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Gallium Indium Phosphide Microstructures with Suppressed Photoluminescence for Applications in Nonlinear Optics

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Gallium indium phosphide ($\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$), lattice matched to gallium arsenide, shows remarkable second-order nonlinear properties, as well as strong photoluminescence due to its direct band gap. By measuring the second-harmonic generation from the GaInP microwaveguide ($0.2 \times 11 \times 1300 \mu\text{m}$) before and after stimulating intrinsic photobleaching, we demonstrate that the photoluminescence could be strongly suppressed ($\sim 34 \text{ dB}$), leaving the nonlinear properties unchanged, making it suitable for low-noise applications. © 2019 Optical Society of America

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INTRODUCTION

Gallium indium phosphide ($\text{Ga}_x\text{In}_{1-x}\text{P}$) is well suited for several applications, including biomedical imaging [1], light-emitting diodes (LEDs) [2, 3], transistors [4, 5] and photovoltaic cells [6–8], because of its typically high carrier mobility and its direct band gap (for certain alloy compositions [9]).

Additionally, $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ shows interesting properties for nonlinear applications, such as large nonlinear coefficient [10] and large refractive index [11], and a transparency window starting around 680 nm. $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ is also lattice matched to gallium arsenide (GaAs), which makes it attractive to fabricate free-standing/substrate-free waveguides and membranes by selectively etching of GaAs.

In spite of these interesting characteristics, the use of this material for nonlinear optical applications has been mainly limited to the so-called telecom wavelengths (1260 – 1625 nm) [12–15]. One of the issues to overcome about using this material in the visible wavelength range (380 to 700 nm) is the strong photoluminescence (PL) of the material at around 1.9 eV [16]. Indeed, the intensity of the PL can supersede other possible effects if appropriate precautions are not applied, and becomes critical when spontaneous parametric down-conversion (SPDC) has to be measured.

In this work, we show how the suppression of PL in GaInP microstructures can be achieved using a continuous-wave (CW)

laser excitation in the visible (405 nm) and we demonstrate that the nonlinear optical properties of the material remains unchanged, by evaluating the behaviour of the second-harmonic generation (SHG) in the microstructures.

A deeper comprehension of PL behavior and photobleaching can be beneficial when using this material for other uses, such as LEDs and photovoltaic cells.

FABRICATION OF THE MICROSTRUCTURES

Fig. 1. Schematics of the fabrication steps: (a) the starting layer configuration. (b) the lithography step, (c) GaInP wet etching, (d) wet etching of the GaAs sacrificial layer, (e) release of the GaInP microstructure and (f) transfer on to glass.

The microstructures were fabricated based on a top-down approach using the wet etching of high quality epitaxially grown $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ layers on a GaAs (100) substrate, with a lattice mismatch $\Delta a/a \approx 1.8 \cdot 10^{-3}$, where a is the lattice parameter. A thin film of GaAs (50 nm) was used below the top GaInP layer (200 nm) in order to obtain substrate-free waveguide structures (Fig. 1(a)).

A thin layer of a positive photoresist was spin-coated onto the GaInP 200 nm thick top layer, and then exposed to UV light through a mask-less photolithographic tool; the light exposure

transfers the pattern containing the microstructures on to the photoresist. The photoresist is also used as a mask for the following wet etching process (Fig. 1(b)).

Thereafter, a wet etching process based on a mixture of hydrochloric acid (HCl) and phosphoric acid (H_3PO_4) with a 1:1 ratio was used to etch the GaInP, whereas a combination of H_3PO_4 , hydrogen peroxide (H_2O_2) and DI water (H_2O) with a ratio of 3:3:20 was used to etch the GaAs sacrificial layer to make the substrate-free waveguides (Fig. 1(c-d)).

The structures were submerged in DI water, resulting in the floating of the microstructures due to the still present resist mask (Fig. 1(e)); this enabled to transfer the microstructures to a silicon dioxide (SiO_2) substrate (Fig. 1(f)). Before proceeding with the cleaning process, it is necessary to verify that the microstructure adhere to the substrate. A drop of acetone is used as a first step to dissolve the resist and then the microstructures are left to dry. Finally the structures were carefully cleaned in an acetone bath in order to remove the photoresist mask followed by rinsing with isopropyl alcohol and DI water and dry blown with a nitrogen flow.

Fig. 2 shows a representative microscope image of the fabricated microstructures, having a width of $\sim 11 \mu\text{m}$ wide at the base and $\sim 1.3 \text{ mm}$ long.

These microstructures can be used as optical waveguides and we estimated an attenuation coefficient of $\alpha \approx 12 \text{ dBcm}^{-1}$ for CW laser with wavelength $\lambda = 780 \text{ nm}$, which includes scattering and transmission losses, a value that can be improved by further reducing the scattering due to the sidewall roughness [17].

Fig. 2. (a) Representative optical microscope image of a GaInP microwaveguide on glass (SiO_2). Inset: schematic of the cross section of the microwaveguide on glass. (b) Cross-sectional profile of the microwaveguide measured using an atomic force microscope (AFM).

The strength of the fabrication process presented here is that the same process, in principle, could be implemented for any type of substrate, with the precaution that the waveguides had the time to dry and stick to the surface.

It is worth mentioning that the Raman spectroscopy performed on the microstructures on SiO_2 indicates a good quality material, having an order parameter of $S=0.3$ [18].

MEASUREMENTS AND CONCLUSIONS

The setup used for the UV exposure and the one used for the characterization of the nonlinearity through the SHG of the microstructures are presented in Fig. 3, (a) and 3(b), respectively. For simplicity of representation the setup has been separated in two schemes, but it is important to highlight that both setups are similar and to change from one configuration to the other only required inserting/removing filters and polarizer; the sample

location and detection area remained unaltered.

The microwaveguide is orthogonal with respect to the laser beams, i.e. the microstructure is not used as a waveguide but as a thin layer, excited along the z-axis as considered in Fig. 2.

Fig. 3. Schematic of the measurements setups. (a) Configuration used when the PL is excited and measured. (b) Configuration used when the SHG light is measured.

A CW laser with wavelength 405 nm passes through a band pass filter for 405 nm (FWHM 10 nm bandwidth) and is focused by an objective 50x on the microstructure after passing through a cold mirror used as dichroic mirror, and excited the PL (Fig. 3(a)). The PL signal is collected through the same objective and is transmitted through the dichroic mirror to the detector. Before the detector, an additional notch filter (Thorlabs NF405-13, FWHM 13 nm bandwidth) is used to block any transmitted source light from the laser and an attenuator (OD 4 - Edmund Optics) is used to lower the the detection intensity. The signal is finally launched into a multimode fiber and detected with a single photon avalanche photodiode (SiAPD). The diameter of the collected and incident light spots were $\sim 4 \mu\text{m}$. The spectrum of the recorded PL at 3 kWcm^{-2} before any exposure and after 5 h of exposure is shown in Fig. 4. The spectra are presented in logarithmic scale since this allows us to show the low signal level after the 5 h of exposure to the UV light. The average dark counts rate is ≈ 180 counts/s. However, for a power density of 30 kWcm^{-2} , a red-shift of 5 nm in the PL spectrum was observed. The shift is reversible, and it can indicate an increase of the temperature [19].

The PL measurements have been recorded with a gate times of 500 and 250 ms, triggered every 1 s by the system: during the measurements we noticed that the different gate times did not influence the values of the maximum PL recorded when the values were normalized to the respective gate times. The optical power was measured with a powermeter positioned after the objective.

To perform the measurements of the SHG the setup in the schematics in Fig. 3(b) was used. A pulsed Ti:Sapphire laser with 100 fs pulses and a central wavelength of 840 nm at 82 MHz repetition rate was used in transmission configuration. Since GaInP has a low transmission at 405 nm affecting mainly the top surface, the configuration chosen allows a better evaluation of the behaviour of the SHG in the same region. The diameter of the laser spot was $\sim 3 \mu\text{m}$, while the diameter of the collected light spot remained the same as for the PL measurements ($\sim 4 \mu\text{m}$). In this case, in the detection branch, only a band pass filter (Schott BG39) was inserted to limit and allow the transmission of 840 nm and 420 nm, respectively, and where a multimode fiber was connected to a spectrometer. In addition, one half-wave plate in the excitation branch and one polariser in the detec-

Fig. 4. PL spectrum recorded before (in orange) and after 5 h (in blue) the exposure for a power density of 3 kWcm^{-2} after an additional long pass filter at 600 nm. The average dark counts rate is ≈ 180 counts/s.

tion branch allowed to record the SHG light in two different configurations of polarization: (i) parallel to the pump and (ii) orthogonal to the pump, which correspond to the rotation angle $\varphi_{\text{SHG}} = \varphi_{\text{PUMP}}$ and $\varphi_{\text{SHG}} = \varphi_{\text{PUMP}} + 90^\circ$; which are shown in blue and red in Fig. 5, respectively.

For GaInP and all the crystals with $-43m$ symmetry, the second-order nonlinear polarization density along the crystallographic axis can be expressed as follows:

$$\begin{aligned} P_x^{(2\omega)} &= 2dE_yE_z = 2dE_TE_z\sin\varphi_{\text{PUMP}}, \\ P_y^{(2\omega)} &= 2dE_xE_z = 2dE_TE_z\cos\varphi_{\text{PUMP}}, \\ P_z^{(2\omega)} &= 2dE_xE_y = d(E_T)^2\sin 2\varphi_{\text{PUMP}}. \end{aligned}$$

where E_T and E_z are the transverse (xy -plane) and the longitudinal electric field of the pump respectively, φ_{PUMP} is the angle between the pump polarization and the x -axis in the xy -plane, i.e. $\varphi_{\text{PUMP}} = 0$ when the system is aligned to the crystallographic x -axis, d is the second-order nonlinear susceptibility [20, 21]. The

Fig. 5. Polarization measurement of the SHG light for a GaInP microstructure. The angle represented in the axis is φ_{SHG} . Red and blue lines: orthogonal and parallel configurations, respectively. (a) Before PL measurements. (b) After 20 h of PL excitation.

results reported in Fig. 5(a) show the typical 4-fold symmetry of a $-43m$ material in the orthogonal as well as in the parallel configuration, where both E_x and E_y contribute to $P_z^{(2)}$. $P_z^{(2)}$ is responsible for the stronger signal, almost twice, in the parallel configuration.

After 20 h-long exposure of the GaInP microstructure to 405 nm

laser at 8 mW (corresponding to a power density of 64 kWcm^{-2}), the PL reduces significantly (-34 dB). To examine the effect of this process on the non-linear properties of the material, SHG measurements under identical condition as in Fig. 5(a) are performed. As clearly visible in Fig. 5(b), the same symmetry and intensities are maintained. This result confirms that the non-linearity does not change after the exposure to UV light of the microstructure. A slight shift in the alignment between $t = 1 \text{ s}$ and $t = 20 \text{ h}$ could have caused a modification of the polar profile for $t = 20 \text{ h}$ with respect to the one measured before the exposure.

Fig. 6. PL decay, shown in a time window of 300 s, for several representative excitation powers due to UV excitation. Both the horizontal and vertical axis are presented in the logarithmic scale. The solid lines and dotted line are used to distinguish the measurements made in air and nitrogen atmosphere, respectively.

In Fig. 6, it is possible to observe the evolution of the PL in time (first 300 s) for several laser powers at the excitation wavelength of 405 nm. The PL data show a linear-like decrease in the logarithmic scale. However, the recorded PL at $t = 1 \text{ s}$ is not always proportional to the laser power. This can be explained by the fact that the PL measured at high powers decreases already during the first sub-seconds period of illumination. It can be derived from Fig. 6 that the maximum PL was recorded for 1.4 mW excitation power (corresponding to $\sim 11 \text{ kWcm}^{-2}$ power density).

In Fig. 7, the behaviour of the PL during the exposure for different laser powers (varying from $20 \mu\text{W}$ to 8.6 mW) at the time $t = 1 \text{ s}$ (a) and $t = 300 \text{ s}$ (b) can be observed. The PL is normalized to the power of the 405 nm laser. In Fig. 7(a) the PL increases for lower powers and reaches the maximum PL signal for a excitation power of 0.5 mW and then for higher powers decreases exponentially (linearly on the logarithmic scale). However, in Fig. 7(b), the PL increases for the lower powers until the maximum PL signal is obtained for a power of 0.125 mW and then decreases for higher powers, but with different relation if compared with Fig. 7(a). This observation is consistent with the data presented in Fig. 6. This behavior can be associated to two effects that have already been reported for other materials, e.g., chalcogenide glasses [22]. In Fig. 7(a), photodarkening is the dominant effect, where a laser power of 0.5 mW (corresponding to $\sim 4 \text{ kWcm}^{-2}$) can be seen as the threshold value. In Fig. 7(b), the dominant effect is photobleaching. However, the results shown are not the result of the photobleaching alone but is the combination of the two processes.

Furthermore, initial tests in nitrogen atmosphere were per-

Fig. 7. Normalized photoluminescence vs. 405 nm pump power. The solid dot and pentagram are used to distinguish the measurements made in air and nitrogen atmosphere, respectively. Power is color coded. (a) Normalized PL measured at the initial time $t = 1$ s. (b) Normalized PL measured at the time $t = 300$ s of excitation.

formed (reported in Fig. 6 by a dotted line and in Fig. 7 by a black pentagram) to investigate the influence of the oxygen atmosphere in the processes. The data show that the behaviour becomes significantly different in the slow photobleaching regime, which suggests that oxidation contribute to the process as reported for other materials [22, 23].

An other aspect to take into account is the risks of damaging the microstructure due to the high excitation intensity. For the microstructures used in this work, a power up to ~ 10 mW (corresponding to ~ 80 kWcm $^{-2}$) could be applied without causing any damage to the microstructure, for an observation time span and illumination of 100 s. For larger powers, after 1-3 s of illumination, structural damages in the material were observable.

Moreover, considering the power density limitations of the GaInP microstructures, an alternative approach was investigated: a power of 10 mW was used for a few seconds and then decreased to 7 mW, in order to speed up the lowering of the PL but not critically damaging the material. We observed that in an equal period of time the PL counts were 20% larger than in case of constant illumination with a stable 8 mW power, although the PL counts were lower at the start.

Finally, by keeping constant the laser power to 8 mW, the PL on this microstructure was reduced below -30 dB after 30 min and up to -34 dB after 20 h, due to the persistent photobleaching.

In conclusion, the presented process can be implemented as a solution to limit the PL in case of localized and relatively small microstructures. Moreover, a proper automated setup that guarantees a uniform exposure of the more complex structures can be considered, as well as modifying the shape of the laser beam used in the photobleaching process. However, using the intrinsic

photobleaching of the GaInP microstructures widens its use as a nonlinear material for optical applications that require low-noise level, such as parametric down-conversion, in an energy range of significant interest, just above the bandgap.

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REFERENCES

1. K. Mattsson, K. Adolfsson, M. T. Ekvall, M. T. Borgström, S. Linse, L. A. Hansson, T. Cedervall, and C. N. Prinz, *Nanotoxicology* **10**, 1160 (2016).
2. V. Dolores-Calzadilla, B. Romeira, F. Pagliano, S. Birindelli, A. Higuera-Rodriguez, P. J. van Veldhoven, M. K. Smit, A. Fiore, and D. Heiss, *Nat. Commun.* **8**, 14323 (2017).
3. C. P. T. Svensson, T. Mårtensson, J. Trägårdh, C. Larsson, M. Rask, D. Hessman, L. Samuelson, and J. Ohlsson, *Nanotechnology* **19** (2008).
4. G. Hamon, N. Paillet, J. Alvarez, A. Larrue, and J. Decobert, *J. Cryst. Growth* **498**, 301 (2018).
5. O. Tohru, O. Kiyoshi, and M. Kazuhiro, *Jpn. J. Appl. Phys.* **40**, 5221 (2001).
6. K. Dey and T. R. Lenka, "Simulation of high efficiency InGaP/InP tandem solar cells under flat plate and concentrator conditions," in *2017 International conference on Microelectronic Devices, Circuits and Systems (ICMDCS)*, (2017), pp. 1–5.
7. N. Bologna, S. Wirths, L. Francaviglia, M. Campanini, H. Schmid, V. Theofylaktopoulos, K. E. Moselund, A. Fontcuberta i Morral, R. Erni, H. Riel, and M. D. Russell, *ACS Appl. Mater. & Interfaces* **10**, 32588 (2018).
8. S. H. Jung, C. Z. Kim, Y. Kim, D. H. Jun, H. K. Kang, and H. Kim, *J. Korean Phys. Soc.* **68**, 792 (2016).
9. Yubo Sun, K. H. Montgomery, X. Wang, S. Tomasulo, M. L. Lee, and P. Bermel, "Modeling wide bandgap GaInP photovoltaic cells for conversion efficiencies up to 16.5%," in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, (2015), pp. 1–6.
10. I. Shoji, T. Kondo, and R. Ito, *Opt. Quantum Electron.* **34**, 797 (2002).
11. M. Schubert, V. Gottschalch, C. M. Herzinger, H. Yao, P. G. Snyder, and J. A. Woollam, *J. Appl. Phys.* **77**, 3416 (1995).
12. U. D. Dave, B. Kuyken, F. Leo, S.-P. Gorza, S. Combré, A. De Rossi, F. Raineri, and G. Roelkens, *Opt. Express* **23**, 4650 (2015).
13. A. Martin, D. Sanchez, S. Combré, A. de Rossi, and F. Raineri, *Opt. Lett.* **42**, 599 (2017).
14. V. Eckhouse, I. Cestier, G. Eisenstein, S. Combré, P. Colman, A. De Rossi, M. Santagiustina, C. G. Someda, and G. Vadalá, *Opt. Lett.* **35**, 1440 (2010).
15. S. Combré, Q. V. Tran, A. De Rossi, C. Husko, and P. Colman, *Appl. Phys. Lett.* **95**, 221108 (2009).
16. I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, *J. Appl. Phys.* **89**, 5815 (2001).
17. U. D. Dave, B. Kuyken, F. Leo, S.-P. Gorza, S. Combré, A. De Rossi, F. Raineri, and G. Roelkens, *Opt. Express* **23**, 4650 (2015).
18. F. Alsina, N. Mestres, J. Pascual, C. Geng, P. Ernst, and F. Scholz, *Phys. Rev. B* **53**, 12994 (1996).
19. H. Hamada, *Mater. (Basel)* **10** (2017).
20. A. Yariv and P. Yeh, *Photonics: Optical Electronics in Modern Communications*, The Oxford Series in Electrical and Computer Engineering (Oxford University Press, 2007), 6th ed.
21. E. De Luca, R. Sanatini, S. Anand, and M. Swillo, *Opt. Mater. Express* **6**, 587 (2016).
22. P. Khan, A. R. Barik, E. M. Vinod, K. S. Sangunni, H. Jain, and K. V. Adarsh, *Opt. Express* **20**, 12416 (2012).
23. Q. Yan, H. Jain, J. Ren, D. Zhao, and G. Chen, *J. Phys. Chem. C* **115**, 21390 (2011).

FULL REFERENCES

1. K. Mattsson, K. Adolfsson, M. T. Ekvall, M. T. Borgström, S. Linse, L. A. Hansson, T. Cedervall, and C. N. Prinz, "Translocation of 40 nm diameter nanowires through the intestinal epithelium of daphnia magna," *Nanotoxicology* **10**, 1160–1167 (2016).
2. V. Dolores-Calzadilla, B. Romeira, F. Pagliano, S. Birindelli, A. Higuera-Rodriguez, P. J. van Veldhoven, M. K. Smit, A. Fiore, and D. Heiss, "Waveguide-coupled nanopillar metal-cavity light-emitting diodes on silicon," *Nat. Commun.* **8**, 14323 (2017).
3. C. P. T. Svensson, T. Mårtensson, J. Trägårdh, C. Larsson, M. Rask, D. Hessman, L. Samuelson, and J. Ohlsson, "Monolithic GaAs/InGaP nanowire light emitting diodes on silicon," *Nanotechnology* **19** (2008).
4. G. Hamon, N. Paillet, J. Alvarez, A. Larrue, and J. Decobert, "Te doping of GaAs and GaInP using diisopropyl telluride (DIPTe) for tunnel junction applications," *J. Cryst. Growth* **498**, 301–306 (2018).
5. O. Tohru, O. Kiyoshi, and M. Kazuhiro, "Characterization of ingap/gaas heterojunction bipolar transistors with a heavily doped base," *Jpn. J. Appl. Phys.* **40**, 5221 (2001).
6. K. Dey and T. R. Lenka, "Simulation of high efficiency InGaP/InP tandem solar cells under flat plate and concentrator conditions," in *2017 International conference on Microelectronic Devices, Circuits and Systems (ICMDCS)*, (2017), pp. 1–5.
7. N. Bologna, S. Wirths, L. Francaviglia, M. Campanini, H. Schmid, V. Theofylaktopoulos, K. E. Moselund, A. Fontcuberta i Morral, R. Erni, H. Riel, and M. D. Rossell, "Dopant-induced modifications of $\text{Ga}_x\text{In}_{(1-x)}\text{P}$ nanowire-based p-n junctions monolithically integrated on Si(111)," *ACS Appl. Mater. & Interfaces* **10**, 32588–32596 (2018).
8. S. H. Jung, C. Z. Kim, Y. Kim, D. H. Jun, H. K. Kang, and H. Kim, "Comparative investigation of InGaP/InGaAs/Ge triple-junction solar cells using different Te-doped InGaP layers in tunnel junctions," *J. Korean Phys. Soc.* **68**, 792–796 (2016).
9. Yubo Sun, K. H. Montgomery, X. Wang, S. Tomasulo, M. L. Lee, and P. Bermel, "Modeling wide bandgap GaInP photovoltaic cells for conversion efficiencies up to 16.5%," in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, (2015), pp. 1–6.
10. I. Shoji, T. Kondo, and R. Ito, "Second-order nonlinear susceptibilities of various dielectric and semiconductor materials," *Opt. Quantum Electron.* **34**, 797–833 (2002).
11. M. Schubert, V. Gottschalch, C. M. Herzinger, H. Yao, P. G. Snyder, and J. A. Woollam, "Optical constants of $\text{Ga}_x\text{In}_{1-x}\text{P}$ lattice matched to GaAs," *J. Appl. Phys.* **77**, 3416–3419 (1995).
12. U. D. Dave, B. Kuyken, F. Leo, S.-P. Gorza, S. Combrie, A. De Rossi, F. Raineri, and G. Roelkens, "Nonlinear properties of dispersion engineered InGaP photonic wire waveguides in the telecommunication wavelength range," *Opt. Express* **23**, 4650–4657 (2015).
13. A. Martin, D. Sanchez, S. Combrié, A. de Rossi, and F. Raineri, "GaInP on oxide nonlinear photonic crystal technology," *Opt. Lett.* **42**, 599–602 (2017).
14. V. Eckhouse, I. Cestier, G. Eisenstein, S. Combrié, P. Colman, A. De Rossi, M. Santagiustina, C. G. Sameda, and G. Vadalá, "Highly efficient four wave mixing in GaInP photonic crystal waveguides," *Opt. Lett.* **35**, 1440–1442 (2010).
15. S. Combrié, Q. V. Tran, A. De Rossi, C. Husko, and P. Colman, "High quality GaInP nonlinear photonic crystals with minimized nonlinear absorption," *Appl. Phys. Lett.* **95**, 221108 (2009).
16. I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, "Band parameters for III–V compound semiconductors and their alloys," *J. Appl. Phys.* **89**, 5815–5875 (2001).
17. U. D. Dave, B. Kuyken, F. Leo, S.-P. Gorza, S. Combrie, A. De Rossi, F. Raineri, and G. Roelkens, "Nonlinear properties of dispersion engineered InGaP photonic wire waveguides in the telecommunication wavelength range," *Opt. Express* **23**, 4650 (2015).
18. F. Alsina, N. Mestres, J. Pascual, C. Geng, P. Ernst, and F. Scholz, "Raman scattering in single-variant spontaneously ordered GaInP_2 ," *Phys. Rev. B* **53**, 12994–13001 (1996).
19. H. Hamada, "Characterization of gallium indium phosphide and progress of aluminum gallium indium phosphide system quantum-well laser diode," *Mater. (Basel)* **10** (2017).
20. A. Yariv and P. Yeh, *Photonics: Optical Electronics in Modern Communications*, The Oxford Series in Electrical and Computer Engineering (Oxford University Press, 2007), 6th ed.
21. E. De Luca, R. Sanatinia, S. Anand, and M. Swillo, "Focused ion beam milling of gallium phosphide nanostructures for photonic applications," *Opt. Mater. Express* **6**, 587–596 (2016).
22. P. Khan, A. R. Barik, E. M. Vinod, K. S. Sangunni, H. Jain, and K. V. Adarsh, "Coexistence of fast photodarkening and slow photobleaching in $\text{Ge}_{19}\text{As}_{21}\text{Se}_{60}$ thin films," *Opt. Express* **20**, 12416 (2012).
23. Q. Yan, H. Jain, J. Ren, D. Zhao, and G. Chen, "Effect of photo-oxidation on photobleaching of GeSe_2 and Ge_2Se_3 films," *J. Phys. Chem. C* **115**, 21390–21395 (2011).