

**SCALABLE NANOMANUFACTURING OF
ATOMICALLY-THIN, HIGHLY-ALIGNED, HIGH-ASPECT-RATIO, HOMOCHIRAL
NANORIBBONS, NANOWIRES, AND QUANTUM WIRES
WITH ANGSTROM-PRECISE MORPHOLOGY**

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This International Patent Application claims the benefit of the U.S. Provisional Patent Application No. 63/513,484 filed on July 13, 2023 and titled “Method for producing highly-aligned nanogaps and nanoribbons with atomically sharp/uniform edges from atomically-thin films”, the entire contents of which are incorporated by reference herein.

**STATEMENT REGARDING FEDERALLY SPONSORED
RESEARCH OR DEVELOPMENT**

[0002] This invention was made with government support under Grant Number 1944638 awarded by the National Science Foundation. The U.S. government has certain rights in the invention.

TECHNICAL FIELD

[0003] The present invention generally relates to formation (generation, creation) of judiciously structured substantially monolayer materials and, in particular, to scalable methodologies of formation of two-dimensional (2D) nanoribbons (NRs) and/or nanowires (NWs) and/or quantum wires (QWs) and/or nanogaps (NGs) to produce highly-uniform 2D materials or their features that not only have edges and/or edge surfaces that are substantially aligned, atomically sharp, uniform, high-aspect ratio, and flat but that also lend themselves to being easily transferred onto a target substrate for a follow-up device integration.

RELATED ART

[0004] The synthesis and processing of two-dimensional and thin-film NRs/NWs/QWs/NGs is in general a very active area of research, because 2D NRs/NWs/QWs/NGs exhibit appealing quantum phenomena and additional degrees of freedom in tunability of various properties that are distinguishing 2D NRs/NWs/QWs/NGs from their 2D monolayer counterparts

due to presence of lateral confinement and engineerable edge states. The thickness, width, edge chirality, edge chemical moieties, roughness of 2D NRs/NWs/QWs/NGs dictate intrinsic multi-physical properties of such structures.

[0005] Current methodologies for synthesizing 2D NRs/NWs/QWs/NGs, for example, include lithography-based methodologies (such as photolithography, e-beam lithography, FIB lithography, imprint lithography- to name just a few), the approaches utilizing unzipping of nanotubes, those employing solid-liquid-vapor etching, bottom-up synthesis, templated growth, and molecular beam epitaxy. Despite previous efforts to develop a practically scalable way to synthesize 2D-NRs/NWs/QWs/NGs via a multitude of bottom-up and top-down approaches, all results produced by related art thus far lack the *uniformity and/or scalability* required for future application needs in high-density integrated circuits and quantum computing and sensing devices.

[0006] For example – and in no particular order - Wang, H. et al. (Seeded growth of single-crystal black phosphorus nanoribbons, in Nature Materials 23, 470–478, 2024) presented the synthesis methodology utilizing seeding the chemical vapor transport growth with black phosphorus nanoparticles. While the approach enabled the formation of single-crystal nanoribbons the control over the thickness and/or orientation of a given ribbon could not be established. Additionally, as the skilled artisan readily recognizes, a process of seeded growth tends to generate geometrically-tapered (as opposed to spatially uniform) ribbons.

[0007] Lyu, B. et al. (Graphene nanoribbons grown in hBN stacks for high-performance electronics; Nature 628, 758–764; 2024) described the directional growth of graphene nanoribbons within stacks of hBN. This method, as a skilled artisan will readily appreciate, is specifically suited for the applications in which nanoribbons need to be embedded within hBN. The very fact that the resulting nanoribbons are embedded, however, understandably makes it particularly difficult to transfer the embedded nanoribbons to target substrates to be used for desired device integration, thereby drastically limiting the practical use of the produced 2D NRs. (As known in related art, such transfer could otherwise be effectuated with use of a transfer/handle layer to pick up the ribbons/wires from the underlying, reposition the picked-up elements onto a target substrate, and then remove the transfer/handle layer; or with the use of, for example, a laser-induced forward transfer printing of the elements at hand onto the target substrate.)

[0008] Similarly, Weiqing Wu et al. (in ACS Applied Nano Materials, 7 (9), 10303-10311, 2024) addressed the fabrication of graphene nanoribbons via laser interference lithography. This methodology produced rather well -aligned nanoribbons, yet the edge roughness and large width of the nanoribbon was impermissibly high to allow for practical scalability of the process and successful applications. Such result is practically inevitable, considering that the spatial resolution of the used lithographic approach is limited by optical diffraction.

[0009] US Patent No. 9,859,513 to Strachan addressed the production of nanogaps and nanoribbons with sharp edges for application in nanoelectronics and quantum transport by requiring and utilizing the process of integration of carbon nanotubes and few-layer graphene with controlled interfaces. The proposed methodology relied on and required the use of etching of tracks by random lateral movement of catalytic nanoparticles (as a result of which the resulting tracks are, generally, uncontrollable).

[0010] Chen, M. et al. (in ACS Nano, 11(9), 9191-9199, 2017) utilized localized/nonuniform strain via necking of thermoplastic polymers to fragment transition metal dichalcogenides (TMDs) monolayers into ordered nanoribbons. The shortcoming of this methodology is the substantially complete lack of control over the width or spacing of nanoribbons due to the fact that the spontaneous fragmentation is determined by the necking front of the polymer. Indeed, the Poisson effect and the processing of necking causes compression of the nanoribbon along its length, rendering a given nanoribbon randomly non-planar and/or wrinkled.

[0011] Kosynkin D.V. et al. (Highly conductive graphene nanoribbons by longitudinal splitting of carbon nanotubes using potassium vapor; in ACS Nano. Feb 22; 5(2): 968-74, 2011) explored longitudinal splitting of carbon nanotubes with the use potassium (K) vapor and then later with solution using sodium-potassium alloy (Na/K) to produce graphene nanoribbons. As the skilled artisan will readily appreciate, the width and edge chirality of nanoribbons obtained through this method is fixed by the diameter and chirality of nanotubes and substantially depends on the alignment of monodisperse nanotubes as precursors (which process is itself the challenge

unresolved in related art). Because of the unzipping process, the edges of the resulting nanoribbons are substantially always unpredictably folded.

[0012] The methodology addressed in this disclosure solved the persisting problems of related art by utilizing a purely physical method for the scalable formation of 2D NRs/NWs/QWs/NGs under ambient conditions, in which the physical fracture that is intrinsic to the initial material itself is expanded to form the edge surface of the resulting one-dimensional (1D), linear 2D-NR and/or NW and/or QW and/or NG structures. As demonstrated empirically, the produced structures necessarily exhibit highly uniform width, spacing, alignment, and edge chirality characterized with precision on an angstrom scale. The proposed methodology enables a skilled person to create an arbitrary 2D- NRs/NWs/QWs/NGs from a variety of 2D crystals and open new avenues for continued dimensional scaling in future semiconductor and quantum devices manufacturing.

SUMMARY OF THE INVENTION

[0013] Embodiments of the invention provide an article of manufacture that includes a sample holder dimensioned to secure a deformable substrate therein, a substrate-deforming agent configured to be actuated with a driver and to generate a variable deformation force applied to the deformable substrate such as to cause a variable deformation or strain in the deformable substrate, and a controller operably coupled with at least one of the sample-holder and the driver. The controller is configured to acquire data representing structural changes in a two-dimensional material sample that is adhered to a second surface of the deformable substrate (here, the structural changes have been caused by the controller via application of the variable deformation force to the substrate with the substrate-deforming agent). In at least one specific case, the substrate-deforming agent may include at least one of (i) a pusher element configured to be repositionable, with the use of the driver, substantially transversely to a plane of the deformable substrate secured in the sample holder; (ii) a flow of fluid (such as gas or air, in one nonlimiting case) directed transversely to a surface of the substrate; and (iii) a difference between a first pressure at a first point and a second pressure at a second point separated from the first point by the deformable substrate secured in the sample holder. Alternatively or in addition – and substantially in every embodiment, the article of

manufacture may be configured to generate physical fractures that are formed across the 2D material sample at a first level of a variable stress formed in the substrate and, upon increase of the variable stress to a second level exceeding the first level, to longitudinally separate from one another strips of a material of the sample formed along the physical fractures. Here, each strip has substantially atomically-sharp edges and substantially uniform width at least when the 2D material sample has a substantially monolayer thickness. Alternatively or in addition – and substantially in every implementation – the article of manufacture may be configured to create, in response to a stress formed in the 2D material sample, longitudinal gaps separating said strips of material from one another and having sub-micron widths at least when the 2D material sample has a substantially monolayer thickness. Furthermore, as used in substantially every embodiment, the controller may include at least one of (i) a measurement apparatus configured to acquire real time measurement data representing said structural changes and/or a dependency of the structural changes on at least one characteristic of the operation the article of manufacture, and (ii) a processor governed by instructions stored in a tangible, non-transient memory medium to operate the driver and/or the measurement apparatus. Optionally, the controller may include an optical imaging system configured to acquire images representing structural changes in the 2D material sample. Substantially in every implementation, when and if the deforming agent includes a pusher element repositionable substantially transversely to the substrate, such pusher element may be equipped with a tip having a surface profile defined by a differentiable function.

[0014] Embodiments additionally provide a method for use of any of the above-identified embodiments of the article of manufacture. Such method includes at least a step of securing, in the sample holder, a deformable supporting substrate with a 2D sample of material located in or on a chosen layer of the substrate and a step of applying a variable deformation force to the substrate to stress the substrate and to form a physical fracture in the 2D sample. The method further includes a steps of increasing a variable stress (which may be, in a non-limiting case, a tensile stress and/or a shear stress) formed in the 2D sample to separate the 2D sample into nanoribbons and/or nanowires and/or quantum wires along a physical fracture in the sample such that the nanoribbons and/or nanowires and/or quantum wires possess substantially atomically-sharp and substantially linear edges that are substantially parallel to one another, and such that immediately neighboring

nanoribbons and/or nanowires and/or quantum wires are longitudinally separated from one another with a nanogap having a substantially constant width along a length thereof. at least in one specific embodiment, the method may additionally include a first complementary step of forming at least one defect on a surface of the 2D sample or a second complementary step of removing material from at least one surface an edge of the 2D sample to define, during said applying, a location of the physical fracture (each of such first and second complementary steps is performed prior to the step of securing. Alternatively or in addition – and substantially in every implementation - the method may additionally effectuate (prior to the applying the variable deformation force) a step of forming a substantially linear array of multiple defects on a surface of the 2D sample to define, during the applying, the orientation of multiple physical fractures to be transverse to an axis of the substantially linear array, and/or the method may additionally include a step of transferring at least some of the nanoribbons and/or nanowires and/or quantum wires from the deformable supporting substrate to a different substrate substantially without changing mutual position and/or orientation of the nanoribbons and/or nanowires and/or quantum wires. Substantially in every implementation, the method may be configured (i) to produce the nanoribbons and/or nanowires and/or quantum wires in the 2D sample of a material, chosen from materials with corresponding fracture strengths at least within a range from about 0.05 to about 100; and/or (ii) to produce the nanoribbon or nanowires or quantum wires with an aspect ratio value within a range from about 10:1 to about 1000:1.

[0015] Embodiments of the invention additionally provide a method that includes forming at least one fracture in a sample of a material (which has a thickness substantially equal to a thickness of a monolayer of the material) by applying a variable deformation force to a tangible surface that is spatially separated from the sample. The method additionally includes spatially separating from one another strips of the sample (that are dimensioned as nanoribbons and/or nanowires and/or quantum wires and that have substantially atomically sharp and uniform edges) along such at least one physical fracture by continuing to apply the variable deformation force such that a gap (separating immediately neighboring each other nanoribbons and/or nanowires and/or quantum wires) has a substantially longitudinally uniform sub-micron width. Optionally, the step of applying a variable deformation force may include (a) increasing a level of a tensile stress in the sample substantially monotonically to a level exceeding a fracture limit of the sample; and/or (b)

applying the variable deformation force for a duration of time sufficient for a stress formed in the sample to exceed a creep limit of the sample; and/or (c) repetitively forming tensile stress and/or compressive stress in the sample to cause cyclic fatigue of said sample. Alternatively or in addition – and substantially in every implementation of the method - each of the forming and spatially separating is performed without the use of light and/or such as to dimension the nanoribbons and/or nanowires and/or quantum ribbons to have substantially longitudinally uniform widths. In at least one – and, preferably, each – embodiment of the method, a length (of the gap and/or nanoribbons and/or nanowires and/or quantum wires separated by the gap) along which the gap and the nanoribbons and/or nanowires and/or quantum wires maintain corresponding widths to be substantially constant, exceeds a width of a nanoribbon and/or nanowire and/or quantum wire by at least one order of magnitude. In at least one – and, preferably, each – embodiment of the method, a length (of the gap and/or nanoribbons and/or nanowires and/or quantum wires separated by the gap) along which the gap and the nanoribbons and/or nanowires and/or quantum wires maintain corresponding widths to be substantially constant, exceeds a width of a nanoribbon and/or nanowire and/or quantum wire by at least two orders of magnitude. Alternatively or in addition, and substantially in every implementation, the method additionally includes defining a location of the at least one fracture by forming a surface and/or subsurface defect on the sample. Optionally – and substantially in every implementation of the method and when at least one physical fracture includes multiple physical fractures – the method may be complemented with the step of defining both locations and orientations of such multiple fractures in the sample by forming an array of surface and/or subsurface defects on the sample or by removing material from at least one surface an edge of the 2D sample to define, during the step of applying, a location of a given physical fracture.

[0016] Embodiments of the invention additionally provide use of variable deformation force, applied to a deformable substrate supporting a substantially 2D material adhered thereto and/or embedded therein, to form (a) an array of nanoribbons and/or nanowires and/or quantum wires having substantially atomically sharp and substantially linear edges, and/or (b) an array of gaps in said 2D material characterized by nano-sized or angstrom-sized widths. In at least one specific step, such use may be judiciously configured to cause a formation of the array of

nanoribbons and/or nanowires and/or quantum wires with aspect ratios within a range from about 10:1 to about 1000:1.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The invention will be more fully understood by referring to the following Detailed Description of Specific Embodiments in conjunction with the Drawings, of which:

[0018] FIGs. 1A, 1B are schematics illustrating the implementation of the idea of the invention.

[0019] FIGs. 2A and 2B provide an illustration of a custom deformation apparatus structured to apply directionally-resolved deformation forces to a substantially 2D layer of a chosen material (such as a substantially monolayer of MoTe₂ or hBN or graphene, as a non-limiting example) and an illustration of the experimental setup, respectively.

[0020] FIGs. 3A, 3B provide illustrations to the alignment of the monolayer of the MoTe₂ crystal (used, for example, as material 206 of FIG. 2B) before the application of the deformation forces. FIG. 3A: uniaxial tensile strain formed along the armchair direction, and FIG. 3B uniaxial tensile strain formed along the zigzag direction.

[0021] FIGs. 4A, 4B, 4C, and 4D illustrate the change in the Raman spectra of a monolayer of 1H-MoTe₂ under applied uniaxial tensile strain along the armchair direction (FIGs. 4A, 4C) and the zigzag direction (FIGs. 4B, 4D). The initial E_{2g}^1 peak position with no applied strain is marked with a vertical dashed line in FIGs. 4A, 4B. The E_{2g}^1 peak position consistently red-shifts with increasing tensile strain along both the armchair direction (FIG. 4C) and the zigzag direction (FIG. 4D) for each of the material samples, exhibiting average shifts of -1.66 ± 0.04 and -0.80 ± 0.07 cm⁻¹%, respectively. Insets to FIGs. 4C, 4D illustrate the E_{2g}^1 vibrational mode of the monolayer 1H-MoTe₂ and applied strain directions with respect to the crystal lattices of the sample.

[0022] FIGs. 5A, 5B, 5C provide additional illustration to the process of formation of a fracture in a 2D material (that leads to the formation of a substantially atomically smooth edge of the 2D material by illustrating non-coherent stress/strain transfer between 1H-MoTe₂ 106 and the

PET substrate 110 under excessive applied deformation forces. Here, FIGs. 5A, 5B show optical images of the monolayer of 1H-MoTe₂ before and after the fracture (indicated in FIG. 5B) appears. FIG. 5C presents Raman spectra of a monolayer 1H-MoTe₂ sample acquired under progressively higher applied uniaxial tensile strain along the armchair direction (see FIG. 3A) of up to 2.2%. Excessive strain (>2%) leads to fracture of the 1H-MoTe₂ crystal with a concomitant blueshift of the E_{2g}^1 peak, thereby evidencing stress/strain relief in the crystal.

[0023] FIGs. 6A, 6B illustrate the results of patterning of deterministic point-like defect nucleation sites within the 2D thin films via laser irradiation to guide fracture initiation and NRs/NWs/QWs/NGs formation.

[0024] FIG. 7 presents a series of optical images (acquired with the use of dark-field microscopy) illustrating in real time propagation of a fracture triggered in a 2D sample of the chosen material with an approximately 2% tensile strain.

[0025] FIGs. 8A, 8B, 8C, 8D present the results of characterization of highly-aligned, atomically-thin 2D nanoribbons formed via mechanical fracturing and self-assembly, according to an embodiment of the invention.

[0026] FIG. 9 shows the image obtained with a bright-field optical microscope and illustrating the influence of the thickness of the initial material sample on a typical resultant width of a ribbon and/or gap formed with the use of an embodiment of the invention.

[0027] FIGs. 10, 11A, 11B illustrate high spatial uniformity of geometrical characteristics and the angstrom-precision linearity of the edges of the NRs/NWs/QWs and NGs between the NRs/NWs/QWs formed with the use of an embodiment of the invention.

[0028] FIGs. 12A, 12B, 12C, 12D, and 12F illustrate an embodiment of preparation of a surface of the 2D material pre-form prior to initiation of the process of formation of NRs/NWs/QWs/NGs from such preform.

[0029] Generally, the sizes and relative scales of elements in Drawings may be set to be different from actual ones to appropriately facilitate simplicity, clarity, and understanding of the Drawings. For the same reason, not all elements present in one Drawing may necessarily be shown in another. While specific embodiments are depicted in the figures with the understanding that

the disclosure is intended to be illustrative, these specific embodiments are not intended to limit the scope of invention the implementations of which are described and illustrated herein.

DETAILED DESCRIPTION

General.

[0030] In December 2023, Intel and TSMC demonstrated (during the 69th annual IEEE International Electron Devices Meeting) their latest transistor design based on nanoribbon FET channels. The nanoribbon used in the RibbonFET are still made of silicon via photolithography, where the resulting thicknesses / sizes are within the confines of the lithographic techniques. However, traditional silicon-based processes will not be compatible with the physiochemical properties and ultimate dimensional scaling of superior, atomically-thin 2D quantum materials in the “beyond Moore” era, thus necessitate entirely new materials processing and nanomanufacturing paradigms. The proposed method for synthesizing 2D nanoribbons and/or nanowires and/or quantum wires and/or nanogaps presented below enable dimensional scaling of atomically-thin 2D materials and their device integration/packaging in future semiconductor, quantum, and neuromorphic computing architectures.

[0031] Specifically, in accord with preferred embodiments of the present invention, methods and apparatus are disclosed for repeatable and scalable fabrication of 2D nanogaps, nanowires, quantum wires, and/or nanoribbons having substantially atomically smooth edges. The problem of inability of related art to achieve such fabrication while controlling the geometry of the produced 2D nanostructures in a scalable fashion is solved by subjecting a chosen 2D material adhered to and/or embedded in a deformable substrate to excessive deformation forces (representing at least uniaxial tensile stress and interfacial shear stress) and causing the resulting deformation of the substrate to systematically induce parallel fractures that are highly aligned across the entire crystal structure of the 2D material, thereby segmenting such material into nanoribbons and/or nanowires and/or quantum wires and/or forming nanogaps while establishing control over the thickness and/or orientation of a given nanoribbon/nanowire/quantum wire/nanogap.

[0032] The idea of the invention stems from the realization that - once the intended-for-use material is prepared as a substantially two-dimensional pre-form (which interchangeably may be

referred to herein as a “crystal”) the surface of which is preferably appropriately modified as identified below - the geometrically precise physical fractures can be formed in such pre-form at the locations defined by the modifications of the surface of the prepared pre-form in response to the controlled stress/strain, which fractures further propagate and align along the preform to generate well-ordered gaps or crevices that separate the individual pieces of the pre-form. The so-formed individual pieces, configured as NRs and/or NWs and/or QWs, have exceptionally linear edges and/or exceptionally uniform widths; the gaps or crevices separating the immediately neighboring pieces have exceptionally uniform widths and heights.

[0033] The preferred modification of a surface of the 2D pre-form, preceding the induced process of formation of the physical fracture according to the idea of the invention, may include a formation of an external defect (a point-like defect, in one specific case) and optionally but not necessarily an array of such extrinsic defects. In at least one implementation, as discussed below, the modification of the surface of the 2D preform may include a removal of an outmost surface layer from a surface (preferably both of the opposing each other surfaces) of the 2D pre-form with the use of, for example, plasma treatment to create a quasi-amorphous surface(s).

[0034] Notably, the controlled deformation force(s) (representing at least uniaxial tensile stress and/or shear stress and causing the strain in the pre-form) is intentionally applied not to the pre-form but to the deformable substrate that supports and carries the pre-form, so as to have the resulting “fractured” into two-dimensional (2D) nanoribbons and/or nanowires and/or quantum wires (QWs) pre-form remain on such deformable supporting substrate for future use and handling. (A skilled person understands that, once the pre-form is fractured into such nano-sized elements, the immediately neighboring elements are separated from one another what is referred here as a nanogap or NG. For simplicity of presentation or claiming, the produced with the use of an embodiment of the proposed methodology two-dimensional nanoribbons and/or nanowires and/or quantum wires may be collectively referred to, interchangeably, as NRs/NWs/QWs and/or as “identified nanostructures”.)

[0035] To further tune the spacing between the so-formed NRs/NWs/QWs, a differential level of tensile or compressive or shear deformation may be applied to the substrate. This two-step stress/strain treatment methodology results in the fabrication of 2D NRs/NWs/QWs with

remarkable angstrom-precision edges and/or edge surfaces as well as controllable substantially uniform (nanogap) spacing. (The deviation of an edge from a straight line, defining a degree of linearity of an edge of a NR/NW/QW and/or associated width uniformity, depending on the specifics of the implementation of an embodiment of the invention, in reference to a deviation measured from about one unit cell of a crystal to about 5 unit cells, or in the alternative – within 10 percent or preferably 5 percent deviation from the average numerical value of the width.)

[0036] The skilled artisan will readily appreciate the advantages provided by embodiments of the proposed methodology over the related art alluded to above. For example, in stark contradistinction with the results of Wang, H. et al., the proposed method permits the fabrication of highly-aligned nanoribbons and/or nanowires that can be as thin as one atomic layer, determined by the precursor crystal. In advantageous comparison with the results of Lyu, B. et al., the 2D NRs, the discussed below approach yields 2D NRs/NWs/QWs already positioned on the surface of a substrate, thereby enabling an easy transfer of such nano-structures onto target substrates to be directly used in the following device fabrication. In contradistinction with the approach described by Weiqing Wu et al., the edges of NRs/NWs/QWs produced with the proposed methodology are substantially atomically sharp and the edge surfaces are substantially atomically flat, since the proposed methodology utilizes the very controlled physical fracture(s) that is(are) intrinsic to the material/crystal itself - instead of localized light-matter interactions as proposed by Wu. The novelty and inventiveness proposed by the disclosed methodology over the US 9,859,513 stems from the same use of controlled physical mechanical fracture(s) present in the initial material (both for general NG and NR/NW/QW production), in advantage over the use of the integration of carbon nanotubes and few-layer graphene pre-forms relied on and required by the '951 patent. Contrary to the lack of control over the width and spacing of the nanoribbons produced with the use of methodology of Chen M. et al., the embodiments of the proposed approach judiciously employ the alignment of the preferred crystal directions on the substrates and/or creation of point defect(s) to guide the propagation of fractures in those preferred crystal directions via strictly uniaxial stress/strain and/or employ fatigue and/or creep deformation instead of large tensile strain to yield finer control over the resultant NRs/NWs/QWs. Further - and in advantageous contradistinction with the method of Ansary, A. et al., the proposed method is carried out in

ambient conditions, thereby mitigating potential material degradation and/or contamination. The novelty and inventiveness over the use of longitudinal splitting of carbon nanotubes with the use of potassium vapor, proposed by Kosynkin D.V., the discussed below embodiments utilize 2D films as precursors that can be easily obtained through top-down isolation or bottom-up synthesis. The resulting edges of NRs/NWs/QWs produced with the proposed method are highly-aligned, atomically sharp, uniform, and flat since the fractures are generated by physical stress/strain and/or fatigue and/or creep instead of chemical etching employed by Kosynkin.

[0037] While the disclosure below presents a discussion involving only particularly identified material(s), for simplicity of illustration, it is understood – and it remains within the scope of the invention – that various 2D materials (such as, but not limited to, graphene, hBN, WS₂, WSe₂, MoTe₂, MoS₂, MoSe₂, perovskite, mica, Ti₄N₃; where the fracture strength of a given material is at least within a range from less than 0.05 GPa to about 100 GPa, see Table 1) can be treated with the used of the proposed approach to realize the above-identified goals.

[0038] Table 1:

Material	Fracture Strength (GPa)
Graphene	100
hBN	100
WS2	19
WSe2	16
MoTe2	12-18
MoS2	11-14
MoSe2	2.9-17
Perovskite	<0.05
Mica (Muscovite)	0.175
Mica (Phlogopite)	1

Non-limiting Examples of Apparatus and Method.

[0039] The idea of the invention is schematically illustrated in the not-to-scale FIGs. 1A, 1B, showing the process of generation of fracture(s) separating pieces of the once single-piece 2D pre-form 106 of a material disposed on the supporting deformable substrate 110. As known in the related art, the term (mechanical) stress refers to a physical quantity that describes forces present

during deformation of a material and the term strain identifies the deformation of the material from stress.

[0040] In practice, deformable substrates 110 were rinsed with water and isopropanol and N₂ blow-dried with N₂ before being pre-flattened by polished Si wafer (prime grade, University Wafer, Inc) under 90°C for 1 h. Then the substrates were treated with oxygen plasma for 10 sec (PlasmaTherm RIE, 50 mbar O₂, 50 W). Bulk crystals of layered 2D materials such as MoTe₂ and hBN were mechanically exfoliated with adhesive tape (Nitto Semiconductor Wafer Tape SWT10). The material-loaded tape was immediately applied to the corresponding deformable substrate and sandwiched with Si wafers and fixed with clamps. The tape was subsequently peeled off from the substrate after heating the whole setup for 10 min at 70°C in an oven and cooling it down to room temperature. The adhesive tape was repeatedly applied to the 2D material pre-forms and released to further thin them down, obtaining substantially monolayer-thick pre-forms 106A, 106B supported by corresponding substrate(s) 110.

[0041] In one specific case, once the exfoliation and positioning / support process was complete, an array of defects was created on the surface of a given 2D pre-form 106 using a controlled methodology. Various techniques were tried and successfully employed, such as laser/ion beam irradiation, nanoindentation, electron beam lithography, to name just a few. Each of these methods enables the precise placement and spatial arrangement of defects on the target 2D pre-form.

[0042] Upon the formation of the defect array(s) 108 on the 2D pre-form 106, the underlying substrate 110 was subjected to a precisely controlled strain or deformation by applying deformation forces causing stress(es) (in particular, but not necessarily limited to, a linear tensile stress and/or shear stress), either in a static or variable (non-static) and/or cycling (cyclical) manner. (When the applied stress(es) was varied cyclically, a given cycle of variation included a combination of an increase of the stress/strain and a decrease of the stress/strain.) As a result, fractures were initiated at the sites of the pre-designed defects, quickly propagating and aligning themselves into NRs/NWs/QWs 112 characterized by exceptional parallelism.

[0043] (The skilled person readily appreciates that, as 2D monolayer crystals are considered “all surface” materials, controlled stress/strain could be introduced to a monolayer-piece of MoTe₂

by stressing/straining a deformable substrate underneath, while the properties of the substrate play a role in effective stress/strain transfer to the MoTe₂. According to shear-lag analysis, it has been theoretically established and experimentally verified that interfacial stress/strain transfer efficiency has a positive correlation with the shear modulus of the substrate, which is determined by the Young's modulus and Poisson ratio. The Poisson ratio also factors into the calculation of the Grüneisen parameter. Substrates with high Young's moduli and strong adhesion allow the stress/strain to be effectively transferred to the 2D material on the surface of and/or embed into the substrate, thus enabling a higher range of stress/strain modulation.)

[0044] The spacing between the so-formed NRs/NWs/QWs 114A, 114B. Subsequently, to further enhance the spacing between the immediately neighboring NRs/NWs/QWs, a variable level of compressive and/or tensile stress/strain could and was applied to the substrate.

[0045] FIG. 2A illustrates schematically an embodiment 200 of a custom deformation apparatus judiciously structured to apply directionally-resolved uniaxial tensile stress/strain to a piece 206 of the 2D material – such as the monolayer 1H-MoTe₂ – carried by the PET substrate 110. In this specific embodiment, the apparatus 100 was designed to utilize a bending agent including a pin with a substantially hemispherical center contact (or, more generally, a pin with a contact surface that a profiled defined by a differentiable function; see 214, in inset of FIG. 2A) to induce bending of the relatively thick (~790 μm) substrate of the material 110. (It is understood, however – as mentioned below – that related implementations of the apparatus may utilize different deformation agents.) During the bending procedure, no non-uniform bending or deformation in the lateral direction perpendicular to the longitudinal strain direction of the PET substrate 110 was observed. FIG. 2B schematically illustrates – in a simplified cross-section view and not to scale – the 2D material sample during the application of uniaxial tensile stress/strain to the 1H-MoTe₂. (The scale of FIG. 2B is exaggerated to emphasize the very small ratio of dimensions of the monolayer of the 1H-MoTe₂ and PET). Due to the minuscule value of such ratio both in a lateral dimension (here, the ratio is $\sim 4 \times 10^{-4}$) and transversely (here, the ratio of thicknesses is $\sim 9 \times 10^{-7}$), the 1H-MoTe₂ layer 206 adhered to the surface of the PET substrate 110 is validly considered to be under uniaxial applied tensile strain when PET sheet 110 is bent, as the skilled artisan will readily appreciate.

[0046] Optionally, as the skilled person will recognize, the operation of such apparatus may be complemented at least with an appropriately designed optical system (not shown for the simplicity of illustration) that enables a real-time (as opposed to post factum) imaging of the sample 206 that is being subjected to stress/strain for characterization of the structural changes occurring in the sample 206 and/or controlled with the use of a processor (also not illustrated) that is programmed to not only perform the application of the strain to the sample 206 via operating the contact pin (or, generally, a pusher element) 214 substantially perpendicularly to a surface of the substrate 110 supporting the sample 206 but also the process of real-time collecting and/or processing at least the optical imaging data from the sample 206. (For the purposes of this disclosure and accompanying claims, a real-time performance of a system is understood as performance which is subject to operational deadlines from a given event to a system's response to that event. For example, a real-time extraction of optical information – such as optical image data – from the optical detection sub-system of an optical imaging system may be one triggered by the user or a computer and executed simultaneously with and without interruption of the process during which such optical information has been generated and/or acquired.)

Examples of characterization and Assessment.

[0047] FIGs. 6A, 6B illustrate the empirical results of patterning the deterministic fracture nucleation sites within a 2D pre-form of a chosen material via laser irradiation to guide fracture and NRs/NWs/QWs formation. Point defects in the 2D sample (seen as black dots) formed by a focused 532 nm laser beam generated highly-aligned and highly-uniform nanoribbons separated from one another by nanogaps, 610, each of which corresponds to a respective fracture nucleation site.

[0048] FIG. 7 presents a set of sequentially acquired (with the use of dark-field microscope) images illustrating the propagation of a given fracture through the 2D sample 206 subjected to at approximately 2% tensile strain (captured at 200 frames per second, fps). The crack initiates from the top edge (not in view of a given image) and propagates downwards, as shown, with a speed exceeding 300 mm/s, showcasing the dynamic fracture and highly-aligned NRs/NWs/QWs formation process. The arrow illustrates the length of the fracture at an indicated instance of time.

[0049] It is understood that, benefiting from the strong surface interaction between 1H-MoTe₂ pre-form 206 and the PET substrate 110, the uniaxial stress/strain applied to the (lower, as shown in the example of FIGs. 2A, 2B) surface of the substrate 110 was coherently transferred to 1H-MoTe₂ pre-form 206 during the mechanical loading process, up to the maximum applied stress/strain. As known in related art, the zigzag edge formation energy (~ 0.569 eV/A) for 1H-MoTe₂ is lower than that of formation energy of the armchair edges (~ 0.645 eV/A). Consequently, the so strained H-MoTe₂ monolayer pre-forms preferentially presented their edges along zigzag directions (FIGs. 3A, 3B). The person of ordinary skill in the art will readily appreciate that the mechanical loading direction can be finely controlled by taking advantage of this phenomenon (in this non-limiting example – by identifying the clean zigzag edges and ensuring that the uniaxial strain is applied strictly along either the armchair or the zigzag direction to study the directional dependence).

[0050] As discussed in Zhewen Yin et al. (Directionally-Resolved Phononic Properties of Monolayer 2D Molybdenum Ditelluride (MoTe₂) under uniaxial elastic strain, in Nano Lett. 2023, 23, 24, 11763-11770; available at <https://doi.org/10.1021/acs.nanolett.3c03706>, the entire contents of which are incorporated by reference herein), the uniaxial tensile stress/strain applied to the surface 1H-MoTe₂ monolayers was estimated by the maximum tensile stress/strain on the surface of the PET substrate, following the relation $\varepsilon = \kappa \cdot t/2$, where t is the thickness of the PET substrate (~ 0.79 mm) and κ (“kappa”) is the curvature of the localized region where the monolayer 1H-MoTe₂ was attached.

[0051] The applied tensile strain was also confirmed from top-view optical images via edge detection by tracking the lateral deformation of 1H-MoTe₂ monolayers (see Table 2). The applied strain quantified by either of the two measurements were nearly identical with a maximum deviation of $<0.2\%$ strain. The kappa-curvature analysis was used to measure the substrate curvature and calculate the applied uniaxial tensile strain based on side-view measurements. Pixel-height edge detection was used to measure the change in lateral dimensions of the monolayer 1H-MoTe₂ crystals from top-view bright field microscopy images. The bright field optical microscopy measurement of the top-view lateral dimensions was diffraction limited, and thus served as an auxiliary verification of the applied uniaxial tensile strain. Due to the extremely

minuscule ratio between the small lateral sizes (tens of microns) as well as atomic-thinness of the 1H-MoTe₂ monolayers relative to the large bending radius of curvature (dozens of millimeters) of the PET substrate, the difference between the length measured from the optical microscopy top-view (projected as a chord length, c) and the length calculated from the substrate curvature (arc length, L) was, understandably, negligible.

[0052] Table 2: Comparison of the uniaxial tensile strain through correlation of a photographic image (taken in side view) and that obtained with the use of the bright-field microscopy (top view):

Strain Increment	Side-view			Top-view	
	Curvature κ (μm^{-1})	Radius R (mm)	Strain $\varepsilon = \kappa \cdot t/2$	Flake length L (μm)	Strain $\varepsilon = \Delta L/L$
0	0.000000	∞	0.0000	46.7	0.0000
1	0.000010	97.56	0.0041	46.9	0.0043
2	0.000018	55.56	0.0072	47.0	0.0064
3	0.000025	40.00	0.0100	47.2	0.0106
4	0.000030	33.33	0.0120	47.3	0.0127
5	0.000036	27.78	0.0144	47.3	0.0127
6	0.000042	23.81	0.0168	47.4	0.0148
7	0.000048	20.83	0.0192	47.6	0.0189

[0053] In at least one specific implementation, *in situ* micro-Raman spectroscopy was additionally used to monitor the phononic response of monolayer 1H-MoTe₂ to varying uniaxial strains along distinct crystallographic directions. With no strain applied, a prominent Raman peak for the E_{2g}^1 mode at $\sim 231 \text{ cm}^{-1}$ was observed (FIG. 4A). Under progressively increasing

uniaxial strains up to 1.9% along the armchair direction, the E_{2g}^1 peak monotonically red-shifted with a rate of $-1.66 \pm 0.04 \text{ cm}^{-1}/\%$ (FIG. 4C). The lower Raman frequency concomitant with larger applied uniaxial strain was attributed to lattice expansion and decay into lower energy phonons. (Notably, at even higher applied strains, fracture occurs in some of the 1H-MoTe₂ monolayers, leading to the strain release reflected by an abrupt blue shift of the E_{2g}^1 peak (FIG. 5C).) When subjected to tensile strain along the zigzag direction, the E_{2g}^1 peak exhibited a comparatively more gradual red shift with a rate of about $-0.80 \pm 0.07 \text{ cm}^{-1}/\%$ (FIGs. 4B, 4D). The average initial E_{2g}^1 peak position for each of the measured samples was within the range of $230.82 \pm 0.13 \text{ cm}^{-1}$. A close agreement in the rate of red-shift can be seen among different monolayer samples screened (FIGs. 4C, 4D), despite small deviations in the initial E_{2g}^1 peak position. The strain-coupled phonon evolution in 1H-MoTe₂ along the zigzag direction was weaker as compared to that in the armchair direction, which is consistent with the directionally anisotropic phase energy landscape of MoTe₂ under uniaxial strain.

[0054] FIGs. 5A, 5B, 5C provide additional illustrations to the process of formation of a fracture in a 2D material (that leads to the formation of a substantially atomically smooth edge of the 2D material by illustrating non-coherent strain transfer between 1H-MoTe₂ 106 and the PET substrate 110 under excessive applied uniaxial tensile strains. Here, FIGs. 5A, 5B show optical images of the monolayer of 1H-MoTe₂ before and after the fracture (indicated in FIG. 5B) appears. FIG. 5C presents Raman spectra of a monolayer 1H-MoTe₂ sample acquired under progressively higher applied uniaxial tensile strain along the armchair direction (see FIG. 3A) of up to 2.2%. Excessive strain (>2%) leads to fracture of the 1H-MoTe₂ crystal with a concomitant blueshift of the E_{2g}^1 peak, thereby evidencing strain relief.

[0055] FIGs. 8A, 8B, 8C, and 8D illustrate the results of an experiment that resulted in formation of highly-aligned, atomically-thin 2D nanoribbons via mechanical fracturing and self-assembly in a few monolayer-thick of the 1T'-MoTe₂ material. Here, FIG. 8A presents dark-field optical microscopy images of the as-exfoliated few-layer sample 206 of 1T'-MoTe₂ prior to the application of strain (on the left) and the highly aligned 2D NRs/NWs/QWs and 2D NGs separating such NRs/NWs/QWs after the application of strain. FIG. 8B presents an AFM image of the

topography of the highly-aligned NRs/NWs/QWs and NGs array of FIG. 8A (on an enlarged scale), emphasizing the extreme high uniformity and atomically-sharp edges of the NRs/NWs/QWs. FIG. 8C presents histograms of the distribution of widths of 280 NRs/NWs/QWs sampled within the array of NRs/NWs/QWs of FIG. 8A. Here, over 34% of the nanoribbons have a width smaller than 500 nm. FIG. 8D presents Raman spectra of a typical NRs/NWs/QWs of FIG. 8A (upper curve), demonstrating the three characteristic 1T'-MoTe₂ Raman peaks and their corresponding phonon vibration modes, matching those in the pristine 1T'-MoTe₂ sample prior to structural fracturing (lower curve), demonstrating that the intrinsic material integrity and crystallinity is preserved. The in-plane B_g phonon mode centered around 163 cm⁻¹ exhibits a slightly decrease in intensity, indicating a strengthened edge effect due to the formation of discrete, highly-aligned NRs/NWs/QWs and NGs.

[0056] It is appreciated that the discussed methodology of the formation of the NRs/NWs/QWs of the chosen material can be applied to samples of various thicknesses. However, in order to form the NRs/NWs/QWs with nano-sizes, the outermost layer of the attended to sample, which is experiencing the highest degrees of strain, should be as close to being a monolayer sample as possible. FIG. 9 shows the dark-field optical microscopy image illustrating the influence of the thickness of the MoTe₂ sample on a typical width of a ribbon formed with the use of an embodiment of the invention. FIG. 9 presents the dark-field optical microscopy image of a sample with three specific areas A, B, and C having different material thicknesses: the thickness of area A is greater than 30 monolayers, the thickness of area B is about 5 to 10 monolayers, and the thickness of the area C is below 3 monolayers. Such difference in material thickness evidenced the differentiation of the apparent widths of the surfaces of the ribbons that were substantially simultaneously formed with the use of the embodiment of the invention: the width of the ribbons formed in the area A was about 20 microns, the widths of the ribbons formed in the area B ranged between about 1 and about 3 microns, while the widths of the ribbons formed in the area C was definitively below 1 microns (~ nanoribbons).

[0057] FIG. 10 evidences the large-scale high-level spatial uniformity of the NRs/NWs/QWs and nanogaps formed with the use of the embodiment of the invention. Specifically FIG. 10 illustrates the measurement data acquired with the use of the optical

microscope (OM), the atomic force microscope (AFM) and the scanning electron microscope (SEM) demonstrating the comparison of geometrical characteristics of the same NRs/NWs/QWs and gaps between the NRs/NWs/QWs along the more than a hundred-micron span of a few-monolayer-thick MoTe₂ sample 206. FIG. 11A presents optical images of the sample 206 (here, the hBN pre-form) before and after applying the cycling tensile strain that forms substantially periodic ribbons with widths of about 5 to 10 microns, while the substantially ideal geometrical characteristics of the edge of a couple of these material ribbons is shown in the AFM image of FIG. 11B.

[0058] Notably – and in stark contradistinction with the geometrical characteristics of typical nanoribbons produced with a templated growth method (see, for example, Jacobberger, R.M. et al., Nat. Comm, 2015; available at <https://doi.org/10.1038/ncomms9006>), in at least one embodiment of the invention, more than 100 nanoribbons or nanowires with lengths exceeding 120 microns were formed from a single “pre-form” (of at least one of the 2D materials having corresponding fracture strengths from less than 0.05 to about 100) while the width of the narrowest of such NRs/NWs/QWs was approximately 200 nm while the width of the widest of such ribbons/wires did not exceed about 5 microns. This demonstrated the capability of the proposed methodology to form nano-sized structured with aspect ratios at least from about 24:1 to those exceeding 600:1, and, as was observed, was practically limited only by the dimensions of the initial pre-form. In a related embodiment, the spread of such aspect ratios was between about 10:1 to about 1000:1.

[0059] The skilled artisan will readily appreciate that, while the idea of the invention is illustrated through the described examples of the specific embodiments, modifications to, and variations of, the illustrated embodiments may be made without departing from the inventive concepts disclosed herein. For example, in at least one specific case the substantially 2D crystal preform may be intentionally oriented on the supporting substrate such as to have a preferred or chosen crystallographic direction to be as perpendicular to the direction of tensile stress/strain, preferably, within an angular deviation of a micro-degree or even a nano-degree to ensure that the formed in the pre-form fracture propagates substantially along the preferred crystallographic direction.

[0060] Alternatively or in addition – as the skilled artisan would readily appreciate – the optional but preferred modification of the 2D pre-form may constitute a removal and/or modification of a surface layer(s) of the pre-form sample (exfoliation and/or etching of the pre-form; preferably – from the upper and lower surface) prior to subjecting the pre-form to the deformation. The high-speed camera observations indicated that the fractures in the pre-form originate at the locations of the externally formed defects (see FIGs. 6A, 6B, 7) or, in the absence of the externally-introduced defects – from the existing defects and/or heterogeneities such as those associated with the corners and/or edges and/or asperities and/or other sources of stress/strain concentration of 2D preform. Such spatial localization of the origins of the desired fractures complicates the production of homogeneous nanoribbons from naturally exfoliated and/or artificially synthesized 2D pre-forms (see FIG. 12A) To address this issue, a modified edge possessing to reduce roughness can be formed (for example, via plasma treatment of the 2D pre-form) so that the existing and/or applied stress/strain can distribute more evenly inside the pre-form. In one implementation, the top edge of a 1T'-MoTe₂ pre-form was exposed to argon plasma and then to the application of the tensile stress/strain ("bending") as discussed above. However, the spatial distribution of the width values of the resulting nanoribbons did not significantly improve (FIG. 12B) because the bottom edge of the pre-form still remained rougher than the top one, thereby dominating the fracture initiation and propagation. When both the top and bottom surfaces of the pre-form were similarly plasma-treated, however, roughness of both upper and lower edges of the pre-form was similarly reduced (FIG. 12C), leading to formation of highly homogeneous NRs/NWs/QWs with widths as small as 100 nm or smaller (as confirmed by the AFM measurement, FIGs. 12C, 12D). These ribbons were over 40 μm long, yielding an aspect ratio exceeding 400:1, which value was limited only by the length of the parental 2D pre-form, and which can be substantially increased by improving the exfoliation and/or synthesis technique. Optical images and characterization data acquired with the use of Raman spectroscopy (FIG. 12F) revealed that, as a result of the plasma treatment, the underlying layer 1210 of the initial 1T'-MoTe₂ pre-form was exposed, neighbored by a transitional region 1220 that may contain some debris of Mo and/or Te and/or their plasma reaction by-products, while the untreated surface 1230 1T'-MoTe₂ retained its original properties. The so treated 2D pre-form demonstrates reduced resistance

to fracturing and enables the formation of fractures with higher spatial density (as compared with the untreated 2D pre-form) and, therefore, the formation of NRs/NWs/QWs with narrower and/or more uniform widths.

[0061] Similarly, while the discussion of the “sample bending” (sample deforming) apparatus was presented above in reference to FIG. 2A showing a very particular arrangement, the skilled person appreciates that, in the alternative, the bending of the substrate 110 carrying the sample 206 can be performed differently (for example, utilizing a 3-point bend setup or a 4-point bend setup) or employing a different deformation agent (such as a flow of fluid or the use of differential of pressure applied to which the upper and the lower surfaces of the supporting substrate are exposed, or the use of magnetic actuation of bending, or actuation with the use of an electrical signal, or the use of thermal expansion mismatch, or the use of acoustic pressure/waves, or the use of radiation (electromagnetic or particle) pressure). Optionally, a combination of several of such deformation agents can be employed to carry out the deformation of the substrate via pulling, ballooning, thermal expansion mismatch, electromagnetic actuation, magnetic actuation, pressure differential, etc.

[0062] Moreover, in a specific case the supporting substrate may be represented by a portion of a bulk of the substantially the same and/or similar and/or dissimilar crystal material as that of the 2D pre-form. In such a case, the substrate made of the material of choice is subjected to the tensile stress/strain as discussed above while the identified upper substantially 2D layer of such crystal experiences the formation and propagation of fracture(s) and “splitting” into substantially 2D nanostructures, as discussed. All these modifications remain within the scope of the invention. Understandably, generally the supporting substrate does not necessarily need to be secured in the sample deforming apparatus at two opposing ends: in the alternative, the substrate may be secured only at one end, leaving the opposite end free.

[0063] References throughout this specification to “one embodiment,” “an embodiment,” “a related embodiment,” or similar language mean that a particular feature, structure, or characteristic described in connection with the referred to “embodiment” is included in at least one embodiment of the present invention. Thus, appearances of the phrases “in one embodiment,” “in an embodiment,” and similar language throughout this specification may, but do not necessarily, all refer to the same

embodiment. It is to be understood that no portion of disclosure, taken on its own and in possible connection with a figure, is intended to provide a complete description of all features of the invention.

[0064] The term "image" as used herein generally refers to an ordered representation of detector output corresponding to spatial positions. For example, a visual image may be formed, in response to a pattern of light detected by an optical detector, on a display device X such as a video screen or printer. The term "A and/or B" is defined to be equivalent to the term "at least one of A and B".

[0065] For the purposes of this disclosure and the appended claims, the use of the terms "substantially", "approximately", "about" and similar terms in reference to a descriptor of a value, element, property or characteristic at hand is intended to emphasize that the value, element, property, or characteristic referred to, while not necessarily being exactly as stated, would nevertheless be considered, for practical purposes, as stated by a person of skill in the art. These terms, as applied to a specified characteristic or quality descriptor means "mostly", "mainly", "considerably", "by and large", "essentially", "to great or significant extent", "largely but not necessarily wholly the same" such as to reasonably denote language of approximation and describe the specified characteristic or descriptor so that its scope would be understood by a person of ordinary skill in the art. In one specific case, the terms "approximately", "substantially", and "about", when used in reference to a numerical value, represent a range of plus or minus 20% with respect to the specified value, more preferably plus or minus 10%, even more preferably plus or minus 5%, most preferably plus or minus 2% with respect to the specified value. As a non-limiting example, two values being "substantially equal" to one another implies that the difference between the two values may be within the range of +/- 20% of the value itself, preferably within the +/- 10% range of the value itself, more preferably within the range of +/- 5% of the value itself, and even more preferably within the range of +/- 2% or less of the value itself. The use of these terms in describing a chosen characteristic or concept neither implies nor provides any basis for indefiniteness and for adding a numerical limitation to the specified characteristic or descriptor. As understood by a skilled artisan, the practical deviation of the exact value or characteristic of such value, element, or property from that stated falls and may vary within a numerical range defined by

an experimental measurement error that is typical when using a measurement method accepted in the art for such purposes.

[0066] The use of these terms in describing a chosen characteristic or concept neither implies nor provides any basis for indefiniteness and for adding a numerical limitation to the specified characteristic or descriptor. As understood by a skilled artisan, the practical deviation of the exact value or characteristic of such value, element, or property from that stated falls and may vary within a numerical range defined by an experimental measurement error that is typical when using a measurement method accepted in the art for such purposes.

[0067] The present invention may be embodied in different forms such as a system, method, or computer program product. For example, those skilled in the art should readily appreciate that functions, operations, decisions, etc. of all or a portion of a method of the invention may be implemented as computer program instructions, software, hardware, firmware or combinations thereof. Those skilled in the art should also readily appreciate that instructions or programs defining the functions of the present invention may be delivered to a processor (of the system implementing the method) in many forms, including, but not limited to, information permanently stored on non-writable storage media (e.g. read-only memory devices within a computer, such as ROM, or devices readable by a computer I/O attachment, such as CD-ROM or DVD disks), information alterably stored on writable storage media (for example, floppy disks, removable flash memory and hard drives) or information conveyed to a computer through communication media, including wired or wireless computer networks.

[0068] In addition, while the invention may be embodied in software, the functions necessary to implement the invention may optionally or alternatively be embodied in part or in whole using firmware and/or hardware components (such as combinatorial logic, Application Specific Integrated Circuits or ASICs, Field-Programmable Gate Arrays or FPGAs, or other hardware or some combination of hardware, software and/or firmware components), and may include a specific electronic circuitry or a processor controlled by instructions stored in a tangible, non-transient memory medium. The computer-usable or computer-readable medium may be, for example, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. For example, computer-usable or computer-readable

medium may include a tangible non-transitory storage medium, such as, without limitation, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a compact disc read-only memory (CDROM), and/or an optical storage memory medium, or any other memory, or combination thereof, suitable for storing control software or other instructions and data. The computer-usable or computer-readable medium may comprise and/or be complemented with an apparatus that contains, stores, communicates, propagates, or transports program code for use by or in connection with the instruction execution system, apparatus, or device. The computer program product may comprise program code stored in a computer readable medium that, when executed on a computing device, causes the computing device to perform and/or govern one or more of the processes described herein. The computer program product can be written in any conventional programming language (such as, in one example, C++) or the like.

[0069] Accordingly, embodiments of the invention may be configured in the form of a computer implemented method for generation of nanoribbons and/or nanowires and/or quantum wires of a chosen material. Such method includes a step of operating, with the computer, a driver to activate a deforming agent that is configured to change a shape of a deformable substrate upon interacting therewith (here, the deformable substrate carries a substantially 2D sample of the chosen material adhered thereto and/or embedded therein). The method additionally includes a step of initiating, with the computer, a process of application of a variable deformation force to a deformable substrate (amounting, in one non-limiting case, to a tensile stress in such substrate) to generate a physical fracture in the substantially 2D sample of the material. The method additionally includes a step of changing, with the computer, a value of a variable stress caused by the deforming agent in the deformable substrate to separate first and second pieces of the substantially 2D sample from one another with a gap while, at the same time, forming edges of the first and second pieces to be substantially atomically sharp and substantially linear. In at least one specific implementation of such method, the deforming agent may include an element that is repositionable, with the use of a driver, substantially transversely to the deformable substrate. Additionally or in the alternative, and substantially in every embodiment, the computer implemented method may additionally include a step of identifying, with the computer, geometrical characteristics of the first

and second pieces to define whether at least one of the first and second pieces represents a nanoribbon or nanowire or quantum wire and/or whether a gap longitudinally separating the first and second pieces from one another on the flexible substrate has a nano-sized or angstrom-sized width. Furthermore, and substantially in every implementation, the method may additionally include (1) a step of operating, with the computer, a measurement apparatus operably connected with the substantially 2D sample of the chosen material to determine at least one of a length and an aspect ratio of geometrical dimensions of at least one of the first and second pieces and a crevice between the first and second pieces; and/or (2) steps of storing in a database, with the computer, each parameter characterizing the first and second pieces as determined by the computer, and tracing, by the computer, that each of the stored parameters can be used by at least one external user. Additionally, embodiments of the invention provide an article of manufacture that comprises a non-transitory computer readable medium include computer readable program code disposed therein for communicating between a physical system configured to cause stress in a chosen object and at least an object holder configured to restrain the chosen object therein, such computer readable program code comprising a series of computer readable program steps which, upon execution effect substantially every embodiment of the above-identified computer implemented method.

[0070] Disclosed aspects, or portions of these aspects, may be combined in ways not listed above. Accordingly, the invention should not be viewed as being limited to the disclosed embodiment(s).

CLAIMS

What is claimed is:

1. **An article of manufacture** comprising:
 - a sample-holder dimensioned to secure a deformable substrate;
 - a substrate-deforming agent configured to be actuated with a driver and to generate a variable deformation force applied to the deformable substrate such as to cause a variable deformation or strain in the deformable substrate;
 - and
 - a controller operably coupled with at least one of the sample-holder and the driver and configured to acquire data representing structural changes in a two-dimensional (2D) material sample that is adhered to a second surface of the deformable substrate, wherein the structural changes have been caused by the controller via application of the variable deformation force to the substrate with the substrate-deforming agent.
2. An article of manufacture according to claim 1, wherein the substrate-deforming agent includes at least one of:
 - (2A) a pusher element configured to be repositionable, with the use of the driver, substantially transversely to a plane of the deformable substrate secured in the sample holder;
 - (2B) a flow of fluid directed transversely to a surface of the substrate; and
 - (2B) a difference between a first pressure at a first point and a second pressure at a second point separated from the first point by the deformable substrate secured in the sample holder;
3. An article of manufacture according to one of claims 1 and 2,
 - wherein the article of manufacture is configured to generate said structural change represented by physical fractures across the 2D material sample at a first level of a variable stress in the substrate and, upon increase of the variable stress to a second level exceeding the first level, by longitudinally separated from one another strips of a material of the sample formed along the physical fractures,

wherein each strip has a substantially atomically-sharp edges and substantially uniform width at least when the 2D material sample has a substantially monolayer thickness.

4. An article of manufacture according to one of claims 1 to 3, configured to create longitudinal gaps separating said strips of material from one another and having sub-micron widths at least when the 2D material sample has a substantially monolayer thickness.

5. An article of manufacture according to one of claims 1 to 4, wherein the controller includes at least one of (i) a measurement apparatus configured to acquire real time measurement data representing said structural changes and/or a dependency of the structural changes on at least one characteristic of the operation the article of manufacture, and (ii) a processor governed by instructions stored in a tangible, non-transient memory medium to operate the driver and/or the measurement apparatus.

6. An article of manufacture according to one of claims 1 to 5, wherein the controller includes an optical imaging system configured to acquire images representing said structural changes.

7. An article of manufacture according to one of claims 1 to 6, wherein, when the deforming agent includes a pusher element repositionable substantially transversely to the substrate, the pusher element has a tip with a surface profile defined by a differentiable function.

8. A method comprising:

with the use of an article of manufacture according to one of claims 1 to 7,

securing, in the sample holder, a deformable supporting substrate with a 2D sample of material located a chosen layer of the substrate;

applying a variable deformation force to the substrate to stress the substrate and to form a physical fracture in the 2D sample;

increasing a variable stress in the 2D sample to separate the 2D sample into nanoribbons and/or nanowires and/or quantum wires along the physical fracture, wherein the nanoribbons and/or

nanowires and/or quantum wires possess substantially atomically-sharp and substantially linear edges that are substantially parallel to one another, and wherein immediately neighboring nanoribbons and/or nanowires and/or quantum wires are longitudinally separated from one another with a nanogap having a substantially constant width along a length thereof.

9. A method according to claim 8, comprising:
prior to the securing,
(9A) forming at least one defect on a surface of the 2D sample; or
(9B) removing material from at least one surface an edge of the 2D sample
to define, during said applying, a location of the physical fracture.
10. A method according to one of claims 8 and 9, comprising:
prior to the applying the variable deformation force, forming a substantially linear array of multiple defects on a surface of the 2D sample to define, during said applying, the orientation of multiple physical fractures to be transverse to an axis of the substantially linear array.
11. A method according to one of claims 8 to 10, further comprising:
transferring at least some of the nanoribbons and/or nanowires and/or quantum wires from the deformable supporting substrate to a different substrate substantially without changing mutual position and/or orientation of the nanoribbons and/or nanowires and/or quantum wires.
12. A method according to one of claims 8 to 11, configured to produce said nanoribbons and/or nanowires and/or quantum wires in the 2D sample of a material, chosen from materials with corresponding fracture strengths at least within a range from about 0.05 to about 100.
13. A method according to one of claims 8 to 12, configured to produce said nanoribbon or nanowires or quantum wires with an aspect ratio value within a range from about 10:1 to about 1000:1.

14. A method comprising:
- forming at least one fracture in a sample of a material that has a thickness that is substantially equal to a thickness of a monolayer of said material by applying a variable deformation to a tangible surface spatially separated from the sample;
- and
- spatially separating from one another strips of the sample, dimensioned as nanoribbons and/or nanowires and/or quantum wires and having substantially atomically sharp and uniform edges, along the at least one physical fracture by continuing to apply the variable deformation force, wherein a gap separating immediately neighboring each other nanoribbons and/or nanowires and/or quantum wires has a substantially longitudinally uniform sub-micron width.
15. A method according to claim 14, wherein said applying a variable deformation force includes:
- increasing a level of a tensile stress in the sample substantially monotonically to a level exceeding a fracture limit of the sample; and/or
- applying the variable deformation force for a duration of time sufficient for a stress formed in the sample to exceed a creep limit of the sample; and/or
- repetitively forming tensile stress and/or compressive stress in the sample to cause cyclic fatigue of said sample.
16. A method according to one of claims 14 and 15, wherein each of the forming and spatially separating does not include the use of light and/or wherein said nanoribbons and/or nanowires and/or quantum ribbons have substantially longitudinally uniform widths.
17. A method according to one of claims 14 to 16, wherein a length, of at least one of the gap and nanoribbons and/or nanowires and/or quantum wires separated by the gap, along which the gap and the nanoribbons and/or nanowires and/or quantum wires maintain corresponding widths to be substantially constant, exceeds a width of a nanoribbon and/or nanowire and/or quantum wire by at least one order of magnitude.

18. A method according to one of claims 14 to 16, wherein a length, of at least one of the gap and nanoribbons and/or nanowires and/or quantum wire separated by the gap, along which the gap and the nanoribbons and/or nanowires and/or quantum wire maintain corresponding widths to be substantially constant, exceeds a width of a nanoribbon and/or nanowire and/or quantum wire by at least two orders of magnitude.
19. A method according to one of claims 14 to 18, further comprising: defining a location of the at least one fracture by forming a surface and/or subsurface defect on the sample.
20. A method according to one of claim 14 to 19, which, when the at least one fracture includes multiple fractures, comprises:
- defining both locations and orientations of said multiple fractures in the sample by forming an array of surface and/or subsurface defects on the sample or by removing material from at least one surface an edge of the 2D sample
 - to define, during said applying, a location of the physical fracture.
21. Use of variable deformation force, applied to a deformable substrate supporting a substantially 2D material adhered thereto and/or embedded therein, to form
- (a) an array of nanoribbons and/or nanowires and/or quantum wires having substantially atomically sharp and substantially linear edges, and/or
 - (b) an array of gaps in said 2D material characterized by nano-sized or angstrom-sized widths.
22. Use according to claim 21, causing a formation of said array of nanoribbons and/or nanowires and/or quantum wires with aspect ratios within a range from about 10:1 to about 1000:1.

23. A computer implemented method for generation of nanoribbons and/or nanowires and/or quantum wires of a chosen material, the method comprising:

operating, with the computer, a driver to activate a deforming agent configured to change a shape of a deformable substrate upon interacting therewith, wherein the deformable substrate carries a substantially 2D sample of the chosen material adhered thereto and/or embedded therein;

initiating, with the computer, a process of application of variable deformation force to the deformable substrate to generate a physical fracture in the substantially 2D sample of the material;

changing, with the computer, a value of a variable stress caused by the deforming agent in the deformable substrate to separate first and second pieces of the substantially 2D sample of the chosen material from one another by a gap while forming edges of said first and second pieces to be substantially atomically sharp and substantially linear.

24. A computer implemented method according to claim 23, wherein the bending agent includes an element repositionable, with the use of a driver, substantially transversely to said deformable substrate.

25. A computer implemented method according to one of claims 23 and 24, further comprising: identifying, with the computer, geometrical characteristics of the first and second pieces to define whether at least one of the first and second pieces represents a nanoribbon or nanowire or quantum wire and/or whether a gap longitudinally separating the first and second pieces from one another on the flexible substrate has a nano-sized or angstrom-sized width.

26. A computer implemented method according to one of claims 23 to 25, further comprising:

operating, with the computer, a measurement apparatus operably connected with the substantially 2D sample of the chosen material to determine at least one of a length and an aspect

ratio of geometrical dimensions of at least one of the first and second pieces and a crevice between the first and second pieces.

27. A computer implemented method according to one of claims 23 to 26, further comprising:

storing in a database, with the computer, each parameter characterizing the first and second pieces as determined by the computer,

and

tracing, by the computer, that each of the stored parameters can be used by at least one external user.

28. An article of manufacture comprising a non-transitory computer readable medium include computer readable program code disposed therein for communicating between a physical system configured to cause stress in a chosen object and at least an object holder configured to restrain said chosen object therein, the computer readable program code comprising a series of computer readable program steps which, upon execution effect the method according to one of claims 23 to 27.