



US005482892A

United States Patent [19]

[11] **Patent Number:** **5,482,892**

Briones

[45] **Date of Patent:** **Jan. 9, 1996**

[54] **METHOD OF PRODUCING WHITE PHOSPHORUS FOR MOLECULAR BEAM EPITAXY**

5,041,719 8/1991 Harris et al. 219/390
5,156,815 10/1992 Streetman et al. 118/715

FOREIGN PATENT DOCUMENTS

[75] Inventor: **Fernando F. Briones**, Madrid, Spain

0132322 1/1985 European Pat. Off. .
0154072 9/1985 European Pat. Off. .

[73] Assignee: **Riber S.A.**, Rueil Malmaison, France

Primary Examiner—R. Bruce Breneman
Assistant Examiner—Ramamohan Rao Paladugu
Attorney, Agent, or Firm—Handal & Morofsky

[21] Appl. No.: **403,975**

[22] Filed: **Mar. 15, 1995**

[57] **ABSTRACT**

Related U.S. Application Data

A phosphorus effusion cell for molecular beam epitaxy is disclosed. It consists of a vessel in which, by sublimation of red phosphorus, the vapor of this element is produced, the vessel being closed by means of a vacuum tight valve which regulates its flow. In the vessel, there are two zones having different temperatures, one of sublimation of red phosphorus and another of condensation and re-evaporation of white phosphorus, both zones being thermally insulated by means of reflecting screens which prevent the temperature of the heating resistance from having to reach temperatures above 350° C. The valve, intermittent closing of which regulates the effusion of phosphorus vapor, is at a temperature slightly above that of the thermostated zone of condensation/re-evaporation of the white phosphorus. It finds applicable in the manufacture of semiconducting structures.

[62] Division of Ser. No. 181,802, Jan. 14, 1994, Pat. No. 5,431,735.

[30] **Foreign Application Priority Data**

Jan. 14, 1993 [ES] Spain 9300063

[51] **Int. Cl.⁶** **H01L 21/20**

[52] **U.S. Cl.** **437/133; 437/105; 437/107; 437/126; 117/84**

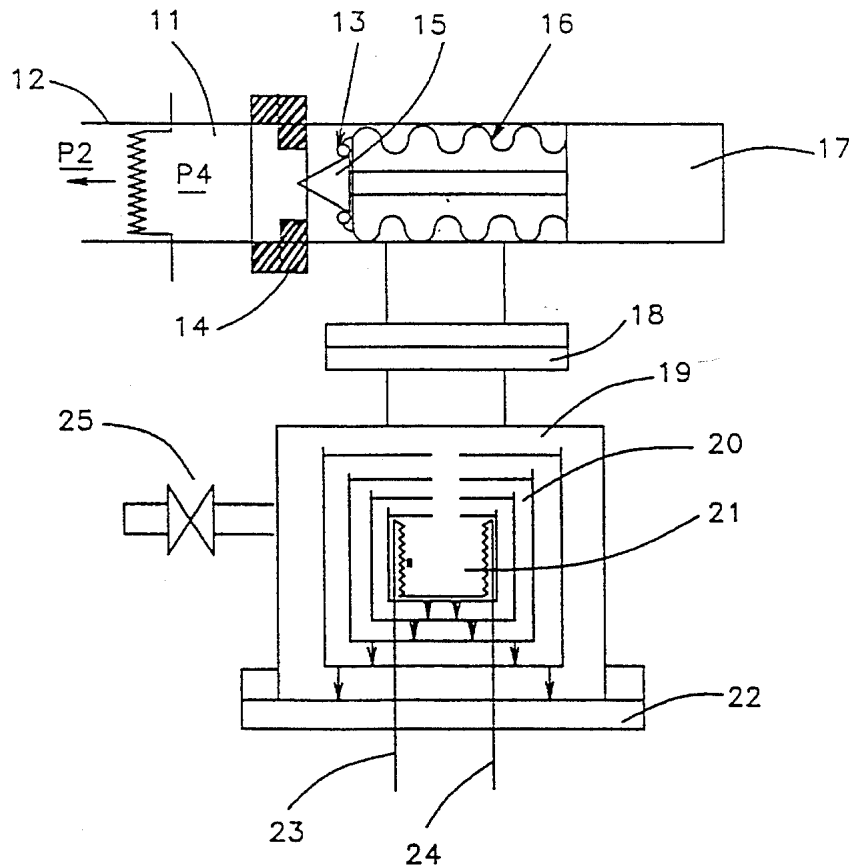
[58] **Field of Search** **437/105, 107, 437/126, 133; 117/84**

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,618,345 10/1986 Kuck et al. 23/293 R

26 Claims, 10 Drawing Sheets



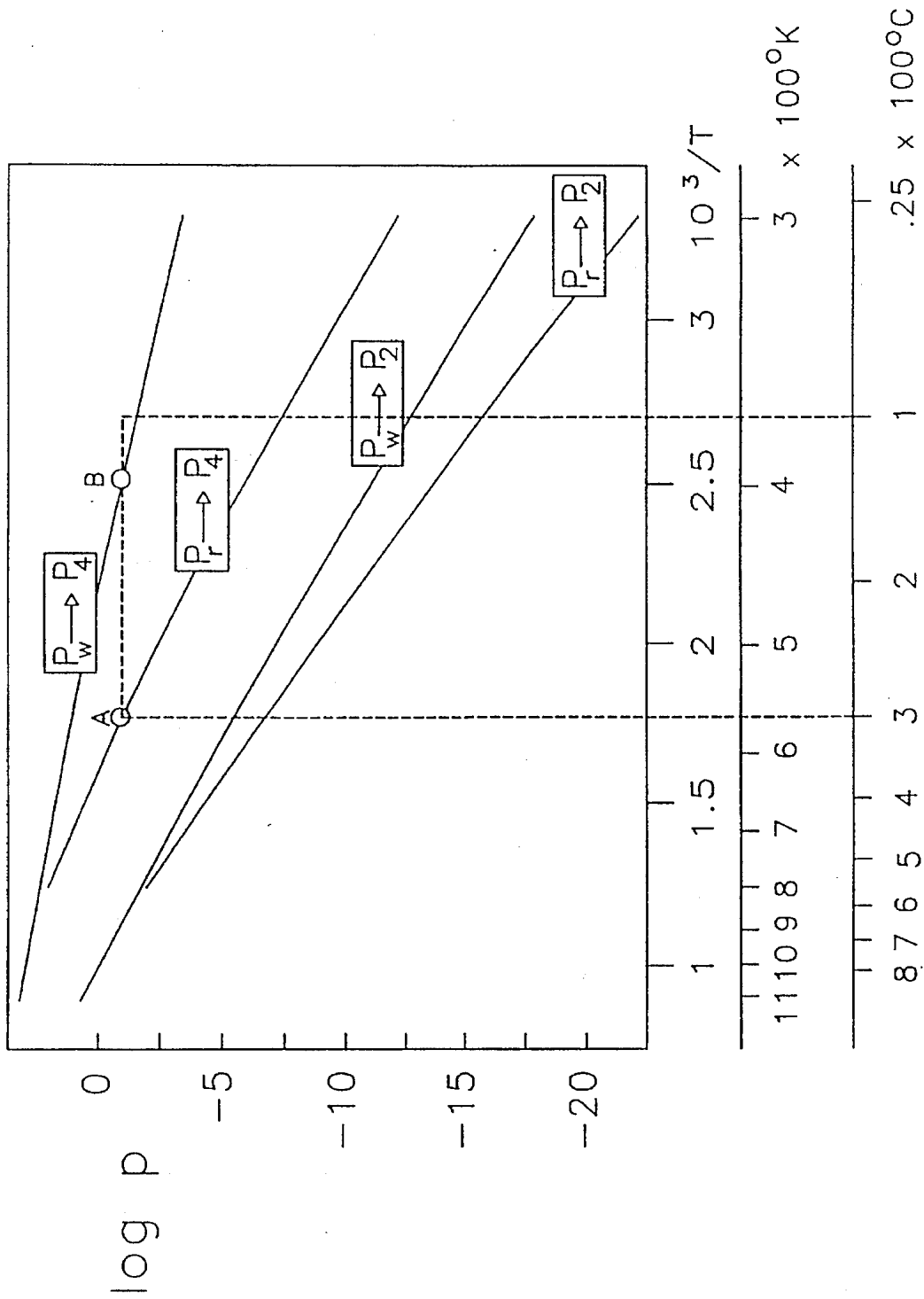


FIGURE 1

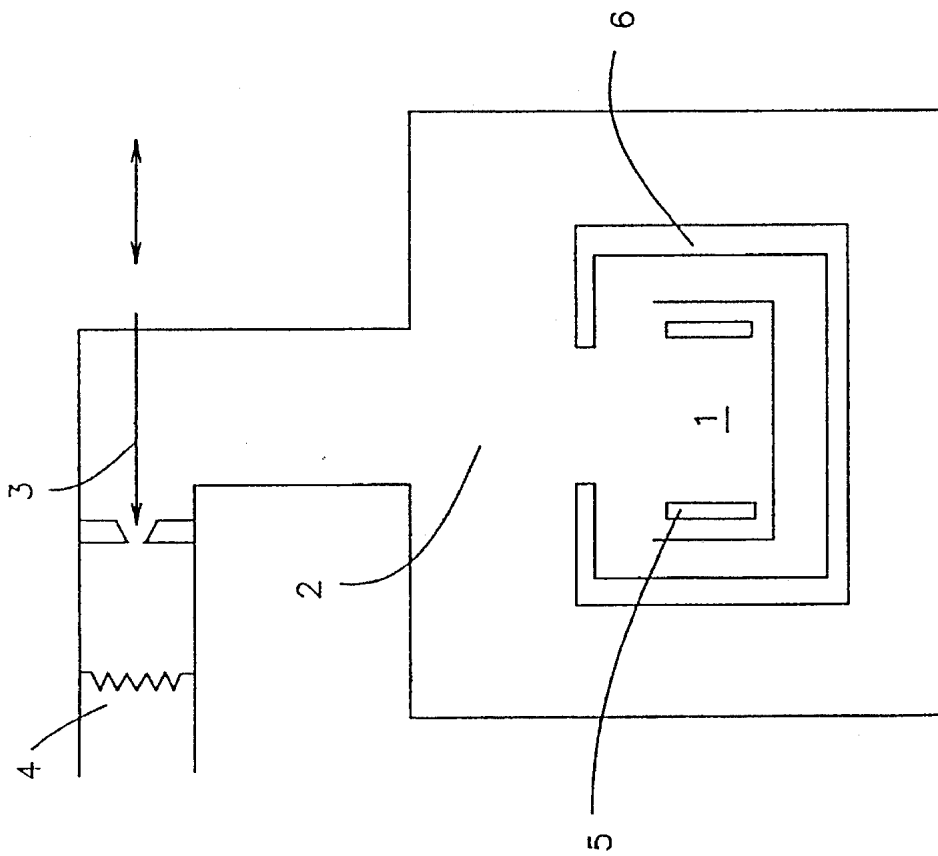


FIGURE 2

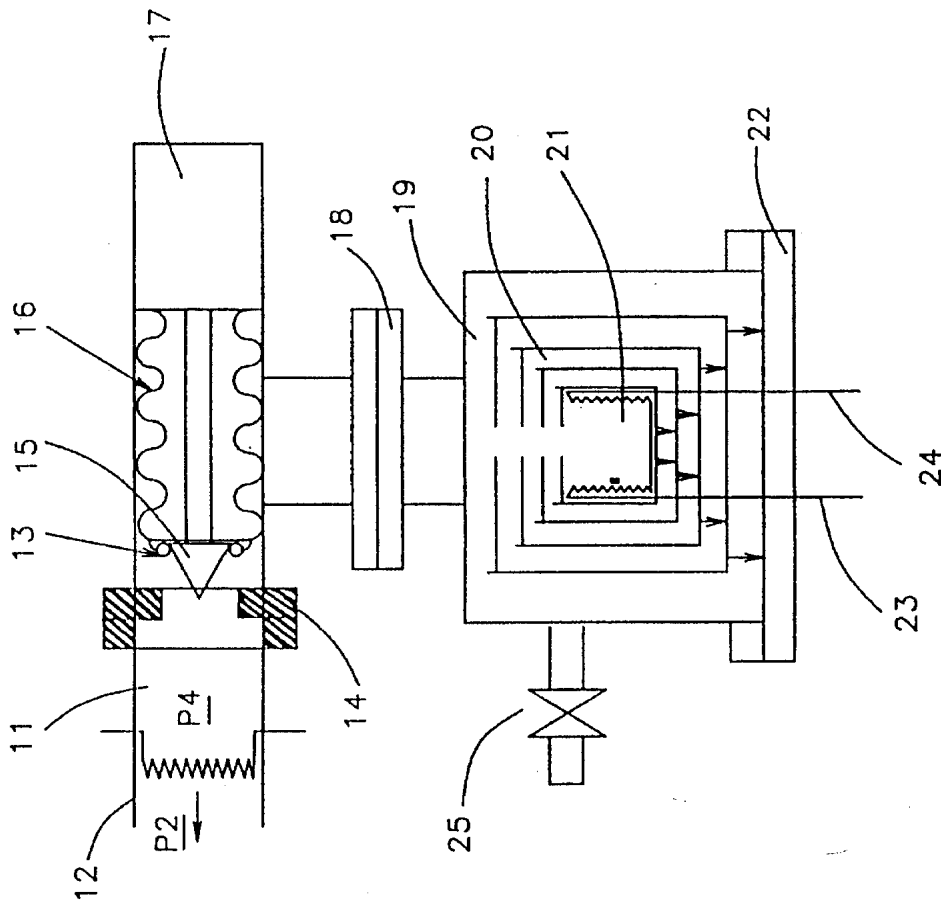


FIGURE 3

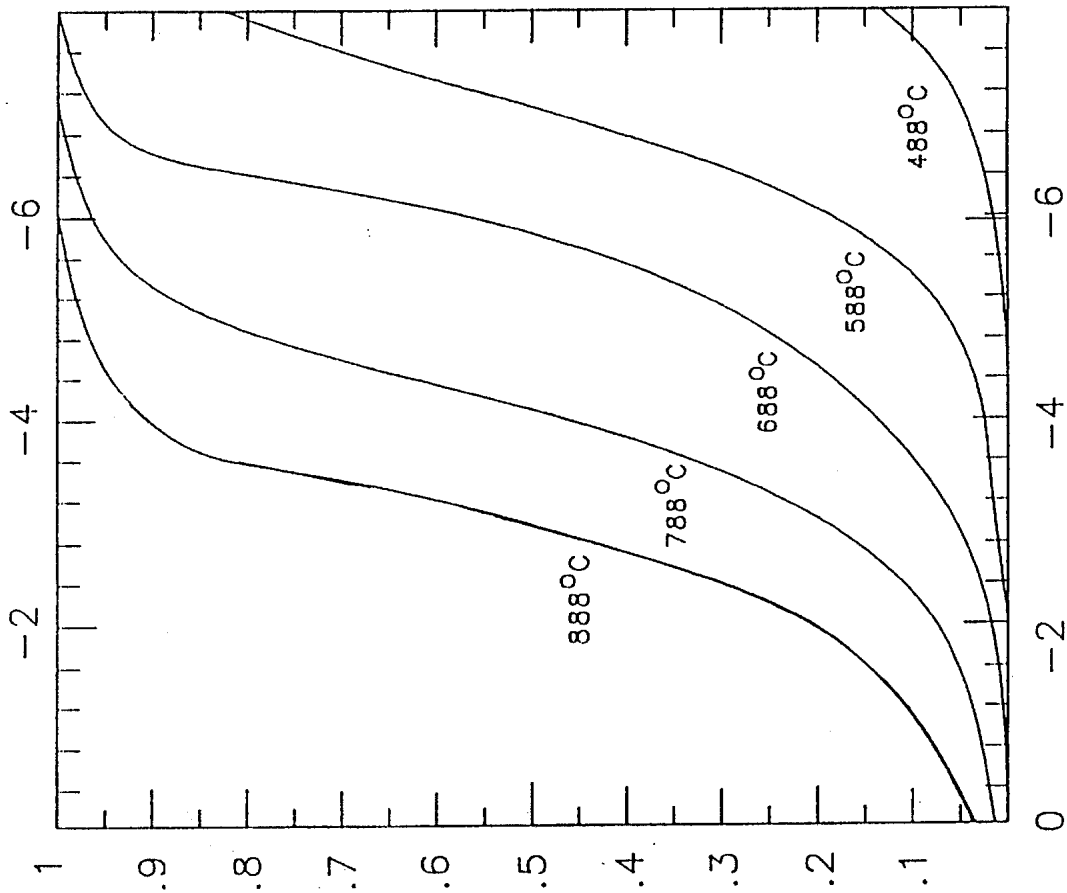


FIGURE 4

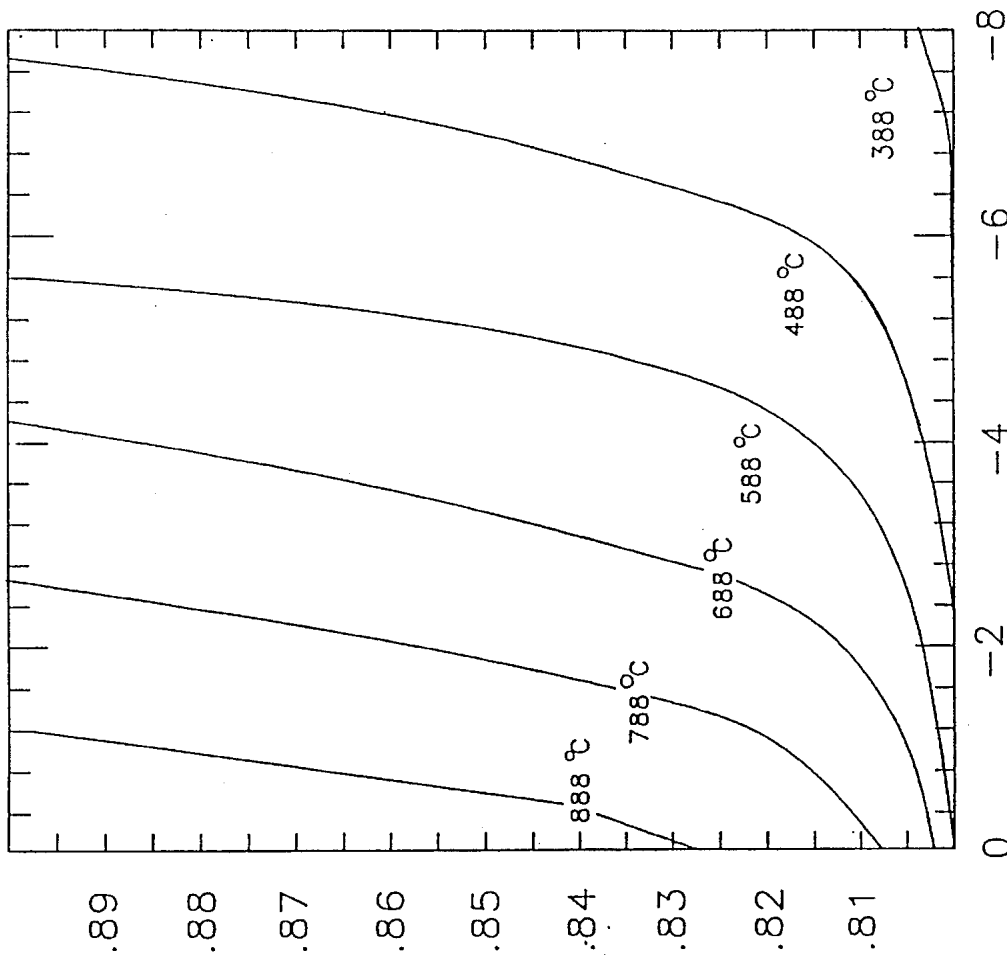


FIGURE 5

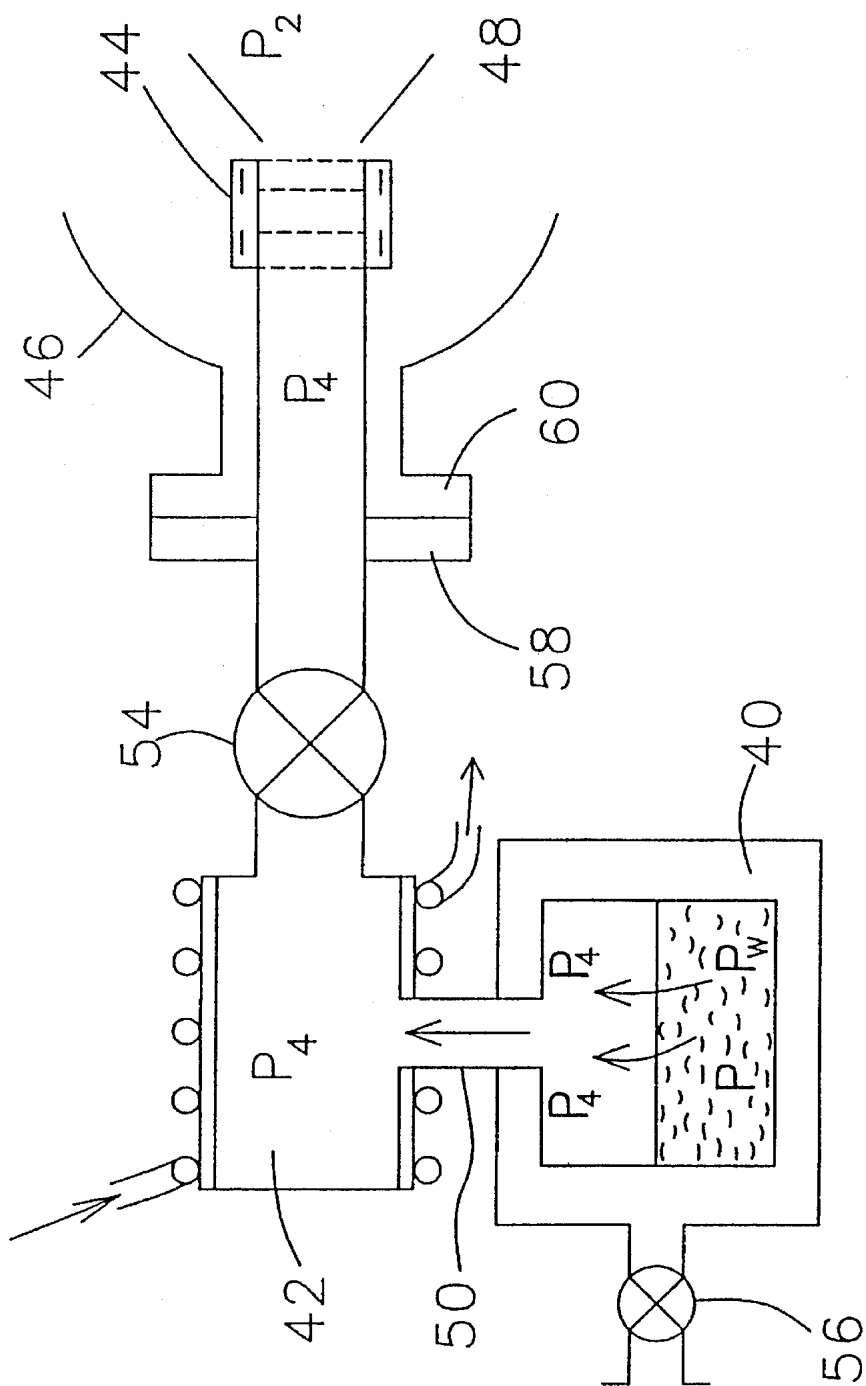


FIGURE 6

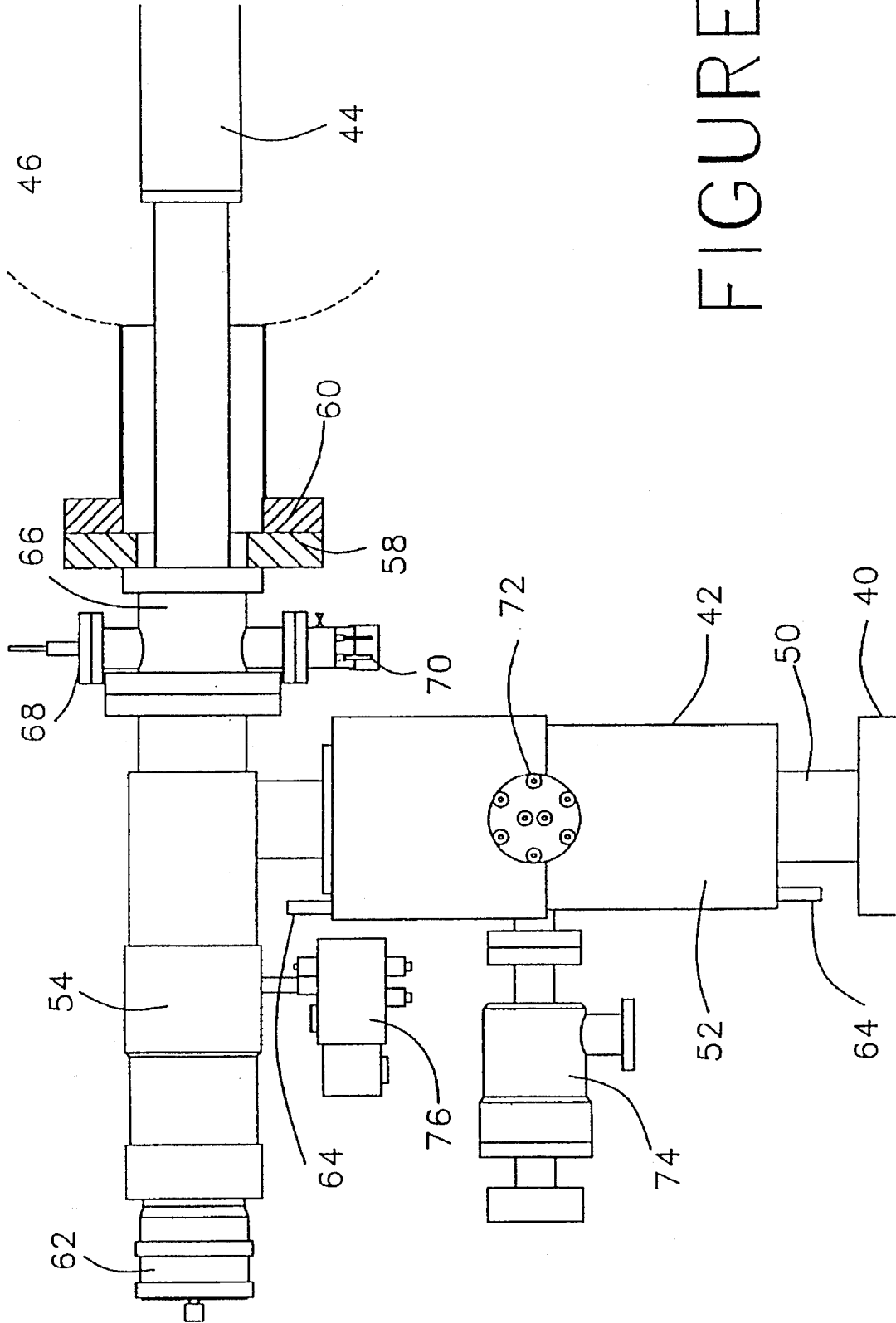


FIGURE 7

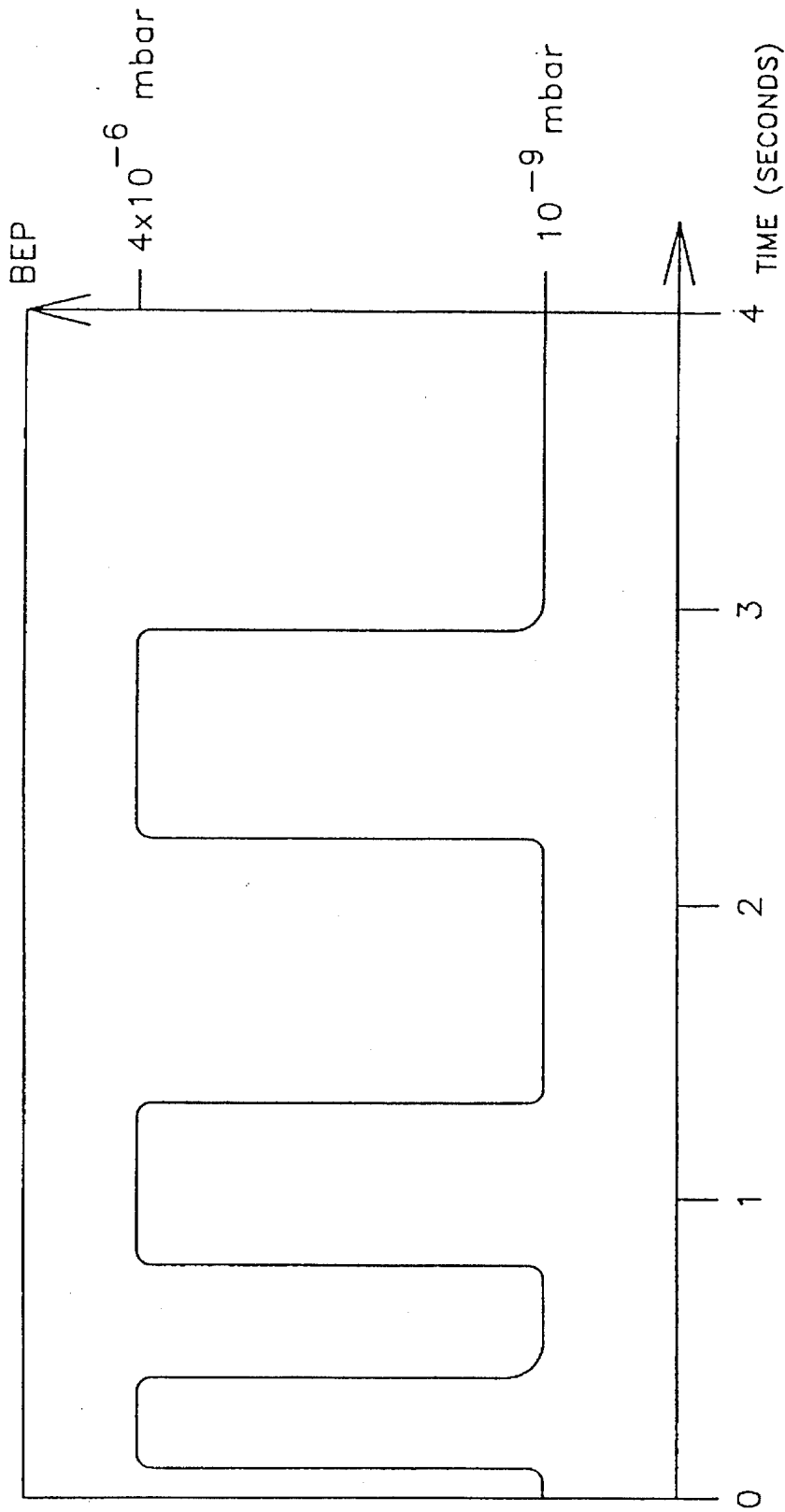


FIGURE 8

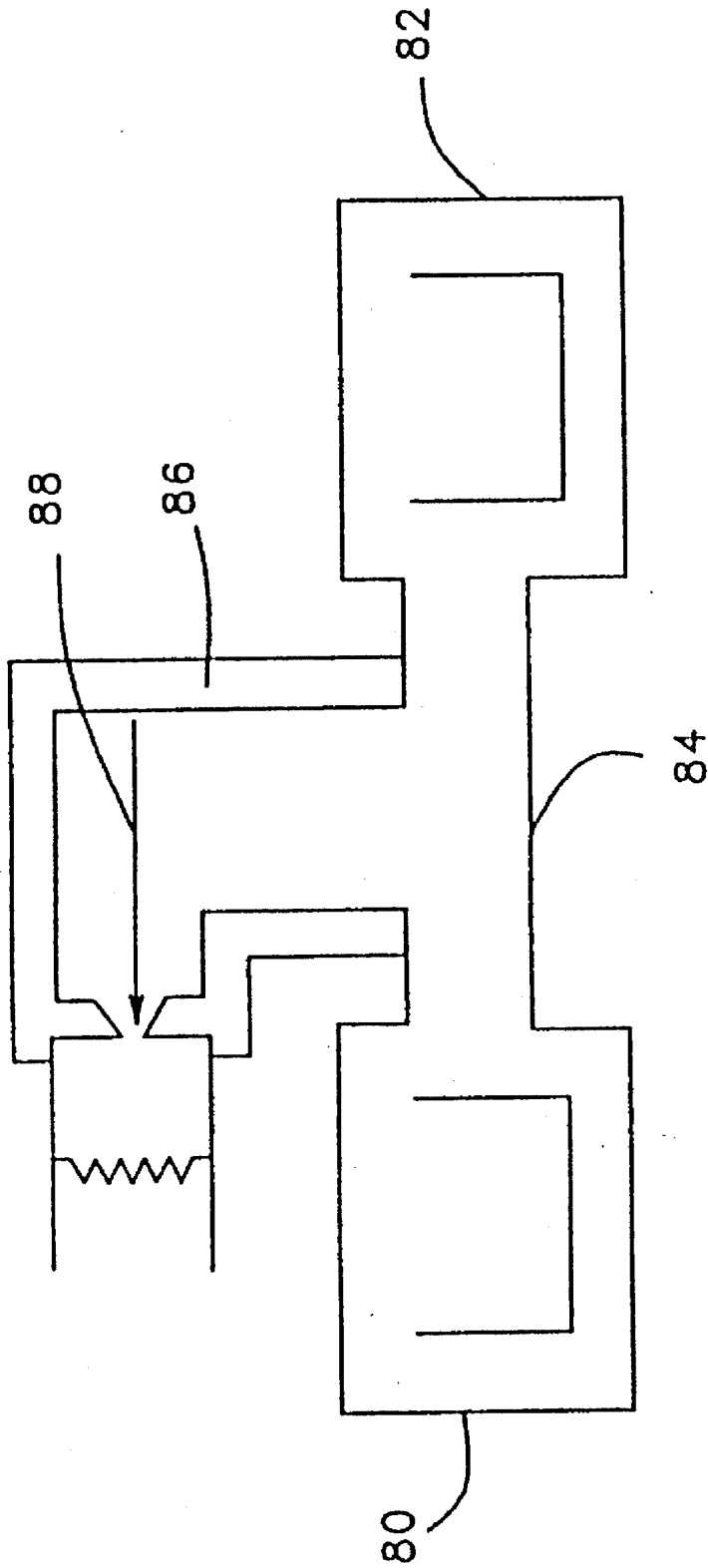


FIGURE 9

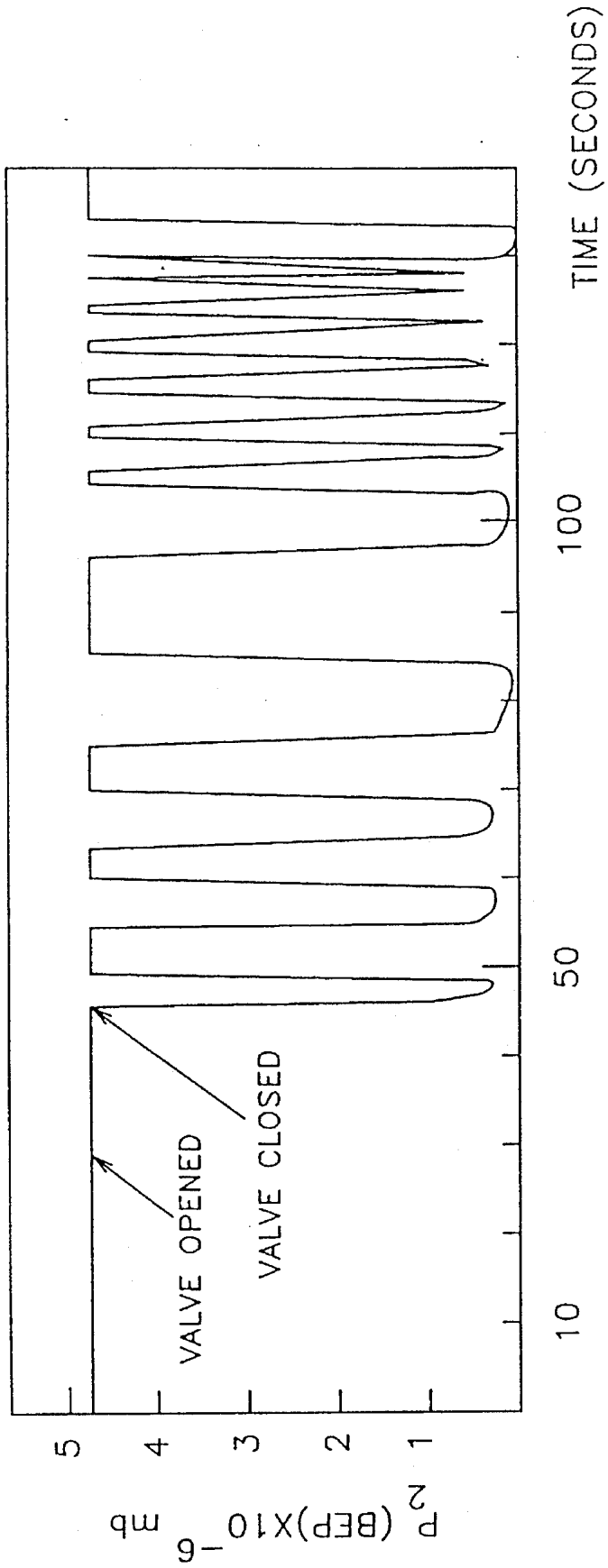


FIGURE 10

METHOD OF PRODUCING WHITE PHOSPHORUS FOR MOLECULAR BEAM EPITAXY

This application is a division of application Ser. No. 08/181,802, filed 14 Jan. 1994, now U.S. Pat. No. 5,431,735.

The present invention relates to an most advanced techniques for the manufacture of Group III-V element semiconducting structures, namely molecular beam epitaxy (abbreviated to "MBE" herein). MBE is based on the chemical reaction of molecular beams of elements of group III of the Periodic System (Ga, Al, In) and of group V (P, As, Sb) on the surface of crystalline substrates at high temperature and under UHV conditions. The molecular beams are generated in effusion cells by thermal sublimation or evaporation of the corresponding or solid elements.

BACKGROUND

The control of the thicknesses and composition of the different epitaxial layers which participate in a complex semiconducting structure is achieved by acting on the molecular beams by means of appropriate screens or valves. In particular, for the controlled production of molecular beams of arsenic (As_4) from the thermal sublimation of solid arsenic, effusion cells in which the opening/closing screen has been replaced by a rapid-actuation valve maintained at high temperature, to prevent condensation of the As_4 molecules therein, have been designed in the Centro Nacional de Microelectronica [National Microelectronics Centro] (C.S.I.C.) and employed successfully.

The crucible or vessel in which the arsenic is sublimed is leak-tight, except for the above-mentioned valve which opens it to the epitaxy reactor, and an auxiliary valve which connects it to a vacuum system. The vessel is maintained at a uniform temperature of the order of 300°–350° C. to obtain flows of As_4 with an equivalent beam pressure in the range 10^{-6} - 10^{-5} mbar. For the production of molecular beams of As_2 , a nozzle provided with tantalum surfaces at high temperature, which are capable of thermally dissociating As_4 molecules to As_2 , was added. At the present time, the company EPI² [III-Vs Feature Review, 4(3), 31 (1990)] commercially produces a cell for As_4 and As_2 which utilizes the same principle and arrangement as the one described above.

When this type of cell was used for the production of molecular beams of P_4 or P_2 from the sublimation of solid phosphorus (red variety), great difficulties arose, both with the CNM cell and with the EPI cell. In particular, at the operating temperature of the cell 300° C., necessary for obtaining an equivalent beam pressure of the order of 10^{-5} – 10^{-6} mbar in the steady state (valve open), a gradual rise takes place in the internal pressure in the cell (valve closed), leading to a strong equivalent beam pressure transient, or pressure burst, at the time of opening the valve. This transient makes it difficult to control the epitaxial process and is detrimental to the UHV pumps.

U.S. Pat. No. 5,156,815 Streetman et al. discloses an arsenic effusion cell, or sublimation and cracking apparatus in which arsenic is sublimed in a primary furnace or sublimator 12 at temperatures of the order of 235° C. and is cracked in a perpendicular cracker at temperatures that are preferably in the range of 750° to 1050° C. The lower end of cracker 14 is described by Streetman et al. as providing a heat sink zone between the cracker and the sublimator (column 4, lines 29–55, column 6, lines 11–24 and column

10, lines 17–31). This heat sink zone, is obtained by restricting the extent of heater filament 78 to an upper portion of cracker 14 and by circulating a, probably gaseous, coolant through a cooling jacket 70 surrounding a lower end of sublimator 12. This exposed, lower heat sink end of cracker tube 18 serves the purpose of minimizing undesired heat transfer between the cracking and sublimator sections.

The heat sink zone is described by Streetman as having a substantially lower operation temperature than the temperature of the primary cracking zone. The lower temperature of the heat sink zone is however substantially above that of the sublimator 12 because of a much higher cracking temperature and because of heat transmission down the cracking tube 18. Streetman et al.'s heat sink zone serves to prevent back transfer of heat from the cracker to the sublimator leading to overpressure due to enhanced sublimation of arsenic. While it may have been suggested to use arsenic effusion cells to generate phosphorus beams, Streetman et al.'s sublimation and cracking apparatus is not designed as a phosphorus effusion cell and provides no means to solve the problems that arise in subliming and cracking phosphorus, specifically the problem of an initial pressure surge and providing a readily controllable, reproducible phosphorus beam.

A further crucial drawback to employing the Streetman et al. teaching for propagating a phosphorus beam for use in MBE is the lack of efficient flux control valving means. Streetman et al. constrained by a high-temperature environment provides only a crude shutter 112 pivoting on a hinge 114, which is neither vacuum-tight nor rapid-acting.

A problem with prior proposals is that they are either unaware of, or have underestimated, the quantity of white phosphorus which is formed by condensation as a result of evaporation of red phosphorus and the pressure impact it creates. The P_4 pressure of white phosphorus at 300° C., a suitable red phosphorus evaporation temperature, is close to 1 bar. This is an enormous pressure compared with desired beam equivalent pressures of about four-millionths of a bar.

The high internal white phosphorus pressures of known cell effusion systems, such as those used for arsenic mean that each time the valve between the sublimation furnace and the cracker is opened, a large burst of pressure is produced. The MBE growth chamber into which this burst of pressure is discharged cannot sustain such high pressure and may require several hours to recover to a practical working pressure. Also the large amount of phosphorus blown into the growth chamber will inevitably provide a high residual background of phosphorus even in subsequent processes where phosphorus may not be required.

A further drawback of known systems is that a stable state is only reached after a long period with the valve constantly open. This is an unacceptable impediment to most researchers or fabricators using molecular phosphorus beams. Such instabilities makes it difficult or impossible for researchers and fabricators to rely upon a particular beam equivalent pressure for accurate calibration of Group III and other Group V fluxes, or to gain flux reproducibility.

SUMMARY OF THE INVENTION

This invention solves a problem. It solves the problem of providing a phosphorus effusion cell capable of producing a controlled phosphorus beam suitable for use in molecular beam epitaxy processes.

I have found that an important drawback of known effusion cells such as the Streetman et al. arsenic cracking cell is that if used for phosphorus they produce a phosphorus beam containing P_4 molecules which condense out as solid white phosphorus on the internal parts of the molecular beam epitaxy chamber. Solid white phosphorus is a volatile,

3

dangerous material, which ignites spontaneously, or explodes in the presence of air and can contaminate vacuum pumps.

Whereas the inadvertent formation of white phosphorus may be seen as a cause of phosphorus effusion cell pressure surge problems, in my invention I have turned this phenomenon to good effect and used it to provide a significantly improved phosphorus effusion cell. By deliberately depositing white phosphorus from vapor, and then re-evaporating it, a controllable, high volatility phosphorus-vapor source is created which is subject to precise management by simple thermostatic means, which eliminates the surge problem and provides other advantages.

In one aspect the invention provides a phosphorus effusion cell for molecular beam epitaxy, consisting of a vessel, closed by means of a vacuum-tight valve which regulates its flow, in which, by sublimation of red phosphorus, the vapor of this element is produced, wherein in the vessel, there are two zones having different temperatures, one hot, of subliming red-phosphorus producing P_4 vapor, and another, cold, of condensation in the form of white phosphorus and re-evaporation of the latter; the two zones are thermostated independently. The output is cracked or supplied to a phosphorus cracker to generate the desired phosphorus beam. In other words, the phosphorus stream to the cracker is processed in two stages, with a pronounced temperature drop from sublimation to condensation leading to distinct phosphorus phase changes.

In another aspect the invention provides a phosphorus effusion cell having a relatively high temperature phosphorus cracker and a relatively lower temperature phosphorus evaporator which incorporates a flux control valve that is sealable against high vacuum and controllable with precision and reproducibility. This is achieved by using low temperature valving with an elastomeric seal, operating on a low temperature phosphorous stream.

While the invention disclosed herein is not bound by any particular theory, it appears that the rise in the internal pressure is the outcome of the coexistence of two phases or allotropic states of phosphorus, red phosphorus of low vapor pressure, which is obtained by condensation of P_2 molecules, and white phosphorus of high vapor pressure (see vapor pressure curves in FIG. 1), which is obtained by condensation of P_4 molecules. However, sublimation of red phosphorus at 300°C . gives rise to P_4 molecules. At equilibrium, with the valve closed, the internal pressure is determined by the phase of higher vapor pressure, white phosphorus, pressures of the order of one bar or one atmosphere being reached at 300°C .

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the invention, including the best known embodiment, will now be described in detail below with reference to the accompanying drawings which illustrate only one specific embodiment of the invention and in which:

FIG. 1 shows known vapor pressure curves for different phases of phosphorus;

FIG. 2 is a schematic sectional view of one embodiment of inventive phosphorus effusion cell;

FIG. 3 is a view similar to FIG. 2 showing another embodiment of phosphorus effusion cell in somewhat more detail; and

FIG. 4 shows known mole fraction curves for P_2 - P_4 mixtures;

4

FIG. 5 is an expanded scale chart similar to FIG. 4;

FIG. 6 is a schematic view of another embodiment of phosphorus effusion cell according to the invention;

FIG. 7 is a more detailed view of an apparatus for realizing the embodiment schematically shown in FIG. 6;

FIG. 8 is a graph of beam equivalent pressures obtainable with apparatus according to FIG. 7;

FIG. 9 is a schematic view, similar to FIG. 2, of another embodiment of phosphorus effusion cell according to the invention; and

FIG. 10 is a further graph of beam equivalent pressures obtainable with apparatus according to FIG. 7.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiment of FIG. 2

Referring to FIG. 2 the phosphorus effusion cell shown provides a hot thermostated evaporation zone comprising a crucible 1 containing red phosphorus and a cold thermostated condenser zone 2 where white phosphorus is condensed and re-evaporated.

The cell further comprises a rapid-actuation valve 3, and a thermostated electrical resistance phosphorus cracker 4. Independent thermostating systems for the evaporator crucible 1, the condenser 2 and the cracker 3 are shown at 5, 6 and 7 respectively.

The phosphorus effusion cell consists (FIG. 2) of a closed vessel in which there are two zones having different temperatures, one, hot, in which red phosphorus sublimates 1, and another, colder, of condensation and re-evaporation of white phosphorus 2; the vessel communicates with the device to which the phosphorus effuses by means of vacuum-tight valve 3.

The condensation zone 2, preferably thermostated at 30°C . (in no case at more than 100°C .), determines the vapor pressure of the P_4 in the vessel, which vapor flows out through the valve 3 with which, by means of intermittent closing and of regulation of the clear section when it is open, the flow of phosphorus vapor is regulated; the said valve should be maintained at a temperature above that of the condensation chamber so as to prevent phosphorus from condensing on it.

Lastly, when the vapor passes through the valve, thermal dissociation of P_4 to P_2 is produced by means of an electrical resistance 4 of refractory metal (for example tantalum).

The two zones, hot 1 and cold 2 and the valve 3 are thermostated independently by the corresponding systems 5, 6 and 7.

In the effusion cell which is the subject of this patent, the problem of the excess pressure caused by the formation of white phosphorus has been avoided by using an airtight vessel with a valve, as described in the prior art, but dividing the said vessel into two zones having different temperatures instead of a single zone having a uniform temperature.

Embodiment of FIG. 3

In the embodiment shown in FIG. 3, a phosphorus effusion tube 11 contains a preferably tantalum electrical resistance 12 for the thermal or thermal catalytic dissociation of P_4 . A conical valve member 15, carried and sealed by a bellows 16, bears a valve seal 13 which can be, for example, an elastomeric O-ring, e.g. made of VITON (trademark), for

hermetic sealing of the cell. Valve member 15 is driven by a pneumatic system 17 (or equivalent electrical mechanism) for actuation of the valve which may be electronically controlled by computer-compatible means, if desired. Valve seal 13 can be of any suitable material and structure which ensures a hermetic, leak-tight closure in the high-vacuum, low-pressure environment of the phosphorus effusion tube 11, for example a soft metal seal such as copper or aluminum. Alternatively, a leak-tight seal may be assured by pressing an exceptionally hard-surfaced member, for example, of sapphire, against a soft metal seal.

Vacuum flange 18 provides a separable unit attachable to cold chamber 19 with thermostated walls. Thermal insulation 20 which is suitable for ultra-high vacuum (UHV) use, comprises for example concentric spot-welded cylinders of tantalum foil or sheet, and lines a crucible 21 for subliming red phosphorus. Vacuum flange 22 has through-connectors and provides support for the cell.

Furnace heating resistance 23 for crucible 21 is controlled by temperature sensor or thermocouple 24. An optional vacuum valve 25 is provided for pumping out the cell.

With the object of providing a better explanation of the present invention, one of the possible modes of construction of the phosphorus effusion cell has been detailed in FIG. 3. The high temperature zone (at $\sim 300^\circ\text{C}$.), in which red phosphorus sublimates to produce P_4 , is located in a crucible 21, thermally insulated under vacuum by means of appropriate screens 20 and electrically heated by means of a resistance 23, the temperature of which is monitored by a sensor (thermocouple, for example) 24.

The internal pressure of the cell is controlled by the temperature of the colder zone, which corresponds to the outer walls of the vessel 19, which are thermostated at a temperature below 100°C ., so that the aforementioned pressure is maintained in the range 10^{-2} – 10^{-0} mbar, an entirely suitable range for obtaining an equivalent beam pressure of the order of 10^{-5} – 10^{-6} mbar with the valve open.

The internal pressure is stabilized by the equilibrium of condensation/sublimation of white phosphorus deposited on the cold zone of the cell, and is maintained practically constant on opening or closing the valve. The transient occurring on opening, which takes place, as explained, with the cells described in the prior art, is thereby avoided.

The valve is composed of an assembly made up of a piece 15 with a conical projection and a flat part into which an O-ring 14, responsible for producing the hermetic seal, is fitted; the conical projection possessed the same degree of taper as the hole in the flange 3, so that, by adjusting the maximum separation of 5 during opening, the clear section for passage of vapor is varied, the maximum flow being regulated in this way. The valve assembly includes an elastic bellows 16 to allow the shaft to move while avoiding leaks, and an actuating system 17, preferably pneumatic. To avoid the condensation of phosphorus on the valve, the latter is maintained at a temperature above that of the cold zone 19.

Consequently, as a result of the valve being at a low temperature (the cold zone can be at 30°C . and the valve at 100°C ., for example), it is possible to use sealing rings 14 of elastomeric material, a reproducible hermetic seal being obtained with a low force of actuation. Thus, valve O-ring or seal 14 can be of any suitable material and structure which ensures a hermetic, leak-tight closure in the high-vacuum, low-pressure environment of the valve, for example a soft metal seal such as copper or aluminum. Alternatively, a leak-tight seal may be assured by pressing an exceptionally hard-surfaced member, for example, of sapphire, against a

soft metal seal.

Physical Chemistry of Phosphorus

In FIGS. 4 and 5, the mole fraction of P_2 in a P_2+P_4 mixture as a function of pressure and temperature is shown. The vertical ordinates are in mole fractions while the horizontal abscissa units are logarithm to base 10 of the total pressure of the mixture, in bars. The curve parameter is temperature in degrees centigrade

FIG. 1 is helpful in understanding the peculiar behavior of the several phases and allotropes of phosphorus and shows $\log_{10}P$, the vapor pressure in bars along the ordinate plotted against $10^3/T$, the absolute temperature in $^\circ\text{K}$., on the abscissa. Vapor pressure of the various varieties of phosphorus (monatomic P is not included) [Adapted from JANAF Thermochemical Tables, 2nd Edition, NERDS-NBS 37, Catalog Number C13.48: 37 US Government Printing Office, Washington, D.C., 1971]

Two auxiliary scales in $^\circ\text{K}$. and $^\circ\text{C}$. have been drawn.

$P_w \rightarrow \text{P}_2$: Vapor pressure of white phosphorus giving diatomic phosphorous gas.

$P_r \rightarrow \text{P}_2$: Vapor pressure of red phosphorus giving diatomic phosphorous gas.

$P_w \rightarrow \text{P}_4$: Vapor pressure of white phosphorus giving tetraatomic phosphorous gas.

$P_r \rightarrow \text{P}_4$: Vapor pressure of red phosphorus giving tetraatomic phosphorous gas.

Whereas, according to FIG. 1, the P_4 pressure of red phosphorus at 300°C . is 8.49 mbar (point A), that of P_2 is 3.97×10^{-5} mbar, as a result of which practically all the phosphorus may be considered to sublime as P_4 . If the cold wall is at less than 100°C . (point B), the P_4 condenses on it in the form of white phosphorus, which is registered as the corresponding vapor pressure of phosphorus in the cell (4.48 mbar at 100° and 7.53×10^{-2} mbar at 30°C .). However, if at some point in the cell (for example in the heating resistance) temperatures above 350°C . were to be reached as a result of the thermal dissociation



the equilibrium of which is shifted to the right, this being favored by low pressures and high temperatures as may be seen in FIGS. 4 and 5, the fraction of P_2 which forms condenses on the walls in the form of red phosphorus and cannot be used in the process.

This condensation is due, as has been explained, to the dissociation of P_4 molecules on heating elements or filaments necessary for subliming red phosphorus contained in the crucible of the high temperature zone. The thermal dissociation of P_4 to P_2 normally requires temperatures above 600°C . in order to achieve a high efficiency of dissociation; however, at temperatures of the order of 300° – 400°C . and on surfaces of refractory metals which act as catalysts, the dissociation yield obtained is sufficient for a condensation of P_2 on the cold walls to be obtained at an internal pressure of the order of 10^{-1} – 10^{-2} mbar (see FIG. 5).

If the internal pressure is high, on the other hand, $\text{P}_2 \rightarrow \text{P}_4$ collisions in the gas phase favor recombination to P_4 . To solve this problem, in the present invention, the temperature of any internal heating element is reduced to a minimum ($\sim 300^\circ\text{C}$.) by means of an optimization of the thermal insulation surrounding the crucible. Better thermal efficiency and greater equality of temperature of the heating

7

elements and of the change of red phosphorus are thereby obtained, the catalytic dissociation and irreversible condensation of P_2 being minimized to the point where it becomes practically insignificant.

Lastly, at the beam exit at **1**, there is an electrical resistance **2** of a refractory metal such as tantalum, which, on raising the temperature of the beam and catalyzing the dissociation of P_4 , gives rise to the formation of P_2 (see FIG. 4), which is necessary for epitaxy.

Embodiments of FIGS. 6 and 7

In the schematic drawing of FIG. 6 an inventive phosphorus effusion cell embodying the principals of the invention comprises an evaporator **14**, a phosphorus condenser **42** and a phosphorus cracker **44**. Phosphorus cracker **44** is shown within an MBE chamber **46** discharging a phosphorus beam **48** comprising substantially only P_2 molecules and red phosphorus P_4 molecules. Here the condenser in chamber **42** is a discrete volume supplied from evaporator **40** through a physically distinct connection **50**.

Condenser chamber **42** is a substantially cylindrical volume clear of heating elements, thermocouples or insulation associated with evaporator **40** and is cooled by a water jacket **52**, the output from condenser chamber **42** is controlled by phosphorus flux valve **54**.

In both this embodiment and the other embodiments described herein, because its probable or preferred operating temperature range is a moderate 50° to 80° C., phosphorus flux valve **54** can be a standard valve for example a conical valve engaging a sealing seat which may be elastomeric, formed for example of VITON (trademark), and is preferably actuated and closed pneumatically and also provided with a mechanically operable vernier control of its degree of opening. Valve **54** seals tightly, even under the ultra high vacuum conditions for practicing the invention. An optional vacuum connection is made to evaporator **40** at **56**. Flange **58** of the effusion cell mates with MBE flange **60** and is such that in conjunction with operation of valve **54**, the effusion cell is separable from the MBE chamber **46** without significant loss of vacuum, for example, for recharging purposes.

In the hardware realization of the FIG. 6 schematic design that is shown in FIG. 7 similar reference numerals are used to indicate similar components.

Referring to FIG. 7, it may be noted that the phosphorus condenser **42** and cracker **44** are generally cylindrical in shape and are disposed approximately orthogonally off-axis, one to another. In addition to common components with FIG. 6, the FIG. 7 embodiment has a flux-adjustment vernier control **62** for valve **54** and water connections **64** for water jacket **52**. Behind the connection flange **58** is disposed a service head **66** which carries a cracking-stage filament connector **68** and a cracking-stage thermocouple flange **70**. Also communicating with condenser chamber **42** are a burn-off filament **72** and an optional venting and pumping down valve **74**. Actuation of valve **54**, which is preferably pneumatic, is shown at **76**.

Burn-off filament **72** enables all residual P_{white} to be evaporated prior to opening the condenser **42** or the evaporator **40** to air for service or recharging. Residual white phosphorus is evaporated as the P_4 form and can be evacuated through the flux valve **54** and cracker **44**, or through an optional vacuum valve **74** connected to an auxiliary vacuum unit.

Some optional but advantageous features of the phosphorus effusion cell shown in FIG. 7 are that the cracker **44** and flux valve **54** can be contained in a relatively long, small-diameter tube which is, for example 10 inches long for a 2.75 inch outside diameter MBE chamber flange. Preferably service head **66** comprises a rotatable flange whereby the

8

evaporator-condenser unit can be oriented within an extensive angular range of for example, 75° to the axis of cracker **44**, facilitating installation of the inventive phosphorus cell on an MBE chamber.

The cell disclosed herein is designed to fit a standard UHV conflat flange, e.g. a 35 CF flange, and has a low weight and large orientation range to be adaptable to most MBE systems.

From the foregoing disclosures, it will be apparent that the unique low-temperature flux control valves employed can be rated for ultra-high vacuum sealing, permitting disassembly of the cell chambers for service or recharging without requiring removal of the unit from the MBE chamber or loss of vacuum in that chamber.

Embodiment of FIG. 9

In FIG. 9, the functions of phosphorus evaporation, white phosphorus condensation, and P_4 cracking to yield a P_2 beam, are clearly physically separated spatially and thermally. In the FIG. 9 concept, a red-phosphorus evaporator **80** and a separately defined white-phosphorus condenser **82** communicate through a separator tube **84**. Separator tube **84** enables distinct temperature zones to be defined between the evaporator **80** and the condenser **82**. Phosphorus vapor, comprised primarily of white phosphorus P_4 molecules, is drawn upwardly through cracker feed column **86** to flux control valve **88**, which is in a low-temperature zone, and then to cracker **90** after which it is output to the MBE chamber.

As well as providing for temperature partitioning, the physical disposition in which evaporator **80** and condenser **82** are opposed along an axis from which cracker feed column **86** extends perpendicularly, provides a compact arrangement which, at the crowded head of an MBE chamber, can be particularly advantageous.

In addition to thermocouple control of the cracker **90**, three further distinct zones of the cell are readily subject to independent temperature control. Evaporator **80** is heated and thermostated while white phosphorus condenser **82** is preferably water cooled. If desired, or necessary, in view of heat transfer from the cracker **90**, the flux control valve **88** can be jacketed and cooled, to a suitable temperature in the range of about 40° to 100° C., depending upon condenser temperature as can the cracker feed column **86**. In any event, valve **88** in this configuration has all the advantages of a relatively low temperature environment, preferably not above 100° C.

Phosphorus Beam Characteristics

FIG. 8 shows sub-second valve pulsing obtainable with a cell constructed in accordance with the invention, for example, employing apparatus as described with reference to FIG. 7. The horizontal abscissa is time in seconds and the vertical ordinate plots beam equivalent pressure, of P_2 in mbar, with an effective plateau at about 4×10^{-6} mbar, and an effective zero at about 10^{-9} mbar. Preferred beam-equivalent pressures for MBE growth of thin layer structures on semiconductor substrates, and especially for atomic layering of gallium and indium arsenide and phosphide materials in sophisticated structures such as strained layer short period superlattices, are in a range of from about 10^{-7} to about 10^{-5} mbar, and more preferably are of the 10^{-6} mbar order of magnitude.

The cell performance curve shown in FIG. 10 plots beam equivalent P_2 pressure in units of 10^{-6} mbar on the ordinate scale versus an extended time scale, in seconds, on the abscissa. Peaks represent fully open valve positions, while the arrow marking a point of valve closure enables the response time to be read, showing a rapid drop in beam pressure after closure. The right-hand side of the curve shows several fully open to fully closed cycles being accomplished in a 10-second interval. Valve operation can be driven by an electronically controlled air supply, preferably digitally, for full integration of phosphorus beam control into the MBE management systems under computer supervision.

As the consistency of the valve-open plateaus at about 4×10^{-6} clearly shows, remarkably precise flux calibration and control is possible. Remarkable also are the speed with which peak flux is restored after reopening the valve as shown by the steepness of the up-ramps, and the complete absence of any measurable pressure overshoot in returning to full amplitude.

The phosphorus condensation zone is preferably cooled, for example by water, or by thermally regulated air flow, and to a preferred temperature which is maintained somewhere of the order of room temperature, for example, from 5° to 40° C. preferably between 10° and 30° C. Physico-chemical considerations dictate that the condenser temperature should be below 100° C. The output of the cooled condenser produces P_4 at a controllable pressure in a desirable pressure range which is approximately the same as that of red phosphorus at 300° C. In other words, the phosphorus output of the white condensation zone is comparable with that of a known high temperature red phosphorus systems but lacks their undesired pressure instabilities.

It follows that when practicing this invention, most of the P_4 molecules in the cracker stage have been generated from white phosphorus. It accordingly becomes possible to control the P_4 production by means of the condenser temperature which in turn is controlled by water or air temperature, if a coolant fluid is circulated around the condenser. Thus, P_2 beam equivalent pressure can be set by a simple thermostat adjustment of the condenser coolant temperature. Unusually low P_2 flux levels, of the order of 10^{-7} mbar, may be maintained by keeping the condenser cell walls at about 0° C.

As emphasized herein, provision of a lower temperature zone between the elevated temperature evaporation and cracking stages of the cell broadens the choices of valves that may be used to control the effusion cell's P_2 flux output because the flux control valve can be maintained in a relatively low temperature environment. In contrast, a known valve design for operating in the region of 300° – 400° C. uses a refractory needle valve having a long shaft to transmit linear valve motion. This valve does not close well and is subject to reproducibility and hysteresis problems. Additional major drawbacks are that such known valves cannot pulse, nor can they seal against atmosphere to enable reloading.

Benefits provided by the invention

In summary, preferred embodiments of the present invention provide many advantages that are important in molecular beam epitaxial fabrication of semiconductor structures. Because a leak-tight separable seal is provided for attaching the cell to a MBE chamber and because the cell has a very short cycle time being the time required to reach temperature and pressure equilibrium, refilling of the phosphorus charge

is easy and can be rapidly accomplished.

In turn, easy refillability facilitates the provision of relatively small capacity units such as 40 cc. 100 cc in addition to more conventional, higher capacity cells such as 200 cc. Though an apparently rather small capacity, such units are adequate for many MBE processes, especially atomic layer growth processes, because very little raw material is consumed. Preferred embodiments can thus have a very low thermal time constant which provides the great advantage, when equipped with suitable valving, as disclosed herein, of enabling them to be operated in pulse mode. Pulsing is of value in MBE fabrication processes and provides new techniques for delimiting semiconductor structures.

By means of the invention, a high-content P_2 beam can be output and, under optimal conditions, P_4 can be substantially eliminated from the output beam. Because low temperature valve systems can be employed the beam is highly controllable mechanically, providing a stable, reproducible beam which can be pulsed and accurately calibrated. Additionally, the inventive phosphorous effusion cell disclosed herein offers a unique capability of producing a sharply defined P_2 flux in either constant or pulse mode without pressure overshoot on opening.

As described above, the problem of an initial pressure burst is also substantially eliminated by the inventive phosphorus condensation means which control the diverse phosphorus vapor phases, leading to good and reproducible phosphorus beam performance.

Also, eliminating risks of discharging white phosphorus reduces potential dangers from phosphorus effusion cell operation. The inventive embodiments are effective in converting white phosphorus into red before discharging the phosphorus beam.

The use of pneumatic control means and mechanically operable vernier control, with vacuum-tight valving, to control the output phosphorus flux permits the beam to be shut off, or turned on and quantitatively controlled accurately, remotely and easily. Such valving systems avoid problems of valve jittering or wobble and excessive hysteresis, to which the high temperature valves necessitated by prior systems are subject.

The unique white-phosphorus condensation zone or stage provided by the present invention supplies a reservoir of volatile phosphorus from which a more controllable vapor stream than heretofore obtainable is generated. In contrast, known systems require relatively high temperatures to generate P_4 flux from red phosphorus and have no means to control phosphorus phase changes. Consequently, the output flux is unstable with time and is not well suited to use in MBE. It is difficult to use in fabricating quaternary layers such as GaInAsP.

Molecular Beam Epitaxy Growth Processes and Products

A problem in fabricating optoelectronic devices by thin-layer, epitaxial growth on silicon substrates employing mixed Group V elements, by means of molecular beam epitaxy, is that considerable difficulty may be encountered, in known methods, in controlling the necessary phosphorus stream. For adequate fabricated device product quality, a desirable phosphorus beam characteristic is a known and steady beam equivalent pressure of P_2 molecules, without any initial burst pressure. Also, desirable are pulsed beam modes with controllable sharp interfaces and sub-second cycle times, or pulse frequencies.

As described extensively herein, the present invention solves these problems by providing a phosphorus effusion cell having all these desired characteristics. By coupling the inventive cell to the cell port of an MBE chamber, new MBE processes become possible, resulting in high quality layered devices which lack the problems of devices produced by known methods and apparatus, and in particular, problems related to excess phosphorus surface growth avoided.

For example, in growing n-type InP good optical quality can be obtained using output from a phosphorus effusion cell according to the invention, with $n \approx 5 \times 10^{16} \text{ cc}^{-3} \text{ P}_2$, and a temperature in the range of about 270° to 350° C. in an otherwise standard MBE system. By controlling the substrate temperature range to avoid phosphorus desorption from the InP surface, efficient incorporation of phosphorus on an In atomic layer, can be achieved, using a low beam equivalent pressure of P_2 , obtained from the inventive cell with a pulse amplitude less than about 10^{-5} mbar and a pulse duration typically less than a second. On/off fluxes of the P_2 beam in excess of 10^3 are obtainable. Such structures have application in fabrication of devices emitting in the region of 1.5 μm .

Similar phosphorus beam characteristics are valuable in new or modified MBE systems for growing strained layer short-period superlattices employing GaAs/GaP growth on GaAs substrates. Such new MBE methods provide a more easily controlled growth system yielding alternative, strained layer short-period superlattices of good quality. The materials can be used as confining material for gallium indium arsenide multiquantum well heterostructures. Other methods and devices that may be produced by new MBE methods exploiting the stable, well-controlled phosphorus beam produced by the novel phosphorus effusion cell and beam propagation methods described herein, will be apparent to those skilled in the art. The present invention extends to such methods and devices.

Phosphorus equivalents

While the invention has been described as a method and apparatus that are particularly adapted to solve problems of a phosphorus diffusion cell and which solve the special problems that arise in subliming or evaporating and cracking red phosphorus, those skilled in the art will appreciate that other materials might be used with adjustments to take account of the respective physical constants of such other materials. In particular, the unique condensation stage provided between sublimation and cracking provides a means of controlling a volatile unstable phase of a starting material displaying multiple phases or allotropes.

While an illustrative embodiment of the invention has been described above, it is, of course, understood that various modifications will be apparent to those of ordinary skill in the art. Such modifications are within the spirit and scope of the invention, which is limited and defined only by the appended claims.

I claim:

1. A method of generating a phosphorous beam for molecular beam epitaxy comprising:

- a) evaporating red phosphorous under vacuum and at an effective sublimation temperature;
- b) condensing the vapor produced in a) at a temperature below said sublimation temperature in order to form accumulation of white phosphorous; and
- c) valving vapor from said white phosphorous to a high-temperature phosphorous cracker to produce a phosphorus beam rich in diatomic phosphorus.

2. A method according to claim 1 wherein said sublimation temperature and said condensation temperature are separately controlled with said condensation temperature being at least 100° C. lower than said sublimation temperature.

3. A molecular beam epitaxial growth method of fabricating layered semiconductor structures employing phosphorus deposition comprising:

- a) supplying a valved pressure-stabilized phosphorus beam from a three-stage phosphorus effusion cell to an evacuated molecular beam epitaxy chamber, said three stages comprising:
 - i) elevated temperature evaporation of red phosphorus;
 - ii) condensation of white phosphorus at a temperature below said elevated temperature; and
 - iii) cracking said white phosphorus; and
- b) conducting a phosphorus-deposition step from said phosphorus beam on to a substrate in said molecular beam epitaxy chamber.

4. A method according to claim 3 wherein said phosphorus beam consists essentially of P_2 phosphorus.

5. A method for generating a phosphorus vapor beam rich in diatomic phosphorus suitable for use in epitaxial growth comprising the steps of:

- a) evaporating solid red phosphorus by heating said phosphorus under vacuum to a sublimation temperature sufficient to produce a phosphorus vapor stream;
- b) passing said vapor stream through a colder zone having a temperature lower than said sublimation temperature; and
- c) cracking said vapor stream at high temperature after exposure to said condensation surface to produce said phosphorus vapor beam rich in diatomic phosphorus; and
- d) valving said phosphorus vapor beam to output with a desired output pressure.

6. A method according to claim 5 wherein white phosphorus is deposited on a condensation surface in said colder zone and said deposited white phosphorus buffers said vapor stream to control phosphorus vapor pressure.

7. A method according to claim 5 wherein said phosphorus vapor beam output pressure is controlled by thermostating said colder zone at a temperature below about 100° C.

8. A method according to claim 5 wherein said colder zone is thermostatted at a temperature below 100° C., to maintain a closed-valve phosphorus vapor pressure in a range of about 10^{-2} to about 10^{-0} mbar.

9. A method according to claim 8 conducted to provide an open-valve phosphorus vapor beam output pressure of the order of 10^{-5} to 10^{-6} mbar.

10. A method according to claim 7 conducted to provide low P_2 flux output levels of the order of 10^{-7} mbar. by thermostating said colder zone at a temperature of about 0° C.

11. A method according to claim 5 conducted in a phosphorus effusion cell wherein white phosphorus is deposited on a condensation surface thermostatted at a temperature below 100° C. in said colder zone in said cell and said deposited white phosphorus buffers said vapor stream to control phosphorus vapor pressure to maintain an internal pressure in a range of about 10^{-2} to about 10^{-0} mbar and an open-valve phosphorus vapor beam output pressure is of the order of 10^{-5} – 10^{-6} mbar.

12. A method according to claim 6 wherein said phosphorus vapor stream comprises tetratomic phosphorus molecules and wherein said cracking comprises cracking tetra-

13

atomic phosphorus molecules to yield diatomic phosphorus molecules.

13. A method according to claim 5 comprising separately thermostating each of said evaporating, condensing, and effusing steps.

14. A method according to claim 5 wherein said sublimation temperature is approximately 300° C.

15. A method according to claim 5 wherein said evaporation of red phosphorus is effected under vacuum in a thermally insulated sublimation zone.

16. A method according to claim 5 comprising maintaining said temperature of said colder zone at between 5° and 40° C.

17. A method according to claim 16 wherein said colder zone temperature is maintained by circulating thermally regulated fluid around said colder zone.

18. A method according to claim 5 wherein said valving is effected by a valve maintained at a temperature not above 100° C.

19. A method according to claim 5 wherein said valving operates cyclically to provide a pulsed flux phosphorus beam output.

20. A method according to claim 5 wherein said phosphorus vapor beam is drawn upwardly through a cracker feed column to a flux control valve, then to a cracker and then output to an MBE chamber.

21. A method according to claim 5 wherein said output phosphorus beam consists essentially of diatomic phosphorus.

14

22. A method according to claim 5 wherein said cracking step comprises thermal dissociation of tetratomic phosphorus vapor to diatomic phosphorus vapor effected by passing said phosphorus vapor beam over an electrical resistance formed of a refractory metal.

23. A method according to claim 5 comprising pulsing said output phosphorus vapor beam with a pulse amplitude less than about 10^{-5} mbar and a pulse duration less than a second.

24. A molecular beam epitaxial growth method according to claim 3 for fabricating optical quality n-type InP at a temperature in the range of about 270° to 350° C. with a substrate temperature controlled to avoid phosphorus desorption from the InP surface, using a low beam equivalent pressure of P_2 , obtained from said phosphorus effusion cell.

25. A molecular beam epitaxial growth method according to claim 24 wherein said phosphorus effusion cell outputs a pulsed molecular phosphorus beam with a pulse amplitude less than about 10^{-5} mbar and a pulse frequency of from greater than one per second to in excess of 10^3 per second.

26. A method according to claim 1 wherein said condensation temperature is from about 200° to about 340° C. lower than said sublimation temperature.

* * * * *