COMPUTER SYSTEM AND METHOD FOR MANUFACTURING A GERMANIUM MEMBRANE

FIELD

[0001] The improvements generally relate to germanium membranes and more specifically to computer-implemented methods and systems for manufacturing of such membranes.

BACKGROUND

[0002] Free-standing single crystal germanium (Ge) membranes have recently gained increasing interest for various applications including infrared waveguides, photodetectors, lasers, biosensors, flexible optoelectronic devices, lightweight solar cells (e.g., high efficiency III-V solar cells), to name only a few example applications. In the latter case, for instance, the widespread use of germanium-based solar cells in both terrestrial and space applications is generally hindered by the weight and cost of bulk germanium substrates. The use of thin germanium membranes as substrates for these devices can thus offer a suitable solution as the resulting device can be detached from a parent germanium substrate and then transferred to a light and low-cost holder. Moreover, once detached, the parent germanium substrate can be reconditioned and reused, thus lowering the overall manufacturing costs.

[0003] There have been some attempts at producing thin germanium membranes that are detachable from their corresponding parent germanium substrates. For instance, Abderraouf *et al.* (see "*Mesoporous germanium morphology transformation for lift-off process and substrate re-use*." Applied Physics Letters 102.1 (2013)) investigated the morphology of electrochemically formed mesoporous Ge double-layer and its transformations during ultra-high-vacuum annealing at 600–700 °C. The transformation process reorganized pores of the bottom porous Ge layer into faceted spherical voids, which could then be broken to allow for detachment of the upper porous Ge layer. Moreover, PCT Publication No. WO 2022/170431 A1 disclosed a process in which two non-porous Ge layers would be deposited at different temperatures on a porous Ge layer. During the annealing, it was demonstrated that the porous Ge layer would undergo significant morphological changes that would allow the detachment of the non-porous Ge layers from the Ge substrate and the formation of the Ge membrane. Although the existing processes for manufacturing thin

germanium membranes were satisfactory to a certain degree, there still remains room for improvement. For example, there remains room for improvement in ensuring that the thin germanium membranes are sufficiently coupled to the parent substrates to avoid self-detachment, but also not too strongly coupled thereto to hinder their timely detachment without breaking. As such, there is thus a need in controlling the degree of attachment of the thin germanium membranes to the parent substrate.

SUMMARY

[0004] Several techniques for manufacturing thin germanium membranes exist including epitaxial lift-off, smart-cut technology, controlled spalling, nanopatterned 2D materials, germanium on nothing, and porous layer lift-off. The latter technique involves the use of porous germanium layers (can also be referred to as “PGe layers”) produced by low-cost and wafer-scalable electrochemical etching techniques as templates for epitaxial structure deposition. The weak porous interface created between the germanium membrane (can also be referred to as “the membrane”) and the corresponding bulk germanium substrate (can also be referred to as “the substrate”) is then used as a facilitator for the detachment of the membrane from the substrate.

[0005] Although a few demonstrations of this approach have been made and high-material quality of the membrane has been demonstrated, it was found that there are challenges stemming from the variability of the coupling strength with which the membrane is mechanically coupled to the substrate. It was found that modifying one or more of the manufacturing parameters can, in turn, modify the resulting coupling strength. There is thus provided a method and system which can, based on a desired coupling strength, determine the right set of manufacturing parameters which will lead to membranes coupled to their respective substrates by the desired coupling strength. The control of such coupling strength can be highly desirable as the coupling strength needs to be strong enough to survive the device processing, and avoid any undesirable auto-attachment, but weak enough to enable a high-yield timely detachment process without breaking said membrane.

[0006] In accordance with a first aspect of the present disclosure, there is provided a method of manufacturing a germanium membrane on a germanium substrate, the method

comprising: selecting a coupling strength indicator, the coupling strength indicator indicative of a force which when applied to the germanium membrane uncouples the germanium membrane from the germanium substrate; determining a set of manufacturing parameters based on the coupling strength indicator using reference data associating a plurality of reference sets of manufacturing parameters with corresponding reference coupling strength indicators, the set of manufacturing parameters including at least a first deposition temperature and a second deposition temperature higher than the first deposition temperature; and manufacturing the germanium membrane on the germanium substrate based on the set of manufacturing parameters, said manufacturing including: at the first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate; and at the second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers.

[0007] In accordance with a second aspect of the present disclosure, there is provided a system for manufacturing a germanium membrane on a germanium substrate, the system comprising: a computer receiving a coupling strength indicator, the coupling strength indicator indicative of a force which when applied to the germanium membrane uncouples the germanium membrane from the germanium substrate; the computer determining a set of manufacturing parameters based on the coupling strength indicator using reference data associating a plurality of reference sets of manufacturing parameters with corresponding reference coupling strength indicators, the set of manufacturing parameters including at least a first deposition temperature and a second deposition temperature higher than the first deposition temperature; a manufacturing device communicatively coupled to the computer, the manufacturing device configured for manufacturing the germanium membrane on the germanium substrate based on the set of manufacturing parameters, said manufacturing including: at the first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate; and at the second deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers; and an uncoupling device communicatively coupled to the computer, said uncoupling device configured for applying an uncoupling force to the germanium membrane, the uncoupling force greater than

the force of the coupling strength indicator, thereby uncoupling the germanium membrane from the germanium substrate.

[0008] In accordance with a third aspect of the present disclosure, there is provided a method of manufacturing a germanium membrane on a germanium substrate, the method comprising: at a first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate; at a second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers; and after said depositing the first non-porous layer and said depositing the second non-porous layer, heating the first and second non-porous layers of germanium and the germanium substrate up to a first annealing temperature for a first period of time, the first annealing temperature greater than the first and second deposition temperatures.

[0009] In accordance with a fourth aspect of the present disclosure, there is provided a method of manufacturing a germanium membrane on a germanium substrate, the method comprising: at a first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate, said depositing the first non-porous layer closing pores of the porous layer, thereby trapping a volume of void within the porous layer, while maintaining an original structure of the pores; at a second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers; and modifying the original structure of the pores by heating the first and second non-porous layers and the germanium substrate to a given temperature for a given period of time, said modifying including reorganizing the pores into a plurality of larger cavities interspersed with a plurality of pillars extending between the germanium substrate and the first non-porous layer, the plurality of pillars having a pillar surface coverage Cps ranging between 1 % and 35 %, the pillar surface coverage given by: $Cps = \frac{\sum_{i=1}^{N} Ap_i}{Am} = Dp \cdot Ap_{avg}$, wherein Ap_i denotes a cross-sectional area of an ith pillar, N denotes a total number of pillars, Am denotes a total area of the germanium membrane, Dp denotes a pillar density, and Ap_{avg} denotes an average pillar cross-sectional area.

[0010] In accordance with the fifth aspect of the present disclosure, there is provided a method of manufacturing a semiconductor membrane on a semiconductor substrate, the method comprising: selecting a coupling strength indicator, the coupling strength indicator indicative of a force which when applied to the semiconductor membrane uncouples the semiconductor membrane from the semiconductor substrate; determining a set of manufacturing parameters based on the coupling strength indicator using reference data associating a plurality of reference sets of manufacturing parameters with corresponding reference coupling strength indicators, the set of manufacturing parameters including at least a first deposition temperature and a second deposition temperature higher than the first deposition temperature; and manufacturing the semiconductor membrane on the semiconductor substrate based on the set of manufacturing parameters, said manufacturing including: at the first deposition temperature, depositing a first non-porous layer of semiconductor material onto a porous layer of the semiconductor substrate; and at the second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of semiconductor material onto the first non-porous layer, the semiconductor membrane having the first and second non-porous layers.

[0011] Further in accordance with the fifth aspect of the present disclosure, the method further comprising applying an uncoupling force to the semiconductor membrane, the uncoupling force greater than the force of the coupling strength indicator, thereby obtaining an uncoupled semiconductor membrane and a semiconductor substrate having a detachment surface.

[0012] Still further in accordance with the fifth aspect of the present disclosure, the method further comprising cleaning the detachment surface of the semiconductor substrate, making another porous layer in the semiconductor substrate, and manufacturing a second semiconductor membrane on the semiconductor substrate.

[0013] Still further in accordance with the fifth aspect of the present disclosure, when the coupling strength indicator is indicative of a weak coupling, the first deposition temperature is set between 275°C and 325°C, and when the coupling strength indicator is indicative of a strong coupling, the first deposition temperature is set between 350°C and 400°C.

[0014] Still further in accordance with the fifth aspect of the present disclosure, when the coupling strength indicator is indicative of a weak coupling, the second deposition temperature is set between 525°C and 575°C, and when the coupling strength indicator is indicative of a strong coupling, the second deposition temperature is set between 425°C and 475°C.

[0015] Still further in accordance with the fifth aspect of the present disclosure, the set of manufacturing parameters has a first annealing temperature, said manufacturing including, after said depositing the second non-porous layer, heating the first and second non-porous layers and the semiconductor substrate up to the first annealing temperature for a given period of time preferably ranging between 45 minutes and 75 minutes.

[0016] Still further in accordance with the fifth aspect of the present disclosure, when said coupling strength indicator is indicative of a weak coupling, the first annealing temperature is set between 500°C and 725°C, and when said coupling strength indicator is indicative of a strong coupling, the first annealing temperature is set between 775°C and 850°C.

[0017] Still further in accordance with the fifth aspect of the present disclosure, the set of manufacturing parameters has at least one of an initial porous layer thickness and an initial porous layer porosity, said manufacturing including, prior to said depositing the first non-porous layer, making the porous layer in the semiconductor substrate based on the at least one of the initial porous layer thickness and the initial porous layer porosity.

[0018] Still further in accordance with the fifth aspect of the present disclosure, when the coupling strength indicator is indicative of a weak coupling, the initial porous layer thickness is set between 250 nm and 400 nm, and when the coupling strength indicator is indicative of a strong coupling, the initial porous layer thickness is set between 100 nm and 200 nm.

[0019] Still further in accordance with the fifth aspect of the present disclosure, when the coupling strength indicator is indicative of a weak coupling, the initial porous layer porosity ranges between 50% and 60%, and when the coupling strength indicator is indicative of a strong coupling, the initial porous layer porosity ranges between 20% and 50%.

[0020] Still further in accordance with the fifth aspect of the present disclosure, said steps of depositing form a plurality of pillars extending within the porous layer of the semiconductor

substrate, said selecting the coupling strength indicator including selecting at least one of a pillar dimension value indicative of an average pillar dimension, a pillar height value indicative of an average pillar height, and a pillar density value indicative of a pillar density.

[0021] In accordance with a sixth aspect of the present disclosure, there is provided a system for manufacturing a semiconductor membrane on a semiconductor substrate, the system comprising: a computer receiving a coupling strength indicator, the coupling strength indicator indicative of a force which when applied to the semiconductor membrane uncouples the semiconductor membrane from the semiconductor substrate; the computer determining a set of manufacturing parameters based on the coupling strength indicator using reference data associating a plurality of reference sets of manufacturing parameters with corresponding reference coupling strength indicators, the set of manufacturing parameters including at least a first deposition temperature and a second deposition temperature higher than the first deposition temperature; a manufacturing device communicatively coupled to the computer, the manufacturing device configured for manufacturing the semiconductor membrane on the semiconductor substrate based on the set of manufacturing parameters, said manufacturing including: at the first deposition temperature, depositing a first non-porous layer of semiconductor material onto a porous layer of the semiconductor substrate; and at the second deposition temperature, depositing a second non-porous layer of semiconductor material onto the first non-porous layer, the semiconductor membrane having the first and second non-porous layers; and an uncoupling device communicatively coupled to the computer, said uncoupling device configured for applying an uncoupling force to the semiconductor membrane, the uncoupling force greater than the force of the coupling strength indicator, thereby uncoupling the semiconductor membrane from the semiconductor substrate.

[0022] Further in accordance with the sixth aspect of the present disclosure, the uncoupling device is configured for pulling the semiconductor membrane from the semiconductor substrate.

[0023] Still further in accordance with the sixth aspect of the present disclosure, the reference data are stored on a non-transitory computer readable memory accessible to the computer.

[0024] In accordance with a seventh aspect of the present disclosure, there is provided a method of manufacturing a semiconductor membrane on a semiconductor substrate, the method comprising: at a first deposition temperature, depositing a first non-porous layer of semiconductor material onto a porous layer of the semiconductor substrate; at a second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of semiconductor material onto the first non-porous layer, the semiconductor membrane having the first and second non-porous layers; and after said depositing the first non-porous layer and said depositing the second non-porous layer, heating the first and second non-porous layers of semiconductor material and the semiconductor substrate up to a first annealing temperature for a first period of time, the first annealing temperature greater than the first and second deposition temperatures.

[0025] Further in accordance with the seventh aspect of the present disclosure, the first annealing temperature ranges between 500°C and 725°C.

[0026] Still further in accordance with the seventh aspect of the present disclosure, the porous layer has a porosity ranging between 50% and 55% and a thickness ranging between 300 nm and 400 nm.

[0027] Still further in accordance with the seventh aspect of the present disclosure, the first annealing temperature ranges between 775°C and 850°C.

[0028] Still further in accordance with the seventh aspect of the present disclosure, the porous layer has a porosity ranging between 50% and 55% and a thickness ranging between 200 nm and 300 nm.

[0029] Still further in accordance with the seventh aspect of the present disclosure, the first annealing temperature ranges between 650°C and 750°C, the first period of time ranges between 45 minutes and 75 minutes, the porous layer having a porosity ranging between 50% and 55%, the porous layer having a thickness ranging between 200 nm and 300 nm.

[0030] In accordance with an eighth aspect of the present disclosure, there is provided a method of manufacturing a semiconductor membrane on a semiconductor substrate, the method comprising: at a first deposition temperature, depositing a first non-porous layer of

semiconductor material onto a porous layer of the semiconductor substrate, said depositing the first non-porous layer closing pores of the porous layer, thereby trapping a volume of void within the porous layer, while maintaining an original structure of the pores; at a second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of semiconductor material onto the first non-porous layer, the semiconductor membrane having the first and second non-porous layers; and modifying the original structure of the pores by heating the semiconductor substrate to a given temperature for a given period of time, said modifying including reorganizing the pores into a plurality of larger cavities interspersed with a plurality of pillars extending between the semiconductor substrate and the first non-porous layer, the plurality of pillars having a pillar surface coverage Cps ranging between 1 % and 35 %, the pillar surface coverage given by: $Cps = \frac{\sum_{i=1}^{N} Ap_i}{Am} = Dp \cdot Ap_{avg}$, wherein Ap_i denotes a cross-sectional area of an ith pillar, N denotes a total number of pillars, Am denotes a total area of the semiconductor membrane, Dp denotes a pillar density, and Ap_{avg} denotes an average pillar cross-sectional area.

[0031] Further in accordance with the eighth aspect of the present disclosure, the semiconductor membrane is coupled to the semiconductor substrate with a coupling strength ranging between 0.25 MPa and 4.5 MPa.

[0032] Still further in accordance with the eighth aspect of the present disclosure, the pillar surface coverage ranges between 1% and 5%, the coupling strength ranging between 0.25 MPa and 0.75 MPa.

[0033] Still further in accordance with the eighth aspect of the present disclosure, the porous layer has a thickness ranging between 300 nm and 500 nm.

[0034] Still further in accordance with the eighth aspect of the present disclosure, the porous layer has a porosity ranging between 50% and 60%.

[0035] Still further in accordance with the eighth aspect of the present disclosure, the pillar surface coverage ranges between 5% and 15%, the coupling strength ranging between 0.75 MPa and 2.25 MPa.

[0036] Still further in accordance with the eighth aspect of the present disclosure, the porous layer has a thickness ranging between 200 nm and 300 nm.

[0037] Still further in accordance with the eighth aspect of the present disclosure, the porous layer has a porosity ranging between 30% and 50%.

[0038] Still further in accordance with the eighth aspect of the present disclosure, the pillar surface coverage ranges between 20% and 35%, the coupling strength ranging between 2.75 MPa and 4.5 MPa.

[0039] Still further in accordance with the eighth aspect of the present disclosure, the porous layer has a thickness ranging between 100 nm and 200 nm.

[0040] Still further in accordance with the eighth aspect of the present disclosure, the porous layer has a porosity ranging between 20% and 30%.

[0041] Still further in accordance with the eighth aspect of the present disclosure, said heating is performed at least one of: i) after said depositing the first non-porous semiconductor layer and prior to said depositing the second non-porous semiconductor layer, ii) during said depositing the second non-porous semiconductor layer, and iii) after depositing the second non-porous semiconductor layer.

[0042] Still further in accordance with the eighth aspect of the present disclosure, the given period of time ranges between 45 minutes and 75 minutes.

[0043] Further in accordance with the fifth, sixth, seventh and/or eighth aspect(s) of the present disclosure, the semiconductor substrate and the semiconductor membrane can for example include germanium.

[0044] Still further in accordance with the fifth, sixth, seventh and/or eighth aspect(s) of the present disclosure, at least one of the semiconductor substrate, the semiconductor membrane, the first non-porous layer and the second non-poyous layer has(have) a semiconductor material selected from the group consisting of: silicon (Si), indium tin oxide (ITO), zinc oxide (ZnO), III-V semiconductor materials such as gallium arsenide (GaAs), indium phosphide (InP), gallium nitride (GaN), Indium gallium arsenide (InGaAs), indium

gallium phosphide (GaInP), aluminum gallium arsenide (AlGaAsP), indium gallium arsenide phosphide (InGaAsP), aluminum gallium indium phosphide (AlGaInP), aluminum gallium indium phosphide (InAlGaP), aluminum gallium indium phosphide (InGaAlP), aluminum gallium indium phosphide (AlInGaP), III-V heterostructures such as gallium nitride on silicon (GaN/Si), aluminum nitride on silicon (AlN/Si), gallium arsenide on silicon (GaAs/Si), gallium phosphide on silicon (GaP/Si), indium gallium arsenide on silicon (InGaAs/Si), aluminum indium nitride on silicon (AlInN/Si), gallium indium nitride on silicon (GaInN/Si), or any other III-V or III-N semiconductor materials.

[0045] It is noted that the term "coupling strength indicator" is meant to encompass any indicator which is indicative of a force which can uncouple the membrane from the parent substrate. For instance, the coupling strength indicator can be provided in the form of a force value, a pressure value, a strength value, or a combination thereof. The force value can be expressed in Newtons (N) whereas the pressure/strength value can be expressed in Pascals (Pa). In some other embodiments, the coupling strength indicator can be provided in the form of a qualitative indicator such as "low coupling," "medium coupling," or "strong coupling." Additionally or alternately, the coupling strength indicator can be provided in the form of one or more parameters pertaining to a morphology of the pillars created within the porous germanium layer. For instance, such parameters can include, but are not limited to, pillar dimension (e.g., average pillar diameter, average pillar height), pillar density, pillar surface coverage, and the like.

[0046] The term "annealing temperature" is meant to refer to a temperature at which an annealing step is performed. The annealing step generally includes a step of heating the germanium substrate, and/or its thin germanium membrane, gradually up to the annealing temperature at a given heating rate and maintaining the annealing temperature for a given period of time.

[0047] The term "uncoupling force" is meant to encompass any type of force that would be applied on the germanium membrane and/or to the germanium substrate to uncouple the membrane from the germanium substrate. The uncoupling force can be a pulling force pulling the germanium membrane away from the germanium substrate, and/or a shearing force

directed along a plane extending between the germanium membrane and the germanium substrate, to name a few examples.

[0048] The term "coupling force" is meant to encompass the force with which the membrane is coupled to the germanium substrate. Typically, to uncouple the membrane from the substrate, an uncoupling force corresponding to or exceeding the coupling force has to be applied.

[0049] The term "pillar surface coverage" is meant to quantify the amount of matter within a plane intersecting the pillars extending between the membrane and the substrate. The amount of void Cvs within the plane intersecting the pillars between the membrane and the substrate would correspond to the unity minus the pillar surface coverage, i.e., $Cvs = 1 - Cps$. The pillar surface coverage can be calculated as follows. For instance, the pillar surface coverage can be given by: $Cps = \frac{\sum_{i=1}^{N} Ap_i}{Am}$, where Ap_i denotes a cross-sectional area of an ith pillar, N denotes a total number of pillars, Am denotes a total area of the germanium membrane. The pillar surface coverage can also be given by: $Cps = Dp \cdot Ap_{avg}$, where Dp denotes a pillar density, and Ap_{avg} denotes an average pillar cross-sectional area. In some embodiments, the pillars have a circular shape. Accordingly, the average pillar cross-sectional area Ap_{avg} can be given by $Ap_{avg} = \pi \left(\frac{D_{avg}}{2}\right)^2$, where D_{avg} denotes an average pillar diameter. Depending on the circumstances, and the measurements made on the pillars, one of the equations will appear as more appropriate.

[0050] All technical implementation details and advantages described with respect to a particular aspect of the present invention are self-evidently mutatis mutandis applicable for all other aspects of the present invention.

[0051] Many further features and combinations thereof concerning the present improvements will appear to those skilled in the art following a reading of the instant disclosure.

DESCRIPTION OF THE FIGURES

[0052] In the figures,

[0053] Fig. 1A is an oblique view of an example of a germanium substrate, showing a porous layer thereof, in accordance with one or more embodiments;

[0054] Fig. 1B is an oblique view of the germanium substrate of Fig. 1A, showing a germanium membrane coupled to the germanium substrate, in accordance with one or more embodiments;

[0055] Fig. 1C is an oblique view of the germanium substrate of Fig. 1B, showing the germanium membrane during uncoupling thereof, in accordance with one or more embodiments;

[0056] Fig. 1D is an oblique view of the germanium substrate after a cleaning process, for instance a chemical etching process and/or a chemo-mechanical removal process, in accordance with one or more embodiments;

[0057] Fig. 2 is a schematic view of an example of a system for manufacturing a germanium membrane on a germanium substrate, in accordance with one or more embodiments;

[0058] Fig. 3 is a schematic view of an example of reference data associating reference sets of manufacturing parameters with corresponding reference coupling strength indicators, in accordance with one or more embodiments;

[0059] Fig. 4 is a flowchart of an example of a method for manufacturing a germanium membrane on a germanium substrate, in accordance with one or more embodiments;

[0060] Fig. 5 is a schematic view of an example of a computing device of a computer of the system of Fig. 2, in accordance with one or more embodiments;

[0061] Fig. 6A is a graph showing deposition temperature as a function of time during the manufacture of a germanium membrane, emphasizing a first deposition step in which a first non-porous germanium layer is deposited on a porous layer at a first deposition temperature, in accordance with one or more embodiments;

[0062] Figs. 6B-D are cross-sectional views of germanium substrates after the deposition of non-porous germanium layers of Fig. 6A with first deposition temperatures of 300°C, 350°C and 400°C, respectively, in accordance with one or more embodiments;

[0063] Figs. 6E-G are atomic force microscopy (AFM) images of the non-porous germanium layers of Figs. 6B-D, in accordance with one or more embodiments;

[0064] Fig. 7A is a graph showing deposition temperature as a function of time during the manufacture of a germanium membrane, emphasizing an annealing step performed after the first deposition step of Fig. 6A, in accordance with one or more embodiments;

[0065] Figs. 7B-D are cross-sectional views of the germanium substrates of Figs. 6B-D after the annealing step of Fig. 7A, in accordance with one or more embodiments;

[0066] Figs. 7E-G are AFM images of the non-porous germanium layers of Figs. 7B-D, in accordance with one or more embodiments;

[0067] Fig. 8A is a graph showing deposition temperature as a function of time during the manufacture of a germanium membrane, emphasizing a second deposition step in which a second non-porous germanium layer is deposited on the first non-porous germanium layer at a second deposition temperature, in accordance with one or more embodiments;

[0068] Figs. 8B-D are cross-sectional views of the germanium substrates of Fig. 7B-D after the second deposition step of Fig. 8A, in accordance with one or more embodiments;

[0069] Figs. 8E-G are AFM images of the non-porous germanium layers of Figs. 8B-D, in accordance with one or more embodiments;

[0070] Fig. 9A is a graph showing pillar diameter and pillar density as a function of the first deposition temperature, in accordance with one or more embodiments;

[0071] Fig. 9B is a graph showing pillar surface coverage as a function of first deposition temperature, showing a detachable region and a high coupling region, in accordance with one or more embodiments;

[0072] Fig. 9C is a graph showing pillar height as a function of first deposition temperature, in accordance with one or more embodiments;

[0073] Figs. 10A-E are cross-sectional views of germanium substrates having porous layers of different thicknesses, in accordance with one or more embodiments;

[0074] Figs. 10F-J are cross-sectional views of the germanium substrates of Figs. 10A-E after the deposition of germanium membranes on the respective porous layers, in accordance with one or more embodiments;

[0075] Fig. 11A is a graph showing pillar diameter as a function of initial porous layer thickness, in accordance with one or more embodiments;

[0076] Fig. 11B is a graph showing pillar height as a function of initial porous layer thickness, in accordance with one or more embodiments;

[0077] Fig. 11C is a graph showing pillar surface coverage as a function of initial porous layer thickness, in accordance with one or more embodiments;

[0078] Fig. 11D is a graph showing coupling strength as a function of initial porous layer thickness, in accordance with one or more embodiments;

[0079] Figs. 12A-D are measurements showing average pore size for the initial porous layer in Fig. 12A, and for the first non-porous germanium layers after a second annealing duration of 5 mins, 10 mins, and 20 mins at 400°C in Figs. 12B-D, respectively, in accordance with one or more embodiments;

[0080] Fig. 12E is a graph showing spacing distance between crystallites as a function of second annealing duration, in accordance with one or more embodiments;

[0081] Fig. 13A is a schematic view of pillars extending from a germanium substrate, in accordance with one or more finite element model (FEM) simulations;

[0082] Fig. 13B is a schematic view of the germanium substrate of Fig. 13A connected to a germanium membrane via the pillars, in accordance with one or more FEM simulations;

[0083] Fig. 14A is a cross-sectional view of an example of a porous layer of a germanium substrate, in accordance with one or more embodiments;

[0084] Fig. 14B is a cross-sectional view of an example structure having a germanium membrane connected to a germanium substrate via pillars, formed with a first deposition temperature of 300°C and a second deposition temperature of 450°C without any annealing step(s) and referred to as the "as-grown structure," in accordance with one or more embodiments;

[0085] Fig. 14C is an AFM image of a detachment surface of the as-grown structure of Fig. 14B, in accordance with one or more embodiments;

[0086] Figs. 15A-E are cross-sectional views of different as-grown structures after a post-deposition annealing step with first annealing temperatures of 650°C, 700°C, 750°C, 800°C, and 850°C, respectively, in accordance with one or more embodiments;

[0087] Fig. 16A shows a scanning electron microscopy (SEM) image of a detachment surface of the as-grown structure, and Fig. 16E is a graph showing a pillar diameter distribution for the resulting as-grown structure, in accordance with one or more embodiments;

[0088] Fig. 16B shows a SEM image of a detachment surface of the as-grown structure after a postdeposition annealing step at a first annealing temperature of 650°C, and Fig. 16F is a graph showing a pillar diameter distribution for the resulting structure, in accordance with one or more embodiments;

[0089] Fig. 16C shows a SEM image of a detachment surface of the as-grown structure after a postdeposition annealing step at a first annealing temperature of 700°C, and Fig. 16G is a graph showing a pillar diameter distribution for the resulting structure, in accordance with one or more embodiments;

[0090] Fig. 16D shows a SEM image of a detachment surface of the as-grown structure after a postdeposition annealing step at a first annealing temperature of 750°C, and Fig. 16H is a graph showing a pillar diameter distribution for the resulting structure, in accordance with one or more embodiments;

[0091] Fig. 17A is a graph showing mean pillar diameter (on the left axis) and pillar density (on the right axis) as a function of first annealing temperature for as-grown structures which have undergone different postdeposition annealing steps, in accordance with one or more embodiments;

[0092] Fig. 17B is a graph showing coupling strength as a function of first annealing temperature, in accordance with one or more embodiments;

[0093] Figs. 18A-D are binary format images of the SEM images of Figs. 16A-D used for the FEM simulations, respectively, in accordance with one or more embodiments;

[0094] Fig. 19 is a graph showing coupling strength as a function of the first annealing temperature, showing experimental and modeled values, in accordance with one or more embodiments; and

[0095] Fig. 20 is a graph showing coupling strength as a function of pillar surface coverage, in accordance with one or more embodiments.

DETAILED DESCRIPTION

[0096] Figs. 1A-1D show oblique views of a parent germanium substrate 100 during the manufacture of a germanium membrane 102 and uncoupling of the membrane 102 from the substrate 100. More specifically, Fig. 1A shows an example of a substrate 100 having a porous layer 104. The porous layer 104 is generally characterized by initial parameters including, but not limited to, initial porous layer thickness and initial porous layer porosity. Fig. 1B shows the substrate of Fig. 1A onto which the membrane 102 has been manufactured. In some embodiments, the membrane manufacture process includes a first germanium deposition step made at a first deposition temperature, and a second germanium deposition step made at a second deposition temperature greater than the first deposition temperature. It is encompassed that the first epitaxial germanium deposition step results in the deposition of a first non-porous germanium layer on the porous layer of the substrate. The first non-porous germanium layer generally closes the pores of the porous layer of the substrate. The second epitaxial germanium deposition step results in the deposition of a second non-porous germanium layer on the first non-porous layer. As the second deposition step is performed at

a higher temperature, the pores of the porous layer generally experience a change in morphology creating pillars 106 extending from the substrate and the first non-porous germanium layer. Examples of such a process are described in detail in PCT Patent Publication No. WO 2022/170431 A1. It was found that the mechanical characteristics of the pillars including, but not limited to, pillar height, pillar diameter, and pillar density, influence the strength of the coupling existing between the substrate and the membrane. It was also found that modifying some manufacturing parameters can in turn modify the mechanical characteristics of the pillars. Accordingly, by modifying one or more of the manufacturing parameters, one can determine the resulting pillar morphology and associated coupling strength, which can be highly desired as some applications may require a stronger coupling between the substrate and the membrane whereas other applications may require a weaker coupling between the substrate and the membrane. Fig. 1C shows an example membrane 102 in the process of being uncoupled (or equivalently detached) from the substrate 100. As shown, the manufacturing parameters of the membrane 100 were selected to yield an expected coupling strength Fc. As such, when an uncoupling force F greater than the expected coupling strength Fc is applied to the membrane 102, it uncouples from the parent substrate 100 leaving broken pillars on a detachment surface of the substrate. Fig. 1D shows the parent substrate after the broken pillars 108 have been removed by an additional process, for instance chemical etching or chemo-mechanical removal. The resulting substrate 100 is thus ready for another membrane manufacturing process, which can reduce manufacturing costs in the long term. It is noted that the germanium membrane 102 and the germanium substrate 100 preferably include monocrystalline germanium.

[0097] Fig. 2 shows an example of a system 200 for manufacturing a germanium membrane on a germanium substrate, in accordance with an embodiment. As depicted, the system has a computer 202, a manufacturing device 204, and an uncoupling device 206. More specifically, the computer 202 is configured for receiving a selected coupling strength indicator 208 indicative of a force which when applied to the membrane uncouples the membrane from the substrate. In some embodiments, the coupling strength indicator 208 can be provided in the form of a force, pressure, or strength value expressed in megapascals, for instance. However, in some embodiments, the coupling strength indicator 208 can be provided in the form of a pillar dimension (e.g., pillar diameter), pillar height, pillar density, and the like. In some

embodiments, it was found that controlling the manufacturing parameters to increase the pillar diameter can in turn increase the coupling strength. In some other embodiments, it was found that controlling the manufacturing parameters to increase the pillar height can in turn weaken the coupling strength. It is intended that different combinations of the dimension, height and density of the pillars can lead to different coupling strengths. In some other embodiments, the coupling strength indicator 208 can be provided in the form of a pillar surface coverage percentage, to present yet another alternative.

[0098] As shown, the computer 202 is configured for determining a set of manufacturing parameters 210 based on the coupling strength indicator using reference data 212 associating a different reference sets of manufacturing parameters with corresponding reference coupling strength indicators. In some embodiments, the computer 202 can also receive desired membrane characteristics 214 for instance indicative of a desired membrane thickness, surface roughness, and the like. In these embodiments, the computer 202 may also factor in the desired membrane characteristics 214 in the determination of the set of manufacturing parameters 210. It is intended that the set of manufacturing parameters 210 includes at least a first deposition temperature indicative of the temperature at which the first non-porous germanium layer is deposited and a second deposition temperature indicative of the temperature at which the second non-porous germanium layer is deposited. However, it is encompassed that the set of manufacturing parameters 210 can include many other manufacturing parameters 210 including, but not limited to, first deposition duration, first deposition thickness, first deposition rate, second deposition duration, second deposition thickness, second deposition rate, and the like. In embodiments where a first annealing step is performed after the first and second depositions, the set of manufacturing parameters 210 can include, but is not limited to, first annealing step presence (this parameter can have a binary value such as yes/no, 1/0), first annealing temperature, first annealing duration, and the like. In embodiments where a second annealing step if performed after the first deposition and before the second deposition, the set of manufacturing parameters 210 can include, but is not limited to, second annealing step presence (this parameter can have a binary value such as yes/no, 1/0), second annealing temperature, second annealing duration, and the like. Additionally or alternately, the set of manufacturing parameters 210 can also include information relating to the initial porous layer of the germanium substrate. For instance, initial

porous layer thickness and initial porous layer porosity can also be relevant manufacturing parameters 210 which can be modified to tune the resulting coupling strength.

[0099] As illustrated, the manufacturing device 204 is communicatively coupled to the computer. As such, the manufacturing device 204 is configured to manufacture the germanium membrane on the germanium substrate based on the determined set of manufacturing parameters. Typically, the manufacturing of the membrane includes the steps of: at the first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate; and, at the second deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers. As such, at the minimum, the first and second deposition temperatures are manufacturing parameters which can be modified to in turn tune the resulting coupling strength. The manufacturing device 204 can be provided in the form of a programmable industrial chemical vapour deposition (CVD) device such as a modified chemical vapor deposition (MCVD) device, a metal-organic chemical vapour deposition (MOCVD) device, and the like, depending on the embodiment.

[00100] Still referring to Fig. 2, it is shown that the system 200 has an uncoupling device 206 communicatively coupled to the computer 202. The uncoupling device 206 is configured for applying an uncoupling force to the membrane. When the uncoupling force is greater than the force of the coupling strength indicator 208, then the germanium membrane is uncoupled from the germanium substrate. The uncoupling device 206 can be embodied by a robotized arm, for example equipped with a blade, or any other device that can satisfactorily uncouple the membrane from the substrate after manufacture. In some embodiments, the uncoupling device 206 is configured to pull the germanium membrane from the germanium substrate.

[00101] It is intended that the reference data 212 can be stored on a non-transitory computer readable memory of the computer or on any computer memory made accessible to the computer. Fig. 3 shows an example of such reference data 312. As shown, three different reference sets of manufacturing parameters are shown. In the first reference set, the manufacturing parameters include a first deposition temperature labelled as “1,” a second deposition temperature labelled as “2,” and no annealing steps. The first reference set of manufacturing parameters can be used when a coupling force corresponding to the reference

coupling strength indicator labelled as “1” is desired. In the second reference set, the manufacturing parameters include a first deposition temperature labelled as “3,” a second deposition temperature labelled as “4,” and a first annealing step is present. More specifically, a first annealing temperature labelled as “5” is provided for the first annealing step. The second reference set of manufacturing parameters can be used when a coupling force corresponding to the reference coupling strength indicator labelled as “2” is desired. In the third reference set, the manufacturing parameters include a first deposition temperature labelled as “3,” a second deposition temperature labelled as “4,” and a second annealing step is present. More specifically, a second annealing temperature labelled as “6” is provided for the second annealing step. The third reference set of manufacturing parameters can be used when a coupling force corresponding to the reference coupling strength indicator labelled as “3” is desired. The reference data can have as many reference sets as experimental, or simulation results can provide. As such, in some embodiments, the reference data can include two or more reference sets. The reference data can include reference parameter(s) such as porosity percentage, pore size, porous layer thickness, and associated reference coupling strength indicator(s).

[00102] Fig. 4 shows a flowchart of an example method 400 of manufacturing a germanium membrane on a germanium substrate. The method 400 can be partially or wholly performed by the system of Fig. 2, using the reference data of Fig. 3 in some embodiments.

[00103] At step 402, a coupling strength indicator is selected. The coupling strength indicator is generally indicative of a force which when applied to the germanium membrane uncouples the germanium membrane from the germanium substrate. As discussed above, the coupling strength indicator can correspond to a desired coupling strength value or to desired pillar characteristics, depending on the embodiment. More specifically, the coupling strength indicator can be provided in the form of a pillar dimension value, a pillar height value, and a pillar density value indicative of a respective one of a pillar dimension, a pillar height and a pillar density associated with pillars formed within the germanium membrane after the deposition steps discussed above.

[00104] At step 404, a set of manufacturing parameters is determined based on the coupling strength indicator. The step 404 of determining can be made using reference data that are

made accessible. The reference data generally associate different reference sets of manufacturing parameters with corresponding reference coupling strength indicators. It is intended that the set of manufacturing parameters includes at least a first deposition temperature and a second deposition temperature higher than the first deposition temperature. As discussed above, the first deposition temperature is generally indicative of the temperature at which a first non-porous germanium layer is deposited on the porous layer of the germanium substrate, whereas the second deposition temperature is indicative of the temperature at which a second non-porous germanium layer is deposited on the first non-porous germanium layer. It is noted that the deposition of the second non-porous germanium layer made at the second, higher deposition temperature, or when an intermediate annealing step (often referred to herein as "the second annealing step"), at least a portion of the porous layer of the substrate changes its morphology and transforms into a pillar containing layer. The pillar containing layer contains pillars extending between the substrate and the first non-porous germanium layer, and typically acts as a weak (or strong) interface which can be broken to uncouple the membrane from the substrate. As discussed above, the pillars can be characterized by height, dimension, density, surface coverage, or a combination thereof.

[00105] In some embodiments, the first deposition temperature can be modified to influence the resulting coupling strength. For instance, in embodiments where the coupling strength indicator is indicative of a weak coupling, the first deposition temperature can be set between 275°C and 325°C. In embodiments where the coupling strength indicator is indicative of a strong coupling, the first deposition temperature can be set between 350°C and 400°C. In embodiments where the coupling strength indicator is indicative of medium coupling, the first deposition temperature can be set between 325°C and 350°C, exclusively, but these embodiments may not be preferred. These first deposition temperatures can depend on one or more other manufacturing parameters including, but not limited to, the first deposition rate, the first deposition duration, the desired membrane thickness, and the like. For instance, the first deposition temperatures presented above are based on a first deposition rate which is considered to be a low deposition rate (e.g., 0.5 µm/h). In embodiments where the first deposition rate is higher (e.g., 2 µm/h), the first temperature deposition temperatures can be higher than the above-mentioned temperatures by 100°C, for instance.

[00106] Additionally or alternately, the second deposition temperature can be modified to tune the resulting coupling strength. More specifically, in embodiments where the coupling strength indicator is indicative of a weak coupling, the second deposition temperature can be set between 525°C and 575°C. In embodiments where the coupling strength indicator is indicative of a strong coupling, the second deposition temperature is set between 425°C and 475°C. In embodiments where the coupling strength indicator is indicative of medium coupling, the second deposition temperature can be set between 475°C and 525°C, exclusively, but these specific embodiments may not be preferred. As discussed above, these temperatures can vary depending on other manufacturing parameters.

[00107] In some embodiments, the set of manufacturing parameters includes a first annealing temperature useful when a first annealing step is made. In this disclosure, the first annealing step includes a step of, after depositing the second non-porous layer, heating the first and second non-porous layers and the germanium substrate up to the first annealing temperature for a given period of time. The given period of time can range between 45 minutes and 75 minutes, depending on the embodiment. In embodiments where the coupling strength indicator is indicative of a weak coupling, the first annealing temperature can be set between 500°C and 725°C. In embodiments where the coupling strength indicator is indicative of a strong coupling, the first annealing temperature can be set between 775°C and 850°C. In embodiments where the coupling strength indicator is indicative of medium coupling, the first annealing temperature can be set between 725°C and 775°C, exclusively, but these embodiments may not be preferred. Again, these temperatures can vary depending on other manufacturing parameters. The first annealing duration was set to 1 hour. However, in some other embodiments, the first annealing duration can be higher than 1 hour, or below than 1 hour, in which case the first annealing temperature threshold of 750°C discussed above can vary. In any case, the maximal temperature for the first annealing temperature should not reach 938°C as it corresponds to the fusion temperature of germanium.

[00108] In some embodiments, the set of manufacturing parameters includes a second annealing temperature which can become relevant when a second annealing step is made. As disclosed herein, the second annealing step includes a step of, after depositing the first non-porous layer and prior to depositing the second non-porous layer, heating the first non-

porous layer up to the second annealing temperature for a given period of time. The given period of time can range between 45 minutes and 75 minutes. In embodiments where the coupling strength indicator is indicative of a strong coupling, the second annealing temperature can be set between 325°C and 350 °C. However, in embodiments where the coupling strength indicator is indicative of a weak coupling, the second annealing temperature is set between 400 °C and 575°C. Again, these temperatures can vary depending on other manufacturing parameters. The second annealing duration was set to 1 hour in some experiments. However, in some other embodiments, the second annealing duration can be higher than 1 hour, or below than 1 hour, in which case the second annealing temperature values discussed above can vary. It is understood that the second annealing temperature should be at least equal to, or preferably higher than, the second deposition temperature.

[00109] In some embodiments, the set of manufacturing parameters has at least one of an initial porous layer thickness and an initial porous layer porosity. In these embodiments, the method 400 includes a step of, prior to depositing the first non-porous layer, making the porous layer in the germanium substrate based on the initial porous layer thickness and/or the initial porous layer porosity. In embodiments where the coupling strength indicator is indicative of a weak coupling, the initial porous layer thickness can be set between 250 nm and 400 nm. In embodiments where the coupling strength indicator is indicative of a strong coupling, the initial porous layer thickness can be set between 100 nm and 200 nm. In embodiments where the coupling strength indicator is indicative of medium coupling, the initial porous layer thickness can be set between 200 nm and 250 nm, exclusively, but these embodiments may not be preferred. Similarly, in embodiments where the coupling strength indicator is indicative of a weak coupling, the initial porous layer porosity can range between 50% and 60%. In embodiments where the coupling strength indicator is indicative of a strong coupling, the initial porous layer porosity can range between 20% and 50%, preferably between about 30% and 50%, and most preferably between 40% and 50%. Generally, the amount of void present in the pillar containing layer defines the resulting coupling strength. In other words, increasing the amount of void in the pillar containing layer (e.g., greater porosity, greater thickness) can lead to weaker coupling. In contrast, decreasing the amount of void pillar containing layer, which can in turn increase the amount of matter (e.g., lower porosity, lower thickness), can lead to stronger coupling.

[00110] At step 406, the germanium membrane is manufactured on the germanium substrate based on the set of manufacturing parameters determined at step 404. The manufacture generally includes a first deposition step including, at the first deposition temperature, depositing the first non-porous layer of germanium onto the porous layer of the germanium substrate, and a second deposition step including, at the second deposition temperature, depositing the second non-porous layer of germanium onto the first non-porous layer. The germanium membrane thereby includes at least the first and second non-porous layers. Other non-porous layers of the same or other semiconductor material can be present in some other embodiments. Examples of such semiconductor material can include, but are not limited to, silicon (Si), indium tin oxide (ITO), zinc oxide (ZnO), III-V semiconductor materials such as gallium arsenide (GaAs), indium phosphide (InP), gallium nitride (GaN), Indium gallium arsenide (InGaAs), indium gallium phosphide (GaInP), aluminum gallium arsenide (AlGaAsP), indium gallium arsenide phosphide (InGaAsP), aluminum gallium indium phosphide (AlGaInP), aluminum gallium indium phosphide (InAlGaP), aluminum gallium indium phosphide (InGaAlP), aluminum gallium indium phosphide (AlInGaP), III-V heterostructures such as gallium nitride on silicon (GaN/Si), aluminum nitride on silicon (AlN/Si), gallium arsenide on silicon (GaAs/Si), gallium phosphide on silicon (GaP/Si), indium gallium arsenide on silicon (InGaAs/Si), aluminum indium nitride on silicon (AlInN/Si), gallium indium nitride on silicon (GaInN/Si), and the like.

[00111] At step 408, an uncoupling force is applied to the germanium membrane. The uncoupling force is greater than the force of the coupling strength indicator. As such, the germanium membrane is uncoupled from the germanium substrate, leaving an uncoupled germanium membrane and a germanium substrate having a detachment surface. It is understood that the step 408 of applying the uncoupling force is optional in some embodiments. Indeed, the membrane could be sold while still coupled to the parent substrate for uncoupling thereof at a remote location by a third party, for instance.

[00112] In some embodiments, the method 400 can include a step of cleaning the detachment surface of the germanium substrate, making another porous layer in the germanium substrate, and manufacturing another germanium membrane on the germanium substrate based on a different set of manufacturing parameters. However, in some

embodiments, the same set of manufacturing parameters can be used repeatedly to form successive germanium membranes on the same parent substrate, for instance. The cleaning process can include any suitable type of cleaning process including, but not limited to, a chemical etching process, a chemo-mechanical removal process, and the like.

[00113] Referring now to Fig. 5, the computer of the system of Fig. 2 can be provided as a combination of hardware and software components. The hardware components can be implemented in the form of a computing device 500, an example of which is described with reference to Fig. 5. The computing device 500 can have a processor 502, a memory 505, and I/O interface 506. Instructions 508 for manufacturing the germanium membrane, for determining the set of manufacturing parameters and/or for instructing the manufacturing device can be stored on the memory 505 and accessible by the processor 502.

[00114] The processor 502 can be, for example, a general-purpose microprocessor or microcomputer, a digital signal processing (DSP) processor, an integrated circuit, a field-programmable gate array (FPGA), a reconfigurable processor, a programmable read-only memory (PROM), a programmable logic computer (PLC), or any combination thereof.

[00115] The memory 505 can include a suitable combination of any type of computer-readable memory that is located either internally or externally such as, for example, random-access memory (RAM), read-only memory (ROM), compact disc read-only memory (CDROM), electro-optical memory, magneto-optical memory, erasable programmable read-only memory (EPROM), and electrically-erasable programmable read-only memory (EEPROM), Ferroelectric RAM (FRAM) or the like.

[00116] Each I/O interface 506 enables the computing device 500 to interconnect with one or more input devices, such as a keyboard(s), mouse(s), or accessible database(s), or with one or more output devices such as monitor(s), external network(s), or accessible database(s).

[00117] Each I/O interface 506 enables the computer to communicate with other components, to exchange data with other components, to access and connect to network resources, to serve applications, and perform other computing applications by connecting to

a network (or multiple networks) capable of carrying data including the Internet, Ethernet, plain old telephone service (POTS) line, public switch telephone network (PSTN), integrated services digital network (ISDN), digital subscriber line (DSL), coaxial cable, fibre optics, satellite, mobile, wireless (e.g., Wi-Fi, WiMAX), SS7 signaling network, fixed line, local area network, wide area network, and others, including any combination of these.

[00118] The computing device 500 and any software application that can be run by the computing device 500 are meant to be examples only. Other suitable embodiments of the computer can also be provided, as it will be apparent to the skilled reader.

[00119] Example 1 – First deposition temperature variation to tune coupling strength variation of detachable germanium membranes via porous germanium transformation

[00120] In this example, experimental tests were made during the manufacture of a membrane. In these embodiments, the method of manufacture includes a step of, after the deposition of the first non-porous layer and prior to the deposition of the second non-porous layer, heating the first non-porous layer up to a second annealing temperature for a given period of time (also referred to as “second annealing temperature”). These tests aimed at determining the effect of the second annealing temperature on the resulting coupling strength.

[00121] More specifically, Fig. 6A shows deposition temperature as a function of time during the manufacture of a germanium membrane, with an emphasis on the first deposition step (denoted as “#1” in the figure) in which the first non-porous germanium layer is deposited on the porous layer at the first deposition temperature. Figs. 6B-D are cross-sectional views of germanium substrates after the deposition of Fig. 6A with first deposition temperatures of 300°C, 350°C and 400°C, respectively. Fig. 7A emphasizes an annealing step (denoted as “#2” in the figure) performed after the first deposition step of Fig. 6A. Figs. 7B-D show the germanium substrates of Figs. 6B-D after the annealing step of Fig. 7A. Fig. 8A puts the emphasis on the second deposition step (denoted as “#3” in the figure) in which the second non-porous germanium layer is deposited on the first non-porous germanium layer at the second deposition temperature. Figs. 8B-D are cross-sectional views of the germanium substrates of Fig. 7B-D after the second deposition step of Fig. 8A. The results of these tests are summarized in Figs. 9A-B. As shown, Fig. 9A shows pillar diameter and pillar density as

a function of the first deposition temperature whereas Fig. 9B shows pillar surface coverage as a function of the first deposition temperature, showing a detachable region and a high coupling region. As can be understood, a stronger coupling region is found when the second annealing temperature is set between 325°C and 350 °C, and a weaker coupling region is found when the second annealing temperature is set between 400 °C and 575°C. In some embodiments, it was found advantageous to determine the annealing temperature based on the initial porous layer porosity, the initial porous layer thickness, or a combination thereof.

[00122] The porous germanium reorganization during sintering under various atmosphere is currently well known but its transformation into a void layer and its relationship with the membrane's adhesion strength has not yet been the subject of in-depth investigation. Moreover, the influence of PGe properties and growth conditions on the mechanical properties of the membranes have not yet been studied. In this example, the influence of the growth temperature and PGe thickness on the voided separation layer properties and its impact on the Ge nanomembrane adhesion strength are reported. It is shown that membrane adhesion strength can be successively tailored from freestanding mode up to quasi-welded structure while maintaining its surface and crystalline quality.

[00123] PGe layers used in this example are prepared using bipolar electrochemical etching (BEE) of p-type, gallium-doped (100) with resistivity of 8-30 mΩ·cm, and 6° miscut towards the (111) direction. To create PGe layers, etching and passivation asymmetric pulses are applied with a 1s pulse duration. The current density applied for the BEE was 0.75 and 1.00 $mA \cdot cm^{-2}$, respectively. The adopted BEE conditions allow for obtaining homogeneous PGe layers with 45% porosity across the 100 mm germanium substrate. Germanium substrates with PGe layer on top are then rinsed with EtOH (99%, anhydrous), dried under N_2 flow.

[00124] The germanium membranes were deposited using 4-inch VG Semicon V90F hybrid CBE/MBE reactor equipped with a liquid nitrogen cryopanel, at a pressure of $4.5 \cdot 10^{-6}$ Torr. A Ge Knudsen cell, heated at 1250°C, was used as a solid Ge source providing a deposition rate of 0.5 µm/h. First, 200 nm thick low temperature (LT) first non-porous layer was deposited and subsequently in situ annealed at 550°C for 10 min prior to the deposition of 700 nm thick second non-porous layer at 475°C. A series of germanium membranes samples have been

produced by varying the first non-porous layer layer deposition temperature (T_g) from 300°C to 400°C as well as the PGe layer thickness from 150 nm to 350 nm.

[00125] The germanium membranes' adhesion strength was assessed by an uncoupling device using a custom-made setup with TA.XTPlus machine operating at a quasi-static regime using an appropriate software. The sample front and backside are glued to proprietary holders using a commercial J-B WELD 8281 epoxy. The layer's separation force is then converted into MPa knowing the detached area.

[00126] Cross-sectional observations were carried out using scanning electron microscopy (SEM) LEO 1540 XB ® and Thermo Scientific Scios 2 Dual Beam to observe PGe layer before and after deposition process. For each SEM, an acceleration tension of 20 keV was used. Surface roughness of germanium membranes was characterized by atomic force microscope (AFM, Park System NX20) in non-contact mode (NCM), with scan size of 5 × 5 μm^2 and a 512 × 512 pixels² resolution.

[00127] To study the impact of the first non-porous layer's deposition temperature on the PGe layer reorganization and the membrane adhesion properties, a 200 nm thick first non-porous layer was deposited on 200 nm thick PGe layer, at T_g of 300°C, 350°C and 400°C. The corresponding cross-sectional SEM and AFM characterization are depicted by the Figs. 6B-G. Indeed, the first non-porous layer's deposition temperature has a strong impact on the morphological transformation of the PGe layer. As shown in Fig. 6B, at a T_g of 300°C, the PGe layer remains unchanged after growing 200 nm thick first non-porous layer. However, when the T_g is increased to 350°C, the overall PGe layer thickness shrinks by approximately 20% (Fig. 6C) as a direct consequence of the thermal-induced PGe layer reorganization. Additionally, further increasing the T_g to 400°C (Fig. 6D) reduces the PGe layer thickness, down to 96 nm, representing a shrinkage by approximately 50%. The observed behaviors can be understood in terms of increased degree of PGe reorganization with increasing the thermal budget according to the Ostwald Ripening (OR) phenomena. Indeed, when the temperature reaches a specific threshold (above 300°C for PGe), the surface mobility of the Ge atoms within the pores increases and the porous structure tends to minimize its surface energy by combining pores, which reduces of their volume to surface ratio. This leads to the formation of densified interconnected pillars-like crystallites, as shown by the Fig. 6C and will be further

discussed later (Figs. 10A-J). Ultimately, this culminates in a structure with few cavities upon coalescence at higher temperatures (Fig. 6D).

[00128] In the meantime, the PGe morphological transformation occurring during the deposition of the first non-porous layer also involves the diffusion of Ge atoms into the PGe layer. Specifically, during the initial stages of Ge deposition on PGe layer at 300°C and below, the PGe layer does not undergoes any transformation limiting adatom diffusion into the PGe layer.. At higher depostion temperatures, the reorganization-induced enlargement of pore diameters increases the diffusion length of the adatoms increases, aiding in pore filling. This enlargement of pores or nano-voids, along with the increased thermal budget, leads to partial filling of the PGe layer during the deposition of the first non-porous layer. This phenomenon has a direct impact on the membrane's surface roughness and separation layer's microstructural properties.

[00129] Accordingly, as shown in Figs. 6E-G, the AFM images reveal a Root Mean Square (RMS) roughness increase with increasing deposition temperature. Indeed, in absence of PGe layer reconstruction, adatoms diffusion, into PGe layer, is limited, allowing the formation of a first non-porous layer with a surface roughness below 1 nm, close to that of the substrate (0.23 ± 0.02 nm). As the deposition temperature increases, the pores get consequently enlarged prohibiting the formation of a smooth membrane's surface. Accordingly, the measured surface roughness is found to increase with increasing Tg to reach an RMS roughness of 5 nm for the structure grown at 400°C. As can be seen through the AFM images of the Figs. 6E and 6F, the RMS roughness increase arises from the presence of pits resulting from Ge nucleation on the rough surface of the reorganized PGe layer. Accordingly, the RMS roughness increases with the degree of PGe reorganization from 1.4 nm at 350°C to 5 nm for the structure grown at 400°C.

[00130] To mitigate the surface roughness through the closure of these pits and being able to form the separation layer, an annealing process is applied to the structures at 550°C. This annealing temperature indicates that the optimal temperature for the PGe reorganization is within the range of 550°C to 600°C. Indeed, at this thermal budget applied, the PGe reorganization kinetics intensified, ultimately forming a separation layer. Figs. 7B-G show a study of the final structure morphology for the same three deposition conditions that were

analyzed in Figs. 6B-G, but with a post-deposition annealing at 550°C for 10 min added to each experiment. The images show that for a Tg of 300°C the separation layer is fully formed with large pores confined within a planar region (Fig. 7B), and the surface remains smooth with a measured RMS roughness bellow 1 nm (Fig. 7E).

[00131] For higher deposition temperatures (350°C), the formation of a separation layer with smaller voids separated by larger pillars (Fig. 7D) was observed, and a rougher resulting surface, around 1 nm RMS (Fig. 7F). For sample grown at 400°C, while the surface roughness has been slightly improved, the PGe layer appears insensitive to the additional annealing step, suggesting a complete reorganization during the first non-porous layer deposition. For each of the three experiments, the surface roughness improved for the sample that was annealed post-deposition, thus confirming the benefit of that extra step in the process. The improvement appears to be more important for the samples with higher first non-porous layer's deposition temperatures, probably due to a rougher surface at the onset of the annealing step. To further improve the surface roughness and increase the membrane thickness, an additional 1 µm-thick second non-porous layer is deposited at 475°C after the high temperature (HT) annealing step. SEM cross-sectional images from these structures reveal the absence of noticeable morphological evolution of the separation layer (Fig. 8B-D), since the employed deposition temperature is lower than that of the annealing step. In the meanwhile, the deposition of 1 µm-thick second non-porous layer considerably improved the surface roughness of all the germanium membranes with an RMS roughness down to 1 nm for the first non-porous layer's T_g = 300°C and to 1.2 nm for T_g = 400°C (Figs. 8F-G). This morphological improvement comes from the reduction in the pit's depth, by the progressive filling. Indeed, using a with a first non-porous layer grown below 300°C, it was possible to obtain a III-V heterostructure with good quality allowing the development of a III-V solar cell with performances close to that obtained with the same III-V structure grown on bulk germanium substrate.

[00132] To further analyze the impact of the first non-porous layer T_g on the separation layer properties, pillar diameters and density have been estimated from SEM cross section images (Fig. 8B-D). The results are depicted in Fig. 9A. Indeed, increasing T_g from 300°C to 400°C, pillar density falls from 33 pillars/µm^2 to around 5 pillars/µm^2 whereas the pillar mean diameter significantly increases from 70 nm to 330 nm. Nevertheless, as illustrated in Fig. 9C, the pillar

height seems to not be affected by the deposition of the 1 µm-thick second non-porous layer, after the annealing step. Indeed, after the annealing step, the average pillar height is around 92.5 nm and after the 1 µm-thick first non-porous layer deposition, this average pillar height is around 98 nm. After the annealing step, the remaining cavities will significantly slow down their migration towards the PGe layer/first non-porous layer interface and will favor a lateral coalescence, thus minimally impacting the pillar height and allowing the formation of pillars with higher diameter. This important evolution of the pore diameter and density has a significant impact on the germanium membrane adhesion. Indeed, for a first non-porous layer deposited at 300°C, the membrane is found to be easily detachable with 100% detachment yield. The corresponding adhesion force has been evaluated around 2 MPa. Meanwhile, the pillars characteristics for membranes with first non-porous layers T_g at 350°C and 400°C yield adhesions force higher than the employed pull test setup limit fixed by the epoxy adhesion strength of 4.5 MPa. The increase in the membrane adhesion strength can be explained by the enhanced pillar surface coverage (Fig. 9B), estimated from the pillar diameter and density. The membrane adhesion force increases with increasing the pillar surface coverage suggesting that larger pillar surface requires higher forces for membrane separation.

[00133] The main reason behind the increased adhesion force is the void annihilation by a combined effect of either PGe layer reorganization or pores filling. The amount of void confined within the separation layer has an impact on the pillar's morphology and distribution and therefore on the membrane adhesion force. To evaluate the impact of the amount of confined void within the separation layer on the membrane adhesion force, an investigation is made on the PGe layer thickness impact on PGe reorganization and adhesion properties using deposition conditions identical to the structure shown by the Fig. 8B preserving a T_g of 300°C for the first non-porous layer. PGe layer thicknesses between 100 nm and 300 nm, with a step of 50 nm were studied, as shown in Figs. 10A-E.

[00134] The separating layer's morphology is found to be strongly dependent on the initial PGe layer thickness. From cross section SEM images in Figs. 10F-J, pillars dimensions are measured and gathered in Figs. 12A and 12B. The PGe structure reorganization toward pillar formation is well presented in Fig. 12B. For PGe layer initial thickness of 100 nm, the formed pillars show a mean height of 50 nm and diameter around 120 nm. The initial increase in PGe

layer thickness leads to a continuous rise in the height of the pillars, reaching up to 90 nm, while simultaneously causing a consistent reduction in their average diameter, which decreases down to 40 nm. Meanwhile, the pillar density increases first, with increasing the PGe layer thickness exceeding 50 pillars/μm^2 for 250 nm thick PGe layer (Fig. *12A*), then decreases drastically to barely 10 pillars/μm^2 for 300 nm thick PGe layer. The latter phenomenon can be a direct consequence of the pillar's diameter decrease. Indeed, pillars with very small diameters below a given threshold, could not be sufficiently stable and are expected to disappear in favor of thickening either their closely spaced pillars or the separation layer's inner surfaces.

[00135] The combination of the results for the pillar diameter with the pillar density allows the evaluation of pillar surface coverage (Fig. 12C). Indeed, a clear decrease of the surface coverage from nearly 22% down to only 1% is found to occur when the PGe layer thickness increases from 100 nm to 300 nm. This behavior has a significant impact on the membrane adhesion strength as shown in Fig. 12D. Indeed, for structures with high pillar surface coverage, corresponding to a PGe layer thickness below 150 nm, germanium membranes show high adhesion strength, exceeding that of the employed epoxy glue. In the meantime, very low surface coverage shown by the membrane deposited on 300 nm thick PGe layer, leads to an easily detachable membrane with an adhesion strength lower than that of the used copper tape. However, PGe layer thicknesses between 150 nm and 300 nm exclusively, present a good suitability for detachable devices on germanium membranes, their adhesion forces allow membrane release (lower than epoxy adhesion) with a mechanically stable structure (higher than copper tape adhesion). It has been already shown that a germanium membrane deposited on a structure of 170 nm with a porosity close to the porosity presented in this study can be detached and can be used for the growth of III-V materials. Furthermore, it has recently been demonstrated that a PGe layer with a thickness of 200 nm and the same porosity as presented here enables the achievement of promising efficiency in III-V solar cells.

[00136] While the present example demonstrates the potentiality of using the first non-porous layer deposition temperature to tune the membrane adhesion force, it is worth mentioning that the first non-porous layer deposition temperatures remain specific for this study. Indeed, the formation of a detachable Ge membrane relies on the ability to form a dense

layer while ensuring the confinement of sufficient void in the PGe layer that allows the formation of pillars with specific surface coverage during the PGe layer reorganization. These conditions are strongly dependent on the deposition temperature and rate. The substrate temperature drives the PGe layer reorganization during deposition. It needs therefore to be as low as possible to avoid fast reorganization. However, the deposition rate defines the total time of materials deposition which needs to be as short as possible to accelerate the formation of dense layer and therefore the void confinement within the separation layer. In this example, the maximum achievable Ge deposition rate using a Ge solid source is around 0.5 um/h, imposing a relatively long deposition time of more than 20 min to obtain the 200 nm thick first non-porous layer. At T_g = 400°C, this also implies a very long annealing time sufficient for PGe layer reorganization and consequent voids annihilation and pores filling that may lead to a completely welded and undetachable membrane. To avoid such a situation, one needs to minimize the thermal budget seen by the PGe layer during the first non-porous layer.

[00137] For the deposition techniques that require high substrate temperature, the solution arises from the increase of the deposition rate to minimize the annealing time. Indeed, a plan view SEM analysis of the annealing time dependent PGe layer reorganization at 400°C is performed. The results are shown by the Figs. 12A-D.

[00138] The increase of the annealing time up to 20 min is found to enhance the PGe layer reorganization through OR phenomenon leading to an enlarged pores diameter. The estimated average pores size of the initial porous structure is estimated around 20 nm as extracted from Fig. 12A and shown in Fig. 12E. This value increases monotonically with increasing the annealing time, reaching an average value of around 80 nm after an annealing time of 20 min (Fig. 12E). This behavior enhances the Ge diffusion and pores filling (void annihilation) during the first non-porous layer formation at 400°C. To limit the impact of the PGe layer reorganization at relatively high deposition temperature, the first non-porous layer needs to be deposited at high deposition rate. For instance, using reduced pressure chemical vapor deposition, Ge the deposition rates can easily reach more than 36 nm/min at 400°C. Using such a deposition rate the minimum required first non-porous layer thickness around 100 nm becomes attainable within 3 minutes. It would therefore be possible to form the germanium membrane and confine sufficient voids to ensure detachable layers.

[00139] In conclusion, this example highlights the significant influence of deposition parameters on the reorganization of porous structures and consequently on the germanium membranes adhesion strength. It was found that by increasing the first non-porous layer deposition temperature at low deposition rate, one can prevent membrane detachment due to the reorganization of the porous material and Ge diffusion within pores. AFM analyses revealed a direct correlation between deposition temperature and surface roughness of the germanium membrane. This roughness can be substantially reduced to an RMS of less than 1 nm through a high-temperature annealing step and subsequent deposition of a 1 µm second non-porous layer. To achieve a detachable germanium membrane with low surface roughness, the deposition temperature of the first non-porous layer should be maintained at around 300°C.

[00140] Additionally, adjusting the thickness of the PGe layer at adequate first non-porous layer deposition temperature, offers another method to control the germanium membrane's adhesion strength. The investigations presented in this example show that increasing PGe layer thickness leads to an overall increase of void within the separation layer, consequently reducing the membrane's adhesion strength. This example particularly shows the ability to tune the membrane adhesion from a easily detachable state to a fully bonded membrane. The results presented herein can constitute new avenues toward adjustable membranes adhesion strength for controllable device detachment.

[00141] Example 2 – Initial PGe layer thickness variation to tune coupling strength variation of detachable germanium membranes via porous germanium transformation

[00142] In this example, experimental tests were made during the manufacture of the membrane. More specifically, the tests aimed at determining whether the initial PGe layer thickness had any impact on the resulting coupling strength. In these embodiments, the manufacturing includes a step of, prior to the deposition of the first non-porous layer, making the PGe layer in the germanium substrate based on an initial PGe layer thickness. As discussed, the initial PGe layer thickness can be part of the set of manufacturing parameters. In these embodiments, the etching conditions with which the germanium substrate is etched can be changed to obtain the initial PGe layer thickness, for instance. Figs. 10A-E show germanium substrates having porous layers of different thicknesses used in these

experiments. Figs. 10F-J are cross-sectional views showing the same germanium substrates after the deposition of germanium membranes on the respective porous layers. As shown, the pillar diameter, pillar height, and pillar density seem to change depending on the initial porous layer thickness. These results are shown in greater detail in Figs. 11A-11D. As such, in embodiments where the coupling strength indicator is indicative of weak coupling, the initial PGe layer thickness can be set to 250 nm or above. In contrast, in embodiments where the coupling strength indicator is indicative of a strong coupling, the initial PGe layer thickness can be set to 200 nm or below.

[00143] Example 3 - Post-deposition annealing temperature to tune coupling strength variation of detachable germanium membranes via porous germanium transformation

[00144] In this example, there is presented a method of manufacturing a germanium membrane on a germanium substrate. The method generally has a first step of, at a first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate. The method further includes a second step of, at a second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers. The method also includes a third step of, after said depositing the first non-porous layer and said depositing the second non-porous layer, heating the first and second non-porous layers of germanium and the germanium substrate up to a first annealing temperature for a first period of time, the first annealing temperature greater than the first and second deposition temperatures. This method is often referred to as the “post-growth annealing” method.

[00145] In embodiments where it is desirable to produce a weak coupling between the germanium membrane and the germanium substrate, the following manufacturing parameters are considered. For instance, in these embodiments, the first annealing temperature preferably ranges between 500°C and 725°C. Additionally or alternately, the porous layer can be produced or selected to exhibit a porosity ranging between 50% and 55% and a thickness ranging between 300 nm and 400 nm.

[00146] In embodiments where it is desirable to provide a strong coupling between the germanium membrane and the germanium substrate, the first annealing temperature typically ranges between 775°C and 850°C. In some embodiments, the porous layer has a porosity ranging between 50% and 55% and a thickness ranging between 200 nm and 300 nm, which can also favor such a stronger coupling.

[00147] In an exemplary application in which the germanium membrane is to be used as a substrate for a photovoltaic device, the first annealing temperature ranges between 650°C and 750°C whereas the first period of time ranges between 45 minutes and 75 minutes. Such conditions would correspond to a weak to medium coupling, and it was found to be satisfactory in photovoltaic applications. Also, regarding the porous layer, porosity ranging between 50% and 55% and a thickness ranging between 200 nm and 300 nm were found to be satisfactory.

[00148] The above method is discussed in the following paragraphs which explore the impact of postdeposition (or equivalently “postgrowth”) thermal annealing on coupling strength of detachable germanium membrane supported by nano-sized pillars on the parent germanium substrate. The postdeposition annealing step is sometimes referred to as the “first annealing step” in this disclosure. The first annealing step can be defined as a step in which the manufacture of the membrane includes, after the deposition of the second non-porous layer, heating the first and second non-porous layers up and the germanium substrate to a first annealing temperature for a given period of time. As discussed in more detail below, it was determined that in embodiments where the coupling strength indicator is indicative of a weak coupling, the first annealing temperature can be set between 500°C and 725°C. In embodiments where the coupling strength indicator is indicative of a strong coupling, the first annealing temperature can be set between 775°C and 850°C. In embodiments where the coupling strength indicator is indicative of medium coupling, the first annealing temperature can be set between 725°C and 775°C, exclusively, but these embodiments may not be preferred. It was demonstrated that the membrane coupling strength can be efficiently engineered through tailoring the pillar density and size by post deposition thermal treatment. Accordingly, pull-test detachment measurements, SEM imaging and FEM-based simulations are brought together to provide a systematic study of the morphological changes of the pillar-based separation layer and its impact on the coupling strength of the detachable membrane.

In addition, the fitting between the simulations and the experiments is used to extract the specific fracture strength of the used Ge structure.

[00149] In this example, post-growth engineering of the coupling strength of a germanium membrane on a PGe substrate was explored by inducing morphological transformations in the separation layer through Thermal Budget (TB) control. Indeed, the pillars formed through PGe sintering during deposition are found to evolve with post-deposition thermal annealing. Scanning electron microscopy (SEM) based on an analysis of the residue of the post detachment broken pillars has been performed showing that the pillar diameters and densities can be tuned by thermal annealing. Depending on the post-deposition annealing temperature, the membranes coupling strength can be successively tailored from 0.5 to up to 3.5 MPa while ensuring 100% detachment yield. The experimental results have been correlated with Finite Element Modeling (FEM) considering realistic pillar distribution revealing that pillar size and density are the dominant factors influencing the membrane coupling strength.

[00150] P-type (100) oriented Ge substrates with 6° miscut towards (111) direction and resistivity of 8-30 mΩ·cm are used in this study. The uniform PGe layers, across the entire 100 mm germanium substrate, are produced using bipolar electrochemical etching (BEE), with 1 $mA \cdot cm^{-2}$ symmetric etching/passivation etching current densities and 1 s pulse duration, in HF:EtOH (4:1;V:V) electrolyte solution. The resulting PGe layers have ~53% porosity and ~230 nm of thickness. After BEE, the substrates are rinsed in EtOH, dried under N_2. The germanium membranes are deposited by a two-step process with a 200 nm first non-porous layer deposited at 300°C, followed by deposition of 700 nm thick second non-porous layer at 450°C, in a hybrid VG Semicon V90F CBE/MBE reactor. The deposition is performed under high vacuum (~10^{-6} Torr) with a solid Ge source with K-cell heated to 1250 °C, and the deposition rate ~0.5µm/h. Following the deposition of germanium membrane, several samples of ~2 cm^2 have been subjected to post-growth thermal treatment under ($Ar:H_2$; 90:10) atmosphere for 1 h at temperatures varying between 650°C and 850°C in a Carbolite insulated tube furnace. This process starts with a ramp of 25°C/min and switches to 5°C/min 25°C before reaching the target value to avoid the overheat. After the annealing, the samples are cooled to room temperature. Surface and cross-sectional SEM imaging is performed using Zeiss LEO 1540 XB and Thermo Scientific Scios 2 Dual Beam SEM tools with acceleration

voltage set to 20 kV. The Root Mean Square (RMS) roughness is measured by atomic force microscopy (AFM) using the Veeco Dimension 3100 with SSS-NCHR silicon probe. The SEM images are processed in ImageJ software to determine the crystallite/void size, the morphology and thickness of the layers.

[00151] Samples are fixed on aluminum blocks (using J-B Weld 8281) from both the germanium membrane and germanium substrate back side, to provide gripping point for the uncoupling device. The force necessary for perpendicular separation of the thin germanium membrane from the parent substrate is measured using conventional pull test method conducted at velocity of 0.1 mm/s. The maximum load provided by the machine can attain 600 N. The measured force required for the vertical layer separation is then divided by the surface are of the detached membrane, to obtain the value of the coupling strength (in MPa). To simulate the pull test detachment process and to study the influence of the pillar characteristics on the epilayer coupling under the quasi-static assumption, a 3D semi-empirical FEM model has been developed using COMSOL Multiphysics [(V 6.0, COMSOL AB, Stockholm, Sweden). This model is referred to as Random Pillar Distribution (RPD) in the following. As illustrated schematically in Fig. 13A, RPD model was used to simulate the realistic case of randomly distributed size and position of pillars. For this purpose, the input geometry is obtained by converting multiple local plan-view SEM images to binary format. A uniform axial stress equal to the load limit of the pull-test machine is then applied on the membrane, while the substrate is clamped, to mimic the experimental configuration.

[00152] Tetrahedral elements and a stationary solver are considered for meshing and solving of the problem (Fig. 13B). The coupling strength is estimated for different configurations of the RPD model, based on extraction of the maximal value of axial stress in the pillars.

[00153] The Ge material properties used for the simulation are 103 GPa for Young's modulus and 0.26 for the Poisson ratio for (100) orientation. Here, we will use the FEM simulation to determine the fracture strength of the used structure.

[00154] After porosification (Fig. 14A), a 200 nm thick Ge first non-porous layer was deposited at low temperature (300°C) on top of the PGe layer, enabling the deposition of the second non-porous layer at 450°C, without affecting the germanium membrane surface

quality. The thermal budget (TB) during the deposition of the first non-porous layer leads to the reconstruction of the PGe layer into pillars connecting the germanium membrane to the germanium substrate as shown in Fig. 14B. The formation of distinct pillars from a continuous sponge-like porous structure can be attributed to the PGe reorganization following the Oswald ripening phenomena. The resulting pillars have a diameter of 79 nm ±10 nm and a height of 110 nm, corresponding to a total initial shrinkage of the PGe layer thickness by 52%. The RMS surface roughness of the germanium membrane is around 0.7 nm ± 0.3 nm (Fig. 14C).

[00155] To study the impact of the thermal budget on the porous microstructure morphology and its relation to the coupling strength. Annealing experiments were conducted; The results are reported in SEM images of Figs. 15A-E, one can observe a well-defined pillars-constituted separation layer was maintained after annealing up to 800°C, while the pillar morphology undergoes substantial morphological transformations.

[00156] Indeed, by increasing the annealing temperature, the overall pillars size and spacing increase, while their overall density decreases. In the meantime, the average pillar height shows a small decrease by approximately 10 nm compared to the as-deposited sample for annealing temperatures below 750°C. At 750°C The large submicron to micron-scale pillars with different shapes appear as shown in Figs. 15C and 16D. This indicates that more and more small size pillars are merging, leading to larger pillars with lower pillar density. This trend is further confirmed at higher temperatures, above 750°C, where the separation layer appears to be dominated by large pillars with micron scale lateral size. Moreover, at these elevated annealing temperatures providing high thermal energy to the system, the inter-pillars void spaces gradually reorganize into bigger cavities having a more energetically favorable 3D shape, tending to spherical shaped voids as depicted in Fig. 15E.

[00157] More insights on the quantitative characteristics of the separation layer morphology are obtained by plan-view SEM imaging. For this purpose, the germanium membranes have been mechanically detached from the substrate, leaving broken pillars on the substrate surface allowing their analysis by plan-view SEM observation. A full detachment yield has been achieved for structures annealed up to 750°C. On the contrary, samples annealed at 800°C and 850°C show a coupling strength higher than setup limits of employed pull test apparatus which is 4.5MPa, therefore the corresponding membranes could not be detached

within our experimental conditions. Consequently, for these structures the pillars characteristics are roughly estimated based on SEM cross-section imaging. Figs. 16A-D show plan-view SEM images of the substrates after the detachment, revealing more details on the pillar spatial and morphological distribution. For more quantitative analysis, these images are analyzed to obtain the pillar distribution, which is then fitted by lognormal function to obtain mean diameter of the pillars for each sample as depicted in Figs. 16E-H.

[00158] The plan-view images confirm the previous assessment of the pillars morphological transformation trend based on the cross-sectional SEM images. Indeed, as the annealing temperature increases, the pillar density decreases, and the average diameter continuously increases, as revealed in Figs. 16E-H. This trend can be understood as the primary transformation of the smaller size pillars into supplementary Ge materials, effectively feeding the inner surfaces of the separation layer. This is likely to induce the overall observed slight shrinkage of the weak layer height as well as a relative pillar diameter increase. Furthermore, closely spaced pillars may also coalesce leading to the observed average diameter growth, while increasing their size dispersion and decreasing their overall density. Indeed, a simple correlation between the cross-sectional and the plan-view images reveals two regimes depending on the TB. Below 750°C, the weak layer characteristics are governed by the smaller size pillars transformation preserving a relatively constant height. For annealing temperature above 750°C, the transformation towards larger lateral size stable and sufficiently spaced pillars leads to the evolution separation layer through the separation void transformation towards more energetically stable faceted 3D voids.

[00159] The evolution of the pillar density and their average diameter as a function of the annealing temperature is shown in Fig. 17A. Initially, the pillar average diameter slowly increases with increasing TB, from 79 nm for the as-grown structure to over 251 nm at 750°C. Then, for 800°C and 850°C, we observe faster pillar size increase, reaching 1.8 µm in diameter, as the voids starts to form faceted 3D features. Additionally, the pillar density decreases exponentially with annealing temperature from $2.6x10^9$ pillars/cm^2 for the as-deposited structure to $1x10^8$ pillars/cm^2 at 750°C, and $1x10^7$ pillars/cm^2 at 850°C. These post-growth annealing induced significant separation layer morphological transformations suggesting considerable impact on its mechanical properties. To evaluate this parameter, we

have studied the influence of separation layer morphology on the coupling strength of the germanium membrane, derived from the detachment force measured by the pull-test setup.

[00160] The average values of the experimental coupling strength are presented as a function of the annealing temperature in Fig. 17B along with the corresponding error bars. The coupling strength is found to initially decrease with increasing annealing temperature, reaching a minimum at 700°C, and then to increase monotonically for higher annealing temperatures. Furthermore, as previously mentioned, the samples annealed at 800°C and 850°C are not detachable within the available pull test experimental conditions indicating a coupling strength higher than 4.5 MPa.

[00161] The observed coupling strength variation can be correlated with the pillars size and density variation represented in Fig. 17A. Indeed, the coupling strength decrease seems to be correlated with the drop in the pillar density rather than the slight diameter increase. However, the increase of the pillars size for annealing temperature above 700°C becomes the dominant factor governing the membrane coupling strength.

[00162] Therefore, depending on the desired application and/or the lift-off method, it is critical to find the right balance between pillar width and density, as excessively high values of either of these parameters can hinder the detachment process. Thus, careful attention needs to be paid to the interplay between the diameter and the density to achieve the desired level of detachment ease.

[00163] To further evaluate the studied structure and experimental coupling strength indicators, FEM simulations were performed using a realistic description of the pillars auto-organization nature based on a random distribution. The exact input pillars geometry for each annealing temperature was built by converting the plan-view SEM images (Figs. 16A-D) to binary images (Figs. 18A-D).

[00164] Given the wide range of available values for the bulk Ge fracture strength, we used the upper (160 MPa) and lower (40 MPa) limit values to determine the simulation range of the membrane coupling strength, represented by the gray area in Fig. 19. Interestingly, the calculated coupling strength follows the same trend as the experimental measurements.

Furthermore, the experimentally measured coupling strength mean value lies between the highest and the lowest simulated coupling force values. The best fitting of the experimental measurements with the FEM simulations allowed to extract a value of 88 MPa as the most suited bulk Ge material fracture strength for the investigated structures. Indeed, as shown in Fig. 19, the simulated coupling strength perfectly matches the mean experimental values regardless of the annealing conditions (pillar density and size distribution). Since the simulation model does not consider any structural defects that may impact the membrane coupling strength, the obtained results are likely to suggest a defect-free separation layer. This finding agrees with our previous investigation using high-resolution transmission electron microscopy of a separation layer with similar nanosized pillars, showing the absence of any structural defects in both pillar interfaces that could facilitate the detachment.

[00165] The FEM simulation is modeled on structure without defects in the interfaces of the pillar with the membrane and the substrate. The agreement between the simulation and the experimental measurements makes the studied morphology more likely to be considered as a defect-free structure suggesting that the coupling variation is governed only by the evolution of the morphology of the pillar.

[00166] The difference between the Ge fracture strength obtained in this work and that reported for the polished germanium substrate (160 MPa) can be explained by the presence of angles in the structure geometry, the perpendicularity of pillars to the substrate and the germanium membrane that weakens the coupling strength and creates fracture seeds.

[00167] To estimate the coupling strength of the un-detached structure at 800°C and 850°C, a different FEM model was used, the extracted data from cross-section images helped to create structure with a uniformly distributed pillars with fixed diameter and spacing between pillars determined from the measured density. The calculated coupling strengths are 5.8 and 7.3 MPa for 800°C and 850°C respectively (Fig. 19).

[00168] In summary, this example reports the post-growth engineering of the germanium membrane coupling strength on a PGe substrate through Thermal Budget-induced transformations of the morphology of the separation layer. Thus, the latter is formed of pillars connecting the detachable membrane to the substrate is found to undergo distinct

morphological transformations depending on the post-deposition annealing temperature. The results show that the density of the pillars decreases, while their average diameter increases with increasing TB. The membrane coupling strength is found to first decrease with increasing the TB within a regime dominated by the pillar density. However, at higher annealing temperatures, increasing the size of the pillars, accompanied by cavities transformation, are found to strengthen the membrane coupling to its parent substrate. 3D FEM simulations of the membrane coupling strength were carried out using the semi-empirical model and compared with experimentally measured values. A bulk fracture strength of 88 MPa was computed by fitting empirical data with the FEM modeling.

[00169] These results highlight the ability to perform controllable post-deposition tuning of the membrane coupling strength to achieve the desired level of detachment ease required for the device lift-off method of choice. Furthermore, the results allow for optimizing the detachable membrane deposition steps to tailor the force with which the membrane can be attached from the substrate based on the allocated TB. These findings pave the way to a controllable membrane detachment, leading to considerable progress towards the development of lightweight and low-cost solar cells and optoelectronic devices.

[00170] Example 4 – Results demonstrating a relationship between coupling strength and pillar surface coverage

[00171] In another aspect, there is presented a method of manufacturing a germanium membrane on a germanium substrate. The method generally has a first step of, at a first deposition temperature, depositing a first non-porous layer of germanium onto a PGe layer of the germanium substrate. This deposition closes pores of the PGe layer, thereby trapping a volume of void within the PGe layer, while maintaining an original structure of the pores. The entrapment of void is favored when the first non-porous germanium layer is deposited swiftly. Accordingly, the deposition rate for this step is important, and can range between 1 nm/min and 20 nm/min, preferably between 1 nm/min and 10 nm/min and most preferably between 1 nm/min and 5 nm/min. The method includes a second step of, at a second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers. The deposition rate for this second step is immaterial, as it will

only impact the thickness of the second non-porous germanium layer and not the resulting coupling strength. The method includes a third step of modifying the original structure of the pores by heating the germanium substrate to a given temperature for a given period of time. The modification includes the transformation of the pores into a number of bigger cavities defining pillars extending between the germanium substrate and the first non-porous layer. The pillars are defined by a pillar surface coverage Cps ranging between 1 % and 35 % in this aspect.

[00172] For instance, the pillar surface coverage can be given by: $Cps = \frac{\sum_{i=1}^{N} Ap_i}{Am}$, where Ap_i denotes a cross-sectional area of an ith pillar, N denotes a total number of pillars, Am denotes a total area of the germanium membrane. The pillar surface coverage can also be given by: $Cps = Dp \cdot Ap_{avg}$, where Dp denotes a pillar density, and Ap_{avg} denotes an average pillar cross-sectional area. In some embodiments, the pillars have a circular shape. Accordingly, the average pillar cross-sectional area Ap_{avg} can be given by $Ap_{avg} = \pi\left(\frac{D_{avg}}{2}\right)^2$, where D_{avg} denotes an average pillar diameter. Depending on the circumstances, and the measurements made on the pillars, one of the equations will appear as appropriate.

[00173] In view of the examples presented above, the application of heat to transform the original morphology/structure of the pores can be performed in more than manner and obtain similar results. More specifically, the step of heating can be performed: 1) during the deposition of the first non-porous germanium layer, ii) after the deposition of the first non-porous germanium layer and prior to the deposition of the second non-porous germanium layer, iii) during the deposition of the second non-porous germanium layer, iv) after the deposition of the second non-porous germanium layer, or a combination thereof. The pillar surface coverage reduces as more heat is applied to the membrane. Indeed, as heat is applied, crystallites (i.e., germanium atoms or groups of germanium atoms) acquire kinetic energy and vibrate, which tend to regroup them with one another. As such, the pillars become gradually larger is size, but reduced in number, which tends to reduce the overall pillar surface coverage. It was found that such a morphology change can occur satisfactorily only when a sufficient amount of void (e.g., air) is trapped within the PGe layer by the deposition of the first non-

porous germanium layer. The above paragraphs and examples show different combinations of how to achieve satisfactory pore transformation.

[00174] Fig. 20 shows experimental results demonstrating the relationship between coupling strength as a function of pillar surface coverage, in accordance with an embodiment. As discussed above, the membrane is linked to the substrate through pillars obtained after the reorganization of the porous structure. The characteristics of the pillars vary with varying initial parameters like the PGe structure thickness and porosity and the applied thermal budget (the applied heat). The adhesion force is directly influenced by the characteristics of the pillars, illustrated generally with some parameters: the pillars mean diameter and the pillar density. Larger pillars and/or higher density gives high adhesion force to the membrane and smaller pillars and/or lower density decrease the adhesion force and facilitate the detachment. It is observed that the increase in pillar mean diameter is generally coupled with the decrease in pillar density which can be explained by the OR phenomena. Pillar surface coverage is a parameter that combines the pillar mean diameter and the pillar density. It represents the percentage of the lateral surface covered by the pillars. As depicted in Fig. 20, it was found that the coupling strength varies linearly with the pillar surface coverage. As shown, across the range of relevant applications, the germanium membrane is coupled to the germanium substrate with a coupling strength ranging between 0.25 MPa and 4.5 MPa.

[00175] In applications where a weak coupling is sought after, the pillar surface coverage ranges between 1% and 5%, and the coupling strength ranges between 0.25 MPa and 0.75 MPa. In addition to the methods described above, such a weak coupling can be obtained by using a porous layer having a thickness ranging between 300 nm and 500 nm. In some embodiments, the porous layer has a porosity ranging between 50% and 60%. Having PGe layers of greater thicknesses and/or greater porosities can help in trapping a greater quantity of void within the PGe layer, which can then help to contribute to a lower pillar surface coverage.

[00176] In applications where an intermediate coupling is desired, the pillar surface coverage generally ranges between 5% and 15%, the coupling strength ranging between 0.75 MPa and 2.25 MPa. In these embodiments, the PGe layer has a thickness ranging between 200 nm and 300 nm and a porosity ranging between 30% and 50%.

[00177] In applications where a strong coupling is preferable, the pillar surface coverage can range between 20% and 35%, and the coupling strength can range between 2.75 MPa and 4.5 MPa. In these embodiments, the PGe layer has a thickness ranging between 100 nm and 200 nm and a porosity ranging between 20% and 30%. Indeed, having thinner PGe layers, or porous layers of reduced porosities, can lead to less void being trapped within the porous layer as the first non-porous germanium layer is deposited, which in turns can contribute to a greater pillar surface coverage.

As can be understood, the examples described above and illustrated are intended to be exemplary only. For instance, in some embodiments, the first and second deposition steps are performed one after the other with a temperature increasing mimicking a step-like function. However, in some embodiments, the first and second deposition steps can be performed in a continuous manner in which the temperature increase is smooth and continuous from the first deposition temperature to the second deposition temperature. It is noted that although the present description emphasizes germanium as semiconductor material, it is intended that the method and system described herein can be applied for any other semiconductor material. Examples of such semiconductor material can include, but are not limited to, silicon (Si), indium tin oxide (ITO), zinc oxide (ZnO), III-V semiconductor materials such as gallium arsenide (GaAs), indium phosphide (InP), gallium nitride (GaN), Indium gallium arsenide (InGaAs), indium gallium phosphide (GaInP), aluminum gallium arsenide (AlGaAsP), indium gallium arsenide phosphide (InGaAsP), aluminum gallium indium phosphide (AlGaInP), aluminum gallium indium phosphide (InAlGaP), aluminum gallium indium phosphide (InGaAlP), aluminum gallium indium phosphide (AlInGaP), III-V heterostructures such as gallium nitride on silicon (GaN/Si), aluminum nitride on silicon (AlN/Si), gallium arsenide on silicon (GaAs/Si), gallium phosphide on silicon (GaP/Si), indium gallium arsenide on silicon (InGaAs/Si), aluminum indium nitride on silicon (AlInN/Si), gallium indium nitride on silicon (GaInN/Si), and other types of suitable semiconductor heterostructures. The semiconductor material can be monocrystalline, polycrystalline, and the like. It is noted that the ranges for deposition temperature, annealing temperature, their corresponding rates and durations, are meant to be exemplary, as they can change depending on which type of manufacturing machines or processes are used. The scope is indicated by the appended claims.

WHAT IS CLAIMED IS:

1. A method of manufacturing a germanium membrane on a germanium substrate, the method comprising:

selecting a coupling strength indicator, the coupling strength indicator indicative of a force which when applied to the germanium membrane uncouples the germanium membrane from the germanium substrate;

determining a set of manufacturing parameters based on the coupling strength indicator using reference data associating a plurality of reference sets of manufacturing parameters with corresponding reference coupling strength indicators, the set of manufacturing parameters including at least a first deposition temperature and a second deposition temperature higher than the first deposition temperature; and

manufacturing the germanium membrane on the germanium substrate based on the set of manufacturing parameters, said manufacturing including:

at the first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate; and

at the second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers.

2. The method of claim 1 further comprising applying an uncoupling force to the germanium membrane, the uncoupling force greater than the force of the coupling strength indicator, thereby obtaining an uncoupled germanium membrane and a germanium substrate having a detachment surface.

3. The method of claim 1 or 2 further comprising cleaning the detachment surface of the germanium substrate, making another porous layer in the germanium substrate, and manufacturing a second germanium membrane on the germanium substrate.

4. The method of any one of claims 1 to 3 wherein when the coupling strength indicator is indicative of a weak coupling, the first deposition temperature is set between 275°C and 325°C, and when the coupling strength indicator is indicative of a strong coupling, the first deposition temperature is set between 350°C and 400°C.

5. The method of any one of claims 1 to 4 wherein when the coupling strength indicator is indicative of a weak coupling, the second deposition temperature is set between 525°C and 575°C, and when the coupling strength indicator is indicative of a strong coupling, the second deposition temperature is set between 425°C and 475°C.

6. The method of any one of claims 1 to 5 wherein the set of manufacturing parameters has a first annealing temperature, said manufacturing including, after said depositing the second non-porous layer, heating the first and second non-porous layers and the germanium substrate up to the first annealing temperature for a given period of time preferably ranging between 45 minutes and 75 minutes.

7. The method of claim 6 wherein when said coupling strength indicator is indicative of a weak coupling, the first annealing temperature is set between 500°C and 725°C, and when said coupling strength indicator is indicative of a strong coupling, the first annealing temperature is set between 775°C and 850°C.

8. The method of any one of claims 1 to 7 wherein the set of manufacturing parameters has at least one of an initial porous layer thickness and an initial porous layer porosity, said manufacturing including, prior to said depositing the first non-porous layer, making the porous layer in the germanium substrate based on the at least one of the initial porous layer thickness and the initial porous layer porosity.

9. The method of claim 8 wherein when the coupling strength indicator is indicative of a weak coupling, the initial porous layer thickness is set between 250 nm and 400 nm, and when the coupling strength indicator is indicative of a strong coupling, the initial porous layer thickness is set between 100 nm and 200 nm.

10. The method of claim 8 wherein when the coupling strength indicator is indicative of a weak coupling, the initial porous layer porosity ranges between 50% and 60%, and

when the coupling strength indicator is indicative of a strong coupling, the initial porous layer porosity ranges between 20% and 50%.

11. The method of any one of claims 1 to 10 wherein said steps of depositing form a plurality of pillars extending within the porous layer of the germanium substrate, said selecting the coupling strength indicator including selecting at least one of a pillar dimension value indicative of an average pillar dimension, a pillar height value indicative of an average pillar height, and a pillar density value indicative of a pillar density.

12. A system for manufacturing a germanium membrane on a germanium substrate, the system comprising:

a computer receiving a coupling strength indicator, the coupling strength indicator indicative of a force which when applied to the germanium membrane uncouples the germanium membrane from the germanium substrate;

the computer determining a set of manufacturing parameters based on the coupling strength indicator using reference data associating a plurality of reference sets of manufacturing parameters with corresponding reference coupling strength indicators, the set of manufacturing parameters including at least a first deposition temperature and a second deposition temperature higher than the first deposition temperature;

a manufacturing device communicatively coupled to the computer, the manufacturing device configured for manufacturing the germanium membrane on the germanium substrate based on the set of manufacturing parameters, said manufacturing including:

at the first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate; and

at the second deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers; and

an uncoupling device communicatively coupled to the computer, said uncoupling device configured for applying an uncoupling force to the germanium membrane, the uncoupling force greater than the force of the coupling strength indicator, thereby uncoupling the germanium membrane from the germanium substrate.

13. The system of claim 12 wherein the uncoupling device is configured for pulling the germanium membrane from the germanium substrate.

14. The system of claim 12 or 13 wherein the reference data are stored on a non-transitory computer readable memory accessible to the computer.

15. A method of manufacturing a germanium membrane on a germanium substrate, the method comprising:

at a first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate;

at a second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers; and

after said depositing the first non-porous layer and said depositing the second non-porous layer, heating the first and second non-porous layers of germanium and the germanium substrate up to a first annealing temperature for a first period of time, the first annealing temperature greater than the first and second deposition temperatures.

16. The method of claim 15 wherein the first annealing temperature ranges between 500°C and 725°C.

17. The method of claim 16 wherein the porous layer has a porosity ranging between 50% and 55% and a thickness ranging between 300 nm and 400 nm.

18. The method of claim 15 wherein the first annealing temperature ranges between 775°C and 850°C.

19. The method of claim 18 wherein the porous layer has a porosity ranging between 50% and 55% and a thickness ranging between 200 nm and 300 nm.

20. The method of any one of claims 15 to 19 wherein the first annealing temperature ranges between 650°C and 750°C, the first period of time ranges between 45 minutes and 75 minutes, the porous layer having a porosity ranging between 50% and 55%, the porous layer having a thickness ranging between 200 nm and 300 nm.

21. A method of manufacturing a germanium membrane on a germanium substrate, the method comprising:

at a first deposition temperature, depositing a first non-porous layer of germanium onto a porous layer of the germanium substrate, said depositing the first non-porous layer closing pores of the porous layer, thereby trapping a volume of void within the porous layer, while maintaining an original structure of the pores;

at a second deposition temperature greater than the first deposition temperature, depositing a second non-porous layer of germanium onto the first non-porous layer, the germanium membrane having the first and second non-porous layers; and

modifying the original structure of the pores by heating the germanium substrate to a given temperature for a given period of time, said modifying including reorganizing the pores into a plurality of larger cavities interspersed with a plurality of pillars extending between the germanium substrate and the first non-porous layer, the plurality of pillars having a pillar surface coverage Cps ranging between 1 % and 35 %, the pillar surface coverage given by:

$$Cps = \frac{\sum_{i=1}^{N} Ap_i}{Am} = Dp \cdot Ap_{avg},$$

wherein Ap_i denotes a cross-sectional area of an ith pillar, N denotes a total number of pillars, Am denotes a total area of the germanium membrane, Dp denotes a pillar density, and Ap_{avg} denotes an average pillar cross-sectional area.

22. The method of claim 21 wherein the germanium membrane is coupled to the germanium substrate with a coupling strength ranging between 0.25 MPa and 4.5 MPa.

23. The method of claim 22 wherein the pillar surface coverage ranges between 1% and 5%, the coupling strength ranging between 0.25 MPa and 0.75 MPa.

24. The method of claim 23 wherein the porous layer has a thickness ranging between 300 nm and 500 nm.

25. The method of claim 23 wherein the porous layer has a porosity ranging between 50% and 60%.

26. The method of claim 22 wherein the pillar surface coverage ranges between 5% and 15%, the coupling strength ranging between 0.75 MPa and 2.25 MPa.

27. The method of claim 26 wherein the porous layer has a thickness ranging between 200 nm and 300 nm.

28. The method of claim 26 wherein the porous layer has a porosity ranging between 30% and 50%.

29. The method of claim 22 wherein the pillar surface coverage ranges between 20% and 35%, the coupling strength ranging between 2.75 MPa and 4.5 MPa.

30. The method of claim 29 wherein the porous layer has a thickness ranging between 100 nm and 200 nm.

31. The method of claim 29 wherein the porous layer has a porosity ranging between 20% and 30%.

32. The method of any one of claims 21 to 31 wherein said heating is performed at least one of: i) after said depositing the first non-porous germanium layer and prior to said depositing the second non-porous germanium layer, ii) during said depositing the second non-porous germanium layer, and iii) after depositing the second non-porous germanium layer.

33. The method of any one of claims 21 to 32 wherein the given period of time ranges between 45 minutes and 75 minutes.