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Buckling-Based Method for Measuring the Strain—Photonic Coupling Effect of GaAs Nanoribbons

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ABSTRACT: The ability to continuously and reversibly tune the band gap and the strain-photonic coupling effect in optoelectronic materials is highly desirable for fundamentally understanding the mechanism of strain engineering and its applications in semiconductors. However, optoelectronic materials (*i.e.*, GaAs) with their natural brittleness cannot be subject to direct mechanical loading processes, such as tension or compression. Here, we report a strategy to induce continuous strain distribution in GaAs nanoribbons by applying structural buckling. Wavy GaAs nanoribbons are fabricated by transfer printing onto a prestrained soft substrate, and then the corresponding photoluminescence is measured to investigate the strain-photonic coupling effect. Theoretical analysis shows the evolution of the band gap due to strain and it is consistent with the experiments. The results demonstrate the potential application of a buckling configuration to delicately measure and tune the band gap and optoelectronic performance.

KEYWORDS: strain-photonic coupling, optoelectronic material, band gap, buckling, nanoribbons

or optoelectronic materials, the study of the strainphotonic coupling effects, potentially related to their applications, consistently remains a focus of research, in which strain engineering provides a controllable means to tune band structure.¹⁻⁵ The induced finite elastic deformation on the material lattice, due to deformation potential, leads to a band gap of material rising or falling predictably with compressive or tensile strain.⁶ For optoelectronic applications, the band gap, that is, the opto-response wavelength, determines its utility whether in solar cells or in light-emitting diodes. In some cases, to broaden the material's application, straininduced modification of the intrinsic band structure of the material represents possible future applications, such as strained germanium.^{7,8} The photonic efficiency has experienced dramatic enhancement compared with the unstrained one, so that the strain-photonic effect is able to make a key contribution to eliminate the deficiency of indirect band gap semiconductor applications in photonic devices. $^{9-11}$

In past decades, several methods were competitively able to induce strain on functional materials, for example, the misfit between growing film and the substrate. The strain resulting from the mismatch on the functional film is biaxial and definite yet unchangeable after growing.^{12,13} Due to the limited availability of alternative substrates, the strain can be slightly tuned into various desired values to realize integrative continuous change. Additionally, in recent years, low-dimensional materials (*e.g.*, nanowires) have gained attention because of their superior elastic properties compared to those of bulk

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Figure 1. (a) Schemetic procedures of fabricating the $Al_xGa_{1-x}As$ wavy geometry on PDMS: (i) line and anchors chemical etching with photoresist protection; (ii) sacrificial layer undercut by dilute HF; (iii) wafer flipping over to transfer onto prestrained PDMS; (iv) wavy configuration formed after PDMS cools. (b-d) From top to bottom: optical microscope image, 3D microstructure, and profile details of a single ribbon for samples A-C, respectively. (e) Buckling amplitude and wavelength *vs* prestrain. Solid square and circle represent measured amplitude and wavelength, respectively. Black and red dashed lines show theoretical prediction of the sizes.

ones,¹⁴ which offers the opportunity for nanomaterials to combine with a nanoscale mechanical platform to form another effective way to tune the band structure in larger deformations.^{5,15,16} Nevertheless, when choosing this method to realize strain—photonic coupling, an inevitable problem is how nanowires are rarely applied in practical optoelectronic devices and how general bulk films cannot undergo the same treatment to achieve a band structure shift. Therefore, designing a systemic structure that not only is suitable for enduring strain of functional films but also realizes a continuous band structure change in the material represents a future bilateral improvement in optoelectronic materials.

Here, we demonstrate a strategy to induce relatively large and continuously variable strain, compared to that caused by epitaxial growth, into an intrinsically brittle semiconductive material, such as gallium arsenide (GaAs), to tune its band structure by using the buckling configuration of nanoribbons.^{17,18} Buckled nanoribbons in a wavy configuration are patterned by lithography and are transfer printed onto the prestrained soft substrate, which arises from thermal treatment according to Feng et al.,¹⁹ where maximum prestrain is near 0.78%. Strain distribution in the wavy nanoribbons of GaAs is revealed by μ -Raman spectra, which is in accord with theoretical calculations. Band gap shift in the nanoribbon is disclosed by μ - photoluminescence (PL) measurements. Results show that the band gap shift varies along the length direction with the profile, and the maximum value is 17 meV. By stretching or compressing the soft substrate, further control and regulation of the band structure of the semiconductive materials, which varies with the configuration of the material, can be realized in a convenient way. This strategy of tuning the

band structure of brittle semiconductive material by continuously varying strain within the same piece of material possesses great potential for inspiring new applications. First, with this spatially varying strain and associated modulation in the band gap, the mechanism of the coupling effect between the band gap and strain can be further understood on the basis of not only the constant strain state but also the effect of the strain gradient on the band gap shift. Second, the wavy configuration, with the characteristics of stretchability and flexibility, can inspire and enable stretchable and flexible photoelectric devices. Furthermore, the regulation of spatially varying strain can be changed *via* different mechanical designs, so that we can possibly obtain various devices based on integration of subunits in only one film.

RESULTS AND DISCUSSION

The designed nanoribbon consists of GaAs/Al_{0.5}Ga_{0.5}As with the same thickness, in which the GaAs's band structure is tuned with induced strain in a wavy configuration and Al_{0.5}Ga_{0.5}As is used to keep the former located at one side of the neutral plane when buckled. The fabrication of wavy GaAs nanoribbons, as shown in Figure 1a, begins with the deposition of a functional Al_xGa_{1-x}As film by metal-organic chemical vapor deposition (MOCVD) on a native GaAs (001) substrate, of which, from the bottom to the top, are Al_{0.9}Ga_{0.1}As/GaAs/Al_{0.5}Ga_{0.5}As/ GaAs (500 nm/300 nm/300 nm/20 nm). The Al_{0.9}Ga_{0.1}As layer functions as the sacrificial layer, whereas the top ultrathin GaAs layer serves as a barrier that protects Al_{0.5}Ga_{0.5}As from oxidation. The composite thin film is patterned into ribbons with an anchor at each end by lithography and wet etching. Undercutting the sacrificial layer by HF causes the nanoribbons to be partially released from the wafer and ready for transfer printing. Soft substrates (made of polydimethylsiloxane, PDMS) are prestrained to 1.8, 2.4, and 2.9% separately by heating up to 120, 150, and 180 °C, respectively, before patterned nanoribbons are integrated. The designed buckling wavy configuration of GaAs nanoribbons develops once the prestrain of the soft substrate is released. The strain distribution of the GaAs thin film in the wavy configuration is a continuous periodical variable rather than an unchangeable constant in the strained semiconductors made of epitaxial heterostructures, as shown in Figure 1a, where the material in the valley is under compression, that in the peak is under tension, and that in the center remains unstrained.

Microscopy images and 3D morphographic images of samples A, B, and C in Figure 1b-d reveal the profile of the buckling structure of the nanoribbons on a soft substrate fabricated by different prestrain (1.8, 2.4, and 2.9%, respectively). The top images in Figure 1b-d are optical microscope images, in which the brighter parts in the ribbon indicate the peak and valley, and the darker ones identify the transition parts between; the profile is similar to the buckled silicon or semiconductor ribbons reported previously.^{17,18} More visually clear images are in the middle of the 3D microscope, from which the deformation of the PDMS substrate to form the bonding relationship between the nanoribbon and the substrate is pictured and clarified. What's important to note is that the debonding of the nanoribbon to the substrate is an important failure mode,^{20,21} so that good bonding to the substrate enables the brittle nanoribbons to be strained and tuned. A detailed and quantitative profile of the GaAs in the wavy configuration is revealed by 3D graphing images at the bottom of Figure 1b-d. As can be seen, the final configuration can be modeled as a cosine function theoretically, which justifies the assumption of the out-of-plane displacement in related theory models. General comparison and contrast of the three samples with different prestrain substrates shows that the wavelength decreases while the amplitude increases with the increased prestrain from A to C. A regular sinusoidal periodic structure of brittle GaAs is successfully obtained on a soft substrate without any fracture or rupture, showing the effectiveness of this strategy to induce periodical and continuous varying strain in semiconductive material without destruction.

Since only <5% prestrain is generated in the substrate, the theoretical model based on a small deformation assumption can be adopted to analyze the profile as well as strain distribution in the wavy GaAs nanoribbons. The profile of the buckled structure can be depicted by amplitude and wavelength, which can be given as^{22,23}

$$\lambda = 2\pi h_{\rm f} \left(\frac{\overline{E}_{\rm f}}{3\overline{E}_{\rm PDMS}}\right)^{1/3}, \quad A \approx h_{\rm f} \sqrt{\frac{\varepsilon_{\rm pre}}{\varepsilon_{\rm c}} - 1}$$
(1)

where $h_{\rm f}$ is the sum of the film thickness (620 nm), $\overline{E}_{\rm f} = \sum_{i}^{n} \overline{E}_{i} h_{i} / h_{\rm f}$ and $\overline{E}_{\rm PDMS}$ are the plane strain modulus of the film and substrate respectively, $\varepsilon_{\rm pre}$ is prestrain, and $\varepsilon_{\rm c} = (3\overline{E}_{\rm PDMS}/\overline{E}_{\rm f})^{2/3}/4$ is the critical strain for buckling. The prestrain involved is estimated by the product of the effective thermal expansion coefficient and temperature difference. The profile of the measured data by 3D microscopy and the predicted value of the theory are drawn in Figure 1e as solid symbols and dashed lines, respectively. Because the Young's modulus of PDMS undergoes changes with operative ambient temperature,²⁴ the Young's modulus is set to 1.18, 1.40, and 1.73 MPa for samples A, B, and C, respectively. In comparison, both wavelength and amplitude agree with the theory that identifies the suitability of a small deformation theory.

Therefore, it is demonstrated that the amplitude and wavelength of the wavy configuration can be controlled by the prestrain of the soft substrate alone in this strategy once the material of the system is determined. Postbuckling analysis indicates that the strain distributed in the wavy configuration here can be further adjusted in a controllable way by compressing or stretching the soft substrate.²⁵

Photonic response of the delicately strained GaAs nanoribbons is detected by μ -Raman and μ -PL spectra. During the measurement, in order to rule out the cross-talk that may arise from the uncertain strain state of a single measuring spot, a thin film layer of Al_{0.5}Ga_{0.5}As is used to locate the target GaAs off the neutral plane when buckled. According to composite beam theory,²⁶ the distance from the mechanically neutral plane to the top surface, denoted as $d_{neutral}$ is about 340 nm away from the top surface (see Methods for more details). Therefore, when the nanoribbons are buckled into a wavy configuration, the strain state of a single measuring spot on the GaAs shall be either in tension or in compression. Besides, the indirect band gap property of the auxiliary Al_{0.5}Ga_{0.5}As also ensures that no interfering heterogeneous spectral signal will be detected by PL spectra.

In semiconductor physics, the band gap is the crucial property that reflects photonic response, which equals conduction band minimum (CBM) minus valence band maximum (VBM). The PL spectrum conveniently provides direct visualization of the band gap measurement. Consistent with semiconductors with constant strain, a continuous and periodic band gap change along with the flexible and stretchable structure is realized by taking advantage of the wavy configuration on the soft substrate. Within a single period, the strain on the surface of the GaAs nanoribbon varies from tension to compression, indicating that the band gap variation is continuous and bidirectional, that is, both positive and negative. Figure 2 shows the band gap of a single period of a wavy GaAs nanoribbon by an overlaid PL mapping scan of the topography tuned by the strain induced by buckling, in which the size, width, and length of the wavy ribbon are normalized and the detailed gap can be read with a contour scale bar. Generally, the band gap changes along with the morphology of the GaAs nanoribbons, with a maximum in the valley and a minimum in the peak. That is, in a single period of wavy nanoribbons, from valley to peak, the band gap exhibits narrowing, and accordingly, the band gap change reverses from the peak to the valley. Here, the strategy of taking advantage of the buckling behavior of the nanoribbons demonstrates that the band gap variation range can be $\sim 1\%$ during a distance of ~ 100 μ m in a single piece of semiconductor material in a periodical way, and the band gap shift is closely related to the position in the wavy configuration, which is believed to have great potential for inspiring numerous new optical and optoelectronic devices or other applications.

For further exploration of the strain effect on the photonic properties of GaAs nanoribbons in a wavy configuration, three normalized PL spectra of selective points with fixed spacing in the scanning trace are drawn in left section of Figure 3, in which panels a–c correspond to samples A, B, and C (with prestrain of 1.8, 2.4, and 2.9%), respectively. The scanning trace is set



Figure 2. Band gap mapping by PL scanning within one period in the wavy ribbon. Wavy length and width have been normalized to its intrinsic values.

from the valley (see Figure 1a) to another nearest valley along the wavy configuration with a step of 10 μ m for samples A and B and 9 μ m for sample C. Due to the strain variation along the wave configuration, the band gap shifts with its relative position on buckling nanoribbons, which can be seen in the left column in Figure 3. Significantly, this symmetric shift in band gap can be detected continuously with periods, that is, structural periodic band gap shifts. Additionally, in the band gap shift range, it shows that the magnitude has a positive correlation with the value of prestrain.

In the center column of Figure 3, μ -Raman shift spectra are plotted in the same sampling conditions as used for performing PL. In the Raman spectra, the Raman signals from the peak, center, and valley are listed and only the long-wavelength optical (LO) phonon is shown. Obviously, the LO phonon experiences the same trend in the spectra where the value at the peak is the smallest while that in the valley is the greatest. In addition, of the three samples, in the center position, LO phonons are observed to have the same value (289.47 cm⁻¹), indicating that the strain state in the center position is the same, where the strain state can be regarded as a mechanically equivalent position. However, the LO phonons at the peak and valley are positioned at 290.01 and 289.21 cm⁻¹, 290.01 and



Figure 3. Strain effect on the photonic property of superficial wavy GaAs. (a-c) Left to right: normalized PL spectra with continuous position intervals in a single period, normalized Raman spectra of GaAs LO phonon on three special positions, and periodic band gap shift in one more period of samples A–C. In the PL spectra, depth in red or blue indicates the magnitude of tension or compression. Inset legend (see Figure 1) shows specific position of red, black, and blue lines representing Raman spectra. In the right section, position = 0 was set as the original measuring spot. Black triangles indicate the band gap calculated by PL, where the dashed line shows the periodic fitting in the structure.



Figure 4. Schematic mechanism of strain condition and the band structure on the wavy ribbon. (a) Lattice deformation in the ribbon; only the top three layers are drawn. For simplification, a zinc blende GaAs lattice is drawn by a simple cubic structure, with six face-centered Ga atoms and four body As atoms are not drawn. Inset shows that the peak range is tensile stressed but the valley is compressed. With sample C as an example, (b) plot of band gap *versus* strain. Band gap tuning with strain fits well with LH contributing to the VB. (c) Band structure tuning in half period; Y = 0 is set in a peak position. Solid black and blue lines are plotted with theoretical calculations of CB and LH for the VB. Yellow shaded area is the drawing of PL data.

288.94 cm⁻¹, and 290.27 and 288.42 cm⁻¹ for sample A–C, respectively. Conclusively, the Raman peak shift ranging from the valley to the peak undergoes a positive increase with applied prestrain on the PDMS soft substrate. Combining these two spectra, it can be found that the peak and the valley correspond to two types of strain states, and within these two, strain changes from one to another gradually, which is in accord with surface strain distribution obtained in the theoretical model where the convex contributes to tensile strain and concave contributes to compression, as shown in Figure 4a.

Because the LO phonon reflected by Raman diffraction has a strain-induced effect and its shift almost agrees with strain linearly on the basis of small deformation, it is used to reveal the strain state in the different positions of the wavy nanoribbons with different prestrain, as shown in the middle column of Figure 3. Followed by mechanical operation, the wavenumber of LO phonon shifts when the lattice endures elastic deformation that depends on the crystallographic direction of the imposed stress and the irradiated light. In our precursory steps, we ensured that the wavy structure extended along the (010) crystallographic direction, and the laser is illuminated perpendicular to the (001) plane. In this case, the precise relationship between the LO phonon shift and strain tensor can be simplified into an identical determinant.²⁷ Theoretically, every strain tensor ε can be decomposed into a hydrostatic factor $\varepsilon_{\rm h}$, showing isotropic deformation, and a distorted factor ε_{d} , representing structural deviation. ε_{h} determines the average shift in the LO phonon by inducing strain, and ε_{d} mainly removes the degeneracy of phonons and generates the splitting-off. In Figure 3, no obvious LO phonon splitting-off is observed; therefore, in a later calculation, only $\varepsilon_{\rm h}$ is taken into consideration. Linear relationship between LO phonon shift and strain is given by

$$\Delta \omega = \frac{(p+2q)}{2\omega_0} \,\overline{\varepsilon} \tag{2}$$

where $\Delta \omega$ is the LO phonon shift, ω_0 is the LO phonon wavenumber without strain (285 cm⁻¹), p and q are phonon deformation potential given -1.137×10^5 cm⁻² and $-1.543 \times$ 10^5 cm⁻², 28 and $\overline{\epsilon}$ is a diagonal element in $\epsilon_{\rm bi}$ $(1 - 2\nu)\epsilon_{\rm vv}/3$ for (010) uniaxial strain and $(4\nu - 2)\varepsilon_{yy}/3(\nu - 1)$ for (001) coplanar strain ($\varepsilon_{\nu\nu}$ is defined as the uniaxial strain along the length of the wave shape). When the wavenumber in center position, 289.47 cm⁻¹, is compared to the value of no strain, 285 cm⁻¹, a biaxial compressive strain of \sim 1.65% is applied to the wavy ribbon, which we consider to be from a growth process and transfer treatment. To treat approximately, the center position is set to be the relative zero strain in the buckled structure so that an ultimate strain state in each position, equaling the bending strain, adds up the biaxial strain directly. By substituting a positional Raman shift into the above theoretical expression, magnitudes of extreme uniaxial strain imposed by a cosinoidal shape are calculated, and the results are 0.28 and -0.58%, 0.57 and -0.58%, and 0.85 and -0.86% for samples A-C, respectively. For the difference in strain between theoretical prediction and Raman calculation, a major contributing aspect is the minimal spectral resolution related to the optical grating, which is 0.27 cm^{-1} . As shown in the listed data of the three samples, a Raman detector can only distinguish the strain condition of our specimens by the minimal resolution, so that a numerical uncertainty of 0.3% is produced into every calculation. To include the uncertainty into the estimated strain state by Raman shift, ± 0.43 , ± 0.58 , and $\pm 0.85\%$ correction should be considered for samples A–C, respectively. After the uncertainty treatment, the mean values obtained agreed with the results in the theory model.

The right column in Figure 3 represents a visible expression of a band gap tuned by strain along with altering position, in which the triangle icons represent the measured data in PL spectra while the dashed lines signify the fitting curve of the measured data. The band gap of GaAs shifts in a continuous and periodic way along the longitudinal direction on the buckled nanoribbons. Moreover, the detailed maximal shifts between the two extremal positions are 11, 15, and 17 meV in samples A, B, and C, respectively. Along the length of the ribbon, on the top surface, the shape experiences the cosine curve in the front view. According to the theoretical model, the strain on the top functional film is a uniaxial strain along (010)that consists of two parts, that is, bending strain $\varepsilon_{\mathrm{bending}}$ related to out-of-plane displacement and film strain $\varepsilon_{\rm film}$ caused by the in-plane. Film strain in this work is considered to be neglected as its value is much smaller than the bending strain. So that the whole strain state can be expressed as $\varepsilon_{\text{bending}} = 2\pi^2 A h_f$ $\lambda^2 \cos(2\pi y/\lambda)$, where y is the in-plane coordinate in the direction of cosinoidal wavelength. Therefore, the absolute extremal strain, apparently existing on the out-of-plane top or bottom position within a period, is 0.48, 0.57, and 0.76% using measured data and 0.48, 0.59, and 0.70% with theory fitting in Figure 2 for sample A, B, and C, respectively.

To theoretically explain the strategy of the band gap tuned by applied strain, generally, the expanding Pikus-Bir Hamiltonian based on the $k \cdot p$ method can be a widely acceptable method used to comprehend band gap widening or narrowing on the special point in k space (e.g., Γ point).²⁹ Similar to the LO phonon, the band structure is alterable with lattice deformation, which causes different electronic wave function. The CBM at Γ point experience a linear increase or decrease with strain whether it is compressive or tensile. However, the valence band at Γ point has three branches with two degeneracies each: light hole (LH), heavy hole (HH), and splitting-off (SO) hole. In the free-strain state, due to spin-orbit coupling, SO splits up and lays under the other two levels. As a result, electron transition from LH and HH to CB and the recombination process in these three states are mainly attributed to the PL spectra. The strain-dependent expression of LH-CB and HH-CB to evaluate the band gap shift is determined by

$$P_{\varepsilon} = \alpha_{v}(1 - 2\nu)\varepsilon_{yy}, \ Q_{\varepsilon} = -b(\nu - 1)\varepsilon_{yy}$$

$$E_{CB-LH} = E_{0} + \alpha_{c}(1 - 2\nu)\varepsilon_{yy} + P_{\varepsilon}$$

$$+ \frac{1}{2}(Q_{\varepsilon} - \Delta + \sqrt{9Q_{\varepsilon}^{2} + 2\Delta Q_{\varepsilon} + \Delta^{2}})$$

$$E_{CB-HH} = E_{0} + \alpha_{c}(1 - 2\nu)\varepsilon_{yy} + P_{\varepsilon} + Q_{\varepsilon}$$
(3)

where $E_{\rm CB-LH}$ is the energy gap from LH to CB, $E_{\rm CB-HH}$ is the energy gap from HH to CB, α_{c} , α_{v} , and *b* are deformation potential parameters, and Δ is the splitting energy, 0.341 eV. The deformation potential $\alpha_{\rm c} = -11$ eV, $\alpha_{\rm v} = -1.16$ eV, and b = -1.85 eV.²⁸

Using eq 3, an item $(1 - 2\nu)$ is observed as eq 2 also has the same factor. Due to atomic stacking, atomic density varies along different crystallographic directions even in high-symmetry face-centered cubic phase. As a result, the Poisson effect in the lattice represents inequivalence in different directions. Overall, the Poisson ratio, ν , which is a direction-related parameter in the material, strongly determines the magnitude of the band gap shift. In this experiment, stress along $\langle 010 \rangle$ makes the factor about 1/3; that is, the hydrostatic component is nearly one-third of the uniaxial strain. Under a tensile state, CB changes toward lower energy while LH and HH undergo falling and rising, respectively. In contrast, CB and LH go up in

compression but HH shifts down. That is, LH reduces the gap difference by inducing strain, but HH prefers to enlarge it. As demonstrated in Figure 4b, under strain, there is a sharper band gap shift due to HH than what is produced by LH. As seen in the experimental data, the gap related to LH seems to possibly be the one we measure. In Figure 4c, the band structure of sample C illustrates the strain-inducing band structure configuration of half a period that depicts visualization of the CBM and VBM change in corresponding positions, especially in the yellow shaded area in figure, where the emitted light photon in the spectra has been found to likely be the electron transition from CB to LH, whether the film is relaxed or constricted. The reason may be the small deviation of HH maximum from Γ point due to zinc blende's lack of inversion.³⁰⁻³² In this case, by photoillumination, injected photons excite electrons in the VB into the empty CB, and the exiting electrons prefer to recombine with the holes in LH rather than those in HH because of the direct transition exceeding the indirect transition. In addition, another factor led to this phenomenon and is attributed to the thermal atmosphere in which the PL measurement was processed at room temperature, yet precise band to band transition commonly requires placing the sample into a cryostat.

Moreover, in our experimental measurement, band gap shifts *versus* per unit strain of our samples are calculated by 12.8, 12.9, and 10.9 meV/% for each. On average, the gap shift rate is about 12 meV/%; however, upon comparison to the reported oriented $\langle 111 \rangle$ GaAs nanowire yielding a change in LH,¹⁵ it is numerically quite small indeed. Next, we attempted to grow the structural design to enhance the systemic property.

CONCLUSION

The strategy of tuning the band structure of a semiconductor in a periodic and continuously varying way is proposed based on the buckling structure of GaAs nanoribbons in a wavy configuration on a soft substrate. The fabrication of the samples involves photolithograghy for patterning the semiconductor material into nanoribbons and transfer printing to integrate the nanoribbons onto the prestrained soft substrate to form the wavy configuration through buckling. μ -PL spectra show that the band gap of the GaAs nanoribbon is tuned by the strain-induced wavy configuration. It is demonstrated that the band gap is closely related to the position with the minimum in the peak and the maximum in the valley. Due to the structural features of the wavy GaAs nanoribbon, the band gap variation range can be tuned to ~1% at a distance of ~100 μ m in a single piece of semiconductor material in a periodical way. The band gap variation range has a positive correlation with the prestrain, which is the only factor use for determining the strain state in the nanoribbon, besides the material parameters. Due to the flexibility and stretchability of the whole system, further modulation and enhancement can be realized through postbuckling of the nanoribbon by inducing tension or compression to the soft substrate.

The theoretical strain effect on the band gap, which has a similar relation as a phonon, is represented to compare the measuring data by μ -PL. After analysis, the transition between the conduction band and light hole band is considered to be the most possible. With induced strain, a change rate, ~12 meV/%, was identified to modify the $\langle 001 \rangle$ GaAs band structure with actual strain applied on films. Significantly, with the assistance of PL spectra, it is found that the band gap is subject to positional deformation where the tuning experiences periodicity

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with the identical period of structure. With this structural design applied, continuous and cyclic optoelectronic properties coexist on the same film, where it demonstrates a broadened vision for photonic applications.

METHODS

Fabrication of the GaAs Nanoribbons in a Wavy Configuration. The fabrication of wavy GaAs nanoribbon begins with the deposition of functional Al_xGa_{1-x}As film by MOCVD on a native (001) GaAs substrate sequentially as $Al_{0.9}Ga_{0.1}As/GaAs/Al_{0.5}Ga_{0.5}As/$ GaAs (500 nm/300 nm/20 nm). The thin film composite is patterned into ribbons (75 μ m wide and 3 mm long) with an anchor $(200 \times 200 \ \mu m)$ at each end by lithography and etching with mixed acid (85% $H_3PO_4/30\% H_2O_2/deionized$ water = 2:1:20) for 2 min 30 s. Then the ribbons are partially released from the wafer by undercutting the sacrificial layer (Al_{0.9}Ga_{0.1}As) by diluted HF acid (40% HF/deionized water = 1:7) and held by the anchors. Before transfer printing, the soft substrate (PDMS) is preprocessed in ultraviolet light for 3 min to clean and activate its surface in order to facilitate the printing process. Then the soft substrates are heated to 120, 150 and 180 °C separately, rendering prestrain of 1.8, 2.4, and 2.9%, respectively. The integration of nanoribbons to the soft substrate is accomplished by transfer printing the undercut thin film to the prestrained PDMS. The buckling structure in the wavy configuration of GaAs comes is developed once the prestrain of the soft substrate is released, which completes the fabrication process.

PL Measurement of the Periodical and Continuously Varying Strain of GaAs Nanoribbons. μ -Raman and μ -PL spectra are measured by a confocal Raman spectrometer (HORIBA LabRAM HR). During measurement, an incident laser (532 nm) is focused onto a single spot with a diameter of ~2 μ m. Measuring the sample in such micrometer-scale is intended to represent resulting data more accurately that can precisely reflect "*in situ*" information. Since wavy nanoribbons were measured in air ambient, focused laser power is set to 0.06 mW in order to eliminate the thermal effect on the material property, which may cross-talk with the desired signal.

Calculation of the Position of the Neutral Plane. According to composite beam theory, for the multilayer of GaAs nanoribbons used here, the distance from the mechanical neutral plane to the top surface, d e n o t e d b y $d_{n e u t r a 1}$, is d e t e r m i n e d a s $d_{neutral} = \sum_{i=1}^{n} \overline{E_i} h_i \left(\sum_{j=1}^{i} h_j - \frac{h_i}{2} \right) / \sum_{i=1}^{n} \overline{E_i} h_i$, where *n* is the number of layers, h_i is the thickness of *i*th layer, and $\overline{E_i}$ is the plane–strain modulus of *i*th layer given by $E_i / (1 - \nu_i^2)$, with Young's modulus E_i and Poisson's ratio ν_i . Here, elastic parameters (on (001) crystallographic plane) of layers are $E_{\text{GaAs}} = 85.3$ GPa, $\nu_{\text{GaAs}} = 0.312$; $E_{\text{Al0.5Ga0.5As}} = 0.318$; and $E_{\text{PDMS}} \approx 1.7$ MPa, $\nu_{\text{PDMS}} = 0.48$. Therefore, the mechanical neutral plane is ~340 nm away from the top surface.

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Notes

The authors declare no competing financial interest.

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