W. David SINCLAIR , 2014. Electronic Metals (In, Ge and Ga): Present and Future Resources. *Acta Geologica Sinica* (English Edition), 88(supp. 2): 463-465.

Electronic Metals (In, Ge and Ga): Present and Future Resources

W. David SINCLAIR

Geological Survey of Canada, 601Booth Sreet, Ottawa, Ontario, Canada K1A 0E8

1 Introduction

Although the annual production of In, Ge and Ga is relatively small, these metals and their compounds have unique properties that are critical for a wide variety of applications in the electronics industry. The principal application of In is in In-Sn oxide (ITO), a transparent, electronically-conductive coating for liquid crystal displays used in a multitude of electronic devices that require electronic display such as computers, TVs and cell phones. Indium is also used in alloys and solders, in semiconductor compounds for light-emitting diodes (LEDs) and in thin-film solar cells. Germanium was first used as a semiconductor in transistors although it has since been replaced by high-purity silicon in this application. The main uses of Ge are currently in fibre-optic systems, infrared optics, as a catalyst in polyester production, and in a variety of electronic applications including thin-film solar cells. The principal application of Ga is in the form of GaAs, a semiconductor that is widely used as a substrate for LEDs and in integrated circuits for cell phones. GaN is also used as a substrate in LEDs as well as in the production of ultraviolet and blue laser diodes, the most popular application of which is in Blu-ray devices.

2 Indium

Global production of In has increased from about 50 t/y in the 1970s to nearly 800 t in 2012. Production is likely to continue to increase, particularly with rising demand for ITO in flat-screen displays and for thin-film solar cells. Current price is about US$700/kg.

Indium minerals such as roquesite ($CuInS_2$) are relatively rare and typically occur only as trace components in In-bearing ores. Indium occurs more commonly as a trace element in ore-forming minerals such as chalcopyrite, bornite and particularly sphalerite, which is currently the source of most primary In production (Schwartz-Schampera, 2014).

The most important deposits for In production are Zn-rich massive sulfide deposits and various poly-metallic vein and replacement deposits. In volcanogenic massive sulfide (VMS) and sediment-hosted exhalative (Sedex) deposits, In grades are in the range of 1 to 50 ppm, but the overall In contents are substantial because of the large tonnages of these deposits. Zinc concentrates are the most common source of In in these deposits, with In contents in the order of 70 to 200 ppm but ranging as high as 800 ppm (Schwartz-Schampera, 2014). However, Cu concentrates may also be important, as at the Kidd Creek (Canada) deposit. At Kidd Creek, roquesite in massive chalcopyrite and chalcopyrite stringer ores has been estimated to account for about 70% of the bulk In in the deposit; the remainder occurs as solid solution in massive sphalerite (Hannington et al., 1999). Indium production at Kidd Creek ended when the Kidd Creek Cu smelter ceased operation in 2010 because the Horne smelter, where the Cu concentrates were subsequently redirected, does not have the capability to extract In (Tolcin, 2012).

Many VMS and Sedex deposits display positive correlation between In and other trace elements such as Ag, Cd and Sn. Deposits in the Bathurst mining camp (Canada) in particular exhibit a strong correlation between In and Sn (Fig.1).

Indium-bearing polymetallic deposits are typically small- to medium-sized, with widely varying In contents ranging from 1 to nearly 200 ppm. Although these deposits can host a variety of minerals containing In, including roquesite, stannite and tin-sulfosalts, the bulk of the indium is generally contained within sphalerite, which is the source of most In produced from these deposits. Indium contents of the sphalerite are typically in the order of 100s to 1000s of ppm In but can range as high as 1% or more. Chalcopyrite can also contain significant levels of In, from 100s to more than 1000 ppm, and represents a potential source of In. The Ashio deposit (Japan), for example, is estimated by Ishihara et al. (2006) to have contained about 1200 t In, most of it in Cu concentrates.

* Corresponding author. E-mail: sinclair@nrcan.gc.ca

Many In-bearing polymetallic deposits also contain Sn and, like VMS and Sedex deposits, exhibit a positive correlation between In and Sn (Fig. 1).

China is the leading producer of In (about 400 t in 2013), mainly from tin-rich polymetallic deposits such as Dachang and Dulong. South Korea produced about 150 t in 2013, from Zn concentrates sourced primarily from Bolivian polymetallic deposits.

In-bearing deposits currently under exploration and/or development include Mount Pleasant Sn-Zn-In, Canada (Adex Mining Corp.), East Kemptville Sn-Cu-Zn, Canada (Avalon Rare Metals Inc.), Logan Zn-Ag, Canada (Yukon Zinc Corp.), West Desert Zn-Cu-In-Fe, USA (InZinc Mining Ltd.), and Pingüino Ag-Au-Pb-Zn-In, Argentina (Argentex Mining Corp.).

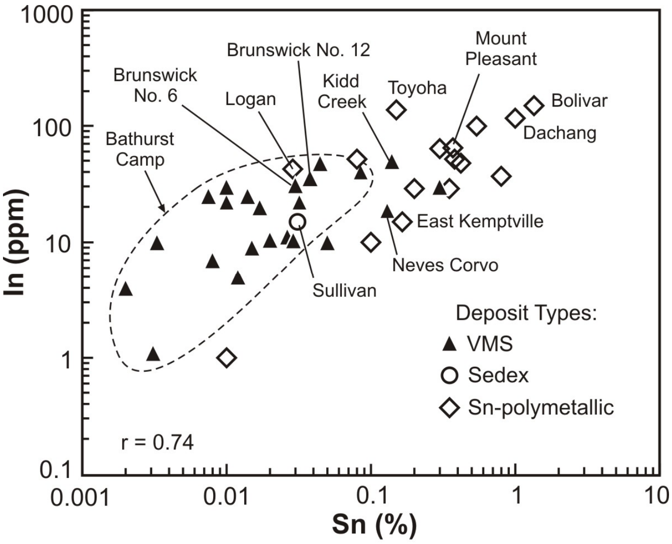

Fig. 1. Sn grades versus In contents in different types of In-bearing deposits. Data are from Schwartz-Schampera and Herzig (2002), Goodfellow and McCutcheon (2003), Murakami and Ishihara (2013) and Sinclair (unpub. data).

3 Germanium

Current (2013) global production of Ge is estimated to be about 150 t (Guberman, 2014), compared to less than 50 t/y in the early 1960s. Current price is about US$1900/kg.

Most Ge is produced as a byproduct of Zn mining, from sphalerite concentrates containing 50 to 3000 ppm Ge. Current production is mainly from Sedex deposits in China and USA (e.g., Red Dog, Alaska). The overall Ge grades in these deposits range from 15 to 100 ppm (Melcher and Buchholz, 2014). The other main source of primary Ge production is the ash produced from lignite deposits in China and Russia. Germanium content of the lignite ranges from 30 to >1000 ppm and can be enriched 5- to 10-fold in the ash (Frenzel et al., 2014).

Future production of Ge will depend mainly on the availability of Ge-bearing Zn ores and Ge-enriched coal ash. In addition to Sedex deposits, other types of zinc-bearing deposits with potential for Ge production include carbonate-hosted, Mississippi Valley-type (MVT) deposits (e.g., Gordonsville/Elmwood, USA-Tennessee) and Ge-enriched, polymetallic Kipushi-type deposits. However, the largest Ge resources are in coal ash (Melcher and Buchholz, 2014), and these are most likely to remain the main source of primary Ge for many years.

4 Gallium

Global production of Ga increased fairly gradually from 10 t/y in the 1970s to 79 t in 2009 (DiFrancesco et al. (2014). Since then, it increased rapidly to 280 t in 2013, due in large part to the rapid growth in GaAs-rich smartphones (Jaskula, 2012). Current price is about US$260/kg.

Gallium minerals such as gallite ($CuGaS_2$) are rare and are known to occur only in Kipushi-type polymetallic deposits at Lubumbashi (Democratic Republic of Congo) and Tsumeb (Namibia). Gallium occurs more commonly in trace amounts in sulfide minerals, particularly sphalerite, ranging up to 100s of ppm in sphalerites from some epithermal and MVT deposits (Cook et al., 2009). However, only a small portion of primary global Ga production is derived from the processing of Zn ores. Currently, nearly all primary production of Ga is by extraction as a byproduct during the processing of bauxite (Butcher and Brown, 2014).

Assuming that the Ga content in bauxite averages about 50 ppm, although it can vary from 10 to 160 ppm, global resources in bauxite have been estimated to be in excess of one million tonnes (Jaskula, 2014). Despite the fact that only a small portion of the Ga in bauxite is actually recovered, bauxite ores are likely to remain the main source of primary Ga production for the foreseeable future (Butcher and Brown, 2014).

References

Butcher, T. and Brown, T., 2014. Gallium, In: Gunn, G. (ed), Critical Metals Handbook, First Edition. *John Wiley & Sons, Ltd.:* 150-176.

Cook, N,J., Ciobanu, C.L., Pring, A., Skinner, W., Shimizu, M., Danyushevsky, L., Saini-Eidukat, B. and Melcher, F., 2009. Trace and minor elements in sphalerite: a LA-ICPMS study. *Geochimica et Cosmochimica Acta,* 73: 4761-4791.

DiFrancesco, C.A., Kramer, D.A. and Jaskula, B., 2014. Gallium statistics. *U.S. Geological Survey,* http://minerals.usgs.gov/minerals/pubs/historical-statistics/#gallium, accessed 5/3/2014.

Frenzel, M., Ketris, M.P. and Gutzmer, J., 2014. On the geological availability of germanium. *Mineralium Deposita,* 49: 471-486.

Goodfellow, W.D. and McCutcheon, S.R., 2003. Geologic and genetic attributes of volcanic sediment-hosted massive sulfide deposits of the Bathurst mining camp, northern New Brunswick−A synthesis, In: Goodfellow, W.D., McCutcheon, S.R. and Peter, J. (eds), Massive Sulfide Deposits of the Bathurst Mining Camp, New Brunswick, and Northern Maine. *Economic Geology Monograph,* 11: 245-301.

Guberman, D.E., 2014. Germanium. Mineral Commodity Summaries, February 2014. *U.S. Geological Survey:* 2 p., http://minerals.usgs.gov/minerals/pubs/commodity/germanium/mcs-2014-germa.pdf, accessed 5/3/2014.

Hannington, M.D., Bleeker, W. and Kjarsgaard, I., 1999. Sulfide mineralogy, geochemistry, and ore genesis of the Kidd Creek deposit: Part I. North, Central and South orebodies, In: Hannington, M.D. and Barrie, C.T. (eds), The Giant Kidd Creek Volcanogenic Massive Sulfide Deposit,Western Abitibi Subprovince, Canada. *Economic Geology Monograph,* 10: 163-224.

Ishihara, S., Hishino, K., Murakami, H. and Endo, Y., 2006. Resource evaluation and some genetic aspects of indium in the Japanese ore deposits. *Resource Geology,* 56: 347-364.

Jaskula, B.W., 2012. Gallium. 2010 Minerals Yearbook. *U.S. Geological Survey,* 7 p., http://minerals.usgs.gov/minerals/pubs/commodity/gallium/myb1-2010-galli.pdf, accessed 5/3/2014.

Jaskula, B.W., 2014. Gallium. Mineral Commodity Summaries, February 2014. *U.S. Geological Survey:* 2 p., http://minerals.usgs.gov/minerals/pubs/commodity/gallium/mcs-2014-galli.pdf, accessed 5/3/2014.

Melcher, F. and Bucholz, P., 2014. Germanium, In: Gunn, G. (ed), Critical Metals Handbook, First Edition. *John Wiley & Sons, Ltd.:* 177-203.

Murakami, H. and Ishihara, S., 2013. Trace elements of indium-bearing sphalerite from tin-polymetallic deposits in Bolivia, China and Japan: A femto-second LA-ICPMS study. *Ore Geology Reviews,* 53: 223-243.

Schwartz-Schampera, U., 2014. Indium, In: Gunn, G. (ed), Critical Metals Handbook, First Edition. *John Wiley & Sons, Ltd.:* 204-229.

Schwartz-Schampera, U. and Herzig, P.M., 2002. Indium: Geology, Mineralogy and Economics. *Springer-Verlag, Berlin,* 257 p.

Tolcin, A.C., 2012. Indium. 2010 Minerals Yearbook. *U.S. Geological Survey,* 6 p., http://minerals.usgs.gov/minerals/pubs/commodity/indium/myb1-2010-indiu.pdf, accessed 5/3/2014.