Solubility of Tetrahydroxybenzophenone (THBP) in Acetone

Manabu Itoh,*,† Yasuo Kuniyoshi,† Masaaki Yokota,‡ Norihito Doki,‡ and Kenji Shimizu‡

Chiba Factory, Toyo Gosei Co., Ltd., 1-51 Miyanodai, Tonosho-Machi, Katori-Gun, Chiba Prefecture, 289-0623 Japan, and Department of Chemical Engineering, Iwate University, 4-3-5 Ueda, Morioka, 020-8551 Japan

Solubilities of nonsolvate and acetone-solvate crystals of tetrahydroxybenzophenone (THBP), a raw material of photoresists, in acetone were measured at temperatures ranging from 283.15 K to 323.15 K and from 288.15 K to 318.15 K, respectively. The solubility of nonsolvate (needle crystal) was higher than that of acetone-solvate (granular crystal) at temperatures lower than 314.85 K, while at temperatures higher than 314.85 K it was lower than that of the granular crystals. The molar ratio of solvated acetone to THBP in the granular crystal was determined to be 1:1 by thermogravimetry and by gas chromatography. The powdery crystals of acetone-solvate THBP were unstable in the air at room temperature and lost acetone gradually during a few hours. Dry powder was obtained by vacuum drying. The solubility of the dry powder was the same as that of the "wet" granular crystals. This suggests that the dry powder returned to the original acetone-solvate when dispersed in acetone solvent.

Introduction

Tetrahydroxybenzophenone (THBP) is a main raw compound of photoresists, light-sensitive materials used in industries for photolithography and photoengraving to form patterned coatings on surfaces. THBP, the chemical structure of which is shown in Figure 1, is purified in industry by cooling crystallization from a mixed solvent of acetone, water, and other organic solvents. However, crystallization behavior is not understood satisfactorily and, therefore, problems sometimes occur in an actual crystallization process.

As a first step toward a fundamental understanding of THBP crystallization, solubility measurements were made in acetone. There are two types of THBP crystal. One is the needle crystal, which is used in industries, and the other is the newly found granular crystal. The granular crystal was different from the usually obtained needle one not only in shape but also in crystal structure. The granular crystal was an acetone-solvate, that is, a pseudo-polymorphic crystal of THBP, whereas the needle crystal was nonsolvate.

Experimental Section

Materials. The THBP nonsolvate crystals used for the solubility measurements are shown in Figure 2 (Photo A). The crystals are thin needle of about 100 μm in length, which were obtained from an actual production unit, where a mixture of acetone, water, and other organic solvents was used as the solvent. The mass fraction purity of the THBP needle crystals, determined by high-performance liquid chromatography, was 99.95 % or more. The mass fraction content of acetone was less than 0.01 %, and therefore the needle crystals were concluded to be nonacetone-solvate.

The newly found granular crystals were obtained at 293.15 K by seeded batch-cooling crystallization from an acetone solution saturated at 313.15 K with respect to the needle crystals. The produced granular crystals were stored in acetone as a concentrated suspension in a closed glass bottle and were used for the solubility measurement. Exposure of the crystals to air was always avoided because the granular crystals were unstable in the air and tended to lose acetone. The granular crystals are

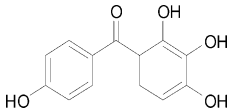

Figure 1. Chemical structure of tetrahydroxybenzophenone (THBP).

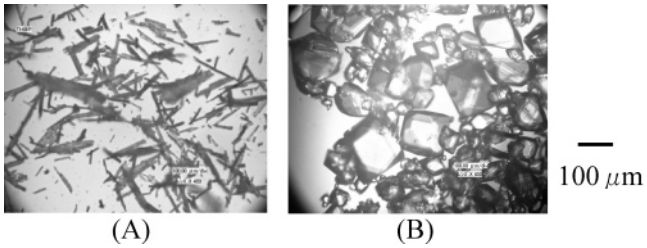

Figure 2. Photographs of THBP crystals: (A) nonsolvate; (B) acetone-solvate.

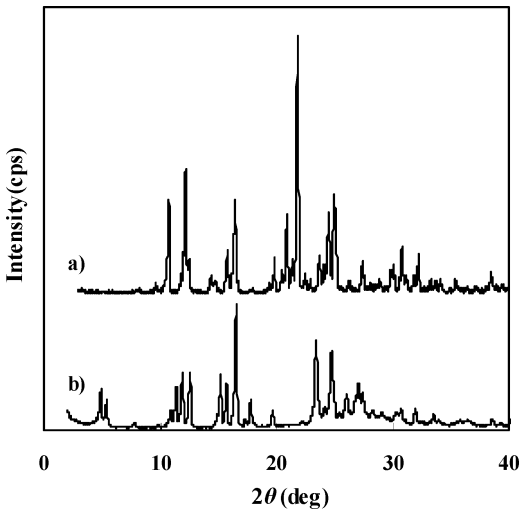

Figure 3. XRD patterns of (a) granular and (b) needle crystals.

* To whom correspondence should be addressed. Phone: +81-478-87-1525. Fax: +81-478-87-0333. E-mail: ma-ito@toyogosei.co.jp.
† Toyo Gosei Co. Ltd.
‡ Iwate University.

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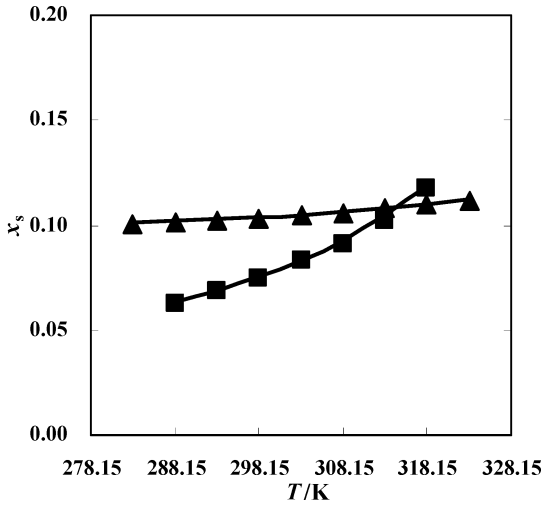

Figure 4. Mole fraction solubility of THBP in acetone. ▲, nonsolvate needle crystal; ■, acetone-solvate granular crystal. Solid lines are best fits of eq 1.

Table 1. Mole Fraction Solubility of THBP in Acetone

needle		granular		
T/K	$x_s^{a,b}$	T/K	x_s^c	uncertainty^d
283.15	0.1004	288.15	0.0623	0.0006
288.15	0.1016	293.15	0.0687	0.0004
293.15	0.1024	298.15	0.0744	0.0007
298.15	0.1033	303.15	0.0835	0.0018
303.15	0.1043	308.15	0.0913	0.0007
308.15	0.1060	313.15	0.1020	0.0012
313.15	0.1081	318.15	0.1180	0.0007
318.15	0.1096			
323.15	0.1115			

[a] One sample. [b]Uncertainty ± 0.0002. [c]The average of three samples from the same solution. [d]Calculated by using three data.

Table 2. Regression Curves of THBP in Acetone[a]

crystal	A	B	C	$10^3\sigma$	R^2
needle	−0.2420	−0.0159	$30.573 \cdot 10^{-6}$	0.537	0.997
granular	6.2126	−0.0782	$163.34 \cdot 10^{-6}$	1.326	0.998

[a] Temperature range is from 283.15 K to 323.15 K for the nonsolvate needle crystals and 288.15 K to 318.15 K for the acetone-solvate granular crystals.

shown in Figure 2 (photograph B). The original granular seed crystals used for the seeded batch crystallization of the granular crystals were obtained by natural evaporation from an acetone solution at a room temperature.

The granular crystal was acetone-solvate, and the appearance of the granular crystal particles changed gradually in the air from transparent to opaque with the loss of acetone. The amount of solvated acetone was determined by thermogravimetry and by gas chromatography. The molar ratio of acetone and THBP in the granular crystal was 1:1.

X-ray powder diffraction (XRD) patterns were measured for the needle crystals and the as-grown granular crystals used for the solubility measurements. The XRD patterns are shown in Figure 3. The acetone used was purchased from Kyowa Hakko Kogyo Co. Ltd. in Japan, and it was used without further purification. According to the manufacturer, the purity was 99.8 mass fraction % with a moisture mass fraction of 0.2 %.

Solubility Measurements of the Granular Crystals. The solubility was determined gravimetrically. An excessive amount

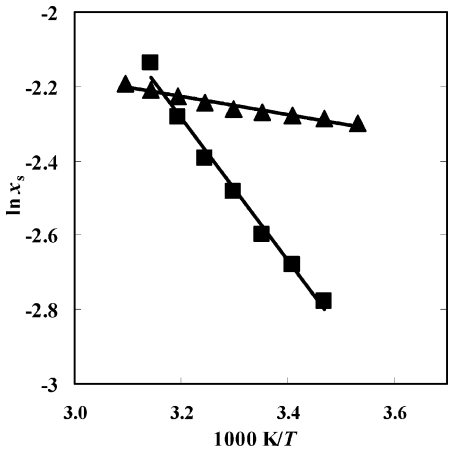

Figure 5. van't Hoff plot of THBP in acetone. ▲, nonsolvate needle crystals; ■, acetone-solvate granular crystal.

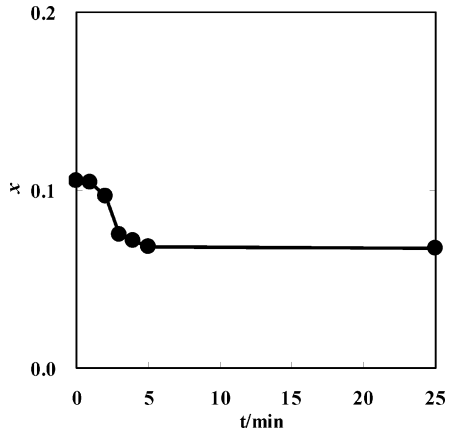

Figure 6. Transient composition x of the solution at 293.15 K showing a typical solution-mediated transformation.

(4 g to 14 g) of the granular crystals was added to the solvent acetone (ca. 10 g) in an eggplant-type flask of 30 mL in volume, which was immersed in a water bath regulated with an ordinary temperature control unit (Thermo-Mate BF-200, Yamato Co. Ltd., Japan). The temperature of the slurry in the flask was controlled to an uncertainty of ± 0.05 K as determined by mercury glass thermometer. The suspension was agitated with a magnetic stirrer at a given temperature for 30 min of which time period was confirmed by preliminary experiments to be enough to attain equilibrium. About 5 mL of the supernatant solution was transferred by using a pipet to a syringe equipped with a filter of 0.5 μm pore size through which the solution was transferred into an eggplant-type flask of 100 mL in volume. Then, the flask was connected to a rotary evaporator to eliminate the solvent to dryness at a reduced pressure of 0.4 kPa. The solubility was calculated from the difference of masses before and after drying. The solubility measurement was made at temperatures ranging from 288.15 K to 318.15 K in 5 K intervals. Although in the temperature range above 314.85 K the granular crystals were unstable, the same gravimetrical method could be applied if a large excess amount of seeds were used. The measurement was made in triple for the same solution at a given temperature.

Solubility Measurements of the Needle Crystals. The gravimetrical method could not be used for the measurements of solubility of the needle crystals, because in the lower temperature range below 314.85 K the needle crystal was thermodynamically

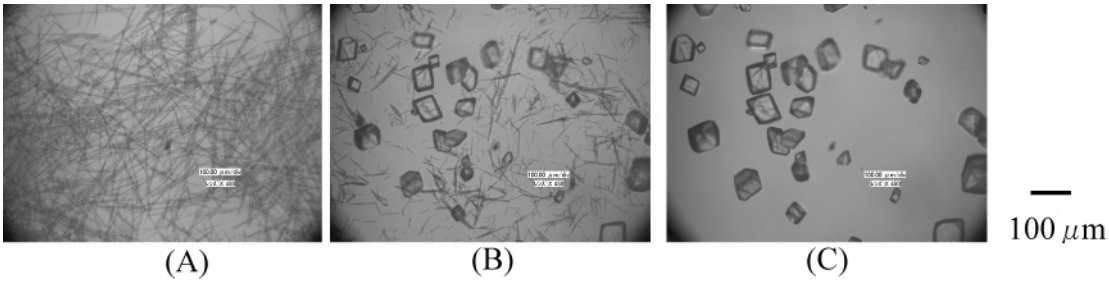

Figure 7. THBP transformation on a slide glass at room temperature: (A) 0 s, (B) 10 s, and (C) 20 s.

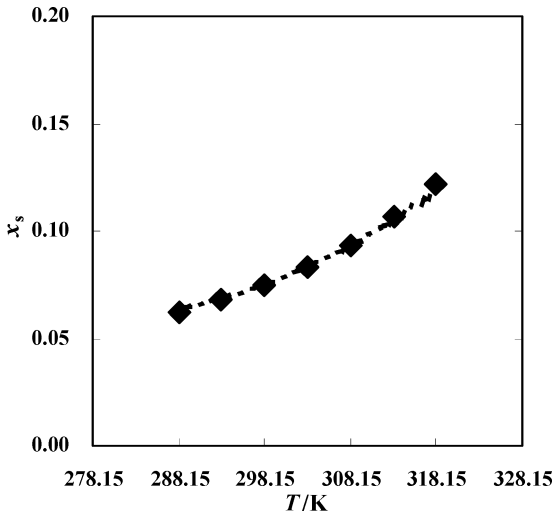

Figure 8. Solubilities of the dry granular crystals x_s of THBP. Dotted line is the solubility of the wet acetone-solvate granular crystals, calculated from eq 1.

unstable and tended to transform naturally to the granular crystals. As an alternative, the isothermal method[2] was used. About 10 g of acetone of which the mass was measured accurately was charged into an eggplant-type flask of 30 mL in volume and was kept at a prescribed temperature. Afterward, the THBP needle crystals were dissolved into the acetone periodically, and the point when the added crystals did not disappear was determined. The judgment of disappearance of the crystals was made visually. The amount of the crystals added at one time was 0.5 g to 1 g in the early stage, but it was decreased to about 0.002 g toward the endpoint. The mole fraction solubility could be reproduced to within an uncertainty of ± 0.0002. In the higher-temperature range above 314.85 K where the needle crystal was the thermodynamically stable crystalline form, the gravimetrical method was also used in a similar way as for the granular crystal. The values determined by the gravimetrical method were 0.1080 (315.65 K), 0.1087 (318.15 K), 0.1096 (320.65 K), and 0.1109 (323.15 K). These values were in good agreement with the values determined by the isothermal method (see Table 2).

Transformation Experiments. Transformations of THBP from the granular to the needle crystals and from the needle to granular crystals were traced by measuring the transient composition x of the solution.

Transformation of the needle to the granular crystals was traced in the following manner. An amount of the needle crystals was added in excess to the solvent acetone (ca. 20 g) prepared in a three-necked flask of 30 mL in volume so that about 1 g of the needle crystals remained undissolved. The suspension was agitated for 30 min with a magnetic stirrer at 293.15 K. Then, a small amount of granular crystals (0.08 g) was charged to initiate transformation. Transient compositions were measured gravimetrically as similarly to the above solubility measurements.

Transformation from the granular to the needle crystals was observed similarly. All the experimental conditions, except for the temperature, were the same as in the transformation experiment of the needle crystals. The temperature where the transformation was observed was 318.15 K.

Results and Discussion

Solubilities. The solubilities of the granular and the needle crystals of THBP in mole fraction x_s are listed in Table 1 and shown in Figure 4. The solubility of the needle crystals is higher than that of the granular crystals in the low-temperature range, while in the higher temperature range it is lower. The two lines cross at a temperature of 314.85 K. The solid lines are the following second-order polynomial[2] fitted to the experimental data

$$\ln x_s = \mathrm{A} + \mathrm{B}(T/\mathrm{K}) + \mathrm{C}(T/\mathrm{K})^2 \qquad (1)$$

where A, B, and C are constants, and T is temperature in Kelvin. The coefficients of the fitted curves are listed in Table 2. The values of R^2, listed also in Table 2, were 0.998 and 0.997 for the granular crystals and the needle crystals, respectively. In Table 2, the root-mean-square deviation (σ) is also listed. It is defined as follows, where N is the number of data points, x_{si} is experimental value and x_{si}^{cal} is calculated ones by eq 1

$$\sigma = \left[\frac{1}{N}\sum_{i=1}^{N}(x_{si} - x_{si}^{cal})^2\right]^{1/2} \qquad (2)$$

Figure 5 shows the so-called van't Hoff plot, where $\ln x_s$ is plotted as a function of $1/T$. The slope of the line is the van't Hoff enthalpy of solution (or the apparent enthalpy of solution).[3] The values of the van't Hoff enthalpy are 1.98 J·mol^{-1} and 15.8 J·mol^{-1} for the nonsolvate needle crystal and the acetone-solvate granular crystal, respectively. The enthalpy of the granular crystal is larger than that of the needle crystal.

Transformation Behavior. A typical transformation curve, the transient concentration of THBP, of the needle crystals is shown in Figure 6. In the region where the concentration is decreasing, the needle and granular crystals were present together, as confirmed by microscopic observation of sampled suspension, and later in the region where the concentration is approaching the final constant level, the needle crystals almost disappeared and only the granular crystals remained. From this, the transformation is concluded to proceed through the solution-mediated mechanism. The transformation was completed within about 5 min under the condition in this study. The time needed for transformation depends on the experimental condition, such as temperature, concentration of solution, the amount of seeds

of the needle crystals initially present, and the granular crystals added to initiate transformation. In Figure 7, a set of photographs is shown, which is another evidence of the solution-mediated transformation from the needle to the granular. It can be seen (photograph B) that needle crystals are dissolving, and granular crystals are growing in the solution placed on a glass plate under a microscope.

Transformation of the granular crystals to the needle crystals proceeded fast. It finished in a few tenths of seconds at 318.15 K. Therefore, we could not obtain the transformation curve.

Solubilities of Dry Granular THBP Crystals. In Figure 8, solulibities of dry granular crystals are shown. The measured values are in good agreement with a solid line, which is the solubility of the granular THBP crystals calculated from eq 1. The solubilities of the dry granular crystals are in agreement with that of the "wet" granular crystals, which is the acetone-solvate. This means that acetone molecules quickly enter into the dry THBP crystals and are incorporated into the crystal structure.

Literature Cited

(1) Espitalier, F.; Biscans, B.; Laguerie, C. Physicochemical Data on Ketoprofen in Solutions. *J. Chem. Eng. Data* **1995**, *40*, 1222−1224.
(2) Mullin, J. W. *Crystallization*, 4th ed.; Butterworth-Heinemann: Oxford, 2000; p 94.
(3) Nordstrom, F. L.; Rasmuson, A. C. Solubility and Melting Properties of Salicylic Acid. *J. Chem. Eng. Data* **2006**, *51*, 1668−1671.

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