FIG. 2
Published:
— with international search report (Art. 21(3))

Declarations under Rule 4.17:
— of inventorship (Rule 4.17(iv))
MECHANICALLY VIBRATED PACKED BED REACTOR AND RELATED METHODS

TECHNICAL FIELD

This disclosure generally relates to reactors, for example reactors used to prepare high purity silicon or doped silicon.

BACKGROUND

Silicon, specifically polysilicon, is a basic material from which a large variety of semiconductor products are made. Silicon forms the foundation of many integrated circuit technologies, as well as photovoltaic transducers. Of particular industry interest is high purity silicon.

BRIEF SUMMARY

A reactor system may be summarized as including a housing having a chamber therein; a pan received in the chamber of the housing, the pan having a major horizontal surface with a periphery and an upward extending peripheral wall that surrounds at least a portion of the periphery of the major horizontal surface; a cover received in the chamber of the housing, the cover having an upper surface, a lower surface, and a peripheral edge, the lower surface of the cover opposed to the major horizontal surface of the pan, wherein the cover, the major horizontal surface of the pan and the upward extending peripheral wall of the pan at least partially form a retention volume to at least partially temporarily retain particulate; an actuator that, in operation, vibrates the pan along at least a first axis perpendicular to the major horizontal surface of the pan to mechanically vibrate particulate in the retention volume to produce a mechanically vibrated packed particulate bed in the retention volume, wherein the cover restrains expansion of a volume of the mechanically vibrated packed particulate bed to an average of less than 7.5% of a volume of the particulate in the retention volume when not vibrated; and a heater that, in
operation, raises a temperature of the mechanically vibrated packed particulate bed in the retention volume above a thermal decomposition temperature of a first gaseous chemical species to thermally decompose the first gaseous chemical species within the mechanically vibrated packed particulate bed to a non-volatile second chemical species, at least a portion of which deposits on at least a portion of the plurality of particulates in the mechanically vibrated packed particulate bed to provide a plurality of coated particles. The cover may restrain expansion of a volume of the mechanically vibrated packed particulate bed to an average of less than about 3% of the volume of the particulate in the retention volume when not vibrated. The cover may be disposed above the major horizontal surface of the pan with the peripheral edge of the cover spaced inwardly of the peripheral wall of the pan with a peripheral gap between the peripheral edge of the cover and the peripheral wall of the pan which may provide a fluidly communicative passage between the retention volume of the pan and the chamber of the housing. The pan may have a circular profile and the cover has a circular profile, and the cover may be disposed above the major horizontal surface of the pan with the peripheral edge of the cover spaced radially inwardly of the peripheral wall of the pan with a peripheral gap between the peripheral edge of the cover and the peripheral wall of the pan which provides a fluidly communicative passage between the retention volume of the pan and the chamber of the housing. The cover may contact at least about 80% of an upper surface area of the mechanically vibrated packed particulate bed and less than 100% of the upper surface area of the mechanically vibrated packed particulate bed. The cover may include a cupola and a rim which surrounds the cupola. At least the bottom surface of the cover that is part of the rim is flat and the cupola may form a concavity in the bottom surface of the cover.

The reactor may further include a product removal tube having an inlet, the inlet positioned above a lowest-most portion of the lower surface of the cover, the lowest-most portion being a portion that is perpendicularly closest to
the major horizontal surface of the pan. The inlet of the product removal tube may be positioned at least ¼ inch above the lowest-most portion of the lower surface of the cover. The inlet of the product removal tube may be positioned at least ½ inch above the lowest-most portion of the lower surface of the cover. The cover may include a cupola that forms a concavity in the bottom surface of the cover and a rim which surrounds the cupola, the lowest-most portion being the rim of the cover. The inlet of the product removal tube may be positioned in a free space region above an upper surface of the mechanically vibrated packed particulate bed.

The reactor system may further include a flange that extends radially from the product removal tube, the flange spaced between the inlet of the product removal tube and the major horizontal surface of the pan. The flange may be positioned about ½ inch below the inlet of the product removal tube. The flange may be a radial flange and is positioned about level with the lowest-most portion of the lower surface of the cover. The product removal tube may extend through and may be hermetically sealingly coupled to the major horizontal surface of the pan.

The reactor system may further include a number of injectors each having a respective outlet, the injectors fluidly coupled to a first gaseous chemical species distribution header, the outlets of the injectors positioned between the major horizontal surface of the pan and the bottom surface of the cover. The injectors may be radially disposed about the product removal tube.

The cover may be apportioned into a raised portion and a non-raised portion, the raised portion may include a portion of the cover directly above and extending radially outward from the product removal tube such that the distance between a lower surface of the raised portion of the cover and the major horizontal surface may be greater than the distance between the lower surface of the non-raised portion of the cover and the major horizontal surface, and may further include a product removal tube having an inlet, the inlet positioned above a level of the non-raised portion of the cover and below a
level of the raised portion of the cover. The non-raised portion of the cover may include a wall that may be symmetrically arrayed about the outlet of the product removal tube.

A method of operation in a reactor system may be summarized as including charging a pan with particles, the pan having a major horizontal surface with a periphery and an upward extending peripheral wall that surrounds at least a portion of the periphery of the major horizontal surface; restraining an expansion of the particles in the pan via a cover in a chamber of a housing, the cover having a lower surface, the lower surface of the cover opposed to the major horizontal surface of the pan, wherein the cover, the major horizontal surface of the pan and the upward extending peripheral wall of the pan at least partially form a retention volume to at least partially temporarily retain particulate; vibrating the pan along at least a first axis perpendicular to the major horizontal surface of the pan to mechanically vibrate particulate in the retention volume to produce a mechanically vibrated packed particulate bed in the retention volume, and raising a temperature of the mechanically vibrated packed particulate bed in the retention volume above a thermal decomposition temperature of a first gaseous chemical species to thermally decompose the first gaseous chemical species within the mechanically vibrated packed particulate bed to a non-volatile second chemical species, at least a portion of which deposits on at least a portion of the plurality of particulates in the mechanically vibrated packed particulate bed to provide a plurality of coated particles. The cover may restrain expansion of a volume of the mechanically vibrated packed particulate bed to an average of less than 7.5% of a volume of the particulate in the retention volume when not vibrated.

The method may further include withdrawing at least some of the coated particles via an inlet of a product removal tube, the inlet of the product removal tube positioned above a lower-most portion of the lower surface of the cover. Raising a temperature of the mechanically vibrated packed particulate
bed may include heating the major horizontal surface via a heating element contained by at least a portion of the pan.

The method may further include adding at least one dopant to the mechanically vibrated packed particulate bed.

5 BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative positions of elements in the drawings are not necessarily drawn to scale. For example, the shapes of various elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements, as drawn, are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of recognition in the drawings.

Figure 1 is a schematic view of an illustrative mechanically vibrated packed bed reactor, according to an illustrated implementation.

Figure 2 is a high level flow diagram of an illustrative crystal production method in which a pan of a reactor is charged with particles, vibrated, and heated while a first gaseous chemical species (e.g., silane) is decomposed in the pan to at least a non-volatile second chemical species (e.g., silicon) and a cover restrains expansion of particles in a vibrated particulate bed in the pan and in which particles are withdrawn from the packed bed, according to an illustrated implementation.

DETAILED DESCRIPTION

The present disclosure includes certain specific details to provide a thorough understanding of various disclosed implementations. The present disclosure makes clear to one of skill in the relevant art that practice of one or more implementations may include or omit one or more of such specific details or may replace or modify such specific details with other elements, features,
functions, or method acts. In other instances, to avoid unnecessarily obscuring
disclosure of the implementations, the present disclosure omits one or more
express explanations or express inclusions of certain specific details that the
present disclosure makes clear to one of skill in the art that practice of one or
more implementations may include or omit one or more of such specific details
or may replace or modify such specific details with other elements, features,
functions, or method acts (e.g., the present disclosure omits well-known
structures that one of skill in the relevant art associates with producing, for
example, silicon such as vessel design details, vessel construction details,
metallurgical properties, piping, control system design, mixer design,
separators, vaporizers, valves, controllers, final control elements, etc.). In one
or more instances, to avoid unnecessarily obscuring disclosure of the
implementations, the present disclosure omits one or more express
explanations or express inclusions of one or more advantageous elements,
features, functions, or method acts that the present disclosure makes clear to
one of skill in the relevant art.

Unless context requires otherwise, throughout the specification
and claims that follow, the word “comprising” is synonymous with “including”
and is inclusive or open-ended (i.e., does not exclude additional, unrecited
elements, features, functions, or method acts).

The present disclosure employs the terms “element,” “feature,”
“function,” “method act,” derivatives thereof, or variants thereof to mean “one or
more elements, features, functions, method acts, structures, characteristics,
materials, results, methods, or processes” (e.g., “element” means “one or more
elements, features, functions, method acts, structures, characteristics,
materials, results, methods, or processes”) unless an express statement or
context clearly dictates otherwise.

Reference throughout the present disclosure to “one
implementation,” “an implementation,” derivatives thereof, or variants thereof
means that one or more implementations include a particular element, feature,
function, or method act that the present disclosure discloses. Thus, any appearances of “in one implementation,” “in an implementation,” derivatives thereof, or variants thereof in the present disclosure do not necessarily all refer to the same implementation. Furthermore, the present disclosure makes clear to one of skill in the relevant art that implementations of the presently disclosed subject matter include each possible combination of the elements, features, functions, or method acts that the present disclosure discloses and that such implementations combine such elements, features, functions, or method acts in any suitable manner. For example, the present disclosure makes clear that respective implementations include individual elements, features, functions, or method acts that the present disclosure discloses (e.g., while the present disclosure may explain “A, B, and C,” a first respective implementation includes implementation of one or more As while a second respective implementation includes implementation of one or more Bs, and a third respective implementation includes implementation of one or more Cs) and also makes clear that various implementations include one or more of such elements, features, functions, or method acts (e.g., implementation of one or more As, Bs, or Cs).

As used in the present disclosure and the appended claims, the singular forms “a,” “an,” and “the” include plural referents (e.g., “the A” means “one or more As”) unless an express statement or context clearly dictates otherwise. As used in the present disclosure and the appended claims, plural forms of any terms in the present disclosure also include singular referents (e.g., “As” means “one or more As”) unless an express statement or context clearly dictates otherwise.

The present disclosure employs the terms “or,” “combination of,” “one or more,” “one or more of,” derivatives thereof, and variants thereof (e.g., “A, B, or C;” “any combination of A, B, or C;” “one or more As, Bs, Cs;” “one or more of A, B, or C;” etc.) to mean “any combination of one or more selected from” (e.g., “A;” “B and B;” “B and C;” “A, A, and C;” “A, B, C, and C” etc.)
without limitation to order, quantity, or inclusion of other elements, features, functions, or method acts unless an express statement or context clearly dictates otherwise.

The headings and Abstract of the Disclosure provided herein are for convenience only and do not interpret the scope or meaning of the implementations.

As used herein, the term "silane" refers to SiH₄. As used herein, the term "silanes" generically refers to silane or any derivatives thereof. As used herein, the term "chlorosilane" refers to a silane derivative wherein one or more hydrogen has been substituted by chlorine. The term "chlorosilanes" refers to one or more species of chlorosilane. Chlorosilanes are exemplified by monochlorosilane (SiH₃Cl or MCS); dichlorosilane (SiH₂Cl₂ or DCS); trichlorosilane (SiHCl₃ or TCS); or tetrachlorosilane, also referred to as silicon tetrachloride (SiCl₄ or STC). The melting point and boiling point of silanes increases with the number of chlorines in the molecule. Thus, for example, silicon is a gas at standard temperature and pressure (0°C/273 K and 101 kPa) while silicon tetrachloride is a liquid. As used herein, the term "silicon" refers to atomic silicon, i.e., silicon having the formula Si. Unless otherwise specified, the terms "silicon" and "polysilicon" are used interchangeably herein when referring to the silicon product of the methods and systems disclosed herein. Unless an express statement or context clearly dictates otherwise, concentrations expressed herein as percentages should be understood to mean that the concentrations are in mole percent.

As used herein, the terms "chemical decomposition," "chemically decomposed," "thermal decomposition," and "thermally decomposed" refer to a process by which a first gaseous chemical species (e.g., silane) is heated to a temperature above a thermal decomposition temperature at which the first gaseous chemical species decomposes to at least a non-volatile second chemical species (e.g., silicon). In some implementations, the first gaseous chemical species may also yield one or more third gaseous chemical...
decomposition byproducts (e.g., hydrogen). Such reactions may be considered as a thermally initiated chemical decomposition or, more simply, as a "thermal decomposition." It should be noted that the thermal decomposition temperature of the first gaseous chemical species is not necessarily a fixed value and may vary with the pressure at which the first gaseous chemical species is maintained.

As used herein, the term "mechanically fluidized" refers to the mechanical suspension or fluidization of particles forming a particulate bed, for example by mechanically oscillating or vibrating the particulate bed in a manner promoting flow and circulation (i.e., the "mechanical fluidization") of the particles. Such mechanical fluidization, generated by a cyclical physical displacement (e.g., vibration or oscillation) of the one or more surfaces supporting the particulate bed or a retention volume about the particulate bed, is therefore distinct from liquid or gaseous (i.e., hydraulic) bed fluidization generated by passage of a liquid or gas through a particulate bed. It should be noted with particularity that a mechanically fluidized particulate bed is not reliant upon passage of a fluid (i.e., liquid or gas) through the particulates of the particulate bed to attain fluid-like behavior. As such, fluid volumes passed through a mechanically fluidized bed can be significantly smaller than the fluid volumes used in a hydraulically fluidized bed. In addition, a quiescent (i.e., non-moving or at rest) plurality of particles represents a "settled bed" which occupies a "settled volume." When fluidized, the same plurality of particles occupies a "fluidized volume" which is greater than the settled volume occupied by the plurality of particles. Unless specified otherwise, the terms "vibration" and "oscillation," and variations of such (e.g., vibrating, oscillating) are used interchangeably herein.

As used herein, the terms "mechanically vibrated packed bed," "mechanically vibrated compressed bed," derivatives thereof, or variants thereof (e.g., mechanically vibrating packed bed, mechanically vibrating compressed bed, vibrated packed bed, vibrated compressed bed, vibrating packed bed,
vibrating compressed bed, packed bed, compressed bed, etc.) refers to a bed of particles that is mechanically vibrated (e.g., movement in at least a vertical direction) while expansion of the particle bed is limited or restrained. For example, mechanically oscillating or vibrating a particulate bed in a manner that a preponderance of particles comprising the particulate bed are in both immediate and sustained contact with each other such that the particles vibrate in three dimensions and rotationally with respect to each other may form a packed or compressed bed. In contrast, particles in a settled bed are fixed in place and do not vibrate or move with respect to one another while the settled bed has a settled volume. While a mechanically fluidized reactor vibrates particles of the settled bed to create a mechanically fluidized bed having a fluidized volume that has an expansion of 10% or more relative to the settled volume (i.e., a fluidized volume of a fluidized bed may be 110% or more of the settled volume of the settled bed), a vibrated packed bed reactor vibrates particles of the settled bed to create a mechanically vibrated packed bed having a packed volume that has an expansion that is limited or restrained to 1% to 5% relative to the settled volume (i.e., the volume of the packed bed may be 101% to 105% of the settled volume). Further, in a mechanically vibrated packed or compressed bed, particles vibrate with respect to each other and move at relatively slow rate, e.g., around 0.5 inches to 1 inch per 60 seconds. In contrast, in a mechanically vibrated fluidized bed, particles move at a rate of, for example, around 1 inch to 3 inches per second.

As used herein, the terms “particulate bed” and “heated particulate bed” refer to any type of particulate bed, including vibrated packed or compressed particulate beds, hydraulically fluidized particulate beds, or mechanically fluidized particulate beds. The term “heated fluidized particulate bed” can refer to a heated hydraulically fluidized particulate bed or a heated mechanically fluidized particulate bed. The term “hydraulically fluidized particulate bed” refers specifically to a fluidized bed created by passage of a fluid (i.e., liquid or gas) through a particulate bed. The term “mechanically
fluidized particulate bed" refers specifically to a fluidized bed created by oscillating or vibrating a surface supporting a particulate bed at an oscillatory frequency and/or oscillatory displacement sufficient to fluidize the particulate bed. The term "mechanically vibrated packed or compressed particulate bed" refers specifically to a bed created by oscillating or vibrating a surface supporting a particulate bed while restraining expansion of the particulate bed, for instance, to between 1% to 5% of height of a settled volume of the particulate bed.

Typically, mechanically vibrated fluidized bed reactors have characteristic vertical and radial patterns of flow of solids, depending on relative acceleration to gravity (Γ), (Γ = 4π²f²a/g, where f is a vibration frequency in cycles/sec, a is a vibration amplitude from a neutral point, and g is a gravitational constant). While there are break-points for the solids’ flow patterns at various Γ values, there are strong analogies between mechanically vibrated fluidized bed reactors and hydraulically fluidized bed reactors. These analogies include heat transfer and reaction kinetics. In a mechanically vibrated fluidized bed reactor, gas circulates around vibrating particles, with a localized gas flow pattern that results primarily from localized particle movement and a net movement of a bottom platen. At a bottom of a fluidized bed, particles move inward while particles rise upward in a middle of the bed and flow radially outward at a top of the bed. At very high Γ values, there can be localized gas pockets that form and collapse. In contrast to fluidized beds, the packed bed reactor of the present disclosure may totally or partially constrain a solids bed, thereby causing the solids bed to act quite differently with regard to particle and gas movement, expansion, segregation, relative acceleration, etc. than if such solids bed were in a fluidized bed reactor.

Figure 1 shows mechanically vibrated packed bed reactor system 4 according to one illustrated implementation. The mechanically vibrated packed bed reactor system 4 includes one or more housings 6 that have one or more respective chambers 8 therein. The housing 6 hermetically seals the
chamber 8 from an exterior of the housing 6. The chamber 8 may receive one or more pans 10 therein. The pan 10 includes one or more major horizontal surfaces 12 (i.e., bottom). The major horizontal surface 12 includes a periphery. One or more upward extending peripheral walls 14 surround at least a portion of the periphery of the major horizontal surface 12.

The chamber 8 may receive one or more covers 16. The cover 16 has one or more upper surfaces 18, lower surfaces 20, and peripheral edges 22. One or more orientations or shapes of the cover 16 cause the lower surface 20 of the cover 16 to oppose the major horizontal surface 12 of the pan 10. The cover 16, the major horizontal surface 12 of the pan 10, and the upwardly extending peripheral wall 14 of the pan 10 at least partially form a retention volume to at least partially retain particles 24.

One or more actuators (e.g., electric motor, solenoid, etc.) 26 coupled (e.g., via a drive train) to one or more of the pan 10, the cover 16, or the housing 6. The actuator 26 mechanically vibrates the pan 10 to vibrate or oscillate the particles 24. The actuator 26 vibrates the pan 10 at least along a vertical axis to produce one or more mechanically vibrated packed particulate beds 28 in the retention volume.

The cover 16 covers 80–95% of a cross-section of the packed particulate bed 28. The cover 16 at least partially constrains the packed particulate bed 28 at a top of the packed particulate bed 28, mechanically limiting the packed particulate bed 28. The cover 16 suppresses radial and vertical solids flow of the particles 24 in the packed particulate bed 28. Implementing baffles, e.g., serpentine baffles, radial baffles, etc., with the cover 16 advantageously further suppresses radial solids flow of the particles 24 in the packed particulate bed 28. The cover 16, however, advantageously allows a very modest bed expansion (e.g., about 1% to about 5%) and some minor degree of vertical particle movement. Unlike any element in a mechanically fluidized bed, the cover 16 may restrain expansion of a volume of the packed particulate bed 28 to an average of less than 7.5% of a volume that the
particles 24 in the retention volume consume when the particles 24 are not vibrated. Accordingly, the cover 16 restrains expansion to only a few percent such that all of the particles 24 in the packed particulate bed 28 simultaneously are in motion and have surfaces nearly always in contact or always in contact.

The cover 16 imposes a degree of constraint or restraint on the particles 24 in the packed particulate bed 28. Varying the degree of the constraint or restraint advantageously adjusts a degree of mechanically grinding of the particles 24 in the packed bed 28 (i.e., permitting further control over particle size). Varying the degree of the constraint or restraint also advantageously adjusts a degree of impedance of flow of reactant gas through the packed bed 28 (i.e., permitting further control over duration that a given portion of gas remains in contact with the particles 24). As the particles 24 grow in the packed bed 28, the particles 24 move very slowly upward in the packed bed 28, generally with little net radial particle motion. For example, net movement of a given particle in the packed particulate bed 28 may be on an order of a few tenths of an inch per minute (a few mm/minute) or an order of a tenth of an inch per second or less. Varying the degree of the constraint or restraint additionally advantageously adjusts movement and a degree of movement of the particles 24 in the packed bed 28. At least because the vibrating packed bed reactor system 4 causes the particles 24 in the packed particulate bed 28 to move at a considerably lower velocity than particles in a mechanically fluidized bed, the packed bed reactor system 4 advantageously reduces likelihood of producing chipped particles 24.

For example, varying the degree of grinding of the particles 24 in the packed bed 28 controls a rate of creating fine particulates (i.e., "fines") in the packed bed 28. Because fines grow to become particles 24 in the packed bed 28, varying the degree of grinding of the particles 24 in the packed bed 28 permits controlling a rate of replacing volume of withdrawn particles. Because the mechanically vibrated packed bed reactor system 4 constrains the packed bed 28, such controlled creation of fines advantageously need not increase
dusting that otherwise would dirty interior surfaces of the housing 6 external to the packed bed 28. In particular, higher gas flow rates or greater velocities of particles in other reactors precludes or substantially precludes retention of fines. Accordingly, the mechanically vibrated packed bed reactor system 4 permits continuous or substantially continuous production while reducing one or more of a frequency or a volume required with regard to feeding seed particulates to the pan 10 from an external source, e.g., a particulate feed system.

The cover 16 may include or delimit one or more open cross-sectional areas (i.e., non-restrained area). The open cross-sectional area may have a shape and size that causes the open-cross sectional area to create one or more non-constrained portions 30 or one or more outlets 32 at the top of the packed particulate bed 28. For example, the cover 16 may include one or more complete passages that fluidly couple the packed bed 28 and one or more upper chambers 34 of the chamber 8 external to the packed bed 28. The cover 16 may include one or more respective rims. The rim may at least partially surround the complete passage at a position on the lower surface 20 of the cover 16. The rim may include a portion of the lower surface 20 of the cover 16 proximate the complete passage. Additionally or alternatively, the peripheral edge 22 of the cover 16 or the peripheral wall 14 of the pan 10 may define the complete passage, e.g., the peripheral outlet 32, as illustrated in Figure 1. For example, the cover 16 may position the peripheral edge 22 inwardly of peripheral wall 14 of the pan 10, thereby forming a peripheral gap between the peripheral edge 22 of the cover 16 and the peripheral wall 14 of the pan 10.

The peripheral gap may define the peripheral outlet 32. For example, the cover 16 may have a circular profile such that the cover 16 is spaced radially inwardly of the peripheral wall 14 of the pan 10, thereby advantageously encouraging radially uniform or substantially radially uniform dispersion of the reactant gas through the packed bed 28 toward the peripheral outlet 32. Such position and construction of the outlet 32 also advantageously encourages the reactant gas
to flow toward peripheral edges of the packed bed 28. For example, responsive to introducing reactant gas proximate the center of the packed bed 28, such positioning and constructing of the outlet 32 advantageously encourages the reactant gas to contact particles that are proximate the center of the packed bed 28 and also particles that are proximate the peripheral edges of the packed bed 28.

Adjusting a size of the peripheral outlet 32 may also change a manner that the reactant gas disperses through the packed bed 28. For example, the peripheral outlet 32 may include a continuous outlet or multiple outlets spaced uniformly along at least one peripheral edge 22 of the cover 16, thereby encouraging reactant gas, when introduced proximate to the center of the packed bed 28, to disperse through the packed bed 28 toward the at least one peripheral edge 22 of the cover 16 in a radially uniform or substantially radially uniform manner. Adjusting the size of the peripheral outlet 32 also advantageously permits controlling a rate of flow of the reactant gas through the packed bed 28.

Additionally or alternatively to the complete passage defining the peripheral outlet 32, the cover 16 may include one or more complete passages that surround a portion of one or more product withdrawal tubes 36 (The term “product withdrawal tube,” the term “overflow tube,” and variants thereof are interchangeably implemented herein.) and create the non-constrained portion 30. The complete passage advantageously reduces likelihood of damaging or blocking the product withdrawal tube 36 or damaging the cover 16 when adjusting the degree of restraint or when adjusting a height of the product withdrawal tube 36. The complete passage also encourages reactant gas to escape through the complete passage, thereby advantageously encouraging the reactant gas to contact particles near the product withdrawal tube 36. The height of the product withdrawal tube 36 may be defined prior to manufacture and fixed. Alternatively, the height of the product withdrawal tube 36 may be adjustable, for instance between production runs in the reactor.
Additionally or alternatively to the complete passage, the cover 16 may include one or more cupolas that form one or more respective concavities in the cover 16. The cover may include one or more respective rims. The rim may at least partially surround the cupola at a position on the lower surface 20 of the cover 16. The rim may include a portion of the lower surface 20 of the cover 16 proximate the cupola. The cupola fluidly decouples the packed bed 28 from the upper chamber 8 external to the packed bed 28. Such fluid decoupling, in combination with movement of the pan 10 relative to the housing 6, causes increases and decreases in pressure in the packed bed 28 or the upper chamber 34 external to the packed bed 28. Such fluid decoupling advantageously encourages reactant gas, when introduced in the packed bed 28 at a position beneath or substantially beneath the cupola, to disperse through the packed bed 28 away from the cupola in a radially uniform or substantially radially uniform manner. Such fluid decoupling also advantageously prevents product from escaping through the cupola to the top surface 18 of the cover 16, thereby reducing likelihood of dirtying the top surface 18 of the cover 16 and subsequently contaminating such escaped particles.

The cupola may surround a portion of the product withdrawal tube 36 and create the non-constrained portion 30 as illustrated in Figure 1. The cupola advantageously reduces likelihood of damaging or blocking the product withdrawal tube 36 or damaging the cover 16 when adjusting the degree of restraint or when adjusting the height of the product withdrawal tube 36. The cupola may include one or more angled interior surfaces that direct particles that contact the one or more interior surfaces toward an opening of the product withdrawal tube 36, advantageously reducing likelihood that such particles repeatedly contact the interior surfaces and, as a result, reducing likelihood of producing chipped such particles. Additionally or alternatively, interior surface of the cupola may include one or more materials or structures that absorb or
disperse energy transferred by particles that contact the interior surfaces, advantageously reducing likelihood of producing chipped particles.

A distance between the lower surface of the cover 16 and the major horizontal surface 12 of the pan 10 may vary as a function of distance from one or more given positions. For example, the lower surface 20 of the cover 16 may vary as a function (e.g., linear function, non-linear function, smooth function — a function that has a defined first derivative at each point, non-smooth function — a function that lacks a defined first derivative at one or more points, rectangular function, step function, smooth step function, etc.) of distance from the peripheral edge 22 of the cover 16. Additionally or alternatively, the lower surface 20 of the cover 16 may vary as a function of distance from the product withdrawal tube 36. For example, at the peripheral edge 22 of the cover 16, the lower surface 20 of the cover 16 may have a first distance to the major horizontal surface 12 of the pan 10 while, at the proximate center of the cover 16, the lower surface 20 of the cover 16 may have a second distance to the major horizontal surface 12 of the pan 10 such that the second distance is greater than or less than the first distance. Accordingly, larger particles migrate toward a position on the lower surface 20 of the cover 16 that has the second distance to the major horizontal surface 12 of the pan 10. As a result, varying the lower surface 20 of the cover 16 as a function of distance from one or more given positions advantageously permits controlling migration of larger particles toward or away from the one or more given positions. Such variance in the lower surface 20 of the cover 16 may advantageously direct larger particles toward the product withdrawal tube 36 or the outlets 32.

Additionally or alternatively, one or more portions of the lower surface 20 of the cover 16 may have a shape and orientation that is parallel to the major horizontal surface 12 of the pan 10. Such parallelism between the lower surface 20 of the cover 16 and the major horizontal surface 12 of the pan 10 advantageously encourages uniform or substantially uniform dispersion of the gas toward the outlet 32 as opposed to congregation of the reactant gas in
volumes below one or more positions on the lower surface 20 of the cover 16 where a distance between the one or more positions and the major horizontal surface 12 of the pan 10 is greater than a distance between another position on the lower surface 20 of the cover 16 and the major horizontal surface 12 of the pan 10.

The product withdrawal tube 36 may have one or more inlets 38. At least because a mechanically fluidized bed reactor does not eject or substantially does not eject particulate of reasonable value above a mechanically fluidized bed of the mechanically fluidized bed reactor, positioning an inlet of a product withdrawal tube above an upper surface of a mechanically fluidized bed would be counterproductive. In a hydraulically fluidized bed of a hydraulically fluidized bed reactor, larger particles drop to a bottom. As a result, positioning an inlet of a product withdrawal tube above an upper surface of a hydraulically fluidized bed also would serve no practical purpose. Positioning the inlet 38 of the product withdrawal tube 36 above an average upper surface (e.g., approximately the lower surface 20 of the cover 16) of the packed bed 28 counterintuitively proves advantageous. Positioning the inlet 38 above a position on the lower surface 20 of the cover 16 that is closest to the major horizontal surface 12 of the pan 10 prevents the constraint of the cover 16 from forcing an excessive volume of particles into the inlet 38, thereby advantageously reducing likelihood of pinching particles against an edge of the inlet 38, also reducing likelihood of clogging the product withdrawal tube 36, and further reducing likelihood of premature withdrawal of particles from the packed bed 28. In particular, when the positioning of the inlet 38 is sufficiently high, such positioning permits withdrawal of particles that exhibit fluid characteristics in the non-constrained portion 30, thereby encouraging withdrawal of particles under a reduced degree of constraint compared to the particles 24 in the packed bed 28. Such withdrawal of particles advantageously permits adjusting a withdrawal rate by adjusting a height of the inlet 38.
For example, positioning the inlet 38 at least 0.25 inches (¼ inch) above the position on the lower surface 20 of the cover 16 that is closest to the major horizontal surface 12 of the pan 10 advantageously provides a substantially constant withdrawal of particles of sufficient size while reducing likelihood of potentially detrimental effects, e.g., those detrimental effects that the present disclosure discloses. As another example, positioning the inlet 38 at least 0.5 inches (½ inch) above the position on the lower surface 20 of the cover 16 that is closest to the major horizontal surface 12 of the pan 10 advantageously provides withdrawal of larger particles. Also as an example, positioning the inlet 38 in the non-constrained portion 30 above the upper surface of the packed bed 28 advantageously permits withdrawal only of particles that exhibit fluid characteristics while substantially ensuring that no withdrawal of particles occurs while such particles are under pressure from the cover 16. Alternatively, the inlet 38 may reside level with the position on the lower surface 20 of the cover 16 that is closest to the major horizontal surface 12 of the pan 10, e.g., proximate the non-constrained portion 30. Such positioning advantageously permits a large withdrawal rate while also preventing flooding the withdrawal particle tube 36 with particles under pressure from the lower surface 20 of the cover 16.

The product withdrawal tube 36 may include one or more flanges 40 that extend radially from the product withdrawal tube 36. The flange 40 may mount to the product withdrawal tube 36. Alternatively, the flange 40 may be integral with the product withdrawal tube 36. The flange 40 may reside below the inlet 38 of the product withdrawal tube 36. The flange 40 may have one or more lower surfaces, one or more upper surfaces, and one or more peripheral edges.

The lower surface of the flange 40 may reside at a given distance above the major horizontal surface 12 of the pan 10. The given distance between the lower surface of the flange 40 and the major horizontal surface 12 of the pan 10 may equate to a distance between the major horizontal surface
12 of the pan 10 and the lower surface 20 of the cover 16 at a position
proximate the flange 40 (e.g., the above disclosed rim). In such a position, the
flange 40 advantageously constrains a volume of the packed bed 28 below the
flange 40 in similar fashion to the lower surface 20 of the cover 16.

Additionally or alternatively, at least one lower surface of the
flange 40 may reside at a particular distance above the major horizontal surface
12 of the pan 10. The particular distance between the lower surface of the
flange 40 and the major horizontal surface 12 of the pan 10 may be less than
the distance between the major horizontal surface 12 of the pan 10 and the
lower surface 20 of the cover 16 at the position proximate the flange 40. In
such a position, the flange 40 advantageously constrains the volume of the
packed bed 28 below the flange 40 in similar fashion to the lower surface 20 of
the cover 16 while impeding horizontal migration of particles on the upper
surface of the packed bed 28.

Additionally or alternatively, at least one lower surface of the
flange 40 may reside at a defined distance above the major horizontal surface
12 of the pan 10. The defined distance between the lower surface of the flange
40 and the major horizontal surface 12 of the pan 10 may be greater than the
distance between the major horizontal surface 12 of the pan 10 and the lower
surface 20 of the cover 16 at the position proximate the flange 40. In such a
position, the flange 40 advantageously constrains the volume of the packed bed
28 below the flange 40 in similar fashion to the lower surface 20 of the cover, thereby
encouraging migration of particles on the upper surface of the packed bed 28
toward the non-constrained portion 30.

At least one lower surface of the flange 40 may be perpendicular
to an outer surface of the product withdrawal tube 36. Additionally or
alternatively to the perpendicular lower surface, at least one lower surface of
the flange 40 may be non-perpendicular to the outer surface of the product
withdrawal tube 36, i.e., an angled lower surface of the flange 40. The angled lower surface of the flange 40 may vary as a function (e.g., linear function, non-linear function, smooth function, non-smooth function, rectangular function, step function, smooth step function, etc.) of distance from the product withdrawal tube 36. For example, the angled lower surface may cause the peripheral edge of the flange 40 to reside at a height above a position on the angled lower surface that resides closer to the product withdrawal tube 36 than such peripheral edge of the flange 40. Additionally or alternatively, the angled lower surface may cause the peripheral edge of the flange 40 to reside at a height below the position on the angled lower surface that resides closer to the product withdrawal tube 36 than such peripheral edge of the flange 40. Such implementations of the lower surface of the flange 40 advantageously promote similar beneficial phenomena and results as explained above with regard to respective implementations of the lower surface 20 of the cover 16.

The upper surface of the flange 40 may reside at a given distance below the inlet 38 of the product withdrawal tube 36. The upper surface of the flange 40 contacts larger particles that migrate upward in the packed bed 28, thereby advantageously encouraging such larger particles to enter the inlet 38 of the product withdrawal tube 36. Varying a position of the upper surface of the flange 40 advantageously controls a size of particles withdrawn from the packed bed 28. For example, positioning the flange 40 at 0.25 inches (∼¼ inch) or about 0.25 inches (∼¼ inch) below the inlet 38 of the product withdrawal tube 36. As another example, positioning the flange 40 at 0.5 inches (∼½ inch) or about 0.5 inches (∼½ inch) below the inlet 38 of the product withdrawal tube 36.

The upper surface of the flange 40 may include one or more materials or structures that absorb or disperse energy transferred by particles that contact the upper surface of the flange 40, advantageously reducing likelihood of producing chipped particles. Additionally or alternatively, the upper surface of the flange 40 may fluidize particles that contact the upper surface of the flange
40, thereby encouraging such particles to enter the inlet 38 of the product withdrawal tube 36.

The upper surface of the flange 40 may be perpendicular or substantially perpendicular to the outer surface of the product withdrawal tube 36. The perpendicular upper surface advantageously creates a large volume above the flange 40, i.e., a large non-constrained portion 30. At least because the upper surface imparts more momentum to larger particles in the non-constrained portion 30 than smaller particles in the non-constrained portion 30, the perpendicular upper surface advantageously encourages larger particles in the non-constrained portion 30 to enter the inlet 38 of the product withdrawal tube 36.

Additionally or alternatively to the perpendicular upper surface, at least one upper surface of the flange 40 may be non-perpendicular to the outer surface of the product withdrawal tube 36, i.e., an angled upper surface of the flange 40. The angled upper surface of the flange 40 may vary as a function (e.g., linear function, non-linear function, smooth function, non-smooth function, rectangular function, step function, smooth step function, etc.) of distance from the product withdrawal tube 36. The angled upper surface of the flange 40 advantageously reduces likelihood of producing chipped particles that migrate into the non-constrained portion 30. For example, the angled upper surface may cause the peripheral edge of the flange 40 to reside at a height above a position on the angled upper surface that resides closer to the product withdrawal tube 36 than such peripheral edge of the flange 40. Such angled upper surface advantageously provides a sloped surface for particles to contact while encouraging particles that contact such angled upper surface to move toward the product withdrawal tube 36. Additionally or alternatively, the angled upper surface may cause peripheral edge of the flange 40 to reside at a height below the position on the angled upper surface that resides closer to the product withdrawal tube 36 than such peripheral edge of the flange 40. Such angled upper surface advantageously provides a sloped surface for particles to
contact while encouraging particles that contact such angled upper surface to return to the packed bed 28.

The peripheral edge of the flange 40 may form one or more gaps between the peripheral edge and the cover 16. For example, the peripheral edge of the flange 40 may form the gap by residing at a position that causes the peripheral edge of the flange 40 to partially or completely avoid contacting or connecting with the cover 16. The gap between the flange 40 and the cover 16 permits larger particles in the packed bed 28 to migrate into a volume above the flange 40, i.e., the non-constrained portion 30. Adjusting size or quantity of the gap between the flange 40 and the cover 16 advantageously permits further control of withdrawal rate and size of withdrawn particles.

Accordingly, the flange 40 advantageously promotes characteristics of the packed bed 28 in the volume below the flange 40 while permitting non-constraint of larger particles that migrate into the non-constrained portion 30 for withdrawal. The flange 40 also advantageously protects particles on the upper surface of the packed bed 28 from impact that particles in the non-constrained portion 30 above the flange 40 may otherwise impose on such particles on the upper surface of the packed bed 28, thereby advantageously reducing likelihood of producing chipped particles.

One or more particles may escape from, for example, the non-constrained portion 30 to a top surface 18 of the cover 16 responsive to the flange 40 contacting such particles while the complete passage defines the non-constrained portion 30. One or more top surfaces 18 of the cover may have one or more angles that encourage such escaped particles to return to the non-constrained portion 30, thereby advantageously reducing loss of product. Additionally or alternatively, the top surface 18 of the cover 16 may have one or more angles that encourage particles that escape to the top surface 18 of the cover 16 to return to a position that is different from the non-constrained portion 30, thereby advantageously causing such escaped particles to repeat a path or
take a new path to the non-constrained portion 30 or another non-restrained area and encouraging further growth of such escaped particles.

The chamber 8, e.g., the upper chamber 34, may receive one or more injectors 42 that fluidly couple to one or more first gaseous chemical species distribution headers 44. The injector 42 or header 44 may have one or more portions in the packed bed 28. Orientation of the portion of the injector 42 or header 44 in the packed bed 28 may render the portion of the injector 42 or header 44 parallel or substantially parallel to the outer surface of the product withdrawal tube 36. Various additional or alternative orientations of the portion of the injector 42 or header 44 advantageously reduce likelihood of grinding a particle that contacts the portion of the injector 42 or header 44 by reducing impedance that the portion of the injector 42 or header 44 impose on migrating particles in the packed bed 28. Various portions of the injector 42 or header 44 in the packed bed may have different orientations from each other. Additionally or alternatively, all portions of the portion of the injector 42 or header 44 in the packed bed 28 may have the same orientation as each other. For example, a given portion of the portion of the injector 42 or header 44 that resides proximate a volumetric center of the packed bed 28 may have an orientation that renders the given portion of the injector 42 or header 44 parallel to the axis that the packed bed 28 vibrates along, thereby advantageously running parallel or substantially parallel to a direction of migration of particles that contact the given portion of the injector 42 or header 44. Additionally or alternatively, a particular portion of the injector 42 or header 44 that resides proximate a portion of the peripheral wall 14 may have an orientation that renders the particular portion of the injector 42 or header 44 parallel or substantially parallel to such portion of the peripheral wall 14, thereby advantageously running parallel or substantially parallel to a direction of migration of particles that contact the particular portion of the injector 42 or header 44. Such parallel orientation also advantageously promotes upward migration of growing particles in the packed bed 28 over an orientation that renders a portion of the
injector 42 or header 44 perpendicular or substantially perpendicular to a
direction of migration of particles that contact such portion of the injector 42 or
header 44.

The injector 42 may include one or more outlets. The outlet may
reside between the major horizontal surface 12 of the pan 10 and the lower
surface 20 of the cover 16. At least two outlets may reside at different depths in
the packed bed 28, thereby advantageously encouraging uniform or
substantially uniform gas dispersion in a vertical dimension. Additionally or
alternatively, at least two respective outlets may reside at a same depth as
each other, thereby advantageously encouraging uniform or substantially
uniform gas exposure among particles at a given depth. The one or more
injectors 42 may be radially disposed about the product withdrawal tube 36,
thereby advantageously promoting uniform or substantially uniform gas
exposure among particles at a given distance from the product withdrawal tube
36.

The packed bed reactor system 4 may include one or more
rounded corners or rounded edges that contact the packed bed 28. For
example, one or more corners or edges of one or more above described
elements or features, e.g., one or more of the flange 40, the pan 10, the cover
16, the injector 42, the header 44, the product withdrawal tube 36, etc., may
include one or more rounded corners or edges. Such rounded corners or
rounded edges advantageously reduce likelihood of producing chipped
particles.

One or more first gaseous chemical species reservoirs 46 may
fluidly connect via the header 44. The first gaseous chemical species
reservoirs 46 may introduce controlled quantities of the first gaseous chemical
species to the packed bed 28 in the pan 10. One or more diluent or dopant
reservoirs 48 also may fluidly connect via the header 44. The diluent or dopant
reservoir 48 may introduce controlled quantities of the diluent to the packed bed
28 in the pan 10. Additionally or alternatively, the diluent or dopant reservoir 48 may fluidly connect via a different header than the header 44.

In some instances, the diluent or dopant feed reservoir 48 supplies one or more dopants to the upper chamber 34 or directly to the particulate bed 28. At times, the diluent or dopant feed reservoir 48 is fluidly coupled to the first gaseous chemical species feed reservoir 46 such that the first gaseous chemical species and the dopant are supplied via a number of injectors 42 to the particulate bed 28. At other times, the diluent or dopant feed reservoir 48 is separately fluidly coupled to the particulate bed 28 and/or the upper chamber 34. The diluent or dopant feed reservoir 48 may add the dopant to the particulate bed 28 contemporaneous with the first gaseous chemical species reservoir 46 adding the first gaseous chemical species to the particulate bed 28, thereby producing doped particles. Additionally or alternatively, the diluent or dopant feed reservoir 48 may add the dopant to the particulate bed 28 at one or more different times than when the first gaseous chemical species reservoir 46 adds the first gaseous chemical species to the particulate bed 28.

Illustrative dopants may include arsenic, germanium, selenium, or gallium. An example doped particle 24 produced by the reactor system 2 includes particles 24 containing boron or phosphorous doped silicon. Selection of the dopant may vary responsive to one or more crystallization techniques.

The mechanically vibrated packed bed reactor system 4 may maintain the gas within the chamber 8 at a low oxygen level (e.g., less than 20 volume percent oxygen) or at a very low oxygen level (e.g., less than 0.001 mole percent oxygen). Such advantageously reduces or eliminates oxide formation on exposed surfaces of the particles 24 in the packed bed.

One or more flexible members 50 may separate the chamber 8 into the upper chamber 34 and one or more lower chambers 52. The flexible member 50 may hermetically seal the upper chamber 34 and the lower
chamber 52 from each other and, thereby, hermetically seal all or a portion of
the packed bed 28 from the lower chamber 52. Such advantageously promotes
production of pure particles by preventing contamination, e.g., contamination
from metal shavings of elements that contact each other in the lower chamber
5 52 while moving relative to each other. By bi-furcating the volume in the
reactor, the flexible member (e.g., bellows) may also advantageously promote a
pumping or piston action, which forces gas (e.g., first gaseous species and/or
dopant) into the packed bed as the pan moves upward. Such may be
10 particularly useful in implementations in which gas is not delivered directly into
the packed bed, for instance via the injectors 42.

The flexible member 50 may include one or more materials,
geometries, or constructions that permit the flexible member 50 to withstand
potentially extended and repeated oscillation or vibration of the pan 10 along
the one or more axes of motion. For example, the flexible member 50 may
15 have a bellows type construction that accommodates the displacement of the
pan 10 along the axes of motion. In other instances, the flexible member 50
can include a boot or similar flexible coupling or membrane that incorporates or
includes a resilient material that is both chemically and thermally resistant to the
physical and chemical environment in both the upper chamber 34 and the lower
20 chamber 52.

In some implementations, the flexible member 50 may include
one or more insulations that retain heat within the upper chamber 34 or that
limit the transfer of heat from the upper chamber 34 to the lower chamber 52.
The insulation of the flexible member 50 may remain exposed to the lower
25 chamber 52 while remaining unexposed to the upper chamber 34. Such
positioning advantageously reduces likelihood of contamination of the
mechanically fluidized particulate bed 28 by the insulation.

The major horizontal surface 12 of the pan 10 includes at least an
upper surface 54 and a lower surface 56. The major horizontal surface 12 of
30 the pan 10 can include an integral, unitary, and single piece surface. Such
unitary structure advantageously reduces abrasion of the particles 24 in the packed bed. The integral, unitary, and single piece surface may include no penetrations or apertures. Such lack of penetrations or apertures advantageously prevents intrusion of contaminants into the packed bed 28. In some instances, the pan 10 may integrate the major horizontal surface with one or more remaining portions of the pan 10. Such integral structure advantageously reduces likelihood of trapping particles or contaminants in the pan 10. In other instances, the pan 10 includes one or more removable portions of the major horizontal surface 12, thereby advantageously facilitating the repair, rejuvenation, or replacement of a worn pan bottom or providing access to one or more thermal energy emitters 58 positioned proximate, integral to or beneath the major horizontal surface 12 of the pan 10.

The perimeter wall 14 may extend about only a portion of the periphery of the major horizontal surface 12 of the pan 10. In some instances, the perimeter wall 14 extends about the entire periphery of the major horizontal surface 12 of the pan 10. The perimeter wall 14 of the pan 10 may extend a fixed height above the major horizontal surface 12 of the pan 10 for the entire length of the perimeter wall 14. At other times, the perimeter wall 14 of the pan 10 may extend a first fixed height above the major horizontal surface 12 of the pan 10 for a first portion of the length of the perimeter wall 14 and a second fixed height above the major horizontal surface 12 of the pan 10 for a second portion of the length of the perimeter wall 14. In some implementations, the height of the perimeter wall 14 is greater than the depth of the packed bed 28 such that, in operation, the entirety of the packed bed 28 is retained internal to the retention volume and proximate the major horizontal surface 12 of the pan 10.

One or more portions of the pan 10 or one or more portions of the housing 6 may include one or more abrasion or erosion resistant materials that resist chemical degradation by the first chemical species, the diluent(s), or the particles 24 in the packed bed 28. Such abrasion or erosion resistant materials
include, for example, one or more fused or non-fused materials such as a graphite, a quartz (e.g., barium doped quartz), a silicon (e.g., silicon nitride, a silicon carbide), a silicide, etc.

Such inclusion of resistant materials advantageously reduces likelihood of contamination of the packed bed 28 by contaminants released from the pan 10 or the housing 6. Such inclusion of resistant materials also advantageously reduces likelihood of product buildup that otherwise would contaminate the packed bed 28. Additionally or alternatively, one or more portions of the pan 10 or one or more portions of interior surfaces of the housing 6, e.g., interior surfaces of the upper chamber 34, may include one or more layers of a coating material or one or more layers of a liner material. The coating or liner material may include a spray fused to the portion of the pan 10 or the portion of the interior surface of the housing 6. The coating or liner material may include the abrasion or erosion resistant materials. Including the coating or liner advantageously facilitates repair of the liner without replacement of elements beneath the coating or liner.

Additionally or alternatively to the abrasion or erosion resistant material, one or more portions of the pan 10 or one or more portions of the housing 6 may include one or more materials that promote, e.g., by reaction with the first chemical species, the diluent(s), or the particles 24 in the packed bed 28, repair or formation of the coating or liner. Such promoting materials include, for example, 316 stainless steel. Such inclusion of promoting materials advantageously reduces or eliminates a requirement to repair the coating, liner, or elements beneath the coating or liner.

Additionally or alternatively to the promoting materials, one or more portions of the pan 10 or one or more portions of the housing 6 may include one or more materials that has a thermal expansion coefficient that matches or substantially matches (i.e., similar) a thermal expansion coefficient of the coating or liner. Such matching materials include, for example, an alloy of molybdenum, an alloy of Super Invar, a graphite alloy, a nickel alloy, a
stainless steel alloy, etc. Such inclusion of matching materials advantageously reduces or minimizes likelihood of the coating or liner spalling from surfaces when the pan 10 or the housing 6 cycles between operating temperature and pressure and atmospheric temperatures and pressures.

The housing 6 of the mechanically vibrated packed bed reactor system 4 can feature either a unitary or multi-piece implementation. An example of a multi-piece implementation includes one or more fastener systems such as one or more flanges, threaded fasteners, and sealing members that connect an upper portion of the housing 6 to a lower portion of the housing 6.

The mechanically vibrated packed bed reactor system 4 may further include one or more of transmission systems, particle feed systems, exhaust gas systems 60, or inert gas feed systems 62.

The mechanically vibrated packed bed reactor system 4 also includes one or more thermal energy emitters 58, such as one or more heaters, that thermally couple to one or more of the pan 10 or the packed bed 28. The thermal energy emitter 58 may transfer thermal energy to the particulate bed 28 via one or more of conductive heat transfer, convective heat transfer, or radiant heat transfer. The thermal energy emitter 58 may be disposed proximate at least a portion of the lower surface 56 of the major horizontal surface 12 of the pan 10. Alternatively, the major horizontal surface 12 may include the thermal energy emitter 58 internal to the major horizontal surface 12.

The thermal energy emitter 58 may include a sealed container or cover or an insulative blanket or material that encompasses one or more portions of the thermal energy emitter 58 while leaving one or more portions of the thermal energy emitter 58 that transfer thermal energy to the packed bed 28, e.g., an upper portion of the thermal energy emitter 58. The thermally insulating material may include, for example, a glass-ceramic material (e.g., Li₂O x Al₂O₃ x nSiO₂-System or LAS System). In some situations, the thermally
insulating material may include one or more rigid or semi-rigid refractory type materials such as calcium silicate.

The thermal energy emitter 58 increases a temperature of the packed bed 28 to a temperature in excess of a decomposition temperature of the first gaseous chemical species as the pan 10 oscillates or vibrates. The thermal energy emitter 58 may maintain or substantially maintain the temperature of the packed bed 28 at the temperature in excess of the decomposition temperature of the first gaseous chemical species as the pan 10 oscillates or vibrates.

The thermal energy emitter 58 advantageously encourages producing reaction product in the packed bed 28 while reducing production of reaction product external to the packed bed 28. In particular, the heated, packed particles 24 in the packed bed 28 provide a substrate upon which a non-volatile second chemical species (e.g., polysilicon) formed by thermal decomposition of the first gaseous chemical species (e.g., silane) deposits. At times, the thermal decomposition of the first gaseous chemical species occurs within the packed bed 28 and either does not occur or occurs minimally in other locations within the upper chamber 34, even though the environment in the upper chamber 34 may be maintained at an elevated temperature and pressure (i.e., elevated relative to atmospheric temperatures and pressures).

For example, the thermal energy emitter 58 may maintain or substantially maintain the temperature of the packed bed 28 above about 100°C, about 200°C, about 300°C, about 400°C, or about 500°C. Additionally or alternatively, the thermal energy emitter 58 may maintain or substantially maintain the temperature of the packed bed 28 below about 500°C, about 600°C, about 700°C, about 800°C, or about 900°C. Such can include maintaining or substantially maintaining the temperature of the packed bed 28 (e.g., 650°C) above a temperature or bulk temperature of gas in the chamber 34 above the packed bed 28 (e.g., 300°C).
The mechanically vibrated packed bed reactor system 4 may include one or more cooling features 64, physically or thermally coupled to one or more portions of an exterior surface of the housing 6. The cooling feature 64 may be disposed at any location on the exterior surface of the housing 6 including a housing top, bottom, and/or sides. In some instances, the cooling feature 64 may include one or more passive cooling features such as extended surface area fins thermally conductively coupled to all or a portion of the exterior surface of the housing 6. In some instances, the cooling feature 64 may include one or more active cooling features such as a jacket and/or cooling coils through which a heat transfer media (e.g., thermal oil, boiler feed water) is circulated. In some instances, the cooling feature 64, such as cooling jackets and/or cooling coils may be disposed at least partially within the chamber 8, e.g., the upper chamber 34 or the lower chamber 52. In some instances, the cooling feature 64 may be integral with the housing wall or may be thermally conductively coupled to the housing wall. The cooling feature 64 may also include other passive or active thermal systems, devices, or combinations of systems and devices that aid in the addition or the removal of thermal energy from the upper chamber 34, the lower chamber 52, or both. The cooling feature 64 may include active thermal transfer systems or devices such as cooling jackets having one or more heat transfer fluids circulated therein, or various combinations of surface features and cooling jackets.

The cooling feature 64 may beneficially maintain a temperature in at least a portion of the upper chamber 34, e.g., some or all space in the upper chamber 34 external to the packed bed 28, below the thermal decomposition temperature of the first gaseous chemical species. In some instances, the cooling feature 64 may be selectively disposed on portions of the chamber 8 or the housing 6 that are prone to localized concentrations of thermal energy to assist in the dissipation or distribution of such thermal energy. By maintaining the temperature in the upper chamber 34 below the thermal decomposition temperature of the first gaseous chemical species, spontaneous decomposition
of the first gaseous chemical species in locations external to the packed bed 28 is advantageously minimized or even eliminated. Such advantageously reduces or even eliminates deposition of the second chemical species on surfaces external to the packed bed 28 and/or the formation of second chemical species "dust" in the upper chamber 34.

The cooling feature 64 may maintain a temperature in the lower chamber 52 below the thermal decomposition temperature of the first gaseous chemical species. Additionally or alternatively, one or more passive or active cooling features may be thermally and/or physically coupled to the transmission system to maintain the temperature of the oscillatory transmission member at or below the thermal decomposition temperature of the first gaseous chemical species. Maintaining the temperature in the lower chamber 52 below the thermal decomposition temperature of the first gaseous chemical species advantageously promotes, via thermal inductance, maintaining the temperature in the upper chamber 34 below the thermal decomposition temperature of the first gaseous chemical species.

For example, the mechanically vibrated packed bed reactor system 4 may maintain or substantially maintain one or more of the temperature or bulk temperature of gas in the upper chamber 34 above the packed bed 28 in a range from about 25°C to about 500°C, from about 25°C to about 300°C, from about 25°C to about 225°C, from about 25°C to about 150°C, or from about 25°C to about 75°C. Additionally or alternatively, the mechanically vibrated packed bed reactor system 4 may maintain or substantially maintain one or more of the temperature or bulk temperature of gas in the upper chamber 34 above the packed bed 28 below the thermal decomposition temperature of the first gaseous species while maintaining or substantially maintaining one or more of the temperature or bulk temperature of gas in the upper chamber 34 above the packed bed 28 below about 100°C, about 200°C, about 300°C, about 400°C, about 500°C, or about 550°C.
One or more gases or gas mixtures supplied to the upper chamber 34 may produce a pressure in the upper chamber 34. The exhaust system 60 may control the pressure in the upper chamber 34, thereby advantageously controlling an amount of force that the actuator 26 must apply to oscillate or vibrate the pan 10 along the one or more axes of motion. Additionally or alternatively, one or more inert gas feed systems 62 may introduce one or more inert gases or inert gas mixtures to the lower chamber 52, thereby reducing a pressure differential between the upper chamber 34 and the lower chamber 52 and advantageously reducing the force to oscillate or vibrate the pan 10.

The mechanically vibrated packed bed reactor system 4 may be an element of a crystal production system. For example, the mechanically vibrated packed bed reactor system 4 may direct one or more particles withdrawn from the packed bed 28 via the inlet 38 of the product withdrawal tube 36 to one or more conduits, melters, crucibles, or pullers of the crystal production system. U.S. patent application Serial No. 62/315,334 filed March 30, 2016 provides further explanations of one or more elements, features, functions, or method acts of such an example crystal production system, and is incorporated herein by reference in entirety with exception to any subject matter in the Background section of that application or any subject matter that contradicts the present disclosure. Such further explanations of such example crystal production system make further advantageous elements, features, or method acts of the mechanically vibrated packed bed reactor system 4 of the present disclosure clear to one of ordinary skill in the art.

Figure 2 shows a high-level block flow diagram of an illustrative crystal production method 300, according to one implementation. The method 200 may involve one or more of the mechanically vibrated packed bed reactor systems 4 or one or more elements, features, functions, or method acts thereof. The method 200 commences at 202. At 204, a pan having a major horizontal surface with a periphery and an upward extending peripheral wall that
surrounds at least a portion of the periphery of the major horizontal surface charges with particles, e.g., in any manner that the present disclosure discloses. A cover in a housing has a lower surface that opposes to the major horizontal surface of the pan. The cover, the major horizontal surface of the pan and the upward extending peripheral wall of the pan at least partially form a retention volume to at least partially temporarily retain particulate. At 206, the cover restrains an expansion of the particles in the pan. In particular, the cover restrains the expansion to an average of less than 7.5% of volume of the particulate in the retention volume when not vibrated.

At 208, the pan vibrates along at least a first axis perpendicular to the major horizontal surface of the pan to mechanically vibrate particulate in the retention volume to produce a mechanically vibrated packed particulate bed in the retention volume. At 210, the temperature of the mechanically vibrated packed particulate bed in the retention volume raises above a thermal decomposition temperature of a first gaseous chemical species to thermally decompose the first gaseous chemical species within the mechanically vibrated packed particulate bed to a non-volatile second chemical species, at least a portion of which deposits on at least a portion of the plurality of particulates in the mechanically vibrated packed particulate bed to provide a plurality of particles via heating the major horizontal surface via a heating element contained by at least a portion of the pan.

At 212, particles withdraw via an inlet of a product removal tube, the inlet of the product removal tube positioned above a lower-most portion of the lower surface of the cover. At 214, dopant adds to the mechanically vibrated packed particulate bed. The method 200 concludes at 216.

These and other changes can be made to the implementations in light of the present disclosure. In general, in the following claims, the terms used should not be construed to limit the claims to the specific implementations disclosed in the specification and the claims, but should be construed to include all possible implementations, including the full scope of equivalents, to which
such claims are entitled. Accordingly, the claims are not limited by the present disclosure.

To the extent that they are not inconsistent with the specific teachings and definitions herein, all of the US patents, US patent application publications, US patent applications, referred to in this specification and/or listed in the Application Data Sheet, including but not limited to U.S. Patent Application Serial No. 62/315,505, filed March 30, 2016, are incorporated herein by reference in their entirety.
CLAIMS

1. A reactor system, comprising:
   a housing having a chamber therein;
   a pan received in the chamber of the housing, the pan having a major horizontal surface with a periphery and an upward extending peripheral wall that surrounds at least a portion of the periphery of the major horizontal surface;
   a cover received in the chamber of the housing, the cover having an upper surface, a lower surface, and a peripheral edge, the lower surface of the cover opposed to the major horizontal surface of the pan, wherein the cover, the major horizontal surface of the pan and the upward extending peripheral wall of the pan at least partially form a retention volume to at least partially temporarily retain particulate;
   an actuator that, in operation, vibrates the pan along at least a first axis perpendicular to the major horizontal surface of the pan to mechanically vibrate particulate in the retention volume to produce a mechanically vibrated packed particulate bed in the retention volume, wherein the cover restrains expansion of a volume of the mechanically vibrated packed particulate bed to an average of less than 7.5% of a volume of the particulate in the retention volume when not vibrated; and
   a heater that, in operation, raises a temperature of the mechanically vibrated packed particulate bed in the retention volume above a thermal decomposition temperature of a first gaseous chemical species to thermally decompose the first gaseous chemical species within the mechanically vibrated packed particulate bed to a non-volatile second chemical species, at least a portion of which deposits on at least a portion of the plurality of particulates in the mechanically vibrated packed particulate bed to provide a plurality of coated particles.
2. The reactor system of claim 1 the cover restrains expansion of a volume of the mechanically vibrated packed particulate bed to an average of less than about 3% of the volume of the particulate in the retention volume when not vibrated.

3. The reactor system of claim 1 wherein the cover is disposed above the major horizontal surface of the pan with the peripheral edge of the cover spaced inwardly of the peripheral wall of the pan with a peripheral gap between the peripheral edge of the cover and the peripheral wall of the pan which provides a fluidly communicative passage between the retention volume of the pan and the chamber of the housing.

4. The reactor system of claim 1 wherein the pan has a circular profile and the cover has a circular profile, and the cover is disposed above the major horizontal surface of the pan with the peripheral edge of the cover spaced radially inwardly of the peripheral wall of the pan with a peripheral gap between the peripheral edge of the cover and the peripheral wall of the pan which provides a fluidly communicative passage between the retention volume of the pan and the chamber of the housing.

5. The reactor system of claim 1 wherein the cover contacts at least about 80% of an upper surface area of the mechanically vibrated packed particulate bed and less than 100% of the upper surface area of the mechanically vibrated packed particulate bed.

6. The reactor system of any of claims 1 through 5 wherein the cover includes a cupola and a rim which surrounds the cupola.
7. The reactor system of claim 6 wherein at least the bottom surface of the cover that is part of the rim is flat and the cupola forms a concavity in the bottom surface of the cover.

8. The reactor system of claim 1, further comprising: a product removal tube having an inlet, the inlet positioned above a lowest-most portion of the lower surface of the cover, the lowest-most portion being a portion that is perpendicularly closest to the major horizontal surface of the pan.

9. The reactor system of claim 8 wherein the inlet of the product removal tube is positioned at least \( \frac{1}{4} \) inch above the lowest-most portion of the lower surface of the cover.

10. The reactor system of claim 8 wherein the inlet of the product removal tube is positioned at least \( \frac{1}{2} \) inch above the lowest-most portion of the lower surface of the cover.

11. The reactor system of any of claims 8 through 10 wherein the cover includes a cupola that forms a concavity in the bottom surface of the cover and a rim which surrounds the cupola, the lowest-most portion being the rim of the cover.

12. The reactor system of any of claims 8 through 11 wherein the inlet of the product removal tube is positioned in a free space region above an upper surface of the mechanically vibrated packed particulate bed.
13. The reactor system of claim 8 through 12, further comprising:
   a flange that extends radially from the product removal tube, the flange spaced between the inlet of the product removal tube and the major horizontal surface of the pan.

14. The reactor system of claim 13 wherein the flange is positioned about ½ inch below the inlet of the product removal tube.

15. The reactor system of claim 13 wherein the flange is a radial flange and is positioned about level with the lowest-most portion of the lower surface of the cover.

16. The reactor system of claim 8 through 15 wherein the product removal tube extends through and is hermetically sealingly coupled to the major horizontal surface of the pan.

17. The reactor system of claims 8 through 16, further comprising:
   a number of injectors each having a respective outlet, the injectors fluidly coupled to a first gaseous chemical species distribution header, the outlets of the injectors positioned between the major horizontal surface of the pan and the bottom surface of the cover.

18. The reactor system of claim 17 wherein the injectors are radially disposed about the product removal tube.

19. The reactor system of any of claims 1 through 5 wherein the cover is apportioned into a raised portion and a non-raised portion, the raised portion comprises a portion of the cover directly above and extending
radially outward from the product removal tube such that the distance between a lower surface of the raised portion of the cover and the major horizontal surface is greater than the distance between the lower surface of the non-raised portion of the cover and the major horizontal surface, and further comprising:

a product removal tube having an inlet, the inlet positioned above a level of the non-raised portion of the cover and below a level of the raised portion of the cover.

20. The reactor system of claim 19 wherein the non-raised portion of the cover includes a wall that is symmetrically arrayed about the outlet of the product removal tube.

21. A method of operation in a reactor system, the method comprising:

charging a pan with particles, the pan having a major horizontal surface with a periphery and an upward extending peripheral wall that surrounds at least a portion of the periphery of the major horizontal surface;

restraining an expansion of the particles in the pan via a cover in a chamber of a housing, the cover having a lower surface, the lower surface of the cover opposed to the major horizontal surface of the pan, wherein the cover, the major horizontal surface of the pan and the upward extending peripheral wall of the pan at least partially form a retention volume to at least partially temporarily retain particulate;

vibrating the pan along at least a first axis perpendicular to the major horizontal surface of the pan to mechanically vibrate particulate in the retention volume to produce a mechanically vibrated packed particulate bed in the retention volume, and

raising a temperature of the mechanically vibrated packed particulate bed in the retention volume above a thermal decomposition
temperature of a first gaseous chemical species to thermally decompose the first gaseous chemical species within the mechanically vibrated packed particulate bed to a non-volatile second chemical species, at least a portion of which deposits on at least a portion of the plurality of particulates in the mechanically vibrated packed particulate bed to provide a plurality of coated particles.

22. The method of claim 21 wherein the cover restrains expansion of a volume of the mechanically vibrated packed particulate bed to an average of less than 7.5% of a volume of the particulate in the retention volume when not vibrated.

23. The method of claim 21 or 22, further comprising; withdrawing at least some of the coated particles via an inlet of a product removal tube, the inlet of the product removal tube positioned above a lower-most portion of the lower surface of the cover.

24. The method of any of claims 21 through 23 wherein raising a temperature of the mechanically vibrated packed particulate bed includes heating the major horizontal surface via a heating element contained by at least a portion of the pan.

25. The method of claim 21 through 24, further comprising: adding at least one dopant to the mechanically vibrated packed particulate bed.
FIG. 1
Start

Charge pan with particles

Restrain expansion of particles via cover in chamber of housing to an average of less than 7.5% of volume of particulate in retention volume when not vibrated

Vibrate pan along first axis to mechanically vibrate particulate in retention volume to produce mechanically vibrated packed particulate bed in retention volume

Raise temperature of mechanically vibrated packed particulate bed above thermal decomposition temperature of first gaseous chemical species to thermally decompose first gaseous chemical species to non-volatile second chemical species to provide plurality of coated particles by heating major horizontal surface via heating element contained by portion of pan

Withdrawing coated particles via inlet of product removal tube positioned above lower-most portion of lower surface of cover

Adding dopant to mechanically vibrated packed particulate bed

End

FIG. 2
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

H01L 21/67(2006.01)j

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01L 21/67; B01J 8/44; C01G 39/02; C01B 33/027; C23C 16/458; B01J 8/00; C22B 1/10; B01J 19/18; B01J 19/08

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: vibrated packed bed reactor, cover, silicon, particle, actuator

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<th>Relevant to claim No.</th>
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Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:
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"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
07 July 2017 (07.07.2017)

Date of mailing of the international search report
11 July 2017 (11.07.2017)

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