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(54) Title: LITHIUM DISILICATE GLASS-CERAMIC COMPOSITIONS AND METHODS THEREOF

(57) Abstract: A bioactive glass-ceramic composition as defined herein. Also disclosed are methods of making and using the disclosed compositions.

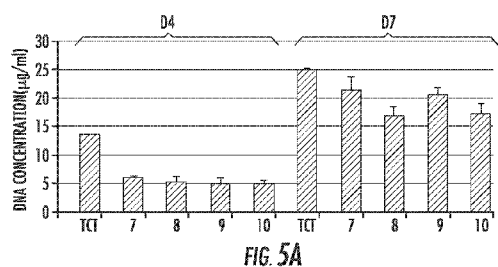


FIG. 5A

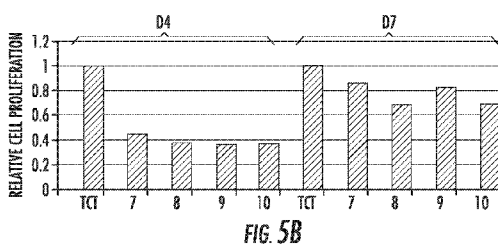


FIG. 5B

FIG. 5

LITHIUM DISILICATE GLASS-CERAMIC COMPOSITIONS AND METHODS THEREOF

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 62/342, 381 filed on May 27, 2016 the content of which is relied upon and incorporated herein by reference in its entirety.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] The present application is related commonly owned and assigned USSN Provisional Application Nos., filed concurrently herewith:

62/342, 384, entitled “BIOACTIVE ALUMINOBORATE GLASSES”;

62/342, 377, entitled “MAGNETIZABLE GLASS CERAMIC COMPOSITION AND METHODS THEREOF”;

62/342,391, entitled “BIODEGRADABLE MICROBEADS”;

62/342, 411, entitled “BIOACTIVE GLASS MICROSPHERES”; and

62/342, 426, entitled “BIOACTIVE BOROPHOSPHATE GLASSES”; but does not claim priority thereto.

[0003] The present application is also related to commonly owned and assigned USSN Application Nos., 62/189,880, filed July 7, 2015, entitled “ANTIMICROBIAL PHASE-SEPARATING GLASS AND GLASS CERAMIC ARTICLES AND LAMINATES,” which mentions a copper containing laminate having a degradable phase, which phase liberates cooper ion, and a non-degradable phase; and 61/874870, filed September 6, 2013, entitled “High strength glass-ceramics having lithium disilicate and beta-spodumene structures,” but does not claim priority thereto

[0004] The entire disclosure of each publication or patent document mentioned herein is incorporated by reference.

Background

[0005] The disclosure relates to glass-ceramic compositions, bioactive glass-ceramic compositions and articles made from the glass-ceramic compositions, and to methods of making and using the bioactive glass-ceramic compositions and articles.

Summary

[0006] In embodiments, the disclosure provides a group of glass-ceramic compositions each having lithium disilicate as a first major crystal phase, and at least one of wollastonite, fluoroapatite, cristobalite, β -quartz, lithiophosphate, or a mixture thereof, as a second minor phase.

[0007] In embodiments, the disclosed compositions can comprise a source of, for example, 50 to 75 wt% SiO_2 , 1 to 5 wt% Al_2O_3 , 1 to 8 wt% P_2O_5 , 2 to 10 wt% CaO , 5 to 20 wt% Li_2O , 0.5 to 5 wt% Na_2O , 0.5 to 8 wt% ZrO_2 , and 0.1 to 1.0 F⁻ wt% (i.e., fluoride ion), based on a 100 wt% total of the composition.

[0008] In embodiments, the disclosed compositions can further comprise a source of, for example, 0.1 to 10 wt% B_2O_3 , based on a 100 wt% total of the composition.

[0009] In embodiments, the disclosure provides a glass-ceramic composition or glass-ceramic articles made from the composition, having a combination of high strength and high toughness.

[0010] In embodiments, the disclosure provides a glass-ceramic composition having excellent biocompatibility.

[0011] In embodiments, the disclosure provides methods of making and using the disclosed compositions.

Brief Description of the Drawings

[0012] In embodiments of the disclosure:

[0013] Fig. 1 shows X-ray diffraction spectra of example compositions 7 to 10. All specimens were cerammed using a cycle of 700°C for 2 hr and then 800°C for 4 hr.

[0014] Figs. 2A to 2D show SEM images of polished surfaces in example compositions 7 to 10 corresponding to Figs. 2A, 2B, 2C, and 2D, respectively.

[0015] Figs. 3A to 3D show confocal SEM images of MC3T3 cell growth in disclosed compositions 7 to 10 corresponding to Figs. 3A, 3B, 3C, and 3D, respectively.

[0016] Figs. 4A and 4B show Day 1 attachment and proliferation of MC3T3 cells on disclosed bioactive glass-ceramic discs: absolute level (absolute cell number; 4A) and relative levels with respect to an *in vitro* control: a Tissue Culture Treated[®] (TCT) well (relative cell number; 4B).

[0017] Figs. 5A and 5B show cell proliferation results for disclosed compositions 7 to 10.

Detailed Description

[0018] Various embodiments of the disclosure will be described in detail with reference to drawings, if any. Reference to various embodiments does not limit the scope of the invention, which is limited only by the scope of the claims attached hereto. Additionally, any examples set forth in this specification are not limiting and merely set forth some of the many possible embodiments of the claimed invention.

[0019] In embodiments, the disclosed method of making and using provide one or more advantageous features or aspects, including for example as discussed below. Features or aspects recited in any of the claims are generally applicable to all facets of the invention. Any recited single or multiple feature or aspect in any one claim can be combined or permuted with any other recited feature or aspect in any other claim or claims.

Definitions

[0019] "Glass," "glasses," or like terms can refer to a glass or a glass-ceramic.

[0020] "Glass article," or like terms can refer to any object made wholly or partly of any of the disclosed glass or glass-ceramic compositions.

[0021] "Bioactivity Index" "index of bioactivity," "I_B," or like terms or symbols refer to, for example, the time for more than 50% of the interface of a specific bioactive material to be bonded by a biological material such as bone, tissue, and like materials. Mathematically, a bioactivity index (according to Hench; see Cao, W., et al., Bioactive Materials, Ceramics International, 22 (1996) 493-507) is, $I_B = 100/t_{0.5bb}$, where $t_{0.5bb}$ is the time for more than 50% of a bioactive material's interface, such as an implant, to be bonded by a biological material such as bone, tissue, and like materials, including osteopductive (Class A having both intracellular and extracellular responses, e.g., 45S5 Bioglass[®]) and osteoconductive (Class B extracellular response only at interface, e.g., synthetic hydroxyapatite) materials.

[0022] "Include," "includes," or like terms means encompassing but not limited to, that is, inclusive and not exclusive.

[0023] "About" modifying, for example, the quantity of an ingredient in a composition, concentrations, volumes, process temperature, process time, yields, flow rates, pressures, viscosities, and like values, and ranges thereof, or a dimension of a component, and like

values, and ranges thereof, employed in describing the embodiments of the disclosure, refers to variation in the numerical quantity that can occur, for example: through typical measuring and handling procedures used for preparing materials, compositions, composites, concentrates, component parts, articles of manufacture, or use formulations; through inadvertent error in these procedures; through differences in the manufacture, source, or purity of starting materials or ingredients used to carry out the methods; and like considerations. The term "about" also encompasses amounts that differ due to aging of a composition or formulation with a particular initial concentration or mixture, and amounts that differ due to mixing or processing a composition or formulation with a particular initial concentration or mixture.

[0024] "Optional" or "optionally" means that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where the event or circumstance occurs and instances where it does not.

[0025] The indefinite article "a" or "an" and its corresponding definite article "the" as used herein means at least one, or one or more, unless specified otherwise.

[0026] Abbreviations, which are well known to one of ordinary skill in the art, may be used (e.g., "h" or "hrs" for hour or hours, "g" or "gm" for gram(s), "mL" for milliliters, "rt" for room temperature, "nm" for nanometers, and like abbreviations).

[0027] Specific and preferred values disclosed for components, ingredients, additives, dimensions, conditions, times, and like aspects, and ranges thereof, are for illustration only; they do not exclude other defined values or other values within defined ranges. The composition and methods of the disclosure can include any value or any combination of the values, specific values, more specific values, and preferred values described herein, including explicit or implicit intermediate values and ranges.

[0028] Bioactive materials having high strength and toughness are in significant demand, for example, for the regeneration of bone and teeth. Glass-ceramics based on lithium disilicate offer highly desirable mechanical properties, including high body strength and fracture toughness, due to their microstructures of randomly-oriented interlocking crystals. Glass-ceramics having fracture toughness values of 2 to 3 MPa•m^{1/2} are achievable in the system of glass-ceramics based on lithium disilicate compositions (see commonly owned and assigned USSN 61/874870). Lithium disilicate glass-ceramics have been widely used in the fabrication of single and multiple dental restorations. However, these glass-ceramics have not been used in bone repair due to their relatively low bioactivity. In contrast, bioceramics based on apatite

and wollastonite have demonstrated high bioactivity but do not have sufficient mechanical strength compared to, for example, cortical bone (Hench, L.L., *Bioceramics, J Am Ceram Soc*, 1998, 81: 1705-1728).

[0029] In embodiments, the disclosure provides a group of glass-ceramic compositions having a phase assemblage containing a major phase of lithium disilicate and a minor phase or phases of, for example, apatite or wollastonite. These superior compositions exhibit an excellent combination of high mechanical strength and high bioactivity, which makes them excellent for hard tissue regeneration.

[0030] WO 2015200017 ('017), entitled "Process for producing a sintered lithium disilicate glass ceramic dental restoration and kit of parts," mentions a process for producing a sintered lithium disilicate glass ceramic dental restoration out of a porous 3-dim article. In contrast, the presently disclosed compositions have a different phase assemblage, for example, the disclosed compositions have lithium disilicate and apatite, whereas '017 has only lithium disilicate, and the presently disclosed compositions are bioactive but not the '017 compositions. Additionally, the presently disclosed compositions have CaO and F⁻ to produce the apatite phase.

[0031] US 20150087493 mentions lithium disilicate apatite glass-ceramics, which are characterized by a high chemical stability and can be used as restoration material in dentistry. However, these materials all include K₂O, which is absent from the presently disclosed compositions.

[0032] US 7166548 mentions an apatite glass ceramic, which contains at least one glass phase and at least one apatite phase and is characterized in that at least one of the apatite phases is a phosphate-free and fluorine-free siliceous oxyapatite phase. However, these materials exclude phosphate and fluorine, which is present in the presently disclosed compositions.

[0033] In embodiments, the disclosure provides a glass-ceramic composition, comprising:
a first crystalline phase comprised of lithium disilicate; and
a second crystalline phase selected from the group consisting of at least one of:
wollastonite, fluoroapatite, cristobalite, β -quartz, lithiophosphate, or a combination thereof.

In embodiments, the disclosure provides a glass-ceramic composition wherein the first crystalline phase and the second crystalline phase, in combination, comprise a source of:

50 to 75 wt% SiO₂,

1 to 5 wt% Al₂O₃,

1 to 8 wt% P_2O_5 ,

2 to 10 wt% CaO ,

5 to 20 wt% Li_2O ,

0.5 to 5 wt% Na_2O ,

0.5 to 8 wt% ZrO_2 , and

0.1 to 1.0 wt% F^- , i.e., fluoride ion, based on a 100 wt% total of the composition.

[0034] In embodiments, the glass-ceramic composition can further comprise a source of 0.1 to 10 wt% B_2O_3 , based on a 100 wt% total of the composition.

[0035] In embodiments, the first crystalline phase and the second crystalline phase, in combination, can comprise a source of:

50 to 60 wt% SiO_2 ,

1 to 3 wt% Al_2O_3 ,

2 to 6 wt% P_2O_5 ,

4 to 8 wt% CaO ,

7.5 to 12.5 wt% Li_2O ,

0.5 to 2 wt% Na_2O ,

1 to 4 wt% ZrO_2 , and

0.2 to 0.8 wt% F^- , based on a 100 wt% total of the composition.

[0036] In embodiments, the abovementioned composition can be a preferred or a most preferred composition and can comprise, consist of, or consist essentially of, the abovementioned composition components.

[0037] In embodiments, the disclosed bioactive compositions and articles can be a preferred or most preferred composition or article and can comprise, consist of, or consist essentially of, the disclosed bioactive composition or article.

[0038] In embodiments, the disclosed methods of making and methods of using can be a preferred or most preferred method and can comprise, consist of, or consist essentially of, the disclosed methods.

[0039] In embodiments, the composition can have a high strength of from 200 MPa to 500 MPa, for example, from at least 200 MPa, at least 300 MPa, or at least 400 MPa, including intermediate values and ranges.

[0040] In embodiments, the composition can have a high fracture toughness of from 1.4 to 2.0 MPa•m^{1/2}, for example, from at least 1.4, 1.6, 1.8, or 2.0 MPa•m^{1/2}, including intermediate values and ranges.

[0041] In embodiments, the composition can have a combination of high strength of from 200 MPa to 500 MPa, and high fracture toughness of from 1.4 to 2.0 MPa•m^{1/2}.

Precursor Glass

[0042] In embodiments, the composition can be prepared from a precursor glass composition comprising a source of, for example:

50 to 75 wt% SiO₂,

1 to 5 wt% Al₂O₃,

1 to 8 wt% P₂O₅,

2 to 10 wt% CaO,

5 to 20 wt% Li₂O,

0.5 to 5 wt% Na₂O,

0.5 to 8 wt% ZrO₂, and

0.1 to 1.0 wt% F⁻, based on a 100 wt% total of the composition.

[0043] In embodiments, the abovementioned precursor glass composition does not change significantly upon ceramming.

[0044] In embodiments, the disclosure provides a method of making the abovementioned glass-ceramic compositions comprising, for example:

ceramming a precursor glass comprising a source of:

50 to 75 wt% SiO₂,

1 to 5 wt% Al₂O₃,

1 to 8 wt% P₂O₅,

2 to 10 wt% CaO,

5 to 20 wt% Li₂O,

0.5 to 5 wt% Na₂O,

0.5 to 8 wt% ZrO₂, and

0.1 to 1.0 wt% F⁻, based on a 100 wt% total of the composition, by heating the glass at 650 to 750 °C for 0.5 to 10 hrs, and then heating at 750 to 850 °C for 0.5 to 20 hrs.

[0045] In embodiments, the method of making can further comprise, for example, ion exchanging the resulting glass-ceramic composition to create at least one compressive stress layer on at least one surface of the article to increase mechanical strength of the article.

Bioactive Composition

[0046] In embodiments, the disclosure provides a bioactive composition, comprising:

a glass-ceramic comprised of:

a first crystalline phase comprised of lithium disilicate; and

a second crystalline phase selected from the group consisting of at least one of: wollastonite, fluoroapatite, cristobalite, β -quartz, lithiophosphate, or a combination thereof; and

one or more live osteoblast cells, that is, a bioactive glass-ceramic including the disclosed composition and cells capable of synthesizing bone.

[0047] In embodiments, in the abovementioned bioactive composition the glass-ceramic composition can comprise, for example, a source of:

50 to 75 wt% SiO_2 ,

1 to 5 wt% Al_2O_3 ,

1 to 8 wt% P_2O_5 ,

2 to 10 wt% CaO ,

5 to 20 wt% Li_2O ,

0.5 to 5 wt% Na_2O ,

0.5 to 8 wt% ZrO_2 , and

0.1 to 1.0 wt% F^- , based on a 100 wt% total of the composition.

[0048] In embodiments, the glass-ceramic composition can comprise, for example, a source of:

50 to 60 wt% SiO_2 ,

1 to 3 wt% Al_2O_3 ,

2 to 6 wt% P_2O_5 ,

4 to 8 wt% CaO ,

7.5 to 12.5 wt% Li_2O ,

0.5 to 2 wt% Na_2O ,

1 to 4 wt% ZrO_2 , and

0.2 to 0.8 wt% F⁻, based on a 100 wt% total of the composition.

[0049] In embodiments, the abovementioned bioactive composition can further comprise, for example, a source of 0.1 to 10 wt% B₂O₃, based on a 100 wt% total of the composition.

[0050] In embodiments, the disclosure provides a method of culturing osteoblast cells, i.e., a method of using the disclosed bioactive composition, comprising, for example:

contacting the abovementioned bioactive composition with a suitable liquid medium.

[0051] In embodiments, the glass-ceramic composition of the bioactive composition can be combined or contacted with the suitable liquid medium prior to being contacted with the live osteoblast cell(s).

[0052] In embodiments, the contacting produces a proliferation of the osteoblast cells on the surface of the bioactive composition.

[0053] In embodiments, the contacting produces a proliferation of the osteoblast cells in the suitable liquid medium, such as the culture medium of MC3T3 cells: i.e., alpha-MEM supplemented with 10% fetal bovine serum and 1 mM sodium pyruvate.

[0054] In embodiments, the suitable liquid medium can include, for example, a simulated body fluid (SBF) composition. SBF is used for testing apatite formation activity of bioactive glasses/glass-ceramics. The disclosed bioactive glass-ceramics form *in-situ* a biologically active apatite layer (e.g., the mineral phase of bone and teeth) that can bond to bone and teeth, and can even bond to soft tissue. The potential applications of the disclosed bioactive glass-ceramics can include, for example, monolithic articles, composites, films, coating, or like forms, for use in repair of load-bearing bones, dental regeneration, treatment of dental hypersensitivity, artificial vertebrae, spinous spacers, intervertebral spacers, iliac spacers, granular fillers, scaffolds, middle-ear implant and in other types of small-bone replacement, wound healing, and like applications. The disclosed bioactive glass-ceramics are biocompatible with, for example, osteoblasts, keratinocytes, human umbilical vein endothelial cells (HUVEC), etc. (see for example, T. Kokubo et al., "How useful is SBF in predicting in vivo bone bioactivity?", *Biomaterials*, 27[15] 2907-15 (2006)).

[0055] In embodiments, the disclosed compositions and disclosed bioactive compositions can also have application in, for example: angiogenesis (HUVEC cells), wound healing (keratinocytes), bone tissue engineering (MC3T3 cells), and like applications.

[0056] In embodiments, the disclosed composition is biocompatible with various cell types in various applications, and are biologically active (i.e., bioactive).

[0057] In embodiments, the disclosed compositions and methods thereof are advantaged in several aspects, including for example:

glass-ceramic compositions having a combination of high strength and high toughness;

glass-ceramic compositions having excellent biocompatibility; and

glass-ceramic compositions having a capability of supporting the growth and functionalization of osteoblastic cells.

[0058] In embodiments, the disclosed bioactive glass-ceramic compositions can further comprise, for example, a form factor selected from a hollow microsphere, a solid microsphere, or a combination thereof, that is, where the glass composition has a particle shape, such as a sphere, an elongated sphere or egg-shape, a rod, or like geometries. Table 1 lists representative examples of the disclosed compositions. The ceramming cycle for all examples 1 to 15 was 700°C for 2 hr and 800°C for 4 hr.

Table 1. Example compositions (Ex. 7 to 15) and control compositions (Ex. C-1 to C-6).

Oxides (wt%)	C-1 ¹	C-2	C-3	C-4	C-5	C-6	7	8
SiO ₂	70	65	60	55	60	60	70	65
B ₂ O ₃	0	0	0	0	0	0	0	0
Al ₂ O ₃	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Li ₂ O	12	12	12	12	15	12	12	12
Na ₂ O	2	2	2	2	2	2	2	2
CaO	6	6	6	6	6	6	6	6
P ₂ O ₅	4	4	4	4	4	4	4	4
ZrO ₂	2	2	2	2	2	4	2	2
F ⁻	0	0	0	0	0	0	0.5	0.5
Phase assemblage ²	A	A	A	B	C	D	E	E
Flexural strength (MPa)	-	-	-	-	-	-	504	407
Fracture toughness (MPa•m ^{1/2})	-	-	-	-	-	-	1.8	1.9

Table 1. continued.

Oxides (wt%)	9	10	11	12	13	14	15
SiO ₂	60	55	60	60	60	60	60
B ₂ O ₃	0	0	0	0	2	4	6
Al ₂ O ₃	2.5	2.5	2.5	2.5	2.5	2.5	2.5

Li ₂ O	12	12	15	12	12	12	12
Na ₂ O	2	2	2	2	2	2	2
CaO	6	6	6	6	6	6	6
P ₂ O ₅	4	4	4	4	4	4	4
ZrO ₂	2	2	2	4	2	2	2
F ⁻	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Phase assemblage ²	F	G	G	H	F	F	F
Flexural strength (MPa)	485	303	-	-	-	-	-
Fracture toughness (MPa·m ^{1/2})	2.2	2.2	-	-	-	-	-

1. "C-#" designation represents a control example (i.e., C- to C-6).

2. Phase assemblage key:

A = Lithium disilicate, cristobalite, wollastonite, β-quartz, lithiophosphate.

B = Lithium disilicate, wollastonite, lithiophosphate.

C = Lithium disilicate, lithium metasilicate, wollastonite, lithiophosphate.

D = Lithium disilicate, β-quartz, lithiophosphate.

E = Lithium disilicate, cristobalite, fluoroapatite, β-quartz.

F = Lithium disilicate, fluoroapatite, β-quartz, lithiophosphate.

G = Lithium disilicate, fluoroapatite, lithium metasilicate, β-quartz.

H = Lithium disilicate, fluoroapatite, β-quartz.

Sample Appearance: Samples of Examples 1 to 8 and 10 to 15 were translucent white; Example 9 was translucent/semi-transparent white.

[0059] In embodiments, the disclosed compositions can be free of (e.g., zero ppm or ppb), or substantially free of (e.g., trace amounts less than several ppm or ppb), at least one of, for example, K₂O, K₂CO₃, Ca₃(PO₄)₂, MgO, TiO₂, As₂O₃, Sb₂O₃, or combinations or mixtures thereof.

[0060] In embodiments, the disclosure provides precursor glass compositions that can be cerammed to produce glass-ceramics having excellent mechanical properties and biocompatibility. In embodiments, the disclosure provides glass-ceramics having high mechanical strength by forming an interlocking structure in the cerammed articles, which forces cracks to propagate along a tortuous path. Additionally, the presence of minor crystallite phases such as fluoroapatite and wollastonite in the disclosed compositions is beneficial to the growth, proliferation, and function of osteoblastic cell lines.

[0061] In embodiments, the precursor glass or source glass can comprise, for example, 50 to 75 wt% SiO₂, 1 to 5 wt% Al₂O₃, 5 to 20 wt% Li₂O, 0.5 to 5 wt% Na₂O, 0.5 to 8 wt% ZrO₂, and 0.1 to 1.0 F⁻ wt% (i.e., fluoride ion), based on a 100 wt% total of the composition.

In embodiments, a more preferred precursor glass composition, can be, for example, 50 to 60 wt% SiO₂, 1.0 to 3.0 wt% Al₂O₃, 0.1 to 4.0 wt% B₂O₃, 7.5 to 12.5 wt% Li₂O, 0.5 to 2.0 wt% Na₂O, 1.0 to 4.0 wt% ZrO₂, and 0.2 to 0.8 wt% F⁻ ion based on a 100 weight percentage total (see Table 1).

[0062] In embodiments, the precursor glasses can be cerammed into glass-ceramic articles having high crystallinity of, for example, 80% or more, such as 80 to 95%. The major crystallite phases are comprised of lithium disilicate. The minor crystallite phases can be comprised of, for example, fluoroapatite, wollastonite, cristobalite, β-quartz, lithiophosphate, or mixtures thereof depending on composition targeted.

[0063] Referring to the Figures, Fig. 1 shows X-ray diffraction spectra of example compositions 7 to 10, where the reference numerals 7, 8, 9, and 10, correspond to example compositions 7 to 10, respectively, in Table 1. The significant peaks are identified (with marker shapes) as: lithium disilicate (asterisk), lithium metasilicate (triangle), fluoroapatite (dot), beta-quartz (square), and cristobalite (diamond). All specimens were cerammed using a cycle of 700°C for 2 hr and then 800°C for 4 hr.

[0064] In embodiments, the disclosed glass-ceramic articles composed of interlocking lithium disilicate can be easily obtained by ceramming precursor glasses at temperatures of from 700 to 900°C for a period of time. A grain size of the lithium disilicate phase can be larger than 1 micrometer having a high aspect ratio that is typically formed in glass-ceramics. Figs. 2A to 2D show SEM images of polished surfaces in example compositions 7 to 10 corresponding to Figs. 2A, 2B, 2C, and 2D, respectively. All specimens were cerammed using a cycle of 700°C for 2 hr and then 800°C for 4 hr. Specimens were etched in 1% HF for one min prior to observation.

[0065] Although not bound by theory, it is believed that the presence of interlocking crystals can be a significant factor in developing toughening mechanisms including, for example, crack deflection and tortuous crack path, which mechanisms can contribute to the observed high fracture toughness and high flexural strength (Table 1). For example, a fracture toughness of over 1.5 MPa•m^{1/2} and a flexural strength of over 300 MPa can be achieved in selected glass-ceramic compositions.

[0066] In embodiments, the disclosed glass-ceramic product or residual glass can be ion exchanged to create a compressive stress layer in the surface of a ware to further improve mechanical strength.

[0067] In embodiments, excellent biocompatibility was demonstrated in the disclosed glass-ceramic compositions. Cell attachment was clearly observed through confocal images on the surfaces of compositions 7 to 9. MC 3T3 cells were cultured one day, fixed with 4% formaldehyde, and then stained with Alexa Fluor 568 phalloidin and DAPI prior to the confocal imaging. Figs. 3A to 3D show confocal SEM images of MC3T3 cell growth in the disclosed compositions 7 to 10 corresponding to Figs. 3A, 3B, 3C, and 3D, respectively. All specimens were cerammed using a cycle of 700°C for 2 hr and then 800°C for 4 hr. Cells were cultured one day, fixed with 4% formaldehyde, and then stained with Alexa Fluor 568 phalloidin and DAPI prior to the confocal imaging.

[0068] The ability of the disclosed glass-ceramics of examples compositions 7 to 10 to support cell proliferation was demonstrated by the expression of DNA from the cultured cells for absolute levels (Fig. 5A) and for relative levels (Fig. 5B) with respect to a TCT control. MCT3 cells were cultured on glass-ceramic discs. On day 4 and day 7, cells were digested with the digestion buffer (125 microgm/mL papain, 2 mM L-cysteine , 2 mMM EDTA) at 65°C for overnight, the dsDNA amount was measured using Quant-iT™ PicoGreen® dsDNA Kit (Thermo Fisher). The increase of DNA concentration with increasing culture time provided additional evidence of the excellent biocompatibility of the disclosed compositions.

[0069] In embodiments, the disclosed glass-ceramics can be manufactured using a thin rolling, a float, a casting process, and like methods; and scaffolds can be produced using, for example, rapid prototyping, polymer foam replication, particle sintering, and like methods. Glass-ceramics of desired forms can be used to support cell growth and hard tissue regeneration.

[0070] In embodiments, the realized mechanical strength, biocompatibility, and biodegradation of the disclosed compositions can be influenced by the glass compositions. In embodiments, the disclosed glass compositions can further include, for example: SiO₂ which serves as the primary glass-forming oxide for precursor glass and can function to stabilize the networking structure of glass and glass-ceramics. In embodiments, the concentration of SiO₂ should be sufficiently high to form a lithium disilicate crystal phase when the precursor glass is heat treated to convert to a glass-ceramic (i.e., cerammed). However, the glasses can't contain too much SiO₂ since the melting temperature (200 poise temperature) of pure SiO₂ or high-SiO₂ glasses is undesirably high. In embodiments, glass or glass-ceramic compositions can comprise, for example, 68 to 82 wt% SiO₂, based on a 100 wt% total weight.

[0071] In embodiments, the Al_2O_3 may also provide stabilization to the networking structure. Al_2O_3 is favorable to the improvement of mechanical properties and chemical durability. However, too much Al_2O_3 generally increases the viscosity of the melt and decreases the fraction of lithium disilicate crystals to an extent that no interlocking structure can be formed. The Al_2O_3 concentration is preferably maintained in a reasonable range of, for example, from 1 to 5 wt%.

[0072] In embodiments, the addition of B_2O_3 can be beneficial to improved crack-resistance of the glass-ceramics, which is helpful for dental applications. Furthermore, a higher boron concentration can increase the degradation rate of the bioactive compositions, which property may be desired in applications such as bone regeneration.

[0073] Li_2O is another significant component in the disclosed precursor glass compositions. Li_2O is advantageous for forming lithium disilicate crystal phases. Li_2O is called for to have at least 8 wt% Li_2O to obtain glass-ceramics having lithium disilicate as a predominant phase. However, when the Li_2O content gets too high, such as greater than 15 wt%, the precursor glasses become very fluid with low resistivity making it difficult to melt or form.

[0074] In embodiments, the disclosed glass and glass-ceramic compositions can include, for example, from 2 to 6 wt% P_2O_5 , for example, as a nucleating agent to produce bulk nucleation. If the P_2O_5 concentration is too low, such as less than 2 wt%, the precursor glass does not crystallize. If the P_2O_5 concentration is too high, such as greater than 6 wt%, the devitrification upon cooling during precursor glass forming, can be difficult to control.

[0075] In embodiments, divalent cation oxides, such as alkaline earth oxides, can also be used to improve the melting behavior and the bioactivity of the glass. For example, CaO was found to combine with P_2O_5 to form apatite, or with SiO_2 to form wollastonite. Both apatite and wollastonite are known bioactive ceramics (see Hench, L. L., *supra*.).

[0076] In embodiments, including Na_2O in the precursor glass in an amount of from 0.1 to 5 wt% can reduce the melting temperature of the precursor glass, and can shorten the ceramming cycle. Furthermore, including Na_2O in the precursor glass can also increase the thermal expansion after ceramming if a higher thermal expansion (i.e., CTE) is desired in the glass-ceramic articles.

[0077] In embodiments, melting was accomplished at an elevated temperature, such as above 1300°C , to fuse the precursor glass materials. In embodiments, ceramming was the heat

treatment of the melted glass that was used to crystallize the glass into a glass-ceramic material.

EXAMPLES

[0078] The following Examples demonstrate making, use, and analysis of the disclosed compositions and methods in accordance with the above general procedures.

Example 1

[0079] **Preparation of Control Examples C-1 to C-6 and Actual Example Glass-Ceramic Compositions 7 to 15** Control and Actual Example Glass-Ceramic Compositions 1 to 15 listed in Table 1, and their respective glass source materials in the indicated amounts, including for example, silica, boric acid, alumina, lithium carbonate, sodium carbonate, limestone, spodumene, aluminum metaphosphate, were individually combined and melted in an electric furnace. Prior to melting, the precursor glass source materials were vigorously mixed in a plastic jar using a Turbula® mixer. Then the mixtures were transferred to a platinum crucible with an internal volume of approximately 650 cc and heated at 700°C for 2hr then 800°C for 4 hr, and then the glass melt was poured on a steel plate, and annealed at 500°C.

Example 2

[0080] **Preparation of Glass-ceramic discs** Glass-ceramic discs were prepared from cerammed parts. Precursor glass patties were cerammed in an electronic furnace using a cycle of 700°C to 2 hr for nucleation and then 800°C for 4 hr for crystal growth. After ceramming, the discs (12.5 mm in diameter × 2.0 mm thick) were core-drilled using a diamond drill, and then ground and polished to a 1.0 micrometer finish using a CeO₂ slurry. All finished discs were cleaned by sonicating in an ultrasonic sonicator for 10 min.

Example 3

[0081] **METHOD OF ATTACHMENT AND GROWTH OF BONE CELLS WITH THE BIOACTIVE COMPOSITION OF Example 1** Glass-ceramic discs of Example 2 (made from compositions of the above working Example 1) were placed in wells of 24 well tissue culture treated microplates. Each composition has duplicate discs. MC 3T3 cells were then seeded (20K/2 mL) into the wells and some wells without any discs (Tissue Culture Treated (TCT) control). The microplates were cultured for 1, 4, or 7 days. Cells in the 1 day

culture microplate were fixed with 4% formaldehyde, and then stained with Alexa Fluor 568 phalloidin and DAPI prior to the confocal imaging.

[0082] Figs. 4A and 4B show Day 1 attachment and proliferation of MC3T3 cells on disclosed bioactive glass-ceramic discs of Example compositions 7, 8, 9, and 19 (see Table 1) with respect to a reference bioactive glass control compositions 1 (C-1) and an *in vitro* control: a Tissue Culture Treated® (TCT) well: absolute level (absolute cell number; 4A) and relative levels (relative cell number; 4B).

[0083] Figs. 5A and 5B show cell proliferation results for disclosed compositions 7 to 10. Cells in the day 4 (D4) and day 7 (D7) culture plates were digested with the digestion buffer (125 microg/mL papain, 2 mM L-cysteine, 2mM EDTA) at 65°C for 16 hrs, the dsDNA amount was measured using Quant-iT™ PicoGreen® dsDNA Kit (Thermo Fisher). The increase of DNA concentration with increasing culture time provides additional evidence of their excellent biocompatibility.

[0084] MC3T3 cells were digested with papain and the amount of DNA was measured using a PicoGreen assay. D4 or D7 refers to Day 4 or Day 7 (as in “the 4th day or 7th day of cell culture”). TCT refers to a tissue culture treated microplate substrate available from Corning, Inc®. Glass-ceramic discs were placed in wells of 24 well tissue culture treated microplates. Each composition has duplicate discs. MC 3T3 cells were then seeded (20K/2 mL) into the wells and some wells without any discs (TCT control). The microplates were cultured for 4 or 7 days. On the day 4 and day 7, cells were digested with a digestion buffer (D-PBS containing 125 microg/mL papain, 2 mM L-cysteine, 2 mM EDTA) at 65°C in humid environment with shaking (60 rpm) for 16 hrs. An attempt was made to remove the lysed DNA from glass-ceramic discs by pipetting digestion solution up and down on the discs. The collected digestion solution was briefly centrifuged to remove any remaining particles. The dsDNA amount in the supernatant was measured using Quant-iT™ PicoGreen® dsDNA Kit (Thermo Fisher) according to the manufacturer’s instruction.

Materials:

[0085] MC3T3E1 Subclone 14 (ATCC® CRL2594™)(see atcc.org/products/all/CRL-2594.aspx).

[0086] Quant-iT™ PicoGreen® dsDNA Kit (Invitrogen, #P11496). This kit contains Quant-iT™ PicoGreen® dsDNA Reagent (10 vials, each containing 100 microL aliquots), 25 mL of

20X TE buffer, 1 mL of 100 microg/mL Lambda DNA (dsDNA standard), Papain (Sigma-Aldrich, #P4762-25MG), L-cysteine (Sigma-Aldrich, #C1276-10G), EDTA (Sigma-Aldrich, #E6511), D-PBS (Thermo Fisher, #14190), a shaker set to 65°C, and a plate reader.

[0087] The disclosure has been described with reference to various specific embodiments and techniques. However, it should be understood that many variations and modifications are possible while remaining within the scope of the disclosure.

What is claimed is:

1. A glass-ceramic composition, comprising:
a first crystalline phase comprised of lithium disilicate; and
a second crystalline phase selected from the group consisting of at least one of:
wollastonite, fluoroapatite, cristobalite, β -quartz, lithiophosphate, or a combination thereof.
2. The glass-ceramic composition of claim 1 wherein the first crystalline phase and the second crystalline phase, in combination, comprise a source of:
50 to 75 wt% SiO_2 ,
1 to 5 wt% Al_2O_3 ,
1 to 8 wt% P_2O_5 ,
2 to 10 wt% CaO ,
5 to 20 wt% Li_2O ,
0.5 to 5 wt% Na_2O ,
0.5 to 8 wt% ZrO_2 , and
0.1 to 1.0 wt% F^- , based on a 100 wt% total of the composition.
3. The glass-ceramic composition of any of claims 1 to 2, further comprising a source of
0.1 to 10 wt% B_2O_3 , based on a 100 wt% total of the composition.
4. The glass-ceramic composition of any of claims 1 to 3, wherein the first crystalline phase and the second crystalline phase, in combination, comprise a source of:
50 to 60 wt% SiO_2 ,
1 to 3 wt% Al_2O_3 ,
2 to 6 wt% P_2O_5 ,
4 to 8 wt% CaO ,
7.5 to 12.5 wt% Li_2O ,
0.5 to 2 wt% Na_2O ,
1 to 4 wt% ZrO_2 , and
0.2 to 0.8 wt% F^- , based on a 100 wt% total of the composition.

5. The glass-ceramic composition of any of claims 1 to 4, wherein the composition has a high strength of from 200 MPa to 500 MPa.
6. The glass-ceramic composition of any of claims 1 to 5, wherein the composition has a high fracture toughness of from 1.4 to 2.0 MPa•m^{1/2}.
7. The glass-ceramic composition of any of claims 1 to 6, wherein the composition has a combination of high strength of from 200 MPa to 500 MPa, and high fracture toughness of from 1.4 to 2.0 MPa•m^{1/2}.
8. The glass-ceramic composition of any of claims 1 to 7, wherein the first crystalline phase comprises lithium disilicate and the second crystalline phase comprises apatite, wollastonite, or a mixture thereof.
9. A glass-ceramic precursor glass composition comprising a source of:
 - 50 to 75 wt% SiO₂,
 - 1 to 5 wt% Al₂O₃,
 - 1 to 8 wt% P₂O₅,
 - 2 to 10 wt% CaO,
 - 5 to 20 wt% Li₂O,
 - 0.5 to 5 wt% Na₂O,
 - 0.5 to 8 wt% ZrO₂, and
 - 0.1 to 1.0 wt% F⁻, based on a 100 wt% total of the composition.
10. A method of making the glass-ceramic composition of any of claims 1 to 8 comprising:
 - ceramming a precursor glass mixture comprising a source of:
 - 50 to 75 wt% SiO₂,
 - 1 to 5 wt% Al₂O₃,
 - 1 to 8 wt% P₂O₅,
 - 2 to 10 wt% CaO,
 - 5 to 20 wt% Li₂O,
 - 0.5 to 5 wt% Na₂O,

0.5 to 8 wt% ZrO_2 , and

0.1 to 1.0 wt% F^- , based on a 100 wt% total of the composition, by heating the mixture at 650 to 750 °C for 0.5 to 10 hrs and then heating at 750 to 850 °C for 0.5 to 20 hrs.

11. The method of claim 10 further comprising ion exchanging the resulting glass-ceramic composition to create at least one compressive stress layer on at least one surface of the article to increase mechanical strength.

12. A bioactive composition, comprising:

a glass-ceramic comprised of:

a first crystalline phase comprised of lithium disilicate; and

a second crystalline phase selected from the group consisting of at least one of: wollastonite, fluoroapatite, cristobalite, β -quartz, lithiophosphate, or a combination thereof; and

at least one live osteoblast cell.

13. The bioactive composition of claim 12 wherein the glass-ceramic composition comprises a source of:

50 to 75 wt% SiO_2 ,

1 to 5 wt% Al_2O_3 ,

1 to 8 wt% P_2O_5 ,

2 to 10 wt% CaO ,

5 to 20 wt% Li_2O ,

0.5 to 5 wt% Na_2O ,

0.5 to 8 wt% ZrO_2 , and

0.1 to 1.0 wt% F^- , based on a 100 wt% total of the composition.

14. The bioactive composition of any of claims 12 to 13, wherein the glass-ceramic composition comprises a source of:

50 to 60 wt% SiO_2 ,

1 to 3 wt% Al_2O_3 ,

2 to 6 wt% P_2O_5 ,

4 to 8 wt% CaO,
7.5 to 12.5 wt% Li₂O,
0.5 to 2 wt% Na₂O,
1 to 4 wt% ZrO₂, and
0.2 to 0.8 wt% F⁻, based on a 100 wt% total of the composition.

15. The bioactive composition of claim 14 further comprising a source of 0.1 to 10 wt% B₂O₃, based on a 100 wt% total of the composition.

16. A method of culturing osteoblast cells comprising:
contacting the bioactive composition of any of claims 12 to 14, with a suitable liquid medium.

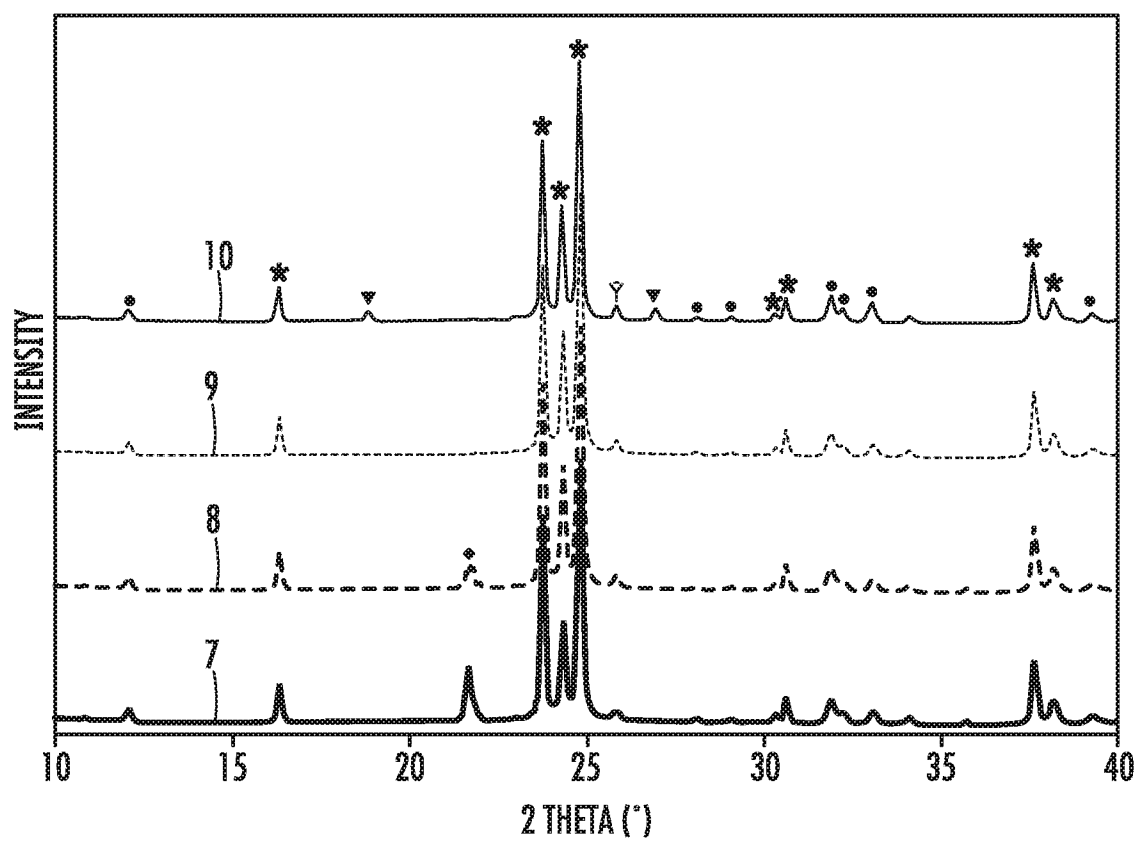
17. The method of claim 16 wherein the contacting produces a proliferation of the osteoblast cells on the surface of the bioactive composition.

18. The method of claim 16 wherein the contacting produces a proliferation of the osteoblast cells in the suitable liquid medium.

19. The method of claim 18 wherein the suitable liquid medium includes a simulated body fluid composition.

20. An article comprising the glass-ceramic composition of claim 1.

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**FIG. 1**

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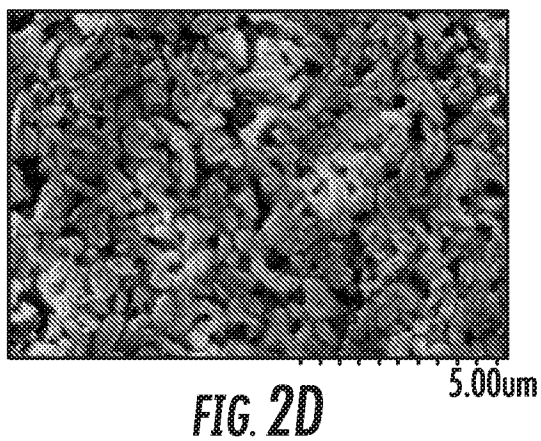
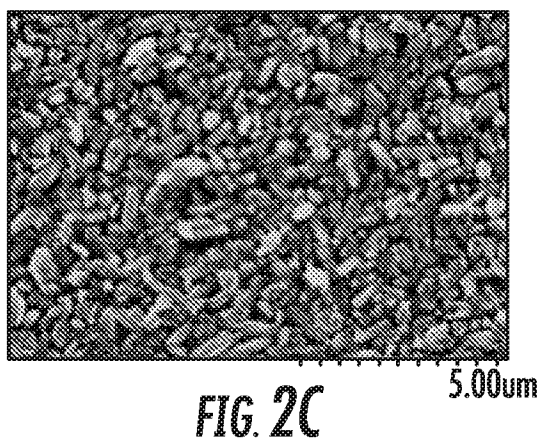
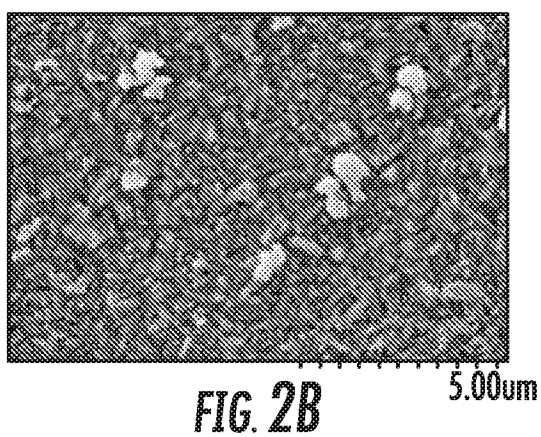
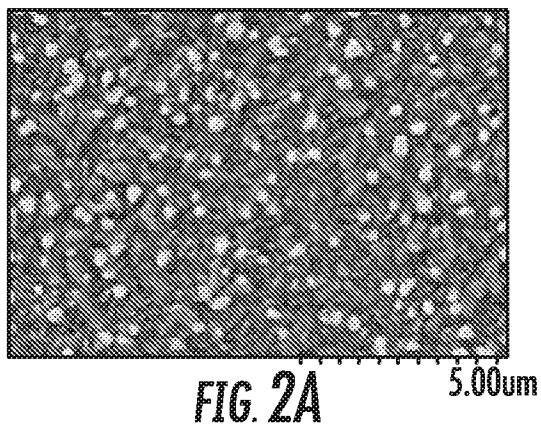


FIG. 2

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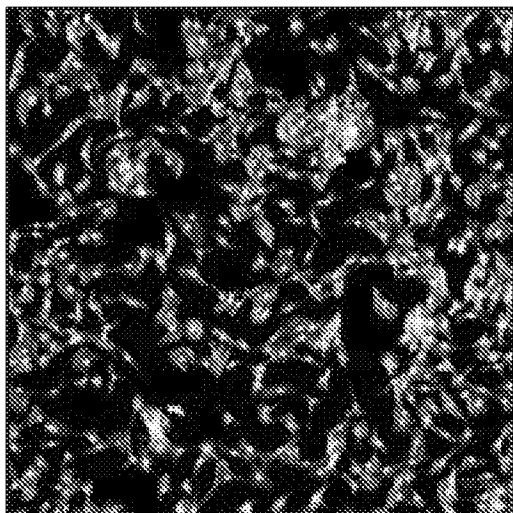


FIG. 3A

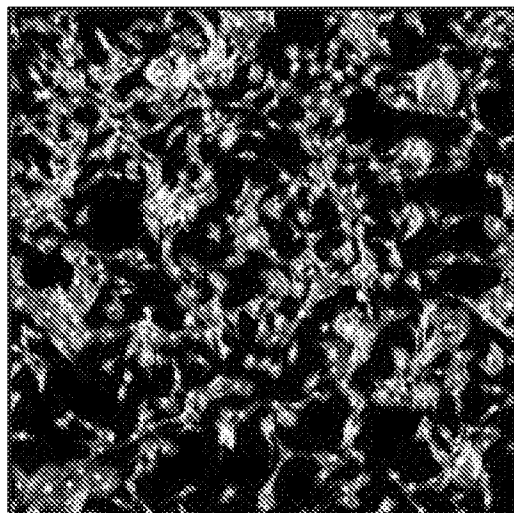


FIG. 3B

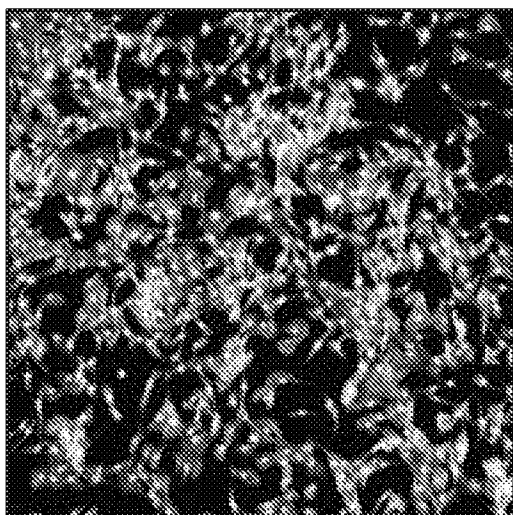


FIG. 3C

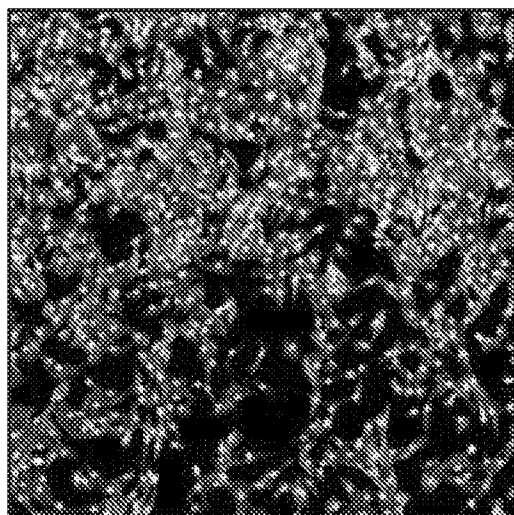
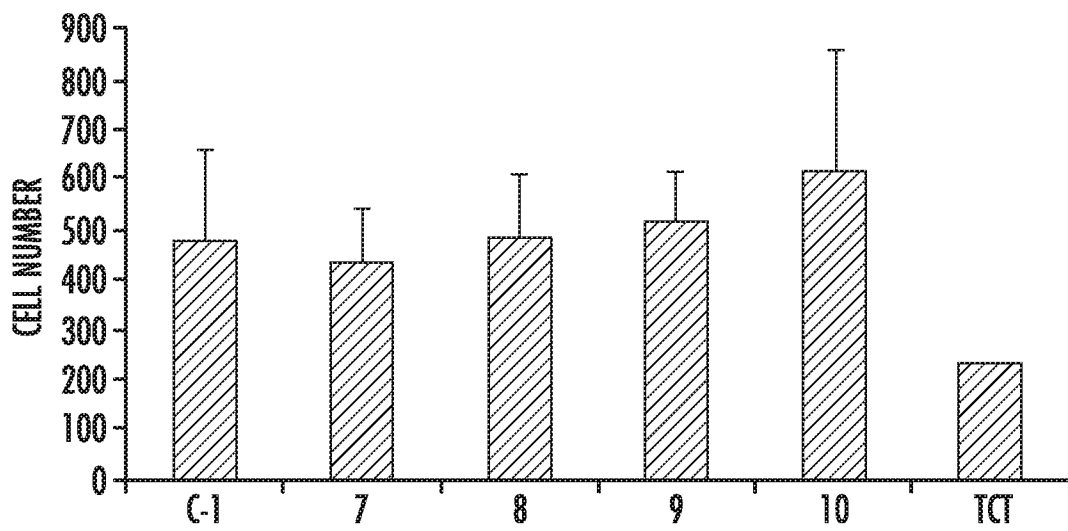
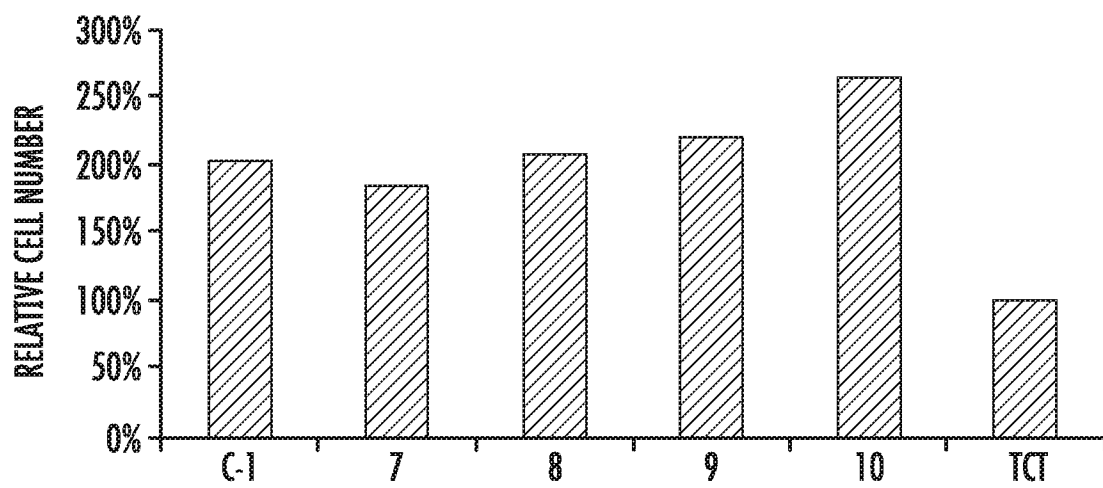


FIG. 3D

FIG. 3

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**FIG. 4A****FIG. 4B****FIG. 4**

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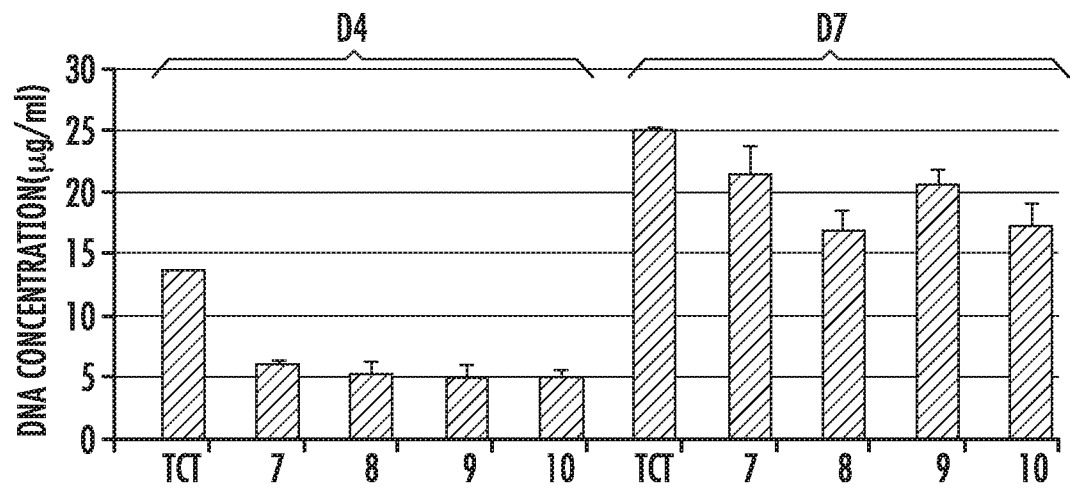


FIG. 5A

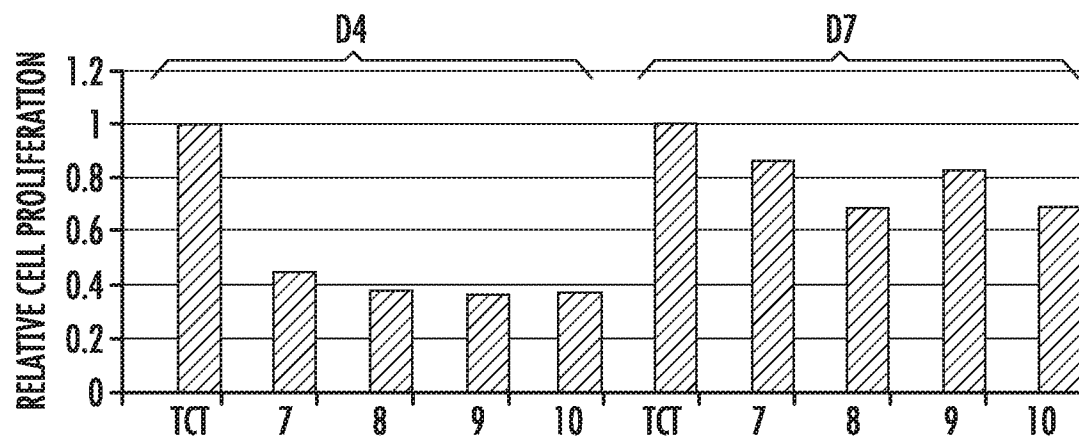


FIG. 5B

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/034421

A. CLASSIFICATION OF SUBJECT MATTER INV. C03C3/097 C03C3/11 C03C3/118 C03C10/00 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) C03C		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 11 July 2017		Date of mailing of the international search report 20/07/2017
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Saldamli, Saltuk

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