Group III-V semiconductors as promising nonlinear integrated photonic platforms

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ABSTRACT
Group III–V semiconductors are based on the elements of groups III and V of the periodic table. The possibility to grow thin-films made of binary, ternary, and quaternary III–V alloys with different fractions of their constituent elements allows for the precise engineering of their optical properties. In addition, since many III–V compounds are direct-bandgap semiconductors, they are suitable for the development of photonic devices and integrated circuits, especially when monolithic integration is required. Moreover, the strong optical nonlinearities of III–V materials enable a fertile field of research in photonic devices for all-optical signal processing, wavelength conversion, and frequency generation. Experimentally accessing the plethora of nonlinear optical phenomena in these materials considerably facilitates the exploration of light-matter interactions. Several demonstrations have explored the optical nonlinearities in waveguides, microring resonators, photonic crystal structures, quantum dots, and lasers. In this review, we survey numerous nonlinear optical studies performed in III–V semiconductor waveguide platforms. In particular, we discuss linear and nonlinear optical properties, material growth and fabrication processes, newer hybrid material platforms, and several nonlinear optical applications of III–V semiconductor integrated optical platforms.

KEYWORDS
III-V semiconductors; nonlinear optics; FWM; SPM; XPM; GaAs; AlGaAs; InP; InGaAsP; GaN; nanofabrication; integrated photonics

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1. Introduction

Photonics enables the generation, processing, and detection of light by means of specially designed micro- and nano-structures. Facilitated by recent developments in nanofabrication technologies, there has been a revolution in the field of integrated photonics, in which many functionalities of a free-space optical setup with bulk components can be downscaled onto an optical chip as small as $1 \text{ cm} \times 1 \text{ cm}$ [1]. Nonlinear photonics, in particular, is a field where the high-intensity regime required for nonlinear optical experiments and applications is readily achieved in photonic devices due to the tight light confinement featured by such structures.

Photonic devices have been demonstrated on a variety of material platforms, such as metals, insulators, polymers, and semiconductors [2–4]. The first nonlinear optical processes were demonstrated in the III–V semiconductors GaAs and AlGaAs in the 1970s and 1980s [5–7]. In the 1990s, the nonlinear photonics research in AlGaAs devices expanded considerably [8–43] alongside with the development of nonlinear photonics in InP, another III–V material [44–49]. Then, in an aim to adapt the fabrication techniques, facilities, and supply chain of the microelectronics industry to photonics, nonlinear photonics in the silicon-on-insulator (SOI) platform gained considerable attention in the 2000s [50–53]. However, there are some drawbacks of using silicon platforms in photonics, such as degraded performance at high temperatures [54], indirect bandgap [55], centro-symmetric crystal structure inhibiting second-order nonlinear optical interactions [56], and the difficulty of true monolithic integration in the mid-infrared region [57]. Nonlinear photonics in SOI, in particular, also suffers from strong two-photon (2PA) and free-carrier (FCA) absorption in the wavelength range below $2.2 \mu\text{m}$ [58,59], leading silicon-based photonics to explore compatible
alternatives like silicon nitride [60–63], silicon-rich nitride [64–68], amorphous silicon [69,70], and high-index silicon oxide (Hydex) [71–74]. Nevertheless, there is a quest to find new materials that can overcome the limitations of silicon-based photonics.

There has been ongoing research to identify other suitable platforms for nonlinear photonics like lithium niobate [75–79], chalcogenide glasses [80–84], and II–VI semiconductors [85]. Meanwhile, nonlinear photonics research in the pioneering group of III–V semiconductors has continued at full strength through the exploration of high optical nonlinearities in new material platforms, alloy compositions, and device geometries. Crucial for photonics, most of the III–V compounds present a direct bandgap, meaning that the minimum of the conduction and the maximum of the valence bands correspond to the same momentum on an energy-momentum diagram. As a consequence, the process of radiative recombination of carriers in direct-bandgap semiconductors obeys the momentum conservation law and thus allows for efficient lasing and photodetection. Therefore, it is possible to monolithically integrate active and passive photonic devices in many III–V-based platforms.

The strong optical nonlinearity of III–V semiconductors is due to various physical mechanisms, depending on the band structure of a particular III–V compound and the spectral range of interest [86–94]. When the photon energies are significantly smaller compared to the bandgap energy, the optical field interacts with bound electrons without inducing their transition to the conduction band, yielding ultrafast nonresonant nonlinear interactions such as instantaneous Kerr effect [18,31]. For the photon energies approaching (but still smaller than) the bandgap energy, we are dealing with strong free-carrier-induced nonlinearities with the speeds limited by the carrier dynamics [86–89]. Furthermore, some semiconductors exhibit strong excitonic resonances in the latter wavelength regime [90]. However, it is the strong non-resonant nonlinearity that makes III–V semiconductors promising material platforms for all-optical signal processing devices and other applications.

In this review, we discuss the recent advances in III–V semiconductor nonlinear guided-wave devices. The most significant results, properties, and applications are presented for well-established material platforms used in nonlinear photonics such as GaAs, AlGaAs, and InP, along with the emerging materials such as GaN, AlN, GaP, and InGaP. The review is organized as follows: In Section 2, we discuss the possible material compositions for binary, ternary, or quaternary III–V alloys, and provide an introduction to the tools and processes that are used in the fabrication of III–V integrated photonic components. Section 3 describes the common nonlinear optical processes, the definitions of important nonlinear optical coefficients, and their associated measurement techniques. Section 4 presents the commonly used III–V material platforms, their nonlinear optical properties, and a summary of different nonlinear optical studies performed in these material
platforms. In Section 5, we highlight the different areas from component-level to system-level where the nonlinear optical properties of III–V semiconductors find applications, followed by a conclusion in Section 6.

2. Fabrication

III–V semiconductors can be binary, ternary, or quaternary alloys, formed by two, three, or four chemical elements, respectively. The concentration of pairs of elements in ternary or quaternary alloys can be varied to adjust the bandgap energy and optical properties, such as the refractive index and absorption coefficient.

In Figure 1, we present the bandgap energy as a function of the lattice constant for various III–V compounds. The wavelength equivalent of the bandgap energy is displayed on the right vertical axis. Binary compounds are represented in the graph by dots. The lines connecting two dots represent ternary compounds formed from the corresponding binary compounds. The areas subtended by the lines of the same color represent quaternary compounds formed from the four binaries (red for InGaPN, blue for AlGaInP, black for AlGaAsSb and grey for InGaAsP). The mutual concentrations of binarics in a ternary alloy provide a degree of freedom that can be varied to modify the alloy’s optical properties. The concentration dependence can be schematically represented as \( A_xB_{1-x}C \) where \( A, B, \) and \( C \) are single elements from the groups III and V of the periodic table, and \( x \) is the content or fraction of the element \( A \). In this regard, quaternary alloys have two degrees of freedom, and therefore provide more flexibility in achieving desired optical properties. They can be represented as \( A_{1-x}B_xC_yD_{1-y} \).

Figure 1. Bandgap energy as a function of lattice constant for different III–V materials.
Vegard’s law provides a description of the desired bandgap energy, parameterized by the relative concentration of the III–V elements: 

\[ E_{ABC} = xE_{AB} + (1 - x)E_{BC}, \]

where \( E \) corresponds to the bandgap energy and \( A, B, \) and \( C \) are the III–V single elements \([95,96]\). Other material properties, like the refractive index, can also be calculated by this law. However, for some compositions or properties, a quadratic dependence on the concentration parameter \( x \), known as the bowing parameter, is required \([95]\). In a similar way, Vegard’s law for a quaternary compound takes the form 

\[ E_{ABCD} = xyE_{BC} + x(1 - y)E_{BD} + y(1 - x)E_{AC} + (1 - x)(1 - y)E_{AD} \]

Epitaxial growth of III–V semiconductors provides high-quality films having low defect density, which is crucial for quantum and nonlinear photonic applications \([98]\). The ternary and quaternary alloys can be grown on binary substrates or on a previously grown epitaxial layer (epilayer). However, the lattice constant of the new layer must be matched to the previous one. Lattice mismatch leads to structural imperfections in the epilayers, which can act as recombination and scattering centers. The presence of such defects can result in significant scattering losses, hampering the integrated optical device’s performance.

If the two materials lie on the same vertical line on the graphic of Figure 1, they can be grown lattice-matched. \( \text{Al}_x\text{Ga}_{1-x}\text{As} \), for instance, can be grown lattice-matched on GaAs with all possible concentrations of aluminum. Substrates also play a crucial role in epitaxial growth. If the substrate is the same as the growth material, the growth is called homoepitaxy. Conversely, if the growth material is different from the substrate, the growth is referred to as heteroepitaxy \([99]\). The presence of defects in heteroepitaxial growth from lattice and thermal mismatches presents a significant challenge. Therefore, buffer layers are often used to optimize the growth of high-quality heteroepitaxial thin films.

Various epitaxial growth techniques are utilized for III–V semiconductors, such as molecular beam epitaxy (MBE) \([100]\), metal-organic chemical vapor deposition (MOCVD) \([101]\), and liquid phase epitaxy (LPE) \([99]\). MBE has a thickness precision at the angstrom level. A molecular beam is focused at a heated substrate and deposits atom-by-atom under controlled growth dynamics. It is capable of growing sharp interfaces and is widely used for electronic and optical devices. However, this growth technique is very costly and offers a slow growth rate, which limits its applicability and availability. MOCVD provides several advantages in this aspect. In particular, MOCVD provides a faster growth rate and lower cost. MOCVD is a chemical vapor deposition technique, which uses a flow of a gas-phase mixture containing precursors over a heated substrate for layer-by-layer deposition. This technique is capable of depositing a controlled thin layer with higher wafer throughput. It is widely used for integrated circuit applications. Finally, LPE is a low-cost deposition technique, which deposits
material from a supersaturated solution. However, it is not capable of forming sharp junctions between two material layers. More recently, other cost-effective, large-area, and faster growth techniques have been explored for III–V semiconductors such as hybrid vapor phase epitaxy (HVPE) [102], close-spaced vapor transport (CSVT) [103], and thin-film vapor-liquid-solid (TF-VLS) growth [104,105]. The ongoing development of these techniques provides a pathway towards the commercialization of a cost-effective approach for III–V semiconductors for photonics.

Integrated optical devices like waveguides, photonic crystals, ring resonators, modulators, and interferometers mostly follow a standard top-down approach for fabrication, which includes the process of depositing a mask, writing the pattern on the mask, and transferring the pattern to the underlying material layers, as shown in Figure 2. The fabrication can be followed by some post-processing if required. Before starting the top-down processes, the substrate with the epitaxial layers on it undergoes cleaning. This is done in several chemical cleaning steps, which usually apply acetone, isopropyl alcohol (IPA), and de-ionized water (DI water). Following this, drying is achieved by passing nitrogen over the surface or heating the material on a hot plate. Some of the important steps in a top-down fabrication process are detailed below.

2.1. Resist deposition

The first step is to deposit a resist, made of polymer-solvent, via spin coating [106]. The chemical properties of the resist change when exposed to light or electrons, depending on the resist type. In particular, there are two types of resists – positive and negative. The chemical bonds of the positive-tone resist loosen at places where they are exposed. As a result, exposed surfaces are dissolved in the developer solvent. Some common positive-tone resists are ZEP520a, PMMA, SPR 3000 series. On the other hand, negative-tone resists
harden on exposure. In contrast to the previous case, areas that have not been hardened by the negative-tone resist dissolve in the developer solvent. Examples of negative-tone resists are HSQ, ma-N 1400 series and SU-8.

### 2.2. Lithography

The lithographic process can be performed with electrons in the case of electron-beam (ebeam) lithography, or with photons in the case of photo-lithography. In research settings, ebeam lithography is most frequently used for writing patterns with sub-micrometer features. With ebeam lithography, a beam of electrons hits the material surface coated with the resist and changes its chemical properties. After passing the electron beam, exposed areas dissolve (or harden) when immersed in the developer solvent. Although ebeam lithography is a slow process, it can produce feature sizes with critical dimensions in the range of 3–5 nm. Photo-lithography exposes the resist to ultraviolet light with typical wavelengths of 100 to 400 nm (UV lithography) [107]. Photo-lithography has seen substantial improvements over the past five years, in particular with extreme ultraviolet (EUV) lithography systems being commercially produced by semiconductor manufacturers like ASML and Intel [108]. With EUV systems, resolution limits can reach sub-20-nm structures using radiation sources with a wavelength of 13.5 nm. However, the throughput achievable with EUV systems is still not comparable to the earlier generations of photo-lithography systems because of limitations such as source brightness and low industry-grade EUV resist availability [109].

### 2.3. Etching

Once the pattern is created in the resist, the process of transferring the pattern to the underlying material, known as etching, is performed. Etching can be done using wet chemicals (wet etching) which results in very isotropic and smooth structures, as well as using plasma etching (dry etching), in which there are more variables to tune and therefore the outcome results in more controlled and anisotropic features. ICP-RIE (Inductively Coupled Plasma Reactive Ion Etching) is the most commonly used system for plasma etching. This method allows for the control of parameters like ICP power, bias power, chamber pressure and temperature, gas flows, etc., which results in increased control over material removal. III–V alloys are often etched in chlorine-based plasma [110], using gases such as Cl₂, BCl₃, CCl₄, SiCl₄.

In some systems, inert gases like argon and helium are also added to increase the etch rate and to achieve a more anisotropic etch result. These gases do not react or combine with the substrate to create new radicals, but contribute more...
to the physical etching by bombarding the substrate with the heavier non-reacting atoms/ions, which ablate the radicals produced by the other gases. The result is an increased etch rate with well-defined vertical sidewalls.

For some III–V device structures which require deeper etch depths, standard resists are insufficient if they are ablated too quickly [111,112]. In these cases, a mask that erodes more slowly is required. Such masks are known as hard masks and provide a much slower etch rate. In addition, they enable a large selection of materials suitable for etching. Thermally deposited oxide (or silica) is known to be a great hard mask with a very low etch rate in chlorine-based chemicals and provides selectivity of around 1:10 for most of the III–V alloys. Selectivity is defined as the ratio of the amount of mask etched to the amount of material etched. In other words, up to 10 nm of III–V material can be etched for each 1 nm of silica mask.

Some integrated photonic devices based on III–V semiconductors require additional steps to ensure proper function. These additional stages are known as post-processing steps. These usually involve treating the components with chemicals to improve device quality; for instance, by creating smoother sidewalls or treating the devices with acids to remove or dissolve some sacrificial layers [113,114].

III–V semiconductors are suitable for the implementation of active (electrically controlled) photonic devices. However, there is an ongoing effort to produce photonic structures compatible with existing capabilities of the microelectronics industry. In addition, optical waveguides in III–V materials often lack in performance when compared to low-loss silicon waveguides. As a result, there has been growing interest in heterogeneous integration to use active III–V components with passive silicon photonic components. Consequently, wafer-bonding is frequently used to attach III–V active structures on silicon platforms. When two smooth surfaces of any material are brought together in close proximity, a combination of Van der Waals forces and other additional inputs like temperature and pressure, it allows for the two materials to form bonds in a process referred to as wafer-bonding [115]. Recently, the wafer-bonding process has been deployed to create novel AlGaAs-on-insulator (AlGaAs-OI) platforms, which continue to find new applications in nonlinear optics [116,117].

In this section, we focused on the fabrication processes for nonlinear photonic devices. However, there are still several other processes, beyond the scope of this review, that are needed to fabricate the electrical pads and circuitry required for electrical signal processing [118,119]. These electrical connections are required for the operation of modulators, interferometers, detectors, heaters, lasers, and other active components. In addition, photonic chips ready for commercialization and perhaps integration in more complex optoelectronic systems, such as the ones described in section 5, typically require further packaging [120–122].
3. Nonlinear optical processes and coefficients

Light-matter interactions can be classically modeled as oscillating electric dipoles (from the electron/proton separation of the material’s atoms) driven by the oscillating electric field of the light wave. The polarization vector \( \mathbf{P} \) can be expressed, in general, in terms of a series of tensor products between the light’s electric field vector \( \mathbf{E} \) and the material’s \( n \)-th order optical susceptibilities, \( \chi^{(n)} \) [123], as

\[
P = \varepsilon_0 \left[ \chi^{(1)} \mathbf{E} + \chi^{(2)} \mathbf{E} \mathbf{E} + \chi^{(3)} \mathbf{E} \mathbf{E} \mathbf{E} + \ldots \right]. \tag{1}
\]

In Equation (1), the \( \chi^{(n)} \) are \( (n + 1) \)-rank tensors. For instance, \( \chi^{(1)} \) is a second-rank tensor \( (3 \times 3 \text{ matrix}) \) related to the linear optical properties of the medium, including anisotropic and birefringent materials. Similarly, the second-order optical susceptibility, \( \chi^{(2)} \), is related to the second-order nonlinear optical phenomena, and the third-order susceptibility, \( \chi^{(3)} \), to the third-order phenomena, and so on [123].

To discuss the nonlinear photonics of each III–V material platform, we introduce some second-order and third-order nonlinear optical phenomena, and define their main nonlinear coefficients.

3.1. Second-order processes

To investigate the second-order processes, let us assume the electric field as \( E(t) = E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t} + \text{c.c.} \), where \( E_{1,2} \) are the electric field amplitudes. Therefore, the second term in Equation (1) can be expressed as

\[
P^{(2)}(t) = \varepsilon_0 \chi^{(2)} E^2(t) \\
= \varepsilon_0 \chi^{(2)} \left( E_1^2 e^{-i2\omega_1 t} + E_2^2 e^{-i2\omega_2 t} + 2E_1E_2 e^{-i(\omega_1 + \omega_2) t} \right) \\
+ 2\varepsilon_0 \chi^{(2)} (E_1^* E_1 + E_2^* E_2). \tag{2}
\]

Four different second-order nonlinear optical phenomena are expressed as the different terms in Equation (2). The first and second terms demonstrate second-harmonic generation (SHG). The third and fourth terms indicate sum-frequency generation (SFG) and difference frequency generation (DFG), respectively. The last term denotes optical rectification (OR) [123].

In terms of energy conservation of the photons’ interactions, SFG, SHG, and DFG can be illustrated as Figure 3(a–c). Each of these processes can be used for some application. For instance, many wavelength conversion systems utilize these nonlinear optical processes. New coherent light components can be generated either at shorter (SHG, SFG) or longer (DFG) wavelengths than those of the incident beams. Yet, they also are the foundation for experimental
techniques used to measure the nonlinear optical property of the sample. For instance, the power of the transmitted or reflected light component generated by SHG, SFG or DFG can be compared to the power(s) of the incident beam(s) to experimentally determine the value of $\chi^{(2)}$. Often, the experiment measures the nonlinear susceptibility tensor elements $d$, related to the susceptibility by $d_{ijk} = \chi^{(2)}_{ijk}/2$ [123]. In some cases, depending on the experimental conditions, the technique is only able to measure the average effect of the tensor elements as an effective nonlinear optical property, i.e. effective $\chi^{(2)}$ or effective $d$.

### 3.2. Third-order processes

Considering the third term in Equation (1) and assuming the electric field as $E(t) = E_1 e^{-i \omega_1 t} + E_2 e^{-i \omega_2 t} + E_3 e^{-i \omega_3 t} + \text{c.c.}$, the third-order polarization $P^{(3)}(t)$ can be calculated, resulting in 44 different frequency terms. Among them, the terms with frequencies $3\omega_1$, $3\omega_2$ and $3\omega_3$ describe the process called third-harmonic generation (THG), in which three photons with the same frequency are annihilated, creating a photon of tripled frequency (Figure 3d). On the other hand, some of the terms with two or three interacting frequencies can lead to another third-order phenomenon known as four-wave mixing (FWM), in which two photons with the same (degenerate case) or different frequencies (nondegenerate case) are annihilated, creating two photons with
different frequencies (Figure 3(d, e)). Other commonly encountered third-order processes are self-phase modulation (SPM) and cross-phase modulation (XPM). In SPM, a propagating intense pulse causes a change in the refractive index of the medium as a consequence of the optical Kerr effect (discussed below). As a result, the pulse obtains a varying phase in terms of intensity and the spectrum is consequently modified, producing spectral broadening or spectral narrowing. XPM is similar to SPM, but involves more than one light beam; the most intense beam changes the refractive index of the medium, affecting the phase and spectral features of the other beam(s).

One of the most important third-order nonlinear optical properties of a photonic material is the nonlinear refractive index \( n_2 \). The nonlinear refractive index characterizes the optical Kerr effect, \( i.e. \) the effect in which the refractive index, \( n \), depends on the intensity, \( I \), of the illuminating light according to

\[
n = n_0 + n_2 I,
\]

where \( n_0 \) is the linear refractive index (refractive index for the low-intensity light regime). The intensity \( I \) is proportional to the square of the electric field amplitude [124].

As the nonlinear component of the refractive index is proportional to the optical intensity, a beam with a non-uniform transverse spatial profile (\( e.g. \) a Gaussian beam) experiences a non-uniform refractive index. As a consequence, the medium behaves like a lens (optical Kerr lens). Positive \( n_2 \) causes self-focusing, while a negative \( n_2 \) causes self-defocusing [123]. These effects are exploited in the closed-aperture Z-Scan technique [125–127] to measure \( n_2 \) of bulk or thin-film materials. In Z-Scan, the sample is moved along a focused Gaussian beam while the transmittance is measured at the far field to quantify the self-(de)focusing strength [125]. However, ZS requires a thin-sample approximation that does not hold for waveguides. Therefore, it is common to measure \( n_2 \) of photonic devices by techniques based mainly on SPM and FWM (see examples in Tables 1, 2, and 3). The sign of \( n_2 \) is positive in semiconductor materials for the photon energies significantly smaller compared to the bandgap energy. This represents the case of self-focusing. However, for the photon energies close to the band edge, \( n_2 \) becomes large and negative [87,90,91,93], which naturally allows one to avoid the catastrophic self-focusing in that highly nonlinear regime.

Photonic waveguides, in particular, bring the possibility of tightly confined light in a small propagation mode area, which results in a high intensity of propagating light. The nonlinear coefficient, \( \gamma \), includes the nonlinear refractive index \( n_2 \) and the confinement strength (mode area) through the relation [128]
\[ \gamma = \frac{2\pi n_2}{\lambda_0 A_{\text{eff}}}, \]  

where \( \lambda_0 \) is the wavelength of light in free space. The \( \gamma \) parameter is often used as a quantitative characteristic that provides insight into the nonlinear interaction strength arising from the combination of the nonlinear index and light confinement.

The effective mode area for a third-order nonlinear process, \( A_{\text{eff}} \), is calculated by the expression

\[ A_{\text{eff}} = \frac{\iint |\mathbf{E}|^2 \, dx \, dy}{\iint |\mathbf{E}|^4 \, dx \, dy}. \]  

The integration in Equation (5) is performed over the entire cross-sectional \( x-y \) plane, and \( \mathbf{E} \) represents the electric field inside the waveguide. This equation is often used in a software for finite-difference eigenmode (FDE) calculations, like the Lumerical Mode Solutions, as a practical way to design and simulate photonic devices. However, it assumes some approximations, such as a constant refractive index. For a more general set of equations for \( \gamma \) and \( A_{\text{eff}} \), including effects of different refractive index in multi-layer waveguides, we refer the reader to Refs. [129,130].

Another key parameter in the characterization of a nonlinear photonic device is the 2PA coefficient \( (\alpha_2) \), related to the 2PA effect (electronic transitions caused by the simultaneous absorption of two-photons). The intensity-dependent nonlinear absorption coefficient \( (\alpha) \), when 2PA is present, is given by:

\[ \alpha = \alpha_0 + \alpha_2 I. \]  

The term \( \alpha_0 \) in Equation (6) represents linear absorption in a bulk material when illuminated at a wavelength in its transparency window. In addition to linear absorption, \( \alpha_0 \) for waveguides includes the effects of mode leakage and light scattering. For this reason, it is often called the propagation loss coefficient. Two-photon absorption usually hampers photonic device performance by increasing optical power loss in the high-intensity nonlinear regime. However, 2PA might be useful in some applications, such as optical switching and optical limiting. For instance, some optical switches use free-carriers generated by 2PA to produce the refractive index changes required for their operation [131]. In the case of optical limiting, 2PA helps protects downstream devices from damages due to high optical power [132].

The 2PA coefficient is often measured by the nonlinear transmittance technique (NLT), where the output intensity, subjected to nonlinear absorption, is expressed as a function of the input intensity [31]. In bulk materials
and thin-films, the open-aperture ZS technique is also a good option for \( \alpha_2 \) measurements [127]. In addition, the data analysis of other third-order nonlinear optical experiments may also include the effect of 2PA. Thus, \( \alpha_2 \) can be also measured by FWM and SPM, for example (see references in Tables 1, 2, and 3).

The nonlinear parameters \( n_2 \) and \( \alpha_2 \) are analytically related to the third-order susceptibility by
\[
\chi^{(3)} = \frac{3\pi}{(4\varepsilon_0 n_0^2 c^3)} \text{Re}(\chi^{(3)}) + \frac{3\pi}{(4\varepsilon_0 n_0^2 c^3)} \text{Im}(\chi^{(3)})
\]
and
\[
\chi^{(3)} = \left[ \frac{3\pi}{(4\varepsilon_0 n_0^2 c^3)} \right] \text{Re}(\chi^{(3)}) + \left[ \frac{3\pi}{(4\varepsilon_0 n_0^2 c^3)} \right] \text{Im}(\chi^{(3)})
\]
respectively [124]. As in the case of second-order coefficients, the measured values of \( n_2 \), \( \alpha_2 \), and \( \chi^{(3)} \) in waveguide structures are often different from the bulk-material values. They are therefore referred to as effective nonlinear coefficients. Additionally, the properties can depend on the light polarization in anisotropic materials. This can be exploited to determine different elements of the \( \chi^{(3)} \) tensor [133,134].

There is at least five orders of magnitude variation between the \( \chi^{(3)} \) values of various semiconductor materials (e.g. ZnSe and InSb). This is greater than the difference in the values of \( n_2 \) in silica and GaAs (\( n_2 \) of GaAs is 500 larger). However, this fits within the prediction of the overall \( \chi^{(3)} \) scaling with the bandgap energy as \( E_g^{-4} \) [93].

### 3.3. Higher-order processes

Experiments on fourth-, fifth-, and higher-order nonlinear optical processes are rare since the lower-order processes typically dominate in nonlinear interactions. An exception is the three-photon absorption (3PA), a fifth-order nonlinear optical process in which three photons are simultaneously absorbed in an electronic transition. The intensity-dependent absorption coefficient, subjected to 3PA, is given by
\[
\alpha = \alpha_0 + \alpha_3 I^2
\]
where \( \alpha_3 \) is the 3PA coefficient. Photonic devices operating in a spectral region without 2PA might still exhibit nonlinear losses associated with 3PA [31].

### 4. Main material platforms

In this section, we introduce the common III–V semiconductor platforms that have been explored for nonlinear photonics applications, present the nonlinear coefficients measured for their representative materials, and give an overview of the devices realized in these platforms. A few nonlinear optical measurements have also been performed in bulk and thin-films of III–V semiconductors, such as InSb and InN [135–137]. However, they are not covered in this review because their technology is not yet mature enough to turn them into platforms for fabrication of nonlinear photonic devices.
4.1. GaAs/AlGaAs

Gallium arsenide (GaAs) is a binary semiconductor with a bandgap close to 1.42 eV (870 nm) [138]. In addition to its applications in electronics and opto-electronics, GaAs is a very well-explored III–V material for photonics. It presents a wide transparency window, from 870 nm to 19 μm, a high refractive index \( n_0 = 3.4 \) at 1550 nm [138]) similar to silicon, and high values of \( \chi^{(2)} \), \( n_2 \), and \( \alpha_2 \) (see Table 1).

GaAs and AlAs have fairly close lattice constants of 565.33 pm and 566.11 pm, respectively [95]. Therefore, Al\(_x\)Ga\(_{1-x}\)As with \( 0 \leq x \leq 1 \) can be epitaxially grown on GaAs substrate with a negligible lattice mismatch.

Many different photonic devices have been demonstrated in (Al)GaAs, for example: low-loss, high-confinement waveguides, micro-ring resonators with high Q-factors, photonic crystal waveguides and cavities for SHG, correlated-photon sources using spontaneous parametric down-conversion (SPDC), superconducting detectors, 100 GHz low-power modulators for fast control and manipulation of photons, and directional couplers for single-photon and two-photon state manipulation [139–143]. Figure 4 represents some waveguide geometries based on AlGaAs platforms that have been used for nonlinear optical processes.

AlGaAs heterostructures [see Figure 4(a)] have been implemented since early 1990s [12,13,15,17,19,21–24,29,31] for \( \chi^{(3)} \) nonlinear experiments. They represent the simplest waveguide structures typically requiring a single-step epitaxy and lithography. The guiding layer (or core) has lower aluminum concentration relative to the surrounded claddings. Consequently, the refractive index contrast is produced, sufficient for light confinement in the core. Optical waveguides produced in such a manner, typically referred to as strip-loaded waveguides, are robust against fabrication errors due to a shallow etching [111,144]. Such devices, however, exhibit moderate nonlinear optical interactions due to their lower compactness and moderate refractive index contrasts. To achieve a higher compactness, deeply-etched waveguide structures, termed AlGaAs nanowires, have been implemented in the 2000\(^\text{th} \) [111,144–148]. Such structures enable superior compactness, dispersion engineering and permit modal-phase-matched (MPM) second-order nonlinear interactions [146].

AlGaAs-on-insulator (AlGaAs-OI) waveguide platform [116,140,149–157], where, using some wet chemical etching and wafer bonding, a thin layer or AlGaAs with epitaxially grown silica as substrate can be bonded onto a template wafer [see Figure 4(b)], has started gaining attention in 2010. AlGaAs-OI devices can have extremely small modal areas and, according to Equation (4), high values of \( \gamma \). As such, they represent efficient nonlinear photonic devices: both \( \chi^{(2)} \) [140,153,156] and \( \chi^{(3)} \) [116,149–151,154,155,157] nonlinear interactions have been readily demonstrated in these waveguides.
Table 1. Experimental values of the nonlinear coefficients measured in bulk GaAs/AlGaAs materials and waveguides.

| Material | Form<sup>a</sup> | Wavelength<sup>b</sup> (nm) | Symbol<sup>c</sup> | Value | Unit | Additional information | Technique<sup>d</sup> | Ref. |
|----------|------------------|-------------------------------|-------------------|-------|------|--------------------------|-------------------|-----|
| GaAs     | Bulk             | 500 to 1340                  | \( \chi^{(2)} \) (852) | 750   | pm/V | –                        | SHG               | [163]|
| Bulk     | 1064             | \( d \)                      | 170               | pm/V  | –    | –                        | SHG               | [164]|
| Bulk     | 1533             | \( a \) (1475)               | 94                | pm/V  | –    | –                        | SHG               | [164]|
| WG       | 1968             | \( a \) (2300)               | 180               | pm/V  | –    | TE mode                  | SHG               | [117]|
| Bulk     | 1680 to 3250     | \( n \) (1680)               | \( 3.0 \times 10^{-11} \) | cm<sup>2</sup>/W | –    | along [110]              | ZS                | [166]|
| Bulk     | 1300 to 1700     | \( a \) (1300)               | 0.35              | cm<sup>2</sup>/GW<sup>2</sup> | –    | NLT                      | SPM               | [166]|
| WG       | 1475 to 1700     | \( a \) (1475)               | 0.35              | cm<sup>2</sup>/GW<sup>2</sup> | –    | NLT                      | SPM               | [19] |
| Bulk     | 1850 to 2500     | \( a \) (2300)               | 0.35              | cm<sup>2</sup>/GW<sup>2</sup> | –    | NLT                      | SPM               | [166]|
| Al<sub>0.18</sub>Ga<sub>0.82</sub>As | WG     | 1490 to 1650 | \( n \) (1490) | \( 1.9 \times 10^{-11} \) | cm<sup>2</sup>/W | TE mode | SPM | [31] |
| Al<sub>0.23</sub>Ga<sub>0.77</sub>As | WG     | 1490 to 1650 | \( a \) (1498) | 0.13  | cm<sup>2</sup>/GW<sup>2</sup> | –    | NLT                      | SPM               | [31] |
| Al<sub>0.61</sub>Ga<sub>0.39</sub>As | WG     | 1600           | \( n \) (1490) | \( 0.21 \times 10^{-11} \) | cm<sup>2</sup>/W | TE mode | SPM | [25] |
| GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As | MOQW  | 1545           | \( n \) (1490) | \( 1.3 \times 10^{-11} \) | cm<sup>2</sup>/W | –    | NLT                      | SPM               | [12] |
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | MOQW  | 1545           | \( a \) (1498) | 0.08  | cm<sup>2</sup>/GW          | –    | NLT                      | SPM               | [12] |
| Al<sub>0.6</sub>Ga<sub>0.4</sub>As | MOQW  | 1545           | \( a \) (1498) | 0.16  | cm<sup>2</sup>/GW<sup>2</sup> | –    | NLT                      | SPM               | [12] |
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | MOQW  | 1620           | \( n \) (1545) | \( 0.87 \times 10^{-11} \) | cm<sup>2</sup>/W | TE mode | SPM | [9] |
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | MOQW  | 1620           | \( a \) (1545) | \( 0.54 \times 10^{-11} \) | cm<sup>2</sup>/W | TM mode | SPM | [9] |
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | MOQW  | 1670           | \( a \) (1545) | \( 0.65 \times 10^{-11} \) | cm<sup>2</sup>/W | TM mode | SPM | [9] |
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | MOQW  | 1670           | \( a \) (1545) | \( 0.4 \) | cm<sup>2</sup>/GW          | –    | NLT                      | SPM               | [9] |
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | MOQW  | 1670           | \( a \) (1545) | \( 2.6 \times 10^{-11} \) | cm<sup>2</sup>/W | TE mode | SPM | [30] |
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | MOQW  | 1670           | \( a \) (1545) | \( 3.3 \times 10^{-11} \) | cm<sup>2</sup>/W | TM mode | SPM | [30] |
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | SLWG  | 1525 to 1605   | \( n \) (1545) | \( 2.8 \times 10^{-11} \) | cm<sup>2</sup>/W | –    | SPM                      | SPM               | [168]|
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | SLWG  | 1525 to 1605   | \( a \) (1545) | \( 1.1 \times 10^{-11} \) | cm<sup>2</sup>/W | –    | SPM                      | SPM               | [168]|
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | SLWG  | 1505 to 1625   | \( a \) (1505) | \( 5.5 \times 10^{-11} \) | cm<sup>2</sup>/W | –    | SPM                      | SPM               | [169]|
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | SLWG  | 1505 to 1625   | \( a \) (1505) | \( 2.4 \times 10^{-11} \) | cm<sup>2</sup>/W | –    | SPM                      | SPM               | [169]|
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | SLWG  | 1505 to 1625   | \( a \) (1505) | \( 3.9 \) | cm<sup>2</sup>/GW          | –    | SPM                      | SPM               | [169]|
| GaAs/Al<sub>2</sub>Ga<sub>0.8</sub>As | SLWG  | 1505 to 1625   | \( a \) (1505) | \( 1.1 \) | cm<sup>2</sup>/GW          | –    | SPM                      | SPM               | [169]|

<sup>a</sup>MQW – Multi-quantum-well waveguide, SLWG – superlattice waveguide, WG – waveguide, BRW – Bragg-reflector waveguide, OP – orientation-patterned.

<sup>b</sup>For measurements of the nonlinear coefficient over a wavelength range, the table presents the lower and upper wavelength limits and the maximum value in the range.

<sup>c</sup>The wavelength corresponding to the maximum value of the coefficient is present in the parentheses.

<sup>d</sup>SHG – second-harmonic generation, ZS – z-scan, NLT – nonlinear transmittance, SPM – self-phase modulation, MZI – Mach-Zehnder interferometry, SFG – sum-frequency generation, NLDC – nonlinear directional coupler switching.
Further, the cladding material of AlGaAs structures can be removed on both the sides using wet chemical etching methods to create air claddings [see Figure 4(c)]. Such structures are known as air-bridged, or suspended, waveguides [158–160]. Suspended structures have the advantage of enabling large index contrasts, which is important for optical confinement. Thanks to their high cross-sectional asymmetry, MPM second-order nonlinear optical interactions are readily achievable [159,160] in these structures.

In terms of the nonlinear optical performance, AlGaAs-OI has presented the record-high nonlinear coefficient among all the AlGaAs platforms: $\gamma = 720 \text{ W}^{-1}\text{m}^{-1}$ [154]. Record-high SHG conversion efficiencies of $1.28 \times 10^4\%/(\text{W cm}^2)$ in suspended AlGaAs [158], $4.7 \times 10^4\%/(\text{W cm}^2)$ in GaAs-OI [161] and FWM conversion efficiency of $-4.2$ dB in AlGaAs-OI waveguides [149] were demonstrated. The achieved FWM conversion bandwidth of 750 nm is also remarkable when compared with other photonic platforms [149].

In Table 1, we summarize the values of the nonlinear coefficients experimentally obtained in bulk GaAs and in (Al)GaAs waveguides of different kinds. For the table entries, we gave preferences to the publications where wavelength dependencies of the nonlinear parameters were presented. A more extensive and detailed list of nonlinear coefficients, conversion efficiencies, and a more in-depth review of (Al)GaAs waveguide platforms will be provided in the upcoming review article [162].

### 4.2. III-nitrides

Group III-nitrides is a popular platform for power electronics, analogue circuits, and optoelectronic applications owing to their wurtzite crystal structure, direct bandgap, high electron mobility, and chemical and thermal stability [100,170,171].

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| Material | Form | Wavelength$^a$ (nm) | $\chi^{(2)}$, $d$ (pm/V) | $n_2$ $(10^{-14}\text{cm}^2/\text{W})$ | $\alpha_2$ (cm/GW) | $\gamma$ $(\text{m}^2/\text{W}^{-1})$ | Technique$^c$ | Ref. |
|----------|------|---------------------|-------------------------|-----------------|-----------------|------------------|----------------|------|
| AlN      | MRR  | 1550                | 6.2 ($\chi^{(2)}$)      | -               | -               | -                | SHG            | [183]|
|          | Bulk | 1450 to 1650        | 0.23 (1550)             | -               | -               | FWM              | [187]         |
| GaN      | WG   | 1560                | 16 ($\chi^{(2)}$)      | -               | -               | SHG              | [178]         |
|          | Bulk | 1064                | 16.5 ($d_{33}$)         | -               | -               | SHG              | [188]         |
|          | Bulk | 1064                | 8.2 ($d_{31}$)          | -               | -               | SHG              | [188]         |
|          | Bulk | 1064                | 8.0 ($d_{15}$)          | -               | -               | SHG              | [188]         |
| WG       | 1550 | -                   | 3.4                     | -               | 1.6             | FWM              | [172]         |
| MRR      | 1450 | 1550                | 1.4 (1550)              | -               | 7.3             | FWM              | [173]         |
| WG       | 1550 | -                   | 1.1                     | -               | 3.1             | PPT              | [189]         |
| Bulk     | 377 to 720 | - | - 16 (400) | - | 0.9 | ZS | [190] |
| Bulk     | 724  | -                   | -                       | -               | -               | -                | -              |      |

$^a$WG – waveguide, MRR – microring resonator.

$^b$For the nonlinear coefficients measured over a range of wavelengths, the table presents the lower and upper wavelength limits and the maximum coefficient in the range.

$^c$SHG – second-harmonic generation, FWM – four-wave mixing, DKS – dissipative Kerr soliton, PPT – pump-probe technique, ZS – z-scan.
Table 3. Nonlinear optical properties of InP/InGaAsP waveguides.

| Geometry/Composition | Forma | Wavelength (nm) | \( n_0 \) | \( n_2 \) (\( 10^{-13} \text{cm}^2/\text{W} \)) | \( a_2 \) (cm/GW) | \( \gamma \) (m/W) | Techniqueb | Ref. |
|---------------------|--------|-----------------|----------|------------------------------------------|-----------------|----------------|-------------|------|
| \( \text{In}_{0.63}\text{Ga}_{0.37}\text{As}_{0.85}\text{P}_{0.2} \) | WG     | 1550            | 3.58     | 1                                        | 15              | 36.85          | SPM         | [193]|
| InP/InGaAsP         | QW     | 1540            | –        | –14                                      | 33              | –              | FWM         | [47] |
| InP/InGaAsP         | QW     | 1510            | 3.25     | 95                                       | 23              | –              | FWM, NLT    | [48] |
| InP/InGaAsP         | MQW    | 1550            | –        | –3                                       | 60              | –              | SPM, NLT    | [44] |

aWG – waveguide, QW – quantum-well waveguide, MQW – multi-quantum-well waveguide.
bSPM – self-phase modulation, FWM – four-wave mixing, NLT – nonlinear transmittance.

The bandgap of III-nitrides can be tuned from 6.2 eV to 0.7 eV by varying the metal composition between Al, Ga, and In to synthesise aluminium nitride (AlN), gallium nitride (GaN), and indium nitride (InN), respectively [170]. Foreign substrates, i.e. sapphire, silicon, and silicon carbide (SiC), are used to grow epitaxial GaN films because of the unavailability of the native substrates [174]. There is a large lattice and thermal mismatch between GaN and the foreign substrates that leads to high dislocation density in GaN. These defects act as recombination centers, thereby leading to additional optical losses. The epitaxial quality of GaN film can be improved by incorporating buffer layers between the GaN and the substrates, which helps in offsetting the mismatch effects [114,175,176].

Group III-nitrides, specially GaN and AlN, owing to their optical properties and wide transmission ranges, are strong candidates for nonlinear optical applications [177]. GaN has a combined transparency range of LiNbO₃ and GaAs (365 nm to 13.6 \( \mu \)m), and therefore this material has a potential of generating wavelengths in either far-IR or near-UV by SFG or DFG [178]. Additionally, GaN exhibits both \( \chi^{(2)} \) and \( \chi^{(3)} \) nonlinearities, and a higher nonlinear refractive index, which is advantageous for the applications in all-optical signal processing at the Telecom wavelengths. Furthermore, the large bandgaps of GaN and AlN ensure the absence of the 2PA and 3PA at the telecommunications wavelengths.

A schematic of nonlinear waveguides based on III-nitrides is shown in Figure 5. Among these are GaN on AlGaN [172], GaN on AlN [171], GaN-on-sapphire [173] and on gallium oxide [114]. Additionally, air-suspended GaN waveguides and photonic crystal membranes have been successfully fabricated [179] [see Figure 6(a)]. Furthermore, a success in the propagation loss reduction in GaN waveguides has been recently achieved. GaN waveguides with the propagation loss coefficients as low as 0.65 dB/cm at 1550 nm, 1 dB/cm at 1550 nm, and 2 dB/cm at 700 nm have been realized [180–182].

Higher-order terms in nonlinear polarization come into play at higher light intensities. Therefore, in integrated photonic devices, where the input power ranges from microwatt to milliwatt, it is crucial to employ resonant structures such as ring resonators with high quality (Q)-factors to observe higher-order nonlinear effects. High-Q-factor microring resonators (MRR) based on GaN have been demonstrated in [173,184]. A quality factor
exceeding $5 \times 10^4$ in the near-infrared, infrared, and visible wavelength ranges [184], and a quality factor of $1 \times 10^5$ at the Telecom wavelength range [173] have been reported. Micromechanical coupled ring resonators have also been fabricated using AlGaN/GaN heterostructures, demonstrating a Q-factor of 8350 at 900.7 MHz [185]. Additionally, AlN-based ring resonators have demonstrated high Q-factors of $2.5 \times 10^6$ with propagation losses as low as 0.14 dB/cm at 1550 nm [186]. Furthermore, a quality factor of 5400 was reported in a photonic crystal waveguide using GaN nanowires, operating at 1500 nm [179]. A successful demonstration of high-Q-factor microcavities based on single-crystal AlN has been performed in [183] [see also Figure 6(b) for an SEM image]. An exemplary SHG conversion efficiency of 17,000%/W has been achieved in these devices [183].

Due to the challenges associated with defect mitigation and lack of native substrate, nonlinear integrated photonics based on III-nitrides is still at an early stage of development. There are only a few studies reporting the measurement of the second- and third-order nonlinear optical coefficients in AlN and GaN waveguides. We present these results, together with some nonlinear coefficient measurements in bulk materials, in Table 2.

### 4.3. InP/InGaAsP

InP is an increasingly important platform for photonic integrated circuits since it allows for the monolithic integration of several active components, such as lasers, semiconductor optical amplifiers, photodetectors, modulators with passive devices [191]. Furthermore, InP-based membranes have been fabricated with high index contrasts, resulting in micron-scale devices with a full set of photonic functions [192].
InGaAsP shows strong potential as a material platform for nonlinear photonic devices [193]. A major limiting factor, however, is the low optical confinement in the ridge waveguide structures on the InP substrate. The low confinement factor results in waveguide dimensions of several micrometers, and minimum bending radii of tens to hundreds of micrometers [194]. Nevertheless, the optical confinement in the waveguides can be tuned by implementing a low-index optical buffer layer between the waveguide and the substrate carrier [195]. Due to its bandgap energy of 1.34 eV, InGaAsP is subject to 2PA at the Telecom C-band wavelengths [114]. The 2PA coefficient of InGaAsP multi-quantum-well waveguides has been reported to be 60 cm/GW at 1550 nm [44], which is much larger than that of AlGaAs (Table 1) and silicon. However, InGaAsP is a well-established material platform for semiconductor lasers. Therefore, combining low-loss optical waveguides with InGaAsP multi-quantum-well lasers on the same chip is a critical research direction for extending the operating range of the lasers to longer wavelengths.

For active InGaAsP/InP integration, free-carrier absorption is typically the main contributor to the propagation loss [196]. This can be tackled by using additional butt-joint or complicated selective area re-growth schemes [197], however, this method significantly complicates the fabrication process because of strict control requirements of etching and epitaxial regrowth.

Figure 7 presents some waveguide structures realized in InGaAsP/InP platform. In particular, Figure 7(a) presents an SEM image from the facet of an InGaAsP strip-loaded (partly etched through the upper cladding) waveguide. Figure 7(b) shows a schematics of the cross-sectional geometry and material composition of a typical InGaAsP waveguide [193]. Figure 7(c) illustrates an InP-based hybrid plasmonic waveguide [198].
In$_x$Ga$_{1-x}$As$_y$P$_{1-y}$/InP strip-loaded waveguides have been experimentally studied by SPM, FWM, and NLT techniques [193]. The nonlinear coefficient, measured by SPM, has a more date value of $\gamma = 36.8 \text{ W}^{-1}\text{m}^{-1}$. The FWM conversion range, defined as the wavelength difference between maximally separated signal and idler spectral components, is measured as 45 nm. The 2PA coefficient was also determined for this waveguide by NLT as $\alpha_2 = 15 \text{ cm/GW}$ at 1568 nm. Finally, FWM was performed in an InGaAsP/InP single-quantum-well waveguide to measure $n_2$ and $\chi^{(3)}$ from 1510 nm to 1560 nm. The maximum values in the range were $\text{Re}(\chi^{(3)}) = 4.4 \times 10^{-17} \text{ m}^2/\text{V}^2$, $\text{Im}(\chi^{(3)}) = 2 \times 10^{-18} \text{ m}^2/\text{V}^2$, and $n_2 = 9.5 \times 10^{-12} \text{ cm}^2/\text{W}$ at 1510 nm [48].

The FWM conversion efficiency was measured as $-11 \text{ dB}$ and around $-23 \text{ dB}$ when the waveguides were pumped at 1540 nm by a picosecond-pulsed laser and continuous-wave (CW) laser, respectively.

Figure 6. Scanning electron microscopy (SEM) images of (a) a GaN wire waveguides suspended with tethers. Reprinted with permission from [179] © The Optical Society; and (b) AlN-based microring resonators before their encapsulation. Reproduced from [183] with the permission of AIP Publishing.
4.4. GaP

GaP is an indirect bandgap semiconductor with a bandgap of 2.26 eV and a large transparency range spanning from the visible to mid-IR (500 nm to 11 μm), which has been traditionally used to make green light emitting diodes. GaP has a wurtzite crystal structure and a large linear refractive index value of around 3.05 in the C- and L-bands. Some measured nonlinear optical parameters are: $n_2 = 1.1 \times 10^{-13} \text{cm}^2/\text{W}$ and $\chi^{(2)} = 70 \text{pm/V}$ at 1000 nm [201,202]. Z-scan measurements were performed in orientation-patterned GaP resulting in $\alpha_3 = 0.15 \text{cm}^3/\text{GW}^2$ at 950 nm and $0.05 \text{cm}^3/\text{GW}^2$ at 1001 nm [203]. Nanophotonic devices based on GaP platform attract significant attention because GaP can be grown on silicon with minimal lattice mismatch, thereby allowing for heterogenous integration. For strong optical confinement in nanophotonic devices, a larger index contrast between the core and cladding is desired. Recently, it was demonstrated that GaP on silica can be fabricated through a wafer-bonding process [204]. Devices, such as waveguides with propagation loss coefficients as low as 1.2 dB/cm, ring resonators with quality factors of $2.5 \times 10^5$, grating couplers with insertion losses as low as $-4.8$ dB, and nonlinear frequency

![Figure 7. Some possible structures for InGaAsP waveguides. (a) Scanning electron microscope image of the facet of a strip-loaded InGaAsP waveguide Reprinted with permission from [193]. (b) and (c) show the schematics of an InGaAsP strip-loaded [193] and an InP-based hybrid-plasmonic waveguide [198], respectively.](image-url)
conversion processes such as SHG and THG have been demonstrated in this platform [204]. Recently, in [205], the authors demonstrated that GaP can be grown directly on sapphire using MBE, which is possible by domain-matching epitaxy. Additionally, metasurfaces supporting high-Q-factor quasi-BIC (bound states in the continuum) have been demonstrated. There have also been efforts made for high-speed all-optical switching with the experimental switching times under 30 fs [206].

4.5. InGaP

InGaP is a ternary alloy commonly used in multi-junction solar cells [207,208], but it has also gained attention for its large linear refractive index of around 3.1 at 1550 nm, and large second-order nonlinearity ($\chi^{(2)} = 220 \text{ pm/V}$), comparable to that of GaAs. Its bandgap energy of 1.9 eV (652 nm) inhibits 2PA in the telecommunications wavelength range. InGaP can be grown on GaAs with negligible lattice mismatch but the index difference between these two materials does not provide enough contrast useful for integrated photonic applications. Therefore, InGaP on silica is used as a common platform, fabricated using the processes of systematic wet etching of some epilayers and wafer bonding.

Waveguides with a propagation loss coefficient of 12 dB/cm, high nonlinear coefficient $\gamma = 475 \text{ W}^{-1}\text{m}^{-1}$, and 3PA coefficient $\alpha_3 = 0.025 \text{ cm}^3/\text{GW}^2$ have been fabricated and used in FWM and NLT experiments conducted in the Telecom C-band [209]. Its high Kerr nonlinearity was employed to demonstrate 1.06-octave-spanning supercontinuum generation [210]. Photonic crystal cavity-based optical parametric oscillator has been demonstrated [211]. Most recently, SHG in high-Q-factor ring resonators ($Q \approx 10^5$) and photon-pair generation via spontaneous parametric downconversion (SPDC) with a rate of 27.5 MHz/µW have also been reported [212].

5. Current and future applications

Mirroring the development of novel applications in more accessible silicon photonics (SiP) platform during the late 2000s and early 2010s, the number of developments in III–V materials has exploded since the end of the recent decade. Owing to their bandgap and lattice constants, much of the research in III–V materials has been driven by a desire to monolithically integrate optical functionalities and controlling electronics together with optical sources and detectors – something difficult to accomplish in SiP. In this section, we present
key recent developments and possible future directions for III–V material applications in three categories: (1) telecommunications, (2) computation and information science, and (3) sensing and imaging.

### 5.1. Telecommunications

Group III–V materials have a long history of use in the telecommunications industry. For instance, InGaAs/GaAs and InGaAsP/InP operating at telecom wavelengths have been extensively studied and commercialized over the past 30 years [213,214]. In addition, quantum-well lasers on GaAs/AlGaAsP platforms have been used for numerous room-temperature applications [215,216]. Even today, InP-based integration platforms are widely used by major telecommunications hardware manufacturers for high-performance transceivers [118], and major industry acquisitions have been driven by desires to excel in InP photonics [217,218].

The implementation of optical frequency combs (OFCs) through Kerr nonlinearities, either FWM or SPM, is an important functionality for optical communication systems. OFCs have been used in a multitude of applications, including precision timing and synchronization, distance measurements, and frequency conversion. Due to their highly nonlinear properties, III–V materials are frequently chosen platforms for OFC generation. For instance, efficient OFC generation devices have been demonstrated in integrated GaP [202], GaN [175], AlN [219], InP/InGaAsP [220,221], and AlGaAs-on-insulator [116,222]. Due to its technical simplicity, another method of generating OFCs is via quantum-dash mode-locked laser diodes (QD-MLLD). Recent demonstrations of QD-MLLDs in InP/InGaAsP platforms have shown promise in the design of compact integrated multiwavelength sources and local oscillators [223] (see Figure 8). Most recently, the operational simplicity of QD-MLLDs has been utilized in the demonstration of a reconfigurable microwave photonic filter [224], opening a wide range of possible applications in radio-frequency signal processing and radio-over-fiber communications.

In addition to OFC generation, III–V platforms are also well-suited for wavelength conversion through various harmonic generation processes. Several of these spectral conversion devices have been demonstrated in AlN [183,225], GaAs [152,153], GaP [226], and AlGaAs [227] at very high efficiency (see Figure 9). Co-integration with electronic components will likely lead to further usage of III–V SHG and THG sources in quantum photonics. In addition, classical coherent communications will see benefits from smaller device footprints and lower pump power requirements [152].

While much of the discussion thus far has focused on guided optical communications, III–V materials are also finding niche free-space applications. One example uses GaAs/AlGaAs to implement
a travelling-wave modulator for V-band space applications \[228\]. GaAs is notable for its temperature stability and high radiation damage threshold and has historically been the III–V material of choice for many satellites’ solar cells, such as the ones used on the Venera 2 and
Venera 3 missions to Venus [229]. Looking forward, GaAs will likely remain a key material platform for integrated photonics in harsh extraterrestrial environments.

5.2. Computation and information science

The field of quantum information science has long looked to the fields of optics and photonics to implement quantum communications protocols. Several quantum key distribution (QKD) protocols have been successfully demonstrated in partially integrated SiP [230,231]. A significant concern with SiP is that sources, gain media, and detectors are difficult to integrate. Current SiP QKD systems rely on off-chip detectors and sources [230,232], which imposes significant operational costs in terms of power consumption and data center floor space. To compete with existing commercial transceivers, future metropolitan-scale QKD systems will need to be miniaturized via integration. A likely resolution to this problem involves monolithic system integration in a III–V material platform, where all necessary active and passive components are readily available.

Moreover, integrated InGaAsP/InP single-photon detectors have been demonstrated with minimal cooling requirements [233] at telecommunications wavelengths, while photon pair generation has been observed via nonlinear processes in AlGaAs [157,234,235]. To complement these functionalities, InP quantum random number generators [236] (see Figure 10) and integrated Fredkin gates [237] could lead to a powerful suite of components to implement quantum algorithms on a chip. As a result, III–V platforms will likely be important materials for the future of quantum information science.

5.3. Sensing and imaging

Photonic biosensors are a promising alternative to costly laboratory procedures, such as enzyme-linked immunosorbent assays. In particular, the ability of photonic biosensors to perform label-free detection makes them subjects of interest for lab-on-chip devices. While much work has been done in this field with SiP platforms, the difficulty of integrating light sources and detectors again creates an opportunity for III–V materials to excel where SiP cannot. Biophotonic functions have been demonstrated in III–Vs, such as GaAs/AlGaAs [238] and InP [239] (see Figure 11) for label-free pathogen detection. The co-integration of broadband frequency comb generators, sensing devices, and detectors may soon lead to rapid, cost-effective home-diagnosis biophotonic chips. In addition to attractive biosensing functionalities, III–V materials are well suited for imaging. A recent biophotonic example uses InP quantum dots to demonstrate tunable, near-infrared photoluminescence and multiplexed in vivo imaging [240].
Figure 10. An integrated quantum random number generator in InP. (a) Operational schematic of QRNG based on two-laser interference. (b) Principle of operation: a pulsed laser interferes with a continuous laser to create a measurable random phase, which is subsequently digitized into a random value. (c) Image of a single chip with two integrated QRNG devices on a 1 Euro cent. Reprinted with permission from [236] © The Optical Society.

Figure 11. A schematic representation of an electronic InP biosensor for label-free detection. The device's active area is functionalized via amination, PEGylation, and covalent coupling of biomolecular receptors to detect the presence of specific ligands. Reprinted with permission from [239].
A topic of note is the use of frequency combs in astrophysics. Astro-combs have been used in several areas of astrophysics, such as measurements of Doppler shifts and high-precision astronomical spectroscopy [241]. Astro-combs are a relatively recent development and have not yet been implemented in III–V materials. One interesting research direction would be to use the high temperature stability of GaAs/AlGaAs systems for space-based satellite imaging and spectroscopy.

6. Conclusions

In summary, we have reviewed a range of important works demonstrating nonlinear optical processes achieved with integrated III–V material platforms. In addition, this work provides a theoretical introduction to nonlinear optical processes, as well as descriptions of some fabrication processes to realize these structures. Although some of these platforms like GaAs/AlGaAs, and InP have been extensively studied for nonlinear optical processes, there still remains much work to be done in the study of newer material platforms, such as III-nitrides, InGaP, and GaP, which provide the advantage of working in wavelengths from visible to the mid-IR. Despite the fact that these materials offer large linear and nonlinear refractive indices, as well as high $\chi^{(2)}$ and $\chi^{(3)}$, there still remain challenges of lowering the linear losses, decreasing production costs, and increasing material availability. Future research directions in III–V photonics are highly dependent on available fabrication services. In particular, progress in application-oriented research is severely limited by the number of foundries offering process design kits (PDKs) for III–V materials. Additionally, the existing III–V foundries offer little available information on nonlinear component performance. Consequently, a system designer wishing to utilize a III–V material for nonlinear photonics often needs to design, fabricate, and characterize their own components. Due to this highly tailored approach, research in III–V materials has not yet constructed an ecosystem like what exists in silicon photonics. As the field matures, it is likely that different research groups working in III–V photonics will develop centralized fabrication services. Such centralized services can potentially enable end-user oriented application research, as we have seen with silicon photonics Regardless of the challenges mentioned above, III–V materials offer excellent platforms for experiments in integrated nonlinear and quantum photonics. With advancements in micro- and nano-fabrication processes, III–V materials will continue to facilitate research in fundamental physics, as well as provide flexible platforms for achieving commercially interesting integrated photonic functions.
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