Institution: University of Southampton

Unit of Assessment: 09 Physics

Title of case study: 09-08 5D Memory

Period when the underpinning research was undertaken: 2000 – 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Peter Kazansky	Professor in Optoelectronics	April 1993 – present
Jeremy Baumberg	Professor of Physics	December 1998 – October 2007
Alexey Kavokin	Professor of Physics	June 2005 – present
John Mills	Senior Research Fellow	January 2001 – present
Bruce Klappauf	Research Fellow	May 2001 – November 2003
Costantino Corbari	Senior Research Fellow	July 2005 – May 2015
Martynas Beresna	Senior Research Fellow	April 2012 – present
Rokas Drevinskas	Research Fellow	April 2016 – February 2018
Masaaki Sakakura	Senior Research Fellow	October 2017 – January 2020
Lei Wang	Research Fellow	November 2017 – June 2020
Yanhao Yu	Research Fellow	September 2018 – April 2020

Period when the claimed impact occurred: August 2013 – December 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Researchers at the University of Southampton have developed a breakthrough method of fusing nanostructures in quartz glass using ultrashort laser pulses. In addition to the 3D coordinates of the resulting nanopores, the dual refractive properties of the glass allow the control of two parameters – *slow axis orientation* and *retardance*. This resulted in **5D Memory**: a virtually everlasting, indestructible storage technology allowing hundreds of terabytes of data per memory crystal.

The huge implications of the technology for long-term data storage were immediately recognised by industry, and in October 2016 Microsoft set up *Project Silica* to translate it into "the first-ever storage technology designed and built from the media up, for the cloud". By December 2020 the dedicated Microsoft team had grown to over 30 researchers and engineers, with the project forming a flagship investment as part of the USD10bn Azure cloud platform. Popularly known as the *Superman memory crystal*, 5D Memory forms the basis of a collaboration with Warner Bros for the long-term storage of films, with resilience at room temperature being a key factor. The Microsoft CEO announced the partnership in a 2019 keynote, including a demonstration in which attempts were made to destroy a small piece of glass storing *Superman (1978)*.

The mind-boggling capability of the technology, in combination with its striking elegance, have captured the fascination of the global creative sectors, cultural heritage industries and the media. Its high-profile applications have included a Magna Carta presented to Salisbury Cathedral, a Bible presented to the Vatican Library, and Isaac Asimov's Foundation Trilogy stored in the glovebox of Elon Musk's Tesla Roadster on board *Falcon Heavy* during its successful test launch.

2. Underpinning research

The demand for long-term data storage is reaching unprecedented levels. By 2025, the world will store 200 zettabytes ($2x10^{23}$ bytes), with half of this on the cloud (2020 Data Attack Surface Report). Operating at such scales requires a fundamental re-think of how we build large-scale storage systems and their underlying technologies. The concept behind this research is the bulk storing of data optically in quartz glass, which is renowned for its high chemical and thermal stability and resistance, and accordingly is notoriously difficult to etch without cracking. Researchers at the University of Southampton were the first to pulse laser quickly enough to encode data in the glass, demonstrating recording and retrieval of digital documents with a nearly unlimited lifetime.

An EPSRC-funded project led by Professor Peter Kazansky (2001-2002, **G1**) studied the embedded structures created within fused silica by a femtosecond Ti:sapphire laser. An initial investigation undertaken by Kazansky and Professor Jeremy Baumberg studied the reflective properties of the structures, which formed the basis of their potential for high-density data storage. The team observed that strong reflection from the modified region occurred only along the direction of polarisation of the writing laser. [**3.1**]

A further investigation observed nanostructures created within the glass using the same process. Backscattering electron images of the spot etched by the laser revealed a periodic structure of stripe-like regions of around 20nm width with a low oxygen concentration, aligned perpendicular to the laser polarisation direction. These self-organised “nanogratings” were the smallest embedded structures ever created by light. [**3.2**]

Kazansky went on to study the dual refractive properties, or birefringence, of the silica glass that had been observed in structures created by intermediate levels of laser light. A consistent model of form birefringence was offered to explain the anisotropic reflection and the negative refractive index change [**3.3**]. Further EPSRC-funded research in collaboration with Kyoto University (2007-2010 **G2**) demonstrated that the slow axis orientation (perpendicular to the writing laser polarisation) and retardance (phase change between reflected laser polarisations) of the nanostructures could be manipulated. Data storage using these properties was demonstrated. [**3.4**]

The method of independent manipulation of these 4th and 5th dimensions was developed in a theoretical model by Professor Alexey Kavokin, who described the role of exciton-polaritons in the self-organisation of the nanogratings. Harnessing the coherent effects of these particles would enable the true encoding in five dimensions. [**3.5**]

EPSRC-funded research (2015-2018, **G3**) explored further the interaction of an ultrashort light pulse with glass to enable the writing of the memory. The research created methods to control the nanostructuring with unprecedented quality and manufacturability, paving the way for practical data storage in glass. This resulted in a ground-breaking demonstration of polarisation multiplexed 5D optical memory [**3.6**].

Further research was funded by Microsoft through *Project Silica*. By 2019, up to 160 layers had been tested using optimised parameters providing a ‘memory crystal’ with unprecedented properties: 360 TB/disc data capacity, thermal stability up to 1,000°C and virtually unlimited lifetime at room temperature – 13.8 billion years at 190°C – opening up a new era of virtually eternal data archiving. Adding to their practicality, the data stored in these memory devices can simply be read with a quantitative polarised light microscope.

3. References to the research

3.1 Embedded anisotropic microreflectors by femtosecond-laser nanomachining, JD Mills, PG Kazansky, E Bricchi and JJ Baumberg, APPLIED PHYSICS LETTERS, Vol 81 (2), 196-198, 2002. https://doi.org/10.1063/1.1492004

3.2 Self-organized nanogratings in glass irradiated by ultrashort light pulses, Y Shimotsuma, PG Kazansky, JR Qiu and K Hirao, PHYSICAL REVIEW LETTERS, Vol 91 (24), 247405, 2003. https://doi.org/10.1103/PhysRevLett.91.247405

3.3 Form birefringence and negative index change created by femtosecond direct writing in transparent materials, E Bricchi, BG Klappauf and PG Kazansky, OPTICS LETERS, Vol 29 (1), 119-121, 2004. https://doi.org/10.1364/OL.29.000119

3.4 Ultrafast manipulation of self-assembled form birefringence in glass, Y Shimotsuma, M Sakakura, PG Kazansky, M Beresna, J Qiu, K Miura and K Hirao, ADVANCED MATERIALS, Vol 22, 4039–4043, 2010 https://doi.org/10.1002/adma.201000921

3.5 Exciton mediated self-organization in glass driven by ultrashort light pulses, M Beresna, M Gecevičius, PG Kazansky, T Taylor and AV Kavokin, APPLIED PHYSICS LETTERS, Vol 101 (5), 053120, 2012. https://doi.org/10.1063/1.4742899

3.6 Seemingly unlimited lIfetime data storage in nanostructured glass, J Zhang, M Gecevicius, M Beresna and PG Kazansky, PHYSICAL REVIEW LETTERS, Vol 112 (3) 033901, 2014. https://doi.org/10.1103/PhysRevLett.112.033901

Underpinning Grants

G1 Femtosecond Direct Write of 3D Photonic Structures, EPSRC GR/N35380/01, PG Kazansky, 1 January 2001 – 31 December 2002, GBP154,310.

G2 3D micro-optics in self-assembled nanostructured transparent materials by femtosecond direct writing, EPSRC EP/E034802/1, PG Kazansky, 1 August 2007 – 31 October 2010, GBP379,890.

G3 Printed optics by ultrafast laser nanostructuring of glass, EPSRC EP/M029042/1, PG Kazansky, 1 July 2015 – 31 October 2018, GBP447,890.

4. Details of the impact

The 21st century has seen rapid growth in our ability to store and access data. With individuals and organisations generating ever-larger datasets, we are in need of more efficient forms of data storage with high capacity, low energy consumption and a long lifetime. Securely storing large amounts of information over even relatively short time scales of 100 years, comparable to the human memory span, is a challenging problem. The major issue is the lack of appropriate technology and a storage medium possessing the advantages of both high capacity and long lifetime. Storage is moving towards large cloud facilities, which is an industry growing at an enormous rate: projections expect the market to grow from around USD50bn in 2020 to more than USD130bn by 2025 [**5.1**]. Microsoft holds 15-20% of market share with its Azure platform. The storage media currently being deployed in the cloud were created before the cloud existed and were designed to support other usage scenarios. As a result, the limits of what is possible with existing technologies are being reached, and a new clean-slate approach is needed for cloud storage.

Investment by Microsoft through *Project Silica*

Following the University's announcement of the research breakthrough and a call for industry partners in February 2016 [**5.2**] the potential of 5D Memory as a long-term data storage solution was recognised by Microsoft, who in October 2016 set up **Project Silica** at Microsoft Research Cambridge (MRC) to determine the technology's real-world feasibility. [text removed for publication]. In May 2017 the MRC team were given the go-ahead to set up a research partnership with the University of Southampton [**5.3**], including the sponsorship of further development of the intellectual property [**5.4**] to advance the technology into real storage media. The partnership itself produced 5 further patent applications as of December 2020 [**5.4**].

The project was established as part of Microsoft's Azure platform, into which the company has reportedly invested at least USD10bn annually since 2015 [**5.5**]. In September 2017 at Microsoft Ignite – the company's annual gathering of technology leaders and practitioners – the CTO of Azure Mark Russinovich described the 5D Memory technology in detail, attracting applause when showing a small piece of glass capable of storing two Libraries of congress (50 terabytes) [**5.6**].

At Microsoft Ignite 2019, attended by 26,000 global industry professionals over 5 days, Satya Nadella used his opening Vision Keynote to announce a collaboration with Warner Bros to use 5D Memory crystal for the long-term storage of films, for which temperature-sensitive magnetic tape has been relied upon for nearly a century. The segment, selected by Microsoft as one of the highlights of the keynote [**5.7**], showed a 5D Memory crystal storing the 1978 film *Superman* being boiled, microwaved, degaussed (magnetic field eliminated) and scratched with steel wool. The result, in Nadella's words, was that "we still have the Superman movie. And so that's the frontier of new storage systems". The CTO of Warner Bros noted publicly that "if Project Silica's storage solution proves to be as cost-effective and as scalable as it could be – and we all recognize it's still early days – this is something we'd love to see adopted by other studios and our peers and other industries… If it works for us, we firmly believe that this will be a benefit to anyone who wants to preserve and archive content." [**5.8**]

[text removed for publication] [**5.3**]

Societal impact through the *Arch Mission Foundation* and *Falcon Heavy* launch

The Arch Mission Foundation [**5.9**] is a non-profit set up in October 2016 by prolific US web entrepreneur Nova Spivack. Its aim is to archive humanity's heritage for future generations by

preserving it in long-term storage units – what the Foundation refers to as "Archs". The University of Southampton became a partner in 2017, joining organisations including Microsoft and Wikipedia, with Kazansky appointed as an advisor to the project. The involvement in the Foundation led the 5D Memory technology to catch the attention of Elon Musk, who agreed to store the Foundation's first "Arch", a 5D Memory crystal of Isaac Asimov's *Foundation* Trilogy (a favourite of Musk's), in the glovebox of the Tesla he was loading on to the test flight of SpaceX's *Falcon Heavy* on 6 February 2018 [**5.10**]. Following the successful launch and jettison of the payload, the car and crystal continue to orbit the sun at a speed of more than 7,000 miles per hour [**5.11**].

The inclusion of the 5D Memory crystal in the car, in addition to being a regular feature as part of the media coverage of the launch, prompted whole features in its own right both from general news and magazine publishers (Fortune, Daily Mail, LadBible) and technology news sites (TechCrunch, ScienceAlert, Mashable), each speculating over the future and symbolism of the crystal to their 10 million+ monthly readers [**5.12**]. This frenzy directed specifically at the crystal occurred in spite of a media embargo on the Archs Foundation in advance of the launch, and the fact that compared to the car, SpaceX "was less vocal about that Roadster's secret cargo: a tiny optical disc, known as an Arch" (Ars Technica). Parallels were drawn between the longevity of the crystal and the plot of the books, in which the protagonist "establishes a long-term plan for the progress of human civilization, and is viewed as a legendary savior for the entire course of human history" (The Verge). Other commentators were in agreement that the 5D Memory crystal was the most fascinating element of the payload, with Mashable noting that "there's a case to be made that the books are a more important story than the flashy car" and Syfy declaring in their headline that "something even cooler than a Tesla launched with the Falcon Heavy." [**5.12**]

Societal impact through the heritage sector, artist collaboration and public recognition

Since the University's initial announcement of the technology in February 2016, Kazansky's research team actively drove the promotion of 5D Memory by travelling to high-profile cultural and heritage institutions to present them with archival crystals of meaningful and practical value, thereby demonstrating their wide-reaching potential. These included the Universal Declaration of Human Rights to UNESCO at the International Year of Light closing ceremony in Mexico (February 2016), the Magna Carta to Salisbury Cathedral (June 2016) and the Holy Bible to the Vatican Library (April 2017), each drawing widespread public attention [**5.13**].

Figure 1: Holy Bible, Universal Declaration of Human Rights and Magna Carta stored on 5D Memory.

Later in April 2017 Kazansky and US visual artist Ben Sarao produced the first art exhibition to be encoded on 5D Memory. Sarao's holographic art series, "Eternal Garden of the Villa Borghese" was exhibited alongside the crystal at ArtExpo in New York in April 2017. The collaboration produced a further exhibition, "Iconic images of contemporary space exploration" at Worldcon 76, San Jose in August 2016, and a conference paper *Virtually Eternal 5D Data Storage* presented at the virtual ASCEND conference in November 2020. [**5.14**]

In August 2018 eternal copies of The Universal Declaration of Human Rights and Stephen Hawking's *A Brief History of Time* were displayed at an exhibition at the V&A museum's "The future starts here", featuring 100 objects that will shape the future. [**5.14**]

The social impact of data storage in space was part of a discussion "Data in the Fifth Dimension" at The Hague in September 2018 between Kazansky and artist Martijn van Boven. They explored the current intentions, possibilities, and questions around sending data into the solar system—whether it be music, a library, or the archived knowledge of humankind. [**5.14**]

In light of these engagement activities, public recognition of the technology included [**5.15**]:

- A nomination for the WIRED Audi Innovation Awards as one of the eight scientific breakthroughs set to revolutionise our future (October 2016);
- 2nd place in the Telegraph's "Ten ground-breaking university research projects" (18 million monthly readers, January 2017);
- Television features on CNN's "Make, Create, Innovate" (April 2017), Channel 4 News' "Hidden Britain" (March 2018) and BBC4's "The Secret Story of Stuff: Materials of the Modern Age" (November 2018).

5. Sources to corroborate the impact

5.1 https://www.marketsandmarkets.com/Market-Reports/cloud-storage-market-902.html

5.2 https://www.southampton.ac.uk/news/2016/02/5d-data-storage-update.page

5.3 Letter from Deputy Lab Director and *Project Silica* Lead, Microsoft Research Cambridge.

5.4 University of Southampton (UoS) intellectual property (IP) covering 5D Memory:

UoS IP included in Microsoft partnership (1 patent, 1 patent application):

a) Space variant polarization converter; M Beresna and P Kazansky; priority 3/5/2011; granted in US as US10156669B2 (18/12/2018) and Europe as EP2705393B1 (27/11/2019; UK, FR, CH, LT, DE): https://worldwide.espacenet.com/patent/search?q=pn%3DUS10156669B2

b) Nanostructured geometric phase optical element, method for fabrication and uses thereof; A Cerkauskaite, R Drevinskas, P Kazansky; priority 15/07/2018; filed US, EP, WO: https://worldwide.espacenet.com/patent/search?q=pn%3DUS2020408953A1

IP from UoS-Microsoft research partnership (2 published applications, 3 unpublished):

c) P Kazansky, M Sakakura, L Wang 26/11/2018. Method For Fabricating Nanostructured Optical Elements Using Polarised Light https://worldwide.espacenet.com/patent/search?q=pn%3DWO2020109767A1

d) P Kazansky, M Sakakura, L Wang 26/11/2018. Method For Fabricating Nanostructured Optical Elements https://worldwide.espacenet.com/patent/search?q=pn%3DWO2020109768A1

5.5 Report of annual GBP10bn investment in Azure https://www.crn.com/news/cloud/300077665/microsoft-qm-we-are-investing-more-in-data-centers-than-10-billion-annual-rd-budget.htm

5.6 Mark Russinovich at Ignite 2017: https://youtu.be/sOw8On1iCa4?t=3672 (1:01:12-1:03:33)

5.7 Satya Nadella at Ignite 2019 https://youtu.be/RibuBbifziY?t=132 (2:12-3:21) linked from https://news.microsoft.com/ignite2019, with 5D Memory heading the news list.

5.8 https://news.microsoft.com/innovation-stories/ignite-project-silica-superman

5.9 Archs Mission Foundation website: https://www.archmission.org

5.10 Archs Mission Foundation's first announcement of the inclusion of 5D memory in *Falcon Heavy*, on day of launch (6 February 2018) https://medium.com/arch-mission-foundation/arch-mission-foundation-announces-our-payload-on-spacex-falcon-heavy-c4c9908d5dd1

5.11 *Falcon Heavy* payload tracker: https://www.whereisroadster.com

5.12 Media report: Selected features specifically covering the 5D Memory Crystal on *Falcon Heavy*.

5.13 University of Southampton 5D Memory website covering high-profile presentations: https://www.5dmemorycrystal.com

5.14 Report: Artist collaborations and exhibitions

5.15 Media report: Coverage of 5D Memory since its announcement in February 2016.