



US 20170158552A1

(19) **United States**(12) **Patent Application Publication**
Ritzberger et al.(10) **Pub. No.: US 2017/0158552 A1**(43) **Pub. Date: Jun. 8, 2017**(54) **LITHIUM SILICATE GLASS CERAMIC AND
GLASS WITH ZRO2 CONTENT****Publication Classification**(71) Applicant: **Ivoclar Vivadent AG**, Schaan (LI)(72) Inventors: **Christian Ritzberger**, Nenzing (AT);
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Vaduz (LI)(21) Appl. No.: **15/442,285**(22) Filed: **Feb. 24, 2017****Related U.S. Application Data**(63) Continuation of application No. 14/977,942, filed on
Dec. 22, 2015, now abandoned, which is a continu-
ation of application No. 14/019,716, filed on Sep. 6,
2013, now Pat. No. 9,249,048, which is a continu-
ation of application No. 13/245,125, filed on Sep. 26,
2011, now Pat. No. 8,557,150, which is a continu-
ation-in-part of application No. 13/079,861, filed on
Apr. 5, 2011, now Pat. No. 8,536,078.**Foreign Application Priority Data**Apr. 16, 2010 (EP) 10160222.5
Apr. 18, 2011 (EP) 11162840.0(51) **Int. Cl.****C03C 10/00** (2006.01)
C03C 8/02 (2006.01)
C04B 35/48 (2006.01)
C04B 41/00 (2006.01)
C04B 41/50 (2006.01)
A61C 13/09 (2006.01)
A61C 5/73 (2006.01)
A61C 5/77 (2006.01)
A61C 8/00 (2006.01)
A61C 13/08 (2006.01)
A61C 13/083 (2006.01)
C03C 4/00 (2006.01)
C04B 41/86 (2006.01)(52) **U.S. Cl.**CPC **C03C 10/0027** (2013.01); **C03C 10/0009**
(2013.01); **C03C 4/0021** (2013.01); **C03C 8/02**
(2013.01); **C04B 35/48** (2013.01); **C04B**
41/009 (2013.01); **C04B 41/5023** (2013.01);
C04B 41/86 (2013.01); **A61C 5/73** (2017.02);
A61C 5/77 (2017.02); **A61C 8/0013** (2013.01);
A61C 8/0048 (2013.01); **A61C 13/082**
(2013.01); **A61C 13/083** (2013.01); **A61C**
13/09 (2013.01); **C03C 2204/00** (2013.01);
C04B 2235/3225 (2013.01); **C04B 2235/3246**
(2013.01)

(57)

ABSTRACTLithium silicate glass ceramics and glasses are described
which can advantageously be applied to zirconium oxide
ceramics in particular by pressing-on in the viscous state and
form a solid bond with these.

Fig. 1

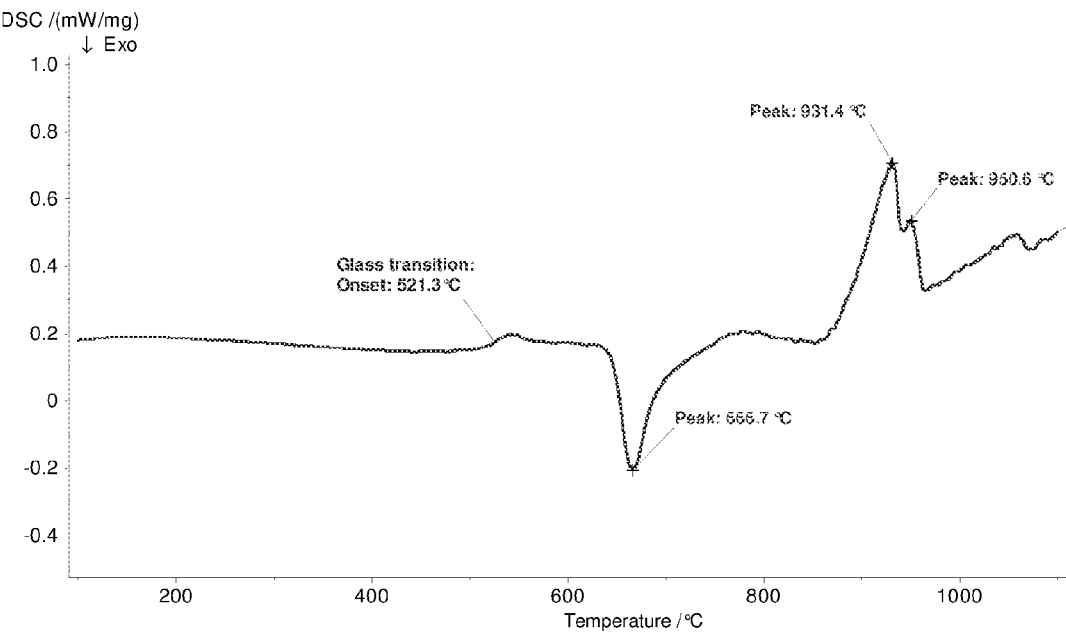


Fig. 2

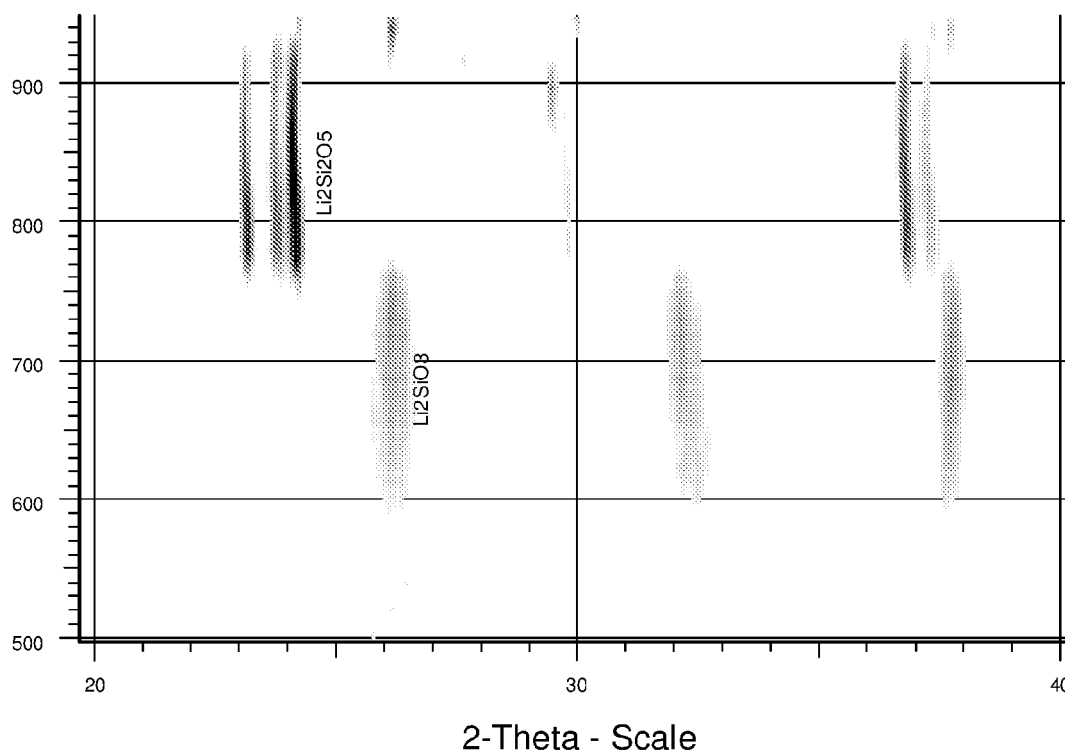


Fig. 3

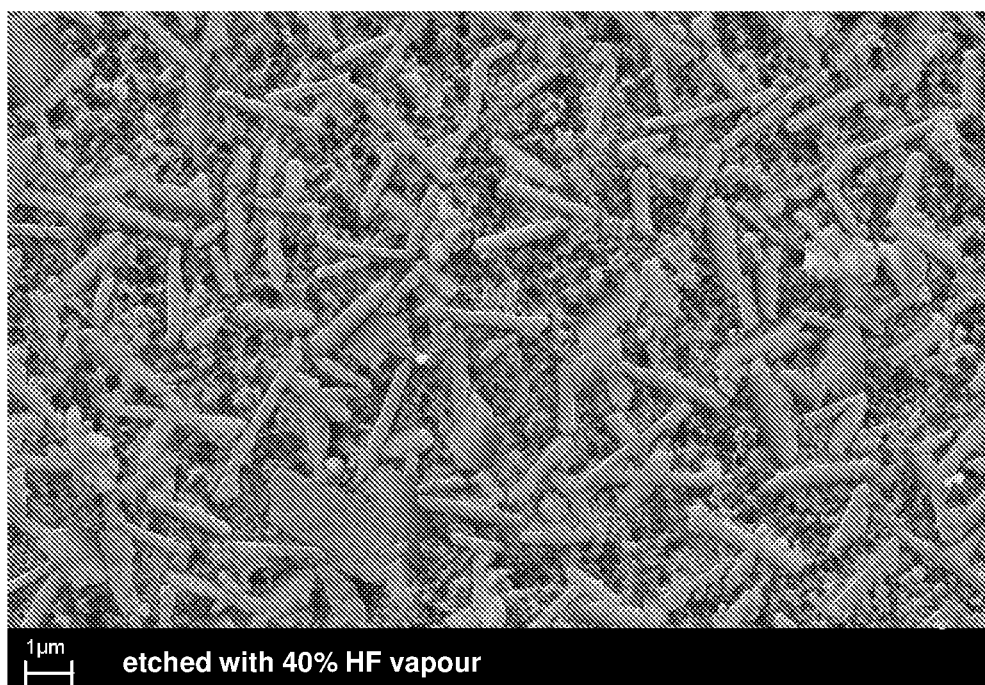
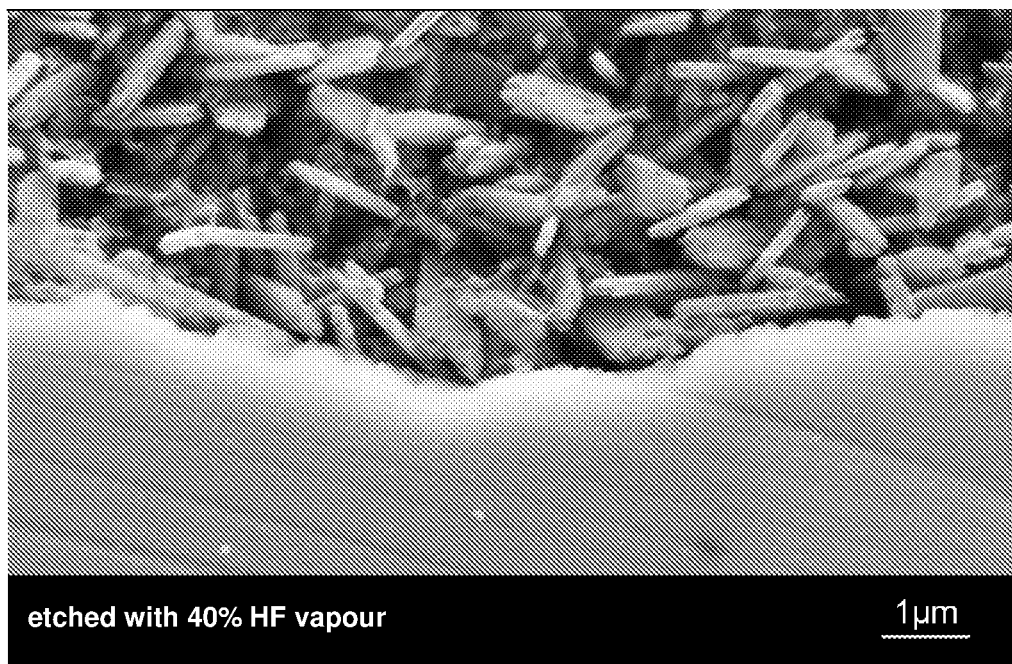


Fig. 4



LITHIUM SILICATE GLASS CERAMIC AND GLASS WITH ZRO₂ CONTENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. application Ser. No. 14/019,716, filed Sep. 6, 2013, which is a continuation of U.S. application Ser. No. 13/245,125, filed Sep. 26, 2011, now U.S. Pat. No. 8,557,150, which is a continuation-in-part application of U.S. application Ser. No. 13/079,861, filed Apr. 5, 2011, now U.S. Pat. No. 8,536,078, which claims the benefit of European Patent Application Serial No. 10160222.5, filed Apr. 16, 2010 and European Patent Application Serial No. 11162840.0 filed Apr. 18, 2011 which are all hereby incorporated by reference in their entirety.

TECHNICAL FIELD

[0002] The invention relates to lithium silicate glass ceramic and glass which comprise ZrO₂ and are suitable in particular for coating zirconium oxide ceramic.

BACKGROUND OF THE INVENTION

[0003] Zirconium oxide ceramics are characterized by excellent biocompatibility and outstanding mechanical properties, which is why in the past they have increasingly been used as a material for implants and prostheses, but also as framework materials for dental restorations. Ceramics based on partially stabilized zirconium oxide are primarily used for this.

[0004] In many cases it is desirable to alter the surface of the zirconium oxide ceramic by coating it with a different material. Specifically when preparing dental restorations based on zirconium oxide ceramic, such a coating is regularly used to give the restoration the desired visual properties.

[0005] Glass ceramics have already been used in the past to coat or veneer oxide ceramics, such as zirconium oxide ceramics. These include feldspar-based ceramics or fluorapatite glass ceramics.

[0006] Lithium disilicate glass ceramics are also known which, because of their high translucency and very good mechanical properties, are used in particular in the dental field and primarily for preparing dental crowns and small bridges.

[0007] EP 1 505 041 and corresponding U.S. Pat. No. 7,316,740, the entirety which is hereby incorporated by reference, describe lithium silicate glass ceramics which can additionally contain 0 to 2 wt.-% ZrO₂. These are processed into the desired dental restorations in particular in the form of lithium metasilicate glass ceramics by means of CAD/CAM methods, wherein a subsequent heat treatment effects the conversion of the metasilicate phase to the high-strength disilicate phase. The glass ceramics can also be used for pressing over ceramic restorations.

[0008] EP 1 688 398 and corresponding U.S. Pat. No. 7,452,836, the entirety which is hereby incorporated by reference, describe similar lithium silicate glass ceramics which are substantially free of ZnO and in addition to other components can contain 0 to 4 wt.-% ZrO₂. To achieve high strengths, however, small quantities of from 0 to 2 wt.-% ZrO₂ are preferred. These glass ceramics also serve in

particular to prepare dental restorations after mechanical processing by means of CAD/CAM.

[0009] However, these lithium silicate glass ceramics known from the state of the art have the disadvantage that they are not suitable for coating zirconium oxide ceramic in particular by means of a pressing-on in the viscous state, since after the pressing-on in the viscous flow process cracks and flaws form in the glass ceramic. Thus, such a composite does not have the mechanical properties that are indispensable specifically for use as dental restoration material.

[0010] Glass ceramics with lithium disilicate as main crystal phase which are to be suitable for veneering dental restorations comprising yttrium-stabilized zirconium dioxide are also known from WO 2008/106958 and corresponding U.S. Published Application No. 2011030423, the entirety which is hereby incorporated by reference. However, these glass ceramics contain quantities of only up to 6.0 wt.-% of ZrO₂ and substantial quantities of Na₂O. The ZrO₂ present acts merely as a standard nucleating agent together with an optionally present further nucleating agent such as TiO₂ in order to effect the formation of the desired lithium disilicate crystal phase.

SUMMARY OF THE INVENTION

[0011] In view of the above-described disadvantages of the already known glass ceramics, the object of the invention is to provide a glass ceramic which can be coated onto a zirconium oxide ceramic in particular by pressing it on in the viscous state and in the process forms a coating substantially free of cracks and flaws. Moreover, the glass ceramic should be capable of forming a solid bond with the zirconium oxide ceramic to be coated, and it should have visual and mechanical properties enabling it to be used in particular as a coating material for dental restorations but also as a material for preparing dental restorations.

[0012] This object is achieved by the lithium silicate glass ceramic according to any one of the claims, incorporated herein. Also a subject of the invention are the lithium silicate glass with nuclei, the starting glass, the process for preparing the glass ceramic and the glass with nuclei, the use, the process for coating a zirconium oxide ceramic and the coated zirconium oxide ceramic.

[0013] The lithium silicate glass ceramic according to the invention is characterized in that it comprises at least 6.1 wt.-% ZrO₂ and in particular at least 6.5, preferably at least 7.0, more preferably at least 8.0 and particularly preferably at least 10.0 wt.-% ZrO₂.

[0014] In a further preferred embodiment, the glass ceramic comprises in particular 6.1 to 20.0 wt.-%, preferably 8.0 to 20.0 wt.-%, particularly preferably 8.0 to 18.0 wt.-% and quite particularly preferably 10.0 to 16.0 wt.-% ZrO₂.

[0015] Further, a glass ceramic which comprises 55.0 to 71.0, preferably 60.0 to 71.0 and in particular 60 to 69 wt.-% SiO₂ is preferred.

[0016] In addition, a glass ceramic which comprises 9.0 to 17.0 and in particular 11 to 15 wt.-% Li₂O is preferred.

[0017] Furthermore, it has proven particularly preferable if the glass ceramic comprises 0.5 to 12.0 and in particular 2.5 to 7.0 wt.-% nucleating agents. Preferred nucleating agents are selected from P₂O₅, TiO₂, Nb₂O₅, metals, e.g. Pt, Pd, Au and Ag, or mixtures thereof. Particularly preferably, the glass ceramic comprises P₂O₅ as nucleating agent. Surprisingly, P₂O₅ as nucleating agent in particular effects the formation of desired lithium disilicate crystals while largely

preventing the formation of ZrO_2 -containing crystal phases which could cause a substantial deterioration in translucency. Through its use the formation of other undesired secondary crystal phases is apparently also largely prevented.

[0018] The glass ceramic according to the invention preferably comprises a further alkali metal oxide in a quantity of from 1.0 to 7.0, preferably 2.0 to 7.0 and particularly preferably 2.0 to 5.0 wt.-%. The term “further alkali metal oxide” denotes alkali metal oxide with the exception of Li_2O . The further alkali metal oxide is in particular K_2O , Cs_2O and/or Rb_2O and is particularly preferably K_2O . It is assumed that the use of K_2O contributes to the strengthening of the glass network compared with the Na_2O used in conventional glass ceramics. It is preferred that the glass ceramic comprises less than 2.0, in particular less than 1.0, preferably less than 0.5 and particularly preferably essentially no Na_2O .

[0019] It is further preferred that the glass ceramic comprises up to 5.0 wt.-% alkaline earth metal oxide, wherein the alkaline earth metal oxide is in particular CaO , BaO , MgO , SrO or a mixture thereof.

[0020] Further, a glass ceramic which comprises 0.2 to 10.0, in particular 2.5 to 7.0 and preferably 2.5 to 3.5 wt.-% oxide of trivalent elements is preferred, wherein this oxide is selected in particular from Al_2O_3 , Y_2O_3 , La_2O_3 , Bi_2O_3 and mixtures thereof, and preferably is Al_2O_3 .

[0021] A glass ceramic which comprises at least one and preferably all of the following components is particularly preferred:

Component	wt.-%
SiO_2	55.0 to 71.0
Li_2O	9.0 to 17.0
K_2O	1.0 to 7.0, in particular 2.0 to 5.0
Al_2O_3	0.5 to 5.0, in particular 2.5 to 3.5
P_2O_5	0.5 to 12.0, in particular 2.5 to 7.0
ZrO_2	6.1 to 20.0, in particular 8.0 to 20.0.

[0022] The glass ceramic according to the invention can moreover also comprise additional components which are selected in particular from further oxides of tetravalent elements, further oxides of pentavalent elements, oxides of hexavalent elements, melt accelerators, colourants and fluorescent agents.

[0023] The term “further oxides of tetravalent elements” denotes oxides of tetravalent elements with the exception of SiO_2 and ZrO_2 . Examples of further oxides of tetravalent elements are SnO_2 and GeO_2 .

[0024] The term “further oxides of pentavalent elements” denotes oxides of pentavalent elements with the exception of P_2O_5 . An example of a further oxide of pentavalent elements is Bi_2O_5 .

[0025] Examples of oxides of hexavalent elements are WO_3 and MoO_3 .

[0026] A glass ceramic which comprises at least one further oxide of tetravalent elements, one further oxide of pentavalent elements or one oxide of hexavalent elements is preferred.

[0027] Examples of melt accelerators are fluorides.

[0028] Examples of colourants and fluorescent agents are oxides of d- and f-elements, such as e.g. the oxides of Ti, Sc, Mn, Fe, Ag, Ta, W, Ce, Pr, Nd, Tb, Er and Yb.

[0029] The term “main crystal phase” used below denotes the crystal phase which has the highest proportion by volume compared with other crystal phases.

[0030] The glass ceramic according to the invention preferably comprises lithium metasilicate as main crystal phase. In particular the glass ceramic comprises more than 10 vol.-%, preferably more than 20 vol.-% and particularly preferably more than 30 vol.-% of lithium metasilicate crystals, relative to the total glass ceramic.

[0031] In a further preferred embodiment, the glass ceramic comprises lithium disilicate as main crystal phase. In particular the glass ceramic comprises more than 10 vol.-%, preferably more than 20 vol.-% and particularly preferably more than 30 vol.-% of lithium disilicate crystals, relative to the total glass ceramic.

BRIEF DESCRIPTION OF THE FIGURES

[0032] Further advantages, details and features emerge from the following description of embodiments of the invention on the basis of the drawings, in which:

[0033] FIG. 1 shows the result of the differential scanning calorimetry (DSC) of a pounded glass cylinder according to Example 29.

[0034] FIG. 2 shows, using high-temperature X-ray diffraction (HT-XRD) of a glass cylinder, the dependence of the formation of lithium metasilicate (Li_2SiO_3) and lithium disilicate ($\text{Li}_2\text{Si}_2\text{O}_5$) from the temperature.

[0035] FIG. 3 shows a scanning electron microscopy (SEM) photograph of a crystallized cylinder of Example 29 which has been polished and etched for 30 s with HF vapour.

[0036] FIG. 4 shows a scanning electron microscopy (SEM) photograph of the bond between a lithium disilicate glass ceramic according to Example 5 and a zirconium oxide ceramic after etching with 40% HF vapour.

DETAILED DESCRIPTION

[0037] The lithium disilicate glass ceramic according to the invention shows particularly good mechanical properties and can be produced by heat treatment of the lithium metasilicate glass ceramic according to the invention.

[0038] It was surprisingly shown that, despite its high ZrO_2 content, the lithium disilicate glass ceramic according to the invention has advantageous mechanical parameters, such as high fracture toughness values, and can be applied to zirconium oxide ceramic in the viscous state by sintering-on or in particular pressing-on, without resultant stresses in the glass ceramic which manifest themselves in cracks or flaws. It is particularly surprising that these very good mechanical properties are achieved although the structure of the glass ceramic has lithium disilicate crystals which are not normally cross-linked to one another. On the other hand, such a cross-linking occurs with the known lithium disilicate glass ceramics and it is regarded as a key reason for their high strengths. It is currently assumed that the ZrO_2 in the glass ceramic according to the invention, unlike in known products, does not serve as a nucleating agent for other crystal phases, but rather strengthens the glass network via Zr—O polyhedra embedded therein. These polyhedra can be $[\text{ZrO}_{6/2}]^{2-}$ or $[\text{ZrO}_{8/2}]^{4-}$ structural units which function as network formers or network modifiers.

[0039] It is also surprising that, despite its high ZrO_2 content, the lithium disilicate glass ceramic according to the invention has a high translucency and that no amorphous-

amorphous phase separation occurs and that it can thus be used for the aesthetically pleasing coating of in particular dental restorations based on zirconium oxide ceramic.

[0040] The lithium disilicate crystals present in the lithium disilicate glass ceramic according to the invention have in particular the form of small plates. It is assumed that this special morphology allows the crack-free material bond with zirconium oxide ceramics. The build-up of critical stresses in the material bond during the thermal cooling phase seems to be less strongly pronounced in the small-plate shaped crystal form than in lithium disilicate glass ceramics with elongated or needle-shaped crystals. In addition, a good fracture toughness, expressed by the K_{IC} value, is achieved with the small-plate shaped crystal morphology.

[0041] The lithium disilicate glass ceramic according to the invention has in particular a fracture toughness, measured as K_{IC} value, of at least $1.5 \text{ MPa}\cdot\text{m}^{0.5}$ and in particular more than $1.8 \text{ MPa}\cdot\text{m}^{0.5}$. Furthermore, it has a high biaxial fracture toughness of preferably from 200 to 500 MPa. Moreover, it shows a high chemical resistance which was determined by mass loss after storage in acetic acid. The chemical resistance is in particular less than $60 \text{ }\mu\text{g}/\text{cm}^2$. Finally, it has a linear coefficient of thermal expansion of in particular less than $10.3 \times 10^{-6} \text{ K}^{-1} \text{ m/m}$, measured in the range of from 100 to 500°C ., which is thus as a rule smaller than that of the zirconium oxide ceramic to be coated.

[0042] The invention also relates to a lithium silicate glass with nuclei that are suitable for forming lithium metasilicate and/or lithium disilicate crystals, wherein the glass comprises the components of the above-described glass ceramics according to the invention. This glass thus comprises at least 6.1 wt.-% ZrO_2 . With regard to preferred embodiments of this glass, reference is made to the above-described preferred embodiments of the glass ceramics according to the invention.

[0043] The glass with nuclei according to the invention can be produced by heat treatment of a correspondingly composed starting glass, which forms a further aspect of the present invention. By a further heat treatment the lithium metasilicate glass ceramic according to the invention can then be formed, which in turn can be converted into the lithium disilicate glass ceramic according to the invention by further heat treatment. The starting glass, the glass with nuclei and the lithium metasilicate glass ceramic can consequently be seen as precursors for the production of the high-strength lithium disilicate glass ceramic.

[0044] The glass ceramic according to the invention and the glass according to the invention are present in particular in the form of powders or blanks, as they can easily be further processed in these forms. They can, however, also be present in the form of dental restorations, such as inlays, onlays, crowns, veneers, or abutments.

[0045] The invention also relates to a process for preparing the glass ceramic according to the invention and the glass with nuclei according to the invention, in which a starting glass with the components of the glass ceramic or the glass is subjected to at least one heat treatment in the range of from 450 to 950°C .

[0046] The starting glass according to the invention therefore comprises at least 6.1 wt.-% ZrO_2 . In addition, it preferably also comprises suitable quantities of SiO_2 and Li_2O in order to make the formation of a lithium silicate glass ceramic possible. Furthermore, the starting glass can also comprise further components, such as are given above

for the lithium silicate glass ceramic according to the invention. Those embodiments are preferred which are also stated as preferred for the glass ceramic.

[0047] To prepare the starting glass, the procedure is in particular that a mixture of suitable starting materials, such as e.g. carbonates, oxides, phosphates and fluorides, is melted at temperatures of in particular from 1300 to 1600°C . for 2 to 10 h. To achieve a particularly high homogeneity, the obtained glass melt is poured into water in order to form a glass granulate, and the obtained granulate is then melted again.

[0048] The melt can then be poured into moulds to produce blanks of the starting glass, so-called solid glass blanks or monolithic blanks.

[0049] It is also possible to pour the melt into water again in order to prepare a granulate. This granulate can then be pressed, after grinding and optionally adding of further components, such as colourants and fluorescent agents, to form a blank, a so-called powder green compact.

[0050] Finally, the starting glass can also be processed to form a powder after granulation.

[0051] The starting glass is then subjected, e.g. in the form of a solid glass blank, a powder green compact or in the form of a powder, to at least one heat treatment in the range of from 450 to 950°C . It is preferred that a first heat treatment is initially carried out at a temperature in the range of from 500 to 600°C . to prepare a glass according to the invention with nuclei which are suitable for forming lithium metasilicate and/or lithium disilicate crystals. This glass can then preferably be subjected to at least one further temperature treatment at a higher temperature and in particular more than 570°C . to effect crystallization of lithium metasilicate or lithium disilicate.

[0052] The at least one heat treatment carried out in the process according to the invention can also take place during the pressing or sintering of the glass according to the invention or the glass ceramic according to the invention onto the selected zirconium oxide ceramic.

[0053] Dental restorations, such as inlays, onlays, crowns, veneers or abutments, can be prepared from the glass ceramic according to the invention and the glass according to the invention. The invention therefore also relates to their use for the preparation of dental restorations. In this connection it is preferred that the glass ceramic or the glass are shaped to the desired dental restoration by means of pressing or machining. The pressing is usually conducted at elevated pressure and elevated temperature. For the pressing in particular the starting glass according to the invention and preferably the glass with nuclei according to the invention, the lithium metasilicate glass ceramic according to the invention and the lithium disilicate glass ceramic according to the invention can be used in a suitable manner, e.g. in the form of blanks. The machining is usually carried in a CAD/CAM process and the machining preferably uses the lithium metasilicate and lithium disilicate glass ceramic according to the invention, in particular in the form of suitable blanks. After preparation of the dental restoration of the desired shape by pressing or machining it is possible to heat treat the restoration to convert precursors, such as the starting glass, the glass with nuclei or lithium metasilicate glass ceramic, into lithium disilicate glass ceramic.

[0054] The glass ceramic according to the invention and the glass according to the invention are, however, suitable in particular for coating zirconium oxide ceramics. The inven-

tion is therefore also directed towards the use of the glass according to the invention or the glass ceramic according to the invention for coating zirconium oxide ceramics.

[0055] The invention also relates to a process for coating zirconium oxide ceramic, in which the glass ceramic according to the invention or the glass according to the invention is applied to the zirconium oxide ceramic and is subjected to increased temperature.

[0056] This can take place in particular by sintering-on and preferably by pressing-on. With the sintering-on, the glass ceramic or the glass is applied to the ceramic to be coated in the usual way, e.g. as powder, and then sintered at increased temperature. With the preferred pressing-on, the glass ceramic according to the invention or the glass according to the invention is pressed on, e.g. in the form of powder green compacts or monolithic blanks, at an increased temperature of e.g. from 700 to 1200° C., applying pressure, e.g. 2 to 10 bar. The methods described in EP 231 773 and the press furnace disclosed there can be used in particular for this. A suitable furnace is e.g. the Programat EP 5000 from Ivoclar Vivadent AG, Liechtenstein.

[0057] It is preferred that, after conclusion of the coating process, the glass ceramic according to the invention is present with lithium disilicate as main crystal phase, as it has particularly good properties. It is surprisingly shown that the glass ceramic according to the invention has practically no flaws and cracks once it has been coated onto the zirconium oxide ceramic, and a solid bond between glass ceramic and ceramic is achieved.

[0058] It is preferred that the zirconium oxide ceramic comprises at least one oxide of Ce, Y, Sr, Ca or Mg for stabilizing the tetragonal phase. The zirconium oxide ceramic can also be present in the form of a composite with other inorganic components.

[0059] The zirconium oxide ceramic coated with the glass ceramic according to the invention or the glass according to the invention forms a further subject of the invention.

[0060] In view of the above-described properties of the glass ceramic according to the invention and the glass according to the invention as its precursor, they are also suitable in particular for use in dentistry. A subject of the invention is therefore also the use of the glass ceramic according to the invention or the glass according to the invention as a dental material and in particular for preparing dental restorations or as a coating material for dental restorations, such as crowns and bridges.

[0061] It is surprising that no cracks in the glass ceramic occur in the bond between the lithium disilicate glass ceramic according to the invention and zirconium oxide ceramic. It is presumed that in particular the special small-plate shaped morphology of the lithium disilicate crystals is of importance for this. The build-up of critical stress in the material bond during the thermal cooling phase seems to be less strongly pronounced in the small-plate shaped crystal form than in lithium disilicate glass ceramics with elongated or needle-shaped crystals. In addition a good fracture toughness of up to 2.1 MPa·m^{0.5} is achieved in particular with the small-plate shaped crystal morphology, although a direct cross-linking of the lithium disilicate crystals is essentially not to be seen in the structure. The coated zirconium oxide ceramic according to the invention is thus a strong compound between high-strength and high-toughness zirconium oxide ceramic on the one hand and tough glass ceramic on the other, which is why this compound can absorb high loads

in the chewing cycle. The glass ceramic according to the invention can thus advantageously also be used directly in the coating of long-span bridges with more than three members based on zirconium oxide ceramic.

[0062] Finally, the glasses and glass ceramics according to the invention can also be mixed with other glasses and glass ceramics to give dental materials having desirably adjusted properties. Therefore, a glass or glass ceramic comprising the glass according to the invention or the glass ceramic according to the invention represents a further embodiment of the invention. The glass according to the invention or the glass ceramic according to the invention can therefore in particular be used as main component of an inorganic-inorganic composite or can be used in combination with a multitude of other glasses and/or glass ceramics. These composites or combinations are preferably used as dental materials. It is particularly preferred to use the composites and combinations in the form of sintered blanks. Examples of other glasses and glass ceramics for producing inorganic-inorganic composites and mixtures are disclosed in DE 43 14 817, corresponding U.S. Pat. No. 5,432,130, DE 44 23 793, corresponding U.S. Pat. No. 5,698,019, DE 44 28 839, corresponding U.S. Pat. No. 5,618,763, DE 196 47 739, corresponding U.S. Pat. Nos. 6,342,458, 5,968,856, and 6,514,893, DE 197 25 552 and DE 100 31 431, all of which are hereby incorporated by reference. These glasses and glass ceramics belong to the silicate, borate, phosphate or aluminosilicate group. Preferred glasses and glass ceramics are of the SiO₂—Al₂O₃—K₂O type (with cubic or tetragonal leucite crystals), SiO₂—B₂O₃—Na₂O type, alkali-silicate type, alkali-zinc-silicate type, silico-phosphate type and/or SiO₂—ZrO₂ type. By mixing such glasses and/or glass ceramics with the glasses and/or glass ceramics according to the invention it is for example possible to adjust the thermal coefficient of expansion in the desired manner in a broad range of 6 to 20·10⁻⁶/K. The invention is described in further detail below with reference to examples.

EXAMPLES

Examples 1 to 28—Composition and Crystal Phases

[0063] A total of 28 glasses and glass ceramics according to the invention with the composition given in tables I to IV were prepared by melting corresponding starting glasses followed by heat treatment for controlled nucleation and crystallization.

[0064] For this, the starting glasses were firstly melted in a 100 to 200 g scale from usual raw materials at 1400 to 1500° C. and transformed into glass frits by pouring them into water. These glass frits were then melted a second time at 1450 to 1550° C. for 1 to 3 h for the homogenization. The obtained glass melts were poured into pre-heated moulds to produce glass monoliths. These glass monoliths were transformed into glasses and glass ceramics according to the invention by thermal treatment.

[0065] The applied thermal treatment for the controlled nucleation and controlled crystallization is given in table V for selected examples. The first heat treatment in the range of from 500 to 560° C. usually led to the formation of lithium silicate glasses with nuclei for lithium metasilicate or lithium disilicate crystals, the second heat treatment at 650 to 710° C. to the formation of lithium metasilicate glass

ceramics and the third heat treatment in the range of from 800 to 920° C. to the formation of lithium disilicate glass ceramics.

[0066] In some examples, a second non-isothermal heat treatment with simultaneous analysis of the formed crystal phases was carried out at the respectively given temperature by high-temperature X-ray diffraction (HT-XRD) after a first heat treatment.

[0067] The crystal phases obtained after conclusion of all the heat treatments are also listed in table V. Surprisingly, glass ceramics with lithium disilicate as main crystal phase were always obtained. Examples 5 and 6 were additionally repeated, by carrying out only the first and second heat treatment. In this way, glass ceramics with lithium metasilicate as main crystal phase were produced.

[0068] Despite the high ZrO₂ content of up to 20 wt.-%, only in example 8 ZrO₂ crystallized as secondary crystal phase.

Example 29—Glass and Glass Ceramic Blanks

[0069] A glass with the composition according to example 5 was prepared by mixing corresponding raw materials in the form of oxides and carbonates for 30 min in a Turbula mixer and then melting the mixture at 1450° C. for 120 min in a platinum crucible. The melt was poured into water in order to obtain a finely divided glass granulate. This glass granulate material was melted again at 1530° C. for 150 min in order to obtain a glass melt with particularly high homogeneity. The temperature was reduced to 1500° C. for 30 min and cylindrical glass blanks with a diameter of 12.5 mm were then poured into pre-heated, separable steel moulds or graphite moulds. The obtained glass cylinders were then stress-relieved at 550° C. A glass with nuclei for lithium metasilicate or lithium disilicate crystals was obtained.

[0070] FIG. 1 shows the result of the differential thermal analysis (DSC) of a pounded glass cylinder.

[0071] FIG. 2 shows, using high-temperature X-ray diffraction (HT-XRD) of a glass cylinder, the dependence of the formation of lithium metasilicate (Li₂SiO₃) and lithium disilicate (Li₂Si₂O₅) from the temperature.

[0072] The glass cylinders were then subjected to a first crystallization at 680 to 700° C. for 20 min. The heating rate was 15° C. per minute. The glass cylinders were then subjected to a second crystallization at 850 to 880° C. for 30 min. After this treatment, the crystal phase analysis showed a glass ceramic according to the invention with lithium disilicate as main crystal phase as well as small proportions of lithium metasilicate and lithium phosphate as secondary phases.

[0073] FIG. 3 shows a scanning electron microscopy (SEM) photograph of a crystallized cylinder which has been polished and etched for 30 s with HF vapour.

[0074] The crystallized cylinders were moreover further processed by hot-pressing at a pressing temperature of 910° C. using an EP600 press furnace, Ivoclar Vivadent AG, to form testpieces. The properties of these testpieces were as follows:

[0075] Colour: white, translucent without fluorescence

[0076] Solubility: 24 µg/cm² (according to ISO 6872 of Sep. 1, 2008)

[0077] Biaxial strength: 420 MPa (according to ISO 6872 of Sep. 1, 2008)

[0078] Fracture toughness: 2.0 MPam^{0.5} (determined as K_{IC} value using the SEVNB method according to ISO 6872 of Sep. 1, 2008)

[0079] Coefficient of thermal expansion: 9.9*10⁻⁶*1/K (in the range 100 to 500° C.)

Example 30—Hot-Pressing onto Zirconium Oxide Ceramic

[0080] The lithium disilicate glass ceramic according to example 5 was pressed by hot-pressing at 920° C. onto zirconium oxide ceramic of the type 3 Y-TZP, obtainable from Tosoh, in a Programat EP 5000 combined press and firing furnace from Ivoclar Vivadent AG, Liechtenstein. After conclusion of the coating process, a defect-free join resulted.

[0081] FIG. 4 shows a scanning electron microscopy (SEM) photograph of this bond after etching with 40% HF vapour.

Example 31—Hot-Pressing onto Small Tooth Caps and Bridge Frameworks

[0082] Single small tooth caps and four-element bridge frameworks of densely sintered zirconium oxide (e.max ZirCAD, Ivoclar Vivadent AG) were made up into anatomically shaped restorations with a plastic that can be burned out (PMMA). Both the bridge frameworks and the plastic parts were manufactured by CAD/CAM processes, whereby a reproducible geometry and layer thickness were able to be achieved. The restorations were invested in dental investment compound (IPS PressVest Speed, Ivoclar Vivadent AG), the plastic was burned out and the crystallized cylinders according to example 29 were pressed directly onto the frameworks at a temperature of 910° C. No intermediate layer (liner) was applied to the zirconium oxide.

[0083] After the complete cooling, the articles were devested with a sandblaster, wherein no special precaution was necessary, because of the high strength of the coated-on glass ceramic. The articles were separated from the compression channels, reworked dry with a diamond grinder, and then treated for 20 min with IPS INVEX Liquid (Ivoclar Vivadent AG) under ultrasound, in order to loosen any remaining residues of investment compound, which were then sandblasted with Al₂O₃ sand with a grain size of 100 µm at 1-2 bar pressure.

[0084] The surface was cleaned with hot steam and glazed twice with IPS e.max Ceram Glaze (Ivoclar Vivadent AG) at 770° C., whereby an attractive gloss was produced. No special cooling (relaxation cooling) was applied during the glazing firing. The thus-prepared restorations, i.e. crowns and bridges, were aesthetically pleasing and defect-free. They showed no cracks, bubbles or raised areas. After sawing, an excellent bond between the coated-on lithium disilicate glass ceramic according to the invention and the zirconium oxide was recognizable by means of SEM in the cross-section.

[0085] In each case 8 crowns and 8 bridges were subjected to thermocycling of from 5 to 55° C. in a chewing machine (Willitec) with 300,000 cycles while stored in water. The test strength was 30, 60 or 90 N during every 100,000 cycles. The load was applied with a frequency of 0.8 Hz. There were no chippings at all in the veneer structure.

Example 32—Glass and Glass Ceramic Blanks

[0086] Example 29 was repeated with the difference that a glass with the composition according to example 23 was used as a starting material. The obtained crystallized cylinders were further processed into testpieces by hot-pressing at a temperature of 905° C. The properties of these testpieces were as follows:

[0087] Colour: tooth coloured, translucent with tooth-like fluorescence

[0088] Solubility: 30 µg/cm² (according to ISO 6872 of Sep. 1, 2008)

[0089] Biaxial strength: 405 MPa (according to ISO 6872 of Sep. 1, 2008)

[0090] Coefficient of thermal expansion: $9.9 \cdot 10^{-6} \cdot 1/K$ (in the range 100 to 500° C.)

Example 33—Hot-Pressing onto Small Tooth Caps and Bridge Frameworks

[0091] Example 31 was repeated with the difference that the crystallized cylinders according to example 32 were used. After up to four final glazing firings, crowns and bridges were obtained which again showed no cracks, bubbles or raised areas.

Example 34—Glass Ceramic Blank (Powder Green Compact)

[0092] Analogously to examples 1 to 28, a starting glass with the composition according to example 24 was melted twice. However, the glass was then not poured into steel moulds, but quenched in water in order to obtain a finely divided glass granulate. The glass granulate material was thermally treated at 550° C. for 20 min and then at 680° C. for 20 min in order to effect the nucleation and the first crystallization. The thus pre-treated granulate was dry-ground to an average grain size of 20 µm and mixed with 0.1 wt.-% of a ceramic colouring pigment. The mixture was moistened with some water and pressed to form a powder green compact at a pressing pressure of 20 MPa. The powder green compact was sintered at 850° C. for 30 min. The crystal phase analysis of the sintered blank showed lithium disilicate as main crystal phase as well as in each case small proportions of lithium metasilicate and lithium phosphate as secondary phases.

[0093] The sintered blanks were further processed into testpieces by hot-pressing at 905° C. using the EP600 press furnace (Ivoclar Vivadent AG). The properties of the testpieces were as follows:

[0094] Colour: tooth coloured, translucent and tooth-like fluorescence

[0095] Biaxial strength: 302 MPa (according to ISO 6872 of Sep. 1, 2008)

Example 35—Hot-Pressing onto Small Tooth Caps

[0096] Example 31 was repeated with the difference that the sintered blanks according to example 34 were used to compress over small tooth caps. After two final glazing firings, crowns were obtained which again showed no cracks, bubbles or raised areas.

Example 36—Sintering onto Small Tooth Caps

[0097] Analogously to example 34, glass ceramic powder of the composition according to example 24 coloured with

0.1 wt.-% pigment was prepared. However, this time, no powder blanks were pressed. The powder was blended with a modelling liquid (e.max Ceram Build Up Liquid, Ivoclar Vivadent AG) and the mixture was applied to a prefabricated zirconium oxide single small tooth cap in order to model an occlusal morphology. The coated-on mixture was then sintered in a dental furnace (P500, Ivoclar Vivadent AG) at a holding temperature of 850° C. and with a residence time of 2 min.

[0098] After the sintering-on, the crowns were trimmed with diamond grinders and coated a second time. Two further glazing firings then took place at a temperature of 770° C. Aesthetically high-quality tooth-coloured crowns with natural-looking fluorescence and opalescence resulted. These also showed no cracks, bubbles or raised areas.

Example 37—Direct Preparation of Dental Restorations by Hot-Pressing or Machining (CAD/CAM)

[0099] (A) Blanks of Glass with Nuclei

[0100] First of all glasses having the composition according to examples 3, 4 and 5 were prepared by mixing corresponding raw materials in the form of oxides and carbonates for 30 min in a Turbula mixer and then melting the mixture at 1450° C. for 120 min in a platinum crucible. The melts were poured into water in order to obtain finely divided glass granulates. These glass granulates were melted again at 1530° C. for 150 min in order to obtain glass melts with particularly high homogeneity. The temperature was reduced to 1500° C. for 30 min and subsequently a) rectangular glass blanks (12.5 mm×14 mm×40 mm) and b) cylindrical glass blanks with a diameter of 12.5 mm were then poured into pre-heated, separable steel moulds or graphite moulds. The obtained rectangular glass blocks or glass cylinders were then heat-treated in the range of 500 to 560° C. depending on the composition to produce nuclei for lithium metasilicate and/or lithium disilicate crystals and to stress-relieve the glass.

[0101] The obtained blanks with nuclei were processed according to the following alternatives to restorations.

(B) Hot-Pressing of Glass with Nuclei, Lithium Metasilicate or Lithium Disilicate Glass Ceramic

[0102] i) The glass cylinders with nuclei (A) were processed by hot-pressing at a temperature of 900-950° C. by means of a pressing furnace EP600, Ivoclar Vivadent AG, to give dental restorations, e.g. inlays, onlays, veneers, partial crowns and crowns.

[0103] ii) The glass cylinders with nuclei (A) were subjected to a first crystallization at 650 to 750° C. for 20 minutes. The heating-up rate was 15° C. per minute. After this first crystallisation lithium metasilicate was detected as main crystalline phase. Through hot-pressing of the lithium metasilicate glass cylinders at a pressing temperature of 900-950° C. using a pressing furnace EP600, Ivoclar Vivadent AG, it was possible to produce dental restorations, e.g. inlays, onlays, veneers, partial crowns and crowns. The hot-pressing converted lithium metasilicate into lithium disilicate.

[0104] iii) The glass cylinders with nuclei (A) were subsequent to a first crystallisation according to ii) subjected to an additional thermal treatment at 840 to 880° C. for 5 to 30 minutes. The analysis of the crystal phases showed after this treatment a glass ceramic according to the invention with lithium disilicate as main crystalline phase. The crystallised

cylinders obtained after this second crystallisation were subsequently processed by hot-pressing at a pressing temperature of 900-950° C. using a pressing furnace EP600, Ivoclar Vivadent AG, to dental restorations, e.g. inlays, onlays, veneers, partial crowns and crowns.

(C) Machining (CAD/CAM Process) of Lithium Metasilicate

[0105] The rectangular glass blocks with nuclei (A) were subjected to a first crystallisation in accordance with (B)(ii) to effect crystallisation of lithium metasilicate. The produced lithium metasilicate glass blocks were then machined by CAD/CAM processes, e.g. Sirona, Cerec 2® or Cerec 3®, to give dental restorations, e.g. inlays, onlays, veneers, partial crowns and crowns. Subsequently, these restorations were subjected to a second crystallisation at 840 to 880° C. for 5 minutes to 1 hour. The analysis of the crystal phases showed after this treatment a glass ceramic according to the invention with lithium disilicate as main crystalline phase.

TABLE I

	1	2	3	4	5	6	7	8	9
SiO ₂	63.8	69.3	67.9	66.4	65.0	63.5	62.0	60.5	61.2
K ₂ O	3.0	3.8	3.7	3.6	3.5	3.4	3.4	3.3	0.8
Li ₂ O	13.6	14.4	14.1	13.8	13.5	13.2	12.9	12.6	13.0
Al ₂ O ₃	3.0	3.3	3.2	3.2	3.1	3.0	2.9	2.9	1.0
P ₂ O ₅	3.0	3.1	3.1	3.0	2.9	2.9	2.8	2.7	4.0
ZrO ₂	9.6	6.1	8.0	10.0	12.0	14.0	16.0	18.0	20.0
MoO ₃	4.0								
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.00

TABLE II

	10	11	12	13	14	15	16	17	18	19	20
SiO ₂	69.8	64.1	65.2	60.5	64.5	64.4	66.4	55.0	70.1	64.3	64.2
K ₂ O	2.0	5.0	3.5	3.3	2.0	2.0		4.0	3.6	3.0	1.0
Li ₂ O	16.0	13.3	12.0	15.0	13.4	13.5	13.6	15.0	9.0	13.2	13.2
Na ₂ O									0.1		
CaO					2.0			2.0			
MgO									0.1		
SrO						2.0			0.1		1.0
Al ₂ O ₃	0.2	5.0	3.1	2.9	2.0	2.0	3.0	4.0	3.5	2.9	0.5
La ₂ O ₃					6.5						
Y ₂ O ₃						6.5					6.5
P ₂ O ₅	3.3	2.9	4.1	5.0	3.5	3.5	3.0	12.0	3.5	2.9	3.5
ZrO ₂	8.6	9.7	12.1	13.3	6.1	6.1	10.0	8.0	10.0	9.7	10.1
Cs ₂ O							4.0			4.0	
VO ₂	0.1										
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE III

	21	22	23	24
SiO ₂	61.3	62.6	64.9	64.9
K ₂ O	3.3	5.0	3.5	3.5
Li ₂ O	12.7	12.7	13.5	13.5
CaO	3.0			
Al ₂ O ₃	2.9	2.9	3.1	3.1
P ₂ O ₅	7.0	3.5	3.0	3.0
ZrO ₂	9.0	11.3	10.4	10.9
F	0.5			
MnO ₂	0.2			
Fe ₂ O ₃	0.1			

TABLE III-continued

	21	22	23	24
V ₂ O ₅			0.1	
Tb ₄ O ₇		0.4	0.5	0.5
CeO ₂		1.3	1.0	0.6
Er ₂ O ₃		0.3		
	100.0	100.0	100.0	100.0

TABLE IV

	25	26	27	28
SiO ₂	66.4	63.8	64.5	63.8
K ₂ O		3.0	3.2	3.0
Li ₂ O	13.6	13.6	13.8	13.6
Rb ₂ O	4.0			
BaO			2.0	
Al ₂ O ₃	3.0	3.0	3.0	3.0
Bi ₂ O ₃				4.0
P ₂ O ₅	3.0	3.0	3.5	3.0
ZrO ₂	10.0	9.6	10.0	9.6
WO ₃		4.0		
	100.0	100.0	100.0	100.0

TABLE V

Glass ceramic, no.	Thermal treatment (° C./min) or HT-XRD	Crystal phases MP = main phase SP = secondary phase(s)
2	500/10, 650/20, 840/7	MP: Li ₂ Si ₂ O ₅ SP: Li ₃ PO ₄ Li ₂ SiO ₃
3	500/10, 650/20, 840/7	MP: Li ₂ Si ₂ O ₅ SP: Li ₃ PO ₄ , Li ₂ SiO ₃
4	500/10, 650/20, 840/7	MP: Li ₂ Si ₂ O ₅ SP: Li ₃ PO ₄ , Li ₂ SiO ₃ ; Li ₄ SiO ₄

TABLE V-continued

Glass ceramic, no.	Thermal treatment (° C./min) or HT-XRD	Crystal phases MP = main phase SP = secondary phase(s)
5	540/10, 690/20	MP: Li_2SiO_3 SP: none
5	540/10, 650/20, 840/7	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_2SiO_3 ; Li_4SiO_4
6	540/10, 710/20	MP: Li_2SiO_3 SP: none
6	540/10, 650/20, 840/7	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_4SiO_4
7	560/10 and HT-XRD with cut-out at 860	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_3PO_4 ; Li_2SiO_3
8	560/10 and HT-XRD with cut-out at 900	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: SiO_2 , ZrO_2
9	560/10 and HT-XRD with cut-out at 920	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_3PO_4
14	520/10, 650/20, 800/10	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_3PO_4
15	520/10, 650/20, 800/10	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_3PO_4 ; Li_2SiO_3
16	520/10, 650/20, 800/10	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_3PO_4
17	HT-XRD with cut-out at 840	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_3PO_4
25	520/10, 650/20, 800/10	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_3PO_4
26	520/10, 650/20, 850/10	MP: $\text{Li}_2\text{Si}_2\text{O}_5$ SP: Li_3PO_4 ; Li_2SiO_3

[0106] In the HT-XRD analysis, a heating rate of approx. 2 K/min was used.

[0107] Although the present invention has been described in connection with preferred embodiments thereof, it will be appreciated by those skilled in the art that additions, deletions, modifications, and substitutions not specifically described may be made without departure from the spirit and scope of the invention as defined in the appended claims.

1) A dental restoration comprising:

a lithium disilicate glass ceramic coated on a zirconium oxide ceramic, wherein the lithium disilicate glass ceramic includes from 55 to 71 weight percent SiO_2 , from 9 to 17 weight percent Li_2O , and at least 6.1 weight percent ZrO_2 based on a mass of the lithium disilicate glass ceramic, and wherein there are practically no flaws or cracks in the lithium disilicate glass ceramic after the lithium disilicate glass ceramic is coated on the zirconium oxide ceramic.

2) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic has a $\text{SiO}_2/\text{Li}_2\text{O}$ molar ratio of 1.8 to 3.

3) The dental restoration of claim 2, wherein the lithium disilicate glass ceramic has a $\text{SiO}_2/\text{Li}_2\text{O}$ molar ratio of 2 to 2.8.

4) The dental restoration of claim 3, wherein the lithium disilicate glass ceramic has a $\text{SiO}_2/\text{Li}_2\text{O}$ molar ratio of 2.1 to 2.6.

5) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic comprises 6.1 to 16 weight percent ZrO_2 based on the mass of the lithium disilicate glass ceramic.

6) The dental restoration of claim 5, wherein the lithium disilicate glass ceramic comprises 6.1 to 14 weight percent ZrO_2 based on the mass of the lithium disilicate glass ceramic.

7) The dental restoration of claim 6, wherein the lithium disilicate glass ceramic comprises 6.1 to 12 weight percent ZrO_2 based on the mass of the lithium disilicate glass ceramic.

8) The dental restoration of claim 1, wherein the zirconium oxide ceramic further comprises at least one oxide of Ce, Y, Sr, Ca, or Mg.

9) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic further comprises Y_2O_3 , and wherein the lithium disilicate glass ceramic includes a combined amount of ZrO_2 and Y_2O_3 of greater than 6.1 to 16 weight percent based on the mass of the lithium disilicate glass ceramic.

10) The dental restoration of claim 9, wherein the lithium disilicate glass ceramic includes a combined amount of ZrO_2 and Y_2O_3 of greater than 6.1 to 14 weight percent based on the mass of the lithium disilicate glass ceramic.

11) The dental restoration of claim 10, wherein the lithium disilicate glass ceramic includes a combined amount of ZrO_2 and Y_2O_3 of greater than 6.1 to 12 weight percent based on the mass of the lithium disilicate glass ceramic.

12) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic further comprises an oxide of pentavalent elements, wherein the oxide of the pentavalent elements is Bi_2O_5 .

13) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic further comprises an oxide of hexavalent elements selected from WO_3 or MoO_3 .

14) The dental restoration of claim 1, wherein the dental restoration is an inlay, onlay, crown, or abutment.

15) The dental restoration of claim 1, wherein no Na_2O oxide is present in the lithium disilicate glass ceramic.

16) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic further comprises at least 0.2 weight percent to less than 5.0 weight percent Al_2O_3 .

17) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic further comprises 0.2 to 3.5 weight percent Al_2O_3 .

18) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic has a biaxial strength of from 200 to 500 MPa.

19) The dental restoration of claim 1, wherein the lithium disilicate glass ceramic includes lithium disilicate crystals with a small-plate shaped crystal form.

20) A method comprising:

- melting a composition comprising lithium disilicate as a main phase;
- heating the composition such that nucleation occurs;
- optionally mixing the composition from b) with at least one coloring pigment; and
- coating a layer of lithium disilicate glass ceramic on a zirconium oxide ceramic wherein there are practically no flaws or cracks in the lithium disilicate glass ceramic after the coating.

21) The method of claim 20, wherein the coating comprises pressing the layer of lithium disilicate glass ceramic on the zirconium oxide ceramic.

22) The method of claim 21, wherein the pressing occurs at a temperature from 700° C. to 900° C.

23) The method of claim 20, wherein the coating comprises sintering the layer of lithium disilicate glass ceramic on the zirconium oxide ceramic.

24) The method of claim 20, wherein the composition comprising lithium disilicate as the main phase further comprises Na_2O .

25) The method of claim 20, wherein the lithium disilicate glass ceramic further comprises nuclei suitable for forming lithium metasilicate and/or lithium disilicate crystals.

26) The method of claim 20, further comprising contacting the melted composition with water such that a glass frit is formed.

27) The method of claim 26, further comprising forming a powder from the glass frit.

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