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Vogt et al.

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(54) **SUBOXIDE MOLECULAR-BEAM EPITAXY AND RELATED STRUCTURES**

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See application file for complete search history.

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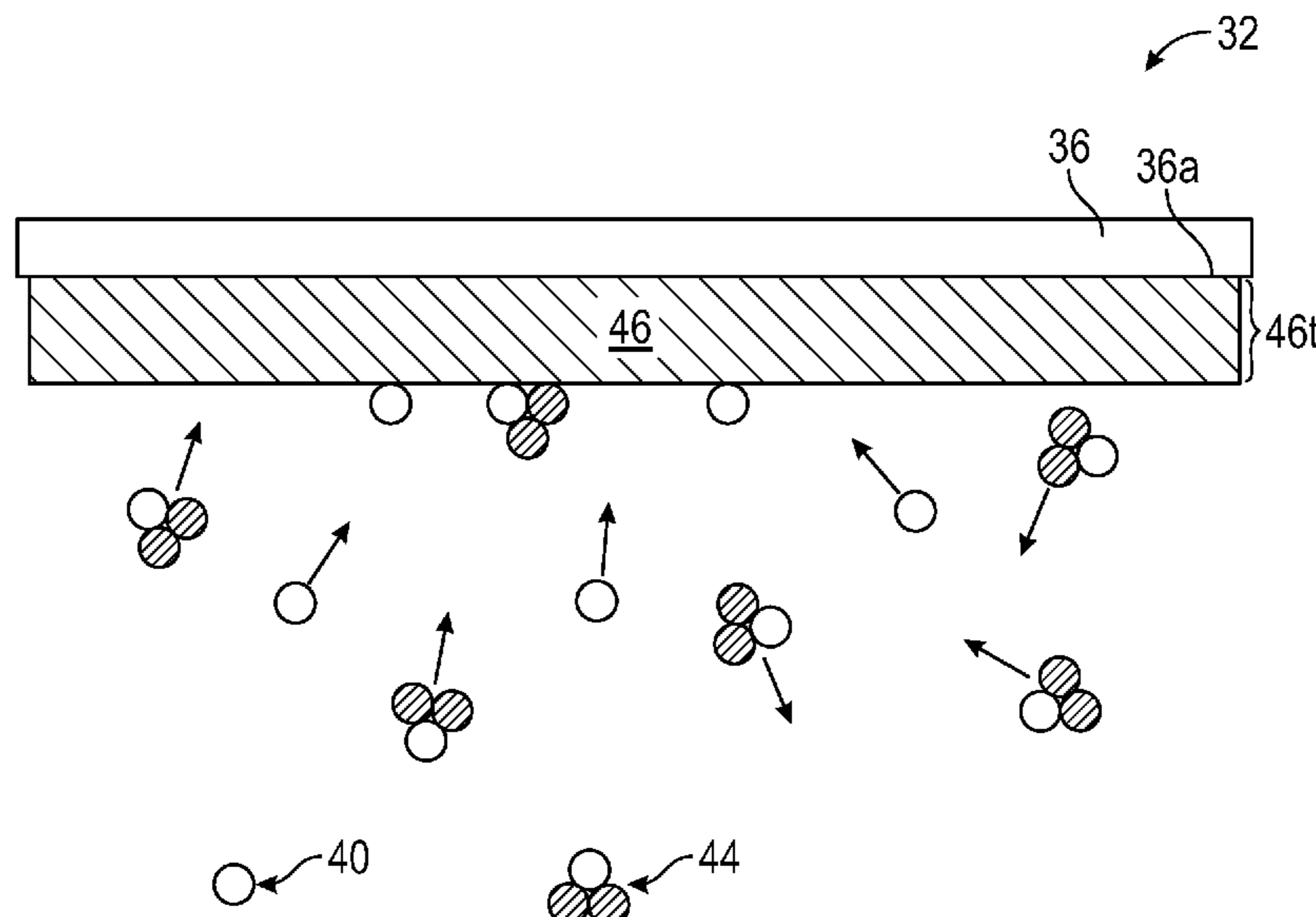
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(57) **ABSTRACT**

Molecular-beam epitaxy (MBE) and more particularly sub-oxide MBE (S-MBE) and related structures are disclosed. S-MBE is disclosed that includes the use of a molecular beam of a suboxide that may be subsequently oxidized in a single step reaction to form an oxide film. By way of example, for a gallium oxide (Ga_2O_3) film, a molecular beam including a suboxide of gallium (Ga_2O) may be provided. S-MBE may be performed in adsorption-controlled regimes where there is an excess of source material containing species in order to promote high growth rates for oxide films with improved crystallinity. Source mixtures for providing molecular beams of suboxides are disclosed that include mixtures of a particular element and an oxide of the element in ratios that promote such adsorption-controlled growth regimes. Related structures include oxide films having increased thickness with reduced crystal defects, including single polymorph films of gallium oxide.

20 Claims, 7 Drawing Sheets



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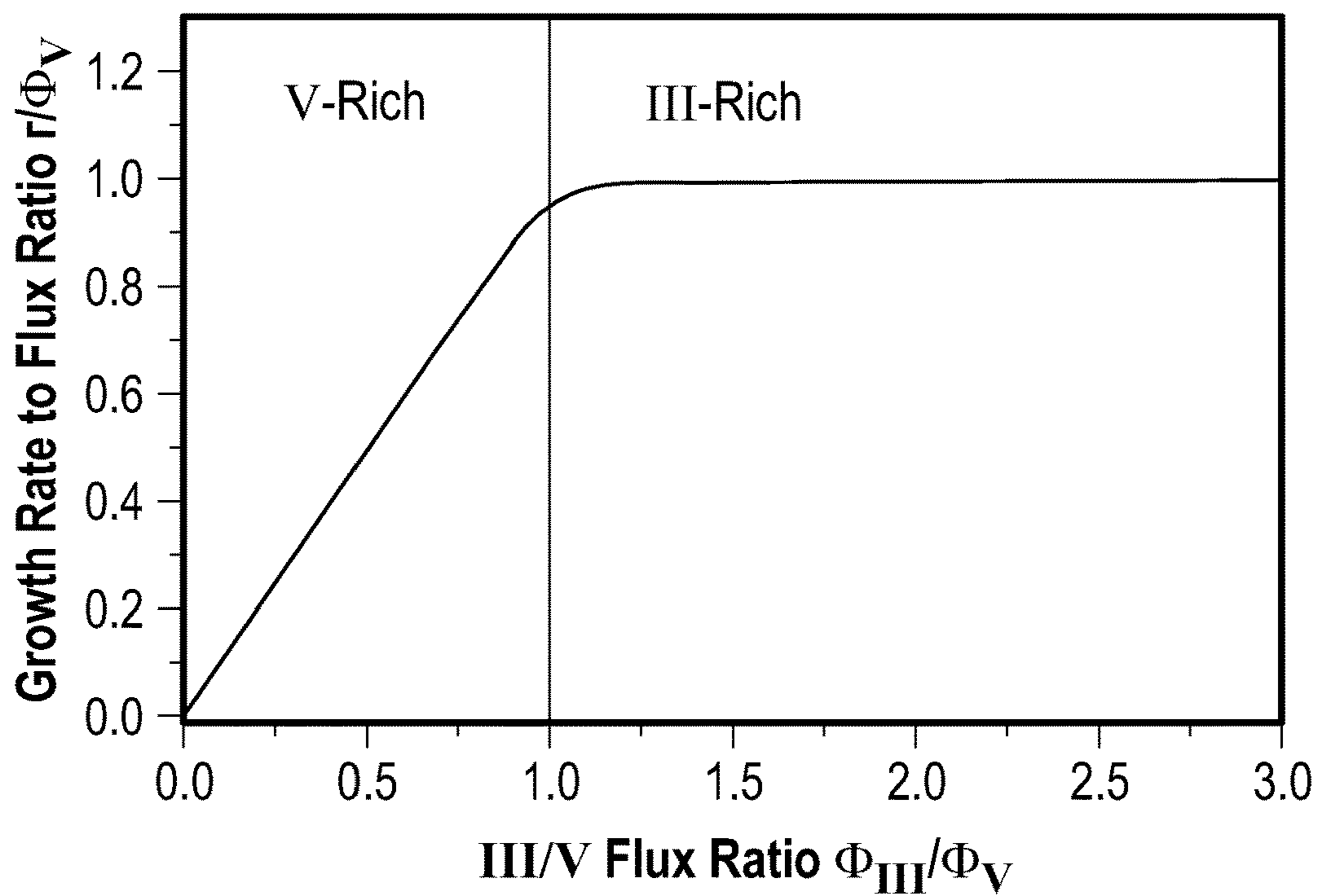


FIG. 1A

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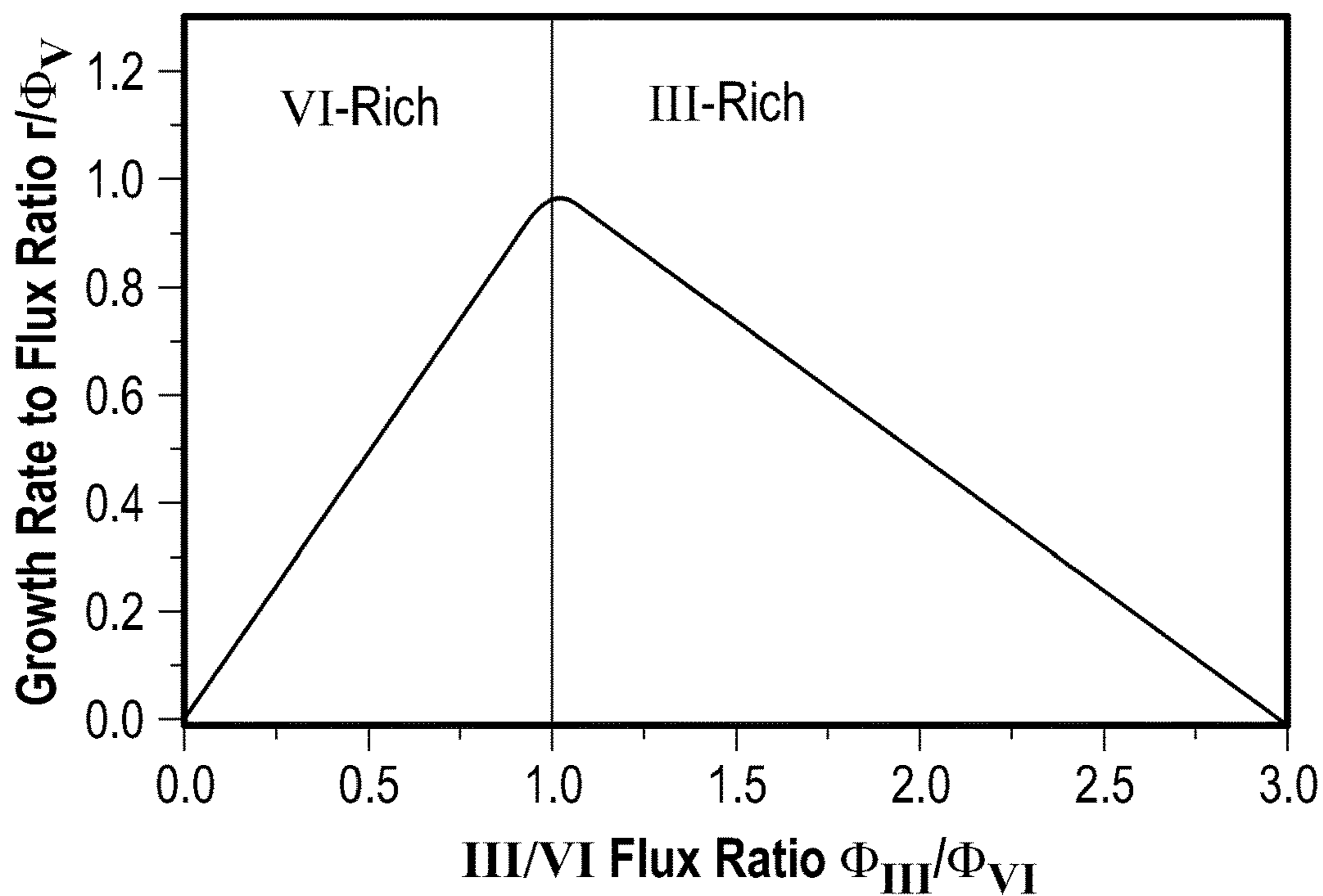


FIG. 1B

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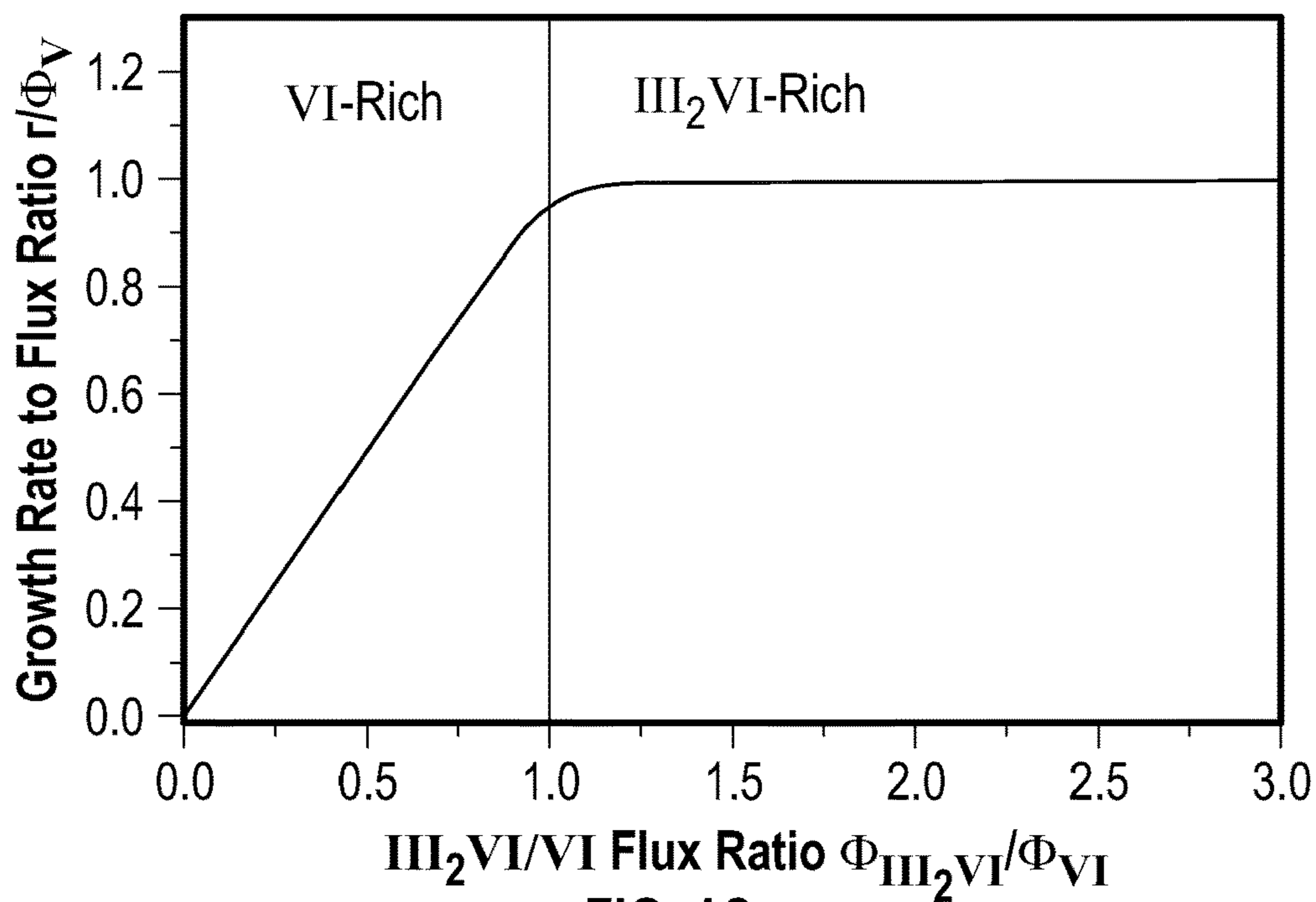


FIG. 1C

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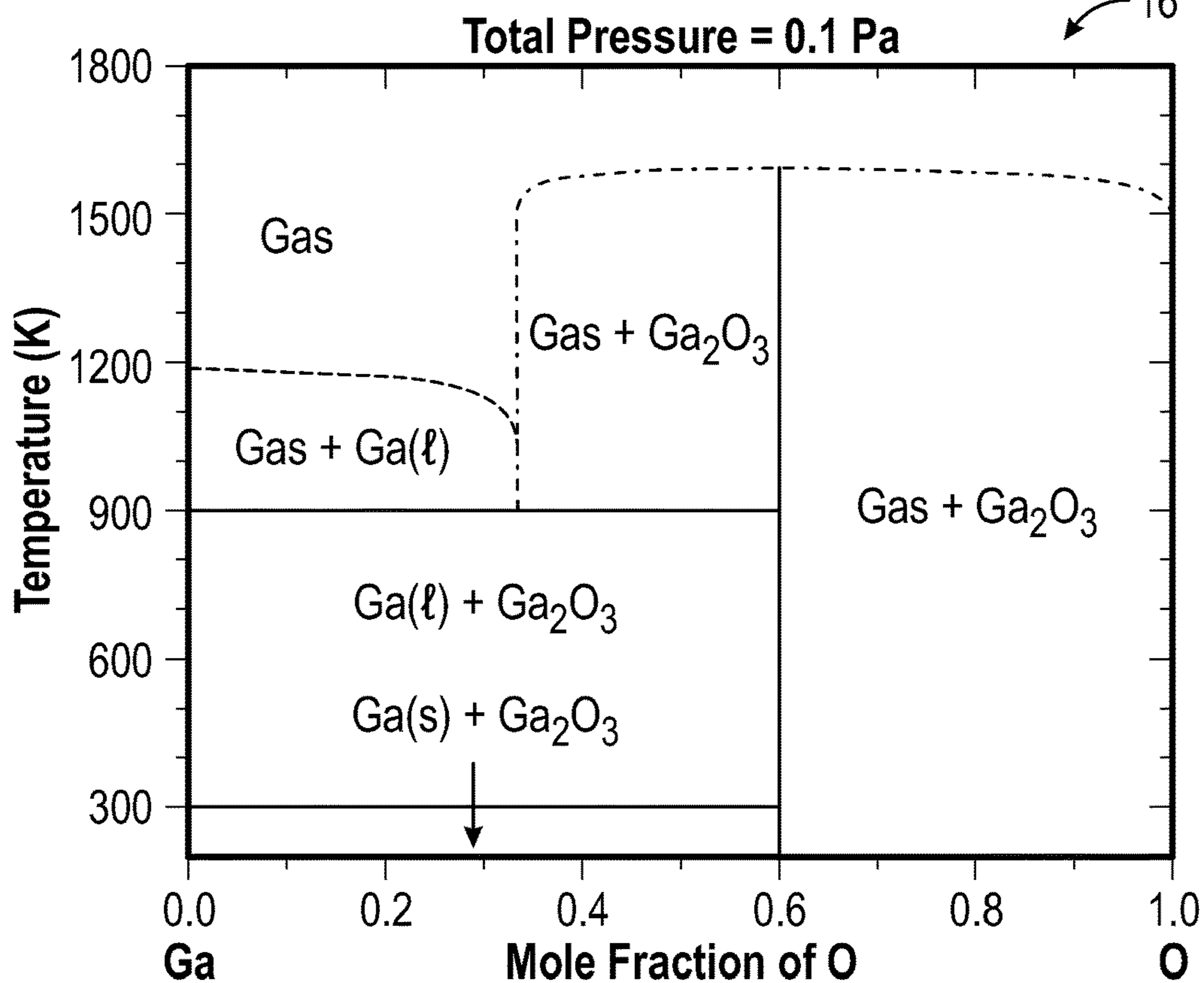


FIG. 2

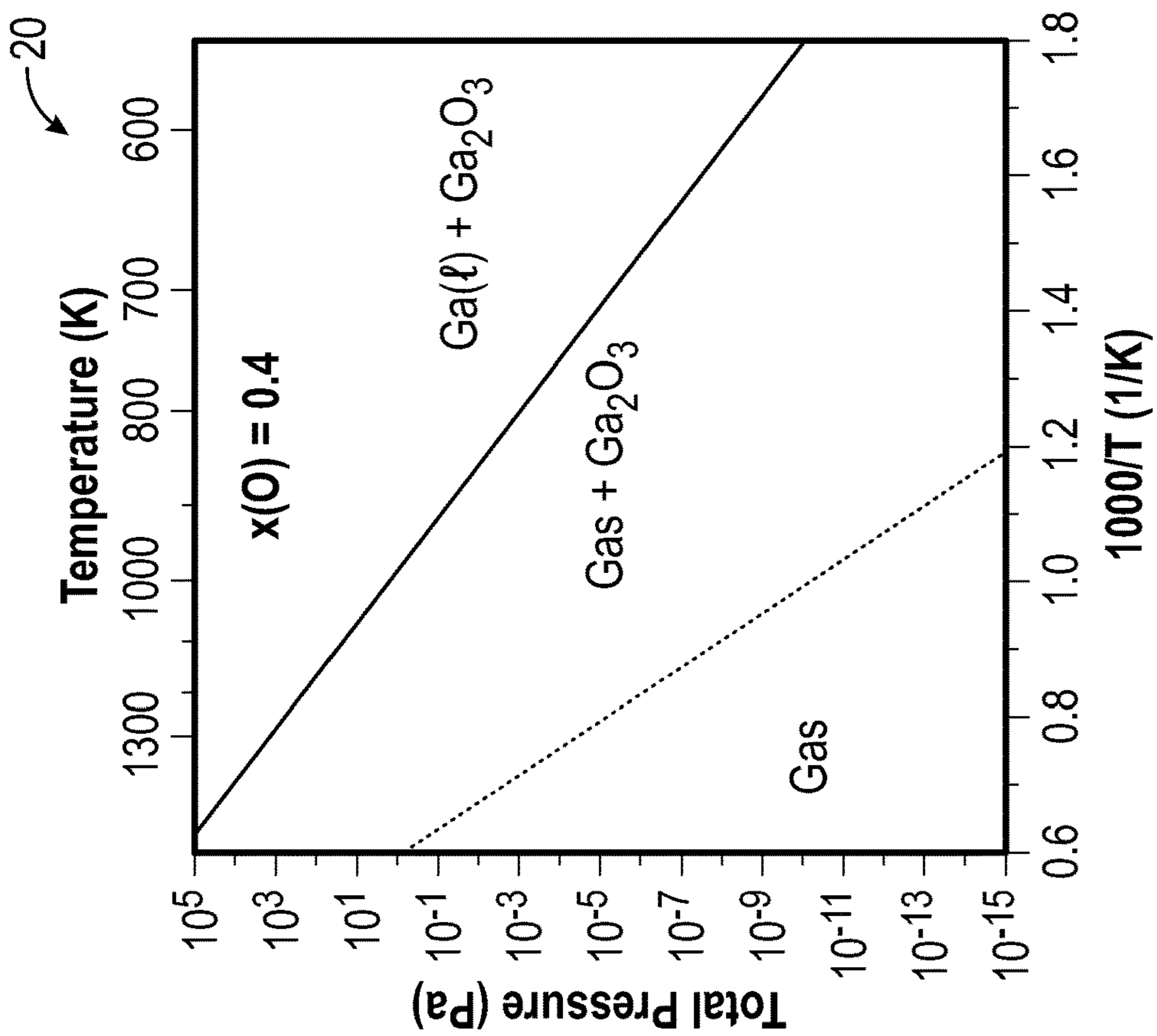


FIG. 3B

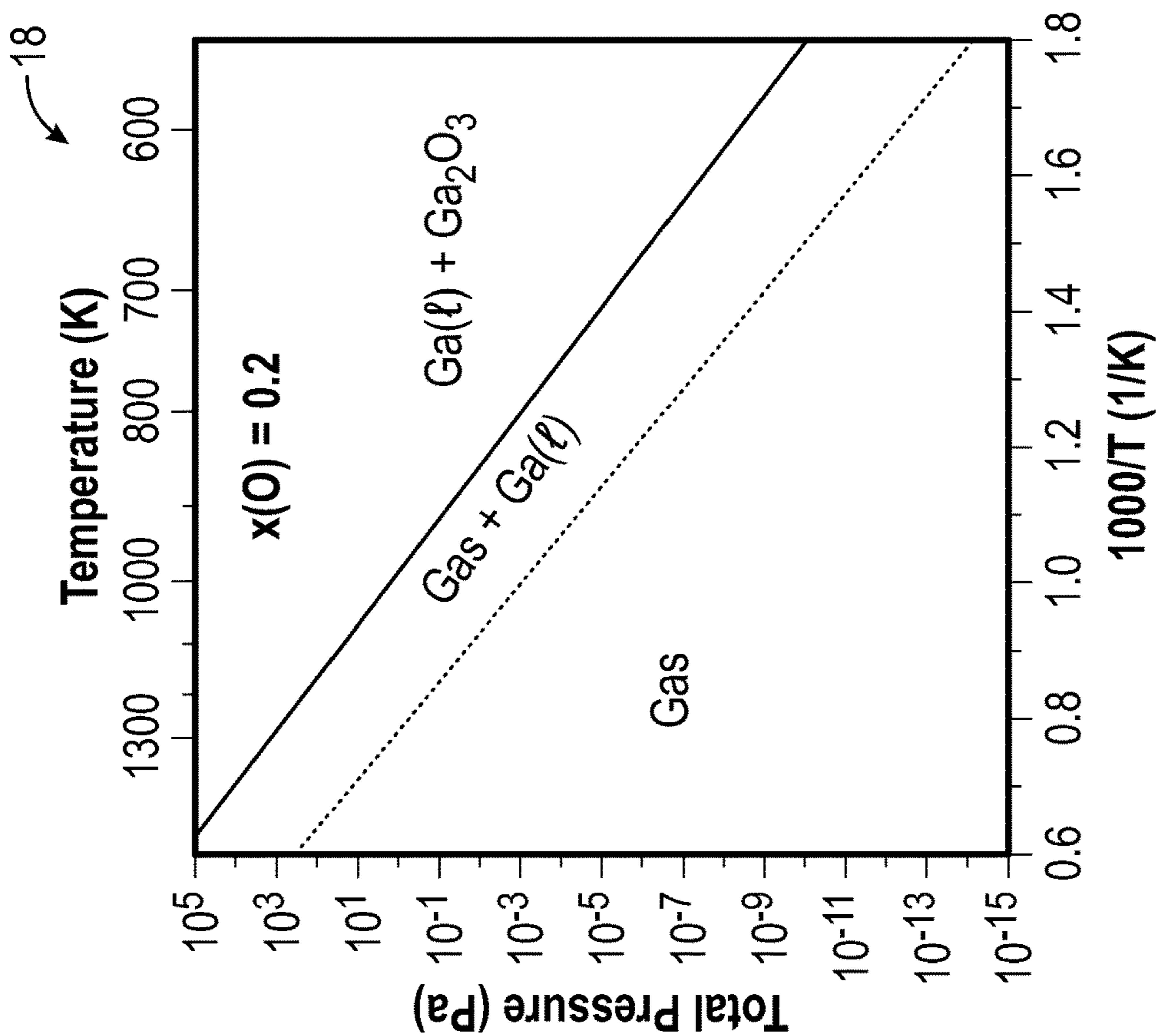


FIG. 3A

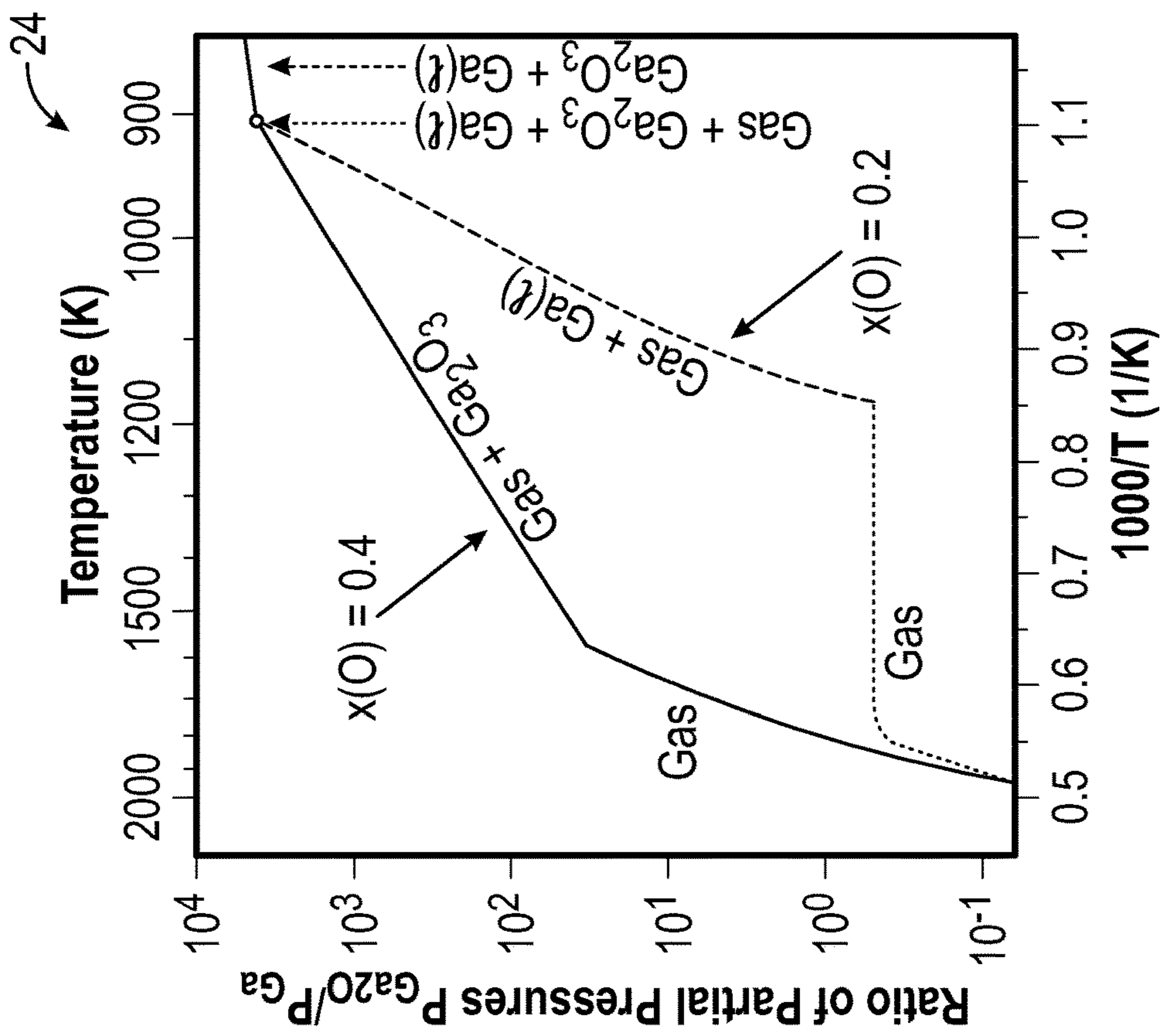


FIG. 4A

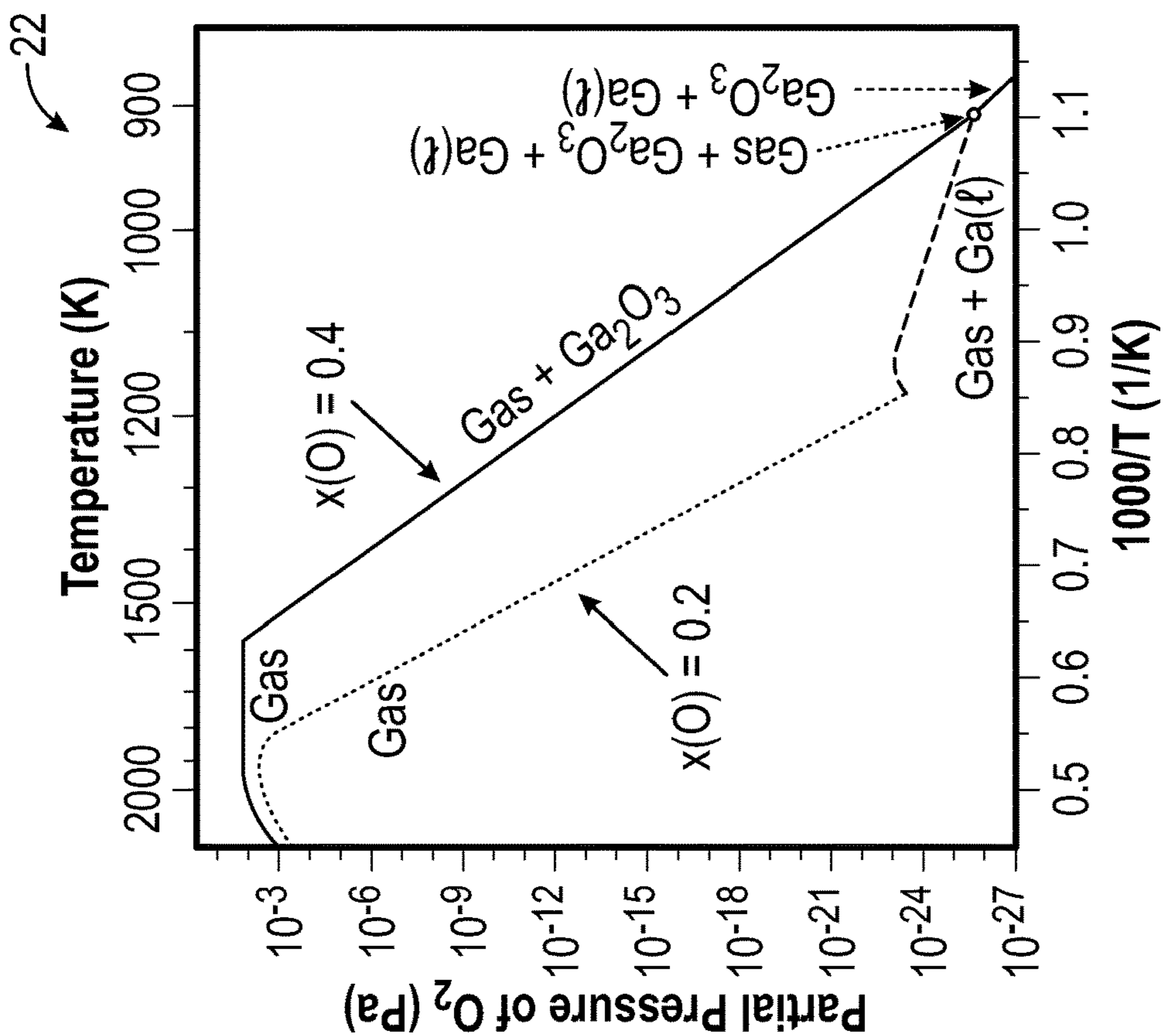


FIG. 4B

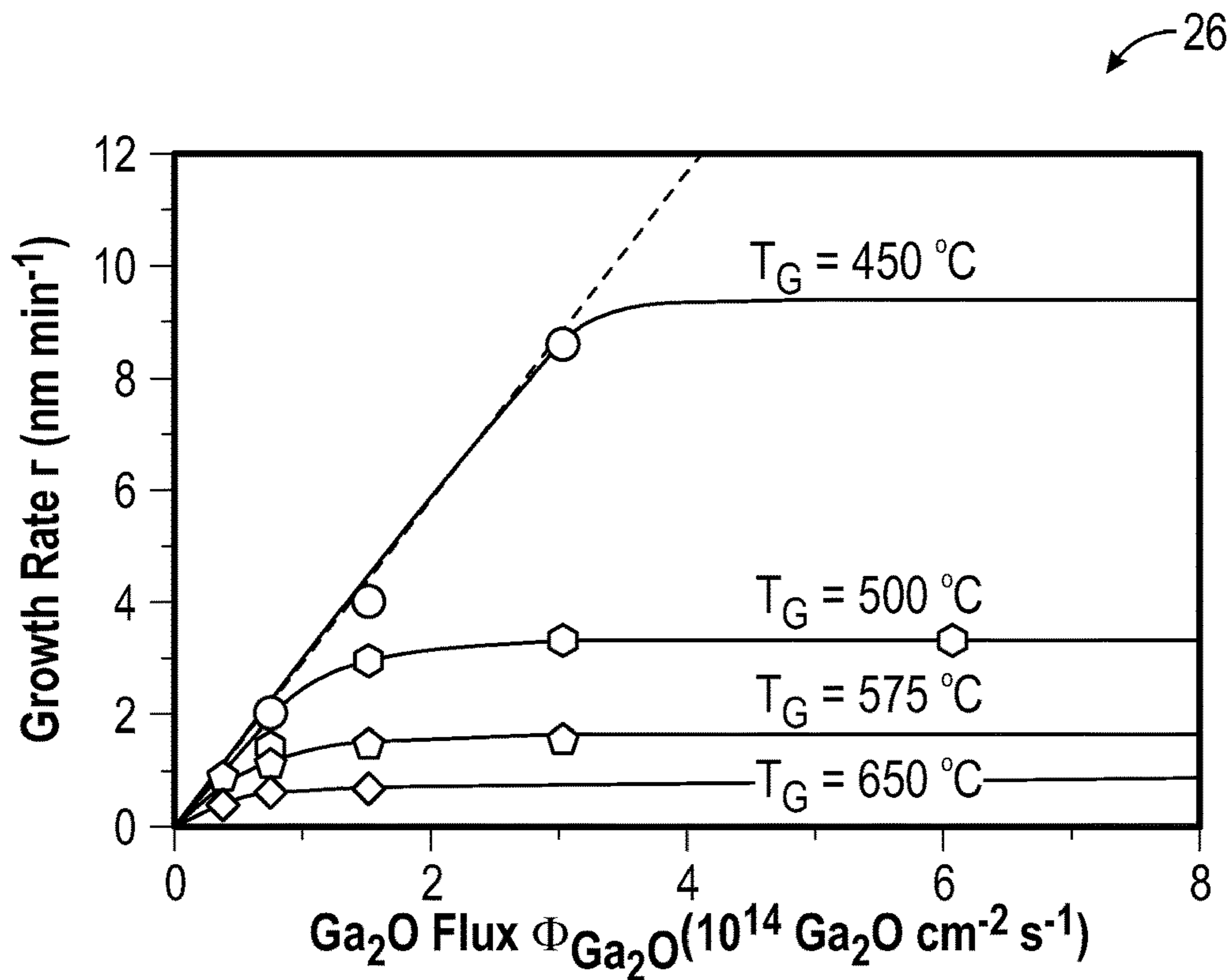


FIG. 5

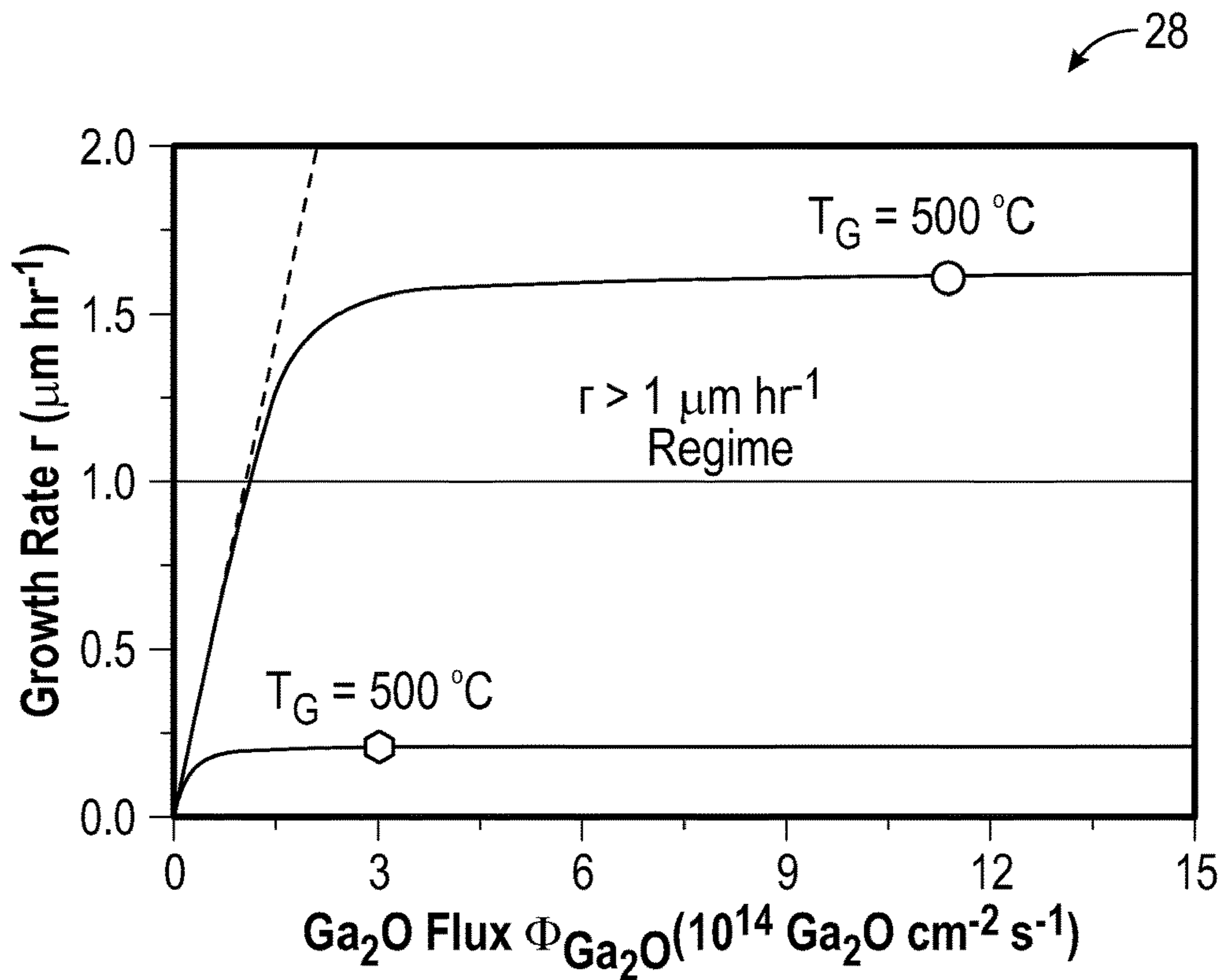


FIG. 6

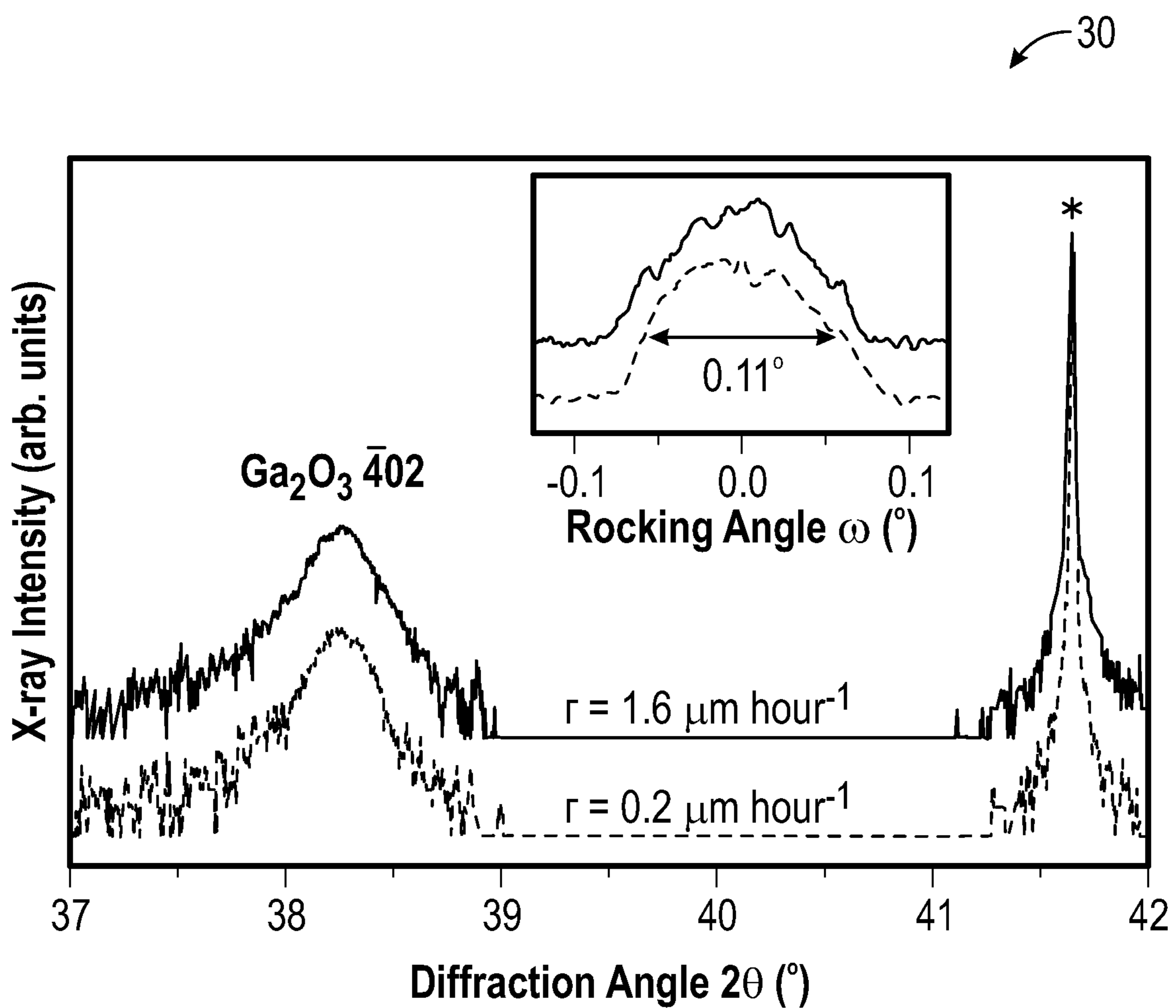


FIG. 7

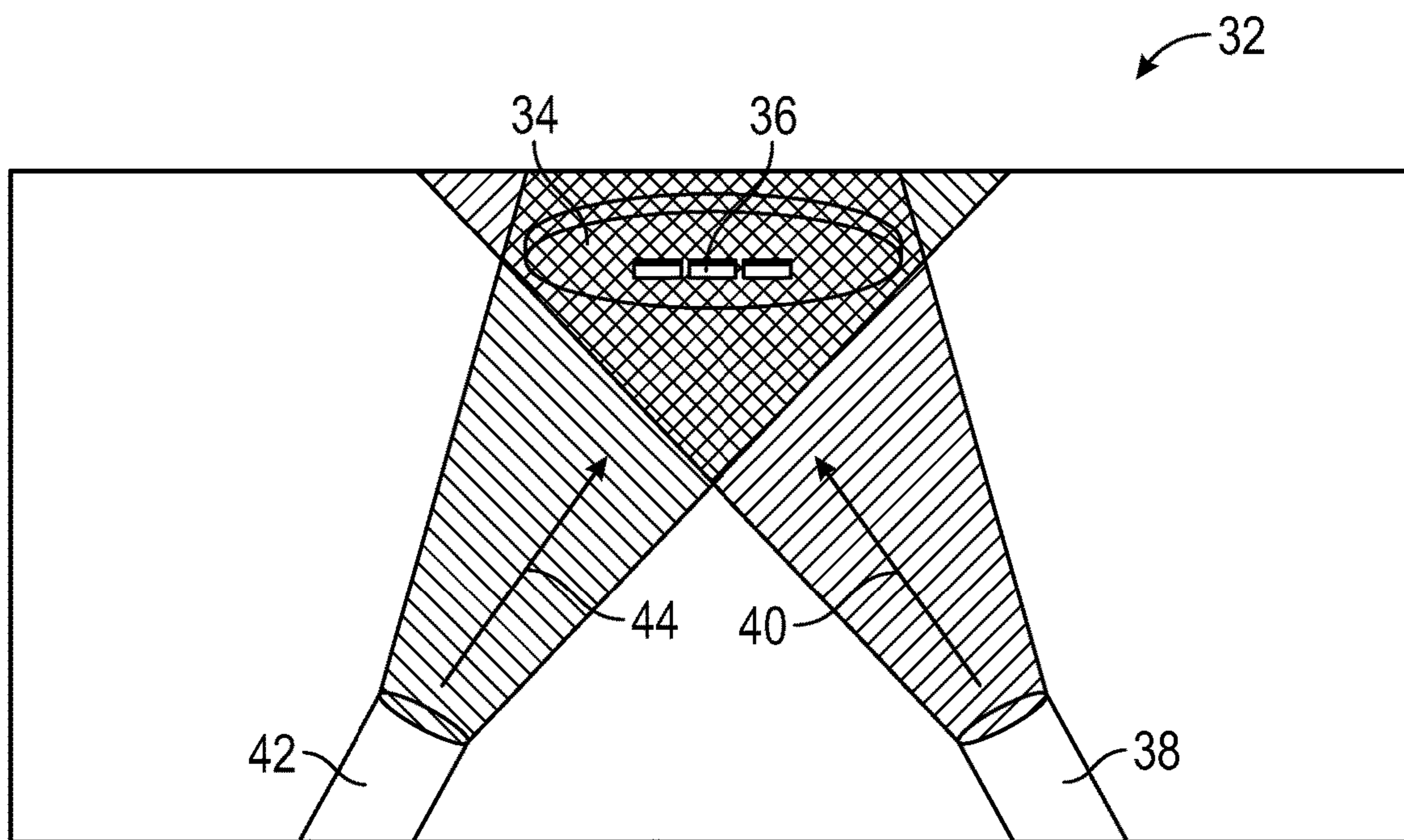


FIG. 8A

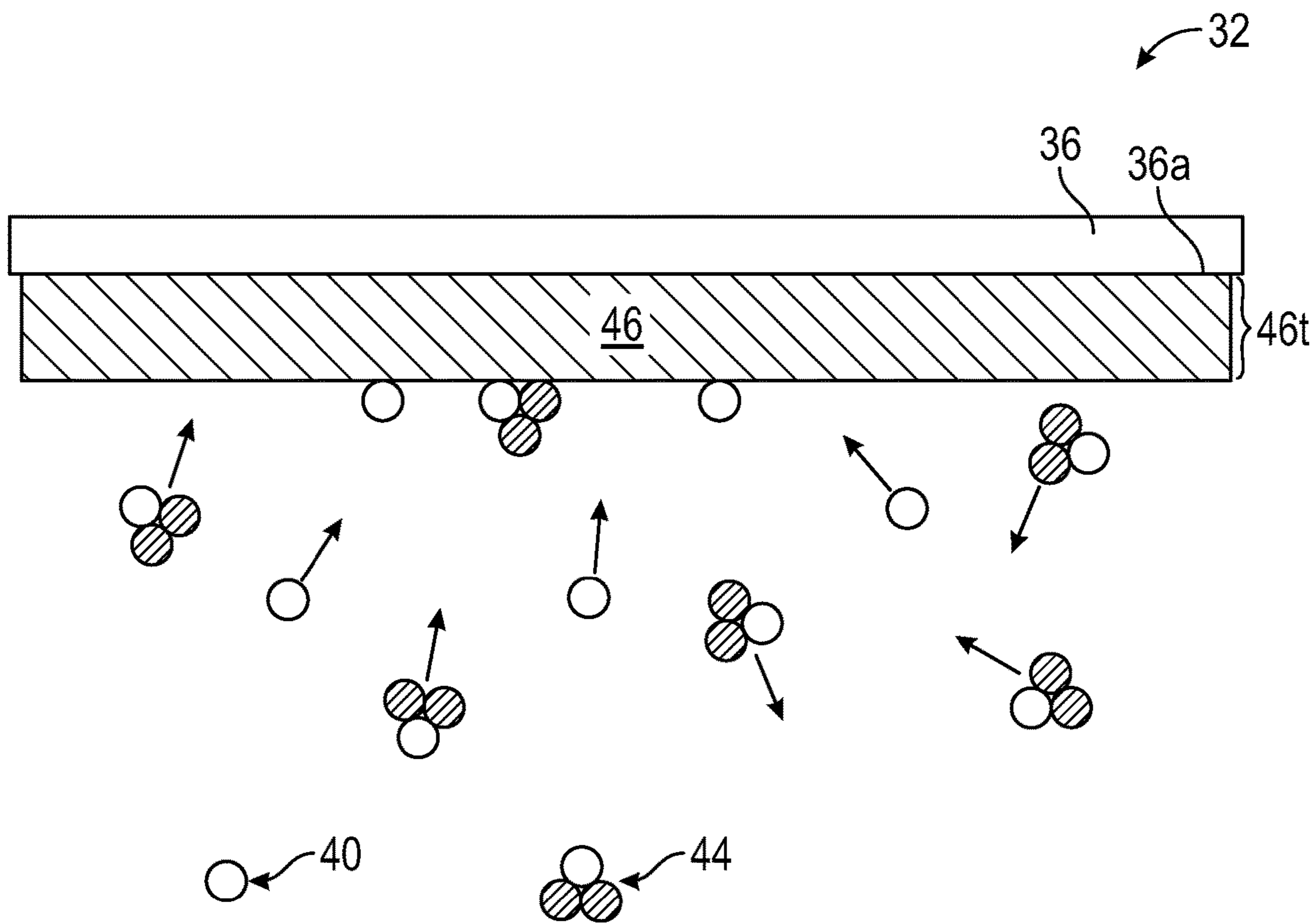


FIG. 8B

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SUBOXIDE MOLECULAR-BEAM EPITAXY
AND RELATED STRUCTURES

GOVERNMENT SUPPORT

This invention was made with government support under Agreement No. HR0011-18-3-0004 awarded by The Defense Advanced Research Projects Agency (DARPA), under Grant Nos. DMR1539918 and CMMI1825538 awarded by the National Science Foundation, under Grant No. FA9550-18-1-0508 awarded by the United States Air Force and under Grant No. 80NSSC18K1168 awarded by the National Aeronautics & Space Administration. The U.S. Government has certain rights in this invention

FIELD OF THE DISCLOSURE

The present disclosure relates to molecular-beam epitaxy (MBE) and more particularly to suboxide MBE (S-MBE) and related device structures.

BACKGROUND

Molecular-beam epitaxy (MBE) involves the growth of epitaxial thin films from molecular beams of source materials. Conventional techniques include solid-source MBE where molecular beams of elements are evaporated from heated solid source materials or gas-source MBE where molecular beams are originated from gas source materials that are provided from individual gas cylinders that are plumbed into MBE systems. Certain gas-source MBE may include metal-organic MBE where gas sources include metal-organic molecules. In the case of gallium (Ga) oxide formed by MBE, solid-source MBE involves generating a molecular beam of Ga from a heated crucible and gas-source MBE involves providing a metal-organic source like trimethylgallium together with an active species of oxygen (O).

Oxides of metals or metalloids are of particular interest for use in semiconductor devices for high-power electronic applications. It is often desired to grow oxide films by MBE in an adsorption-controlled growth regime where excess amounts of source metals or metalloids are supplied to provide improved crystal quality, smooth surface morphology, suppressed formation of undesired oxidation states, and suppressed formation of electrically compensating defects. Growth rates and film quality of such oxides may be limited by conventional MBE techniques due to the formation and subsequent desorption of volatile precursor species. For example, suboxides may initially form on a growth surface before either being desorbed from the growth surface or further oxidized to form the intended oxide layer. In the adsorption-controlled growth regime, growth rates are reduced since there is not enough active species of O to further oxidize the suboxides to the intended oxide.

The art continues to seek improved MBE techniques and corresponding films that are capable of overcoming challenges associated with conventional MBE.

SUMMARY

The present disclosure relates to molecular-beam epitaxy (MBE) and more particularly to suboxide MBE (S-MBE) and related device structures. S-MBE is disclosed that includes the use of a molecular beam of a suboxide that may be subsequently oxidized in a single step reaction to form an oxide film. By way of example, for a gallium oxide (Ga_2O_3) film, a molecular beam including a suboxide of gallium

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(Ga_2O) may be provided. S-MBE may be performed in adsorption-controlled regimes where there is an excess of source material containing species in order to promote high growth rates for oxide films with improved crystallinity.

5 Source mixtures for providing molecular beams of suboxides are disclosed that include mixtures of a particular element and an oxide of the element in ratios that promote such adsorption-controlled growth regimes. Related structures include oxide films having increased thickness with reduced crystal defects, such as a film that includes a single polymorph of gallium oxide in certain examples.

In one aspect, an MBE method comprises: providing a molecular beam that comprises a suboxide of an element; providing an oxidant species; and growing a oxide film of the element by oxidizing the suboxide with the oxidant species, wherein the oxide film is grown with a growth rate in a range from 0.5 microns per hour ($\mu\text{m/hr}$) to 5 $\mu\text{m/hr}$. In certain embodiments, the growth rate is in a range from 1 $\mu\text{m/hr}$ to 5 $\mu\text{m/hr}$. In certain embodiments, the element comprises at least one of aluminum, cerium, gallium, germanium, hafnium, indium, lanthanum, praseodymium, silicon, tin, tantalum, and zirconium. The element may comprise gallium, the suboxide may comprise Ga_2O , and the oxide film may comprise Ga_2O_3 . In certain embodiments, a flux ratio in the molecular beam of an amount of the Ga_2O to an amount of the oxidant species is greater than 1. The flux ratio may further be in a range from greater than 1 to 10. In certain embodiments, the molecular beam is produced from a source mixture that includes elemental gallium and an oxide of gallium. The source mixture may be heated to produce the molecular beam and a purity of the molecular beam is at least 99.5% Ga_2O . In certain embodiments, a mole fraction of oxygen in the source mixture is between 0.333 and 0.6. In certain embodiments, providing the molecular beam comprises heating the source mixture to a temperature that is in a range from 907 K to 1594 K, or to a temperature that is less than or equal to 1500 K. In certain embodiments, a purity of the molecular beam of the Ga_2O is at least 99%. The MBE method may further comprise supplying at least one of a molecular beam of SnO , a molecular beam of SiO , and a molecular beam of GeO to provide an n-type dopant for the Ga_2O_3 .

In another aspect, a device comprises: a substrate; and a layer of gallium oxide on the substrate, wherein the layer of gallium oxide comprises a single polymorph of gallium oxide with a thickness in a range from 1 μm to 20 μm . In certain embodiments, the thickness is in a range from 1 μm to 5 μm . The layer of gallium oxide may comprise Ga_2O_3 . In certain embodiments, the single polymorph comprises monoclinic gallium oxide ($\beta\text{-Ga}_2\text{O}_3$). The substrate may comprise a diameter in a range from 2 inches to 12 inches. In certain embodiments, the layer of gallium oxide is doped with an n-type impurity that comprises at least one of tin, germanium, and silicon. In certain embodiments, a concentration of gallium vacancy defects in the layer of gallium oxide is in a range from $1 \times 10^{14} \text{ cm}^{-3}$ to $1 \times 10^{17} \text{ cm}^{-3}$.

In another aspect, any of the foregoing aspects individually or together, and/or various separate aspects and features as described herein, may be combined for additional advantage. Any of the various features and elements as disclosed herein may be combined with one or more other disclosed features and elements unless indicated to the contrary herein.

Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWING
FIGURES

The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain the principles of the disclosure.

FIG. 1A is a schematic plot illustrating a growth rate as observed for III-V compounds, in this case gallium nitride (GaN), as a function of III/V flux ratio when a group III cation is supplied by a molecular beam of a group III element (e.g., Ga).

FIG. 1B is a schematic plot illustrating a growth rate as observed for III-VI compounds, in this case gallium oxide (Ga_2O_3), as a function of III/VI flux ratio when the group III cation is supplied by a molecular beam of a group III element (e.g., Ga).

FIG. 1C is a schematic plot illustrating growth kinetics of III-VI compounds, in this case Ga_2O_3 , as a function of III₂VI/VI flux ratio when the group III cation is supplied by a molecular beam of a III₂VI subcompound containing a group III constituent (e.g., Ga_2O).

FIG. 2 illustrates a calculated Ga—O phase diagram under a constant pressure of 0.1 pascal (Pa).

FIG. 3A illustrates a total Ga—O pressure versus temperature phase diagram at a fixed mole fraction of oxygen $x(\text{O})$ of 0.2, corresponding to a Ga-rich mixture.

FIG. 3B illustrates a total Ga—O pressure versus temperature phase diagram at a fixed mole fraction of oxygen $x(\text{O})$ of 0.4, corresponding to a Ga_2O_3 -rich mixture.

FIG. 4A illustrates a plot of a partial pressure of oxygen in a gas phase as a function of temperature at a total pressure of 0.1 Pa for a Ga-rich mixture at $x(\text{O})=0.2$ and a Ga_2O_3 -rich mixture at $x(\text{O})=0.4$.

FIG. 4B illustrates a plot of a ratio of a partial pressure of Ga_2O to that of Ga plotted as a function of temperature at a total pressure of 0.1 Pa for the Ga-rich mixture of $x(\text{O})=0.2$ and the Ga_2O_3 -rich mixture of $x(\text{O})=0.4$ of FIG. 4A.

FIG. 5 is a plot that illustrates growth rates of Ga_2O_3 as a function of source flux at different growth temperatures and with a constant oxygen flux.

FIG. 6 is a plot that represents exemplary growth rates for samples according to suboxide molecular-beam epitaxy (S-MBE) principles of the present disclosure.

FIG. 7 is a plot that illustrates θ - 2θ longitudinal x-ray diffraction (XRD) scans of selected Ga_2O_3 films as described for the samples as described for FIG. 6.

FIG. 8A illustrates an exemplary MBE system that is configured for S-MBE deposition according to principles of the present disclosure.

FIG. 8B is a magnified illustration of a portion of the MBE system of FIG. 8A along a growth surface of a substrate according to principles of the present disclosure.

DETAILED DESCRIPTION

The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of the present disclosure. As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

It will be understood that when an element such as a layer, region, or substrate is referred to as being “on” or extending “onto” another element, it can be directly on or extend directly onto the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly on” or extending “directly onto” another element, there are no intervening elements present. Likewise, it will be understood that when an element such as a layer, region, or substrate is referred to as being “over” or extending “over” another element, it can be directly over or extend directly over the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly over” or extending “directly over” another element, there are no intervening elements present. It will also be understood that when an element is referred to as being “connected” or “coupled” to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being “directly connected” or “directly coupled” to another element, there are no intervening elements present.

Relative terms such as “below” or “above” or “upper” or “lower” or “horizontal” or “vertical” may be used herein to describe a relationship of one element, layer, or region to another element, layer, or region as illustrated in the Figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the disclosure. As used herein, the singular forms “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises,” “comprising,” “includes,” and/or “including” when used herein specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

Embodiments are described herein with reference to schematic illustrations of embodiments of the disclosure. As such, the actual dimensions of the layers and elements can be different, and variations from the shapes of the illustrations as a result, for example, of manufacturing techniques and/or tolerances, are expected. For example, a region illustrated or described as square or rectangular can have rounded or curved features, and regions shown as straight

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lines may have some irregularity. Thus, the regions illustrated in the figures are schematic and their shapes are not intended to illustrate the precise shape of a region of a device and are not intended to limit the scope of the disclosure. Additionally, sizes of structures or regions may be exaggerated relative to other structures or regions for illustrative purposes and, thus, are provided to illustrate the general structures of the present subject matter and may or may not be drawn to scale. Common elements between figures may be shown herein with common element numbers and may not be subsequently re-described.

The present disclosure relates to molecular-beam epitaxy (MBE) and more particularly to suboxide MBE (S-MBE) and related device structures. S-MBE is disclosed that includes the use of a molecular beam of a suboxide that may be subsequently oxidized in a single step reaction to form an oxide film. By way of example, for a gallium oxide (Ga_2O_3) film, a molecular beam including a suboxide of gallium (Ga_2O) may be provided. S-MBE may be performed in adsorption-controlled regimes where there is an excess of source material containing species in order to promote high growth rates for oxide films with improved crystallinity. Source mixtures for providing molecular beams of suboxides are disclosed that include mixtures of a particular element and an oxide of the element in ratios that promote such adsorption-controlled growth regimes. Related structures include oxide films having increased thickness with reduced crystal defects, such as a film that includes a single polymorph of gallium oxide in certain examples.

As used herein, "suboxide MBE" refers to an MBE growth process that utilizes at least one molecular beam of a suboxide of an element. In certain embodiments, at least one molecular beam of the suboxide of the element may be combined with an active oxygen species, or oxidant species, to promote thin film growth of an oxide of the element. By way of example, providing a suboxide for growth of a gallium sesquioxide (Ga_2O_3) film may include supplying a molecular beam of a suboxide of gallium such as Ga_2O that is subsequently oxidized to form the Ga_2O_3 . As disclosed herein, suboxide MBE may also be referred to S-MBE. In addition to gallium sesquioxide, Ga_2O_3 may also be referred to as gallium trioxide, or even generally as gallium oxide.

By way of example, the following disclosure is provided detailing reaction behaviors of gallium nitride (GaN) and Ga_2O_3 in MBE. However, the principles of the present disclosure are also applicable for the MBE growth of aluminum nitride (AlN), indium nitride (InN), aluminum gallium nitride (AlGaN), indium aluminum gallium nitride (AlInGaN), III-VI compounds, II-VI compounds, or any oxides of elements aluminum (Al), cerium (Ce), gallium (Ga), germanium (Ge), hafnium (Hf), indium (In) including In_2O_3 , lanthanum (La), praseodymium (Pr), silicon (Si), tin (Sn), tantalum (Ta), and zirconium (Zr).

Ga_2O_3 synthesized in its various polymorphs such as rhombohedral ($\alpha\text{-Ga}_2\text{O}_3$), monoclinic ($\beta\text{-Ga}_2\text{O}_3$), cubic spinel ($\gamma\text{-Ga}_2\text{O}_3$), hexagonal ($\varepsilon\text{-Ga}_2\text{O}_3$), and orthorhombic ($\kappa\text{-Ga}_2\text{O}_3$), is an emerging material for use in semiconductor devices for high-power electronics. This is due to its large band gap of about 5 electron-volts (eV) and very high breakdown field of up to 8 megavolts (MV) cm^{-1} . The band gap of Ga_2O_3 may be widened by alloying Ga_2O_3 with Al_2O_3 to form $(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$. For example, the synthesis of $(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3/\text{Ga}_2\text{O}_3$ heterostructures with high Al content x is desired for high-power transistors with large band gap offsets.

Conventional MBE of Ga_2O_3 involves supplying monoatomic Ga and an active oxygen species or oxidant, such as

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ozone or any other activated O-species including oxygen plasma-assisted MBE as well as other chemical oxidants including N_2O or NO_2 , during growth. Such conventional MBE is strongly limited by the formation and subsequent desorption of volatile suboxides of gallium (Ga_2O) during growth. In the adsorption-controlled regime where there is an excess of Ga species, the growth rate of the resulting Ga_2O_3 film on a substrate strongly decreases with increasing Ga flux (ϕ_{Ga}) because not enough oxygen is available to oxidize the physisorbed Ga_2O to Ga_2O_3 (s) and the Ga_2O tends to desorb from the hot growth surface of the substrate. At sufficiently high ϕ_{Ga} , film growth stops, and may even go negative such that the Ga_2O_3 film can be etched. This effect is enhanced as the growth temperature (T_G) increases due to the thermally activated desorption of Ga_2O from the growth surface.

The decreasing growth rate of Ga_2O_3 may be microscopically explained by a complex two-step reaction mechanism. In a first reaction step, all Ga oxidizes to form the suboxide Ga_2O via the reaction equation:



with adsorbate and gaseous phases denoted as a and g , respectively. The Ga_2O formed may either desorb from the growth surface in the oxygen-deficient regime or at an elevated T_G . The Ga_2O may also be further oxidized to Ga_2O_3 via a second reaction step through the reaction equation:



with the solid phase denoted as s . This two-step reaction mechanism and the resulting Ga_2O desorption define the growth rate-limiting step for the conventional MBE of Ga_2O_3 and other related materials, resulting in a narrow growth window associated with very low growth rates in the adsorption-controlled regime. A similar growth rate-limiting behavior, based on this two-step reaction mechanism, is also provided during conventional MBE growth of other III-VI compounds such as In_2O_3 and IV-VI compounds such as SnO_2 .

According to embodiments of the present disclosure, MBE techniques are disclosed that provide a single-step reaction mechanism of films such as III-VI and IV-VI compounds. While established MBE techniques provide a single-step reaction mechanism for the growth of III-V and II-VI materials, the different electronic configurations of III-VI and IV-VI compounds result in a two-step reaction mechanism when these compounds are grown by conventional MBE. These same differences in electronic configuration underly the different compound stoichiometries of III-VI and IV-VI materials compared with III-V and II-VI materials. In certain embodiments, the single-step reaction may be provided by S-MBE where the first reaction step, or reaction equation (1), described above for conventional MBE is avoided by directly supplying a suboxide of gallium (e.g., Ga_2O (g)) as a molecular beam to a growth front on a substrate surface. Using this approach, the growth rate-limiting step in the adsorption-controlled regime for conventional MBE growth of Ga_2O_3 is bypassed by removing the oxygen consuming step for formation of Ga_2O that would otherwise occur on the substrate. In this regard, S-MBE enables the synthesis of Ga_2O_3 in the highly adsorption-controlled regime, at growth rates greater than 1 micron per hour ($\mu\text{m/hr}$), with dramatically improved crystal quality of $\text{Ga}_2\text{O}_3/\text{Al}_2\text{O}_3$ heterostructures at relatively low T_G . The higher growth rates provided by S-MBE are competitive with other established growth methods used in the semicon-

ductor industry such as chemical vapor deposition (CVD) or metal-organic chemical vapor deposition (MOVPE) and moreover, S-MBE may lead to improved crystal properties of the obtained thin films. In this regard, an improvement of n-type donor mobilities in S-MBE grown Ga₂O₃ thin films doped with impurities such as Sn, Ge, and/or Si may be realized. Additionally, the relatively low T_G at which it becomes possible to grow high-quality films by S-MBE is enabling for materials integration where temperatures are limited, such as back end of line (BEOL) processes.

FIGS. 1A-1C are schematic plots for comparing measured and predicted reaction kinetics during the MBE growth of III-V and III-VI materials. In particular, FIGS. 1A-1C are schematic plots representing how growth rate depends on cation flux during MBE growth of different types of compounds, where both axes are normalized by anion flux. FIG. 1A is a schematic plot illustrating a growth rate as observed for III-V compounds, in this case GaN, as a function of the III/V flux ratio (e.g., ϕ_{Ga}/ϕ_N) when the group III cation is supplied by a molecular beam of the group III element (e.g., Ga). FIG. 1B is a schematic plot illustrating a growth rate as observed for III-VI compounds, in this case Ga₂O₃, as a function of the III/VI flux ratio (e.g., ϕ_{Ga}/ϕ_O) when the group III cation is supplied by a molecular beam of the group III element (e.g., Ga). FIG. 1C is a schematic plot illustrating anticipated growth rates of III-VI compounds, in this case Ga₂O₃, as a function of the III₂VI/VI flux ratio

$$\left(\text{e.g., } \frac{\Phi_{Ga_2O}}{\Phi_O} \right)$$

when the group III cation is supplied by a molecular beam of a III₂VI subcompound containing a group III constituent (e.g., Ga₂O). All schematic growth rate evolutions in FIGS. 1A-1C are normalized by the respective fluxes of active available group V (ϕ_V) and group VI elements (ϕ_{VI}) at constant T_G. Anion-rich regimes are indicated as V-rich (FIG. 1A) or VI-rich (FIGS. 1B-1C) and cation-rich regimes are indicated as III-rich (FIGS. 1A-1B) or III₂VI-rich (FIG. 1C). The units of each axis in FIGS. 1A-1C are selected to provide regime crossover at an x-axis value of 1.0. As illustrated in FIGS. 1A-1C, the growth rate of GaN and Ga₂O₃ increases linearly with increasing ϕ_{Ga} in the V-rich (e.g., N) regime of FIG. 1A and the VI-rich regimes (e.g., O) of FIGS. 1B and 1C respectively. In this manner, the incorporation of Ga is limited by the impinging Ga flux or Ga₂O flux in a Ga-transport or Ga₂O-transport limited growth regime.

For GaN MBE as illustrated in FIG. 1A, once the supplied ϕ_{Ga} exceeds the flux ϕ_N of active available N, the growth rate saturates to be independent of the ϕ_{Ga}/ϕ_N ratio, and thereby be limited by ϕ_N and T_G. The measured plateau in growth rate for GaN MBE in the III-rich (Ga) regime results from its single-step reaction kinetics. Here, Ga reacts directly with activated N via the reaction equation:



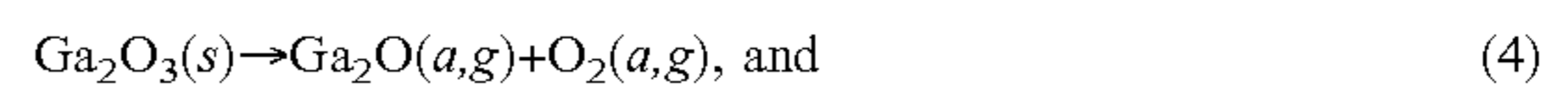
and excess Ga either adsorbs or desorbs off the growth surface depending upon ϕ_N and T_G.

FIG. 1B depicts the reaction kinetics of Ga₂O₃ in the III-rich (Ga) regime by supplying ϕ_{Ga} . Here, the growth rate linearly decreases with increasing ϕ_{Ga} , and the growth eventually stops at $\phi_{Ga} \geq 3\phi_O$ (in growth rate units). In this manner, desorbing Ga₂O removes Ga and O from the growth

surface that cannot contribute to Ga₂O₃ formation, leading to the decreasing growth rate in the III-rich regime. This behavior may be microscopically governed by the two-step reaction process described above and is fundamentally different from the single-step reaction kinetics governing the MBE of GaN as illustrated in FIG. 1A.

In FIG. 1C, the anticipated growth kinetics of Ga₂O₃ while using a Ga₂O molecular beam is depicted, showing a constant growth rate in the III₂VI-rich (Ga₂O) regime. The III₂VI-rich regime in FIG. 1C is provided for a flux ratio of III₂VI (e.g., Ga₂O) flux to VI (e.g., O) flux is greater than 1, or in a range from greater than 1 to 30, or in a range from greater than 1 to 10. Excess Ga₂O that cannot be oxidized to Ga₂O₃ may either accumulate or desorb off the growth surface without consuming or removing active O from its adsorbate reservoir, in a manner similar to the growth of GaN as described for FIG. 1A. In this regard, embodiments of the present disclosure as provided by S-MBE may effectively achieve single-step reaction kinetics for Ga₂O₃ MBE. Based on the knowledge of observed and anticipated growth kinetics for the growth of GaN and Ga₂O₃ by MBE provided in FIGS. 1A-1C, constant and highly scalable growth rates in the Ga₂O-rich regime may be achieved, allowing the ultra-fast synthesis of Ga₂O₃ thin films with improved crystallinity at relatively low T_G by S-MBE.

Conventional use of a Ga₂O (g) molecular beam to grow Ga₂O₃ (s) thin films by MBE in the O-rich regime has been demonstrated by placing a stoichiometric solid of the compound Ga₂O₃ into a crucible and using it as an MBE source. Possible reaction equations that produce a Ga₂O molecular beam by the thermal decomposition of Ga₂O₃ are:



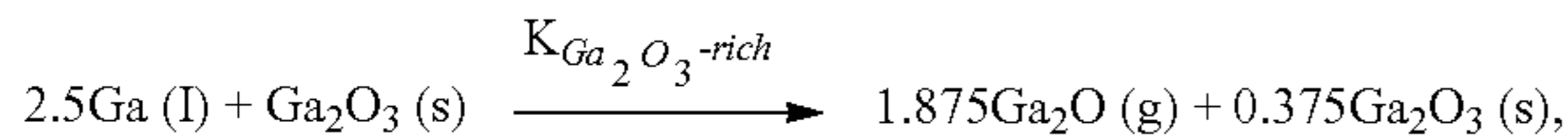
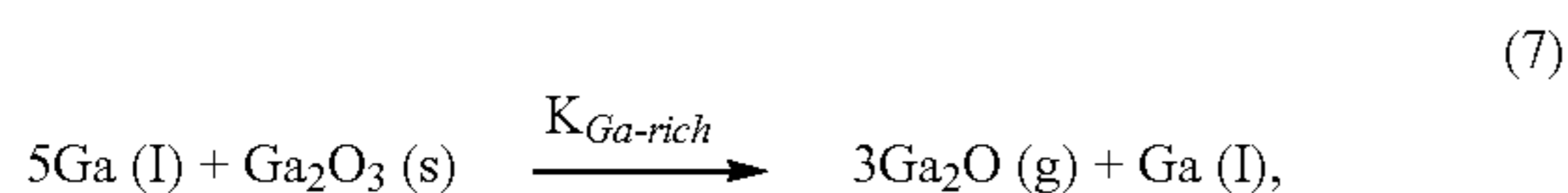
One disadvantage of using a solid source of Ga₂O₃ for MBE is that the resulting Ga₂O (g) molecular beam leaving the crucible of the MBE effusion cell contains O-species, such as undefined beams of Ga₂O/O₂ and/or Ga₂O/O. This leads to undefined adsorbate densities of Ga₂O and O species on the growth surface, making the reproducible and controlled growth of Ga₂O₃ thin films very challenging. The other disadvantage is the low achievable Φ_{Ga_2O} at relatively high MBE effusion cell temperatures that may exceed 1600° C., thereby hampering the synthesis of Ga₂O₃ at industrially relevant growth rates of at least 1 μm/hr with device-relevant film quality. Ga+Ga₂O₃-mixed sources producing a Ga₂O molecular beam have been demonstrated without providing the synthesis of Ga₂O₃ thin films. Using this mixed source, a Ga₂O (g) molecular beam may be produced by the chemical reaction equation:



with the liquid phase denoted as l. This method utilizes the thermodynamic and kinetic properties of Ga+Ga₂O₃ mixtures favoring reaction under MBE conditions.

According to embodiments of the present disclosure for S-MBE of Ga₂O₃, Ga-rich and Ga₂O₃-rich mixtures of Ga+Ga₂O₃ may be employed with stoichiometries according to the reaction equations:

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respectively. The corresponding reaction rate constants $K_{\text{Ga-rich}}$ and $K_{\text{Ga}_2\text{O}_3\text{-rich}}$ define the production rate of $\text{Ga}_2\text{O (g)}$ at a given temperature (T_{mix}) of the $\text{Ga}+\text{Ga}_2\text{O}_3$ source mixture. The flux of $\text{Ga}_2\text{O (g)}$ in the molecular beam emanating from the mixed $\text{Ga}+\text{Ga}_2\text{O}_3$ sources may be significantly larger than that of Ga (g) emanating from the same source. The resulting flux ratio where $\text{Ga}_2\text{O}/\text{Ga}$ is greater than 1 may provide a more controllable and cleaner growth environment than previously accessible by decomposing a stoichiometric Ga_2O_3 source, which produces molecular beam ratios of $\text{Ga}_2\text{O}/\text{O}_2$ or $\text{Ga}_2\text{O}/\text{O}$. In this regard, the growth surface of the substrate during film growth using S-MBE may only include controllable densities of Ga_2O and reactive O adsorbates.

According to embodiments of the present disclosure, a Ga_2O_3 -rich source mixture enables higher T_{mix} and increased, purer $\text{Ga}_2\text{O (g)}$ molecular beams than a Ga-rich mixture, thereby providing S-MBE that achieves higher growth rates. As used herein, a Ga_2O_3 -rich source mixture may refer to a mixture of Ga (l) and $\text{Ga}_2\text{O}_3 \text{ (s)}$ that when heated to a temperature where the $\text{Ga}_2\text{O (g)}$ that it evolves has a vapor pressure of 0.1 Pa (a vapor pressure typical for MBE growth) emits a molecular beam containing a ratio of Ga_2O to elemental Ga in the gas phase that is greater than 199, i.e., the molecular beam is at least 99.5% Ga_2O . This experimental observation may be confirmed by thermodynamic calculations of the phase diagram of $\text{Ga (l)}+\text{Ga}_2\text{O}_3 \text{ (s)}$ mixtures. In this regard, FIG. 2 illustrates a calculated Ga—O phase diagram 16 under a constant pressure of 0.1 pascal (Pa) that shows that at a T_{mix} below a three-phase equilibrium of $\text{gas}+\text{Ga (l)}+\text{Ga}_2\text{O}_3 \text{ (s)}$ around 907 Kelvin (K), a two-phase region of $\text{Ga (l)}+\text{Ga}_2\text{O}_3 \text{ (s)}$ forms, which does not change with respect to temperature for a mole fraction of oxygen between 0 and 0.6. All thermodynamic calculations in the present disclosure were performed using a scientific group thermodata europe (SGTE) substance database (SSUB5) within a Thermo-Calc software. For T_{mix} above 907 K, the two-phase regions are $\text{gas}+\text{Ga (l)}$ when the mole fraction of oxygen is below one third, corresponding to Ga-rich mixtures as described herein, and $\text{gas}+\text{Ga}_2\text{O}_3 \text{ (s)}$ when the mole fraction of oxygen is between one 0.333 and 0.6, corresponding to as Ga_2O_3 -rich mixtures as described herein. These two-phase regions become a single gas-phase region at T_{mix} values of 907 to 1189 K for Ga-rich mixtures and at T_{mix} values 907 to 1594 K for Ga_2O_3 -rich mixtures, respectively. As further illustrated in the pressure versus temperature (P-T) phase diagrams of FIGS. 3A and 3B, all of these phase transition temperatures decrease with decreasing pressure.

FIG. 3A illustrates a Ga—O total pressure versus temperature phase diagram 18 at a fixed mole fraction of oxygen $x(\text{O})$ of 0.2, corresponding to a Ga-rich mixture. FIG. 3B illustrates a Ga—O total pressure versus temperature phase diagram 20 at a fixed mole fraction of oxygen $x(\text{O})$ of 0.4, corresponding to a Ga_2O_3 -rich mixture. In order to contrast the difference between Ga-rich versus Ga_2O_3 -rich mixtures, thermodynamic calculations were performed at the chosen oxygen mole fractions of $x(\text{O})=0.2$ and $x(\text{O})=0.4$. In FIGS.

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3A and 3B, the solid lines denote a three-phase equilibrium between $\text{gas}+\text{Ga (l)}+\text{Ga}_2\text{O}_3 \text{ (s)}$ that is identical at $x(\text{O})=0.2$ and $x(\text{O})=0.4$. The dashed lines in FIGS. 3A and 3B denote an equilibrium between the gas and $\text{gas}+\text{Ga (l)}$ phase regions for $x(\text{O})=0.2$ and the gas and $\text{gas}+\text{Ga}_2\text{O}_3 \text{ (s)}$ phase regions for $x(\text{O})=0.4$. Stated differently, the dashed lines represent respective boiling temperature/pressure values.

FIG. 4A illustrates a plot 22 of a partial pressure of oxygen in a gas phase as a function of temperature at a total pressure of 0.1 Pa for a Ga-rich mixture at $x(\text{O})=0.2$ and a Ga_2O_3 -rich mixture at $x(\text{O})=0.4$. FIG. 4B illustrates a plot 24 of a ratio of a partial pressure of Ga_2O to that of Ga plotted as a function of temperature at a total pressure of 0.1 Pa for the for the Ga-rich mixture of $x(\text{O})=0.2$ and the Ga_2O_3 -rich mixture of $x(\text{O})=0.4$. In FIGS. 4A and 4B, the dashed lines denote mole fractions of oxygen at $x(\text{O})=0.2$ and the solid lines denote mole fractions of oxygen at $x(\text{O})=0.4$, respectively.

As illustrated in FIG. 4A, the oxygen partial pressure in the Ga_2O_3 -rich mixture at $x(\text{O})=0.4$ is orders of magnitude higher than that at $x(\text{O})=0.2$ at relevant MBE growth temperatures. For example, the value of the partial pressure of oxygen at $T_{\text{mix}}=1000$ K for the mole fraction $x(\text{O})=0.2$ is 5.6×10^{-25} Pa and the value of the partial pressure of oxygen at $T_{\text{mix}}=1000$ K for the mole fraction of $x(\text{O})=0.4$ is 4.5×10^{-21} Pa. In this regard, the higher oxygen activity of Ga_2O_3 -rich mixtures compared with Ga-rich mixtures makes it easier to form fully oxidized Ga_2O_3 thin films. At lower total pressure values, all lines shift to lower temperatures.

The thermodynamic calculations plotted in FIG. 4B show the ratio of the partial pressures of Ga_2O to Ga in the gas phase as a function of the temperature of the Ga-rich mixture $x(\text{O})=0.2$ and of the Ga_2O_3 -rich mixture $x(\text{O})=0.4$ where the total pressure is fixed at 0.1 Pa. The ratio of the partial pressures of Ga_2O to Ga

$$\left(\frac{P_{\text{Ga}_2\text{O}}}{P_{\text{Ga}}} \right)$$

in the Ga-rich mixture with $x(\text{O})=0.2$ is much lower than the corresponding ratio in the Ga_2O_3 -rich mixture $x(\text{O})=0.4$. For example, the $P_{\text{Ga}_2\text{O}}/P_{\text{Ga}}$ ratio is 158 in the Ga-rich mixture and 1496 in the Ga_2O_3 -rich mixture at a T_{mix} value of 1000 K. The higher $\text{Ga}_2\text{O}/\text{Ga}$ ratios are another reason that Ga_2O_3 -mixtures are advantageous since higher $\text{Ga}_2\text{O}/\text{Ga}$ ratios correspond to a purer Ga_2O molecular beam, which more exactly satisfies the single-step formation reaction of Ga_2O_3 described above.

By way of example, a Ga metal (7N purity) and a Ga_2O_3 powder (5N purity) were used to provide a $\text{Ga}+\text{Ga}_2\text{O}_3$ mixture that was loaded into a 40 cm^3 aluminum oxide (Al_2O_3) crucible and inserted it into a commercial dual-filament, medium temperature MBE effusion cell. After mounting the effusion cell to a commercially available MBE system and evacuating the source, the $\text{Ga}+\text{Ga}_2\text{O}_3$ mixture was heated, out-gassed, and set for a desired Ga_2O flux for S-MBE growth of Ga_2O_3 . In certain embodiments, the $\text{Ga}+\text{Ga}_2\text{O}_3$ mixture is heated to a temperature (T_{mix}) that is less than or equal to 1000 K, or less than or equal to 1500 K, thereby reducing potential contamination from the crucible or other hot parts of the effusion cell that may otherwise form at higher temperatures. The flux of the $\text{Ga}_2\text{O (g)}$ molecular beam reaching the growth surface prior to and after growth was measured using a quartz crystal microbal-

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ance. After growth, x-ray reflectivity (XRR) was used to measure a thickness of the Ga₂O₃ films formed by S-MBE to determine a corresponding growth rate. Based on thermodynamic calculations, a purity of the Ga₂O (g) molecular beam described above for a mole fraction x(O)=0.4 is at least 99.5%, or at least 99.9%, or at least 99.98%, thereby providing improve crystallinity with reduced defects and unwanted polymorphs in the resulting Ga₂O₃ film. In particular, the resulting Ga₂O₃ film may be grown with a single polymorph, such as β-Ga₂O₃, across a sapphire wafer with a diameter of at least 12 inches. In certain embodiments, a concentration of gallium vacancy defects in the Ga₂O₃ film may be less than 1×10¹⁷ cm⁻³, or less than 5×10¹⁶ cm⁻³, or less than 1×10¹⁶ cm⁻³, or in a range from 1×10¹⁴ cm⁻³ to 1×10¹⁷ cm⁻³. Additionally, the reduced crucible contamination provided by the lower T_{ux} may provide a Ga₂O₃ film that is devoid of foreign species and/or contaminants.

FIG. 5 is a plot 26 that illustrates growth rates of Ga₂O₃ as a function of source flux Φ_{Ga₂O} at different T_G values with a constant oxygen flux Φ_O. Measured growth rates of Ga₂O₃(201) on Al₂O₃(0001) are provided as a function of Φ_{Ga₂O} at the different T_G values. The Φ was provided by an oxidant in the form of a mixture of O₂ and approximately 80% O₃ and supplied continuously during growth. Solid lines represent model calculations while dashed lines denote an intersection between O-rich and Ga₂O-rich growth regimes to indicate a maximum available Φ_O for Ga₂O to Ga₂O₃ oxidation at given T_G values. Growth rates were obtained by measuring XRR fringe spacings, which are directly correlated to a corresponding thickness of the thin films as grown, or by measuring the film thickness by optical reflectivity in a microscope. The growth rates obtained follow the anticipated growth kinetics as illustrated by FIG. 1C. In the adsorption-controlled regime, an increase in Φ_{Ga₂O} at otherwise constant growth parameters does not lead to a decrease in the growth rate as observed for the conventional Ga₂O₃ MBE as illustrated by FIG. 1B, but instead results in a constant growth rate or a growth rate-plateau for all T_G values. In this regard, S-MBE growth kinetics according to the present disclosure may overcome the growth rate-limiting step by using a Ga₂O (g) suboxide molecular beam to provide a single-step reaction mechanism, thereby reducing the complexity of Ga₂O₃ reaction kinetics from the conventional two-step reaction mechanisms described by the reaction equations (1) and (2) above.

The S-MBE kinetics for the Ga₂O₃ growth may be described in a similar way as the conventional III-V reaction equation (3) above and for II-VI MBE. In this regard, a simple reaction-rate model describing the growth of Ga₂O₃ (s) and other III-VI and IV-VI compounds by S-MBE may be represented by the reaction equations:

$$\frac{dn_{Ga_2O}}{dt} = \Phi_{Ga_2O} - \kappa_{Ga_2O} n_{Ga_2O} n_O^2 - \gamma_{Ga_2O} n_{Ga_2O}, \quad (9)$$

$$\frac{dn_O}{dt} = \sigma \Phi_O - 2\kappa_{Ga_2O} n_{Ga_2O} n_O^2 - \gamma_O n_O, \text{ and} \quad (10)$$

$$\frac{dn_{Ga_2O_3}}{dt} = \Gamma = \kappa_{Ga_2O} n_{Ga_2O} n_O^2. \quad (11)$$

The Ga₂O₃, Ga₂O, and oxygen adsorbate densities are respectively denoted as n_{Ga₂O₃}, n_{Ga₂O}, and n_O with a time derivative described by the operator d/dt. The reaction rate constant κ_{Ga₂O} describes the growth rate Γ of Ga₂O₃ (s) on the growth surface, and γ_{Ga₂O} and γ_O denote the desorption

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rate constants of Ga₂O and oxygen adsorbates, respectively. The flux of available oxygen adsorbates, for Ga₂O to Ga₂O₃ oxidation at a given T_G, is determined by its sticking coefficient σ on the Ga₂O₃ growth surface and described by the arbitrarily chosen function:

$$\sigma(T_G) = \left[\sigma_0 \exp\left(-\frac{\Delta\sigma}{k_B(T_G - dT_G)}\right) + 1 \right]^{-1} \quad (12)$$

with dimensionless pre-factor σ₀, energy Δσ, and temperature off-set dT_G. The function (12) reflects the decreasing probability of the oxygen species to adsorb as the T_G is increased. In this manner, an effectively lower surface density of active oxygen for Ga₂O oxidation and a corresponding lower growth rate is provided.

For a supplied flux of Φ_O corresponding to a background pressure of 1×10⁻⁶ Torr involving mixtures of O₂ and approximately 10% O₃ and 80% O₃, the values of the variables given in the function (12) are: σ₀=40, Δσ=29 meV, and dT_G=675° C. These values are extracted by fitting the maximum growth rate defined as the plateau-regime as a function of T_G, for example as illustrated in FIG. 5. It is found that a does not depend on the concentration of active oxygen; but rather it only depends on the partial pressure of active oxygen. Thus, the active oxygen species may be scaled up or down by either changing the concentration of O₃ in the O₃ beam or by changing the partial pressure of O₃ in the MBE chamber. It is noted that O₃ supplies oxygen to the surface of the growing film as it decomposes by the reaction: O₃ (g)→O₂ (g)+O (g). A similar behavior of an increasing desorption or recombination rate of active oxygen species with increasing T_G has also been observed during oxygen plasma-assisted MBE using monoatomic Ga and oxygen molecular beams.

Based on this model, Φ_O may be scaled up in order to achieve Ga₂O₃ (s) growth rates that exceed 1 μm/hr. FIG. 6 is a plot 28 that represents exemplary growth rates according to S-MBE principles of the present disclosure. In FIG. 6, a growth rate of 1.6 μm/hr for a Ga₂O₃ thin film grown on Al₂O₃(0001) is demonstrated at a T_G of 500° C. for the data line that includes the data point plotted as a circle. For comparison, the data point plotted as a hexagon shows the highest possible growth rate at a five times lower active Φ_O and at the same T_G. In this regard, the above-described models for growth of Ga₂O₃ thin film according to S-MBE are provided that exceed 1 μm/hr.

The impact of variable growth conditions (i.e., Φ_{Ga₂O}, Φ_O, and T_G) on the structural properties and crystallinity of Ga₂O₃ (s) grown on Al₂O₃(0001) was investigated. FIG. 7 is a plot 30 that illustrates θ-2θ longitudinal x-ray diffraction (XRD) scans of selected Ga₂O₃ films as described for the same samples as described for FIG. 6. The solid line corresponds to a film grown at Φ_{Ga₂O}=11.4×10¹⁴ Ga₂O molecules cm⁻² s⁻¹ and Φ_O was provided by an oxidant (O₂+80% O₃) at a background pressure of 5×10⁻⁶ Torr. The dashed line corresponds to a Ga₂O₃ film growth with Φ_{Ga₂O}=3.0×10¹⁴ Ga₂O molecules cm⁻² s⁻¹ and Φ_O was provided by an oxidant (O₂+80% O₃) at a background pressure of 1×10⁻⁶ Torr. For both samples, T_G was set at 500° C. The reflections from the Ga₂O₃ film are identified to originate from the monoclinic β-phase, and the transverse scans across the 402 peak with its full width at half maximum indicated in FIG. 7 have the same value for both films. The 0006 peaks of the Al₂O₃ substrates are marked by an asterisk.

The reflections of the films coincide with the β -Ga₂O₃ phase grown with their (201) plane parallel to the plane of the substrate. The inset portion of the plot 30 represents transverse scans or rocking curves across the symmetric 402 reflection of the same layers. The full width at half maxima in ω of the profiles provides a measure of an out-of-plane mosaic spread of the Ga₂O₃ layer. The obtained $\Delta\omega=0.11^\circ$ does not change with growth rate and is particularly notable since β -Ga₂O₃(201) films grown on Al₂O₃(0001), using monoatomic Ga or compound Ga₂O₃ sources, typically show broader line profiles in their out-of-plane crystal distributions (from $\Delta\omega\approx 0.23^\circ$ to $\Delta\omega\sim 1.00^\circ$). Thus, the profiles in FIG. 7 reveal a well-oriented and high quality epitaxial Ga₂O₃(201) thin film. Furthermore, reflection high-energy electron diffraction and XRR measurements reveal a sharp and well-defined interface between Ga₂O₃(201) and Al₂O₃ as well as a smooth surface morphology obtained by S-MBE.

FIG. 8A illustrates an exemplary MBE system 32 that is configured for S-MBE deposition according to principles of the present disclosure. The MBE system 32 includes a substrate holder 34 that supports one or more substrates 36 in an arrangement for thin film growth. The substrates 36 may comprise sapphire substrates having any available diameter, such as 3 inch, or 6 inch, or 12 inch wafers. For S-MBE growth according to embodiments of the present disclosure, an oxygen source 38 is arranged to provide an active oxygen species 40 or oxidant, such as ozone, or by oxygen plasma-assisted deposition, to the substrates 36 and an effusion cell 42 is arranged to provide a molecular beam of a suboxide 44 to the substrates 36. In this regard, an oxide film formed by S-MBE according to the present disclosure may be represented as M_xO_y, where M represents a metal or metalloid. For example, M may include one or more of Al, Ce, Ga, Ge, Hf, In, La, Pr, Si, Sn, Ta, and Zr. The corresponding M_xO_y may include Al₂O₃, Ce₂O₃ or CeO₂, Ga₂O₃, GeO₂, HfO₂, In₂O₃, La₂O₃, Pr₂O₃ or Pr₆O₁₁ or PrO₂, SiO₂, SnO₂, Ta₂O₅, and ZrO₂. For deposition of the M_xO_y film (with M₂O₃ for III-VI compounds and MO₂ for IV-VI compounds), the suboxide 44 may be represented as M_zO (with M₂O for group-III suboxides and MO for group-IV suboxides) and the suboxide 44 may be provided with a flux that allows the M_xO_y film to form by a single-step reaction mechanism within an adsorption-controlled regime where excess amounts of Mz_o are present. The suboxide of Mz_o may be provided by loading a mixture of elemental M and a M_xO_y powder in the effusion cell 42 and subsequently heating, outgassing, and setting it to provide a desired M_zO flux. In certain embodiments, the mixture of M and M_xO_y powder may be configured as M_xO_y-rich to promote the desired flux for the suboxide 44. By way of example, for S-MBE deposition where M is Ga and the resulting film is Ga₂O₃, a Ga metal and a Ga₂O₃ powder may be loaded into the effusion cell 42 to provide a Ga+Ga₂O₃ source mixture. The Ga+Ga₂O₃ mixture may be configured as a Ga₂O₃-rich mixture as provided in the previously described reaction equation (8) and in the Ga—O phase diagram 16 of FIG. 2. In this regard, formation of the resulting film may occur in the adsorption-controlled regime where excess amounts of Ga₂O molecules are present as provided by the Ga₂O flux, thereby allowing higher growth rates with improved crystal quality and reduced amounts of undesired polymorphs.

FIG. 8B is a magnified illustration of a portion of the MBE system 32 of FIG. 8A along a growth surface 36a of one of the substrates 36. The active oxygen species 40 and the suboxide 44 are provided to the growth surface 36a of the substrate 36 to form an oxide film 46, which may also be

referred to as an oxide layer. When the suboxide 44 is represented as Mz_o, the oxide film 46 may be represented as M_xO_y. Continuing the example discussed above for FIG. 8A, the oxide film 46 may be Ga₂O₃ for embodiments where a Ga+Ga₂O₃ source mixture is used to provide the suboxide 44 of Ga₂O. By forming the oxide film 46 by a single-step reaction mechanism within an adsorption-controlled regime according to principles of the present disclosure, the oxide film 46 may form with significantly increased growth rates not otherwise possible by conventional MBE techniques. For example, the growth rate of the oxide film 46 (e.g., Ga₂O₃) may be at least 0.5 $\mu\text{m/hr}$, or at least 1 $\mu\text{m/hr}$, or at least 2 $\mu\text{m/hr}$, or at least 5 $\mu\text{m/hr}$, or in a range from 0.5 $\mu\text{m/hr}$ to 5 $\mu\text{m/hr}$, or in a range from 1 $\mu\text{m/hr}$ to 5 $\mu\text{m/hr}$ depending on the application. For oxygen plasma-assisted S-MBE, the growth rate may exceed 5 $\mu\text{m/hr}$. The resulting oxide film 46 may thereby form with a thickness 46t as measured in a direction perpendicular to the growth surface 36a that is at least 1 μm , or at least 5 μm , or in a range from 1 μm to 20 μm . Of course, lower thickness 46t values below 1 μm may also be provided according to the S-MBE principles of the present disclosure. Additionally, the oxide film 46 may be grown with high crystal quality over large substrate diameters, such as a single polymorph film of Ga₂O₃ grown over a substrate having a diameter of up to 12 inches or more.

As disclosed herein, the growth of high quality Ga₂O₃ (s) thin films by S-MBE in the adsorption-controlled regime using Ga (l)+Ga₂O₃ (s) source mixtures is provided. The accomplished growth rate of at least 0.5 $\mu\text{m/hr}$, or at least 1 $\mu\text{m/hr}$, and improved crystal quality of the obtained Ga₂O₃ films on Al₂O₃ heterostructures may enable improved mobilities of Ga₂O₃ thin films containing n-type donors (Sn, Ge, Si) grown by S-MBE. In certain embodiments, the principles of the present disclosure may also provide mixtures of Sn+SnO₂ and/or Ge+GeO₂ and/or Si+SiO₂ in order to produce SnO (g) and/or GeO (g) and/or SiO (g) molecular beams as n-type donors in such Ga₂O₃-based heterostructures. Moreover, Ga₂O₃ doped with SnO using Ga₂O and SnO beams may achieve improved control of Sn-doping levels in the Ga₂O₃ films.

Based on thermodynamic analysis of the volatility of various binary oxides plus additional two-phase mixtures of metals with their binary oxides, such as Ga+Ga₂O₃, the principles of the present disclosure are applicable to additional systems appropriate for growth by S-MBE. By applying this thermodynamic knowledge with the S-MBE growth of Ga₂O₃ as described herein, source mixtures of In+In₂O₃ and Ta+Ta₂O₅ may be provided that allow growth of high quality bixbyite In₂O₃ and In₂O₃:SnO₂ (ITO, with up to 30% Sn) and rutile TaO₂ by S-MBE, respectively.

Growing thin films with very high crystalline qualities at high growth rates by using suboxide molecular beams allows S-MBE to be competitive with other established synthesis methods, such as chemical vapor deposition (CVD) or metalorganic vapor phase epitaxy (MOVPE). The growth temperatures as described herein for high quality Ga₂O₃ layers grown by S-MBE are significantly lower than what has previously been demonstrated for the growth of Ga₂O₃ films by CVD or MOVPE. This makes S-MBE advantageous for BEOL processing. Additionally, Ga₂O₃ grown in the adsorption-controlled regime with excess supply of Ga₂O (g) and high oxygen activity in Ga₂O₃-rich source mixtures may suppress Ga vacancies in the resulting Ga₂O₃ films, which are believed to act as compensating acceptors, thereby improving the electrical performance of n-type Ga₂O₃-based devices.

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Moreover, the principles of the present disclosure may be applicable to provide Al+Al₂O₃ source mixtures for the growth of epitaxial Al₂O₃ and (Al_xGa_{1-x})₂O₃ at comparably high growth rates by S-MBE. In order to fabricate vertical high-power devices, thin film thicknesses in the μm range are desired. In this manner, S-MBE as described herein allows the epitaxy of such devices in relatively short growth times, such as a few hours. In addition, the use of Al₂O (g) and Ga₂O (g) molecular beams during (Al_xGa_{1-x})₂O₃ S-MBE may also extend its growth domain towards higher adsorption-controlled regimes, thereby being advantageous for the performance of (Al_xGa_{1-x})₂O₃-based devices.

Additionally, the principles of the present disclosure for S-MBE may be applicable to all materials that form via intermediate reaction products, such as a subcompound. For example, ZrO₂, Pb(Zr,Ti)O₃, and (Hf,Zr)O₂ may be formed by S-MBE that includes supply of a molecular beam of ZrO. In other examples, Ga₂Se₃ may be formed with inclusion of a molecular beam of Ga₂Se; In₂Se₃ may be formed with inclusion of a molecular beam of In₂Se; In₂Te₃ may be formed with inclusion of a molecular beam of In₂Te; and Sn₂Se may be formed with inclusion of a molecular beam of SnSe.

It is contemplated that any of the foregoing aspects, and/or various separate aspects and features as described herein, may be combined for additional advantage. Any of the various embodiments as disclosed herein may be combined with one or more other disclosed embodiments unless indicated to the contrary herein.

Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

What is claimed is:

1. A molecular-beam epitaxy (MBE) method comprising: providing a molecular beam that comprises a suboxide of an element; providing an oxidant species; and growing an oxide film of the element by oxidizing the suboxide with the oxidant species, wherein the oxide film is grown with a growth rate in a range from 0.5 microns per hour (μm/hr) to 5 μm/hr.
2. The MBE method of claim 1, wherein the growth rate is in a range from 1 μm/hr to 5 μm/hr.
3. The MBE method of claim 1, wherein the element comprises at least one of aluminum, cerium, gallium, germanium, hafnium, indium, lanthanum, praseodymium, silicon, tin, tantalum, and zirconium.

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4. The MBE method of claim 1, wherein the element comprises gallium, the suboxide comprises Ga₂O, and the oxide film comprises Ga₂O₃.

5. The MBE method of claim 4, wherein a flux ratio in the molecular beam of an amount of the Ga₂O to an amount of the oxidant species is greater than 1.

6. The MBE method of claim 5, wherein the flux ratio is in a range from greater than 1 to 10.

7. The MBE method of claim 4, wherein the molecular beam is produced from a source mixture that includes elemental gallium and an oxide of gallium.

8. The MBE method of claim 7, wherein the source mixture is heated to produce the molecular beam and a purity of the molecular beam is at least 99.5% Ga₂O.

9. The MBE method of claim 7, wherein a mole fraction of oxygen in the source mixture is between 0.333 and 0.6.

10. The MBE method of claim 7, wherein providing the molecular beam comprises heating the source mixture to a temperature that is in a range from 907 K to 1594 K.

11. The MBE method of claim 7, wherein providing the molecular beam comprises heating the source mixture to a temperature that is less than or equal to 1500 K.

12. The MBE method of claim 4, wherein a purity of the molecular beam of the Ga₂O is at least 99%.

13. The MBE method of claim 4, further comprising supplying at least one of a molecular beam of SnO, a molecular beam of SiO, and a molecular beam of GeO to provide an n-type dopant for the Ga₂O₃.

14. A device comprising:

a substrate; and

a layer of gallium oxide on the substrate, wherein the substrate and the gallium oxide form a heterostructure, and wherein the layer of gallium oxide comprises a single polymorph of gallium oxide with a thickness in a range from 1 micron (μm) to 20 μm.

15. The device of claim 14, wherein the thickness is in a range from 1 μm to 5 μm.

16. The device of claim 14, wherein the layer of gallium oxide comprises Ga₂O₃.

17. The device of claim 14, wherein the single polymorph comprises monoclinic gallium oxide (β-Ga₂O₃).

18. The device of claim 14, wherein the substrate comprises a diameter in a range from 2 inches to 12 inches.

19. The device of claim 14, wherein the layer of gallium oxide is doped with an n-type impurity that comprises at least one of tin, germanium, and silicon.

20. The device of claim 14, wherein a concentration of gallium vacancy defects in the layer of gallium oxide is in a range from 1×10¹⁴ cm⁻³ to 1×10¹⁷ cm³.

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