Daniela Vitzthum and Hubert Huppertz*

High-pressure synthesis and crystal structure of the mixed-cation borate \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \)

Abstract: The mixed cation triel borate \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \) was synthesized in a Walker-type multianvil apparatus at high-pressure/high-temperature conditions of 12.5 GPa and 1300 °C. Although the product could not be reproduced in further experiments, its crystal structure could be reliably determined via single-crystal X-ray diffraction data. \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \) crystallizes in the tetragonal space group \( I4_1/\text{a} \) (origin choice 2) with the lattice parameters \( a=11.382(2), \quad c=15.244(2) \, \text{Å}, \) and \( V=1974.9(4) \, \text{Å}^3 \). The structure of the quaternary triel borate consists of a complex network of BO\(_4\) tetrahedra, edge-sharing InO\(_6\) octahedra in dinuclear units, and very dense edge-sharing GaO\(_6\) octahedra in tetranuclear units.

Keywords: crystal structure; gallium borate; high pressure; indium borate.

1 Introduction

In the last decade, extensive research has been carried out in the field of group 13 element borates which yielded numerous new structures featuring interesting properties. For instance, triel borates have been reported to show luminescence when being doped with a suitable activator ion [1–4], and acentric compounds have been described as possible NLO materials [5–7]. Especially gallium and indium borates shifted into the research focus due to their photocatalytic properties. During the last 5 years, the results of seven photocatalytic studies of indium or gallium borates have been published [1, 8–13]. Up to date, 14 borates are known in the systems Ga-B-O(-H) and In-B-O(-H), from which 12 have been published since 2010. This emerging research field has benefited from the advancement of high-pressure techniques. More than half of all existing indium or gallium borates in these (partially hydroxylated) ternary systems were synthesized with a multianvil apparatus and formed under conditions of at least 10 GPa.

Likewise, the new compound \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \) has now been synthesized at high-pressure conditions via a multianvil press. As usual in such dense structures, this mixed cation triel borate solely consists of boron atoms that are coordinated by four oxygen atoms. Ga\(^{3+}\) and In\(^{3+}\) form diverse edge-sharing octahedral entities. Unlike the solid solution \( \text{In}_{1-x}\text{Ga}_x\text{BO}_3 \) (\( 0 \leq x \leq 0.5 \)) [14], in which the indium position is optionally replaced by gallium, our title compound is the first triel borate containing indium and gallium in crystallographically different positions.

In the following, the synthesis and crystal structure of \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \) are described in detail.

2 Experimental section

2.1 Synthesis

\( \text{In}_2\text{O}_3 \) (99.9%, ChemPUR, Karlsruhe, Germany), \( \text{Ga}_2\text{O}_3 \) (99.998%, Strem Chemicals, Kehl, Germany), and \( \text{H}_3\text{BO}_3 \) (99.5%, Carl Roth, Karlsruhe, Germany) were weighed in a molar ratio of 1:3:8 and ground in an agate mortar. Then, the mixture was encapsulated in gold foil (99.99%, 0.025 mm, Sigma-Aldrich, USA) and transferred into a boron nitride crucible (\( \alpha \)-BN, Henze Boron Nitride Products AG, Kempten, Germany). The detailed procedure is described in the literature [15–17]. \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \), formed under conditions of 12.5 GPa and 1300°C. The maximum pressure was built up within 342 min and held for 42 min during the heating period. Within 7 min, the maximum temperature of 1300°C was reached, kept for 5 min and afterwards the temperature was decreased to 900°C within 30 min. The following careful pressure reduction to ambient conditions took 1013 min.

*Corresponding author: Hubert Huppertz, Institute for General, Inorganic, and Theoretical Chemistry, University of Innsbruck, Innrain 80–82, A-6020 Innsbruck, Austria, e-mail: hubert.huppertz@uibk.ac.at
Daniela Vitzthum: Institute for General, Inorganic, and Theoretical Chemistry, University of Innsbruck, Innrain 80–82, A-6020 Innsbruck, Austria
The reaction product appeared grey-white and its powder pattern did not match that of any known phase. A suitable single-crystal was isolated from the sample. The solution of the structure of Ga₄In₄B₁₅O₃₃(OH)₃ explains some of the reflections in the powder pattern of the reaction product (see Fig. 1). However, the majority of the reflections is still unknown up to now. All subsequent attempts to purposefully and stoichiometrically synthesize Ga₄In₄B₁₅O₃₃(OH)₃ failed up to now.

### 2.2 X-ray structure determination

At first, the reaction product was analyzed with a Stoe Stadi P powder diffractometer equipped with a Mythen 1 K detector (Dectris, Switzerland). The measurement was carried out with Ge(111)-monochromatized MoKα₁ radiation (\(\lambda = 0.7093 \text{ Å}\)) in transmission geometry across a 2θ range of 2.0–60.5°. Figure 1 shows the experimental powder pattern. Most of the reflections could not be associated with any known phases. All reflections that do not match with the simulation of Ga₄In₄B₁₅O₃₃(OH)₃ derived from single-crystal data are marked with asterisks.

A colorless, prismatic single-crystal of Ga₄In₄B₁₅O₃₃(OH)₃ was isolated from the reaction product and measured on a Bruker D8 Quest diffractometer equipped with a Photon 100 CMOS detector. The data was

**Table 1:** Crystal data and structure refinement of tetragonal Ga₄In₄B₁₅O₃₃(OH)₃.

| Parameter                                      | Value                                      |
|------------------------------------------------|--------------------------------------------|
| Empirical formula                              | Ga₄In₄B₁₅O₃₃(OH)₃                         |
| Molar mass, g mol⁻¹                             | 1479.33                                    |
| Crystal system                                 | tetragonal                                 |
| Space group                                    | I₄₁/a (no. 88, origin choice 2)            |
| Single-crystal diffractometer                  | Bruker D8 Quest Kappa                      |
| Radiation                                      | MoKα₁ (\(\lambda = 0.71073 \text{ Å}\))    |
| a, Å                                           | 11.382(2)                                  |
| c, Å                                           | 15.244(2)                                  |
| V, Å³                                          | 1974.9(4)                                  |
| Formula units per cell Z                       | 4                                          |
| Calculated density, g cm⁻³                     | 4.98                                       |
| Crystal size, mm³                               | 0.05 × 0.04 × 0.02                         |
| Temperature, K                                 | 297(2)                                     |
| Detector distance, mm                          | 50                                         |
| Exposure time, s⁻¹                             | 130                                        |
| Absorption coefficient, mm⁻¹                   | 10.2                                       |
| \(F(000)\), e                                  | 2744                                       |
| \(\theta\) range, deg                          | 2.2–36.0                                   |
| Range in \(hkl\)                               | ±18; ±18; ±25                              |
| Reflections total/independent                   | 28476/2348                                 |
| \(R_m\)                                        | 0.0450                                     |
| Reflections with \(I \geq 2 \sigma(I)\)       | 2260                                       |
| \(R_p\)                                        | 0.0202                                     |
| Data/ref. parameters/restraints                | 2348/139/1                                 |
| Absorption correction                          | multi-scan                                 |
| Final \(R_1/wR_2\) \((I \geq 2 \sigma(I))\)   | 0.0175/0.0417                              |
| Final \(R_1/wR_2\) (all data)                 | 0.0192/0.0422                              |
| Goodness-of-fit on \(F^2\)                    | 1.078                                      |
| Largest diff. peak/hole, e Å⁻³                 | 0.53/–1.78                                 |
collected at room temperature and a multiscan absorption correction was performed with SADABS 2014/5 [18].

For the structure solution and parameter refinement, the SHELXS/1-2013 [19, 20] software implemented in the program WINGX-2013.3 [21] was used. The single-crystal was treated as a non-merohedral twin with a domain fraction of 0.165–0.835 and was refined with the twin matrix [010 100 001̅]. Aside from the proton, all atoms in Ga₄In₄B₁₅O₃₃(OH)₃ could be refined anisotropically with site occupancy factors of 1. The proton position was fixed with the DFIX command in a distance of 0.83 Å to O₈, since this is the only oxygen atom with otherwise only two coordination partners. Due to charge neutrality reasons, the proton H₈ was refined with a site occupancy factor of 0.75. In the end, the refinement of Ga₄In₄B₁₅O₃₃(OH)₃ led to satisfying results with total $R$ (all data) values of $R_1 = 0.0192$ and $wR_2 = 0.0422$ as well as a Goodness-of-fit of 1.078.

CCDC 1895780 (Ga₄In₄B₁₅O₃₃(OH)₃) contains the supplementary crystallographic data for this paper. The data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

3 Results and discussion

3.1 Crystal structure

Table 2: Wyckoff positions, occupancy factors, atomic coordinates, isotropic $U_{iso}$ or equivalent isotropic displacement parameters $U_{eq}$ (Å²) of Ga₄In₄B₁₅O₃₃(OH)₃.

| Atom | Wyckoff position | Occupancy | $x$       | $y$       | $z$       | $U_{eq}$ ($U_{iso}$ for H₈) |
|------|------------------|-----------|-----------|-----------|-----------|-----------------------------|
| In1  | 16f              | 1         | 0.23415(2) | 0.65795(2) | 0.32996(2) | 0.00510(3)                  |
| Ga1  | 16f              | 1         | 0.41303(2) | 0.64704(2) | 0.70048(2) | 0.00335(4)                  |
| B1   | 16f              | 1         | 0.1577(2)  | 0.9068(2)  | 0.6132(2)  | 0.0037(3)                   |
| B2   | 8e               | 1         | 0         | 0.6196(2)  | 0.0041(5)  | 0.0037(3)                   |
| B3   | 16f              | 0         | 0.1624(2)  | 0.7336(2)  | 0.5071(2)  | 0.0042(3)                   |
| B4   | 4b               | 1         | 0         | 0.0069(7)  |           | 0.0069(7)                   |
| B5   | 16f              | 1         | 0.3358(2)  | 0.5774(2)  | 0.5190(2)  | 0.0041(3)                   |
| O1   | 16f              | 1         | 0.0752(2)  | 0.8315(2)  | 0.67198(9) | 0.0048(2)                   |
| O2   | 16f              | 1         | 0.0798(2)  | 0.6775(2)  | 0.56575(9) | 0.0052(2)                   |
| O3   | 16f              | 1         | 0.2279(2)  | 0.8245(2)  | 0.5570(2)  | 0.0049(2)                   |
| O4   | 16f              | 1         | 0.1010(2)  | 0.7899(2)  | 0.60340(9) | 0.0052(2)                   |
| O5   | 16f              | 1         | 0.2484(2)  | 0.6495(2)  | 0.47177(9) | 0.0043(2)                   |
| O6   | 16f              | 1         | 0.0894(2)  | 0.9828(2)  | 0.55999(9) | 0.0049(2)                   |
| O7   | 16f              | 1         | 0.2430(2)  | 0.9697(2)  | 0.66984(9) | 0.0044(2)                   |
| O8   | 16f              | 1         | 0.4032(2)  | 0.5060(2)  | 0.45766(9) | 0.0059(2)                   |
| O9   | 16f              | 1         | 0.4178(2)  | 0.6616(2)  | 0.56737(9) | 0.0048(2)                   |
| H8   | 16f              | 0.75      | 0.446(6)   | 0.553(6)   | 0.432(4)   | 0.09(3)                     |

$U_{eq}$ is defined as one third of the trace of the orthogonalized $U_{ij}$ tensor (standard deviations in parentheses).
forms a hydroxyl group with the donor atom O8, is the only atom site that shows a diminished occupancy factor of 0.75 for charge neutrality reasons. A complete list of occupancy factors, Wyckoff positions, fractional atomic coordinates and isotropic or equivalent isotropic displacement parameters can be found in Table 2. All anisotropic

| Atom | \( U_{11} \) | \( U_{22} \) | \( U_{33} \) | \( U_{12} \) | \( U_{13} \) | \( U_{23} \) |
|------|-------------|-------------|-------------|-------------|-------------|-------------|
| In1  | 0.00709(6)  | 0.00417(6)  | 0.00403(5)  | -0.00103(4) | -0.00059(4) | 0.00039(4)  |
| Ga1  | 0.00390(9)  | 0.00346(9)  | 0.00274(8)  | -0.00011(7) | 0.00015(6)  | 0.00007(6)  |
| B1   | 0.0030(8)   | 0.0048(8)   | 0.0032(7)   | -0.0006(6)  | 0.0002(6)   | 0.0004(6)   |
| B2   | 0.0032(2)   | 0.0052(2)   | 0.0042(2)   | -0.0005(9)  | 0.0002(3)   | 0.0004(6)   |
| B3   | 0.0048(7)   | 0.0040(7)   | 0.0037(7)   | -0.0005(6)  | 0.0003(3)   | 0.0004(6)   |
| B4   | 0.0082(2)   | 0.0082(2)   | 0.0052(2)   | 0            | 0            | 0            |
| B5   | 0.0047(6)   | 0.0043(6)   | 0.0034(6)   | 0.0005(6)   | 0.0003(6)   | 0.00011(6)  |
| O1   | 0.0053(6)   | 0.0058(6)   | 0.0035(5)   | -0.0023(5)  | 0.0009(4)   | -0.0002(4)  |
| O2   | 0.0057(6)   | 0.0038(6)   | 0.0061(5)   | -0.0006(4)  | 0.0025(4)   | 0.0003(4)   |
| O3   | 0.0055(6)   | 0.0055(6)   | 0.0058(5)   | -0.0007(4)  | 0.0009(4)   | -0.0024(4)  |
| O4   | 0.0051(6)   | 0.0046(6)   | 0.0055(5)   | -0.0012(5)  | -0.0009(4)  | 0.0006(4)   |
| O5   | 0.0048(6)   | 0.0046(6)   | 0.0035(5)   | 0.0014(5)   | 0.0001(4)   | -0.0002(4)  |
| O6   | 0.0039(6)   | 0.0059(6)   | 0.0049(5)   | 0.0002(5)   | -0.0001(4)  | 0.0007(4)   |
| O7   | 0.0038(6)   | 0.0040(6)   | 0.0053(5)   | -0.0004(5)  | -0.0019(4)  | -0.0012(4)  |
| O8   | 0.0058(6)   | 0.0055(6)   | 0.0064(5)   | 0.0000(5)   | 0.0022(4)   | -0.0012(4)  |
| O9   | 0.0045(6)   | 0.0047(6)   | 0.0050(5)   | -0.0003(5)  | -0.0004(4)  | -0.0003(4)  |

Fig. 3: Isolated edge-sharing InO₆ octahedra (top left, yellow) and GaO₆ octahedra (bottom left, green) and their arrangement in the unit cell of Ga₄In₄B₁₅O₃₃(OH)₁₃ (middle and right).
displacement parameters are listed in Table 3. The structure of \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \) will now be explained in detail starting with the In-O and Ga-O networks.

Both metal atoms are coordinated octahedrally by oxygen atoms. Due to the symmetry of the space group, indium forms edge-sharing octahedra in dinuclear units caused by an inversion axis, and gallium assembles dense units of four edge-sharing octahedra induced by the 4̅ axis. The whole unit cell contains four isolated tetranuclear Ga–O units and eight isolated dinuclear In–O units. Figure 3 shows both octahedral units and their arrangement in the unit cell of \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \). All metal-oxygen distances are in good accordance with values reported in the literature (Ga–O = 1.928(2)–2.126(2) Å, Ø = 2.00 Å; In–O = 2.121(2)–2.219(2) Å, Ø = 2.17 Å) [1, 7, 8, 22], while the axial angles with average values of 168.6° for O–Ga–O and 170.3° for O–In–O are a bit smaller than the expected one of 180°. A complete list of distances and angles is given in Tables 4 and 5.

The complex network of exclusively corner-sharing \( \text{BO}_4 \) tetrahedra interconnects the various isolated metal-oxygen units. In doing so, the different \( \text{BO}_4 \) tetrahedra form \textit{dreier} and \textit{vierer} rings [23]. \( \text{B}_{5}\text{O}_8 \) is the only tetrahedron that does not contribute to a ring system but connects to the proton H8 \textit{via} O8 instead (see Fig. 4). The complete structure is shown in Fig. 5. The hydrogen bonding situation is illustrated in Fig. 6. Angles and distances of the hydrogen bonds are given in Table 6. All B–O bond lengths are within the range of 1.418(3)–1.556(3) Å (average 1.49 Å) and fit to reported distances in tetrahedral borate groups [24]. The average O–B–O angles of 109.4° (for B1) and 109.5° (for B2–5) indicate perfectly shaped polyhedra.

To evaluate the charge distribution, we performed bond-length/bond-strength calculations (see Table 7) [25, 26]. Solely O9 shows an unusually high charge which can be attributed to the number of bonding partners. While all other oxygen atoms in \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \) coordinate

| Table 4: Interatomic distances (Å) in \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \) (standard deviations in parentheses). |
|-----------------|-----------------|-----------------|
| In1–O6          | 2.121(2)        | Ga1–O8          | 1.928(2)        |
| In1–O6          | 2.134(2)        | Ga1–O3          | 1.933(2)        |
| In1–O7          | 2.145(2)        | Ga1–O1          | 1.964(2)        |
| In1–O5          | 2.170(2)        | Ga1–O9          | 2.029(2)        |
| In1–O2          | 2.216(2)        | Ga1–O9          | 2.037(2)        |
| In1–O4          | 2.219(2)        | Ga1–O9          | 2.126(2)        |
| ØIn1–O          | 1.17           | ØGa1–O          | 2.00           |
| B1–O6           | 1.418(3)        | B4–O4           | 1.496(2)        |
| B1–O7           | 1.484(3)        | ØB4–O           | 1.50           |
| B1–O3           | 1.500(3)        |                |                |
| B1–O1           | 1.556(3)        | B5–O8           | 1.458(3)        |
| ØB1–O           | 1.49           | B5–O5           | 1.477(3)        |
|                 |                | B5–O7           | 1.480(3)        |
| B2–O2           | 1.477(2) 2×     | B5–O9           | 1.527(3)        |
| B2–O1           | 1.493(2) 2×     | ØB5–O           | 1.49           |
| ØB2–O           | 1.49           |                |                |
| B3–O2           | 1.446(3)        |                |                |
| B3–O5           | 1.471(3)        |                |                |
| B3–O3           | 1.485(3)        |                |                |
| B3–O4           | 1.507(3)        |                |                |
| ØB3–O           | 1.48           |                |                |

| Table 5: Interatomic angles (deg) in \( \text{Ga}_4\text{In}_4\text{B}_{15}\text{O}_{33}(\text{OH})_3 \) (standard deviations in parentheses). |
|-----------------|-----------------|-----------------|
| In1–Ga1–O6      | 75.45(6)        | O9–Ga1–O9       | 78.00(6)        |
| In1–Ga1–O6      | 81.01(6)        | O9–Ga1–O9       | 80.26(6)        |
| In1–Ga1–O6      | 84.74(6)        | O9–Ga1–O9       | 82.83(7)        |
| In1–Ga1–O4      | 85.62(6)        | O8–Ga1–O9       | 87.90(6)        |
| In1–Ga1–O5      | 87.17(5)        | O1–Ga1–O9       | 90.21(6)        |
| In1–Ga1–O7      | 90.04(6)        | O8–Ga1–O1       | 90.44(6)        |
| In1–Ga1–O9      | 90.92(5)        | O3–Ga1–O9       | 91.17(6)        |
| In1–Ga1–O9      | 91.50(5)        | O3–Ga1–O9       | 92.19(6)        |
| In1–Ga1–O9      | 98.17(5)        | O8–Ga1–O1       | 94.59(6)        |
| In1–Ga1–O9      | 102.20(6)       | O3–Ga1–O1       | 100.19(6)       |
| ØIn1–Ga1–O9     | 89.8           | ØO–Ga1–O9       | 89.8           |
| O6–In1–O6       | 164.69(6)       | O1–Ga1–O9       | 166.98(6)       |
| O2–In1–O4       | 170.32(5)       | O3–Ga1–O9       | 168.6(4)        |
| O6–In1–O5       | 175.76(6)       | O8–Ga1–O1       | 170.15(6)       |
| ØO–In1–O160     | 170.3           | ØO–Ga1–O160     | 168.6           |
| B1–O7–B1–O3     | 106.5(2)        | O4–B4–O4        | 108.47(6) 3×    |
| B3–O5–B1–O1     | 109.7(2)        | O4–B4–O4        | 108.48(6)       |
| B3–O5–B1–O1     | 109.0(2)        | O4–B4–O4        | 111.5(2) 2×     |
| B3–O5–B1–O1     | 109.6(2)        | ØO–B4–O          | 109.5          |
| B3–O5–B1–O1     | 110.3(2)        |                |                |
| B3–O5–B1–O1     | 113.4(2)        | B5               |                |
| ØO–B1–O         | 109.4           | O8–B5–O9        | 105.4(2)        |
| ØO–B1–O         | 115.4(2)        | ØO–B5–O         | 109.5          |
| B2–O2–O2        | 106.99(8) 2×    | O8–B5–O5        | 110.6(2)        |
| O2–B2–O2        | 107.61(8) 2×    | O7–B5–O9        | 111.4(2)        |
| O2–B2–O2        | 112.4(2)        | O5–B5–O7        | 112.4(2)        |
| O2–B2–O2        | 115.4(2)        | ØO–B5–O         | 109.5          |
| ØO–B2–O         | 109.5           |                |                |
| B3–O5–B3–O4     | 107.5(2)        |                |                |
| B3–O5–B3–O4     | 107.9(2)        |                |                |
| B3–O5–B3–O4     | 108.5(2)        |                |                |
| B3–O5–B3–O4     | 109.5(2)        |                |                |
| B3–O5–B3–O4     | 111.5(2)        |                |                |
| B3–O5–B3–O4     | 111.8(2)        |                |                |
| ØO–B3–O         | 109.5           |                |                |
three other atoms, O9 forms quite long but nonetheless definite bonds to three Ga atoms and one B atom.

4 Conclusions

A high-pressure/high-temperature experiment in a multianvil press led to the formation of the first mixed cation triel borate in which indium and gallium occupy crystallographically different positions. Although the bulk reaction product was not phase pure, the structure of Ga$_4$In$_4$B$_{15}$O$_{33}$(OH)$_3$ could be determined reliably via a single-crystal structure determination. This new hydroxyated high-pressure borate is built up of a complex, dense BO$_4$ tetrahedra network. Indium and gallium form di- or tetranuclear units of edge-sharing octahedra, respectively. This finding complements a series of current publications in the aspiring research field of triel borates.

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References

[1] D. Vitzthum, K. Wurst, J. Pann, P. Brüggeller, M. Seibald, H. Huppertz, Angew. Chem. Int. Ed. 2018, 57, 11451.
[2] C. Yin, R. Wang, P. Jiang, R. Cong, T. Yang, J. Solid State Chem. 2019, 269, 30.
[3] E. Y. Borovikova, K. N. Boldyrev, S. M. Aksenov, E. A. Dobretsova, V. S. Kurazhkovskaya, N. I. Leonyuk, A. E. Savon, D. V. Deyneko, D. A. Ksenofontov, Opt. Mater. 2015, 49, 304.
[4] P.-L. Xu, C.-C. Jin, T.-T. Deng, E.-R. Wang, J.-W. Cheng, J. Cluster Sci. 2017, 28, 1431.
[5] T. Tran, N. Z. Koocher, J. M. Rondinelli, P. S. Halasyamani, Angew. Chem. 2017, 129, 3015.
[6] D. An, M. Zhang, D. Li, S. Pan, H. Chen, Z. Yang, Y. Zhu, Y. Sun, H. Zhang, Y. Li, J. Mater. Res. 2015, 30, 2319.
[7] D. Vitzthum, L. Bayarjargal, B. Winkler, H. Huppertz, Inorg. Chem. 2018, 57, 5554.
[8] D. Vitzthum, K. Wurst, J. Prock, P. Brüggeller, H. Huppertz, Inorg. Chem. 2016, 55, 11473.
[9] D. Vitzthum, M. Schauperl, C. M. Strabler, P. Brüggeller, K. R. Liedl, U. J. Griesser, H. Huppertz, Inorg. Chem. 2016, 55, 676.
[10] K. Song, M. Yue, W. Gao, R. Cong, T. Yang, J. Alloys Compd. 2016, 684, 346.
[11] B. Ma, R. Cong, W. Gao, T. Yang, Catal. Commun. 2015, 71, 17.
[12] G. Wang, Y. Jia, J. Ju, D. Yang, J. Yang, W. Gao, R. Cong, T. Yang, Inorg. Chem. 2015, 54, 2945.
[13] W. Gao, Y. Jia, J. Yang, Z. Zhou, D. Yang, J. Sun, J. Lin, R. Cong, T. Yang, Inorg. Chem. 2014, 53, 2364.
[14] Y. Yang, K. Song, M. Yue, L. Li, R. Cong, W. Gao, T. Yang, Eur. J. Inorg. Chem. 2017, 63.
[15] H. Huppertz, Z. Kristallogr. 2004, 219, 330.
[16] D. Walker, M. A. Carpenter, C. M. Hitch, Am. Mineral. 1990, 75, 1020.
[17] D. Walker, Am. Mineral. 1991, 76, 1092.
[18] SADABS 2014/5, Bruker AXS Inc., Madison, Wisconsin (USA) 2001.
[19] G. M. Sheldrick, Acta Crystallogr. 2008, A64, 112.
[20] G. M. Sheldrick, Acta Crystallogr. 2015, C71, 3.
[21] L. J. Farrugia, J. Appl. Crystallogr. 2012, 45, 849.
[22] D. Vitzthum, S. A. Hering, L. Perfler, H. Huppertz, Z. Naturforsch. 2015, 70b, 207.
[23] F. Liebau, Structural Chemistry of Silicates, Springer-Verlag, Berlin, 1985.
[24] E. Zobetz, Z. Kristallogr. 1990, 191, 45.
[25] I. D. Brown, D. Altermatt, Acta Crystallogr. 1985, B41, 244.
[26] N. E. Brese, M. O’Keeffe, Acta Crystallogr. 1991, B47, 192.