Vapor Phase Epitaxy System

[0001] The section headings used herein are for organizational purposes only and should not to be construed as limiting the subject matter described in the present application in any way.

Related Application Section

[0002] This application claims priority to U.S. Provisional Patent Application Serial Number 61/195,093 filed October 3, 2008, entitled "Chemical Vapor Deposition with Energy Input," the entire application of which is incorporated herein by reference.

Introduction

[0003] Vapor phase epitaxy (VPE) is a type of chemical vapor deposition (CVD) which involves directing one or more gases containing chemical species onto a surface of a substrate so that the reactive species react and form a film on the surface of the substrate. For example, VPE can be used to grow compound semiconductor material on a substrate. The substrate is typically a crystalline material in the form of a disc, which is commonly referred to as a "wafer." Materials are typically grown by injecting at least a first and a second precursor gas into a process chamber containing the crystalline substrate.

[0004] Compound semiconductors, such as III-V semiconductors, can be formed by growing various layers of semiconductor materials on a substrate using a hydride precursor gas and an organometalic precursor gas. Metalorganic vapor phase epitaxy (MOVPE) is a vapor deposition method that is commonly used to grow compound semiconductors using a surface

reaction of metalorganics and metal hydrides containing the required chemical elements. For example, indium phosphide could be grown in a reactor on a substrate by introducing trimethylindium and phosphine. Alternative names for MOVPE used in the art include organometallic vapor phase epitaxy (OMVPE), metalorganic chemical vapor deposition (MOCVD), and organometallic chemical vapor deposition (OMCVD). In these processes, the gases are reacted with one another at the surface of a substrate, such as a sapphire, Si, GaAs, InP, InAs or GaP substrate, to form a III-V compound of the general formula $In_XGa_YAl_ZN_AAs_BP_CSb_D$, where X+Y+Z equals approximately one, and A+B+C+D equals approximately one, and each of X, Y, Z, A, B, C, and D can be between zero and one. In some instances, bismuth may be used in place of some or all of the other Group III metals.

[0005] Compound semiconductors, such as III-V semiconductors, can also be formed by growing various layers of semiconductor materials on a substrate using a hydride or a halide precursor gas process. In one halide vapor phase epitaxy (HVPE) process, Group III nitrides (e.g., GaN, AlN) are formed by reacting hot gaseous metal chlorides (e.g., GaCl or AlCl) with ammonia gas (NH_3). The metal chlorides are generated by passing hot HCl gas over the hot Group III metals. All reactions are done in a temperature controlled quartz furnace. One feature of HVPE is that it can have a very high growth rate, up to 100 μm per hour for some state-of-the-art processes. Another feature of HVPE is that it can be used to deposit relatively high quality films because films are grown in a carbon free environment and because the hot HCl gas provides a self-cleaning effect.

[0006] In these processes, the substrate is maintained at an elevated temperature within a reaction chamber. The precursor gases are typically mixed with inert carrier gases and are then directed into the reaction chamber. Typically, the gases are at a relatively low temperature when

they are introduced into the reaction chamber. As the gases reach the hot substrate, their temperature, and hence their available energy for reaction, increases. Formation of the epitaxial layer occurs by final pyrolysis of the constituent chemicals at the substrate surface. Crystals are formed by a chemical reaction and not by physical deposition processes. Growth occurs in the gas phase at moderate pressures. Consequently VPE is a desirable growth technique for thermodynamically metastable alloys. Currently, VPE is commonly used for manufacturing laser diodes, solar cells, and LEDs.

Brief Description of the Drawings

[0007] The present teaching, in accordance with preferred and exemplary embodiments, together with further advantages thereof, is more particularly described in the following detailed description, taken in conjunction with the accompanying drawings. The skilled person in the art will understand that the drawings, described below, are for illustration purposes only. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating principles of the teaching. The drawings are not intended to limit the scope of the Applicant's teaching in any way.

[0008] FIG. 1 illustrates a known vapor phase epitaxy system used to form compound semiconductors.

[0009] FIG. 2 illustrates a vapor phase epitaxy system according to the present teachings that includes at least one electrode positioned in a flow of a first precursor gas and being substantially isolated from a flow of a second precursor gas.

[0010] FIG. 3 illustrates a top-view of one embodiment of a disk-shaped gas injector

according to the present teaching that includes a first region that is positioned in quadrants of the gas injector and a second region extending radially through the quadrants.

[0011] FIG. 4A illustrates a cross-section of one embodiment of a disk-shaped gas injector according to the present teaching that includes a plurality of first and second regions which alternates across the gas injector.

[0012] FIG. 4B illustrates an expanded view of the disk-shaped gas injector illustrating mechanical or chemical barriers that isolate the electrodes from the second precursor gas.

[0013] FIG. 5 illustrates a perspective top-view of a vapor phase epitaxy system according to the present teachings that includes a horizontal flow gas injector.

[0014] FIG. 6 illustrates a foil-shaped electrode positioned close to the surface of the platen for thermally activating a precursor gas in a vapor phase epitaxy system according to the present teaching.

Description of Various Embodiments

[0015] Reference in the specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the teaching. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment.

[0016] It should be understood that the individual steps of the methods of the present teachings may be performed in any order and/or simultaneously as long as the teaching remains

operable. Furthermore, it should be understood that the apparatus and methods of the present teachings can include any number or all of the described embodiments as long as the teaching remains operable.

[0017] The present teaching will now be described in more detail with reference to exemplary embodiments thereof as shown in the accompanying drawings. While the present teachings are described in conjunction with various embodiments and examples, it is not intended that the present teachings be limited to such embodiments. On the contrary, the present teachings encompass various alternatives, modifications and equivalents, as will be appreciated by those of skill in the art. Those of ordinary skill in the art having access to the teaching herein will recognize additional implementations, modifications, and embodiments, as well as other fields of use, which are within the scope of the present disclosure as described herein.

[0018] The term "available energy" as used in the present disclosure refers to the chemical potential of a reactant species that is used in a chemical reaction. The chemical potential is a term commonly used in thermodynamics, physics, and chemistry to describe the energy of a system (particle, molecule, vibrational or electronic states, reaction equilibrium, etc.). However, more specific substitutions for the term chemical potential may be used in various academic disciplines, including Gibbs free energy (thermodynamics) and Fermi level (solid state physics), etc.. Unless otherwise specified, references to the available energy should be understood as referring to the chemical potential of the specified material.

[0019] FIG. 1 illustrates a known VPE system 100 used to form compound semiconductors. This system 100 includes a reaction chamber 101 having a spindle 102 mounted therein. The spindle 102 is rotatable about an axis 104 by a rotary drive mechanism

106. The axis 104 extends in an upstream direction U and a downstream direction D as shown in FIG. 1. A platen 108, which in many systems is a disc-like substrate carrier, is mounted on the spindle 102 for rotation therewith. Typically, the platen 108 and spindle 102 rotate at rotation rates that are in the range of about 100-2,000 revolutions per minute. The platen 108 is adapted to hold a plurality of disc-like substrates 110 so that surfaces 112 of the substrates 110 are in a plane perpendicular to axis 104 and face in the upstream direction U.

[0020] A heater 114, such as a resistance heating element, is positioned within the reaction chamber 101 proximate to the platen 108. The heater 114 heats the substrate carrier to the desired processing temperature. A gas injector 116, which is sometimes known in the art as a flow inlet element, is mounted upstream of the platen 108 and spindle 102. The gas injector 116 is connected to process gas sources 118, 120, and 122. The gas injector 116 directs streams of various process gases into the reaction chamber 101. A fluid coolant supply 117 is coupled to liquid cooling channels in the flow injector 116 to circulate the cooling fluid in order to control the temperature of the gas injector 116.

[0021] In operation, streams of process gases from the process gas sources 118, 120, and 122 flow generally downstream toward the platen 108 and substrates 110 in a region of the reaction chamber 101 between the gas injector 116 and the platen 108, that is referred to herein as the "flow region 124." In known systems, this downward flow does not result in substantial mixing between separate streams of downwardly flowing gas. It is typically desirable to design and operate the system 100 so that there is laminar flow in the flow region 124. In normal operation, the platen 108 is rotated rapidly about the axis 104 with the rotary drive 106 so that the surface of the platen 108 and the surfaces of the substrates 110 are moving rapidly. The rapid motion of the platen 108 and substrates 110 entrains the gases into rotational motion about

axis 104. Consequently, the process gases flow radially away from axis 104, thereby causing the process gases in the various streams to mix with one another within a boundary layer that is schematically indicated in boundary layer region 126.

[0022] In practice, there is a gradual transition between the generally downstream gas flow indicated by arrows 128 in the flow region 124 and the rapid rotational flow and mixing in the boundary layer 126. Nevertheless, the boundary layer 126 is generally regarded as a region in which the gas flow is substantially parallel to the surfaces of the substrates 110. In some methods of operation, the thickness of the boundary layer 126 is on order of about 1 cm and the distance from the downstream face of gas injector 116 to the surfaces 112 of the substrates 110 is about 5-8 cm. Thus, the flow region 124 occupies the major portion of the space between the gas injector 116 and the platen 108. The rotational motion of the platen 108 pumps the gases outwardly around the peripheral edges of the platen 108, and hence the gases pass downstream to an exhaust system 130. In many methods of operation, the reaction chamber 101 is maintained under an absolute pressure from about 25-1,000 Torr. Many processes operate at an absolute pressure of about 50-760 Torr.

[0023] The gas injector 116 is maintained at a relatively low temperature, which is typically about 60°C or less, although higher temperatures are sometimes used. In Halide VPE systems, the Group III halide is maintained at an elevated temperature to prevent condensation. This elevated temperature is below the temperature of the substrates 110 where deposition occurs. The relatively low temperature is chosen to inhibit decomposition of reactants and/or to inhibit the formation of undesired reactions of the reactants in the gas injector 116 and in the flow region 124. Also, in many processes, the walls 101' of reaction chamber 101 are cooled to about 25°C in order to minimize the rate of any reactions of the process gases in the flow region

124 remote from the platen 108.

[0024] It is desirable to promote rapid reactions between the gases in the boundary layer 126 at the surfaces of the substrates 110 because the residence time of the gases in the boundary layer 126 is relatively brief. In a conventional VPE system, the reaction energy is provided primarily by heat from the platen 108 and substrates 110. For example, in some processes, the reaction energy is the energy required to dissociate a Group V hydride, such as NH_3, to form reactive intermediates, such as NH_2 and NH. However, increasing the temperature of the platen 108 and substrates 110 also tends to increase dissociation of the deposited compound semiconductors. For example, increasing the temperature of the platen 108 and substrates 110 can result in a loss of nitrogen from the semiconductor especially when growing Indium-rich compounds such as InGaN and InN.

[0025] In one aspect of the present teachings, VPE systems include one or more electrically active electrodes that are used to add additional energy to a process gas in order to increase the reaction rate or to modify the reaction chemistry. One skilled in the art will appreciate that any type of electrically active electrode can be used, such as wires and filaments in any shape, which are exposed to a process gas in the process chamber 101.

[0026] In many embodiments of the present teachings, it is desirable to supply energy to one of the process gases without supplying significant energy to other process gases. For example, in many Group III-V deposition processes, it is desirable to apply additional energy to the Group V hydride precursor gases, which for example, can be ammonia (NH3) without supplying significant energy to the Group III metal precursor gases. One skilled in the art will appreciate that selective application of energy to one or more of process gases can be

accomplished in numerous ways. For example, the one or more electrically active electrodes can be physically isolated from a precursor gas that will react in the presence of the elevated temperatures. Physical isolation can be achieved by introducing the gases separately in different regions of the reactor and by using baffles and/or gas curtains as described herein. One feature of the present teachings is that gases can be introduced separately, but at the same distance from the substrates 110 in order to maintain laminar flow over the surfaces of the substrates 110.

[0027] FIG. 2 illustrates a vapor phase epitaxy system 200 according to the present teachings that includes at least one electrode positioned in a flow of a first precursor gas and being substantially isolated from a flow of a second precursor gas. The VPE system 200 is similar to the VPE system described in connection with FIG. 1. The VPE system 200 includes a process chamber 201 for containing process gasses. In addition, the VPE system 200 includes a platen 202, which is a disk-shaped substrate carrier that supports substrates 204 for vapor phase epitaxy.

[0028] The VPE system 200 includes a gas injector 206 comprising multiple regions that are separated by physical barriers and/or chemical barriers. For example, the VPE system 200 can include a first region 208 that is coupled to a first precursor gas source 210 and a second region 212 that is coupled to a second precursor gas source 214. Any type of precursor gas can be used in the VPE system according to the present teachings. In various other embodiments, the gas injector 206 can include additional regions that are separated by physical barriers and/or chemical barriers that may or may not be coupled to additional precursor and/or inert gas sources 211.

[0029] As described herein, there are many possible gas injector designs that inject

different precursor gases into different regions of the process chamber 201. For example, in one embodiment that is described in connection with FIG. 3, the first region 208 in the gas injector 206 is positioned in quadrants of a disk and a second region 212 extends radially through the quadrants. In another embodiment that is described in connection with FIG. 4A, the first and second regions 208, 212 in the gas injector 206 include a plurality of first and second regions that alternate across at least a portion of the gas injector 206. In many practical embodiments, the gas injector 206 comprises liquid cooling channels to control a temperature of the gas injector 206. A fluid coolant supply 216 is coupled to liquid cooling channels in the flow injector 206 to circulate the cooling fluid in order to control the temperature of the gas injector 206.

[0030] In various embodiments, the gas injector 206 is designed to flow the first and second precursor gases over the platen 202 that supports the substrates 204 with either a laminar flow or a non-laminar flow. Also, in various embodiments, the gas injector 206 flows the first and second precursor gases in various directions relative to the platen 202 that supports the substrates 204. For example, in some VPE systems according to the present invention, the gas injector 206 flows at least one of the first and second precursor gases in a direction that is perpendicular to the surface of platen 202 that supports the substrates 204. Also, in some VPE systems, the gas injector 206 flows at least one of the first and second precursor gases in a direction that is parallel to the platen 202 that supports the substrates 204. In one particular, VPE system, the gas injector 206 flows one of the first and second precursor gases in a direction that is substantially parallel to the platen 202 that supports the substrates 204 and the other of the first and second precursor gases through the gas injector 206 in a direction that is substantially perpendicular to the platen 202 that supports the substrates 204.

[0031] Electrodes 218, 219 are positioned in the first region 212 so that first precursor

gas flows in contact with or in close proximity to the electrodes 218, 219. In addition, the electrodes 218, 219 are positioned so that they are substantially isolated from the flow of the second precursor gas. The electrodes 218, 219 can be oriented in numerous ways. For example, the electrodes 218, 219 can be oriented in a plane of the gas injector 206 (e.g. electrode 218). The electrodes 218, 219 can also be oriented perpendicular to the plane of the gas injector 206 (e.g. electrode 219). In addition, the electrodes 218, 219 can be positioned anywhere between the gas injector 206 and the platen 202 that supports the substrates 204 including in close proximity to the gas injector 206 and in close proximity to the platen 202 that supports the substrates 204.

[0032] In various embodiments, the electrodes 218, 219 can be formed of any type of electrode material. However, the electrodes 218, 219 are typically formed of a material that is resistant to corrosion so that they do not introduce any contamination into the VPE system 200. Also, in various embodiments, any type of electrode configuration can be used including any number of electrodes, which can include only one electrode. In addition, in various embodiments, the electrodes 218, 219 can be formed in any shape. For example, the VPE system 200 shows two different types of electrodes, a linear (straight) electrode 218 and a non-linear electrode 219, such as a coiled electrode or other structure that increases or maximizes the surface area of the electrode that is exposed to the first precursor gas. In many systems, the same type of electrode is used, but in some systems two or more different types of electrodes are used.

[0033] The electrodes 218, 219 are electrically active. In the embodiment shown in FIG. 2, the electrodes 218, 219 are at a floating potential when not powered. An output of a power supply 220 is electrically connected to the electrodes 218, 219. The power supply 220 generates a current that heats the electrodes 218, 219 so as to thermally activate at least some of the first

precursor gas molecules flowing in contact with or proximate to the electrodes 218, 219.

[0034] One skilled in the art will appreciate that there are numerous ways of isolating the electrodes 218, 219 so that they are substantially isolated from the flow of the second precursor gas. For example, in one embodiment, the gas injector 206 includes one or more baffles 222 or other types of physical structure that physically separates the first region 208 from the second region 212 so as to isolate the electrodes 218, 219 from the flow of the second precursor gas. In many embodiments, the one or more baffles 222 are formed of non-thermally conductive materials so that the thermal profile in the process chamber 201 does not significantly change from thermal radiation emitted by the baffles 222. In one embodiment, the one or more baffles 222 are shaped to preserve laminar flow of at least one of the first and second precursor gases across the platen 202 that supports the substrates 204.

[0035] In one embodiment, the electrodes 218, 219 are formed of a catalytic material. A heater can be positioned in thermal communication with the catalytic material so as to increase a reaction rate of the catalytic material. One skilled in the art will appreciate that numerous types of catalytic materials can be used. For example, in some embodiments, the electrodes 218, 219 are formed of a catalytic material including at least one of rhenium, tungsten, niobium, tantalum, and molybdenum. In various embodiments, the electrodes 218, 219 can be formed of refractory and/or transition metals.

[0036] A method of operating a vapor phase epitaxy system according to the present teachings includes injecting a first precursor gas for vapor phase epitaxy in the first region 208 proximate to a platen 202 supporting substrates 204 and injecting a second precursor gas for vapor phase epitaxy in a second region 212 proximate to the platen 202 supporting substrates. In

one method, the first and second precursor gases are injected in a plurality of respective alternating first and second regions as described in connection with FIG. 4A.

[0037] Any type of VPE precursor gases can be used. For example, the first precursor gas can be a hydride precursor gas, such as NH_3 and the second precursor gas can be an organometalic precursor gas, such as trimethyl gallium, that is used to grow GaN by VPE. Also, the first precursor gas can be a hydride precursor gas, such as NH_3 and the second precursor gas can be a metal halide precursor gas, such as gallium chloride, that is used to grow GaN by VPE. In some methods, three precursor gases are used. For example in these methods, the first precursor gas can be a hydride precursor gas, such as NH_3, and the second precursor gas can be an organometalic precursor gas, such as trimethyl gallium. The third precursor gas can be a halide precursor gas, such as HCl. With these three precursor gases, the halide precursor gas and the organometallic precursor gas react to form a metal halide. In methods using three precursor gases, the gas injector 206 can include a third region for injecting the third precursor gas. Alternatively, the third precursor gas can be injected in the either the first or the second regions 208, 212.

[0038] The first and second precursor gases can be injected at any angle including perpendicular and parallel to the platen 202 supporting substrates 204. The angle of injection for the second precursor gas can be the same as or different from the angle of injection of the first precursor gas. First precursor gas molecules flow in contact with or in close proximity to the electrodes 218, 219. However, the electrodes 218, 219 are at least partially isolated from the flow of the injected second precursor gas. The electrodes 218, 219 are then electrically activated. In some methods, the electrodes 218, 219 are isolated from a flow of the injected second precursor gas with physical baffles 222. The baffles 222 can be performed so as to

preserves laminar flow over the platen 202 supporting substrates 204 as described in connection with FIG. 6.

[0039] In methods using gas curtains, inert gases are injected in regions that isolate the electrodes 218, 219 from a flow of the second precursor gas. The term "inert gas" as used herein refers to a gas which does not substantially participate in the growth reactions. Inert gases are often mixed with the precursor gases. Such inert gases are referred to in the art as "carrier gases." For example, when growing III-V semiconductor materials, gases, such as N2, H2, He or mixtures thereof, are commonly used as carrier gases for precursor gases.

[0040] The power supply 220 generates a current that flows through the electrodes 218, 219 so that the electrodes 218, 219 generates heat that thermally activates the first precursor gas molecules without activating a substantial amount of second precursor gas molecules. The heated electrodes 218, 219 transfer energy to the first precursor gas molecules by various mechanisms including thermionic emission of electrons and interaction of the electrons with the reactant species. In some methods according to the present teachings, the electrons do not have sufficient energy to ionize the reactant species. One example where the electrons do not have sufficient energy to ionize the reactant species is ionizing NH_3. In methods that ionize NH_3, the electrons interact with the reactant species so as to promote the species to a higher energy state.

[0041] In some VPE systems according to the present teachings, the electrodes 218, 219 are catalytic electrodes, which are formed of a catalytic material capable of catalyzing the first precursor gas if conditions are favorable. The catalytic electrode can be heated with a separate heater to enhance the catalytic reaction. In some methods, such a catalytic electrode is useful to decompose NH_3 close to the gas injector 206 surface because it is far from the platen 202

supporting the substrate 204 and, therefore, may not have enough thermal energy for decomposition. Using a catalytic electrode lowers the activation energy for decomposition and, therefore, increases the probability of NH_3 decomposition even in regions of the process chamber 201 that have relatively low temperatures (i.e. regions close to the gas injector 206 away from the substrate). The catalytic electrode allows the reaction to proceed or, if the reaction was inclined to occur, to proceed more rapidly by lowering the activation energy of the reaction or having the reaction proceed through a different reaction pathway. In one VPE system according to the present teachings, the catalytic electrode is positioned proximate to the boundary layer region 126 (FIG. 1) so that the first precursor gas mixes with the second precursor gas shortly after the first precursor gas interacts with the catalytic electrode.

[0042] Other VPE systems according to the present teachings include a catalytic electrode that is not energized. This is a catalytic electrode that is not powered by a power supply and that uses only the catalytic material and ambient heat to enhance the catalytic reaction. In various VPE systems according to the present teachings, a catalytic electrode can be positioned anywhere in the process chamber 201. In some of these VPE systems, the catalytic electrode is positioned proximate to the platen 202. Catalytic electrodes positioned proximate to the platen 202 can reach effective catalytic activity through secondary heating from the platen 202 alone.

[0043] Slab-like streams of thermally activated first precursor gas molecules flow generally downstream toward the platen 202 and substrates 204 in a flow region 224 of the reaction chamber 201 between the gas injector 206 and the platen 202. In many methods according to the present teachings, the downward flow does not result in substantial mixing between separate streams of downwardly flowing gas. It is sometimes desirable to design and

operate the system 200 so that there is laminar flow in the flow region 224. The platen 202 is rotated rapidly about the axis 104 with the rotary drive 106 so that the surface of the platen 202 and the surfaces of the substrates 204 are moving rapidly. The rapid motion of the platen 202 and substrates 204 entrains the gases into rotational motion about axis 104. Consequently, the process gases flow radially away from axis 104, thereby causing the process gases in the various streams to mix with one another within a boundary layer that is schematically indicated in boundary layer region 126. The activated first precursor gas molecules and the second precursor gas molecules in the mixture within the boundary layer flow over the surface of the substrates 204, thereby reacting to form a VPE film.

[0044] In conventional VPE systems, precursor gasses are introduced into the process chamber 201 at a relatively low temperature, and hence have low available energy, typically well below the energy required to induce rapid reaction of the reactants on the surface of the substrate 204. In conventional methods of VPE, there may be some heating of the reactants by radiant heat transfer as the reactants pass downstream from the inlet towards the boundary layer region 126. However, most of the heating, and hence most of the increase in available energy of the reactants, occurs within the boundary layer region 126. In these conventional VPE systems, substantially all of the heating depends upon the temperature of the substrate 204 and platen 202.

[0045] In VPE systems according to the present teachings, substantial energy is supplied to at least one precursor gas other than energy applied by heat transfer from the substrate, platen, and chamber walls. The location where the energy is applied can be controlled. For example, by applying the energy to the first precursor gas near the transition between the flow region 124 (FIG. 1) and the boundary layer region 126, the time between the moment when a given portion of a first precursor gas reaches a high available energy and the time when that portion encounters

the substrate surface can be minimized. Such control can help to minimize undesired side reactions. For example, ammonia having high available energy may spontaneously decompose into species such as NH_2 and NH, and then these species in turn may decompose to monatomic nitrogen, which very rapidly forms N_2. Nitrogen is essentially unavailable for reaction with a metal organic. By applying the energy to the ammonia just before or just as the ammonia enters the boundary layer, the desired reactions which deposit the semiconductor at the surface, such as reaction of the excited NH_3 with the metal organic or reaction of NH_2 or NH species with the metal organic at the substrate surface can be enhanced, whereas the undesirable side reaction can be suppressed.

[0046] Thus, one feature of the present teachings is that by using the electrodes according to the present invention, the operator has the ability to control the available energy of at least one precursor gas independently of the temperature of the substrates 204. Thus, the available energy of at least one precursor gas in the boundary layer region 126 (FIG. 1) can be increased without increasing the temperature of the substrates 204 and the platen 202. Conversely, the substrates 204 and the platen 202 can be maintained at a lower temperature while still maintaining an acceptable level of available energy.

[0047] FIG. 3 illustrates a top-view of one embodiment of a disk-shaped gas injector 300 according to the present teaching which includes a first region 302 that is positioned in quadrants of the gas injector 300 and a second region 304 extending radially through the quadrants. The top-view shown in FIG. 3 is presented looking upstream toward the precursor gas inlets in the gas injector 300. The disk-shaped gas injector 300 includes mechanical or chemical barriers 305 that isolate the first and second regions 302, 304. As described herein, the mechanical or chemical barriers 305 can be physical structures, such as baffles and/or gas curtains that inject

inert gases to isolate the first and second regions 302, 304.

[0048] FIG. 3 shows electrodes 306, 308 in two quadrants for clarity. In many VPE systems according to the present invention, electrodes 306, 308 are positioned in each of the quadrants of the first region 302. In some embodiments, each of the electrodes 306, 308 is suspended with an insulating support structure so that the electrodes 306, 308 are electrically floating and easily connected to the power supply 220 (FIG. 2). In various embodiments, the electrodes can be linear (straight) electrodes or non-linear electrodes, such as coiled electrodes or other structures that increases or maximizes the surface area of the electrodes 306, 308 that are exposed to the first precursor gas.

[0049] In many systems, the same type of electrode is used throughout the first region 302, but in some systems two or more different types of electrodes are used in different positions in the first region 302. For example, the type of electrode near the second region 304 (at the edges of the first region 302) can be different from the type of electrode in the middle of the first region 302. For the purpose of illustrating the positioning of different types of electrodes, FIG. 3 shows a first type of electrode 306, which can be either linear or non-linear, positioned in the plane of the first precursor gas flow. In addition, FIG. 3 shows a second type of electrode 308 positioned in the plane of the gas injector 300. FIG. 3 shows the second type of electrode 308 in a linear pattern. However, it should be understood that the second type of electrode can also be formed in a non-linear pattern, such as a coil.

[0050] The electrodes 306, 308 are positioned far enough from the second region 304 so that the chemical potential of the second precursor is not changed based on its proximity to the electrodes 306, 308. In other words, the electrodes 306, 308 have essentially no interaction with

the second precursor gas. One feature of the VPE system of the present teachings is that the first and second precursor gases can be injected at the same distance from the substrate 204 (FIG. 2). In other words, the second precursor gas does not have to be injected below the first precursor gas in the process chamber 201 to avoid activation. Injecting both the first and the second precursor gases at the same level in the process chamber 201 is important in many VPE processes because such injection can achieve laminar flow over large areas in vertical flow VPE process chambers. Laminar flow is desirable for many VPE processes because it improves uniformity.

[0051] Methods of operating VPE systems comprising the gas injector 300 of FIG. 3 include injecting the first precursor gas in the quadrants of the first region 302 so that first precursor gas molecules contact the electrodes 306, 308. The electrodes 306, 308 are powered with power supply 220 (FIG. 2) so that they thermally activate the first precursor gas molecules. For example, the first precursor gas can be a hydride precursor gas precursor gas admixture with a carrier gas. The second precursor gas is injected in the second region 304 adjacent to the electrodes 306, 308. For example, the second precursor gas can be an organometallic admixture with a carrier gas such as nitrogen. Process conditions are chosen so that the second precursor gas does not flow close enough to the electrodes 306, 308 to be thermally activated by heat generated by the electrodes. The activated first precursor gas molecules and the second precursor gas molecules then flow over the surface of the substrates 204 (FIG. 2), thereby reacting to form a VPE film.

[0052] FIG. 4A illustrates a cross-section of one embodiment of a disk-shaped gas injector 400 according to the present teaching that includes a plurality of first and second regions 402, 404 which alternates across the gas injector 400. The top-view shown in FIG. 4A is

presented looking upstream toward the precursor gas inlets in the gas injector 400. The plurality of first regions 402 includes gas inlets for injecting hydride or halide precursor gases with a carrier gas. The plurality of second regions 404 includes gas inlets for injecting organometallic gases with a carrier gas.

[0053] In many VPE systems according to the present teachings, the area of the first regions 402 is larger than the area of the second regions 404. The flow rates of the first and second precursor gases and of the carrier gases during operation can be adjusted for the particular dimensions of the first and the second regions 402, 404 so that the desired volumes and concentrations of precursor gases flow across the substrates 204 (FIG. 2) being processed.

[0054] The gas injector 400 includes a plurality of electrodes 406, 408 positioned in the plurality of first regions 402. In many VPE systems according to the present invention, the plurality of electrodes 406, 408 are positioned in the first region 402 or as far from the flow of the second precursor gas as possible so as to minimize the activation of second precursor gas molecules with the electrodes 406, 408. FIG. 4A illustrates electrodes 406, 408 in two different orientations. Electrodes are only shown in a few sections of the plurality of first regions 402 for clarity. In many VPE systems according to the present teachings, electrodes 406, 408 are positioned in each of the plurality of the first regions 402. In some embodiments, each of the electrodes 406, 408 is suspended with an insulating support structure so that the electrodes 406, 408 are electrically floating and easily connected to the power supply 220 (FIG. 2). In various embodiments, the electrodes 406, 408 can be linear (straight) electrodes or non-linear electrodes, such as coiled electrodes or other structures that increases or maximizes the surface area of the electrodes 406, 408 that are exposed to the first precursor gas.

[0055] In many systems, the same type of electrode is used throughout the first region 402, but in some systems two or more different types of electrodes are used in different positions in the first region 402. For the purpose of illustrating the positioning of different types of electrodes, FIG. 4A shows a first type of electrode 406, which can be either linear or non-linear, positioned in the plane of the first precursor gas flow. In addition, FIG. 4A shows a second type of electrode 408 positioned in the plane of the gas injector 400. FIG. 4A shows the second type of electrode 408 as a non-linear electrode that can also be coiled. However, it should be understood that the second type of electrode 408 can also be a linear electrode.

[0056] FIG. 4B illustrates an expanded view of the disk-shaped gas injector 400 illustrating mechanical or chemical barriers 405 that isolate the electrodes 406 (FIG. 4A), 408 from the second precursor gas. The mechanical or chemical barriers 405 isolate the electrodes 406, 408 in first region 402 from the precursor gas flowing in the second region 404. As described herein, the barriers 405 can be a physical structure, such as baffle. In addition, the barriers 405 can be a gas curtains that inject inert gases between the first and second regions 402, 404 as described herein.

[0057] Methods of operating VPE systems comprising the gas injector 400 of FIGS. 4A and 4B include injecting the first precursor gas in the plurality of first regions 402 so that first precursor gas molecules contact the electrodes 406, 408. The electrodes 406, 408 are powered with the power supply 220 (FIG. 2) so that they thermally activate the first precursor gas molecules. For example, the first precursor gas can be a hydride precursor gas admixture with a carrier gas that is thermally activated when it flows in contact with the electrodes 406, 408. The second precursor gas is injected in the plurality of second regions 404. For example, the second precursor gas can be an organometallic admixture with a carrier gas. Process conditions are

chosen so that the second precursor gas does not flow close enough to the electrodes 406, 408 to be thermally activated by heat generated by the electrodes 406, 408. The activated first precursor gas molecules and the second precursor gas molecules then flow over the surface of the substrates 204 (FIG. 2), thereby reacting to form a VPE film.

[0058] FIG. 5 illustrates a perspective top-view of a VPE system 500 according to the present teachings that includes a horizontal flow gas injector 502. The VPE system 500 is similar to the VPE system 200 that was described in connection with FIG. 2. However, the VPE system 500 includes circular gas injectors 504, 506, and 508 that inject precursor gases and inert gases in the plane of the platen 510 (i.e. horizontal flow into the process chamber).

[0059] In the embodiment shown in FIG. 5, the first circular gas injector 504 is coupled to a first precursor gas source 512. The second circular gas injector 506 is coupled to an inert gas source 514. The third circular gas injector 508 is coupled to a second precursor gas source 516. In some VPE systems according to the present teachings, the first and third circular gas injectors 504, 508 are also coupled to a carrier gas source. The first circular gas injector 504 injects the first precursor gas in a first horizontal region 518. The third circular gas injector 508 injects the second precursor gas in a second horizontal region 520.

[0060] A circular electrode 522 is positioned in the first horizontal region 518 so that first precursor gas molecules flow in contact with or proximate to the circular electrode 522. A physical or chemical barrier can be positioned between the first and the second horizontal regions 518, 520 in order to isolate the circular electrode 522 from the flow of the second precursor gas molecules. In some systems according to the present teachings, a baffle is positioned above the circular electrode 522 to substantially prevent the first precursor gas

molecules from being thermally activated by the electrode 522 as they flow to the platen 510.

[0061] In some systems according to the present teachings, a gas curtain is used to separate the first and the second horizontal regions 518 and 520. In these systems, the second circular gas injector 506 injects inert gas between the first and the second horizontal regions 518, 520 in a pattern that substantially prevents the second precursor gas molecules from being activated by the circular electrode 522.

[0062] Methods of operating the VPE system 500 of FIG. 5 include injecting the first precursor gas with the first circular gas injectors 504 and injecting the second precursor gas with the third circular gas injectors 508. An inert gas is injected between the first and the second horizontal regions 518, 520 with the second circular gas injectors 506 to form a chemical barrier that prevents the second precursor gas molecules from being activated by the circular electrode 522. When the circular electrode 522 is powered by a power supply 220 (FIG. 2), the circular electrode 522 thermally activates first precursor gas molecules injected by the first circular gas injector 504 that flow in contact with or in close proximity to the circular electrode 522. The activated first precursor gas molecules and the second precursor gas molecules then flow over the surface of the substrates 524, thereby reacting to form a VPE film.

[0063] FIG. 6 illustrates a foil-shaped electrode 600 positioned close to the surface of the platen 602 for thermally activating a precursor gas in a VPE system according to the present teaching. The electrode 600 is positioned close to the surface of the platen 602 and substrate 604 being processed. The electrode 600 shown in FIG. 6 is shaped as an airfoil in order to provide a laminar or near laminar flow of precursor gases across the surface of the substrate 604. In addition, in embodiments where the electrode 600 is formed of a catalytic material, the electrode

600 can be shaped to provide a relatively large surface area for the catalytic reaction.

Equivalents

[0064] While the applicant's teaching are described in conjunction with various embodiments, it is not intended that the applicant's teaching be limited to such embodiments. On the contrary, the applicant's teaching encompass various alternatives, modifications, and equivalents, as will be appreciated by those of skill in the art, which may be made therein without departing from the spirit and scope of the teaching.

What is claimed is:

1. A vapor phase epitaxy system comprising:

a. a platen that supports substrates for vapor phase epitaxy;

b. a gas injector comprising a first region that is coupled to a first precursor gas source and a second region that is coupled to a second precursor gas source, the gas injector injecting the first precursor gas into the first region and injecting the second precursor gas into the second region;

c. at least one electrode that is positioned in the first region so that first precursor gas molecules flow proximate to the at least one electrode and positioned to be substantially isolated from a flow of the second precursor gas; and

d. a power supply having an output that is electrically connected to the at least one electrode, the power supply generating a current that heats the at least one electrode so as to thermally activate at least some of the first precursor gas molecules flowing proximate to the at least one electrode.

2. The system of claim 1 wherein the gas injector comprises liquid cooling channels to control a temperature of the gas injector.

3. The system of claim 1 wherein the first and second regions in the gas injector comprise a plurality of first and second regions that alternate across at least a portion of the gas injector.

4. The system of claim 1 wherein at least one of the first and second precursor gases flows through the gas injector in a direction that is perpendicular to the platen that supports the substrates.

5. The system of claim 1 wherein at least one of the first and second precursor gases flows through the gas injector in a direction that is parallel to the platen that supports the substrates.

6. The system of claim 1 wherein one of the first and second precursor gases flow through the gas injector in a direction that is substantially parallel to the platen that supports the substrates and the other of the first and second precursor gases flow through the gas injector in a direction that is substantially perpendicular to the platen that supports the substrates.

7. The system of claim 1 wherein the gas injector flows the first and second precursor gases over the platen with a laminar flow.

8. The system of claim 1 wherein the gas injector flows the first and second precursor gas over the platen with a non-laminar flow.

9. The system of claim 1 wherein the gas injector further comprises a baffle that physically separates the first and the second regions.

10. The system of claim 9 wherein the baffle is shaped to preserve laminar flow of the first and second precursor gases across the platen that supports the substrates.

11. The system of claim 9 wherein the baffle is formed of a non-thermally conductive

material.

12. The system of claim 1 wherein the at least one electrode is formed of a catalytic material.

13. The system of claim 12 wherein the catalytic material comprises at least one of tungsten, rhenium, and molybdenum.

14. The system of claim 1 further comprising a catalytic electrode positioned proximate to the platen.

15. The system of claim 1 wherein the electrode is formed in a non-linear structure.

16. The system of claim 1 wherein the electrode is oriented in a plane of the gas injector.

17. The system of claim 1 wherein the electrode is oriented in a plane that is perpendicular to the gas injector.

18. The system of claim 1 wherein the electrode is positioned proximate to the platen.

19. A method of vapor phase epitaxy, the method comprising:

a. injecting a first precursor gas for vapor phase epitaxy in a first region proximate to a platen supporting substrates;

b. injecting a second precursor gas for vapor phase epitaxy in a second region proximate to the platen supporting substrates;

c. positioning an electrode in a flow of the injected first precursor gas;

d. isolating the electrode from a flow of the injected second precursor gas; and

e. activating the first precursor gas with the electrode.

20. The method of claim 19 wherein the activating the first precursor gas generates first precursor gas radicals.

21. The method of claim 19 wherein the activating the first precursor gas comprises energizing the electrode to thermally activate the first precursor gas.

22. The method of claim 19 wherein the activating the first precursor gas comprises catalytically activating the first precursor gas with a catalytic electrode material.

23. The method of claim 19 wherein the injecting the first precursor gas comprises injecting a hydride precursor gas and the injecting the second precursor gas comprises injecting an organometalic precursor gas.

24. The method of claim 23 further comprising injecting a halide precursor gas.

25. The method of claim 19 wherein the injecting the first precursor gas for vapor phase epitaxy comprises injecting a hydride precursor gas and the injecting the second precursor gas for vapor phase epitaxy comprises injecting an metal halide precursor gas.

26. The method of claim 19 wherein the injecting the first and second precursor gases for vapor phase epitaxy comprise injecting the first and second precursor gases parallel to the platen supporting substrates.

27. The method of claim 19 wherein the injecting the first and second precursor gases for vapor phase epitaxy comprise injecting the first and second precursor gases perpendicular to the platen supporting substrates.

28. The method of claim 19 wherein the injecting the first and second precursor gases for vapor phase epitaxy comprise injecting one of the first and second precursor gases perpendicular to the platen supporting substrates and injecting the other of the first and second precursor gases parallel to the platen supporting substrates.

29. The method of claim 19 wherein the injecting the first and second precursor gases comprise injecting the first and second precursor gases in a plurality of alternating first and second regions wherein the first precursor gas is injected in the first regions and the second precursor gas is injected in the second regions of the plurality of alternating first and second regions.

30. The method of claim 19 wherein the isolating the electrode from a flow of the injected second precursor gas comprises baffling the electrode.

31. The method of claim 30 wherein the baffling preserves laminar flow over the platen supporting substrates.

32. A vapor phase epitaxy system comprising:

a. a means for injecting a first precursor gas for vapor phase epitaxy in a first region proximate to a platen supporting substrates;

b. a means for injecting a second precursor gas for vapor phase epitaxy in a

second region proximate to the platen supporting substrates;

c. an electrode positioned in a flow of the injected first precursor gas;

d. a means for isolating the electrode from a flow of the injected second precursor gas; and

e. a means for activating the first precursor gas with the electrode.

33. The system of claim 32 wherein the means for activating the first precursor gas with the electrode comprises energizing the electrode.

34. The system of claim 32 wherein the means for activating the first precursor gas with the electrode comprises forming a catalytic reaction with the electrode.

35. The system of claim 32 wherein the means for isolating the electrode from a flow of the injected second precursor gas comprises baffling the electrode.

36. A method of vapor phase epitaxy, the method comprising:

a. injecting a first precursor gas comprising H_2 and N_2 for vapor phase epitaxy in a first region proximate to a platen supporting substrates;

b. injecting a second precursor gas for vapor phase epitaxy in a second region proximate to the platen supporting substrates;

c. positioning a catalytic electrode in a flow of the injected first precursor gas;

d. isolating the electrode from a flow of the injected second precursor gas;

and

e. energizing the catalytic electrode to activate the first precursor gas to generate at least one of NH_2 and NH.

37. The method of claim 36 further comprising positioning a second catalytic electrode in thermal communication with the platen supporting substrates that is not energized.