

HIGH VOLUME DELIVERY SYSTEM FOR GALLIUM TRICHLORIDE

FIELD OF THE INVENTION

The present invention relates to the field of semiconductor processing equipment and methods, and provides, in particular, equipment and methods for the high volume manufacturing of Group III-V compound semiconductor wafers that are suitable for fabrication of optic and electronic components, for use as substrates for epitaxial deposition, and so forth. In preferred embodiments, the equipment and methods are directed to producing Group III-nitride semiconductor wafers, and specifically to producing gallium nitride (GaN) wafers.

BACKGROUND OF THE INVENTION

Group III-V compounds are important and widely used semiconductor materials. Group III nitrides in particular have wide, direct band gaps, which make them particularly useful for fabricating optic components (particularly, short wavelength LEDs and lasers) and certain electronic components (particularly, high-temperature/high-power transistors).

The Group III nitrides have been known for decades to have particularly advantageous semiconductor properties. However, their commercial use has been substantially hindered by the lack of readily available single crystal substrates. It is a practical impossibility to grow bulk single crystal substrates of the Group III-nitride compounds using traditional methods, such as Czochralski, vertical gradient freeze, Bridgeman or float zone, that have been used for other semiconductors such as silicon or GaAs. The reason for this is the high binding energy of the Ga-N bond which results in decomposition, and not melting of GaN at atmospheric pressure. Very high pressure and temperatures (2500°C and >4GPa pressure are required to achieve melted GaN. While various high pressure techniques have been investigated, they are extremely complicated and have lead to only very small irregular crystals. (A. Denis *et al*, Mat. Sci. Eng. R50 (2006) 167.)

The lack of a native single crystal substrate greatly increases the difficulty in making epitaxial Group III-nitride layers with low defect densities and desirable electrical and optical properties. A further difficulty has been the inability to make p-type GaN with sufficient conductivity for use in practical devices. Although attempts to produce semiconductor grade GaN began at least in the early 1970s, no usable progress was made until the late 1990's when two breakthroughs were developed. The first was the use of low temperature GaN and AlN buffer layers which led to acceptable growth of Group III-nitride layers on sapphire. The

second was the development of a process to achieve acceptable p-type conductivity. In spite of these technological advances, the defect density in Group III-nitride layers is still extremely high ($10^9 - 10^{11} \text{ cm}^{-2}$ for dislocations) and the p-type conductivity is not as high as in other semiconductors. Despite these limitations, these advances led to commercial production of III-nitride epitaxial films suitable for LEDs (see, e.g., Nakamura et al, 2nd ed. 2000, *The Blue Laser Diode*, Springer-Verlag, Berlin).

The high defect density is a result of growth on a non-native substrate. Sapphire is the most widely used substrate, followed by silicon carbide. Differences in the lattice constant, thermal coefficient of expansion and crystal structure between the III-nitride epitaxial layer and the substrate lead to a high density of defects, stress and cracking of the III-nitride films or the substrate. Furthermore, sapphire has a very high resistivity (cannot be made conductive) and has poor thermal conductivity.

SiC substrates can be produced in both conductive and highly resistive forms, but is much more expensive than sapphire and only available in smaller diameters (typically 50mm diameter with 150mm and 200mm as demonstrations). This is in contrast to sapphire and native substrates for other semiconductors such as GaAs and silicon, which are available at lower cost and in much larger diameters (150mm diameter for sapphire; 300mm for GaAs).

While the use of sapphire and SiC are suitable for some device applications, the high defect density associated with III-nitride layers grown on these substrates leads to short lifetime in laser diodes. III-nitride laser diodes are of particular interest because their shorter wavelength permits much higher information density in optical recording methods. It is expected that substrates with lower defect densities will lead to higher brightness LEDs which are required for replacement of incandescent and fluorescent bulbs. Finally, Group III-nitride materials have desirable properties for high frequency, high power electronic devices but commercialization of these devices has not occurred, in part because of substrate limitations. The high defect density leads to poor performance and reliability issues in electronic devices. The low conductivity of sapphire makes it unsuitable for use with high power devices where it is vital to be able to remove heat from the active device region. The small diameter and high cost of SiC substrates are not commercially usable in the electronic device market, where larger device sizes (compared to lasers or LEDs) require lower cost, large area substrates.

A large number of methods have been investigated to further reduce the defect density in epitaxial III-nitrides on non-native substrates. Unfortunately the successful methods are also cumbersome and expensive and non-ideal even if cost is not an object. One common approach is to use a form of epitaxial lateral overgrowth (ELO). In this technique the

substrate is partially masked and the III-nitride layer is coerced to grow laterally over the mask. The epitaxial film over the mask has a greatly reduced dislocation density. However, the epitaxial film in the open regions still have the same high dislocation density as achieved on a non-masked substrate. In addition, further defects are generated where adjacent laterally overgrown regions meet. To further reduce the dislocation density, one can perform multiple ELO steps. It is clear that this is a very expensive and time consuming process, and in the end produces a non-homogeneous substrate, with some areas of low dislocation density and some areas with high dislocation density.

The most successful approach to date to reducing defect densities is to grow very thick layers of the III-nitride material. Because the dislocations are not oriented perfectly parallel with the growth direction, as growth proceeds, some of the dislocations meet and annihilate each other. For this to be effective one needs to grow layers on the order of 300 to 1000 μm . The advantage of this approach is that the layer is homogeneous across the substrate. The difficulty is finding a growth chemistry and associated equipment that can practically achieve these layer thicknesses. MOVPE or MBE techniques have growth rates on the order of less than 1 to about 5 $\mu\text{m}/\text{hour}$ and thus are too slow, even for many of the ELO techniques discussed above, which require several to tens of microns of growth. The only growth technique that has successfully achieved high growth rates is hydride vapor phase epitaxy (HVPE).

In summary, the current state of the art in producing low dislocation Group III nitride material is to use HVPE to produce very thick layers. However the current HVPE process and equipment technology, while able to achieve high growth rates, has a number of disadvantages. Embodiments of the present invention now seek to overcome these disadvantages and provide relatively low cost, high quality Group II nitride lead to new, innovative applications, e.g., in residential and commercial lighting systems.

SUMMARY OF THE INVENTION

According to an aspect of the present invention, there is provided a high volume manufacturing process for depositing gallium nitride on a substrate by delivering a gaseous form of gallium trichloride to a reaction zone, comprising: providing a carrier gas selected
5 from the group consisting of: hydrogen, nitrogen, helium, argon and mixtures thereof at a pressure above atmospheric pressure; heating the carrier gas to a temperature of at least 110°C; heating gallium trichloride in a solid form held in a container, so as to create a bath of a liquid form of gallium trichloride; injecting the carrier gas into said bath of a liquid form of the gallium trichloride, the gallium trichloride in the bath being heated in the temperature
10 range of 110°C to 130°C; and conveying the carrier gas and any entrained gallium trichloride from the bath to a reaction zone at a controlled temperature such that the temperature does not decrease from the source to the reaction zone, at a controllable mass flow of gallium of at least 50g per hour for a time of at least 48 hours without requiring interruption of said high volume manufacturing process for synthesizing said gallium nitride.

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One preferred gaseous Group III precursor is a gallium compound that is continuously provided as a mass flow that continuously delivers at least 5kg gallium. In particular, this gallium compound is gallium trichloride and it is provided by heating solid gallium trichloride. When the solid gallium trichloride is heated to a liquid, the method may include encouraging increased evaporation of the gallium trichloride during the heating to provide a mass flow rate of gaseous gallium trichloride of at least 100g gallium/hour. Preferably, the solid gallium trichloride is initially heated to a temperature sufficient to induce a low viscosity liquid state on the order of ambient temperature water, such as by heating the solid gallium trichloride to a temperature of 110 to 130°C. Advantageously, a carrier gas is bubbled into the liquid gallium trichloride during the heating to generate the gaseous gallium trichloride. The carrier gas may be hydrogen, helium, neon, argon or mixtures thereof.

Alternatively, the gaseous precursor may be a Group III halide, with the method further comprising heating the halide to a temperature below its melting point but sufficiently high to generate a vapor pressure that achieves the mass flow. In addition to a gallium halide, this embodiment is useful for providing gaseous indium chloride or aluminum chloride precursors.

According to another aspect of the present invention, there is provided a system for facilitating a high volume manufacturing process for depositing gallium nitride on a substrate, which comprises a source of gaseous gallium trichloride, characterized in that said gallium trichloride source is capable of holding at least 25 kg of gallium trichloride and in that said source comprises: a container holding a solid form of said gallium trichloride, said container having a corrosion resistant inner surface for holding a liquid form of the gallium trichloride; a container heater for heating the container to a temperature sufficient to melt a solid form of the gallium trichloride in the temperature range of 110°C to 130°C; a source of a carrier gas and a carrier gas heater for heating the carrier gas to a temperature of at least 110°C; a dip tube in the container with an outlet for bubbling said carrier gas through a liquid in the container; a valve controlled container inlet leading to the dip tube; and a valve controlled container outlet leading to a delivery line; the delivery line for carrying the carrier gas and a gaseous form of the gallium trichloride to a reaction zone for conversion of the gallium trichloride into gallium nitride, the delivery line being configured to control the temperature such that the temperature does not decrease from the container to the reaction zone; such that said gallium trichloride source is able to provide a controllable mass flow of gallium of at least 50g per hour for a time of at least 48 hours without requiring interruption of the high volume manufacturing process.

Advantageously, the source of Group III precursor is operatively associated with a mass flow controller to deliver the desired amount to form the semiconductor material. Generally, the source of Group III precursor further includes a heating arrangement for heating the precursor and for generating a gas flow of the precursor. In addition, the container
5 may be operatively associated with a source of carrier gas and a related conduit that introduces the carrier gas into the container in a manner which facilitates formation of the gas flow of the precursor. When the gaseous Group III precursor is a gallium compound, the system is capable of providing it in a mass flow that continuously delivers at least 5kg gallium.

Containers of various sizes may be used, as desired for the high volume manufacture
10 of the semiconductor material. Generally, the container may initially hold at least 10 to 60 Kg of a solid Group III halide with the heating arrangement is configured and dimensioned to heat the solid halide sufficiently to provide the gaseous precursor. The container can hold at least

25Kg of solid halides such as indium trichloride or aluminum trichloride, with the heating arrangement configured and dimensioned to heat the trichloride sufficiently to provide the gaseous precursor. Also, the heating arrangement may be configured and dimensioned to heat the trichloride to provide a mass flow rate of at least 75g Group III element/hour. For further extended manufacture, a plurality of container can be connected in series to facilitate delivery of the gaseous precursor for a longer time than if a single container is used.

A preferred Group III halide is gallium trichloride, with the container and heating arrangement configured and dimensioned to heat the solid gallium trichloride to a liquid. This can be achieved by heating solid gallium trichloride to a temperature sufficient to induce a low viscosity liquid state on the order of ambient temperature water with the container further including a mechanism for encouraging increased evaporation of the gallium trichloride during the heating to provide a mass flow rate of gaseous gallium trichloride of at least 100g gallium/hour. The solid gallium trichloride is typically heated to a temperature of 110 to 130°C while the mechanism for encouraging increased evaporation includes a source of carrier gas and a conduit associated with the container for bubbling the carrier gas into the liquid gallium trichloride during the heating to generate the gaseous gallium trichloride. The source of carrier gas may be any supply of hydrogen, helium, neon, argon or mixtures thereof.

There are also disclosed systems that facilitate high volume manufacturing of a Group III - V semiconductor material and includes a source of a gaseous Group III precursor at a controllable mass flow of Group III element of at least 50g per hour for a time of at least 48 hours without requiring interruption of the high volume manufacturing process. Specifically, the controllable mass flow of the Group III element is sufficient to enable deposition rates of the Group III-V semiconductor material equivalent to at least 100 $\mu\text{m}/\text{hour}$ on a 200mm substrate during the time that the precursor is provided.

The precursor source can include a container having a corrosion resistant inner surface for holding a liquid form of the Group III precursor, a dip tube in the container with an outlet for bubbling a carrier gas through a liquid in the container, a valve controlled container inlet leading to the dip tube; and a valve controlled container outlet leading to a delivery line; the delivery line for carrying the carrier gas and a gaseous form of the Group III precursor to a reaction zone for conversion of the Group III precursor into a Group III - V semiconductor material. Also disclosed is a purifier capable of removing moisture from the carrier gas down to no more than 5 parts per billion; or a carrier gas filter downstream of the carrier gas purifier; or a container heater for heating the container to a temperature sufficient to melt a solid form of the Group III precursor; a source of a carrier gas and a carrier

gas heater for heating the carrier gas to a temperature of at least 110°C; or a carrier gas line configured with sinusoidal bends for providing increased heat exchange surface proximate to the carrier gas heater; or the carrier gas being hydrogen, helium, neon, argon or mixtures thereof and heated to a temperature of 110°C to 130°C; or a mass flow controller for
5 controlling the mass flow of the carrier gas; or an insulating outer portion for the container; or a delivery line further includes a coaxial portion having an inner line conveying the carrier gas and the Group III precursor and an enclosing coaxial line providing an annular space for containing a heating medium.

The container, or the delivery line, or the valved inlet, the valved outlet and the valves
10 in such inlet and outlet include stainless steel, Hastelloy, Monel, or combinations thereof; that the valves or the inner surface of the container include polytetrafluoroethylene seats; and that at least one of the container, the valved inlet, the valved outlet, the inlet valves, the outlet valves, or the delivery line further include a material selected from a group consisting of a nickel-based alloy, tantalum, a tantalum-based alloy, silicon carbide, boron nitride, boron
15 carbide, aluminum nitride, fused silica layer, bonded amorphous silicon layer, and other known chlorine resistant materials.

There are also disclosed processes for delivering a gaseous form of a Group III precursor to a reaction zone for synthesizing gallium nitride that include the steps of providing a carrier gas selected from the group consisting of: hydrogen, nitrogen, helium, argon and
20 mixtures thereof at a pressure above atmospheric pressure; heating the carrier gas to a temperature of at least 110°C; injecting the carrier gas into a bath of a liquid form of the Group III precursor; and conveying the carrier gas and any entrained Group III precursor from the bath to a reaction zone for synthesizing a Group III nitride delivering. The carrier gas and entrained Group III precursor is delivered to the reaction zone at a temperature of at least
25 110°C; or the carrier gas is purified by removal of moisture to no more than 5 parts per billion; or the carrier gas is provided at a flow rate of 5 to 15 liters per minute; or the Group III precursor in the bath is heated to a temperature in the range of 110°C to 130°C; or the Group III precursor includes gallium trichloride.

Further aspects and details and alternate combinations of the elements of this invention
30 will be apparent from the appended drawings and following detailed description and these are also within the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention may be understood more fully by reference to the following detailed description of the preferred embodiment of the present invention, illustrative examples of specific embodiments of the invention and the appended figures in which:

Fig. 1 illustrates schematically systems of the invention;

Figs. 2A-C illustrates preferred GaCl_3 sources;

Figs. 3A-C illustrates preferred reaction chambers;

Fig. 4 schematically preferred transfer/reaction chamber combinations;

Fig. 5 schematically illustrates preferred inlet manifold structures; and

Fig. 6 illustrates schematically an alternative reactant gas inlet arrangement.

The same reference numbers are used to identify the same structures appearing on different figures.

DETAIL DESCRIPTION OF THE PREFERRED EMBODIMENTS

This invention provides equipment and methods for high growth rate and high volume manufacturing of Group III-V compound semiconductor wafers not hitherto possible. The equipment is capable of sustained production in that over periods of weeks or months production does not need to be shut down for maintenance. The equipment is capable of high-throughput production in that at least a wafer (or a batch of wafers) can be produced every one to four hours. The Group III-V compound semiconductor wafers so produced are suitable for fabrication of optical and electronic components, for substrates for further epitaxial deposition and for other semiconductor material applications.

In preferred embodiments, the equipment and methods are specifically directed to producing GaN nitride wafers, and such embodiments are the focus of much of the subsequent description. This focus is for brevity only and should not to be taken as limiting the invention. It will be appreciated that the preferred embodiments can readily be adapted to producing wafers of other Group III nitrides, e.g., aluminum nitride, indium nitride, and mixed aluminum/gallium/indium nitrides, and to producing wafers of Group III phosphides and arsenides. Accordingly, producing semiconductor wafers of any of the III-V compound semiconductors are within the scope of this invention.

This invention can be particularly cost effective because particular embodiments can be realized by modifying equipment already commercially available for epitaxial deposition of Si. Thereby, focus can be on the elements and features that are especially important to GaN epitaxy while aspects related to high volume manufacturing, which are well developed in

silicon technology, can be maintained. Also, the equipment of this invention is designed to have a significant duty cycle so that it is capable of high volume manufacturing. Also, the invention provides for virtually 100% efficiency in the use of expensive Ga by recovering and recycling of Ga that is not actually deposited and is therefore exhausted from the reaction chamber equipment; with limited downtime needed. Also, the inventive process and apparatus include an economical use of Ga precursors.

The invention includes the use of a known low thermal mass susceptor (substrate holder) and lamp heating with temperature controlled reactor walls. The use of lamp heating permits the heat energy to mainly be coupled to the susceptor and not heat the reactor walls. The lamp heating system is equipped with a control system to permit very fast power changes to the lamps. The low thermal mass susceptor coupled with the lamp heating system permit very fast temperature changes, both up and down. Temperature ramp rates are in the range of 2-10 degrees/second and preferably on the order of 4-7 degrees/second.

The invention includes reactor walls that are controlled to a specific temperature to minimize undesired gas phase reactions and prevent deposition on the walls. The lack of wall deposition permits straightforward use of in-situ monitoring for growth rate, stress and other pertinent growth parameters.

The invention includes one or more external sources for the Group III precursor(s). The flow of the Group III precursor is directly controlled by an electronic mass flow controller. There is no practical limit on the size of the external Group III source. Group III source containers can be in the range of 50 to 100 to 300 kg, and several source containers could be manifolded together to permit switching between containers with no down time. For the deposition of GaN, the Ga precursor is GaCl₃. This Ga source is based on the observations and discoveries that, when GaCl₃ is in a sufficiently low viscosity state, routine physical means, e.g., bubbling a carrier gas through liquid GaCl₃, can provide a sufficient evaporation rate of GaCl₃, and that GaCl₃ assumes such a sufficiently low viscosity state in a preferred temperatures of range of 110 to 130°C.

The invention includes equipment for maintaining the GaCl₃ at a constant temperature and pressure in the low viscosity state and equipment for flowing a controlled amount of gas through the liquid GaCl₃ and delivering the GaCl₃ vapor to the reactor. This equipment can sustain high mass flows of GaCl₃ (in the range of 200 to 400 g/hour) that result in GaN deposition rates in the range of 100 to 400 μm/hour on one 200mm diameter substrates or any number of smaller wafers that fit on the susceptor. The delivery system from the GaCl₃

container is maintained with a specific temperature profile to prevent condensation of the GaCl_3 .

The invention also includes an inlet manifold structure that keeps the Group III and Group V gases separate until the deposition zone and also provides a method for achieving high gas phase homogeneity in the deposition zone, thus achieving a uniform flow of process gases into the reaction chamber and across the susceptor supporting the substrates. The process gas flow is designed to be substantially uniform in both flow velocity (therefore, non-turbulent) and chemical composition (therefore, a uniform III/V ratio). In a preferred embodiment, this is realized by providing separate primary inlet ports for the Group III and Group V gases that provide uniform distribution of gas across the width of the reactor, and to achieve high uniformity. In preferred embodiments, the manifold and port structures are designed and refined by modeling gas flows according to principles of fluid dynamics.

The invention also includes a method to add energy to either or both the Group III or Group V inlets to enhance the reaction efficiency of these precursors. In a preferred embodiment, this would include a method for thermal decomposition of the dimer form of the Group III precursor Ga_2Cl_6 into the monomer GaCl_3 . In another preferred embodiment, this would include a method for decomposition of the ammonia precursor, for example by thermal decomposition or plasma.

The invention also includes equipment for automated wafer handling, including fully automatic cassette-to-cassette loading, separate cooling stages, load locks, non-contact wafer handlers, all of which are fully computer controlled and interfaced to the overall growth program.

The invention also includes temperature control of the reactor inlet and outlet flanges and the exhaust system and a specially designed pressure regulating valve that can operate at reduced pressure and high temperatures. Temperature control in these areas prevents premature gas phase reactions and minimizes deposits of GaN as well as various reaction byproducts. A major reaction byproduct is NH_4Cl . The temperature of the entire exhaust downstream of the reactor is controlled to prevent condensation of NH_4Cl .

The invention also includes a gas-purged gate valve to reduce deposits on the valve material and the side walls of the reactor and to reduce gas recirculation and reduce residence time of the gases in the reactor.

Additional aspects and details of the invention include the use of a susceptor that can hold one or more wafers during one growth run and a susceptor designed to prevent attachment of the substrate to the susceptor during thick growth runs.

The present invention is based on the discovery that specific metal halide compounds have certain unique chemical properties, and that when coupled with an apparatus designed in light of these properties, the combination can be used to deposit thick layers of Group III-V compound semiconductors, and in particular gallium nitride, with heretofore unachievable high throughput, high uptime and low cost in a manner characteristic of high volume manufacturing.

For this invention, "high volume manufacturing" (or HVM) is characterized by high throughput, high precursor efficiency and high equipment utilization. Throughput means the number of wafers/hour that can be processed. Precursor efficiency means that a large fraction of the material input to the system goes into the product and is not wasted. Although there are a large number of variables associated with the material, process and structure, HVM deposition rates range from around 50 g Group III element (such as gallium) per hour for a period of at least 48 hours, to 100 g Group III element per hour for a period of at least 100 hours, to 200 g Group III element per hour for a period of at least one week, to as much as 300 to 400 g Group III element per hour for a period of at least a month. A typical source capacity can range from 5Kg to 60 Kg in one vessel and for increased HVM; multiple vessels can be operated in series. This can provide Group III-V material throughputs that are similar to those obtained in silicon manufacture.

Equipment utilization means the ratio of the time that the substrate is in the reactor compared to a given time period, such as 24 hours. For HVM, most of the time is spent producing product as opposed to set-up, calibration, cleaning or maintenance. Quantitative ranges for these measures are available for mature silicon semiconductor processing technology. The equipment utilization for HVM of Group III-V material is on the order of about 75 to 85%, which is similar to that of silicon epitaxial deposition equipment.

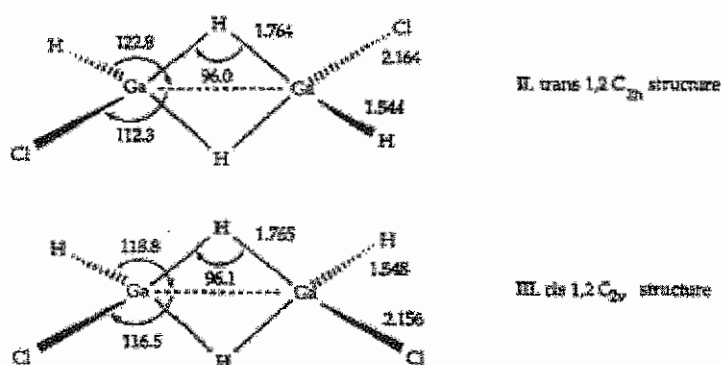
Reactor utilization is the period of time during which growth of the material on the substrate is occurring in the reactor. For conventional HVPE reactors, this value is on the order of 40 to 45%, while for a HVM reactor such as those disclosed herein, this value is on the order of 65 to 70%.

Growth utilization is the overhead time in the reactor, meaning that it is the time during which growth is occurring in the reactor after a substrate is provided therein. For conventional HVPE reactors, this value is on the order of 65 to 70%, while for a HVM reactor such as those disclosed herein, this value is on the order of 95% to close to 100%, i.e., close to that of a silicon manufacturing process.

The present invention addresses the main limitations of the current HVPE technology which prevent high volume manufacturing. This is done by replacing the current HVPE in-situ source generation with an external source and replacing the current HVPE high thermal mass hot wall reactor with a low thermal mass reactor with temperature controlled walls. The use of an external source eliminates the need to stop production to charge the precursors, greatly increasing the equipment utilization. Furthermore, the mass flux of the precursor is controlled directly by an electronic mass flow controller, resulting in improved control of the growth process and improve yield. The low thermal mass reactor with temperature controlled walls greatly reduces the time required for heating and cooling, both during growth and maintenance. The ability to rapidly heat and cool the substrate also permits the use of multi-temperature processes, which are not practically possible in the current HVPE hot wall system. The ability to control the wall temperature reduces gas phase reactions and almost completely eliminates wall deposits. Elimination of wall deposits greatly increases the time between cleaning, leading to high reactor utilization.

The present invention is based on the fact that certain metal halide compounds can be used as an external source for HVPE deposition of III-V compound semiconductors and can provide, in conjunction with specific delivery equipment detailed in this invention, a sufficiently high mass flux to achieve and maintain high deposition rates on large areas. In particular, when melted, GaCl_3 is in a sufficiently low viscosity state to permit routine physical means, e.g. bubbling with a carrier gas through liquid GaCl_3 , can provide a sufficient evaporation rate of GaCl_3 , and that GaCl_3 assumes such a sufficiently low viscosity state at temperatures in a range about approximately 130°C . Furthermore this invention is based on the fact that GaCl_3 , in the liquid phase and in the gas phase at temperatures below about 400°C is actually a dimer. The chemical formula for the dimer can be written either as $(\text{GaCl}_3)_2$ or Ga_2Cl_6 .

In addition to Ga_2Cl_6 related chlorogallanes can also be used as a Ga precursor. These compounds are similar to Ga_2Cl_6 but with H replacing one or more Cl atoms. For example monochlorogallane has the two bridge Cl atoms replace by H atoms. As shown below, the terminal Ga-bonded atoms can also be replaced by H (note that there is a cis and trans version of this compound). According to B.J.Duke *et al*, Inorg. Chem. **30** (1991) 4225, the stability of the dimer decreases with increasing chlorination of the terminal Ga-x bonds by 1-2 kcal/mol per Cl substitution and increases by 6-8 kcal/mol with each Cl substitution for a bridging H atom. Thus as the number of substituted Cl atoms decreases, the fraction of the monomer, at a given temperature, would decrease.



The growth of In- and Al-containing compounds can be achieved using substantially similar equipment but with the limitation that these sources are not as easily kept in a liquid state. InCl_3 melts at 583°C . While the present invention described for GaCl_3 may be modified to operate at temperatures above 583°C , this is practically quite difficult. An alternate approach is to heat the InCl_3 to a temperature below the melting point but where the vapor pressure is sufficient to achieve acceptable deposition rates.

AlCl_3 sublimates at 178°C and melts at 190°C and 2.5 atm. The present invention described for GaCl_3 can be modified to operate at higher than atmospheric pressure and temperatures above the melting point of AlCl_3 . Additionally, the alternate approach described above for InCl_3 , heating below the melting point to achieve a sufficiently high vapor pressure, will also work. AlCl_3 also forms a dimer $(\text{AlCl}_3)_2$ in the liquid phase and in the gas phase at low temperatures.

Another main component of this invention is a low thermal mass reactor. The low thermal mass reactor with temperature controlled walls greatly reduces the time required for heating and cooling, both during growth and maintenance. The ability to rapidly heat and cool the substrate also permits the use of multi-temperature processes, which are not practically possible in the current HVPE hot wall system. The ability to control the wall temperature reduces gas phase reactions and almost completely eliminates wall deposits. Elimination of wall deposits greatly increases the time between cleaning, leading to high reactor utilization.

The low thermal mass is achieved by using what is traditionally called a cold wall system, but in this invention the wall temperature is controlled to a specific temperature. The current hot wall systems are heated by being enclosed in a furnace. In the new system, only the substrate holder and substrate are heated. There are many ways to achieve this including lamp heating, induction heating or resistance heating. In one embodiment, the system consists of a reactor chamber constructed from quartz and a substrate heater constructed of graphite.

The graphite is heated by lamps on the outside of the quartz reactor. The quartz reactor walls can be controlled using a variety of methods. In most cases the wall temperature control system consists of one or more methods to measure the wall temperature in a variety of locations, combined with a feedback system to adjust either cooling or heating input to the wall region to maintain the temperature at a preset value. In another embodiment, the wall temperature is controlled by fans that blow air onto the exterior of the reactor walls for cooling. The wall temperature is not constrained to be constant at all times; the temperature controller can be programmed to vary the temperature to achieve improved performance either during growth or maintenance.

Although the focus of the following description is primarily on preferred embodiments for producing gallium nitride (GaN) wafers, it will be appreciated that the equipment and methods described can be readily adapted by one of average skill in the art to also produce wafers of any of the III-V compound semiconductors are within the scope of this invention. Accordingly, such equipment is within the scope of the invention. Headings are used throughout for clarity only and without intended limitation.

Also the invention provides equipment for high volume manufacturing of GaN wafers that is economical to construct and operation. Preferred embodiments of the invention can be economically realized/constructed by adapting/modifying existing VPE equipment that has been designed for and is commercially available for silicon (Si) epitaxy. To practice this invention, it is not necessary to undertake an expensive and time consuming process of designing and constructing all components for GaN deposition equipment from scratch. Instead, sustained, high-throughput GaN deposition equipment of the invention can be more rapidly and economically realized/constructed making targeted and limited modifications to existing Si processing production proven equipment. Along with such modified existing equipment, however, the invention also encompasses de novo construction.

Accordingly, the following description is first directed to the generally preferred features to be incorporated into existing Si equipment for GaN production. Features that can be retained from Si processing are not described in details as they are well known in the art. In different embodiments, different ones of the features to be described can be implemented; the invention is not limited to embodiments implemented all these features. However, for higher levels of sustained, high-throughout production, most of all of these features are advantageous and they include cassette to cassette loading, load locks and fully automated wafer handling with separate cooling stage which allows fast loading and unloading and processing a wafer while the other one is cooling. The loadlocks eliminate undesirable

exposure of the reactor to atmosphere to minimize introduction of oxygen and water vapor and greatly reduce purge/bake time before running. Moreover the automated handling reduces yield loss and wafer breakage from manual handling of wafers. In some cases a Bernoulli wand is used to handle the wafers which allows to perform hot loading and unloading at temperature as high as 900°C and save long cooling time.

General embodiments of the preferred features of this invention are first described in the context of a generic VPE system. It will become apparent how these general embodiments can be routinely adapted to particular, commercially available, Si epitaxy equipment. The following description is then directed to a particular preferred embodiment of this invention and of its preferred features that is based on one of the EPSILON® series of single-wafer epitaxial reactors available from ASM America, Inc. (Phoenix, AZ). It is apparent, however, that the invention is not limited to this particular preferred embodiment. As another example the inventions could easily be adapted to the CENTURA® series of AMAT (Santa Clara, CA).

Preferred embodiments of the equipment and methods of the invention (for producing GaN wafers) are described in general with reference to Fig. 1. Particular preferred embodiments are then described in more detailed with reference to Figs. 2-5. Generally, the equipment of this invention is designed and sized both for high volume manufacturing of epitaxial GaN layers on substrates and also for economy of construction and operation.

- **GENERAL EMBODIMENTS OF THE INVENTION**

For convenience and without limitation, the invention is generally described with reference to Fig. 1 in terms of three basic subsystems: subsystems 1 for providing process gases (or liquids); subsystems 3 including a reaction chamber; and subsystems 5 for waste abatement.

As noted above, HVM is an attribute of a combination of various physical features of the system including the generic features described herein:

- **1. EXTERNAL SOURCE OF GaCl₃**

The structure of the first subsystem, the process gas subsystem, especially the gallium compound vapor source, is an important feature of the invention. Known GaN VPE processes are now briefly described. GaN VPE epitaxy comprises synthesizing GaN directly on the surface of a heated substrate from precursor gases containing nitrogen (N) and gallium (Ga) (and, optionally, one or more other Group III metal containing gases in order to form mixed

nitrides and optionally, one or more dopants to provide specific electronic conductivity). The Ga-containing gas is usually gallium monochloride (GaCl) or gallium trichloride (GaCl_3), or a gallium-organic compound, e.g., tri-ethyl-gallium (TEG) or tri-methyl-gallium (TMG). In the first case, the process is referred to as HVPE (Halide Vapor Pressure Epitaxy and in the second as MOVPE (Metal Organic Vapor Pressure Epitaxy).

The chemical properties of GaCl (stability only at high temperatures) require that GaCl vapor be synthesized in situ in the reaction vessel, e.g., by passing HCl over a boat containing liquid Ga. In contrast, GaCl_3 is a stable solid at ambient conditions (in the absence of moisture) which is commonly supplied in sealed quartz ampoules each with about 100 g or so. TMG and TEG are volatile liquids. The N-containing gas is usually ammonia (NH_3), and semiconductor quality NH_3 is available in standard cylinders.

Alternately plasma-activated N_2 , e.g., containing N ions or radicals, can be used as the N-containing gas. Molecular N_2 is substantially unreactive with GaCl_3 or GaCl even at high process temperatures. Nitrogen radicals can be prepared in a manner known in the art, in general, by providing energy to split a nitrogen molecule. For example, by adding a RF source to nitrogen line to generate electromagnetically induced plasma. When operating in this mode, the pressure in the reactor is usually reduced.

Of the known VPE processes, MOCVD and GaCl HVPE have been found to be less desirable for sustained, high Volume Manufacturing of Group III nitride layers. First, MOCVD is less desirable for the growth of films greater than 10 μm because achievable deposition rates are less than 5% of the deposition rates achievable by HVPE processes. For example, HVPE deposition rate can be in the range of 100- 1000 $\mu\text{/hour}$ or more, while MOCVD rates are typically less than 10 $\mu\text{/hour}$. Second, GaCl HVPE is less desirable because this process requires that a supply of liquid Ga be present in the reaction chamber in order to form GaCl by reaction with HCl . It has been found that maintaining such a supply of liquid Ga in a form that remains reactive with HCl and that is sufficient for high volume manufacturing is difficult.

Therefore, equipment of the invention is primarily directed to GaCl_3 HVPE for high volume manufacturing. Optionally, it can also provide for MOCVD for, e.g., deposition of buffer layers and the like. However, use of GaCl_3 HVPE for high volume manufacturing requires a source of GaCl_3 vapor that achieves a sufficient flow rate that can be maintained without interruption (except for wafer loading/unloading in the reaction chamber) for a sufficient period. Preferably, an average sustained deposition rate is in the range of 100 to

1000 $\mu\text{m}/\text{hour}$ of GaN per hour so that approximately one wafer (or one batch of multiple wafers) requires no more than one or two hours of deposition time for even thick GaN layers. Achieving such a preferred deposition rate requires that the source provide a mass flow of GaCl_3 vapor at about approximately 250 or 300 g/hour (a 200 mm circular 300 μm thick layer of GaN comprises about approximately 56 g of Ga while GaCl_3 is about 40% Ga by weight). Further, such a flow rate can preferably be maintained for a sufficient duration so that production interruptions required to recharge/service the source are limited to at most one per week, or more preferably one at least every two to four weeks. Accordingly, it is preferred that the flow rate can be maintained for at least 50 wafers (or batches of multiple wafers), and preferably for at least 100, or 150, or 200, or 250 to 300 wafers or batches or more. Such a source is not known in the prior art.

The equipment of the invention provides a GaCl_3 source that overcomes problems in order to achieve preferred flow rates and durations. Achieving preferred flow rates has been hindered in the past by certain physical properties of GaCl_3 . First, at ambient conditions, GaCl_3 is a solid, and vapor can be formed only by sublimation. However, it has been determined that GaCl_3 sublimation rates are inadequate for providing vapor at preferred mass flow rates. Second, GaCl_3 melts at about 78°C , and vapor can then be formed by evaporation from the liquid surface. However, it has also been determined that evaporation rates are inadequate for providing preferred mass flow rates. Further, typical physical means for increasing rate of evaporation, e.g., agitation, bubbling, and the like, do not increase evaporation rate sufficiently because GaCl_3 liquid is known to be relatively viscous,

What is needed is form of liquid GaCl_3 of sufficiently lower viscosity and it has been observed and discovered that beginning at about approximately 120°C , and especially at about approximately 130°C or above, GaCl_3 assumes such a lower viscosity state with a viscosity similar to, e.g., that of water. And further, it has been observed and discovered that in this lower viscosity state, routine physical means are capable of effectively raising the GaCl_3 evaporation rate sufficiently to provide the preferred mass flow rates.

Accordingly, the GaCl_3 source of this invention maintains a reservoir of liquid GaCl_3 with temperature T_1 controlled to about approximately 130°C and provides physical means for enhancing the evaporation rate. Such physical means can include: agitate the liquid; spray the liquid; flow carrier gas rapidly over the liquid; bubble carrier gas through the liquid; ultrasonically disperse the liquid; and the like. In particular, it has been discovered that bubbling an inert carrier gas, such as He, N_2 or H_2 or Ar, by arrangements known in the art

through a lower viscosity state of liquid GaCl_3 , e.g., GaCl_3 at about 130°C , is capable of providing the preferred mass flow rates of GaCl_3 . Preferred configurations of the GaCl_3 source have increased total surface area in proportion to their volume in order to achieve better temperature control using heating elements outside of the reservoir. For example, the illustrated GaCl_3 source is cylindrical with a height that is considerably greater than the diameter. For GaCl_3 , this would be around 120 g per hour for a period of at least 48 hours, to 250 g per hour for a period of at least 100 hours, to 500 g per hour for a period of at least one week, to as high as 750 to 1000 g per hour for a period of at least a month.

Moreover, a GaCl_3 source capable of the preferred flow rate and duration cannot rely on GaCl_3 supplied in individual 100 g ampoules. Such an amount would be sufficient for only 15 to 45 minutes of uninterrupted deposition. Therefore, a further aspect of the GaCl_3 source of this invention is large GaCl_3 capacity. To achieve the high-throughput goals of this invention, the time spent recharging GaCl_3 source is preferably limited. However, recharging is made more complicated by the tendency of GaCl_3 to react readily with atmospheric moisture. The GaCl_3 charge, the source, and the GaCl_3 supply lines must be free of moisture prior to wafer production. Depending on the throughput goals of various embodiments, the invention includes source capable of holding at least about 25 kg of GaCl_3 , or at least about 35 kg, or at least about 50 to 70 kg (with an upper limit determined by requirements of size and weight in view of the advantages of positioning the source in close proximity to the reaction chamber). In a preferred embodiment, the GaCl_3 source can hold between about 50 and 100 kg of GaCl_3 , preferably between about 60 and 70 kg. It will be realized that there is no real upper limit to the capacity of the GaCl_3 source other than the logistics of its construction and use. Furthermore, multiple sources of GaCl_3 could be set up through a manifold to permit switching from one source to another with no reactor downtime. The empty source could then be removed while the reactor is operating and replaced with a new full source.

A further aspect of the GaCl_3 source of this invention is careful temperature control of the supply lines between the source and the reaction chamber. The temperature of the GaCl_3 supply lines and associated mass flow sensors, controllers, and the like preferably increase gradually from T_2 at the exit from the source up to T_3 at reaction chamber inlet 33 in order to prevent condensation of the GaCl_3 vapor in the supply lines and the like. However, temperatures at the reaction chamber entry must not be so high that they might damage sealing materials (and other materials) used in the supply lines and chamber inlet, e.g., to seal to the quartz reaction chamber, for gaskets, O-rings, and the like. Currently, sealing materials resistant to Cl exposure and available for routine commercial use in the semiconductor

industry generally cannot withstand temperatures greater than about 160°C. Therefore, the invention includes sensing the temperature of the GaCl₃ supply lines and then heating or cooling the lines as necessary (generally, "controlling" the supply line temperatures) so that the supply line temperatures increase (or at least do not decrease) along the supply line from the source, which is preferably at about approximately 130°C, up to a maximum at the reaction chamber inlet, which is preferably about approximately 145 to 155°C (or other temperature that is safely below the high temperature tolerance of O-rings or other sealing materials). To better realize the necessary temperature control, the length of the supply line between the source apparatus and the reaction chamber inlet should be short, preferably less than about approximately 1 ft., or 2 ft. or 3 ft. The pressure over the GaCl₃ source is controlled by a pressure control system 17.

A further aspect of the GaCl₃ source of this invention is precise control of the GaCl₃ flux into the chamber. In a bubbler embodiment, the GaCl₃ flux from the source is dependent on the temperature of the GaCl₃, the pressure over the GaCl₃ and the flow of gas that is bubbled through the GaCl₃. While the mass flux of GaCl₃ can in principle be controlled by any of these parameters, a preferred embodiment is to control the mass flux by varying the flow of a carrier gas by controller 21. Routinely-available gas composition sensors such as a Piezocor, and the like 71 can be used to provide additional control of the actual GaCl₃ mass flux, e.g., in grams per second, into the reaction chamber. In addition, the pressure over the GaCl₃ source can be controlled by a pressure control system 17 placed on the outlet of the bubbler. The pressure control system, e.g. a back pressure regulator, allows for control of the over pressure in the source container. Control of the container pressure in conjunction with the controlled temperature of the bubbler and the flow rate of the carrier gas facilitates an improved determination of precursor flow rate. Optionally, the container also includes an insulating outer portion.

It is desirable that the materials used in the GaCl₃ source, in the GaCl₃ supply lines, and in the inlet manifold structures in contact with GaCl₃ are chlorine resistant. For metal components, a nickel-based alloy such as Hastelloy, or tantalum or a tantalum-based alloy is preferred. Further corrosion resistance for metal components can be provided through a protective corrosion resistant coating. Such coatings can comprise silicon carbide, boron nitride, boron carbide, aluminum nitride and in a preferred embodiment the metal components can be coated with a fused silica layer or a bonded amorphous silicon layer, for example Siltek® and Silcosteel® (commercially available from Restek Corporation) has been demonstrated to provide increased corrosion resistance against oxidizing environments. For

non-metal components, chlorine resistant polymeric materials (either carbon or silicone polymers) are preferred.

In preferred embodiments, the equipment of this invention can also provide for sources for Group III metal organic compounds so that MOCVD processes can be performed. For example, MOCVD can be used to, e.g., deposit thin GaN or AlN buffer layers, thin intermediate layers, layers of mixed metal nitrides, and so forth. Additional process gases can be routinely supplied as known in the art.

The group V precursor is a gas containing one or more Group V atoms. Examples of such gases include NH_3 , AsH_3 and PH_3 . For the growth of GaN, NH_3 is typically used because it can provide sufficient incorporation of N at typical growth temperatures. Ammonia and other N precursors are external sources. For example, semiconductor grade NH_3 is readily available in cylinders 19 of various sizes, and carrier gases 72 are available as cryogenic liquids or as gases, also in containers of various sizes. Fluxes of these gases can be routinely controlled by mass flow controllers 21 and the like. In alternative embodiments, the equipment of this invention can also provide for sources of other Group III chlorides.

• 2. REACTOR GEOMETRY

Next, to achieve increased economy, the reactor subsystems are preferably adaptations of commercially available reactor systems. Available reactors preferred for adaptation and use in this invention include as-is most or all of the features to be next described. These features have been determined to be useful for HVM of GaN layers with the modifications and enhancements disclosed herein. Although the following description is directed mainly to embodiments that adapt existing equipment, reactors and reactor systems can be purpose built to include the to-be-described features. The invention includes both redesigning and modifying existing equipment and designing and fabricating new equipment. The invention also includes the resulting equipment.

Generally, preferred reaction chambers have horizontal process-gas flow and are shaped in an approximately box-like or hemi-sphere like configuration with lesser vertical dimensions and greater horizontal dimensions. Certain features of horizontal reaction chambers are important in limiting unproductive reactor time and achieving HVM of quality GaN wafers.

- **3. LOW THERMAL MASS SUSCEPTOR AND LAMP HEATING**

First, time spent ramping-up temperature after introducing new wafers and time spent ramping-down temperature after a deposition run is not productive and should be limited or minimized. Therefore, preferred reactors and heating equipment also have lower thermal masses (i.e., ability to absorb heat quickly), and the lower the thermal masses the more preferred. A preferred such reactor is heated with infrared (IR) heating lamps and has IR transparent walls Fig. 1 illustrates reactor 25 made of quartz and heated by lower longitudinal IR lamps 27 and upper transverse IR lamps 29. Quartz is a preferred chamber wall material, since it is sufficiently IR transparent, sufficiently Cl resistant, and sufficiently refractory.

- **4. CLOSED LOOP TEMPERATURE CONTROL ON CHAMBER WALLS AND FLANGES**

Time spent cleaning reaction chamber interiors is also not productive and also should be limited or minimized. During GaN deposition processes, precursors, products, or byproducts can deposit or condense on interior walls. Such deposition or condensation can be significantly limited or abated by controlling the temperature of the chamber walls generally by cooling them to an intermediate temperature that is sufficiently high to prevent condensation of precursors and byproducts, but that is sufficiently low to prevent GaN formation and deposition on the walls. Precursors used in GaCl₃ HVPE processes condense at below about 70 to 80°C; the principal byproduct, NH₄Cl, condenses only below about 140°C; and GaN begins to form and deposit at temperatures exceeding about 500 °C. Chamber walls are controlled to temperature T5 that is preferably between 200°C, which has been found to be sufficiently high to significantly limit precursor and byproduct condensation, and 500°C, which has been found to be sufficiently low to significantly limit GaN deposition on chamber walls. A preferred temperature range for the chamber walls is 250 to 350°C.

Temperature control to preferred ranges generally requires cooling chamber walls. Although IR transparent, chamber walls are nevertheless heated to some degree by heat transferred from the high temperature susceptor. Fig. 1 illustrates a preferred cooling arrangement in which reaction chamber 25 is housed in a full or partial shroud 37 and cooling air is directed through the shroud and over and around the exterior of the reaction chamber. Wall temperatures can be measured by infrared pyrometry and cooling air flow can be adjusted accordingly. For example, a multi-speed or a variable speed fan (or fans) can be provided and controlled by sensors sensitive to chamber wall temperatures.

- **5. LOAD LOCK, CASSETTE TO CASSETTE**

Wafer loading and unloading time is also not productive. This time can be routinely limited by automatic equipment schematically illustrated at 39. As it known in the art, this equipment can store wafers, load wafers into, and unload wafers from the reaction chamber, and generally comprises, e.g., robotic arms and the like that move wafers, e.g., using transfer wands, between external holders and the susceptor in the reaction chamber. During wafer transfer, the reaction chamber can be isolated from ambient exposure by intermediate wafer transfer chambers. For example, controllable doors between the transfer chamber and the exterior can permit loading and unloading and can then seal the transfer chamber for ambient exposure. After flushing and preparation, further controllable doors between the transfer chamber and the reactor can open to permit placement and removal of wafers on the susceptor. Such a system also prevents exposure of the reactor interior to oxygen, moisture or other atmospheric contaminants and reduces purging times prior to load and unload of wafers. It is preferred to use a quartz Bernoulli transfer wand because it reduces unproductive time by allowing handling of hot wafers without causing contamination.

- **6. SEPARATE INJECTION**

Process gas flow control, from inlet manifold 33 in the direction of arrow 31 to outlet manifold 35, is important for depositing high quality GaN layers. This flow includes the following preferred characteristics for the process gases. First, the gallium containing gas, e.g., GaCl_3 , and the nitrogen containing gas, e.g., NH_3 , preferably enter the reaction chamber through separate inlets. They should not be mixed outside the reaction chamber because such mixing can lead to undesirable reactions, e.g., forming complexes of GaCl_3 and NH_3 molecules, that interfere with subsequent GaN deposition.

Then, after separate entry, the GaCl_3 and NH_3 flows are preferably arranged so that the gas has a uniform composition in space and time over the susceptor. It has been found that the III/V ratio should vary over the face of the susceptor (and supported wafer or wafers) at any particular time preferably by less than approximately 5%, or more preferably by less than approximately 3% or 2% or 1%. Also, the III/V ratio should be similarly substantially uniform in time over all portions of the face of the susceptor. Accordingly, the GaCl_3 and NH_3 velocity profiles should provide that both gases both spread laterally across the width of the reaction chamber so that upon arriving at the susceptor both gases have a non-turbulent flow that is uniform across the width of the reaction chamber and preferably at least across the diameter of the susceptor.

Finally, the flow should not have recirculation zones or regions of anomalously low flow rates, where one or more of the process gases can accumulate with an anomalously high concentration. Localized regions of low gas flow, or even of gas stagnation, are best avoided.

Preferred process gas flow is achieved by careful design or redesign of the inlet manifold of a new or existing reaction chamber. As used here the term "inlet manifold" refers to the structures that admit process and carrier gases into a reaction chamber whether these structures are unitary or whether they comprise two or more physically separate units.

Inlet manifold designed and fabricated to have the following general features have been found to achieve preferred process gas flows. However, for most embodiments, it is advantageous for the gas flow into a selected reaction chamber produced by a proposed inlet manifold design to be modeled using fluid dynamic modeling software packages known in the art. The proposed design can thereby be iteratively improved to achieve increased uniformity prior to actual fabrication.

First, it has been found advantageous that process gas entry into the reaction chamber be distributed across some, most or all of the width of the chamber. For example, multiple gas inlet ports or one or more slots through which gas can enter can be distributed laterally across the width of the chamber. A carrier gas such as nitrogen or hydrogen can be introduced to assist in directing the GaCl_3 and the NH_3 gases through the reactor to the desired reaction location above the susceptor. Further, to prevent spurious deposition in the vicinity of the inlet ports, it is advantageous for the actual inlet ports to be spaced with respect to the heated susceptor so that they are not heated above approximately 400-500°C. Alternately, the inlet ports can be cooled or can be spaced apart so the process gases do not mix in their vicinity.

Next it has been found that gas flow properties produced by a particular configuration of the GaCl_3 and NH_3 inlets can be improved, or "tuned" dynamically. Secondary purge gas flows impinging on or originating for example from under the susceptor and mixing with the primary GaCl_3 , and NH_3 flows can be used to alter these flows to increase uniformity of composition and velocity or prevent deposition on reactor components. For example, in embodiments where the GaCl_3 and NH_3 flows enter the reaction chamber from different inlets, it has been found advantageous to provide a purge gas flow entering into the reaction chamber somewhat upstream of GaCl_3 , and NH_3 flows to confine the process gases above the intended deposition zone and to shield the side walls of the reactor from unintended deposition. For these purposes, it is advantageous to introduce a greater amount of carrier gas laterally near the chamber walls and a lesser amount centrally about the middle of the chamber.

Also, preferred inlet manifolds provide for dynamic adjustment of, at least, one of the process gas flows so that non-uniformities observed during operation can be ameliorated. For example, inlets for a process gas can be divided into two or more streams and individual flow control valves can be provided to independently adjust the flow of each stream. In a preferred embodiment, GaCl_3 inlets are arranged into five streams with independently controllable relative flow.

Further aspects of a preferred inlet manifold include temperature control. Thereby, inlet manifold temperatures T3 can be controlled both to prevent the condensation of precursors, e.g., GaCl_3 , and to prevent damage to temperature-sensitive materials, e.g., gasket or O-ring materials. As discussed, the GaCl_3 inlet ports should be at a temperature no less than the highest temperatures reached in the GaCl_3 supply line, which is preferably increase from about approximately 130°C to about approximately 150°C. Commercially available chlorine-resistant, sealing materials, such as gasket materials and O-ring materials, available for use in the inlet manifold, in particular for sealing the manifold to the quartz reaction chamber, begin to deteriorate at temperatures in excess of about approximately 160°C. Chlorine-resistant sealing materials such silicone o-rings usable to higher temperatures, if available, can also be used, in which case the inlet manifold upper temperature limit can be raised.

Accordingly, inlet manifold temperature T3 should be controlled to remain in the range of about approximately 155 to 160°C by either supplying heat to raise the temperature from ambient or removing transferred from the hot reaction chamber and very hot susceptor. In preferred embodiments, an inlet manifold includes temperature sensors and channels for temperature control fluids. For example, temperatures of 155 to 160°C can be achieved by circulating a temperature-controlled GALDEN™ fluid. Other known fluids can be used for other temperature ranges. The fluid channels preferably run in proximity to the temperature sensitive portions of the inlet manifold, e.g., the GaCl_3 inlet ports and sealing O-rings. Channel arrangement can be chosen more precisely in view of thermal modeling using software packages known in the art.

GaCl_3 molecules whether in the solid or liquid or vapor phase are known to exist mainly in the Ga_2Cl_6 dimer form. That form is actually very stable up to 800°C, Thermodynamic calculations corroborated by gas phase raman spectroscopy have confirmed that at 300°C more than 90% of the gas phase is composed of the dimer molecule and at 700°C more than 99% of the dimer has decomposed into the GaCl_3 monomer.

As the dimer molecule is injected through a metallic injection port kept at temperatures at or below 150°C, the decomposition of the dimer will occur only in contact with the hot susceptor which is at temperature above 1000°C. Depending on the velocity of the gas above the susceptor or its residence time the portion of the dimer that will be decomposed might be too small to sustain a high growth rate on the wafer. The GaN deposition process proceeds through the adsorption of GaCl_3 and its further decomposition to GaCl_x with $x < 3$ until all chlorine has been removed to obtain an adsorbed atom of Ga. It is therefore desired to operate from the monomer form of GaCl_3 . A preferred embodiment of the invention introduces the dimer through a quartz tube under the reactor chamber situated upstream of the susceptor region. This quartz tube connects to the reactor chamber through a funnel with an oval cross-section. Energy is provided to the dimer while in the funnel to decompose the dimer to the monomer. A preferred embodiment uses IR radiation from IR lamps located and shaped in such a way that the quartz tube and funnel receive a high flux of IR radiation. In this embodiment, the funnel region is filled with IR absorbant materials and the radiation power adjusted to bring the IR absorbant material to a temperature of 600°C or more preferably 700°C or higher. As the dimer form of GaCl_3 is injected in the quartz injector and passes through the hot funnel zone, the dimer will be decomposed to the monomer and be injected in the reaction chamber just upstream of the susceptor. Preferably the region between the injection point of the GaCl_3 into the reactor and the susceptor is maintained at a temperature above 800°C to prevent the re-formation of the dimer. A preferred embodiment is to use a SiC plate between the funnel and the susceptor which is heated by the IR heating lamps to maintain a temperature above 700°C and preferably above 800°C.

• 7. SUSCEPTOR AND MULTI-WAFER SUSCEPTOR

The susceptor and its mounting can be of standard construction as generally known in the art. For example, it can comprise graphite coated with silicon carbide or silicon nitride, or alternatively, a refractory metal or alloy. The susceptor is preferably mounted for rotation on a shaft. During GaN deposition, susceptor temperatures T_4 can be approximately 1000 to 1100°C (or higher) and are maintained by the quartz IR lamps controlled by known temperature control circuitry. To avoid forming a dead zone beneath the susceptor, the susceptor mounting preferably provides for injection of purge gas. This injection is also advantageous because it can limit or minimize unwanted deposition on the underside of the

heated susceptor and of adjacent components that may also be heated (directly or indirectly). The susceptor can be configured to hold one or more substrates.

• 8. HEATED EXHAUST

Reaction chamber outlet manifold 35 provides for the free and unobstructed flow of exhaust gases from the reaction chamber through the exhaust lines 41 and to waste abatement system 5. The exhaust system can also include a pump (42) and associated pressure control system (pressure control valve (44), pressure gauge (46) and associated control equipment to permit operation at reduced pressure). The outlet manifold exhaust lines and pressure control equipment (if used) are advantageously also temperature controlled to limit condensation of reaction products. Exhaust gases and reaction products typically comprise the carrier gases; un-reacted process gases, GaCl_3 and NH_3 ; reaction byproducts which are primarily NH_4Cl , NH_4GaCl_4 , HCl , and H_2 . As described above, temperatures above about approximately 130°C are required to prevent condensation of GaCl_3 . NH_4Cl condenses into a powdery material below about approximately 140°C , and the outlet manifold and exhaust system should be kept above this temperature. On the other hand, to prevent deterioration of sealing materials, the outlet manifold temperature should not exceed about approximately 160°C .

Accordingly, outlet manifold temperature T6 is preferably maintained in the range of about approximately 155 to 160°C by temperature control means similar to those used for inlet manifold temperature control (including optional thermal modeling). Maximum exhaust line temperature T7 is limited by the maximum allowable temperature for the seals, preferably in the range of about 155 to 160°C .

• 9. WASTE MANAGEMENT

Considering next waste abatement subsystems 5, a preferred abatement system can assist in economical operation of the invention by recovery of waste gallium compounds exhausted from the reaction chamber. A single embodiment of the invention can exhaust 30 kg, or 60 kg, or more during (assuming approximately 50% waste) during a month of sustained, high volume manufacturing. At current Ga prices, it is economical to recover this waste Ga and recycle it into GaCl_3 precursor, thereby achieving effectively approximately 90 to 100% Ga efficiency.

Fig. 1 also schematically illustrates a preferred embodiment of waste abatement subsystem 5 that provides for gallium recovery and that can be readily adapted from commercially available products. The stream exhausted from reaction chamber 25 passes

through exhaust lines 41 temperature controlled at T7 to limit condensation of exhaust products, e.g., in the range of about 155 to 160°C or greater as convenient, and then into burner unit 43. The burner unit oxidizes the exhaust gases by passing it through high temperature combustion zone 45 comprising, e.g., H_2/O_2 combustion. The oxidized exhaust stream then passes through tube 47 into countercurrent water scrubber unit 49 where it moves in a countercurrent fashion with respect to water stream 51. The water stream removes substantially all water soluble and particulate components from the oxidized exhaust stream. The scrubbed exhaust gas is then released from the system 57.

The water stream with the soluble and particulate materials passes to separator 59 where particulate components, primarily particulate gallium oxides (e.g., Ga_2O_3), are separated 61 from the water soluble components, primarily dissolved NH_4Cl and HCl . Separation can be obtained by known techniques, such as screening, filtering, centrifugation, flocculation, and so forth. A single embodiment of the invention can produce 60kg, or up to 120kg, or more, of particulate Ga_2O_3 during each month of operation. The particulate gallium oxides gallates are collected and the Ga is advantageously recovered and recycled into, e.g., $GaCl_3$ by known chemical techniques. See, e.g., Barman, 2003, Gallium Trichloride, SYNLETT 2003, no. 15, p. 2440-2441. The water-soluble components are passed from the system.

- **A PREFERRED PARTICULAR EMBODIMENT OF THE INVENTION**

Next described is a particular preferred embodiment of the invention that has been generally described above. This embodiment is based on the modification and adaptation of an EPSILON® series, single-wafer epitaxial reactor from ASM America, Inc. Accordingly many of the following features are specific to this preferred particular embodiment. However, these features are not limiting. Other particular embodiments can be based on modification and adaptation of other available epitaxial reactors and are within the scope of the invention.

Figs. 2A-C illustrate aspects of $GaCl_3$ delivery system 101 including reservoir 103, which can hold 50 to 75 kg of $GaCl_3$ and can maintain it at as a liquid at a controlled temperature of up to about approximately 130 to 150°C, and supply assembly with supply lines, valves and controls 105, which provide a controlled mass flow of $GaCl_3$ to the reactor chamber while limiting or preventing $GaCl_3$ condensation within the lines. The reservoir includes internal means for enhancing evaporation of the liquid $GaCl_3$. In a preferred embodiment, these include a bubbler apparatus as known in the art; in alternative

embodiments, these can include means for physical agitation of the GaCl_3 liquid, for spraying the liquid, for ultrasonic dispersal of the liquid, and so forth.

Fig. 2C illustrates an exemplary arrangement of delivery system 101 in cabinet 135 which is positioned adjacent to conventional process gas control cabinet 137. To limit the length of the GaCl_3 supply line, cabinet 135 is also positioned adjacent to the reaction chamber, which here is hidden by cabinet 137. Process gas control cabinet 137 includes, for example, gas control panel 139 and separate portions 141 - 147 for additional process gases or liquids, such as a Group III metal organic compounds. Optionally, the supply line (or delivery line) includes a coaxial portion having an inner line conveying the carrier gas and the Group III precursor and an enclosing coaxial line providing an annular space inside the enclosing line but outside the inner line. The annular space can contain a heating medium.

Fig. 2B illustrates preferred supply assembly 105 in more detail. Valves 107 and 109 control lines that conduct carrier gas into reservoir 103, then through the internal bubbler in the reservoir, and then out from the reservoir along with evaporated GaCl_3 vapor. They can isolate the reservoir for maintenance and so forth. Valve 110 facilitates the purging of the system above the outlet and inlet valves of the container system. In particular, since condensation can possibly occur in the pig-tail elements 111, 112, valve 110 is useful in order to purge these areas. Control of the container pressure in conjunction with the controlled temperature of the bubbler and the flow rate of the carrier gas facilitates improved determination of precursor flow rate. The addition of valve 110 allows the complete delivery system to be purged with non-corrosive carrier gas when not in growth mode, thereby reducing exposure of the system to a corrosive environment and consequently improving equipment lifetime. The assembly also includes valves 111 - 121 for controlling various aspects of flow through the supply lines. It also includes pressure controller and transducer 129 to maintain a constant pressure over the GaCl_3 container. Also provided is a mass flow controller 131 to provide a precise flow of carrier gas to the GaCl_3 container. These act to provide a controlled and calibrated mass flow of GaCl_3 into the reaction chamber. It also includes pressure regulators 125 and 127. The supply line assembly, including the supply lines, valves, and controllers, is enclosed in multiple aluminum heating blocks in clamshell form to enclose each component. The aluminum blocks also containing temperature sensors that control supply line component temperatures so that the temperature increases (or at least does not decrease) from the output of the reservoir up to the inlet of the reaction chamber. A gas heater is provided to heat the inlet gas to the GaCl_3 source, preferably to a temperature of at least 110°C .

Optionally, a purifier capable of removing moisture from the carrier gas down to no more than 5 parts per billion is placed in a carrier gas inlet line, and further a carrier gas filter is downstream of the carrier gas purifier. The carrier gas can be optionally configured with sinusoidal bends, e.g., pigtail 112, for providing increased heat exchange surface proximate to the carrier gas heater.

Figs. 3A and 3B illustrate top views of a preferred embodiment of the reaction chamber 201. This reaction chamber has quartz walls and is generally shaped as an elongated rectangular box structure with a greater width and lesser height. A number of quartz ridges 203 span transversely across the chamber walls and support the walls especially when the chamber is operated under vacuum. The reaction chamber is enclosed in a shroud that directs cooling air in order that the chamber walls can be controlled to a temperature substantially lower than that of the susceptor. This shroud generally has a suitcase-like arrangement that can be opened, as it is in these figures, to expose the reaction chamber. Visible here are the longer sides 205 and the top 207 of the shroud. Susceptor 215 (not visible in this drawing) is positioned within the reactor. The susceptor is heated by quartz lamps which are arranged into two arrays of parallel lamps. Upper lamp array 209 is visible in the top of the shroud; a lower array is hidden below the reaction chamber. Portions of the inlet manifold are visible.

Fig. 3C illustrates a longitudinal cross-section through particular preferred reaction chamber 301 but omitting for strengthening ribs 203. Illustrated here are top quartz wall 303, bottom quartz wall 305 and one quartz side wall 307. Quartz flange 313 seals the inlet end of the reaction chamber to the inlet manifold structures, and quartz flange 309 seals the outlet end of the reaction chamber to the outlet manifold structures. Port 315 provides for entry of process gases, carrier gases, and so forth, and port 311 provides for exit of exhaust gases. The susceptor is generally positioned in semi-circular opening 319 so that its top surface is coplanar with the top of quartz shelf 317. Thereby a substantially smooth surface is presented to process gases entering from the inlet manifold structures so that these gases can pass across the top of the susceptor without becoming turbulent or being diverted under the susceptor. Cylindrical quartz tube 321 provides for a susceptor support shaft on which the susceptor can rotate. Advantageously, carrier gas can be injected through this tube to purge the volume under the susceptor to prevent dead zones where process gases can accumulate. In particular, build up of GaCl_3 under the heated susceptor is limited.

The inlet manifold structures provide process gases through both port 315 and slit-like port 329. Gases reach port 329 first through quartz tube 323; this tube opens into flattened funnel 325 which allows gases to spread transversely (transverse to process gas flow in the

reaction chamber); this funnel opens into the base of the reaction chamber through a transversely-arranged slot in shelf 317.

With reference to Fig. 6, the funnel is compactly filled with beads of silicon carbide 607 and a silicon carbide insert 327 in the top of the flattened funnel provides slit-like port 329 for entry of GaCl_3 from funnel 325 into the reaction chamber. Two IR spot lamps 601 and their reflector optics are located on each side of the funnel. A quartz sheath 603 containing a thermocouple 605 is inserted through the bottom of the quartz tube 323 up to about the middle of the funnel height in the middle of the SiC beads in order to enable close loop control of the spot lamp power to maintain the SiC beads at a temperature of about 800°C . Preferably, GaCl_3 is introduced through port 329 and NH_3 is introduced through port 315. Alternatively, GaCl_3 can be introduced through port 315 and NH_3 can be introduced through port 329. Alternatively, an RF field may be created as known in the art in a lower portion of tube 323 so that the NH_3 can be activated by the creation of ions or radicals. Alternatively, some or all of the NH_3 can be replaced by N_2 which will be similarly activated by the RF field. A SiC extension plate 335 is disposed between the slit port 329 and the edge of the susceptor. This SiC extension plate is heated by the main heating lamps to ensure that the dimer does not reform in the gas phase between the slit-like port 329 and the susceptor. The temperature of the SiC extension plate should be above 700°C and preferably above 800°C .

Fig. 4 illustrates a diagonally cut-away view of a particular preferred reaction/transfer chamber assembly comprising wafer transfer chamber 401 assembly mated to reaction chamber assembly 403. Structures which have been previously identified in Figs. 2 and 3 are identified in this figure with the same reference numbers. Exemplary transfer chamber 401 houses a robot arm, Bernoulli wand, and other means (not illustrated) for transferring substrates from the outside of the system into the reaction chamber and from the reaction chamber back to the outside. Transfer chambers of other designs can be used in this invention.

The reaction chamber assembly includes reaction chamber 301 mounted within shroud 405. Illustrated here are portions of bottom wall 407 and far wall 205 of the shroud. The shroud serves to conduct cooling air over the reaction chamber to maintain a controlled wall temperature. Certain reaction chamber structures have already been described including: bottom wall 305, side wall 307, flange 309 to outlet manifold, shelf 317, susceptor 215, and cylindrical tube 321 for susceptor support and optional purge gas flow. The susceptor rotates in a circular opening 319 in rounded plate 409 which provides lateral stability to the susceptor

and is coplanar with shelf 317, SiC extension plate 335 and slit-like port 329. The planarity of these components ensures a smooth gas flow from the gas inlet to the susceptor. Outlet manifold structures include plenum 407 which conducts exhaust gases from the reaction chamber in the indicated directions and into exhaust line 419. The outlet manifold and flange 309 on the reaction chamber are sealed together with, e.g., a gasket or O-ring (not illustrated) made from temperature and chlorine resistant materials.

Inlet manifold structures (as this term is used herein) are illustrated within dashed box 411. Plenum 211, described below, is sealed to the front flange of the reaction chamber with a gasket or O-ring (not illustrated) or the like made from temperature and chlorine resistant materials. Gate valve 413 between the transfer chamber and the reaction chamber rotates clockwise (downward) to open a passage between the two chambers, and counterclockwise (upward) to close and seal the passage between the two chambers. The gate valve can be sealed against face plate 415 by means of, e.g., a gasket or O-ring. The preferred material for the O-ring is the same as that mentioned above for other O-rings. The gate valve preferably also provides ports for gas entry as described below. The structure of the lower gas inlet, as previously described, includes communicating quartz tube 323, flattened funnel 325, and slit-like port 329.

Fig. 5 illustrates details of the particular preferred inlet manifold structures and their arrangement in the reaction chamber assembly. Structures which have been previously identified in Figs. 2 and 3 are identified in this figure with the same reference numbers. Considering first the surrounding reaction chamber assembly, reaction chamber assembly 403, including shroud 405 and reaction chamber 301, is at the left, while transfer chamber structures 401 are at the right. Susceptor 215 and susceptor stabilizing plate 409 are inside the reaction chamber. Quartz flange 313 of the reaction chamber is urged against plenum structure 211 by extension 501 of shroud 405. The reaction chamber flange and plenum structure are sealed by O-ring gasket 503 which is visible in cross-section on both sides of port 315.

Considering now the inlet structure leading through slit-like port 329 for GaCl_3 (preferably, but optionally, NH_3 instead). It is comprised of a quartz tube 323, and funnel 325 that is longitudinally flattened but extended transversely so that it opens across a significant fraction of the bottom wall of the reaction chamber. Small beads or small tubes or any form of a porous IR absorbent material fill the funnel 325. Insert 327 fits into the upper opening of the funnel and includes slit-like port 329 that is angled towards the susceptor with an extension plate 335 that covers the space between the susceptor and the slit-like port. In

operation, GaCl_3 (and optional carrier gases) moves upward in the supply tube, spreads transversely in the funnel, and is directed by the slit towards into the reaction chamber and towards the susceptor. Thereby, GaCl_3 moves from port 329 towards susceptor 215 in a laminar flow substantially uniform across the width of the reaction chamber.

Considering now inlet structures leading through port 315, these structures include plenum structure 211, face plate 415, and gate valve 413. NH_3 (preferably, but optionally, GaCl_3 instead) vapor is introduced into the plenum structure through supply line 517 and passes downward towards the reaction chamber through the number of vertical tubes 519. NH_3 vapor then exits the vertical tubes, or optionally through distributed ports in which each vertical tube is lined to a group of distributed ports, and passes around lip 511 of the plenum. Thereby, NH_3 vapor moves towards the susceptor in a laminar flow substantially uniform across the width of the reaction chamber. Flow through each vertical tube is controlled by a separate valve mechanism 509 all of which are externally adjustable 213. The plenum also includes tubes for conducting temperature-control fluids, e.g., GALDENT™ fluid having temperatures controlled so that the plenum structures through which NH_3 passes are maintained within the above-described temperature ranges and so that plenum structure adjacent to O-ring 503 are maintained within the operational range for the sealing materials used in the O-ring. As noted, the preferred material for the O-ring is the same as that mentioned above for other O-rings. Temperature control tube 505 is visible (a corresponding tube is also visible below port 315) adjacent to O-ring 503. In typically operation, this tube serves to cool the O-ring so that it remains within its operational range.

Gate valve 413 advantageously includes a number of gas inlet ports 515 as well as serving to isolate the reaction and transfer chambers. It is opened and closed to provide controlled access for wafers and substrates between the transfer chamber and the reaction chamber through port 315. It is illustrated in a closed position in which it is sealed to face plate 415 by O-ring 507. In preferred embodiments, gas inlet ports 515 are used to inject purge gases, e.g., N_2 . Their size and spacing, which here is denser near the edge portions of the gate valve (and reaction chamber) and sparser at the central portions of the gate valve (and reaction chamber), are designed to improve the uniformity in composition and velocity of the process gases as they flow across the susceptor and build a purge gas curtain along the side walls of the chamber to prevent GaCl_3 gas from flowing underneath the susceptor to avoid undesired deposition of GaN in this location.

Generally, for deposition of high quality epitaxial layers the inlet manifold and port structures cooperate to provide a process gas flow that is substantially laminar (thus non-

turbulent) and that is substantially uniform in velocity and composition. The substantially laminar and uniform flow should extend longitudinally up to and over the susceptor and transversely across the reaction chamber (or at least across the surface of the susceptor). Preferably, process gas flows in the reaction chamber are uniform in velocity and composition across the chamber to at least 5%, or more preferably 2% or 1%. Composition uniformity means uniformity of the III/V ratio (i.e., $\text{GaCl}_3/\text{NH}_3$ ratio). This is achieved by: first, designing the process gas inlet ports to provide an already approximately uniform flow of process gases through the reaction chamber; and second, by designing selective injection of carrier gases to cause the approximately uniform flow to become increasingly uniform. Control of flow downstream from the susceptor is less important.

Numerical modeling of the gas flow dynamics of the particular preferred embodiment has determined a preferred process gas inlet port configuration so that a substantially uniform flow is produced. Guidelines for total process gas flow rates are established according to the selected GaN deposition conditions and rates needed for intended sustained, high-throughput operation. Next, within these overall flow guidelines, insert 327 and slit 329 have been designed so the modeled GaCl_3 flow into the reaction chamber is substantially uniform across the reaction chamber. Also, modeling of intended GaCl_3 flows has indicated that after the NH_3 vapor emerges around lip 511 into the reaction chamber, this flow also becomes substantially uniform across the reaction chamber. Further, valves 509 can be controlled to ameliorate non-uniformities that may arise during operation.

Further, guided by numerical modeling, secondary carrier gas inlets have been added to increase the uniformity of the primary-process gases flows. For example, in the particular preferred embodiment, it has been found that supply of purge gases through gate valve 413 provides improvement by preventing accumulation of high concentrations of GaCl_3 vapor between the face of gate valve 413 and lip 511 (i.e., the regions enclosed by face plate 415). Also, it has been found that arranging inlets to provide greater carrier gas flow at the edges of the reaction chamber and lesser purge gas flow at the center also improves uniformity of composition and velocity of flow at the susceptor and better maintains the reactive gas above the surface of the susceptor.

EXAMPLE

The invention is now compared to a standard or conventional HVPE system to illustrate the advantages and unexpected benefits that are provided when conducting HVM of

Group III-V material according to the invention. Prior to setting forth this comparison and by way of introduction, conventional HVPE systems are first briefly described in relevant part.

A conventional HVPE system consists of a hot-wall tube furnace usually fabricated of quartz. The Group III precursor is formed in-situ in the reactor by flowing HCl over a boat holding the Group III metal in a liquid form. The Group V precursor is supplied from external storage, e.g., a high pressure cylinder. Conventional HVPE has been used for the growth of arsenide, phosphide and nitride semiconductors. For the growth of GaN, the Group III source is typically molten Ga in a quartz boat (with which the HCl reacts to form GaCl), and the Group V source is usually ammonia gas.

In more detail, the quartz tube can be oriented either vertically or horizontally. The surrounding furnace is usually of a resistive type with at least two temperature zones: one for maintaining the Group III metal at a temperature above its melting point; and the other for maintaining the substrate/wafer at a sufficiently high temperature for epitaxial growth. The Group III-metal source equipment including a boat for liquid Group III metal, the substrate/wafer holder, and gas inlets are placed and arranged in one end of the quartz furnace tube; the other end serves for exhausting reaction by-products. All this equipment (or at least that which enters the furnace tube) must be fabricated of quartz; stainless steel cannot be used. Most reactors process only one wafer at a time at atmospheric pressure. Multiple wafers must be arranged in a reactor so that the surfaces of all wafers are directly in line of the gas flow in order to achieve uniform deposition.

Wafers are loaded by first placing them on a substrate support and then by positioning the substrate support into a high-temperature zone in the quartz furnace tube. Wafers are unloaded by removing the support from the furnace and then lifting the wafer off the support. The mechanism for positioning the substrate support, e.g., a push/pull rod, must also be fabricated of quartz since they are also exposed to full growth temperatures. Supported wafers, the substrate support, and the positioning mechanism must be positioned in the usually hot reactor tube with great care in order to prevent thermal damage, e.g., cracking of the wafers and/or substrate support. Also, the reactor tube itself can be exposed to air during wafer loading and unloading.

Such conventional HVPE reactors are not capable of the sustained high volume manufacturing that is possible with the HVM methods and systems of this invention for a number of reasons. One reason is that the reactors of this invention require less unproductive heating and cooling time than do conventional HVPE reactors because they can have considerably lower thermal masses. In the reactors of this invention, only the susceptor

(substrate/wafer support) needs to be heated, and it is heated by rapidly-acting IR lamps. Heating and cooling can thus be rapid. However, in conventional HVPE reactors, the resistive furnace can require prolonged heating and (especially) cooling times, up to several to tens of hours. During such prolonged heating and cooling times, this system is idle, and wafer production, reactor cleaning, system maintenance, and the like must be delayed. Furthermore, despite risks of thermal damage, wafers are usually placed in and removed from the reactor when it is near operating temperatures to avoid further heating and cooling delays. For these reasons, the systems and methods of this invention can achieve higher throughputs than can conventional HVPE systems.

Another reason limiting the throughput of conventional HVPE systems is that such systems require considerably more reactor cleaning than do the reactors of this invention. Because all internal components of conventional HVPE reactors are heated by the external resistive furnace, III-V material can grow throughout the inside of the reactor, and not only on the substrate where it is desired. Such undesired deposits must be frequently cleaned from the reactor or else they can form dust and flakes which contaminate wafers. Cleaning requires time during which the reactor is not productive.

Also, the Group III precursor is inefficiently used; most is deposited on the interior of the reactor; a small fraction is deposited on the substrate wafer as desired; and little or none appears in the reactor exhaust where it might be recycled for reuse. The Group V precursor is also inefficiently used, and excess can react with unused HCl to form chlorides (e.g., NH_4Cl) that can deposit on cold areas down stream of the reaction zone. Such chloride deposits must also be cleaned from the reactor.

In contrast, the reactors of this invention have temperature controlled walls so that little or no undesired growth of Group III-V material occurs. Reactors of this invention can be more productive since unproductive cleaning and maintenance either can be shorter, or need not be as frequent, or both. For these reasons also, the systems and methods of this invention can achieve higher throughputs than can conventional HVPE systems.

Another reason limiting the throughput of conventional HVPE systems are that their conventional internal Ga sources require recharging (with liquid Ga or other Group III metal) considerably more frequently than do the external Ga sources of this invention (which are recharged with the Ga precursor GaCl_3). The external source of this invention delivers a flow of Ga precursor that can be controlled in both rate and composition at maximum sustained rates up to approximately 200 gm/hr or greater. Since the capacity of the external source is not limited by reactor geometry, it can be sufficient for many days or

weeks of sustained production. For example, an external source can store up to many tens of kilograms of Ga, e.g., approximately 60 kg, and multiple sources can be operated in series for essentially unlimited sustained production.

In conventional HVPE systems, the Ga source has a strictly limited capacity. Since the source must fit inside the reactor and can be no larger than the reactor itself, it is believed that an upper limit to a conventional source is less than 5 kg of Ga. For example, for 3 kg of Ga, a boat of approximately 7x7x20 cm filled with liquid Ga 4 cm deep is required. Disclosure of such a large Ga boat has not heretofore been found in the prior art. Further the rate and composition of the source cannot be well controlled, because the Ga precursor (GaCl) is formed in situ by passing HCl and over the liquid Ga in the Ga source boat inside the reactor. The efficiency of this reaction is dependent upon reactor geometry and exact process conditions, e.g., the temperature in the source zone, and various efficiency values from 60% to over 90% have been reported. Furthermore, as the level of the Ga decreases and as the Ga source ages, the flux of GaCl to the deposition zone can vary even with a constant process conditions. For these reasons also, the systems and methods of this invention can achieve higher throughputs than conventional HVPE systems.

Another reason limiting the throughput of conventional HVPE systems is that heretofore their construction is not standardized, and in fact such systems are often individually designed and fabricated for specific users. Lack of standardization leads to, for example, slow and complex maintenance. Because they can often include complex and fragile quartz components that are difficult to work with, such reactors are time-consuming to disassemble and reassemble. In particular, the Group III source zone is intricate as it contains a separate quartz inlet for HCl, a quartz boat positioned adjacent to the HCl inlet, a separate quartz inlet for the Group V precursor (which must be kept separate from the Group III precursor), and a possible additional quartz inlet for a carrier gas. In contrast, the systems and methods of the present invention are to a great extent adaptations of tested and standardized designs known for Si processing, which have been optimized for efficient operation and maintenance and which include commercially-available components. For example, the particular preferred embodiment includes a Group III source zone with a gate valve and Group III precursor plenum and inlet ports partially fabricated from metal. The gate valve requires only a short time to open and close, and the Group III precursor plenum and inlet ports are considerably less fragile. For these reasons also, the systems and methods of this invention can achieve higher throughputs than conventional HVPE systems.

The qualitative design choices that differentiate systems of this invention from conventional HVPE systems leads to surprising quantitative benefits in epitaxial growth efficiencies, reactor utilizations and wafer production rates, and precursor utilization efficiencies. These surprising quantitative benefits are reviewed below using the data in Tables 1, 2, and 3, which compare a conventional HVPE system designed to handle one 100 mm diameter substrate and including a reactor tube of about 20 cm in diameter and about 200 cm in length with a corresponding system of this invention

Considering first achievable epitaxial growth efficiencies, the data of Table 1 demonstrate that the HVM systems of this invention can be considerably more efficient than conventional HVPE systems.

TABLE 1 – Epitaxial growth efficiencies

Epitaxial growth efficiencies		Conventional HVPE	HVM
Reactor Information			
Wafer diameter	cm	15	15
Reactor length	cm	200	
Reactor diameter	cm	20	
Hot zone length	cm	40	
# wafers processed simultaneously		1	1
Reactor production times			
- wafer load/unload time			
Pull/push rate	cm/min	2	
Total pull and push length	cm	160	0
Total pull and push time	min	80	2
Wafer load/unload time	min	9.5	2
Total load/unload time	min	89.5	3
Operation overhead	%	10%	10%
Total load/unload time in cont. operation	min	52.0	2.2
- epitaxial growth time			
Time to grow template	min	0	0
Growth rate	um/hr (um/min)	200 (3.3)	200 (3.3)
Layer thickness	um	300	300
Time to heat and cool	min	0	6
Time to grow layer	min	90	90
Operation overhead	%	10%	10%
Total growth time	min	99	106
Total wafer-in-reactor time	min	151.0	107.8
Reactor utilization (R.U.)			
R. U. - growth time/wafer-in-reactor time	%	66%	98%

Epitaxial growth efficiencies can be represented by the ratio of the actual epitaxial growth times to the sum of the actual epitaxial growth times and the reactor load/unload times. It can be seen that the HVM systems and methods of this invention can be loaded/unloaded significantly faster than can conventional HVPE systems, and thus can achieve higher epitaxial growth efficiencies. It is also expected that in actual operation, the external Ga sources of this invention will allow sustained operation for considerably longer periods than possible with conventional systems.

Because, in conventional HVPE system, the reactor is maintained at near deposition temperature between runs, the substrate must be pulled from or pushed into the reactor at a slow enough rates to avoid thermal damage. Assuming that distance of the substrate holder from the reactor inlet is about 80 cm and a pull rate of no more than 2 cm/min to avoid thermal damage, about 40 min. are required to pull the substrate from and also to push the substrate into the reactor. Further, once the substrate and wafer are positioned in the reactor, up to 10 min can be required for thermal stabilization, reactor purge, and set-up of process gasses. (With load locks the purge and gas setup might require 5 minutes each; without load locks, setup would be much longer.) Thus, the total load/unload time is about 90 min, or 52 min in continuous production (where some times would be shared equally between two successive runs).

In contrast, in the HVM systems of this invention, wafers can be rapidly loaded/unloaded at lower temperatures without risk of thermal damage thus eliminating extended wafer positioning times. Because of their low thermal mass and IR-lamp heating, reactors used (and specifically the susceptor and wafer in such reactors) in the HVM systems and methods of this invention can be rapidly cycled between higher deposition temperatures and lower temperatures loading/unloading temperatures. Therefore, the HVM systems and methods of this invention achieve considerably shorter loading/unloading times than are possible in conventional HVPE reactors.

Once loaded and assuming Ga precursor sources used in conventional HVPE systems are able to maintain an adequate mass flow rate of precursor, actual epitaxial growth times of conventional systems and of the systems of this invention are of approximately the same magnitude. However, it is expected that the Ga precursor source used in the HVM systems and methods of this invention has significant advantages over Ga precursor source used in conventional HVPE systems, so that in actual operation the systems and methods of this invention will achieve relative epitaxial growth efficiencies even greater than the efficiencies presented in Table 1.

For example, even if capable of adequate mass flow for an initial period, it is unlikely that convention Ga sources can sustain adequate mass flow for extended periods.

Conventional HVPE systems generate Ga precursor in-situ to the reactor by the passing HCl gas over metallic gallium in a liquid form. Because the efficiency of this process depends strongly on reactor geometry and process conditions (e.g., from about 60% to over about 90% depending on Ga temperature), the actual mass flow of Ga precursor (GaCl) will also vary. Further, as the level of the Ga decreases and the Ga source ages, the flux of Ga precursor can vary even with a constant process conditions (e.g., constant temperature and input HCl flux). Further, conventional Ga sources (in particular the liquid Ga boat) must be within the reactor, and their capacities are thus constrained by reactor geometry. The largest boat believed to be reasonably possible (and not believed to be disclosed in the known in the prior art) in a conventional HVPE system could hold no more than about approximately 3 to 5 kg and would be approximately 7x7x20 cm in size and be filled 4 cm deep with liquid Ga.

In contrast, the HVM systems and methods of this invention employ an external Ga source which can provide constant, unvarying flow of Ga precursor at up to 200 gm of Ga/hr and greater (sufficient to support growth rates in excess of 300 um/hr) that can be sustained for extended periods of time. First, this source can provide GaCl₃ vapor in a manner so that the Ga mass flux can be measured and controlled even during epitaxial growth. Second, this external Ga source is capable of sustained, uninterrupted operation because Ga precursor is supplied from a reservoir holding 10's of kilograms of precursor. Additionally, multiple reservoirs can be operated in series for effectively unlimited operation.

In summary, relative epitaxial growth efficiencies can be summarized by reactor utilization (R.U.) defined by the fraction of the time that a wafer is in the reactor during which actual growth is occurring. It is seen that the HVM systems and methods of this invention achieve such a R.U. of about 95% or more, while conventional HVPE systems can achieve such a R.U. of no more than about 65%. And it is expected that the HVM systems and methods of this invention will achieve even greater relative epitaxial growth efficiencies in actual operation.

Next considering first achievable reactor utilizations and wafer production rates, the data of Table 2 demonstrate that the HVM systems of this invention can be more efficient than conventional HVPE systems.

TABLE 2 - Reactor utilizations and achievable wafer production rates

Reactor maintenance times and wafer production rates		Conventional HVPE	HVM
- in-situ reactor cleaning time			
# runs between in-situ cleaning		5	5
Time to open/close reactor	min	26.6	2
Total thickness to be etched	um	1500	300
Etch rate	um/min	8	8
Etch time	min	187.5	18.8
bake time	min	30	15
Time to load Ga with in-situ etch	min	45	0.0
Operation overhead	%	18%	15%
Total in-situ cleaning time	min	339.8	41.1
- ex-situ reactor cleaning time			
# runs between ex-situ cleaning		15	15
time to close reactor after unloading	min	13.3	1.0
time to cool reactor	min	180	20
time to take reactor apart	min	120	120
time to put reactor back together	min	180	120
time to leak check and other	min	45	45
Time to load Ga with ex-situ etch	min	10	0
time to heat reactor	min	75	20
Wafer testing time	min	60	60
Preventive maintenance	min	120	120
Operation overhead	%	25%	20%
Total ex-situ cleaning time	min	959.2	571.2
Reactor utilization (R.U.) and wafer production rate			
R. U. - wafer-in-reactor time/total use time	%	59%	76%
R. U. - growth time/total use time	%	39%	75%
# runs (wafers)		15	15
total use time for #runs (wafers)	min	3734	1996
# wafers/hour		0.24	0.45
# hours/wafer		4.15	2.22
# wafers/24 hours		5.8	10.8

Reactors must be periodically taken out of production for cleaning and preventive maintenance. Since the HVM systems and methods of this invention can be rapidly cleaned and maintained, they can achieve higher will be the reactor utilizations and wafer production rates than can conventional HVPE systems.

During operation, materials grow on undesired locations in the reactor, e.g., on the reactor walls and on other internal reactor components, and excessive growth of these materials can cause problems, e.g., wafer contamination. Cleaning is required to remove these

undesired materials, and can be performed either in-situ, that is without disassembling the reactor, or ex-situ, after disassembling the reactor. In-situ cleaning is often performed by etching undesired deposits with HCl. After a number of in-situ etchings or cleanings, more thorough ex-situ cleaning is advantageous.

HVM systems of this invention require considerably less in-situ cleaning time than conventional HVPE systems. The reactors of this invention have walls with controlled lower temperatures so that little material deposits thereon during wafer production. In contrast, conventional HVPE reactors operate at higher deposition temperatures so that the same amount of material grows on reactor walls and internal reactor parts as grows on the wafers and substrates. Table 2 presents a scenario which assumes that no more than 1.5 mm of unwanted GaN can be allowed to deposit on reactor walls and internal reactor parts.

For conventional HVPE systems, in-situ cleaning is required every 5 runs, during which 1.5 mm of unwanted GaN (300 um per run and) will have grown on the reactor interior. In contrast, if in-situ cleaning of the reactors of this invention is also performed every 5 runs, only a nominal amount (e.g., 20% or less of the amount that will have grown in conventional HVPE systems) of GaN will have grown on the reactor interior. (In fact, in-situ cleaning of the HVM systems of this invention could reasonably be delayed to only every 15 runs.) Therefore, in-situ cleaning times of conventional HVPE reactors are at least 5 times (and up to 15 times) longer than the in-situ cleaning time of the HVM reactors of this invention.

Also, the HVM systems of this invention require considerably less ex-situ cleaning time than conventional HVPE systems. First, these HVM systems have significantly shorter cooling/heating times which must precede and follow, respectively, ex-situ cleaning. Also, their disassembly/cleaning/reassembly times are similar to the shorter times known for Si processing systems, because the HVM systems and methods of this invention comprise commercially available designs and components already known for Si processing. The designs and components incorporated from Si processing systems include: rapidly-acting reactor gates, fully automated wafer handling with cassette-to-cassette loading, the ability to perform hot load/unload, separate cooling stages, in-situ growth rate monitoring and load locks to prevent exposure of the reactor to atmosphere.

And, as already discussed, the Ga precursor sources, i.e., the Ga boat, used in conventional HVPE systems must be periodically recharged in order both to maintain constant precursor flow and also because of their limited capacity. This precursor recharging, which can be performed during cleaning, further lengthens cleaning times of these conventional

systems. In contrast, the external Ga sources of the HVM systems and methods of this invention can operate with little or no interruption for extended periods of time.

In summary, reactor maintenance times can be summarized by a further R.U. and a wafer production rate. This second R.U. represents the ratio of the time that a wafer is in the reactor to the sum of the times that a wafer is in the reactor plus the cleaning/maintenance times. It can be seen that the HVM system and methods of this invention achieve a R.U. of about 75% or more, while conventional HVPE systems can achieve such a R.U. of no more than about 60%.

Relative system efficiencies can be represented by wafer production rates, which can be derived by dividing a number of wafers produced by the total time required to produce these wafers. Since a complete cycle of wafer production runs, in-situ cleanings, and ex-situ cleanings, rates comprises 15 runs (according to the assumptions of Tables 1 and 2), these rates are determined by dividing 15 by the total time for producing 15 wafers (including load/unload time, in-situ cleaning time, in-situ cleaning time, maintenance time, and source recharge time). It can be seen that the total time the HVM systems and methods of this invention require to produce 15 wafers (runs) is considerably shorter than the total time required by convention HVPE systems. Therefore, the systems and methods of this invention achieve an approximately 2 fold throughput improvement over the prior art. As discussed above, a greater throughput improvement is expected during actual operation.

Lastly, considering comparative precursor efficiencies, the HVM systems and methods of this invention utilize precursors, especially Ga precursors, more efficiently than conventional HVPE systems. This is exemplified by the data in Table 3.

TABLE 3 - Precursor utilizations

Precursor utilization		Conventional HVPE	HVM
- ammonia (both processes)			
Ammonia Flow	slpm	14	10
Total ammonia flow time	min	132.0	97.7
Total ammonia for 90 min. run	mole	82.5	43.6
- HCl (convention HVPE)			
Moles of HCl /min during run	mole/min	0.024	
Liters HCl used in run	liter	51.2	
- gallium (convention HVPE)			
Input V/III ratio		30	
Moles/min of ammonia during run	mole/min	0.6250	
Moles/min of Ga required by ammonia flow	mole/min	0.0208	
Conversion of GaCl ₃ to GaN	%	95%	
Actual moles/min of Ga used in run	mole/min	0.0219	
Additional moles of Ga	%	10%	
moles of Ga/min for run	mole/min	0.024	
Weight of Ga/min for run	gm/min	1.76 gm Ga/min; 100 gm Ga/hr	
Weight of Ga per run	gm	151.4	
- gallium (HVM)			
Input V/III ratio			30
moles of ammonia/min during run	mole/min		0.4464
moles/min of Ga to meet V/III	mole/min		0.0149
Conversion of GaCl ₃ to GaN	%		95%
moles of GaCl ₃ dimer/min required to meet V/III	mole/min		0.0082
Additional moles of GaCl ₃ dimer	%		10%
Total moles GaCl ₃ dimer for run	mole		0.82
Atomic weight GaCl ₃ dimer	gm/mole		352.2
Total weight of GaCl ₃ dimer for run	gm		287.4
Percent of GaCl ₃ dimer that is Ga	%		40%
Weight of Ga for run	gm		114
Weight of Ga/hour for run	gm		75 gm Ga/hr
Ga utilization	%	21%	25%
Utilization with Ga recycling (est.)	%	27%	80%

Ga utilization is determined in Table 3 by, first, considering that a conventional HVPE system suitable for a 15 cm wafer can be expected to use approximately 14 slpm (standard liters per minute) of ammonia. Assuming a V/III ratio of 30 and a 95% conversion of the Ga precursor into GaN, the conventional system can be expected to use approximately 1.8 gm/min of Ga. A 90 minute run sufficient to grow 300 um of GaN at 200 um/hr therefore

requires about 151 gm of Ga. Since there is about 31 gm of Ga in a 300 um layer on a 15 cm wafer, the Ga efficiency of the conventional HVPE reactor is approximately 21% ($= 31/151$). Since most of the remaining 120 gm ($= 151-31$) is deposited on the insides of the reactor, little is thus unavailable recycling and reuse. It is expected that even with recycling and reuse of Ga exhausted from the reactor, the Ga efficiency of the conventional HVPE reactor is no more than approximately 25%.

In contrast, HVM systems and methods can be expected to use a lower ammonia flow (e.g., 10 slpm) and therefore a lower Ga flow and a lower total Ga required for a 15 cm wafer (e.g., 114 gm). Therefore, the HVM systems and methods of this invention can achieve Ga efficiencies of 27% ($= 31/114$) without recycling and reuse and up to perhaps 80% or greater Ga efficiency with recycling and reuse of Ga exhausted from the reactor. Additionally, since little of the remaining 83 gm ($= 114-31$) is deposited on the insides of the reactor, most of this unused Ga appears in the reactor exhaust where it is available recycling and reuse. It is expected that with recycling and reuse of exhaust Ga, the Ga efficiency of the HVM systems and methods of this invention can reach 80% or greater.

The preferred embodiments of the invention described above do not limit the scope of the invention, since these embodiments are illustrations of several preferred aspects of the invention. Any equivalent embodiments are intended to be within the scope of this invention. Indeed, various modifications of the invention in addition to those shown and described herein, such as alternate useful combinations of the elements described, will become apparent to those skilled in the art from the subsequent description. Such modifications are also intended to fall within the scope of the appended claims. In the following (and in the application as a whole), headings and legends are used for clarity and convenience only.

A number of references are cited herein, the entire disclosures of which are incorporated herein, in their entirety, by reference for all purposes. Further, none of the cited references, regardless of how characterized above, is admitted as prior to the invention of the subject matter claimed herein.

Claims:

1. A system for facilitating a high volume manufacturing process for depositing gallium nitride on a substrate, which comprises a source of gaseous gallium trichloride, characterized in that said gallium trichloride source is capable of holding at least 25 kg of gallium trichloride and in that said source comprises:

a container holding a solid form of said gallium trichloride, said container having a corrosion resistant inner surface for holding a liquid form of the gallium trichloride;

a container heater for heating the container to a temperature sufficient to melt a solid form of the gallium trichloride in the temperature range of 110°C to 130°C;

a source of a carrier gas and a carrier gas heater for heating the carrier gas to a temperature of at least 110°C;

a dip tube in the container with an outlet for bubbling said carrier gas through a liquid in the container;

a valve controlled container inlet leading to the dip tube; and

a valve controlled container outlet leading to a delivery line;

the delivery line for carrying the carrier gas and a gaseous form of the gallium trichloride to a reaction zone for conversion of the gallium trichloride into gallium nitride, the delivery line being configured to control the temperature such that the temperature does not decrease from the container to the reaction zone;

such that said gallium trichloride source is able to provide a controllable mass flow of gallium of at least 50g per hour for a time of at least 48 hours without requiring interruption of the high volume manufacturing process.

2. System according to claim 1, characterised in that the controllable mass flow of gallium is sufficient to enable deposition rates of the gallium nitride equivalent to at least 100 µm/hour on a 200mm substrate during the time that the gallium trichloride is provided.

3. System according to any of claims 1 or 2, characterised in that it comprises a mass flow controller for controlling the mass flow of the carrier gas.

4. System according to any of claims 1 to 3, characterised in that it comprises a carrier gas line configured with sinusoidal bends for providing increased heat exchange surface proximate to

the carrier gas heater, wherein the carrier gas is hydrogen, helium, neon, argon or mixtures thereof and is heated to a temperature of 110°C to 130°C.

5. System according to any of claims 1 to 4, characterised in that the delivery line further comprises a coaxial portion having an inner line conveying the carrier gas and the Group III trichloride precursor and an enclosing coaxial line providing an annular space for containing a heating medium.

6. System according to any of claims 1 to 5, characterised in that the container, and/or the delivery line, and/or the valved inlet, the valved outlet and the valves in such inlet and outlet comprise stainless steel, Hastelloy, Monel, or combinations thereof.

7. A high volume manufacturing process for depositing gallium nitride on a substrate by delivering a gaseous form of gallium trichloride to a reaction zone, comprising:

providing a carrier gas selected from the group consisting of: hydrogen, nitrogen, helium, argon and mixtures thereof at a pressure above atmospheric pressure;

heating the carrier gas to a temperature of at least 110°C;

heating gallium trichloride in a solid form held in a container, so as to create a bath of a liquid form of gallium trichloride;

injecting the carrier gas into said bath of a liquid form of the gallium trichloride, the gallium trichloride in the bath being heated in the temperature range of 110°C to 130°C; and

conveying the carrier gas and any entrained gallium trichloride from the bath to a reaction zone at a controlled temperature such that the temperature does not decrease from the source to the reaction zone, at a controllable mass flow of gallium of at least 50g per hour for a time of at least 48 hours without requiring interruption of said high volume manufacturing process for synthesizing said gallium nitride.

8. Process according to claim 7, characterised in that the carrier gas and entrained gallium trichloride is delivered to the reaction zone at a temperature of at least 110°C.

9. Process according to any of claims 7 or 8, characterised in that it comprises purifying the carrier gas by removal of moisture to no more than 5 parts per billion.

10. Process according to any of claims 7 to 9, characterised in that the carrier gas is provided at a flow rate of 5 to 15 litres per minute.

HIGH VOLUME DELIVERY SYSTEM FOR GALLIUM TRICHLORIDE

ABSTRACT

The present invention is related to the field of semiconductor processing equipment and methods and provides, in particular, methods and equipment for the sustained, high-volume production of Group III-V compound semiconductor material suitable for fabrication of optic and electronic components, for use as substrates for epitaxial deposition, for wafers and so forth. In preferred embodiments, these methods and equipment are optimized for producing Group III-N (nitrogen) compound semiconductor wafers and specifically for producing GaN wafers. Specifically, the precursor is provided at a mass flow of at least 50g Group III element/hour for a time of at least 48 hours to facilitate high volume manufacture of the semiconductor material. Advantageously, the mass flow of the gaseous Group III precursor is controlled to deliver the desired amount.

Fig. 2A