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Highly soluble germanium dioxide as a new source of germanium for derivatization with organic compounds

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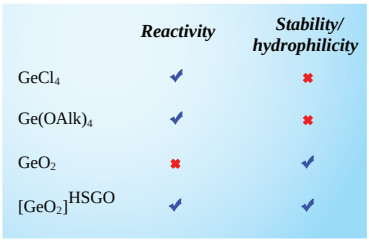
In modern germanium chemistry, toxic, corrosive and water-sensitive halogen and alkoxy derivatives, or poorly reactive polymeric dioxide are generally utilized. Recently developed highly water-soluble germanium dioxide was herein treated with diols and N-donor bases to produce novel highly reactive hydrophilic germanium source suitable for further derivatization.



Keywords: germanium chemistry, synthesis, highly soluble GeO_2, germanium oxide, catechols, cyclic voltammetry, UV spectroscopy, thermal analysis.

Germanium occupies a special place in the chemistry of the main group elements, as well as in the periodic table, as an element with predicted properties. Its discovery, after gallium and scandium, contributed to the final and general acceptance of the Periodic Law.[1] Germanium played a key role in the semiconductor boom of the 1950s, gradually giving way to silicon, however, recent years have seen a resurgence in its uses.[1] Today, germanium-based materials and its compounds are used in photovoltaics,[2] new power sources,[3,4] catalysis,[5] medicine[6] and other areas. The starting agents used for producing these materials and derivatives, as a rule, are either germanium halides (typically $GeCl_4$) or its alkoxy derivatives,[7] as well as GeO_2.[8] The first two groups comprise rather labile compounds vulnerable to water and other proton donors. In contrast, GeO_2 is highly stable in air and low reactive compared to halides and alkoxides, and it is poorly soluble in water.

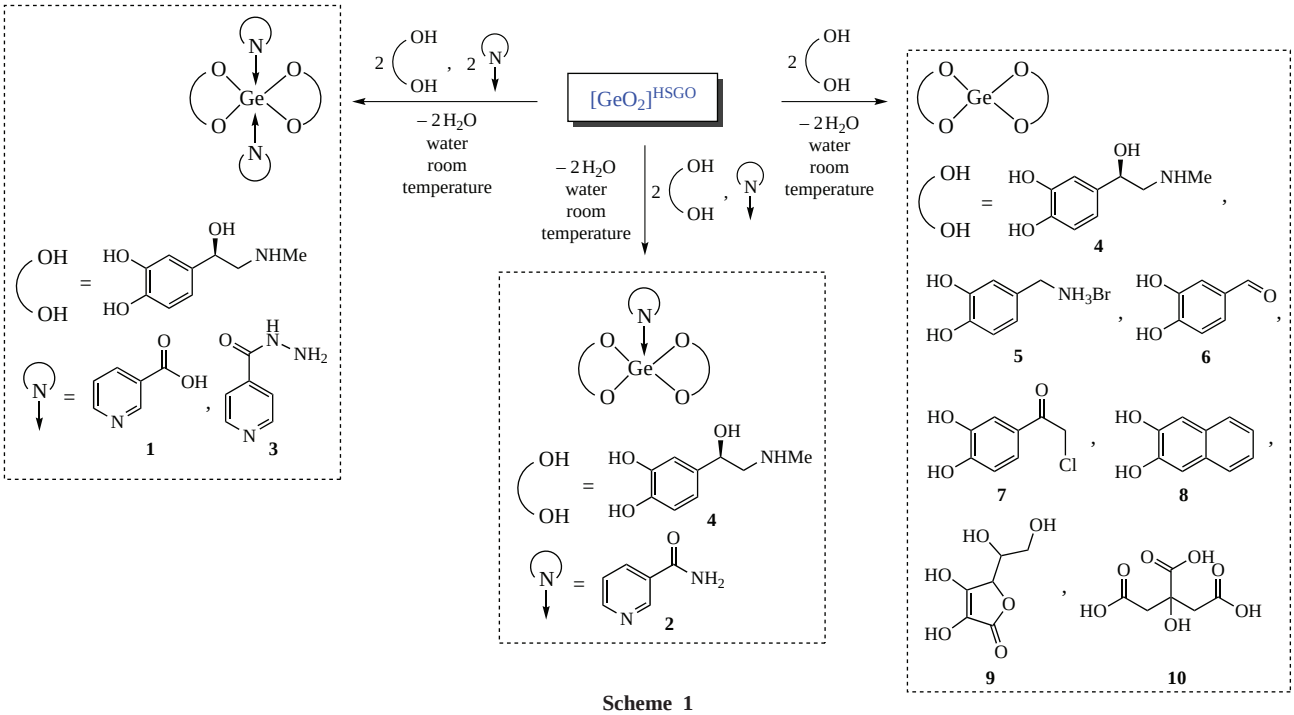
Recently, an approach to obtaining highly soluble germanium oxide (HSGO) has been proposed.[9] Its solubility in water (100 g dm^{-3}) exceeds that of commercial GeO_2 by a factor of 20, and the dissolution occurs almost immediately after adding water (see video in supporting information of ref. 9). In contrast, common GeO_2 has to be stirred in water for a long time to reach maximum concentration, and the stirring time can be shortened by boiling. The use of HSGO as a precursor in the synthesis of inorganic germanium derivatives was documented.[9]

This work was aimed at the study of the possible use of HSGO as a substrate in the synthesis of germanium derivatives with organic compounds. Its reactions with aromatic 1,2-diols (catechols, Scheme 1) were chosen as the test ones. The corresponding derivatives can be of interest as biologically active compounds,[10] can be used for obtaining other germanium derivatives,[11] are powerful Lewis acids[12] and possess interesting physicochemical properties.[13] making them promising in materials science.

To obtain such compounds in aqueous or aqueous-organic media from common GeO_2 and catechols, prolonged heating and boiling are usually required. Moreover, keeping the reaction mixture from contact with air is necessary as catechols are easily oxidized. A different situation is observed when HSGO is used. All the products presented in Scheme 1 were herein obtained at room temperature with quantitative yields by simple simultaneous dissolution of the reactants in water and subsequent removal of the solvent.

HSGO was prepared as described[9] by thermal treatment of ammonium peroxogermanate synthesized by the reaction of $GeCl_4$ with 5% H_2O_2 and 12.5% NH_4OH. Complexes **1** and **2** (see Scheme 1) were obtained by simultaneous dissolution of HSGO with epinephrine (a hormone) and nicotinic acid or nicotinamide (vitamins B_3). They seem to be the first known germanium derivatives with catechols and N-donors, which are completely formed by physiological ligands. A derivative with the medicine isoniazid **3** was prepared in a similar way. The obtained compounds were characterized by ^1H and ^{13}C NMR and IR spectroscopy. Previously,[14,15] we were unable to detect molecular ion peak in mass spectra of germanium derivatives with catechols and monodentant N-donors. This was associated with the relative lability of the donor–acceptor bond N→Ge, which was broken upon ionization in a spray, and, even more, by electron impact. In this work, it was pleasant to find that MALDI spectroscopy allowed detecting molecular ion of the complex **1** (see Online Supplementary Materials, Figure S31).

Further, a germanium derivative with epinephrine **4** was prepared in the absence of N-donors. Unlike epinephrine, other amino catechols are often commercially available as



Scheme 1

hydrochlorides and hydrobromides. Being in the form of a salt, they are more stable during storage, however, their reactivity with HSGO also decreases. Specifically, a germanium derivative with 3,4-dihydroxybenzylamine hydrobromide **5** is completely formed when the reaction mixture is kept for 48 h, and the reaction with dopamine hydrochloride proceeds noticeably only when the reaction mixture is heated.

The presence of not a donor, but an acceptor substituent in catechol, as in the case of 3,4-dihydroxybenzaldehyde, does not prevent the reaction with HSGO, and a derivative **6** is formed easily and fast. The derivatives with water-insoluble catechols can be obtained using alternative approaches involving the use of an aqueous-organic medium or carrying out the reaction under heterogeneous conditions. Specifically, a derivative with 2-chloro-3′,4′-dihydroxyacetophenone **7** was obtained in the water/methanol (1 : 1) mixture, and the reaction was complete in 48 h. In the case of 2,3-dihydroxynaphthalene, both the starting catechol and product **8** are insoluble in water, therefore, stirring of the suspension for 48 h was required for the reaction to proceed completely. Finally, germanium derivatives with ascorbic (**9**) and citric (**10**) acids are readily formed from HSGO in aqueous medium. The latter was recently proposed as a precursor for preparing germanium nanoparticles for anodes of high-capacity lithium-ion batteries.[16]

Physicochemical properties of novel derivatives **1**–**3** were studied by cyclic voltammetry (CV), UV spectroscopy, thermogravimetric analysis (TGA) and differential thermal analysis (DTA). Figure 1 represents oxidation CV curves recorded in a phosphate buffer solution with pH 6.86 for epinephrine, its mixture with nicotinic acid, it after adding HSGO and it after adding HSGO and nicotinic acid, as well as the curve for the separately synthesized complex **1**. It is seen that epinephrine is oxidized irreversibly at the peak potential of 0.51 V, which can be compared with the published data on oxidation at 0.58 V (pH 5) and 0.35 V (pH 7).[17] The addition of HSGO to a solution of epinephrine, accompanied by the formation of **4**, leads to a shift of the oxidation peak anodically by 0.34 V, in the same way as it was shown earlier when using commercial GeO_2.[10] Harder oxidation of the complex after introduction of germanium into the system, which is less electronegative than hydrogen, is apparently due to the fact that free epinephrine, being a sufficiently strong acid, is oxidized in dissociated form. The subsequent addition of nicotinic acid to the solution results in somewhat (by ~25 mV) easier oxidation, which indicates, firstly, its donor effect on the system, and, secondly, that this interaction is rather weak. Notably, the oxidation curve of the mixture of three compounds is identical to that of the separately synthesized complex **1**. No oxidation peaks are observed within the stability window of the supporting electrolyte in the case of adding HSGO to a solution of nicotinic acid in the absence of adrenaline (see Figure 1, curve *6*). There are no peaks on the reduction curves of all the mentioned solutions. A similar series of experiments with nicotinamide and isoniazid (see Online Supplementary Materials) leads to comparable results with the difference that nicotinamide and its complex are electrochemically reduced under these conditions, while isoniazid is both reduced and oxidized.

Figure 2 represents UV spectra of aqueous solutions of epinephrine, nicotinic acid, a mixture of epinephrine and HSGO, the latter after adding nicotinic acid and the separately synthesized complex **1**. It is seen that all the listed objects, being colourless compounds, absorb only in the UV region. The lowest-energy transition in the spectrum of epinephrine (curve *1*) is observed at 280 nm, which is consistent with the literature

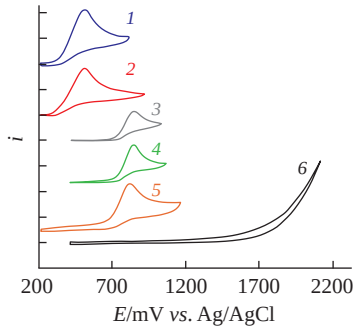


Figure 1 CV curves for (*1*) 2 mM of epinephrine, (*2*) a mixture of 2 mM of epinephrine and nicotinic acid, a mixture of 2 mM of epinephrine and 1 mM of HSGO (*3*) before and (*4*) after adding 2 mM nicotinic acid, (*5*) 1 mM of **1**, and (*6*) a mixture of 2 mM of nicotinic acid and 1 mM of HSGO, recorded on a glassy carbon disc electrode in a phosphate buffer solution (KH_2PO_4/Na_2HPO_4, pH 6.86). A scan rate 0.1 V s^{-1}.

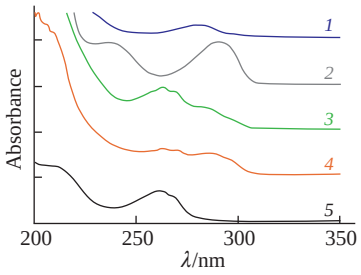


Figure 2 UV spectra for (*1*) 0.2 mM of epinephrine, a mixture of 0.2 mM of epinephrine and 0.1 mM of HSGO (*2*) before and (*3*) after adding 0.2 mM nicotinic acid, (*4*) 0.1 mM of **1**, and (*5*) 0.2 mM of nicotinic acid in deionized water.

data.[18] The adding of HSGO to this solution (curve *2*) results in a bathochromic shift of the band to 291 nm. The subsequent adding of nicotinic acid (curve *3*) does not lead to a noticeable shift of this band, however, its intensity decreases significantly. In the latter case, the spectrum is identical to that of the independently synthesized **1**. Similar observations can be made in the experiments with nicotinamide and isoniazid (see Online Supplementary Materials). Thus, the UV spectroscopy data confirm the general conclusion that can be drawn from the results of the voltammetric study: the interaction of germanium with the studied N-donors in an aqueous solution is rather weak.

Figure 3 represents the results of TGA and DTA in argon atmosphere for complexes **1** and **4** compared to the data for epinephrine and nicotinic acid. The last two are stable up to about 200 °C, after which epinephrine is gradually losing mass while nicotinic acid is losing mass quickly almost to zero. These processes correspond to endothermic peaks on the DTA curves with minima at 213 and 237 °C, respectively. This is consistent with published data, reporting that melting with decomposition of epinephrine occurs at 211 °C,[19] and of nicotinic acid at 236.6 °C.[20] At the same time, the curves for **1** and **4**, in which epinephrine and nicotinic acid are in a bound form, do not have such pronounced peaks. By 500 °C, complex **4** loses 34% of its initial mass, while for epinephrine this value is 62%. The mass of the organic part of complex **4** can be estimated at 70–83% (without and with oxygen atoms of C–O–Ge bonds). Given this and excluding the effect of germanium on the thermal stability of epinephrine, a weight loss of at least 43% could be expected for complex **4**, which indicates the stability of the complex. Further, complex **1**, differing from **4** by the presence of nicotinic acid in its structure, loses 53% of its mass by 500 °C. Free nicotinic acid is 100% consumed under these conditions, and its mass fraction in **1** is 36%. Given this, the mass loss for a hypothetical mixture of non-interacting **4** and nicotinic acid is expected to be 58%.

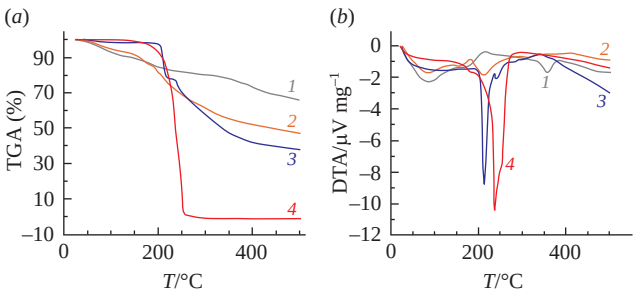


Figure 3 (*a*) TGA and (*b*) DTA curves for (*1*) **4**, (*2*) **1**, (*3*) epinephrine, and (*4*) nicotinic acid obtained at a heating rate of 10 K min^{-1} in the range from ambient temperature up to 500 °C under argon atmosphere.

Thus, we can conclude that participation of nicotinic acid in complexation also stabilizes the corresponding structural motive.

In conclusion, we believe that highly soluble germanium oxide will become a promising highly reactive hydrophilic precursor in the organic and coordination chemistry of germanium compounds.

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Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2022.01.007.

References

1 S. C. Burdette and B. F. Thornton, *Nature Chem.*, 2018, **10**, 244.
2 A. Alcañiz, G. López, I. Martín, A. Jiménez, A. Datas, E. Calle, E. Ros, L. G. Gerling, C. Voz, C. del Cañizo and R. Alcubilla, *Solar Energy*, 2019, **181**, 357.
3 Y. Wang, S. Luo, M. Chen and L. Wu, *Adv. Funct. Mater.*, 2020, **30**, 2000373.
4 E. A. Saverina, R. R. Kapaev, P. V. Stishenko, A. S. Galushko, V. A. Balycheva, V. P. Ananikov, M. P. Egorov, V. V. Jouikov, P. A. Troshin and M. A. Syroeshkin, *ChemSusChem*, 2020, **13**, 3137.
5 D. Sarkar, S. Dutta, C. Weetman, E. Schubert, D. Koley and S. Inoue, *Chem. – Eur. J.*, 2021, **27**, 13072.
6 A. V. Kadomtseva, G. M. Mochalov and O. V. Kuzina, *Russ. J. Org. Chem.*, 2021, **57**, 879 (*Zh. Org. Khim.*, 2021, **57**, 788).
7 V. Romanovs, D. M. Vakhrusheva, I. V. Krylova, B. N. Mankaev, A. Ya. Kozmenkova, M. A. Syroeshkin, M. P. Egorov and V. V. Jouikov, *Mendeleev Commun.*, 2020, **30**, 567.
8 I. V. Krylova, E. A. Saverina, S. S. Rynin, A. V. Lalov, M. E. Minyaev, E. N. Nikolaevskaya, M. A. Syroeshkin and M. P. Egorov, *Mendeleev Commun.*, 2020, **30**, 563.
9 D. A. Grishanov, A. V. Churakov, A. G. Medvedev, A. A. Mikhaylov, O. Lev and P. V. Prikhodchenko, *Inorg. Chem.*, 2019, **58**, 1905.
10 E. N. Nikolaevskaya, A. V. Kansuzyan, G. E. Filonova, V. A. Zelenova, V. M. Pechennikov, I. V. Krylova, M. P. Egorov, V. V. Jouikov and M. A Syroeshkin, *Eur. J. Inorg. Chem.*, 2019, 676.
11 M. Glavinović, M. Krause, L. Yang, J. A. McLeod, L. Liu, K. M. Baines, T. Friščic and J.-P. Lumb, *Sci. Adv.*, 2017, **3**, e1700149.
12 D. Roth, H. Wadepohl and L. Greb, *Angew. Chem., Int. Ed.*, 2020, **59**, 20930.
13 P. G. Shangin, I. V. Krylova, A. V. Lalov, A. Y. Kozmenkova, E. A. Saverina, P. A. Buikin, A. A. Korlyukov, A. A. Starikova, E. N. Nikolaevskaya, M. P. Egorov and M. A. Syroeshkin, *RSC Adv.*, 2021, **11**, 21527.
14 E. N. Nikolaevskaya, E. A. Saverina, A. A. Starikova, A. Farhati, M. A. Kiskin, M. A. Syroeshkin, M. P. Egorov and V. V. Jouikov, *Dalton Trans.*, 2018, **47**, 17127.
15 E. N. Nikolaevskaya, P. G. Shangin, A. A. Starikova, V. V. Jouikov, M. P. Egorov and M. A. Syroeshkin, *Inorg. Chim. Acta*, 2019, **495**, 119007.
16 E. A. Saverina, V. Sivasankaran, R. R. Kapaev, A. S. Galushko, V. P. Ananikov, M. P. Egorov, V. V. Jouikov, P. A. Troshin and M. A. Syroeshkin, *Green Chem.*, 2020, **22**, 359.
17 S.-M. Chen and K.-T. Peng, *J. Electroanal. Chem.*, 2003, **547**, 179.
18 Y. Kitamura, T. Takatsuki, M. Kawamoto, M. Saito, A. Iwado, I. Tsukamoto, M. Mifune and Y. Saito, *Chem. Pharm. Bull.*, 2007, **55**, 500.
19 H. Jensen, *J. Am. Chem. Soc.*, 1935, **57**, 1765.
20 T. Rittirod, T. Hatanaka, N. Kagami, K. Katayama and T. Koizumi, *Biol. Pharm. Bull.*, 1999, **22**, 305.

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