A process for producing boron nitride nanotubes and/or boron-carbon-nitrogen nanotubes of the general formula $B_xC_yN_z$. The process utilizes a combination of laser light and nitrogen gas flow to support a boron ball target during heating of the boron ball target and production of a boron vapor plume which reacts with nitrogen or nitrogen and carbon to produce boron nitride nanotubes and/or boron-carbon-nitrogen nanotubes of the general formula $B_xC_yN_z$. 

19 Claims, 2 Drawing Sheets
Boron ball force balance

Evaporation

Gravity

Light from below

Light from slightly above

$N_2$ buoyancy, convection and circulation flow

FIG. 1
The invention relates generally to the production of nanotubes and in particular to the formation of long-strand boron nitride and boron carbon and nitrogen (B\(_x\)C\(_y\)N\(_z\)) nanotubes.

**BACKGROUND**

Since the announcement of the successful synthesis of high-aspect-ratio-few-walled boron nitride nanotubes (FW-BNNTs) in 1995, little progress had been made until very recently in the scale-up of their synthesis. In spite of the theoretical capabilities of FW-BNNTs to provide high strength-to-weight, high temperature resistance, piezo actuation, and radiation shielding (via the boron content), the aerospace industry has had to rely on micron-sized graphite or boron materials for structural applications. Further, despite their very desirable properties, neither FW-BNNTs nor single wall carbon nanotubes are used widely in aerospace manufacturing and similar industries, as industries are generally unwilling to pay the premium price for these high performance materials.

Prior to recent inventions of the present inventors, high-aspect ratio FW-BNNTs had only been produced in small amounts (from individual tubes to milligrams) by arc-discharge or laser heating methods. Further, these small amounts of FW-BNNTs were in the form of films not strands or fibers several centimeters in length. A separate class of boron nitride nanotubes know in the prior has been produced by chemical vapor deposition of nitrogen compounds (e.g. ammonia) over ball-milled precursors, but these tubes are of large diameter, and do not exhibit the continuous crystalline sp\(^2\)-type bonding structure which has drawn most theoretical interest.

The Inventors’ recent work in the field of boron nitride nanotubes is described in three U.S. Patent Applications and their entireties.

**SUMMARY OF INVENTION**

The invention provides process for producing boron nitride nanotubes. The process comprising the steps of (a) providing a boron ball target, a first laser beam having an adjustable power level and a gas flow comprising nitrogen; (b) positioning the boron ball target in a reaction position above the first laser beam and in the gas flow, the reaction position comprising a vertical reaction position and a horizontal reaction position; (c) adjusting the power level of the first laser beam to provide sufficient force from the first laser beam to the boron ball target to balance the force of gravity and the force of a light from above the boron ball target acting downward on the boron ball target and maintain the boron ball target in the vertical reaction position; (d) heating the boron ball target with the first laser beam wherein the heating evaporates a portion of the boron ball target and forms a boron vapor plume; (e) adjusting the power level of the first laser beam to maintain the heated boron ball target balanced in the vertical reaction position as the boron vapor plume moves upward from the boron ball target; (f) providing at least one second laser beam positioned above and to the side of the boron ball target, wherein the at least one second laser beam exerts a second laser beam force to maintain the heated boron ball target balanced in the horizontal reaction position; and (g) forming a plurality of boron nitride nanotubes as the upward moving boron vapor plume contacts the nitrogen in the gas flow.

The invention also provides a process for producing boron-carbon-nitrogen nanotubes of the general formula B\(_x\)C\(_y\)N\(_z\). The process comprising the steps of (a) providing a boron ball target, a first laser beam having an adjustable power level, a gas flow comprising nitrogen, and a carbon source; (b) positioning the boron ball target in a reaction position above the first laser beam and in the gas flow, the reaction position comprising a vertical reaction position and a horizontal reaction position; (c) adjusting the power level of the first laser beam to provide sufficient force from the first laser beam to the boron ball target to balance the force of gravity and the force of a light from above the boron ball target acting downward on the boron ball target and maintain the boron ball target in the vertical reaction position; (d) heating the boron ball target with the first laser beam wherein the heating evaporates a portion of the boron ball target and forms a boron vapor plume and vaporizes the carbon source to form carbon atoms; (e) adjusting the power level of the first laser beam to maintain the heated boron ball target balanced in the vertical reaction position as the boron vapor plume moves upward from the boron ball target; (f) providing at least one second laser beam...
positioned above and to the side of the boron ball target, wherein the at least one second laser beam exerts a second laser beam force to maintain the heated boron ball target balanced in the horizontal reaction position; and (g) forming a plurality of boron-carbon-nitrogen nanotubes of the general formula $B_xC_yN_z$ as the upward moving boron vapor plume contacts the nitrogen in the gas flow and carbon atoms.

**DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a schematic representation of the forces acting on the boron ball target in the combined laser-gas flow levitation process.

FIG. 2 is a schematic representation of the formation of boron containing nanotubes in the combined laser-gas flow levitation process.

**DETAILED DESCRIPTION OF THE INVENTION**

The process described herein utilizes a combination of laser light and nitrogen gas flow to support a boron ball target during heating of the boron ball target and production of a boron vapor plume.

Boron nitride nanotubes are formed when hot boron vapor (about 4000°C) from a boron ball target combines with atomic nitrogen near the correct 1:1 stoichiometric ratio. If a source of carbon is present with the hot boron and atomic nitrogen, boron-carbon-nitrogen nanotubes of the general formula $B_xC_yN_z$ are formed. The carbon may be supplied as a carbon rich gas such as methane or acetylene that is mixed with the nitrogen gas that is supplied to the reaction system or alternatively may be solid carbon such as carbon fibers, carbon powder or particle included in a solid boron target which is vaporized as the boron is vaporized. Lasers including, but not limited to a free electron laser(s), a fiber laser(s), a solid state laser(s), or a gas laser(s) including standard commercial CO₂ or laser(s) may supply the energy for the process of the invention, for example. The laser(s) should be sufficiently powerful to produce a laser beam(s) that maintain the hot boron ball target in the reaction position and heat the boron ball target to produce boron vapor. The light from the laser beam both directly heats the boron and indirectly heats nitrogen gas flowing past the boron ball to dissociate the nitrogen gas into atomic nitrogen.

Referring to FIG. 1 which is a schematic representation of the forces acting on the boron ball target in the combined laser-gas flow levitation process. As the diagram shows the boron ball target experiences upward forces from nitrogen gas buoyancy, convection, and circulation flow, and the laser light from below; and downward forces due to evaporation of boron vapor from the boron ball target, gravity, and light from above and slightly to the side of the boron ball target.

FIG. 2 is a schematic representation of the formation of boron containing nanotubes in the combined laser-gas flow levitation process. As the boron ball target 3 is heated from ambient temperature to about 4000°C, the evaporation begins and continues as the boron ball target 3 evaporates, the power of the first laser beam 10 below and the nitrogen gas flow 2 are adjusted to stabilize the position of the boron ball target. In one embodiment evaporation of the boron ball target 3 continues until the boron ball target 3 is entirely evaporated.

As shown in FIG. 2, one laser is used to produce the first laser beam that impinges on the bottom of the boron ball target; however, as one skilled in the art will appreciate, in some embodiments the use of a plurality of lasers to produce the first laser beam that impinges on the bottom of the boron ball target may be desirable. Similarly, the at least one second laser beam that impinges onto the upper portion of the boron ball target from above and slightly to the side may be produced by a plurality of lasers or alternatively the beam of a single laser may be split into a plurality of beams and directed through optics to produce light that impinges at more than one position on the upper portion of the boron ball target and/or boron vapor plume. Alternatively, laser beam from a single laser may be split to provide multiple laser beams that can be used for one or more of the first laser beam and the at least one second laser beam. If beam splitting is employed it is preferable that each of the resulting beams is independently controllable.

The boron ball target should be maintained in a nearly constant position (i.e. a reaction position) throughout the process. The reaction position comprises a vertical reaction position and a horizontal reaction position. The reaction position is maintained by balancing the four main forces on the boron ball target. The four main forces in effect on the ball are gravity, light pressure, gas flow including buoyancy, and evaporation.

**Gravity.**

The boron ball target is forced down due to the force of gravity. As the boron ball evaporates (vaporizes to form the boron vapor plume), the force of gravity is lessened. The force of gravity is: $F_g = mg$ where $m$ is the mass of the ball and $g$ is the acceleration due to gravity (i.e. 9.8 m/s²).

**Light Pressure.**

Light carries momentum (i.e., $p = E/c$, or in terms of power of the light, $P$ force is $F_l = P/E$ where $F_l$ is the force of light, and $c$ is the speed of light). When light is absorbed, the impacted object absorbs the momentum. If light is perfectly
reflected, the momentum is twice as much. The net force of the light along the vertical is also dependent on the direction of the light. For the geometry shown in FIG. 2, the light coming from below has most of its force directed upward to the boron ball target and light coming from above and slightly to the side of the boron ball target has most of its force substantially directed towards the sides of the boron ball target and/or boron vapor plume such that the net sideways or horizontal force on the boron ball target is balanced so that the net sideways or horizontal force on the boron ball target is zero. As the boron ball target is very hot during the process there is a small downward net force from the radiated light coming from the top of the boron ball target being slightly more radiated than the radiated light from the bottom of the boron ball target.

Gas Flow.

There are two sources of gas flow. These sources are: (1) a fan or pump system that moves the nitrogen gas or combinations of nitrogen gas and carbon bearing gas in the desired direction and (2) the hot boron ball target and boron vapor plume heating the surrounding gas flow thereby creating a convective flow. The sum of the two sources is maintained such that gas going around the boron ball target remains non-turbulent, i.e. laminar flow conditions. This speed is dependent on the size of the ball, the gas temperature near the ball and the gas pressure. The range of applicable gas pressure is from about atmospheric of about 15 psi to around 20,000 psi, the pressure where the boron ball would become buoyant and simply float up and away with pressures of about 100 to about 2,000 psi preferred in some embodiments. The vertical flow force, \( F_v \), from the gas flow is dependent on the diameter of the boron ball, buoyancy effects, the speed of the gas flow, the gas pressure and the temperature.

Evaporation.

When the ball approaches its vaporization temperature, i.e. about 4000° C., it begins to produce boron vapor (i.e. a boron vapor plume). The cooler part of the boron ball target will be near the bottom of the boron ball target due to the additional heat being provided by the laser(s) producing light from above and slightly to the side and the tendency of the hotter material which is lighter to rise to the top. The preferential release of boron as boron vapor on the top of the boron ball target will create a net evaporative force, \( F_e \), downwards on the ball though there will be some upwards evaporative force from boron evaporating on the bottom side of the ball.

The process for producing boron nitride nanotubes and/or boron-carbon-nitrogen nanotubes of the general formula \( B_xC_yN_z \) comprises the steps of:

1. A room temperature boron ball target is placed into a reaction position. Suitable methods for placing the boron ball target into position include, but are not limited to, using a boron target ball that has slight whiskers attached that are used to mechanically place and hold the ball in position until heating is initiated, or alternatively propelling the boron ball target upward such that the top of its near parabolic arc (slightly modified by drag) is at the desired position.

2. Once the boron ball target is in position, a laser is activated to produce a laser beam of a sufficient force to add the additional force (in addition to buoyancy and the gas flow forces) needed to balance the downward force due to gravity and light from above and to side of the boron ball target on the boron ball target.

3. The boron ball target heats and as it heats it acquires additional upwards force due to convection heating of the gas flow. There are several sources of feedback to stabilize the position of the boron ball target in the reaction position. First, the first laser beam is focused at a point below the boron ball target such that some of the light near the periphery of the boron ball target impinges at an angle such that the vertical force on the boron ball target increases as the boron ball target moves downwards closer to the focal point. Secondly, feedback from the location of the boron ball target is monitored and the power of the first laser beam and the rate of flow of the gas are adjusted based on this feedback to keep the forces on the ball vertically balanced. Thirdly, the horizontal position of the boron ball target is also monitored and the strength of the at least one second laser beam’s horizontal components of force is adjusted to keep the ball directly above the focal point of the first laser beam coming from below. The horizontal forces are due to a combination of the force of the at least one second laser beam and the differential evaporation rates in the horizontal directions. Any combination or all of the effects may be employed to provide feedback for maintaining the boron ball target in a substantially stable reaction position.

4. When the boron ball target reaches the vaporization temperature of boron, the power levels of the laser(s) are adjusted in real-time to stabilize both the vaporization rate and the position of the boron ball target.

5. As the boron ball target continues to vaporize the laser(s) are further adjusted in real-time to stabilize both the vaporization and position of the boron ball target by balancing the forces of gravity, impinging light, gas flow and evaporation acting on the boron ball target (i.e. the sum of the forces gravity, impinging light, gas flow and evaporation acting on the boron ball target should be about zero.)

6. The vaporized boron formed rises upward from the boron ball target as a plume of boron vapor and contacts the nitrogen gas flow creating a nanotube formation interface in which nanotubes are formed. The nanotubes thus formed are carried upward by the boron vapor plume and/or nitrogen gas flow and are collected at the terminus of the boron vapor plume.

In a preferred embodiment the steps of the process described above are performed sequentially in the order set forth above. The process can continue until the boron ball target becomes so small that it is carried away in the gas flow. The process may be repeated by obtaining a new boron ball target.

The process for the production of boron-carbon-nitrogen and nanotubes of the general formula \( B_xC_yN_z \) comprises essentially the same steps as for the production of few-walled boron nitride nanotubes. The specific compositional empirical formula of the \( B_xC_yN_z \) nanotubes is determined by the relative amounts of boron, carbon and nitrogen used. For boron nitride nanotubes a boron-containing target of compressed boron powder, compressed boron nitride powder, and mixtures thereof, for example is suitable and no carbon is used in either the target or the gas flow. For nanotubes of the general formula \( B_xC_yN_z \) carbon is introduced into the reaction. The carbon may be a solid component of the target, a carbon rich gas, mixture of carbon rich gases or a combination thereof. When a carbon rich gas is used, the proportion used is readily controlled by regulating the fractional pressure of the carbon rich gas in the nitrogen carbon rich gas mixture. Solid forms of carbon suitable for inclusion in the boron ball target are carbon fibers, carbon powder (carbon black) and mixtures thereof. Suitable carbon rich gases include, but are not limited to, hydrocarbons such as methane, ethane, ethylene, acetylene, substituted acetylenes, propane, propene, aromatic hydrocarbons such as benzene, toluene, xylene, naphthene, and polyaromatic hydrocarbons, and combinations thereof.

Optionally, multiple types of carbon rich gases can be introduced simultaneously into the reaction or alternatively a
been shown and described herein. It will be obvious to those
readily amendable to continuous production of material.
process. Accordingly, unlike for carbon nanotubes, the Inven-
tions to keep the gas low rate constant and vary the laser
target can be rapidly changed, it is preferable in some embodi-
the laser beam impinging on the bottom of the boron ball
used with suitable flow. As the laser power and hence force of
indicates that pressures of about 100 to about 2,000 psi can be
needed for the gas buoyancy and flow and heating convection
the reflection term roughly cancels the angular effect.
the gas flow would be roughly equal to this at 5,000 psi so the
buoyancy component of
the force due to
the reflection term roughly cancels the angular effect.

Example 1

The following example is provided for illustrative pur-
poses. For an example using a 1.5 mm diameter boron ball
target, the downward force of gravity is about 3.5x10^-5 N. If
an 8 kW laser is used to produce the light that impinges on the
underside of the boron ball target the available upward force
of the light is about 2.5x10^-7 N assuming that the force due to
the reflection term roughly cancels the angular effect.
To balance the force in this example, the upward force
required for the gas buoyancy and flow and heating convection
by the gas flow would be roughly equal to this at 5,000 psi so the
pressure is kept below this level. For operational reasons
(including safety) relying more on flow rather than buoyancy
indicates that pressures of about 100 to about 2,000 psi can be
used with suitable flow. As the laser power and hence force of
the laser beam impinging on the bottom of the boron ball
target can be rapidly changed, it is preferable in some embodi-
ments to keep the gas low rate constant and vary the laser
power to stabilize or maintain the reaction position of the
boron ball target as boron evaporates from the boron ball
target.

What is at present considered the preferred embodiment and alternative embodiments of the present invention has
been shown and described herein. It will be obvious to those
skilled in the art that various changes and modifications may
be made therein without departing from the scope of the
invention as defined by the appended claims.

What is claimed is:
1. A process for producing boron-carbon-nitrogen nano-
tube fibers of the general formula B_xC_yN_z, the process comprising the steps;
a. providing a boron ball target, a first laser beam having an
adjustable power level, a nitrogen gas flow, and a carbon
source;
b. positioning said boron ball target in a reaction position
above said first laser beam and in said nitrogen gas flow,
to form a reaction position comprising a vertical reaction
position and a horizontal reaction position;
c. adjusting the power level of said first laser beam to
provide sufficient force from said first laser beam to
balance said boron ball target against the force of gravity
and maintain said boron ball target in said vertical reaction
position;
d. heating said boron ball target with said first laser beam to a
temperature wherein the heating vaporizes a portion of
said boron ball target and vaporizes said carbon source
to form a boron and carbon vapor plume and disassoci-
ates said nitrogen gas into atomic nitrogen;
e. adjusting the power level of said first laser beam to
maintain said heated boron ball target balanced in said
vertical reaction position as said boron and carbon vapor
plume moves upward and contacts said atomic nitrogen.
2. The process of claim 1, wherein said first laser beam is
focused though optics to give an optical focal point positioned
between said first laser beam and said boron ball target
thereby keeping said boron ball target in said vertical reaction
position as boron evaporates from said boron ball target.
3. The process of claim 1 wherein maintain said boron ball
target in said vertical reaction position includes monitoring
feedback from the location of said boron ball target and
adjusting the power of said first laser beam and the rate of said
nitrogen gas flow to keep the forces on the ball vertically
balanced.
4. The process of claim 1, wherein said carbon source is
selected from the group including carbon rich gas and solid
carbon.
5. The process of claim 4, wherein said carbon rich gas is
selected from the group including methane, ethane, ethylene,
acetylene, substituted acetylenes, propane, propene, benzene,
toluene, xylene, aniline, polyaromatic hydrocarbons, and
combinations thereof.
6. The process of claim 4, wherein said solid carbon is
selected from the group including carbon fibers, carbon pow-
der, graphite, and mixtures thereof.
7. The process of claim 1, wherein said carbon source is a
carbon rich gas and said process includes regulating the frac-
tional pressure of the carbon rich gas in the nitrogen to control
the proportion of carbon used.
8. The process of claim 1, wherein said first laser and said
second laser is selected from the group including free electron
laser, a fiber laser, a solid state laser, and gas laser.
9. The process of claim 1, wherein said boron and carbon vapor plume includes a terminus; and said boron-carbon-nitrogen nanotubes are collected at said terminus of said boron and carbon vapor plume.

10. The process of claim 1, wherein said temperature is at least 4000°C.

11. The process of claim 1, wherein said nitrogen gas flow around said boron ball target is maintained in a laminar flow condition.

12. The process of claim 1, wherein said nitrogen gas flow is maintained at a pressure of 15 psi to 20,000 psi.

13. The process of claim 1, wherein said nitrogen gas flow is maintained at a pressure of 100 psi to 2,000 psi.

14. The process of claim 1, wherein the boron ball target includes whiskers attached, said whiskers are used to mechanically place and hold the ball in position until heating is initiated.

15. The process of claim 1, wherein the boron ball target is positioned above the first laser beam by propelling the boron ball upward in a near parabolic arc of motion with a top wherein the top of the near parabolic arc of motion is at the reaction position.

16. The process of claim 1, wherein the heated boron ball target is acted upon by the forces of gravity, light, gas flow and evaporation and the forces are balanced such that the net force acting on the heated boron ball target is zero.

17. The process of claim 1, further comprising collecting the boron-carbon-nitrogen nanotubes of the general formula $B_xC_yN_z$.

18. The process of claim 1, wherein the specific compositional empirical formula of the $B_xC_yN_z$ nanotubes is determined by the relative amounts of boron, carbon and nitrogen used.

19. The process of claim 1, wherein said first laser beam and said second laser beam are provided by a single laser producing a single laser beam and wherein a first portion of said single laser beam forms said first laser beam and a second portion of said single laser beam forms said second laser beam.

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