Manufacture of Bulk Crystals in Western Europe

A study by
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ABSTRACT

A survey has been made of the status of bulk crystal *manufacture* in Western Europe as a contribution to the panel discussion at The Third International Workshop on Crystal Growth Technology, IWCGT-3, Beatenberg, Switzerland, 10 – 18 September, 2005. The technical scope focuses on manufacture and supply (not R&D) of bulk, single- and large grained multi-crystals of primarily, inorganic materials, namely Group IV semiconductors, (Si, Ge, SiC and diamond); IIIV Compound Semiconductors; IIVI Compound Semiconductors and other Chalcogenides; Oxides; Halides and Metals/Alloys. Excluded from the survey were: bulk crystallization, glass-based materials; cut and polished wafers, epitaxial- and thin film materials; polycrystalline starting materials and related infrastructural capabilities such as equipment suppliers. The geographical scope excluded suppliers in Russia and States of the FSU which were studied separately.

The aim of the survey was to identify the major suppliers in each crystal category, (including those companies owned outside- but located in W. Europe), and to estimate the most recent (ca 2004) annual turnover of each crystal category in terms of crystal weight and value. Turnover figures of crystals at the individual company level are usually confidential and are rarely published openly. Furthermore, crystals are not usually sold as discrete products but are often further processed into products such as wafers (as-sawn or polished) or as epitaxial substrates which have significantly greater value than the intermediate bulk crystal. Subsequent processing into devices may also take place within the company itself if it is vertically integrated (captive supplier), although most crystal producers are merchant suppliers to the open market. An additional factor to be considered is the sudden change in market demand which may change dramatically the turnover figures from one year to the next – some recent examples are the downturn in the telecommunications market and the upturn in the solar cell market.

The above factors contrive to make the study of bulk crystal turnover very difficult, and in many cases only estimates can be made – not an exact science! In cases where crystal turnover figures were not available, estimates were made from available information such as overall company turnover, cost of starting materials, cost of processing, process difficulty (yield), cost of wafers and the cost of the wafering process, including yield losses in going from a bulk crystal to a wafer product. Semi-quantitative data have been generated to make interesting comparisons between the different crystal categories in W Europe and between other regions of the world. However, it should be remembered that the data and information presented here constitute only a snapshot of a changing scenario.

58 companies have been identified as current manufacturers of bulk crystals in W Europe. Germany hosts the most suppliers – about one third of the total - and is represented in all crystal categories.
In most of the crystal categories W Europe has at least one leading manufacturer with a significant share of its particular world market, e.g.: Siltronic (Single Crystal Si); Crystalox (Multicrystalline Si); Umicore (Ge); Element Six (Synthetic Diamond); Freiberger Compound Materials(GaAs); SELEX & AIM (CMT); Djeva (sapphire); Schott Lithotec (CaF_2); Rolls Royce (Ni-based Super Alloys).

In 2004 the total turnover of bulk crystals in W Europe was ~6,000 metric tonnes at a value of almost $1Bn.

Western Europe is a leading supplier of crystalline silicon, thanks largely to its pre-eminent position in the fabrication of Multicrystalline Silicon (MC-Si) for the solar cell market which has experienced rapid growth in the past few years. W European suppliers of MC-Si had >40% market share of the ~1GWatt world solar market in 2004 – which now represents a larger output than that of the traditional *single* crystal silicon producers in W Europe. The combined turnover for the two types of bulk silicon crystal in W Europe was ~33% of the total world output (~16,000 tonnes), i.e. >5000 tonnes, with a total value exceeding $0.5Bn, which is ~60% of the total W European turnover in value of all crystals. In terms of crystal weight the >5,000 tonne output of silicon in W Europe is significantly larger than that of all other crystal categories added together and represents ~92% of total turnover by weight.

W Europe has a significant world presence in many crystal categories in addition to that of MC-Si, e.g. metal super alloys and sapphire, but it has no major grower of quartz which is dominated by suppliers in Japan, Russia, China and USA. However, the oxide (and organic) crystal category is often the basis for new (and often complex) materials which offer exciting properties (scintillators, NLO, Terahertz sources and detectors etc) and new market opportunities. Therefore, this crystal category probably contains more start-up companies (nuclei) than other categories in W Europe. Challenges imposed by difficult technology as well as a fickle and competitive marketplace have to be overcome for such companies to survive (*critical* nuclei) and grow to become stable, established suppliers (Ostwald Ripening).

1. Introduction & Background

In the summer of 2005 I was asked by Professor Hans Scheel to carry out a study of bulk crystal growth in Western Europe for presentation at The Third International Workshop on Crystal Growth Technology, IWCGT-3 in Beatenberg, Switzerland, 10 -18 September, 2005. This was part of a much larger ongoing survey of crystal growth activities across the world initiated by Hans. In particular I was asked to determine the level of W. European activity in terms of company names and total crystal turnover by weight and value. Since the study has not been published and still has some relevance, I have decided to make it available via the World Wide Web by adding a few words to some of the slides used at the IWCGT-3 meeting.
It came as a great surprise that this type of information is not widely available, and it is quite remarkable that knowledge of the commercial output of such an important enabling technology as crystal growth is so sparse, not only on a local basis but also worldwide. I hope, therefore, that this information is useful to all those involved in the many aspects of this key technology: researchers, teachers, students, users, sponsors, etc. Bulk crystals are the cornerstones of key technologies such as microelectronics, optoelectronics and, increasingly, renewable energy technologies. The current commercial turnover of bulk crystal growth is the end product of tens of thousands of man years of R&D effort over more than half a century. The present study aims to indicate the scale of this important activity in one particular region of the world.
The article is not concerned with technical details – the emphasis is on commercial issues such as user markets, names of companies and scale of turnover. It is implicitly assumed that the reader is familiar with the various crystal growth technologies mentioned in this survey without detailed explanation.

2. Scope

Fig 1 illustrates the scope of the study. The main emphasis was on commercial manufacture of bulk single crystals not R&D although, of course, some organisations do both. However, organisations selling a few crystals from essentially an R&D base (e.g. Institutes & Universities) have generally been excluded from the survey. Also excluded were agencies selling crystals on behalf of other manufacturers. Merchant- and captive suppliers of bulk crystals were included. Activities on thin films and added value wafering of bulk crystals were excluded as were glasses and bulk crystallization; also excluded were the important infrastructural activities supporting crystal growth such as equipment and raw material suppliers and their turnover. The emphasis was on single crystal growth, but the related activity of controlled solidification of multicrystals to maximize grain size was also included. Activities in Russia and States of FSU were excluded since this geographical area was being studied separately – as were other regions of the world. The aim was to gather information on crystal growth companies, including those owned outside W. Europe, and the most recent turnover of bulk crystals by weight and value (i.e.ca 2004), not capacity.

However, it should be noted that when market demand is changing rapidly then some of the information at the detailed level may already be out of date.

Figure 1 Scope of Survey

3. Crystal Groups

It was decided to carry out the study by crystal type, i.e. by technical group rather than by market. The groups are listed in Fig.2 below

Figure 2 Technical Crystal Groups used in the study

4. Approach

Information was gathered via the available literature, but particularly from individual contacts via 'phone calls and the internet. Over 30 individuals were contacted.
Information on turnover was particularly difficult to obtain on an individual company basis, and these data were aggregated by crystal group – see below. Generally the crystal "turnover" in value terms was estimated as an internal cost, not price (cost plus profit) since in many cases, e.g. in the case of semiconductors, bulk crystals are an internal product for externally marketed products such as wafers. The method of estimation varied. The added value in transforming a raw starting material of known cost to a grown crystal can be estimated from the process cost which will depend on a range of factors for individual materials, such as process temperature, growth time, capital depreciation, cost of manpower, consumables, utilities and, of course yield. It is also possible to work backwards from available information on company turnover, number of employees, etc. For those cases in which crystals are not sold as bulk crystals, but as wafers, it is also possible to estimate the turnover of crystals from wafer turnover, based on factors such as wafer area sold, cost of wafering (yield losses etc), wafer price, number of wafers sold and estimated profit margins on marketed wafer products.

5. Companies in W Europe

The names of the major W. European companies growing bulk crystals are shown in the Table 1 below, along with key contact details, country of operation and main technical area of activity. Note that only those companies known to be active in the field of crystal growth are included; some companies advertised activity but did not respond when contacted and were excluded from the list. A total of 58 active companies were identified. Germany hosts the most companies, 19, followed by France 11, UK 8 and Switzerland 5.

NAME	WEBSITE/CONTACT	LOCATION	TECHNICAL GROUP
Snecma	www.snecma.com	France	Metals
Rolls Royce	www.rolls-royce.com	UK	Metals
AETC	Magna Road, Wigston Leicester LE18 4ZH	UK	Metals
Howmet	www.alcoa.com/howmet/en/product.asp?	UK & France	Metals
Doncasters	www.doncasters.com	Germany	Metals

NAME	WEBSITE/CONTACT	LOCATION	TECHNICAL GROUP
Element Six	www.e6.com	IOM, IRE, UK, Sweden.	Diamond
Diaccon	www.diaccon.de	Germany	Diamond
Diamond Materials	www.diamond-materials.com/	Germany	Diamond
CSEM	www.csem.ch/	Switzerland	Diamond
Umicore	substrates.umicore.com	Belgium	Ge & IIVI
Photonic Sense	http://www.photonic-sense.com/	Germany	Ge & Si
VB-Tec GmbH	www.pbtsilicon.com/	Germany	Ge
Wafer Technology	www.wafertech.co.uk/	UK	IIIV
Freiberger Compound Materials GmbH	www.freiberger.com	Germany	IIIV
CMK	www.cmk.sk/	Slovakia	IIIV
Phostec	www.vgfgapleds.sk	Slovakia	IIIV
Lumilog	www.lumilog.com/	France	IIIV
TopGan	www.topgan.fr.pl/	Poland	IIIV
InPACT	www.inpactsemicon.com/	France	IIIV
Siltronic (was Wacker Siltronic)	www.siltronic.com	Germany	Si
MEMC	www.memc.com	Italy	Si
Siltronix	www.siltronix.com	France	Si
Okmetic	www.okmetic.com/	Finland	Si
Topsil	www.topsil.com	Denmark	Si
Cemat Silicon	www.cematsil.com.	Poland	Si
ASi Industries	www.eco-web.com/register/00997.html	Germany	Si
On Semiconductor	www.onsemi.com/PowerSolutions/content.do?id=1142	Czech	Si
Deutsche Solar AG	www.deutschesolar.de/	Germany	Si
Crystalox	www.crystalox.com/	UK	Si

NAME	WEBSITE/CONTACT	LOCATION	TECHNICAL GROUP
REC ScanWafer	www.scanwafer.com/	Norway	Si
Photowatt	www.photowatt.com/	France	Si
RWE Schott	www.schott.com/photovoltaic/english/index.html	Germany	Si
SiCrystal AG	www.sicrystal.de/index.php	Germany	SiC
Norstel AB	www.norstel.com/	Sweden	SiC
RSA Le Rubis	www.rubisrsa.com/	France	Oxides
Saint-Gobain	crismatec.com	France	Oxides & Halides
FEE	www.fee-io.de/produktframe.htm	Germany	Oxides
Hilger Crystals	www.hilger-crystals.co.uk/	UK	Oxide & Halides
Cristal Laser	www.cristal-laser.fr	France	Oxides
SAES Getters	www.saesgetters.com/	Italy	Oxides
Korth Kristalle GmbH	www.korth.de/	Germany	Oxides, IIVI & Halides
Rainbow Photonics AG	www.rainbowphotonics.com/	Switzerland	Oxides & Organics
Crytur	www.crytur.cz/	Czech	Oxide & Halides
Hrand Djevahirdjian SA	www.djeva.com/	Switzerland	Oxides
Comadur SA	www.comadur.ch/	Switzerland	Oxides
Kistler Instruments	www.kistler.com	Switzerland	Oxides
HAM	www.laser-crystals.info/e/ktp.html	Germany	Oxides
Wiedes Carbidwerk	www.wiedes.com/	Germany	Oxides
Piezocryst	www.piezocryst.com/index.php	Austria	Oxides
Minhorst	www.minhorst.de/	Germany	Oxides
ITME	www.itme.edu.pl/general.htm	Poland	Oxides
Schott Lithotec	www.schott.com/lithotec/english/company/	Germany	Halides
Gamma Technical Corporation	www.freeweb.hu/amamet/cgi-bin/gammatech/index.cgi?site=index&lang=eng	Hungary	Halides

NAME	WEBSITE/CONTACT	LOCATION	TECHNICAL GROUP
Selex	www.selex-sas.com/pukinf_sas.html	UK	IIVI
Sofradir	www.sofradir.com/	France	IIVI
AIM	www.aim-ir.com/?lan=en	Germany	IIVI
Eurorad	www.eurorad.com/normal/index1.html	France	IIVI
Vitron Spezialwerkstoffe GmbH	www.vitron.de/english/index.php	Germany	IIV1
TOTAL 58		**19 GE; 11 FR; 8 UK**	

Table 1 Company names, contact details, location and technical group

6. Turnover

It is estimated (see section 7) that 5,897 metric (m) tonnes of crystals were produced in W. Europe in 2004. Most of this is attributed to multicrystalline- and single crystal silicon which constitute ~92% of the total at ~5,400 m tonnes pa. In value terms it is estimated that ~$850M of bulk crystal were produced in 2004, with over $510M pa of multicrystalline- and single crystal silicon contributing ~60% of the total.
Silicon is by far the most important category, followed by the oxide- and metal (Nickel-based superalloys) categories. Details of individual categories are summarised in the pie charts of Figure 3 and described in Section 7.

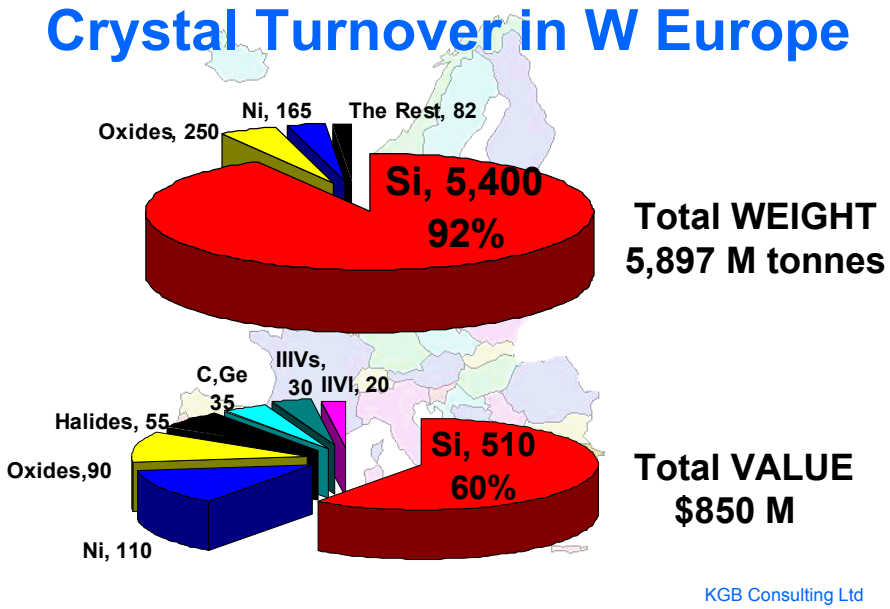

Figure 3 Turnover of crystals in W. Europe by weight, value and crystal category in 2004

7 Individual Categories

Each of the technical categories is analysed below with respect to markets, major companies and turnover.

7.1 Germanium, Silicon Carbide, Diamond

Fig 4 shows the data for all Group IV materials excluding silicon which is considered separately below in 7.2 (Fig. 5) and 7.3 (Fig 6).
In total there are 9 companies producing 6 tonnes of Group IV crystals at a value of ~$35M. Most of this turnover is dominated by germanium and diamond. Markets are diverse, ranging from optics (Ge) and engineering (Diamond), to electronics (Ge, SiC). Synthetic diamond dominates the overall value whilst germanium dominates the tonnage. There was very little bulk silicon carbide produced in W Europe in 2004, although two new start-ups Norstel AB and SiCrystal AG had just entered the market.
Element Six has a number of diamond operations in W Europe but these tend to be focused on high value, low volume diamond products such as CVD diamond;

the bulk of the High Pressure, High Temperature (HPHT) diamond is manufactured in regions of the world with lower labour costs due to the continuing pressure on synthetic diamond prices, particularly from The Far East. This survey does not include the increasing number of companies in Western Europe offering thin film CVD diamond coating services for an increasing range of applications.
Umicore is the largest producer of germanium with a significant share of the world market. The present analysis only includes germanium crystals used in optical applications and substrates for solar cells in space applications; it does not include the more significant amounts of germanium used to make optical fibres.

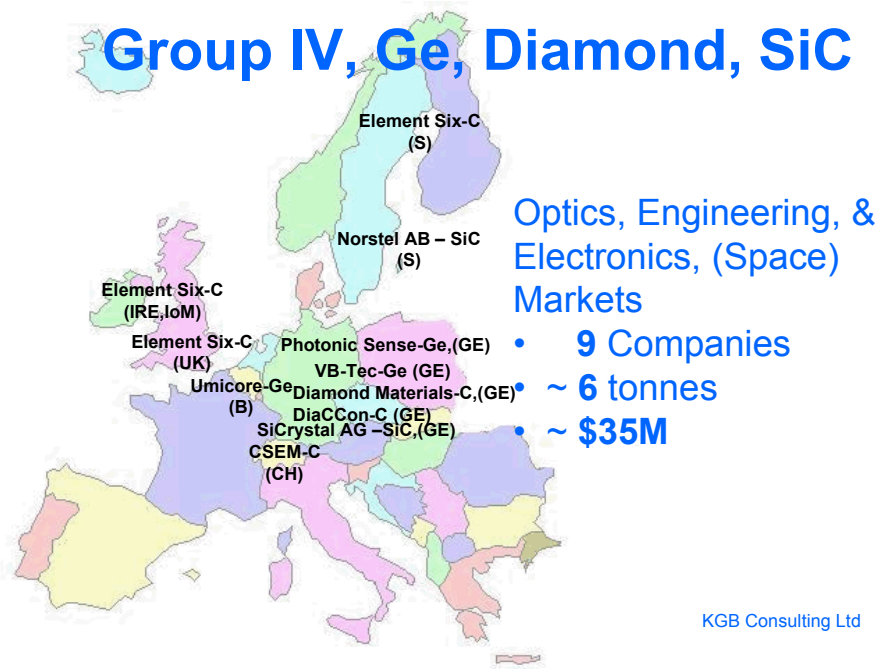

Fig 4 Markets, Companies and Turnover for Group IV Crystals, Ge, C, SiC

7.2 Multicrystalline Silicon

Multicrystalline silicon, MC-Si is grown from the melt using techniques such as Edge-Defined Film Fed Growth (EFG), casting and directional solidification. It is distinguished from other types of polycrystalline silicon produced in arc furnaces (Metallurgical Grade silicon) and also by chemical vapour deposition processes. The aim is to grow high purity, large grained material at low cost, particularly for photovoltaic solar cell applications. In Europe the dominant technique is directional solidification, although one company, RWE Schott Solar uses the EFG technique.
In 2004 the worldwide photovoltaic solar cell business grew by ~40% to >1GWatt output. The 5 major companies shown in Figure 5 all experienced rapid growth in 2004, and the turnover by weight of MC-Si was ~3,000 tonnes at a value of ~ $270M.These figures are estimated to be slightly larger than the turnover of silicon single crystal in W Europe (see 7.3 below) and represent an output equivalent to 400MW or 40% of the world output of bulk silicon. Companies such as Crystalox and Scanwafer are major world players in MC-Si.
It should be noted however, that this is an area currently experiencing rapid change due to market forces. Business growth in 2006 is currently limited by the availability and supply of polycrystalline silicon starting material which is also the main feedstock for single crystal silicon growth -discussed in section 7.3. Any significant increase in feedstock cost obviously increases the value of the crystal.

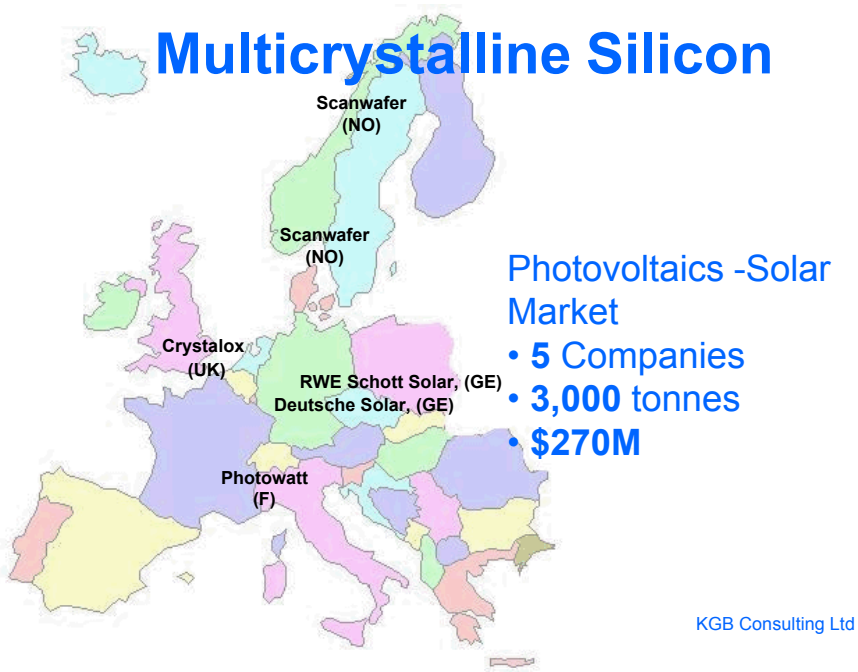

Fig 5 Markets, Companies and Turnover for Multicrystalline Silicon, MC-SI

7.3 Single Crystal Silicon

This Group includes single crystal silicon grown by both the Czochralski (Cz) and Floating Zone (Fz) techniques (Fig.6). The major markets are Microelectronics & Photovoltaics (solar) for Cz-Si, and Power Electronics for Fz-Si.
There are 9 companies growing silicon single crystals in Europe. Wacker, now known as Siltronic is by far the largest, and operates two plants in Germany.
W. Europe also hosts a plant of another world player, MEMC in Italy.
The estimated 2004 turnover was 2,400 tonnes with an estimated value of $240M**.** This is slightly less than the turnover in MC-Si (Section 7.2) and represents approx 20% of the world output in 2004 (~ 12,000 tonnes and $1.2Bn).
W Europe continues to be very strong in Fz-Si, with an estimated 35% share of an 800 tonne pa world market as a result of major contributions from Siltronic and Topsil (Denmark).

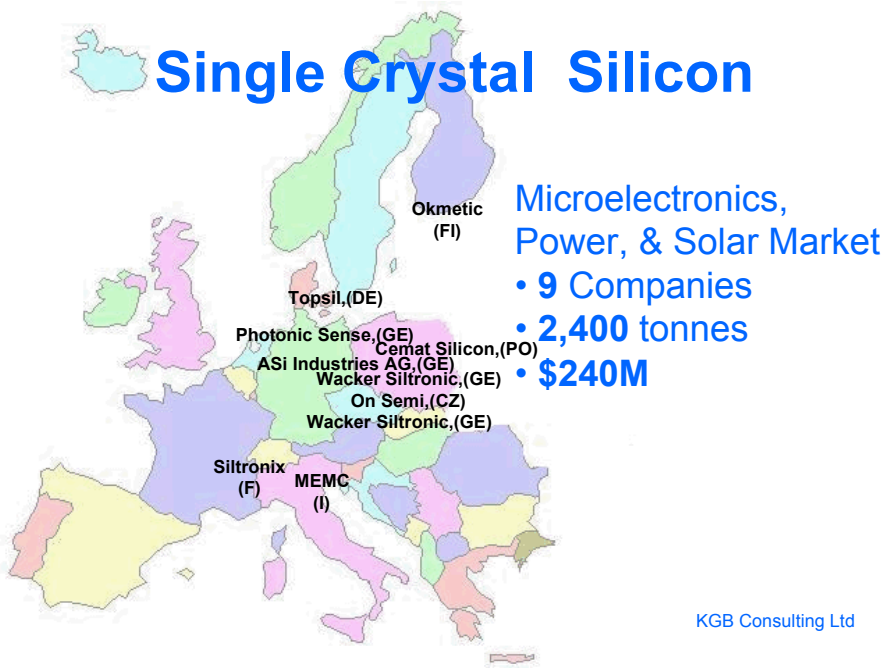

Fig 6 Markets, Companies and Turnover for Single Crystal Silicon, Cz-Si & Fz-Si

7.4 Group IIIV Semiconductors

The markets for Group IIIV compound semiconductor crystals are primarily microwave and optoelectronics, Fig 7. There are 7 companies identified in this group which is dominated by GaAs grown by either the Liquid Encapsulation Czochralski process or the Gradient Freeze technique, in approximately equal proportions. Turnover of all other materials –InP, InSb, GaP, GaN, - is in the noise, especially following the recent decrease in demand for InP substrates for the fibre optic communications infrastructure. There is very little bulk GaP and GaN grown in W. Europe.
Turnover for GaAs is mainly due to the output of Freiberger Compound Materials in Germany– with smaller contributions from WaferTechnology and CMK.
The estimated turnover of all IIIV crystals in 2004 was ~ 25 tonnes and ~$30M which represent ~20% of the world market. W Europe, therefore, has similar market share in GaAs as single crystal silicon but note that the turnover by weight of GaAs is 2 orders of magnitude smaller than that of single crystal silicon and about 1 order of magnitude smaller in value.

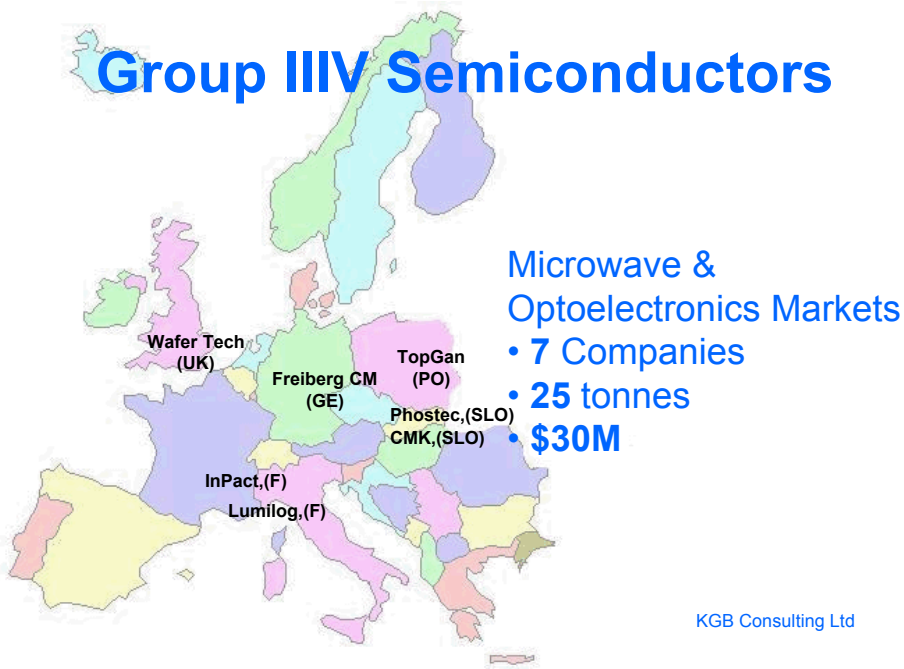

Fig 7 Markets, Companies and Turnover for IIIV Compound Semiconductor Crystals

7.5 Group IIVI Semiconductors

The principle markets for these crystals are in optical components (e.g. ir windows) and in infrared detectors. W. Europe has a relatively strong capability in Cadmium Mercury Telluride and related IIVI compounds such as CdTe and CdZnTe for application in IR detectors which dominate value turnover in this category. However, the corresponding turnover in weight is very small, probably at the kilogramme level. The zinc chalcogenides are used in infrared optical applications and have a larger turnover by weight, estimated at ~1 tonne, but much lower value than crystals for ir detectors.
There are 7 companies within this group.Total turnover by weight is probably only ~1tonne – but with high overall value in the range $10 – 20 M, Fig 8.

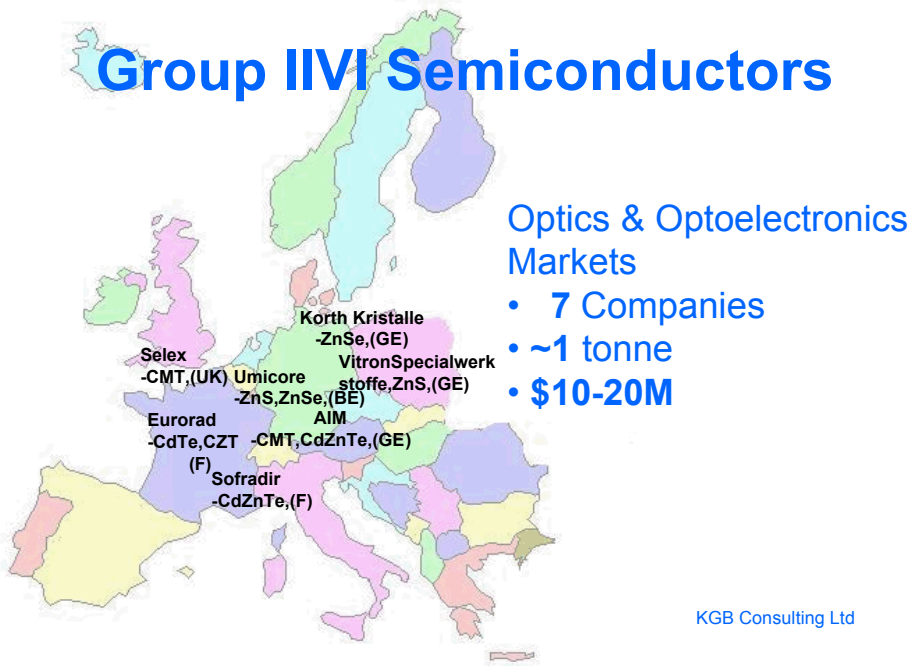

Fig 8 Markets, Companies and Turnover for IIVI Compound Semiconductor Crystals

7.6 Oxide Group

The oxide group consists of many materials ranging from simple oxides such as sapphire (Al_2O_3) and quartz (SiO_2) to more complex mixed oxides such as garnets.
The group addresses diverse markets spanning, optics, optoelectronics, piezoelectric and the gemstone market, Fig.9. Some solid state oxide lasers are under threat from semiconductor lasers and this is generally not a growing market. In the artificial gemstone market, lower cost artificial diamond and moissonite (SiC) are displacing materials such as cubic zirconia. W. Europe does not have a large manufacturer of piezoelectric quartz which has the second largest turnover in the world of bulk crystals, next to silicon. W European quartz manufacturers have been squeezed out by suppliers in the Rest of the World (e.g. Japan, Russia, China,USA) who continue to provide high quality crystals at lower cost. There are some small, specialist companies growing new piezoelectric oxide crystals. W Europe is also relatively small in scintillator- and non linear optical crystals. The much heralded demand six years ago for non linear optical crystals of $LiNbO_3$ and $LiTaO_3$ plummeted when the telecoms market collapsed.

There are many companies in W Europe in the oxide group, 17 in total, but most are relatively small with only a few $M annual turnover. This is the group which tends to contain new start up companies growing specialist materials for niche applications. Challenges imposed by difficult technology as well as a fickle and competitive marketplace have to be overcome for such companies, initially, to survive (*critical* nuclei) and then grow to become stable, established suppliers (Ostwald Ripening).

W. European production of oxide crystals is dominated by the manufacture of clear sapphire, mainly for the watch industry (scratch-free glass) & industrial applications, (total ~200tonnes pa) with an annual value of ~ $45M. Major players are Djeva and Comadur in Switzerland.
Rubies & Spinels are the next most important oxides at ~30 tonnes annual turnover and a value of ~$4M.
Non linear optical- and laser materials (Garnets & KTP etc) are quite small in volume (~1 tonne level) but they have a relatively high value (~ $13M).

Turnover of all oxide crystals in W. Europe is estimated at ~ 250 tonnes pa & ~ $90M pa in value.

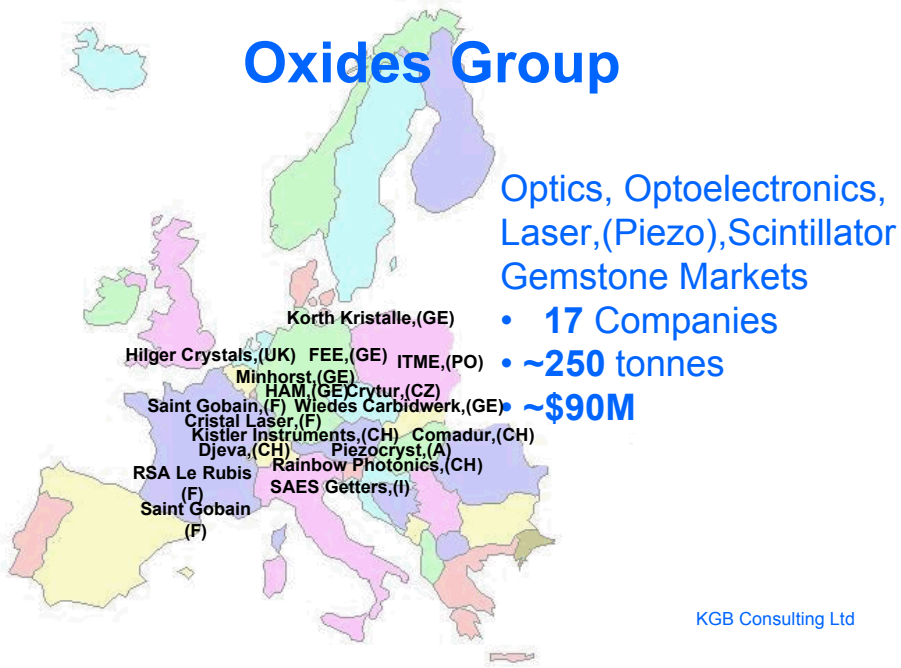

Fig 9 Markets, Companies and Turnover for Oxide Crystals

7.7 Halide Group

Many companies growing halide crystals also grow oxide crystals since both groups of materials address the scintillator- and optical components markets, Table 1 and Fig 10.
The cost of halide crystals varies significantly across the group. For example, the cost of alkali metal halide crystals is relatively low at a few $100s per Kg, whereas the higher melting point alkaline earth metal halides may cost several $1000s per Kg, especially high quality optical grades for which yields can be very low.
Schott Lithotec (GE) is a major world supplier of large diameter, high quality optical grade CaF_2 crystals. However, the perceived demand for these crystals in advanced 157nm lithography equipment did not materialise and, at the time of this survey, there was excess capacity as a result of key users switching to a different technology which did not rely on high quality CaF_2 crystals. Such sudden changes in the marketplace and the wide range in value of halide crystals made it extremely difficult to estimate the 2004 turnover for the complete halide group. Best estimates are ~50 tonnes and ~$55M pa turnover.

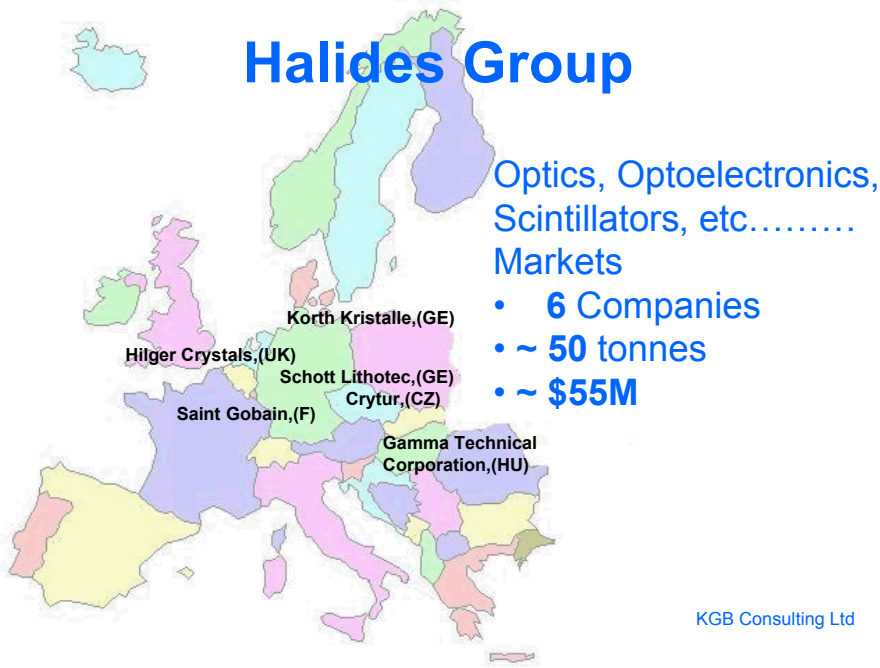

Fig 10 Markets, Companies and Turnover for Halide Crystals

7.8 Metal Group

This group is dominated by cast single crystal- and directionally solidified, (DS) multicrystalline nickel- based superalloys (Fig. 11). The major applications are in high performance turbine blades manufactured for jet engines in the Aerospace market which accounts for 90% of turnover. The remaining 10% is attributed to similar applications in Industrial Gas Turbines for the power generation market. Europe has a strong position in this technology – with world class performers in Rolls Royce (UK) and a USA firm, Howmet, which has operations in Exeter, (UK) and Dives (France).
The approximate 2004 turnover was 165 tonnes of cast single- & DS crystal valued at approx $110M. This is a significant activity in W. Europe, second only to silicon in value of turnover and 3rd overall in turnover by weight.

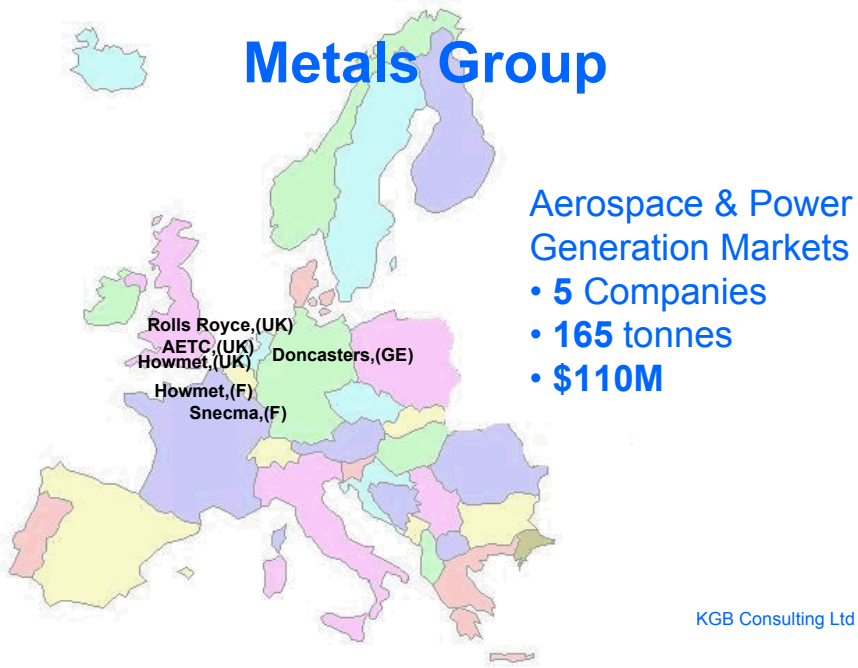

Fig 11 Markets, Companies and Turnover for Metal Crystals, primarily single crystal - and multicrystal Nickel-based super alloys

8. Summary

This survey shows that bulk crystal growth in W. Europe is ~$1Bn pa turnover business with ~58 active commercial organizations producing ~6,000 tonnes of material pa.
Silicon is the most significant material in both single crystal- and multicrystal form. Silicon dominates W. European turnover of all crystals by weight (92%) and also represents ~60% of the overall value. W. Europe is a leading supplier of multicrystalline silicon materials for the solar market and single crystal Fz-Si for the power electronics market.
W. Europe is also playing a leading role in nickel-based superalloys for aerospace markets and in sapphire crystals for the watch industry.
By contrast W. Europe has no significant supplier of quartz crystals, with supply dominated by manufacturers in Russia and the Far East. There are many small companies growing a range of oxide crystals for niche markets, and this is the area where new start-up companies often appear.

Movement of large scale manufacture to other parts of the world is also the trend in the case of high volume synthetic diamond, with W. Europe focusing on high value/low volume diamond products.
A significant fraction of the crystal growth activity in W. Europe is based in Germany which has by far the largest number of companies (19 out of 58,i.e. one third of total), with representatives in all crystal categories, including W. Europe's leading suppliers in single crystal silicon and gallium arsenide. France is the next largest supplier, with 11 companies spanning a wide range of technical capability; UK is the third largest supplier, with 8 companies, including leading suppliers in MC-Si and Nickel –based super alloys.

9. Acknowledgements

It would not have been possible to assemble the information in this paper without the valuable input from many individuals in industry, research institutes and universities across W. Europe. I am grateful for their contributions and, since many wished to remain anonymous I have not included individual names. However, particular mention should be made of Professor Hans Scheel who provided the stimulus and encouragement for the whole project, in addition to many valuable inputs on the commercial crystal growth capabilities in Switzerland.
I also wish to acknowledge here the contribution of the many individuals who pioneered crystal growth in Europe over half a century ago. Sadly, many are no longer with us, but their legacy of a growing $1bn industry in the 21st century is a fitting tribute to their efforts.

