



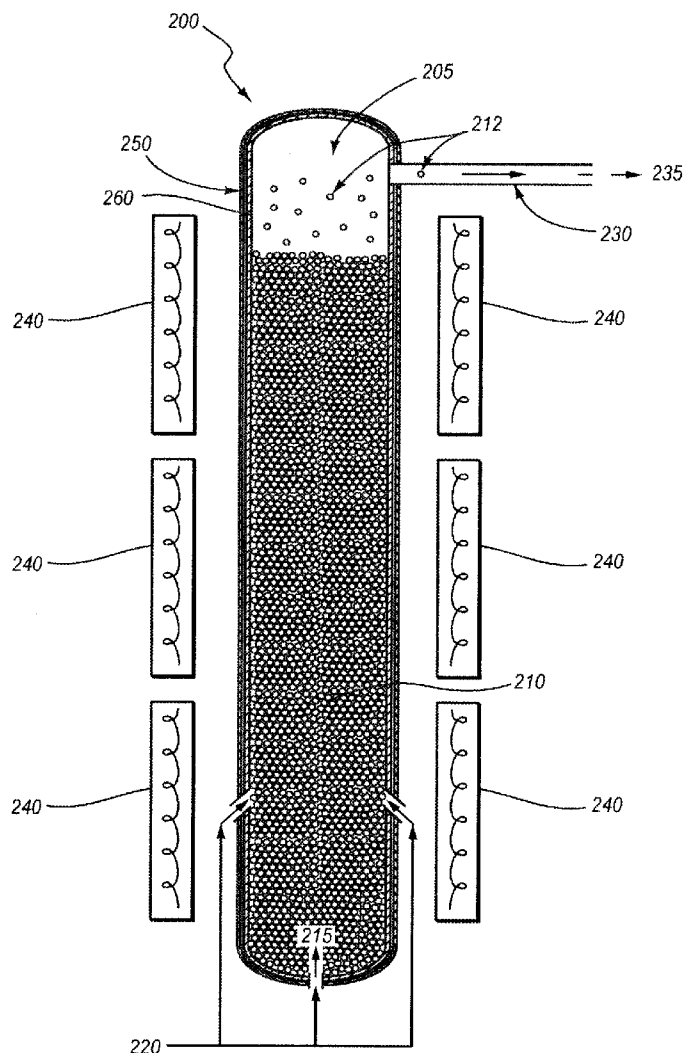
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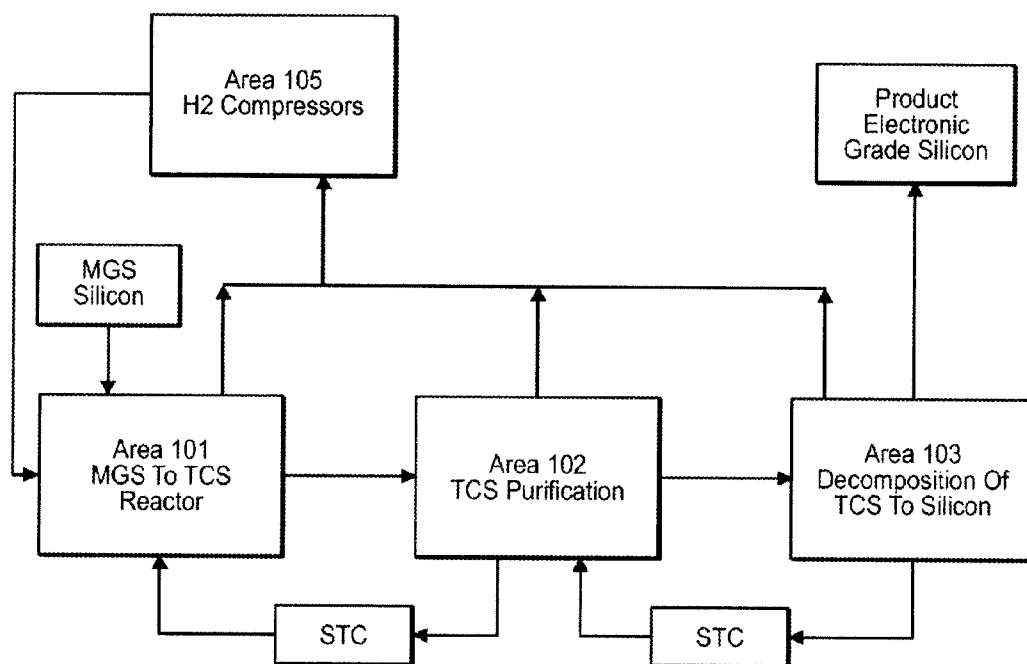
(19) **United States**(12) **Patent Application Publication**
Segundo Sanchez et al.(10) **Pub. No.: US 2012/0171102 A1**(43) **Pub. Date: Jul. 5, 2012**(54) **FLUIDIZED BED REACTOR FOR
PRODUCTION OF HIGH PURITY SILICON**(22) Filed: **Mar. 14, 2012****Related U.S. Application Data**

(60) Continuation of application No. 12/903,994, filed on Oct. 13, 2010, now Pat. No. 8,158,093, which is a division of application No. 12/393,852, filed on Feb. 26, 2009, now Pat. No. 8,168,123.

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C01B 33/03 (2006.01)(52) **U.S. Cl.** **423/349; 422/145; 422/139**(57) **ABSTRACT**

Methods and apparatus for the production of high purity silicon including a fluidized bed reactor with one or more protective layers deposited on an inside surface of the fluidized bed reactor. The protective layer may be resistant to corrosion by fluidizing gases and silicon-bearing gases.

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**FIG. 1**

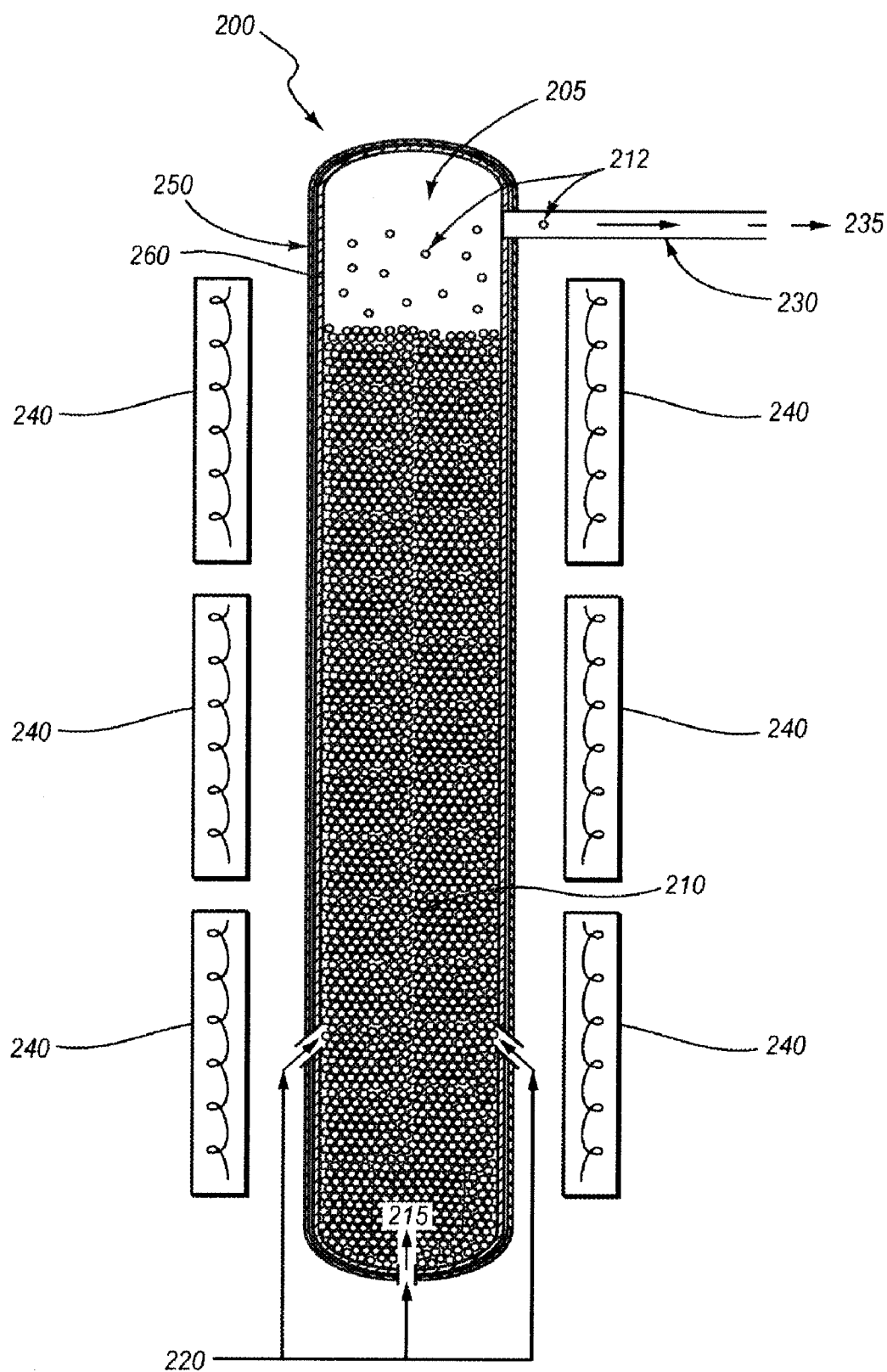
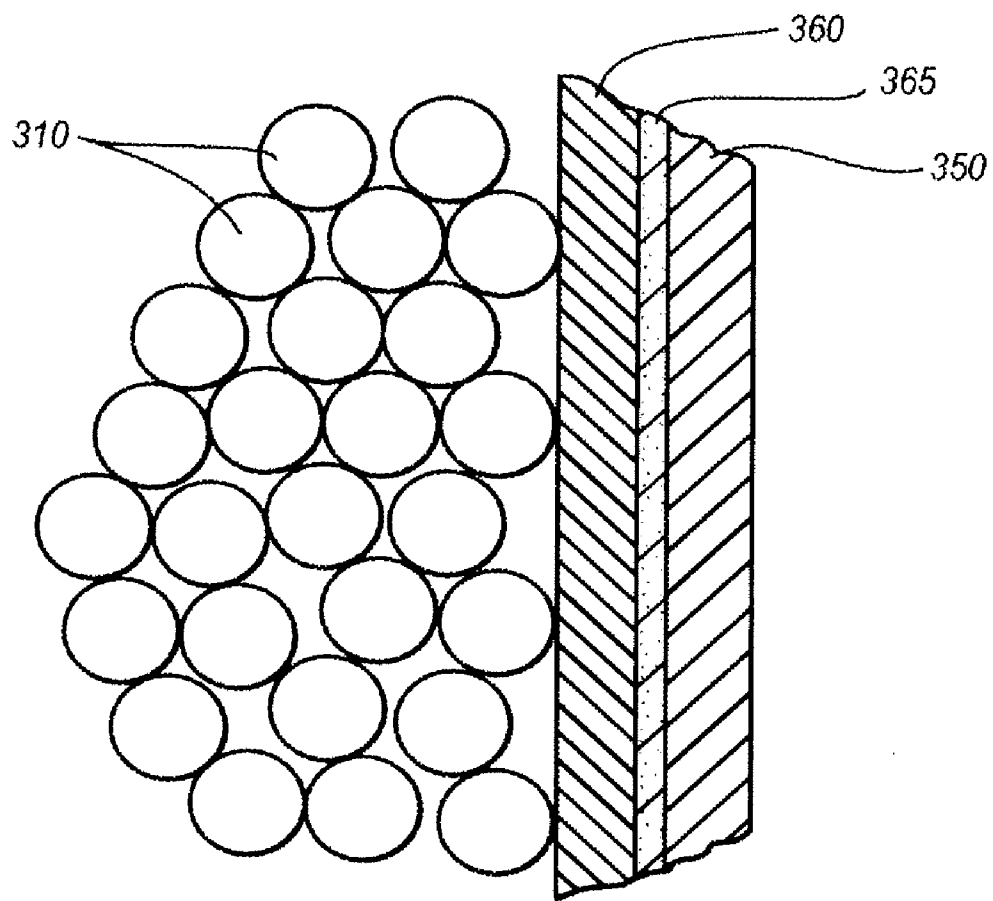


FIG. 2

**FIG. 3**

FLUIDIZED BED REACTOR FOR PRODUCTION OF HIGH PURITY SILICON

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application is a continuation of now pending U.S. patent application Ser. No. 12/903,994, entitled FLUIDIZED BED REACTOR FOR PRODUCTION OF HIGH PURITY SILICON, filed on Oct. 13, 2010, which is a divisional of U.S. patent application Ser. No. 12/393,852, entitled FLUIDIZED BED REACTOR FOR PRODUCTION OF HIGH PURITY SILICON, filed on Feb. 26, 2009, each of which is fully incorporated by reference herein.

TECHNICAL FIELD

[0002] The present disclosure relates to methods for producing high purity electronic grade silicon. More particularly, this disclosure relates to methods for producing high purity silicon beads by chemical vapor deposition (CVD) of a silicon-bearing gas on seed particles by decomposition in a fluidized bed reactor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] FIG. 1 shows one embodiment of a process for the purification of silicon.

[0004] FIG. 2 shows one embodiment of a fluidized bed reactor used for the purification of silicon.

[0005] FIG. 3 shows a close-up cross section of one embodiment of a fluidized bed reactor as disclosed herein.

DETAILED DESCRIPTION

[0006] Polycrystalline silicon may be used in the production of electronic components and solar panel construction. One conventional method of producing polycrystalline silicon is feeding a mixture comprising hydrogen and silane (SiH_4) or a mixture comprising hydrogen and a halosilane, such as trichlorosilane (HSiCl_3), is fed to a decomposition reactor containing a hot wire or hot substrate rods. This method requires a high amount of energy per unit of mass of produced silicon, and the silicon rods produced by this method need further processing to be used in a silicon ingot growing process.

[0007] An alternate silicon production method is to feed a mixture comprising hydrogen and silane or a mixture comprising hydrogen and trichlorosilane to a fluidized bed containing silicon beads that are maintained at high temperature. Decomposition of silane or trichlorosilane causes the deposition of elemental silicon on the surface of the beads. Therefore, the silicon beads grow in size, and when large enough, are passed out of the fluidized bed reactor as a high purity silicon product. In comparison to the substrate used in wire or rod substrate reactors, fluidized bed reactors allow for a much larger contact area between the beads and the silicon-bearing gases in a heated chamber, enhancing the thermal decomposition of the silicon-bearing gases thereby forming high purity elemental silicon on the surface of existing beads.

[0008] As described herein, the purity of the silicon produced using a fluidized bed reactor may be preserved by constructing the reactor out of materials that do not contaminate the silicon product. In one such embodiment, a fluidized bed reactor, or reactor, or reactor system used for the production of high purity silicon may be constructed out of a material that prevents or minimizes the contamination of the polycryst-

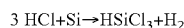
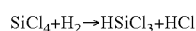
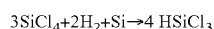
talline silicon product due to the diffusion of impurities from the materials used to construct the reactor. In another embodiment, the reactor may be constructed or lined or coated with a material that is inert or resistant to the reactor feed gases and fluidized gases and the other gases or products that may be produced during the use of a fluidized bed reactor.

[0009] In one embodiment, a fluidized bed reactor according to the disclosure herein may include an elongate chamber or column comprising one or more inlet openings and one or more outlet openings. In one such embodiment, a fluidized bed reactor may include a bed of granular solid materials, such as a bed of silicon beads that can be used as seed beads to seed a silicon decomposition reaction during which the seed beads can increase in size because of the deposition of additional silicon on the surface of the seed beads. The seed beads with the added silicon product may be eventually removed from the reactor to recover the high purity silicon product. The seed beads may be "fluidized", or suspended in the reactor, by injecting fluidizing gases into the reactor at sufficient velocities to agitate the beads. The fluidizing gases may be injected into the reactor through one or more inlet openings located around the reactor such as at the ends of the column and at the sides of the reactor column. In one embodiment, the fluidizing gases or the silicon product may be removed from the reactor through one or more outlet openings. In one such embodiment, the reactor may be constructed or lined or coated with a material that is inert or resistant to the fluidizing gases used to fluidize the bed of silicon beads.

[0010] A silicon-bearing gas may be injected into a fluidized bed reactor that may be constructed, lined or coated with a material that is inert or resistant to the silicon-bearing gas. In one embodiment, the silicon-bearing gas may be trichlorosilane (TCS) that can be injected into the reactor at the same location or a location adjacent to the fluidizing gas. When heated, TCS decomposes in the reactor to form silicon on the seed silicon beads thereby increasing the diameter of the seed silicon beads over time and producing the desired high purity silicon product. One reason that the resulting polycrystalline silicon product is of high purity is because the reactor has been constructed out of a material that prevents or minimizes the contamination of the silicon during decomposition. The resulting silicon product beads may then be recovered from the reactor and used for the production of semiconductors and photovoltaic cells.

[0011] Methods for the production of high purity silicon may include the use of a fluidized bed reactor configured to avoid reactor corrosion and prevent the contamination of a silicon product. In one embodiment, a method of silicon production may include the conversion of metallurgical grade silicon (MGS) into a hydrohalosilane such as trichlorosilane (TCS); the purification of the hydrohalosilane, such as by distillation; and the decomposition of the hydrohalosilane back to silicon.

[0012] In one embodiment, the conversion of MGS into hydrohalosilane may be accomplished by reacting silicon with silicon tetrachloride (STC), hydrogen and hydrogen chloride to form TCS and hydrogen. With reference to FIG. 1, the following reactions may occur inside area 101:

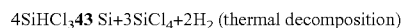


[0013] In one embodiment, the result of the reaction in area **101** may be a mix of gases including TCS, STC, and H_2 that can be removed from area **101** and then introduced in area **102** for purification by distillation.

[0014] The purification of TCS by distillation of the hydrohalosilanes may occur in area **102** as shown in FIG. 1. In one embodiment, the gas stream from area **101**, including TCS, STC and other hydrohalosilanes, may be injected into a distillation column in area **102** resulting in high purity TCS. Hydrogen may be recycled for use in area **101** after further purity removal. The resulting TCS vapor is a silicon-bearing gas that may be injected into a fluidized bed reactor that may be used for a silicon decomposition process in area **103**.

[0015] Area **103** may comprise multiple elements for the conversion of TCS into high purity silicon. For example, area **103** may comprise one or more of the following: fluidized bed reactor, storage tank, evaporator, reactor heater, gas separator, granular separator, cyclone, heat recovery system, product recovery system and other devices and systems for the production of high purity silicon. The term hydrohalosilanes refers to any silane species having one or more halide atoms and one or more hydrogen atoms bonded to silicon and includes, but is not limited to monochlorosilane (H_3SiCl), dichlorosilane (H_2SiCl_2), trichlorosilane ($HSiCl_3$) and various chlorinated disilanes such as pentachlorodisilane.

[0016] In one embodiment, a silicon-bearing gas, such as a TCS vapor, may be used for the production of high purity silicon. The conversion of TCS into high purity silicon may be accomplished using a fluidized bed reactor **200** as shown in FIG. 2, in which the following reaction may occur:



[0017] The fluidized bed reactor **200** used in the decomposition process may include an elongate chamber or column **205** which includes a bed of silicon beads **210**, which may be used to seed silicon a decomposition reaction. The beads **210** may be "fluidized" by initially injecting gases, such as fluidizing gases **215** from inlet **220** into the column **205** to agitate or fluidize the silicon beads **210**. In one embodiment, the fluidizing gases **215** may include hydrogen and silicon tetrachloride $SiCl_4$. In another embodiment, the fluidizing gas may be one or a mixture selected from the group consisting of hydrogen, helium, argon, silicon tetrachloride, silicon tetrabromide and silicon tetraiodide. In one such embodiment, the fluidizing gases **215** may be injected into the column **205** from several areas of the reactor **200** such as at the bottom or sides of the column **205**, such as through inlet **220**.

[0018] The fluidized bed reactor **200** may be heated by one or more heaters **240** placed around or near the body of reactor **200**. The heaters **240** may be radiant, conductive, electromagnetic, infrared or other type of heaters known by those of skill in the art. In one embodiment, the surface of the reactor wall **250** may be textured, etched or sand-blasted in order to increase the thermal emissivity or the thermal power transfer efficiency of the reactor wall **250** and improve heating by the heater **240** of the column **205** and the inside of the reactor **200**.

[0019] In another embodiment, a heating device, such as heater **240**, may be in total or partial contact with the reactor wall **250**. In yet another embodiment, the heater **240** may have no direct contact with reactor wall **250**. In one such embodiment, the heater **240** may be positioned outside the reactor wall **250** and configured as a group of cylinders partially or completely covering one or more outlet surfaces of the reactor **200**. In still another embodiment, the heater **240** may be

configured to use radiation or a mix of direct heat conduction and heat radiation to heat the silicon beads **210** and the silicon-bearing gases to a temperature sufficient for the decomposition reaction.

[0020] In one embodiment, the fluidized bed reactor **200** may be heated during the production of high purity silicon to temperatures ranging from approximately $500^\circ C.$ to approximately $1200^\circ C.$ For example, the fluidized bed reactor **200** may be heated by the heaters **240** such that the silicon beads **210**, the silicon-bearing gases, and the fluidizing gases **215** within the column **205** are heated to a temperature ranging from approximately $600^\circ C.$ to $1100^\circ C.$, or from $700^\circ C.$ to $1000^\circ C.$, or from $700^\circ C.$ to $900^\circ C.$, or from $750^\circ C.$ to $850^\circ C.$, or from $800^\circ C.$ to $1000^\circ C.$

[0021] The fluidized bed reactor **200** may be configured to withstand the conditions during the decomposition reaction including temperatures ranging from approximately $500^\circ C.$ to approximately $1200^\circ C.$ and internal pressures ranging from approximately 50 mbar to approximately 6000 mbar. For example, the fluidized bed reactor **200** as described herein, may be constructed to withstand pressures of approximately up to 50 mbar, 100 mbar, 200 mbar, 500 mbar, 750 mbar, 1000 mbar, 1500 mbar, 2000 mbar, 2500 mbar, 3000 mbar, 3500 mbar, 4000 mbar, 4500 mbar, 5000 mbar, 5500 mbar and 6000 mbar. In another embodiment, the fluidized bed reactor **200** may be contained within another structure or enclosure configured to support pressures ranging from approximately 50 mbar to approximately 6000 mbar.

[0022] In one embodiment, one or more silicon-bearing gases, such as TCS, may be injected into the reactor **200**. For example, the silicon-bearing gas may be injected into the reactor **200** through the inlet **220** into the column **205**. In one such embodiment, a silicon-bearing gas, like TCS, decomposes to form silicon on the beads **210**, increasing the diameter of the beads **210** over time until they may become a silicon product bead **212**. In still another embodiment, the silicon-bearing gas may comprise a gas which decomposes when heated to form silicon and is a gas or a mixture of gases selected from the group of monosilane, disilane, trisilane, trichlorosilane, dichlorosilane, monochlorosilane, tribromosilane, dibromosilane, monobromosilane, triiodosilane, diiodosilane and monoiodosilane. In one embodiment, the high purity silicon product beads **212** may be recovered from the reactor **200** near the top of the column **205** at outlet **230** along with the effluent gas stream **235** that may include hydrogen, STC, HCl, unreacted TCS and monochlorosilane (MCS) and dichlorosilane (DCS).

[0023] In one embodiment, the concentration of the silicon-bearing gases in the feed stream to the fluidized bed reactor **200** may range from approximately 20 mol % to 100 mol %. In one embodiment, the average diameter of the fluidized silicon beads **210** may range from 0.5 mm to 4 mm. In another embodiment, the average diameter of the silicon beads **210** may range from 0.25 mm to 1.2 mm, or alternatively, 0.6 mm to 1.6 mm. In one embodiment, the silicon beads **210** may remain in the reactor **200** until a desired size is reached and the silicon product beads **212** are extracted from the reactor **200**. In another embodiment, the time that the silicon beads **210** may remain in the reactor **200** may depend on the starting size of silicon beads **210**. In one embodiment, the growth rate of the silicon beads **210** may depend, among other things, on the reaction conditions including gas concentrations, temperature and pressure. The minimum fluidization velocity and design operational velocity may be determined by one of

ordinary skill in the art based on various factors. The minimum fluidization velocity may be influenced by factors including gravitational acceleration, fluid density, fluid viscosity, solid density, and solid particle size. The operational velocity may be influenced by factors including heat transfer and kinetic properties, such as height of the fluidized bed, total surface area, flow rate of silicon precursor in the feed gas stream, pressure, gas and solids temperature, concentrations of species, and thermodynamic equilibrium point.

[0024] In one embodiment, one or more surfaces of the fluidized bed reactor **200** may be made of a metal or a metal alloy. In one such embodiment, one or more surfaces of the reactor **200** may include a metal or metal alloy capable of withstanding the reaction temperatures. For example, the reactor wall **250** may be constructed of iron based-alloys, such as: stainless steel alloys, chromium-nickel alloys, and nickel based alloys including nickel-chromium alloys and nickel-chromium-molybdenum alloys, which may optionally include manganese, molybdenum, silicon, cobalt, tungsten, etc., which would be apparent to those having skill in the art with the aid of the present disclosure. In certain embodiments, the metal alloys may be chosen from: steel 1.4841, steel 1.4959, steel 2.4856, steel 2.4819 or steel 2.4617. For example, the reactor wall **250** may be configured to be thermoresistant to temperatures in the range of approximately 500° C. to 1,200° C. For example, the reactor wall **250** can be constructed to tolerate temperatures ranging from approximately 500° C. to 600° C., or from 500° C. to 700° C., or from 600° C. to 800° C., or from 800° C. to 900° C., or from 800° C. to 1000° C., or from 900° C. to 1100° C., or from 900° C. to 1200° C.

[0025] As shown by FIG. 2, the inside surface of the reactor wall **250** may be partially or completely coated with a protective layer **260** to avoid or minimize the contamination of the product beads **212** by diffusion of impurities from the reactor **200** or the reactor wall **250**. In one such embodiment, the protective layer **260** may comprise materials that are inert or resistant to the conditions in the reactor **200**, such as a metal or metal alloy capable of withstanding the reaction conditions within the reactor **200** and be compatible with the application of the protective layer **260**. For example, the protective layer **260** may comprise materials that are resistant to heat, pressure, and corrosion by the fluidizing gases **215** or the silicon-bearing gases that are injected into the reactor **200**.

[0026] In one embodiment, the fluidized bed reactor **200** may be lined with a protective layer **260** comprising a ceramic material that is resistant to corrosion or breakdown by the conditions in the reactor **200**. In one such embodiment, the protective layer **260** may comprise at least one of the following materials: Alumina (Al_2O_3), Zirconium dioxide (ZrO_2) and Zirconium dioxide—yttrium stabilized. In another embodiment, the protective layer is a ceramic material made from a composition other than silicon-based or carbon-based. In yet another embodiment, the protective layer **260** may comprise at least one of Alumina (Al_2O_3), Zirconium dioxide (ZrO_2) and Zirconium dioxide—yttrium stabilized in combination with at least one of polycrystalline silicon, silicon carbide, silicon carbide coated graphite, silica, silicon nitride, tungsten carbide or molybdenum. In still another embodiment, the fluidized bed reactor **200** may include at least one of Alumina (Al_2O_3), Zirconium dioxide (ZrO_2) and Zirconium dioxide—yttrium stabilized in combination with one of: quartz, graphite, carbon fiber, or combinations thereof.

[0027] FIG. 3 is close-up view of a cross section of a wall of a fluidized bed reactor as described herein with silicon beads **310** disposed therein. In the embodiment shown by FIG. 3, the reactor wall **350** comprises a protective layer **360** and an adhesion layer **365** applied to the reactor wall **350** before the deposition of the protective layer **360**. The adhesion layer **365** may provide a substrate to which the protective layer **360** may bind or attach improving the durability and function of the protective layer **360**. In one such embodiment, an adhesion layer **365** may comprise a nickel based alloy with or without yttrium, particularly when iron based alloys, such as Cr—Ni alloys, comprise the reactor wall **250**.

[0028] In one embodiment, the protective layer **260** may comprise a coating which has a depth of approximately 3 to 1000 microns. In one such example, the protective layer **260** has a depth ranging from approximately 5 to 900 microns, 10 to 700 microns, 20 to 500 microns, 25 to 400 microns or 40 to 300 microns. In another embodiment, the protective coating may have a depth of up to 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 95, 100, 150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, or 900 microns.

[0029] The protective layer, such as protective layer **260** shown in FIG. 2, or protective layer **360** shown in FIG. 3, can be formed or deposited by one or more methods known by those of skill in the art including thermal projection, chemical vapor deposition, physical vapor deposition, solgel, electrophoretic deposition and aerosol thermal spraying.

[0030] In one embodiment, the deposition of the protective layer **260** or protective layer **360** may be followed by a thermal treatment. For example, the protective layer **260** may be annealed with a thermal treatment of temperatures ranging from approximately 900° C. to 1,300° C. In one such embodiment, the thermal treatment may comprise temperatures ranging from 900° C. to 1,000° C., or from 900° C. to 1,100° C., or from 1,000° C. to 1,200° C., or from 1,000° C. to 1,300° C.

EXAMPLES

[0031] The specific examples included herein are for illustrative purposes only and are not to be considered as limiting to this disclosure. The compositions referred to and used in the following examples are either commercially available or can be prepared according to standard literature procedures by those skilled in the art.

Example 1

Effects of Decomposition Conditions on Steel 1.4841

[0032] A. Nitrogen Gas

[0033] A sample of thermoresistant steel 1.4841 was subjected to decomposition conditions at 900° C. in the presence of silicon beads and a N_2 gas stream. After 100 hours under reaction conditions, the sample steel 1.4841 was removed from the reactor and cooled to room temperature.

[0034] Cross sections of the sample steel 1.4841 were then prepared for analysis with a scanning electron microscope (SEM). The SEM analysis revealed that the steel had been corroded as evidenced by a silicide layer extending into the metal to a depth of approximately 2 microns.

[0035] B. HCl and Hydrogen Gas

[0036] A sample of thermoresistant steel 1.4841 was subjected to decomposition conditions at 900° C. in the presence of silicon beads and HCl and H_2 (5:1). After 100 hours under

reaction conditions, the sample steel 1.4841 was removed from the reactor and cooled to room temperature.

[0037] Cross sections of the sample steel 1.4841 were prepared as before for SEM analysis. The SEM analysis revealed a 50 micron silicide layer on the metal resulting from corrosion of the metal substrate by the chloride. The SEM analysis also revealed the formation of chlorides including iron and chromium chlorides.

[0038] C. Steel with Cr_2O_3 Layer

[0039] A sample of steel 1.4841 was coated with a 50 micron layer of Cr_2O_3 using chemical vapor deposition. The Cr_2O_3 coated steel was heated to 900°C . in the presence of silicon beads and N_2 gas. After 100 hours, the Cr_2O_3 coated steel was cooled to room temperature. SEM analysis showed the presence of silica and chromium on the surface of the steel, potentially due to the following reaction: $2\text{Cr}_2\text{O}_3 + 3\text{Si} \rightarrow 4\text{Cr} + 3\text{SiO}_2$.

[0040] D. Steel with Adhesion Layer and ZrO_2 —Yttrium Stabilized Protective Layer

[0041] A sample of steel 1.4841 was prepared with a nickel alloy adhesion layer to improve the adhesion of the ceramic layer. The nickel alloy adhesion layer (NiCrAlY) was deposited using an atmospheric plasma spray process. Next, the sample was covered with a 100 micron ceramic coating of ZrO_2 —yttrium stabilized, and heated to 900°C ., as before, in conditions simulating a fluidized bed reactor with silicon beads and in the presence of HCl and H_2 (5:1). After 100 hours, the ZrO_2 —yttrium stabilized coated steel was cooled to room temperature. SEM analysis showed the steel 1.4841 with the ceramic coating of ZrO_2 —yttrium stabilized resisted corrosion or degradation thereby minimizing or eliminating likely contamination of a silicon product. More particularly, SEM data showed that there was no migration of aluminum outside of the NiCrAlY adhesion layer. Likewise, there was no migration of chromium, manganese, and nickel outside of the steel 1.4841 and the NiCrAlY adhesion layer. Additionally, the SEM analysis showed that only a few particles of iron from the steel 1.4841 were present in the base of the NiCrAlY adhesion layer and, there was no iron migration into the ZrO_2 —yttrium stabilized protective layer. Therefore, there was no contamination of the ZrO_2 —yttrium stabilized protective layer that would threaten the purity of a silicon product.

[0042] E. Steel with Adhesion Layer and Al_2O_3 Protective Layer

[0043] As before, a sample of steel 1.4841 was prepared with a nickel alloy adhesion layer followed by the addition of an Al_2O_3 protective layer. The prepared sample was heated for 100 hours at 900°C . in a fluidized bed reactor with silicon beads fluidized with HCl and H_2 (5:1). After cooling to room temperature, SEM analysis showed that the Al_2O_3 protective layer prevented corrosion of the steel sample.

Example 2

Heat Transfer by a Radiant Heater

[0044] A. Untreated Stainless Steel

[0045] A stainless steel tube (AISI316L) approximately 0.5 meters long and with an outside diameter of 21.3 mm and a thickness of 2.77 mm was used to measure radiation heat transfer. A radiation heater with an inside diameter of 40 mm was positioned around the steel tube without contacting the surface of the steel tube. The steel tube and the radiation heater were insulated with 300 mm thick ceramic fiber. A

stream of N_2 gas at mass flow rate of 15 Kg/h was passed along the inside of the steel tube horizontally. Thermowells were used to measure the temperature of the radiation heater, the external temperature of the steel tube at the inlet and outlet points of the N_2 gas stream, and the temperature of the N_2 gas stream at the inlet and outlet points. In steady state, the following temperatures were measured: N_2 inlet temperature= 21°C .; N_2 outlet temperature= 315°C .; outer wall tube temperature at the inlet= 569°C ., and at the outlet= 773°C . The thermal power absorbed in the system was 1.325 W.

[0046] B. Sand-Blasted Stainless Steel

[0047] A stainless steel tube was prepared as previously described followed by sand-blasting the surface of the steel tube. After sand-blasting, the following temperatures from the stainless steel tube were measured: N_2 inlet temperature= 20°C .; N_2 outlet temperature= 445°C .; outer wall tube temperature at the inlet= 953°C ., and at the outlet= $1,055^\circ\text{C}$. With the surface treatment, the thermal power absorbed in the system was 1.970 W.

[0048] The analysis showed that the thermal power transfer with the sand-blasting treatment was approximately 1.5 times greater than the untreated steel tube. The thermal power transfer to the N_2 gas stream is due to a combination of radiation from the heater to the outlet wall of the steel tube, conduction through the wall of the steel tube, and convection from the inner wall of the steel tube to the N_2 gas stream. The surface treatment resulted in a decreased reflectivity of the steel tube and an increased ability of the steel tube to absorb heat, thereby increasing the efficiency of heat transfer to the gas stream inside the steel tube. An estimation of the new emissivity value was calculated using the combination of the radiation, conduction and convection heat transfer. Values of the theoretical thermal power transfer were calculated in order to estimate the new value of the emissivity.

[0049] Not being bound by any particular theory, a calculation model using the following equations was used:

[0050] Dittus-Boelter Equation:

$$Nu_D = 0.023 \cdot Re_D^{0.8} \cdot Pr^n$$

$$h_{int} = \frac{Nu \cdot k}{D}$$

[0051] A grey body completely enclosed into another grey body equivalent convection coefficient due to radiation:

$$h_{ext} = \frac{\sigma}{\frac{1}{\varepsilon_1} + \frac{r_1}{r_2} \cdot \left(\frac{1 - \varepsilon_2}{\varepsilon_2} \right)} \cdot \frac{T_1^4 - T_2^4}{T_1 - T_2}$$

[0052] Universal coefficient of heat transfer at the inlet and at the outlet of the pipe:

$$U = \frac{1}{\frac{r_{ext}}{r_{int} \cdot h_{int}} + \frac{r_{ext}}{k} \cdot \ln\left(\frac{r_{ext}}{r_{int}}\right) + \frac{1}{h_{ext}}}$$

[0053] The calculation model introduced the concept of mean logarithmic difference of universal coefficients of heat transfer, and temperatures, because U and ΔT vary along the heat exchanger.

[0054] The emissivity value of the heater was $\epsilon=0.7$ according to the manufacturer datasheet. The emissivity of stainless steel is 0.18 at 500° C.

[0055] The values of the first test were implemented in order to adjust the model, and in a second stage the values of the second test were implemented in order to obtain the new emissivity values through an iterative process. The sand-blasted stainless steel emissivity calculated was 0.52. Hence, the radiation heat transfer ratio was increased approximately 3 times by the sand-blasting surface treatment.

[0056] It will be obvious to those having skill in the art that many changes may be made to the details of the above-described embodiments without departing from the underlying principles of the invention. The scope of the present invention should, therefore, be determined only by the following claims.

1. A method of producing high purity silicon comprising: injecting at least one fluidizing gas into a fluidized bed reactor, wherein the fluidized bed reactor comprises: a chamber constructed of a metal alloy, the chamber including a gas inlet and an effluent outlet; a ceramic protective layer deposited on an inside surface of the chamber, wherein the ceramic protective layer comprises at least one of the following: alumina (Al_2O_3) and zirconium dioxide (ZrO_2); a bed of silicon beads disposed within the chamber; and at least one reactor heater; injecting at least one silicon-bearing gas into the fluidized bed reactor, heating the fluidized bed reactor with the at least one reactor heater to a temperature sufficient for thermal decomposition of silicon; and collecting the high purity silicon that has been produced and deposited on the fluidized silicon beads; wherein the ceramic protective layer is resistant to corrosion by the at least one fluidizing gas or the at least one silicon-bearing gas.
2. The method of claim 1, wherein the metal alloy is an iron-based alloy selected from at least one of the following: a stainless steel alloy and a chromium-nickel alloy.
3. The method of claim 1, wherein the metal alloy is a nickel-based alloy selected from at least one of the following: a nickel-molybdenum alloy and a nickelchromium-molybdenum alloy.
4. The method of claim 1, further comprising an adhesion layer positioned between the protective layer and the inside surface of the chamber.
5. The method of claim 4, wherein the adhesion layer comprises a nickel alloy layer, or a nickel-chromium-yttrium alloy layer.
6. The method of claim 1, wherein the protective layer is deposited on the inside surface of the chamber by at least one of the following: thermal projection, chemical vapor deposition, physical vapor deposition, solgel, electrophoretic deposition and aerosol thermal spraying.
7. The method of claim 1, wherein an external surface of the chamber is sandblasted to improve the thermal power transfer efficiency of the chamber compared to an untreated external surface.

8. The method of claim 1, wherein the fluidizing gas is at least one of the following:

hydrogen, helium, argon, silicon tetrachloride, silicon tetrabromide and silicon tetraiodide.

9. The method of claim 1, wherein the silicon-bearing gas is at least one of the following: monosilane, disilane, trisilane, trichlorosilane, dichlorosilane, monochlorosilane, tribromosilane, dibromosilane, monobromosilane, triiodosilane, diiodosilane and monoiodosilane.

10. The method of claim 1, wherein heating the fluidized bed reactor with the at least one reactor heater to a temperature sufficient for thermal decomposition of silicon comprises heating the fluidized bed reactor to a temperature of between approximately 500° C. to approximately 1200° C.

11. The method of claim 10, wherein the fluidized bed reactor is heated to a temperature ranging from approximately 700° C. to approximately 900° C.

12. A fluidized bed reactor for the production of high purity silicon, the fluidized bed reactor comprising:

a chamber having dimensions to contain silicon particles capable of being fluidized therein, the chamber having a wall constructed of a metal alloy;

a gas inlet in the chamber configured to receive a gas to fluidize the particles inside the chamber, wherein the gas inlet is coupled to a source of silicon-bearing gas;

a silicon particle inlet configured for the addition of silicon particles into the chamber;

an outlet in the chamber configured to allow the recovery of the high-purity silicon;

an outlet configured to allow an effluent gas stream to leave the chamber; and

a ceramic protective layer deposited on at least a portion of an inside surface of the chamber wherein the ceramic protective layer comprises at least one of the following: alumina (Al_2O_3) and zirconium dioxide (ZrO_2); and wherein the ceramic protective layer is configured to be resistant to corrosion by the fluidizing gas.

13. The fluidized bed reactor of claim 12, wherein the metal alloy is an iron-based alloy selected from at least one of the following: a stainless steel alloy and a chromium-nickel alloy.

14. The fluidized bed reactor of claim 13, wherein the metal alloy further includes at least one of the following: manganese, molybdenum, silicon, cobalt and tungsten.

15. The fluidized bed reactor of claim 12, wherein the metal alloy is a nickel-based alloy selected from at least one of the following: a nickel-molybdenum alloy and a nickel-chromium-molybdenum alloy.

16. The fluidized bed reactor of claim 15, wherein the metal alloy further includes at least one of the following: manganese, molybdenum, silicon, cobalt and tungsten.

17. The fluidized bed reactor of claim 12, further comprising an adhesion layer positioned between the protective layer and the inside surface of the chamber.

18. The fluidized bed reactor of claim 17, wherein the adhesion layer comprises at least one of the following: a nickel alloy layer and a nickel-chromium-yttrium layer.

19. The fluidized bed reactor of claim 12, wherein the ceramic protective layer deposited on the inside surface of the chamber is deposited by at least one of the following: thermal projection, chemical vapor deposition, physical vapor deposition, solgel, electrophoretic deposition and aerosol thermal spraying.

20. The fluidized bed reactor of claim 12, wherein the chamber comprises an external surface and, wherein at least a

portion of the external surface of the chamber has been treated to improve the thermal power transfer efficiency of the chamber compared to an untreated external surface.

21. The fluidized bed reactor of claim **20**, wherein the external surface of the chamber is sand-blasted to improve the thermal power transfer efficiency of the chamber.

22. The fluidized bed reactor of claim **12**, wherein the chamber is constructed of a material configured to withstand internal pressures ranging from approximately 50 mbar to approximately 5000 mbar.

23. The fluidized bed reactor of claim **12**, wherein the chamber is constructed of a material configured to withstand temperatures ranging from approximately 500° C. to approximately 1200° C.

24. The fluidized bed reactor of claim **12**, wherein the silicon particles comprise silicon beads and the gas comprises at least one of the following:

hydrogen, helium, argon, silicon tetrachloride, silicon tetrabromide, silicon tetraiodide, monosilane, disilane, trisilane, trichlorosilane, dichlorosilane, monochlorosilane, tribromosilane, dibromosilane, monobromosilane, triiodosilane, diiodosilane and monoiodosilane.

25. The fluidized bed reactor of claim **12**, further comprising at least one reactor heater, wherein the at least one reactor heater comprises at least one of the following: a radiation heater and a conduction heater.

26. A fluidized bed reactor used in the production of high-purity silicon, comprising:

a chamber having dimensions to receive silicon beads capable of being fluidized therein, the chamber having a wall constructed of a metal alloy;

a gas inlet in the chamber configured to receive a fluidizing gas and a silicon-bearing gas to fluidize the particles inside the chamber, wherein the gas inlet is coupled to a source of the fluidizing gas and the silicon-bearing gas; an outlet in the chamber configured to allow a recovery of the high-purity silicon; an outlet configured to allow an effluent gas stream to leave the chamber; and

a protective layer deposited on at least a portion of an inside surface of the chamber wherein the protective layer comprises at least one of the following: alumina (Al_2O_3) and zirconium dioxide (ZrO_2).

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