Recovery of Indium and Gallium from Spent IGZO Targets by Leaching and Solvent Extraction

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Indium, gallium, and zinc oxide (IGZO) is a semiconducting material that is widely used in the manufacturing of semiconductors, touch panels, displays, etc. This work aims to shed some light on the recovery and separation of indium, gallium, and zinc from spent IGZO targets by solvent extraction (SX). The process involved leaching, SX in high acidity, stripping, re-extraction in low acidity, and re-stripping, followed by the cementation of the gallium and indium with zinc dust. Triisobutyl phosphate (T-iso-BP) was employed as the extractant to separate the majority of zinc from indium and gallium in the leaching solution. The leaching solution was utilized directly without further adjustment, to avoid consuming an enormous amount of water. The loaded organic (LO) solution was then stripped with HCl solution at pH 2, moving the majority of indium and gallium from LO phase to aqueous phase. The leaching and stripping process enabled the transfer of indium and gallium from the leaching solution (8–8.5 mol/L HCl solution) to HCl solution at pH 2, without diluting the leaching solution with an enormous amount of water. The stripped solution was then extracted with di-(2-ethylhexyl) phosphoric acid to separate indium from gallium. The optimum extraction conditions and stripping conditions were studied. From the actual spent IGZO target, 97.8% of indium with a purity of 98.3% and 96.2% of gallium with a purity of 99.6% were separated and recovered.

Introduction

IGZO (InGaZnO₄, In₂Ga₂ZnO₇ etc.) is a semiconducting material consisting of indium, gallium, zinc, and oxygen. IGZO was first prepared by Prof. Hideo Hosono’s group at the Tokyo Institute of Technology (Nomura et al., 2003), and was subsequently used as the electrode material in flat panel displays (Nomura et al., 2004; Yabuta et al., 2006; Park et al., 2007). IGZO was considered to be the most promising thin-film transistor (TFT) for next-generation organic light-emitting devices (OLED) (Hsieh et al., 2010) owing to its excellent physical–chemical properties, which improve the speed and resolution of the display while consumes less energy (Kwon et al., 2008; Kang et al., 2011; Zhou et al., 2015). IGZO–TFT was first commercialized in 2012 by Sharp; since then, the demands for indium and gallium have increased dramatically (Gibson and Hayes, 2011), with an estimated yearly demand growth rate of 15% and 15–20% for indium and gallium, respectively. However, the discrete deposits and the sparse distributions of indium and gallium worldwide make it difficult to separate and recover these materials from mineral ores. Because indium does not form primary mineral deposits, it is principally recovered as a byproduct from zinc sulfide mineral processing, with the concentration of indium ranging from less than 1 to 100 ppm (Salazar and McNutt, 2012). Gallium is mostly produced as a byproduct of treating bauxite and zinc-processing residues, the average content being 50ppm (Salazar and McNutt, 2012). The contents of indium and gallium in spent IGZO targets range from 36 to 43% and 22 to 26%, respectively. That is, the indium and gallium in spent IGZO targets are thousands of times more concentrated than those in minerals. Spent IGZO targets as urban mines could become the main resource of indium and gallium (Moss et al., 2011; Chancerel et al., 2015; Jin et al., 2016; Van Eygen et al., 2016).

At present, there are two main methods to separate and recycle indium, gallium, and zinc from IGZO: extraction resin and solvent extraction (SX). Liu et al. (2006) studied the P507 resin (HR,PO₄, where R: 2-ethylhexyl phosphonic acid mono(2-ethylhexyl) ester) in the separation of indium, gallium, and zinc from sulfate solution. The results showed that a theoretical separation of indium, gallium, and zinc from dilute solutions could be achieved by controlling pH and using different concentrations of hydrogen chloride eluent, although this consumes vast amounts of water. Sasaki et al. (2016, 2017) utilized different extractants to separate indium, gallium, and zinc from IGZO. The α-dodecylaminobenzylphosphonic acid mono-butyl ester with an aliphatic amine showed a relatively high selectivity towards indium and gallium; and the newly synthesized[N,N-di(2ethylhexyl)amino]methylphenylphosphinic acid was found to be effective for the extraction of indium, gallium, and zinc ions in nitric acid solution. Chen et al. (2017) used di-(2-ethylhexyl) phosphoric acid (D2EHPA) to separate indium from gallium and zinc, after which the same extractant was used to separate gallium
from zinc in nitric acid solution. Spent IGZO targets are expected to increase rapidly in the near future, while the extraction of indium and gallium from IGZO in HCl solution has not been studied in detail yet. As mentioned, the SX of IGZO in nitric acid solution has been studied repeatedly. Nevertheless, NO₃⁻ is one of the main sources of water eutrophication and thus should be avoided. (Findlay and Kaskan, 1990; Paerl, 2009; Tang et al., 2011; Jovan et al., 2012) We, on the other hand, have studied the extraction behavior of indium, gallium, and zinc from a spent IGZO target in HCl solution. As for the extractants, D2EHPA has been utilized to separate indium from gallium (Lee et al., 2002) or zinc (Li et al., 2015); tributyl phosphate (Virolainen et al., 2011) was used to selectively extract indium from an indium tin oxide (ITO) leaching solution; and Cyanex 923 (Gupta et al., 2004), Cyanex 925 (Ahmed et al., 2013), and Cyanex 272 (Gupta et al., 2007) and other extractants have been adopted to extract indium in acid solutions (Gupta et al., 2004; Gupta et al., 2007; Ahmed et al., 2013; Zhang et al., 2015). To separate valuable metals (indium and gallium) from spent IGZO targets in a sustainable and commercially viable manner, a two-step SX process using commercially available extractants without diluting the leaching solution before extraction was proposed. The recycling process includes: leaching of IGZO targets, separation of zinc from indium and gallium by trisobutyl phosphate (T-iso-BP) at high acidity, stripping of indium and gallium from T-iso-BP by HCl at pH 2, extraction of indium from gallium by D2EHPA at low acidity, stripping of indium from D2EHPA with 1 mol/L HCl, and cementation of indium and gallium. D2EHPA and T-iso-BP were chosen as the extractants in this study because they showed better extraction and separation efficiency in low and high acidity, respectively (Lee et al., 2002; Gupta et al., 2007). The scrubbing step was abridged because the main impurity (zinc ions) can be separated from indium and gallium in the cementation process.

1. Experiments

1.1 Materials and methods

Indium(III) chloride tetrahydrate (InCl₃·4H₂O, 99.99%, analytically pure, Alfa Aesar), GaCl₃ (99.99%, analytically pure, Alfa Aesar), ZnCl₂ (99.9%, analytically pure, Alfa Aesar), and HCl (37%, reagent grade, Sigma-Aldrich, Co. LLC.) were used as received. The extractants D2EHPA and T-iso-BP were purchased from Tokyo Kasei Co. and Wako Pure Chemical Industries, Ltd., respectively. Both extractants were used without further purification. T-iso-BP was utilized owing to its high stability in high acid concentrations (Chiarizia et al., 2006). Kerosene purchased from Wako Pure Chemical Industries, Ltd. was used as the diluent. The HCl was diluted with distilled water. Aqua regia was used to determine the exact composition of IGZO immediately after its synthesis in the laboratory. The leaching process was conducted in a beaker equipped with a stirring hot plate (RET control-visc, IKA-Werke GmbH & CO. KG) to control the stirring speed and leaching temperature. The SX process was carried out in a shaking incubator (SSI5, Shel Lab Sheldon Manufacturing, Inc.) at 200 rpm (peripheral velocity: 12.56 cm/s) at 30°C. The spent IGZO target material was ground to fine powder (Figure 1) and analyzed with X-ray fluorescence (Supermini WDXRF Rigaku Corp.) and inductively coupled plasma optical emission spectrometry (ICP-OES, Optima 5300 DV PerkinElmer, Inc.). The composition of the spent IGZO target was measured by XRF, and the mass fraction of the IGZO target was obtained by standard FP quantification program (SQX) analysis. Since SQX is only a semi-quantitative analysis method, the actual mass fraction of indium, gallium, and zinc in the spent target was determined by ICP-OES after dissolving the IGZO target using aqua regia. The results of the analysis are shown in Table 1.

1.2 HCl leaching

The spent IGZO target was crushed and milled to fine powder with an average particle size less than 2.5µm, as shown in Figure 1(b). The powder was then dissolved in HCl leaching solution under different acid concentrations, solid-liquid (S/L) ratios, temperatures, and leaching time. The concentration of HCl was varied from 1 to 9 mol/L (i.e., 1, 3, 5, 7, and 9 mol/L) with the S/L ratio ranging from 1 to 20 g/L (i.e., 1, 5, 10, and 20 g/L). The leaching temperature was varied from 30 to 70°C (i.e., 30, 40, 50, 60, and 70°C) with the leaching time ranging from 5 to 120 min (i.e., 5, 10, 30, 60,
1.3 SX of indium and gallium
T-iso-BP and D2EHPA were used as the extractants to separate and recover indium, gallium, and zinc from the leaching solution of the spent IGZO target. Simulated solutions at different HCl concentrations were used to test the extraction behavior of T-iso-BP and D2EHPA. The simulated solutions were prepared by adding the same ratio of indium chloride, gallium chloride, and zinc chloride as in the IGZO target into different concentrations of HCl solutions. The extraction behaviors of T-iso-BP were carried out in high HCl concentrations (0.01 to 9 mol/L) and the T-iso-BP volume ratio in the organic phase was varied from 20 to 70% (i.e., 20, 30, 40, 50, 60, and 70%). The aqueous–organic (A/O) ratio ranged from 4:1 to 1:3 (i.e., 4:1, 3:1, 2:1, 1:1, 1:2, and 1:3) with the extraction time varying from 1 to 9 min (i.e., 1, 3, 5, 7, and 9 min). The extraction behaviors of D2EHPA were analyzed in low HCl concentrations (pH: 0 to 6) with the D2EHPA volume ratio in the organic phase ranging from 5 to 30% (i.e., 5, 10, 15, 20, 25, and 30%). The A/O ratio was varied from 4:1 to 1:3 (i.e., 4:1, 3:1, 2:1, 1:1, 1:2, and 1:3) with the extraction time varying from 1 to 9 min (i.e., 1, 3, 5, 7, and 9 min).

1.4 Stripping process
HCl, at different concentrations, was used as the stripping agent. HCl was mixed with the organic phase, obtained from the extraction process. Indium, gallium, and zinc were stripped out of the loaded T-iso-BP phase into HCl solution at pH 2. HCl solution (1 mol/L) was utilized to strip indium and gallium from the loaded D2EHPA phase.

1.5 Cementation process
Zinc dust was chosen as the reductant in the cementation process owing to the lower galvanic series of zinc compared with indium and gallium. In the cementation process, indium and gallium ions react with zinc dust, forming zero valence indium and gallium, respectively. In the cementation process, only indium and gallium ions were reduced, leaving the zinc ions in the solution, which made the scrubbing step unnecessary in this study. A stoichiometric amount of zinc dust was added twice for the total precipitation of indium and gallium. The higher equivalent amount of zinc dust was unnecessary in this study. A stoichiometric amount of zinc dust was added twice for the total precipitation of indium and gallium. The higher equivalent amount of zinc dust was unnecessary in this study.

1.6 Regeneration of organic phase
There were two stripped organics from this recovery process: the stripped organic of T-iso-BP, and the stripped organic of D2EHPA. The stripped organic of T-iso-BP could be regenerated by HCl at pH 1 with an A/O ratio of 1:1. The stripped organic of D2EHPA could be regenerated by 1 mol/L HCl with an A/O ratio of 1:1.

2. Results and Discussion

2.1 HCl leaching
The optimum conditions for the leaching, such as acid concentration, S/L ratio, temperature, and time, were determined as shown in Figure 2. The leaching was conducted by dissolving the spent IGZO target under different concentrations of HCl at a stirring rate of 500 rpm (peripheral velocity: 31.4 cm/s). Figure 2(a) shows the leaching rate (LR) of IGZO as a function of the concentration of HCl solution. The LR of all elements in the spent IGZO target increased with increasing concentration of HCl solution. The effect of S/L ratio on the LR of IGZO is shown in Figure 2(b), which shows that the leaching ratio decreased with increasing S/L ratio. Almost all the IGZO could be dissolved when the S/L ratio was less than 5 g/L. As shown in Figure 2(c), the LR of IGZO increased with increasing temperature. Most of the IGZO could be dissolved when the temperature was higher than 40°C. Finally, the effect of leaching time on the LR is shown in Figure 2(d). When the leaching time was longer than 30 min, most of the IGZO was dissolved. Overall, the optimum leaching conditions were determined to be: 9 mol/L HCl, S/L ratio of 5 g/L, leaching temperature of 50°C, and leaching time of 60 min. The leaching results of the optimum condition are given in Table 2, which shows

![Graphs](Fig 2 Equilibrium of leaching with HCl at different conditions. (a) Effect of HCl concentration on the LR of IGZO target with a temperature of 50°C, leaching time of 60 min, and S/L ratio of 1 g/L; (b) effect of S/L ratio on the LR of the IGZO target with a temperature of 50°C, leaching time of 60 min, and HCl concentration of 9 mol/L; (c) effect of leaching temperature on the LR of the IGZO target with a leaching time of 60 min, S/L ratio of 5 g/L, and HCl concentration of 9 mol/L; (d) effect of leaching time on the LR of the IGZO target with a temperature of 50°C, S/L ratio of 5 g/L, and HCl concentration of 9 mol/L.)

<table>
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<tr>
<th>IGZO [g]</th>
<th>In [g]</th>
<th>Ga [g]</th>
<th>Zn [g]</th>
<th>LR In [%]</th>
<th>LR Ga [%]</th>
<th>LR Zn [%]</th>
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Table 2 LR of IGZO with 9 mol/L HCl, S/L ratio of 5 g/L, temperature of 50°C, and leaching time of 60 min.
that more than 99.9% of indium, gallium, and zinc could be dissolved. Considering the leaching results given in Tables 1 and 2, it is safe to say that all IGZO was dissolved under the optimum leaching conditions. Some modifications, i.e., a leaching column (Hodson et al., 2001), cross-current (Rochetti et al., 2015), or counter current (Shen et al., 2008), could be adopted during the actual production process to lower the HCl concentration of the leaching solution.

2.2 SX of indium, gallium, and zinc with T-iso-BP

Figure 3 shows the extraction behavior of indium, gallium, and zinc by T-iso-BP. Figure 3(a) shows the effect of initial HCl concentrations on the extraction of indium, gallium, and zinc. As can be seen, more than 90% of indium and gallium were extracted into the organic phase when the concentration was greater than 5 mol/L, while the extraction percentage of zinc was less than 70%. The extraction percentage of indium and gallium increased with the increase of HCl concentration. However, the extraction percentage of zinc increased when the concentration of HCl was less than 5 mol/L, and the extraction percentage decreased when the HCl concentration was more than 5 mol/L. The extraction percentages of indium and gallium in 0.01 mol/L HCl solution were less than 1%. Figure 3(b) shows the effect of A/O ratio on the extraction behavior of indium, gallium, and zinc with the following experimental conditions: \( C(HCl) = 9 \text{ mol/L} \); T-iso-BP volume ratio in organic phase: 50%; extraction temperature: 30°C; and extraction time: 5 min. More than 90% of indium and gallium could be extracted into the organic phase, whereas less than 10% of zinc was extracted when the A/O was less than 2:1. The extraction percentages of indium, gallium, and zinc increased with the decreasing A/O ratio. The extraction percentage of zinc increased rapidly after the A/O ratio passed 2:1. Figure 3(c) shows the effect of T-iso-BP volume ratio in organic phase on the extraction behavior of indium, gallium, and zinc with the experimental conditions: \( C(HCl) = 9 \text{ mol/L} \); A/O = 2:1; extraction temperature: 30°C; and extraction time: 5 min. The extraction percentages of indium and zinc increased with increasing T-iso-BP volume ratio in the organic phase, whereas the extraction percentage of gallium was around 90% in the whole T-iso-BP ratio range. The extraction percentage of indium was more than 90% when the T-iso-BP ratio was more than 40%. The extraction percentage of zinc was much smaller than those of indium and gallium across the whole T-iso-BP volume ratio range. Figure 3(d) shows the effect of extraction time on the extraction behavior of indium, gallium, and zinc with the experimental conditions: \( C(HCl) = 9 \text{ mol/L} \); A/O = 2:1; T-iso-BP volume ratio in organic phase: 30%; and extraction temperature: 30°C. As can be seen, more than 80% of indium and 90% of gallium were extracted after 3 min. This means that the extraction process has relatively fast kinetics. In other words, indium and gallium can be separated from zinc at high acidity with T-iso-BP.

![Figure 3](image)

Fig. 3 Extraction behavior of indium, gallium, and zinc in T-iso-BP solution. (a) Effect of initial HCl concentration on the extraction behavior of indium, gallium, and zinc with the experimental conditions: A/O = 1:1; T-iso-BP volume ratio in organic phase: 50%; extraction temperature: 30°C, and extraction time: 5 min. (b) Effect of A/O ratio on the extraction behavior of indium, gallium, and zinc with the experimental conditions: \( C(HCl) = 9 \text{ mol/L} \); T-iso-BP volume ratio in organic phase: 50%; extraction temperature: 30°C, and extraction time: 5 min. (c) Effect of T-iso-BP volume ratio in organic phase on the extraction behavior of indium, gallium, and zinc with the experimental conditions: \( C(HCl) = 9 \text{ mol/L} \); A/O = 2:1; extraction temperature: 30°C, and extraction time: 5 min. (d) Effect of extraction time on the extraction behavior of indium, gallium, and zinc with the experimental conditions: \( C(HCl) = 9 \text{ mol/L} \); A/O = 2:1; T-iso-BP volume ratio in organic phase: 30%; and extraction temperature: 30°C

2.3 SX of indium, gallium, and zinc with D2EHPA

Figure 4 shows the extraction behavior of indium, gallium, and zinc using D2EHPA. Figure 4(a) shows the effect of initial pH on the extraction behavior with the extraction conditions of A/O = 1:1, D2EHPA volume ratio in the organic phase of 20%, extraction temperature of 30°C, and extraction time of 5 min. More than 90% of indium could be extracted into organic phase at pH greater than 2, while most of the gallium and zinc remained in the aqueous phase. The extraction percentages of indium, gallium, and zinc increased with increasing of pH. Unlike the extraction behavior of indium and gallium in T-iso-BP at high HCl concentrations, the extraction percentages of indium and gallium decreased with the increase of HCl concentrations in low acidity. Figure 4(b) shows the effect of A/O ratio on the extraction behavior of indium, gallium, and zinc with the experimental conditions: pH 2; D2EHPA volume ratio in organic phase: 20%; extraction temperature: 30°C; and extraction time: 5 min. As can be seen, the extraction percentages of indium, gallium, and zinc increased with the increase of A/O ratio; more than 80% of indium and 90% of gallium were extracted after 3 min. This means that the extraction process has relatively fast kinetics. In other words, indium and gallium can be separated from zinc at high acidity with T-iso-BP.
experimental conditions: pH 2; A/O ratio in organic phase: 20%; extraction temperature: 30°C; and extraction time: 5 min. (b) Effect of A/O ratio on the extraction behavior of indium, gallium, and zinc, with experimental conditions: pH 2; D2EHPA volume ratio in organic phase: 20%; extraction temperature: 30°C; and extraction time: 5 min. (c) Effect of D2EHPA volume ratio in organic phase on the extraction behavior of indium, gallium, and zinc, with experimental conditions: pH 2; A/O = 2 : 1; extraction temperature: 30°C; and extraction time: 5 min. (d) Effect of extraction time on the extraction behavior of indium, gallium, and zinc, with experimental conditions: pH 2; A/O = 2 : 1; D2EHPA volume ratio in organic phase: 15%; and extraction temperature: 30°C.

2.4 Extraction isotherms

The McCabe–Thiele diagram was adopted to determine the theoretical extraction stages required for the separation and recovery of indium and gallium from aqueous phase

2.5 Stripping of indium and gallium from T-iso-BP and D2EHPA

The stripping of indium and gallium from T-iso-BP should be performed at pH 2 with HCl, according to the results shown in Figure 3. HCl solution was mixed with the loaded T-iso-BP from the extraction step. Indium and gallium ions were then stripped into HCl solution. The stripping...
results at different A/O ratios are shown in Figure 6, with the stripping temperature and time being 30°C and 5 min, respectively. As can be seen from Figure 6(a), the stripping rate of indium and gallium increased with the increase of A/O ratio. At A/O = 4:1, 99.51% of indium, 99.62% of gallium, and 89.5% of zinc could be stripped out of the organic phase into aqueous phase. The stripping of indium from the loaded D2EHPA was performed with 1 mol/L HCl at 30°C for 5 min. Figure 6(b) shows the stripping results at different A/O ratios. The stripping rates of indium, gallium, and zinc increased with increasing A/O ratio. At A/O = 4:1, 99.08% of indium, 92.11% of gallium, and 95.98% of zinc could be stripped into aqueous solution.

2.6 Separation and recovery process of indium, gallium, and zinc with T-iso-BP and D2EHPA

Both D2EHPA and T-iso-BP can be used to extract indium from the leaching solution. In either case, the leaching solution should be diluted with an enormous amount of aqueous solution, especially when D2EHPA is utilized. Based on the extraction behavior of D2EHPA and T-iso-BP, a reasonable process is proposed here. Figure 7 shows the separation process that starts with leaching of the spent IGZO targets by using 9 mol/L HCl, after which the leaching solution was directly extracted with 30% T-iso-BP to separate the majority of zinc from indium and gallium. The composition of the raffinate was 0.5% of indium, 0.2% of gallium, and 86% of zinc. After this, the LO phase containing 99.5% of indium, 99.8% of gallium, and 14% of zinc was stripped by HCl at pH 2, and 99.0% of indium, 99.4% of gallium, and 12.53% of zinc were transferred into the resulting HCl solution. The remnants of indium, gallium, and zinc remained in the organic phase. At this point, the majority of indium and gallium, with a small portion of zinc, was successfully transferred into hydrochloride solution at low acidity. The significance of the above steps can be demonstrated in the following ways. First, the acidity of the solution was successfully adjusted to pH 2 without diluting the leaching solution. According to calculation, diluting 1 L of the leaching solution from 9 mol/L HCl to pH 2 requires 899 L of distilled water, whereas only 4 L of HCl solution is required at pH 2 and 1 L of 30% T-iso-BP in kerosene to transfer the majority of indium and gallium from the leaching solution to HCl solution at pH 2. Second, the low acidity of the solution enabled the separation of indium and gallium with D2EHPA. Third, the low acidity also made it possible to precipitate indium and gallium with zinc dust in the cementation step. Last, but not least, the precipitated indium and gallium would not re-dissolve into the solution in low acidity. The stripped solution was re-extracted with 15% of D2EHPA to separate gallium from indium. The raffinate at this step consisted of 0.2% of indium, 96.1% of gallium, and 0.2% of zinc; hence, the recovery rate of gallium was 96.1% and its purity was 99.6%, calculated by dividing the weight of gallium by the weight of the mixture. The majority of indium remaining in

Fig. 6 Stripping results of indium, gallium, and zinc. (a) Stripping results of indium, gallium, and zinc from T-iso-BP with HCl at pH 2 at different A/O ratios measured by ICP-OES. (b) Stripping results of indium from 15% D2EHPA with 1 mol/L HCl at different A/O ratios measured by ICP-OES

Fig. 7 Proposed recovery and separation process of indium, gallium, and zinc from spent IGZO target
the D2EHPA phase was then stripped into 1 mol/L HCl solution with 97.8% of indium, 3.036% of gallium, and 1.15% of zinc. The 0.1% of indium, 0.264% of gallium, and 0.05% of zinc residues remained in the organic phase. The stripped solution went through the same cementation process as described above. Finally, 97.8% of indium was recovered with a purity of 98.3%. For the raffinate of the leaching solution, a purity of 99.6% were recovered. The extraction process by T-iso-BP and D2EHPA were: pH 2; A/O = 2:1; D2EHPA volume ratio in organic phase: 30%; extraction temperature: 30°C; and extraction time: 7 min. After the stripping of D2EHPA with 1 mol/L HCl, the majority of the indium was stripped into the aqueous phase, which could also be precipitated by zinc. In the actual process, spent IGZO target was used. First, 96.2% of gallium with a purity of 99.6% was obtained. Afterwards, 97.8% indium with a purity of 98.3% was recovered. The extraction process by T-iso-BP and D2EHPA were carried out twice, as has been suggested by McCabe–Thiele plots.

Conclusions

A recovery and separation process of indium and gallium from spent IGZO targets was proposed and tested in practice. In this process, HCl was chosen as the leaching agent to avoid eutrophication. The process involves leaching, extraction in high acidity with 30% T-iso-BP, stripping with HCl at pH 2, re-extraction with 15% D2EHPA, and, finally, stripping with 1 mol/L HCl solution. The optimum leaching conditions were: 9 mol/L HCl, S/L ratio of 5 g/L, leaching temperature of 50°C, and leaching time of 60 min. As a high acid concentration was necessary to dissolve all the elements in IGZO, T-iso-BP was chosen as the extraction agent to extract indium and gallium at high acidity. By utilizing T-iso-BP, the dilution process can be avoided, which saves an enormous amount of water. Utilizing the excellent extraction property of T-iso-BP in high HCl solution, the majority of indium and gallium was separated from zinc, while the stripping of indium and gallium in low acidity allowed the separation of indium and gallium with D2EHPA. The stripping of indium and gallium in low acidity also facilitates the cementation process with zinc. The optimum extraction conditions in high acidity with T-iso-BP were: $C_{\text{HCl}} = 9$ mol/L; A/O = 2:1; T-iso-BP volume ratio in organic phase: 30%; extraction temperature: 30°C; and extraction time: 5 min. The optimum extraction conditions in low acidity with D2EHPA were: pH 2; A/O = 2:1; D2EHPA volume ratio in organic phase: 15%; extraction temperature: 30°C; and extraction time: 7 min. After the stripping of D2EHPA with 1 mol/L HCl, the majority of the indium was stripped into the aqueous phase, which could also be precipitated by zinc. In the actual process, spent IGZO target was used. First, 96.2% of gallium with a purity of 99.6% was obtained. Afterwards, 97.8% indium with a purity of 98.3% was recovered. The extraction process by T-iso-BP and D2EHPA were carried out twice, as has been suggested by McCabe–Thiele plots.

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