Institution: University of Durham

Unit of Assessment: 9/Physics

Title of case study: Large semiconductor crystals for security and medical imaging (**Kromek**)

1. Summary of the impact

Research on vapour growth of semiconductor compounds led to a key breakthrough in growing large crystals which form the basis for sensitive X- and gamma-ray detectors. The process was commercialised by a Durham University spin-out company, Kromek Ltd., which floated on AIM at £55M and has over 100 employees in the UK and USA. The X-ray detectors are in use in Kromek's security systems for screening liquids at airports, significantly reducing restrictions on duty free goods. This application won the $400,000 international prize in the 2009 Global Security Challenge. The company also markets gamma-ray detectors for nuclear isotope identification. These have won contracts totalling $7.5M from the US Defense Threat Reduction Agency and are in use at Fukushima.

2. Underpinning research

The late Professor Andy Brinkman (member of Durham Physics department from 1980-2010) led an established research group that worked on the growth, characterisation and exploitation of group II-VI compound semiconductors. He had a longstanding interest in CdTe and CdZnTe, which form the basis of energy sensitive X- (CdTe) and gamma-ray (CdZnTe) detectors, and can also be used as substrates for thermal imaging devices. However, commercial applications of these were limited by problems in growing large crystals. Standard melt growth processes only produce wafers less than 2 inches in diameter, whereas medical imaging applications require larger area detectors. While these can be made by butting several smaller crystals together, this is uneconomic as the cost scales with the number of crystals rather than their size.

Prof Brinkman (in collaboration with Profs Tanner (Durham Physics 1973-present) and Durose (Durham Physics 1992-2011) led a BRITE-EURAM grant (1994-1997), with major academic partners including the Universities of Freiburg: Germany, Athens: Greece and Ancona: Italy) to explore and develop methods to improve the growth of CdTe. He realised that vapour growth was not subject to the same size limitations as melt growth processes, but the resulting material was largely polycrystalline as the crystal growth was disrupted by the heat from the vapour source. The key breakthrough in growing high perfection single crystals was made by Dr John Mullins, a postdoc working with Prof Brinkman in Durham, funded by the BRITE-EURAM grant. He realised that the vapour source and deposition region could be thermally decoupled by using a bent tube rather than a straight tube, so that the growing crystal was not heated directly by the source. The first high quality CdTe crystals were grown using this technique in 1997, and the process was patented in 1998 [P1]. The first results were published in a peer reviewed journal in 1999 [1], with a full description of the growth system in 2000 [2].

Research on this technique continued with £0.17M grant support from EPSRC (2000-2003). The potential of the process became increasingly clear, and development of this into a commercial product was supported by a £0.15M PPARC PIPPS grant (2005-2006) and £0.93M from a DTI basic technology award via EPSRC (2006-2010). This work culminated in 2007 with the heteroepitaxial growth of the first high perfection wafers of CdTe with good electrical qualities, using GaAs as the substrate [e.g. 3-5]. By 2009 they could scale this up to grow 4 inch diameter crystals of CdTe, and in 2011 succeeded in making similarly large crystals of CdZnTe [6].

3. References to the research

All Journals are international and peer reviewed

[1] Characterisation of cadmium telluride bulk crystals grown by a novel multi-tube vapour growth technique *Journal of Crystal Growth 198/199 (1999) 984*
N.M. Aitken, M.D.G. Potter, D.J. Buckley, J.T. Mullins, J. Carles, D.P. Halliday, K. Durose, B.K. Tanner, A.W. Brinkman

[2] A novel multi-tube vapour growth system and its application to the growth of bulk crystals of cadmium telluride *Journal of Crystal Growth 208 (2000) 211*
J.T. Mullins, J. Carles, N.M. Aitken, A.W. Brinkman

[3] Control of mass transport in the vapour growth of bulk crystals of CdTe and related compounds *Journal of Crystal Growth 275 (2005) e543-e547* B.J. Cantwell, A.W. Brinkman, A. Basu

[4] Vapor-Phase Growth of Bulk Crystals of Cadmium Telluride and Cadmium Zinc Telluride on Gallium Arsenide Seeds *J. Electron. Materials 37 (2008) 1460* J.T. Mullins, B.J. Cantwell, A. Basu, Q. Jiang, A. Choubey, A.W. Brinkman, and B.K. Tanner
[5] Crystal growth of large-diameter bulk CdTe on GaAs wafer seed plates *Journal of Crystal Growth 310 (2008) 2058-2061* J.T. Mullins, B.J. Cantwell, A. Basu, Q. Jiang, A. Choubey, A.W. Brinkman
[6] Growth by the multi-tube physical vapour transport method and characterisation of bulk (Cd,Zn)Te *Journal of Crystal Growth 352 (2012) 120-123* A. Choubey, P.Veeramani, A.T.G. Pym, J.T. Mullins, P.J. Sellin, A.W. Brinkman, I. Radley, A. Basu and B.K. Tanner

[P1] Granted Patents: Apparatus and process for crystal growth, US 6375739 B1, EP1019568A1 filed July 27 1998

Grants to Prof Brinkman:
EPSRC GR/N04287 £177,480 Jan 2000 to Dec 2002. Controlled Vapour Growth of CdTe
PIPPS PP/C503470/1 £152,545 Jan 2005 to Dec 2006. Evaluation of Foreign and Hybrid crystal growth
EPSRC EP/DO48737/1 £931,012 Jul 2006 to June 2010.New Materials for High Energy Colour X-ray Imaging

4. Details of the impact

In 2003, with venture capital from Prof. Max Robinson, a business angel who was at that time a member of the Durham University Technology Transfer team, the intellectual property was licensed to a spin-out company, Durham Scientific Crystals, subsequently renamed Kromek, in order to directly exploit the new vapour growth process. Supplemented by a DTI SMART award, the first commercial crystal growth facility was established in the company's first premises in the Mountjoy Research Centre, which was then the University business incubator. There were initially two staff members, Drs Arnab Basu and Ben Cantwell, both of whom had just completed their PhDs with Prof Brinkman in the Physics Department in Durham. The company rapidly outgrew its original accommodation and moved to NETPark (North East Technology Park), Sedgefield in 2005. Continued growth necessitated a move to larger, purpose built premises in NETPark (see Fig 1 & 2), opened by Prince Andrew in 2010 [C1]. The company now employs over 50 people, including several sub-contractors, at NETPark.

The business model initially focused on the growth of large, high purity CdTe and CdZnTe crystals for sale to other companies building X- and gamma- ray detectors or infrared imaging systems. However, the company then took the strategic decision to move up the product value chain by fabricating their own imaging detectors, incorporating ASIC (Application Specific Integrated Circuit) electronics. The potential of these attracted £1M investment in 2005 from Amphion, the UK arm of a US venture capital company investing in high tech start-up companies. Subsequent calls for venture capital resulted in investment of over £24M, with a round in 2009

Fig 1 Kromek's NETPark (Sedgefield) premises


Fig 2 Part of the crystal growth facility

raising £12.3M [C2].

To ensure direct supply of the ASIC technology, Kromek bought Nova R&D in 2010, an electronics company employing 13 staff at its Riverside, California base [C3]. In June 2011,

Kromek and Nova held 34 granted patents. In February 2013, Kromek acquired Endicott Interconnect Detection and Imaging Systems (EIDS), based in Saxonburg, PA, USA in a strategic move to consolidate the market in melt-grown CdZnTe material. This acquisition added another 40 staff, 25 patents and 300 trade secrets to the Kromek Group. EIDS is now trading again as eV Products [C4].

Initially the company explored applications in the medical imaging market where there are multiple applications for colour X-ray imaging. Kromek had a $1.5M contract from the US National Institute for Health to develop an advanced X-ray camera for breast cancer detection, building on expertise developed from an earlier contract with Siemens to build pixelated X-ray detectors for computerised tomography (CT) scanners [C5]. However, security systems presented even more opportunities with new requirements for screening airport carry-on baggage since 9/11. Supported by the UK Home Office and its investors, the company incorporated their detectors into X-ray systems for liquid explosive detection. In 2008 (the same year it was awarded the ISO2001 manufacturing quality stamp) it launched a bottle scanner which can deal with individual containers. The system, now in use at airports around the world, has a direct impact on all airline passengers as it allows duty free liquids to be carried through airport security screens [C6]. The liquid scanning system (see Fig 3) readily distinguishes *Coca-Cola* from *Pepsi*, and was awarded the newly created Standard 3 for Liquid Explosive Detection Systems (LEDS) following recent regulatory trials (August 2013). Kromek Chief Executive Officer, Dr Arnab Basu said: *"This achievement, together with a 20% reduction in scan time, design changes that include a much faster and simpler user interface, and a roadmap to further reduce the scanning time by 50% put Kromek's explosives detection equipment ahead of the pack…..What makes the Identifier unique is its ability to scan metal cans, Tetra Pak and foil pouches, in addition to all types of glass and plastic containers; this means the Kromek Identifier is the only ECAC Standard 3 approved system that can scan every container type with a simple one button operation*." [C7]

Fig 3. Bottle scanner in use in airport security

The company went from winning regional awards in 2007 (Business Link North East Business award, Business Innovation Centre), to national competitions in 2008 (IET Innovation award), and European success in 2009 (Western Europe Global Security Challenge for Best Security SME). This series culminated in the $400,000 Global Security Challenge award in 2009 for Best Security SME, while Dr Arnab Basu, now Kromek's CEO, won the 2009 Ernst and Young title of UK Young Entrepreneur of the Year [C8].

Other security applications use CdZnTe (CZT) crystals for gamma-ray detection systems. In 2010 the company won a $4M contract with the US Defense Threat Reduction Agency (DTRA) to develop detectors for radioactive materials as part of its on-going anti-terrorist measures [C9], and the resulting products are also on sale as handheld radiation monitors e.g. Kromek's GR1 detectors (Fig 4) which are in use at Fukushima for decommissioning the nuclear plant [C10]. These can be combined with a wall climbing, radio controlled robot to provide nuclide identification in hard-to-reach, high-risk environments where safety is paramount (Fig 5). The company has also developed a home radiation monitor, RadAngel, which can be used with most iOS or Windows devices. This product was launched in Japan in July 2012 and is now available directly to consumers for around $2000 (Fig 5). Other Kromek products [C11] include the RayMon10 handheld radiation monitor and isotope identifier, and RadViz a CZT based gamma ray camera that enables remote nuclear characterisation with 3D dose mapping capability for the nuclear industry. Kromek was awarded a further $3.5M from the DTRA in collaboration with Northrop Grumman.

Fig 4: GR1 gamma ray detector as used in Fukushima

Fig 5: radio controlled wall climbing vehicle with GR1

Fig 6: RadAngel home radiation monitor

Since the original company spun out, there has been continuing research collaboration between the University and the company. Prof. Tanner, a member of staff of the Physics Department, is the Deputy Chairman of the company board and Prof Brinkman was a Kromek Director until his death in 2011. The company has supported PhD students, as well as staff time buyout for Prof Brinkman. A former CASE student in the group, (Paul Scott), and an ex-PhD student of Prof Tanner, (Alex Pym), have been employed by Kromek, as is the original inventor of the growth technique, Dr. John Mullins.

The company was valued in May 2013 (and also on 7th November) at £74M. Turnover grew from £13,231 in 2006-7 to £2.8M in 2011-12 and £2.7M for the year ending April 2013. It is predicted to be £5.07M for the year ending April 2013; shipments of product and services in April 2013 alone reached £1M. The order book stood at $5.85M in May 2013. The Kromek Group plc was listed on the London AIM Stock Exchange on 16th October 2013 at a value of £55M, raising £15M on the floatation.

5. Sources to corroborate the impact

C1 Prince Andrew opening Kromek building
http://www.nebusiness.co.uk/business-news/latest-business-news/2010/07/14/kromek-s-crowning-glory-51140-26850379/
C2. Amphion 2009 Investment funding http://www.amphionplc.com/regulatory_03152010.php
C3 Nova R&D acquisition http://www.kromek.com/aboutus_nova.asp
C4 EDIS now ev products acquisition http://www.kromek.com/aboutus_evproducts.asp
C5. Medical imaging
http://www.proactiveinvestors.co.uk/companies/news/23431/amphion-innovations-partner-kromek-secures-us15m-contract-from-umass-23431.html
C6. Newcastle airport trials http://news.bbc.co.uk/1/hi/uk/8244150.stm
C7 Identifier bottle scanner achieves Standard 3 for Liquid Explosive Detection Systems
http://www.kromek.com/news_loadstory.asp?NewsID=431&KeepThis=true&TB_iframe=true&height=520& width =800
C8. Awards http://www.kromek.com/news_awards.asp
C9 US Defence Threat Reduction Agency
http://www.nebusiness.co.uk/business-news/latest-business-news/2009/12/03/kromek-secures-2-4m-deal-with-us-government-51140-25309390/
C10 GR1 in use at Fukushima
http://www.iii.co.uk/investment/detail/?display=discussion&code=cotn%3AAMP.L&it=le&action=detail&id=8795623
C11 Kromek Products http://www.kromek.com/products.asp