B and Cheng H M 2018 *Chem. Soc. Rev.* **47**(16) 6224–6266 URL <http://dx.doi.org/10.1039/C8CS00254A>
- [142] Momeni K, Ji Y, Wang Y, Paul S, Neshani S, Yilmaz D E, Shin Y K, Zhang D, Jiang J W, Park H S, Sinnott S, van Duin A, Crespi V and Chen L Q 2020 *npj Computational Materials* **6** 22 URL <https://doi.org/10.1038/s41524-020-0280-2>
- [143] Ji J, Kwak H M, Yu J, Park S, Park J H, Kim H, Kim S, Kim S, Lee D S and Kum H S 2023 *Nano Convergence* **10** 19 URL <https://doi.org/10.1186/s40580-023-00368-4>
- [144] Ruzmetov D, Zhang K, Stan G, Kalanyan B, Bhimanapati G R, Eichfeld S M, Burke R A, Shah P B, O'Regan T P, Crowne F J, Birdwell A G, Robinson J A, Davydov A V and Ivanov T G 2016 *ACS Nano* **10** 3580–3588 pMID: 26866442 (Preprint <https://doi.org/10.1021/acsnano.5b08008>) URL <https://doi.org/10.1021/acsnano.5b08008>
- [145] Wan Y, Xiao J, Li J, Fang X, Zhang K, Fu L, Li P, Song Z, Zhang H, Wang Y, Zhao M, Lu J, Tang N, Ran G, Zhang X, Ye Y and Dai L 2018 *Advanced Materials* **30** 1703888 (Preprint <https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.201703888>) URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201703888>
- [146] Gupta P, Rahman A A, Subramanian S, Gupta S, Thamizhavel A, Orlova T, Rouvimov S, Vishwanath S, Protasenko V, Laskar M R, Xing H G, Jena D and Bhattacharya A 2016 *Scientific Reports* **6** 23708 URL <https://doi.org/10.1038/srep23708>
- [147] Castellanos-Gomez A, Buscema M, Molenaar R, Singh V, Janssen L, van der Zant H S J and Steele G A 2014 *2D Materials* **1** 011002 URL <https://dx.doi.org/10.1088/2053-1583/1/1/011002>
- [148] Journot T, Bouchiat V, Gayral B, Dijon J and Hyot B 2018 *ACS Applied Materials & Interfaces* **10** 18857–18862 URL <https://doi.org/10.1021/acsmi.8b01194>
- [149] Tangi M, Mishra P, Tseng C C, Ng T K, Hedhili M N, Anjum D H, Alias M S, Wei N, Li L J and Ooi B S 2017 *ACS Applied Materials & Interfaces* **9** 9110–9117 URL <https://doi.org/10.1021/acsmi.6b15370>
- [150] Moun M, Kumar M, Garg M, Pathak R and Singh R 2018 *Scientific Reports* **8** 11799 URL <https://doi.org/10.1038/s41598-018-30237-8>
- [151] Jain S K, Kumar R R, Aggarwal N, Vashishtha P, Goswami L, Kuriakose S, Pandey A, Bhaskaran M, Walia S and Gupta G 2020 *ACS Applied Electronic Materials* **2** 710–718 URL <https://doi.org/10.1021/acsaelm.9b00793>
- [152] Jain S K, Low M X, Taylor P D, Tawfik S A, Spencer M J S, Kuriakose S, Arash A, Xu C, Sriram S, Gupta G, Bhaskaran M and Walia S 2021 *ACS Applied Electronic Materials* **3** 2407–2414 URL <https://doi.org/10.1021/acsaelm.1c00299>
- [153] Janardhanam V, Zummukhozol M, Jyothi I, Shim K H and Choi C J 2023 *Sensors and Actuators A: Physical* **360** 114534 ISSN 0924-4247 URL <https://www.sciencedirect.com/science/article/pii/S0924424723003837>
- [154] Reddeppa M, Park B G, Murali G, Choi S H, Chinh N D, Kim D, Yang W and Kim M D 2020 *Sensors and Actuators B: Chemical* **308** 127700 ISSN 0925-4005 URL <https://www.sciencedirect.com/science/article/pii/S0925400520300472>
- [155] Zheng Q, Qiu Z, Zhang Q, Yang M, Lei J, Han L, Tang L, Zheng Z, Wang X and Li J 2023 *ACS Applied Nano Materials* **6** 15490–15497 URL <https://doi.org/10.1021/acsanm.3c02054>
- [156] Massicotte M, Schmidt P, Vialla F, Schädler K G, Reserbat-Plantey A, Watanabe K, Taniguchi T, Tielrooij K J and Koppens F H L 2016 *Nature Nanotechnology* **11** 42–46 URL <https://doi.org/10.1038/nnano.2015.227>
- [157] Poudel Y, Sławińska J, Gopal P, Seetharaman S, Hennighausen Z, Kar S, D'souza F, Nardelli M B and Neogi A 2019 *Photon. Res.* **7** 1511–1520 URL <https://opg.optica.org/prj/abstract.cfm?URI=prj-7-12-1511>

- [158] Wang P J, Chang C J, Lin S Y, Sheu J K and Sun C K 2023 *Photoacoustics* **30** 100477 ISSN 2213-5979 URL <https://www.sciencedirect.com/science/article/pii/S2213597923000307>
- [159] Chen H, Guo K, Yin J, He S, Qiu G, Zhang M, Xu Z, Zhu G, Yang J and Yan P 2021 *Laser & Photonics Reviews* **15** 2170023 (*Preprint* <https://onlinelibrary.wiley.com/doi/pdf/10.1002/lpor.202170023>) URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/lpor.202170023>
- [160] Aristegui R, Lefebvre P, Brimont C, Guillet T, Vladimirova M, Paradisanos I, Robert C, Marie X, Urbaszek B, Chenot S, Cordier Y and Damilano B 2023 *Phys. Rev. B* **108**(12) 125421 URL <https://link.aps.org/doi/10.1103/PhysRevB.108.125421>
- [161] Stier A V, Wilson N P, Clark G, Xu X and Crooker S A 2016 *Nano Letters* **16** 7054–7060 URL <https://doi.org/10.1021/acs.nanolett.6b03276>
- [162] Cadiz F, Courtade E, Robert C, Wang G, Shen Y, Cai H, Taniguchi T, Watanabe K, Carrere H, Lagarde D, Manca M, Amand T, Renucci P, Tongay S, Marie X and Urbaszek B 2017 *Phys. Rev. X* **7**(2) 021026 URL <https://link.aps.org/doi/10.1103/PhysRevX.7.021026>
- [163] Raja A, Chaves A, Yu J, Arefe G, Hill H M, Rigosi A F, Berkelbach T C, Nagler P, Schüller C, Korn T, Nuckolls C, Hone J, Brus L E, Heinz T F, Reichman D R and Chernikov A 2017 *Nature Communications* **8** 15251 URL <https://doi.org/10.1038/ncomms15251>
- [164] Liu A, Xu L, Xu X B, Chen G J, Zhang P, Xiang G Y, Guo G C, Wang Q and Zou C L 2022 *Phys. Rev. A* **106**(3) 033104 URL <https://link.aps.org/doi/10.1103/PhysRevA.106.033104>