Institution: University of Southampton		
Unit of Assessment: 08 Chemistry		
Title of case study: 08-06 The Electrochemical Circus and the Water Transistor: Increasing public understanding of the role of electrochemistry research in modern electronic devices.		
Period when the underpinning research was undertaken: 2011 – 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:**
Philip Bartlett, FRS	Professor of Electrochemistry	1992 – present
Gill Reid	Professor of Inorganic Chemistry	1991 – present
Andrew Hector	Professor of Materials Chemistry	1995 – present
Period when the claimed impact occurred: 2014 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

University of Southampton (UoS) research into new electrochemical processes for the development of smaller-faster-smarter electronic devices has been used to introduce new audiences to electrochemistry, enhancing public awareness and understanding of its importance in our daily lives. Researchers worked with teachers and other professionals to develop a public engagement programme, built around hands-on demonstrations of the *Electrochemical Circus* and a 6 m × 2 m interactive *Water Transistor* exhibit, reaching >100,000 people at science venues and festivals, delivering ~6,000 face-to-face interactions, including with widening-access schools, and engaging ~30,000 people through digital animations. Rigorous evaluations revealed significant percentage rises (as much as 50% for some learning outcomes) in the number of people displaying enhanced knowledge of electrodeposition and transistors and provided evidence of inspiring STEM study.

2. Underpinning research

The deposition of functional materials on electrode surfaces in a patterned form underpins the fabrication of all the computer chips, data storage devices and solid-state lasers in everyday use. Advances in electrodeposition methods, such as supercritical fluid electrodeposition (SCFED), offer new opportunities for novel nanomaterials that can be deposited with greater precision and the complexity of the nanostructures that can be formed. They open up the possibility of developing higher performing devices across a broad range of applications, for example ultra-high-density memory for computers, micro-thrusters for satellites, energy-harvesting and nanomedicine.

Multidisciplinary research led by the School of Chemistry has addressed an overarching objective: the development of (non-aqueous) electrodeposition as an industrially viable technology that enables electrodeposition of metals and semiconductors inside 2D and 3D patterned templates. UoS researchers saw an opportunity for this fundamental science to have an immediate impact by addressing low public knowledge of the electrochemistry that underpins modern electronic devices. A concurrent public engagement programme was designed to provide inspiring and interactive examples of how UoS researchers are exploiting the distinctive attributes of electrochemical processes to advance technologies that are fundamental to everyone's lives.

Since 2011, two EPSRC programme grants worth a combined £11.5m, along with responsive mode grants totalling £1.7m, have led to significant advances in the field of electrodeposition. The principles underlying these breakthroughs directly informed public engagement exhibits, hands-on activities, and online and offline educational resources. Under the first programme [**G1**,**G3**], the research team exploited the unique pore penetrating ability of supercritical fluids to develop a novel process for the electrodeposition of copper, silver and tellurium inside extreme nanoscale pores [**3.1**,**3.3**]. Anodic aluminium oxide membranes were used as templates for the electrodeposition [**3.3**]; these principles were reflected in a hands-on, gold-plated fingerprinting activity that became a core component of the Electrochemical Circus programme described in Section 4. Transistor devices were fabricated from individual tellurium nanowires and their electrical properties were characterised [**3.3**]. This work gave rise to the interactive Water Transistor exhibit (Section 4), as a physical analogue of a field effect transistor (FET), to demonstrate the importance of transistors in modern electronics and how the UoS is developing nanoscale transistors for even smaller and faster devices. Through the ADEPT programme [**G2**], UoS researchers further developed the emerging technologies, including the production of sub-7 nm tin nanowires by electrodeposition from a supercritical fluid [**3.4**]. Through [**G3**], UoS researchers reported a new method for electrodeposition of metal chalcogenide semiconductor films and nanostructures to create switchable phase change memory devices [**3.2**]. This opened up the prospect of electrochemical growth of other metal chalcogenides with applications ranging from electronics to thermoelectric devices and photovoltaics. The method was developed [**G2**] to produce a 3D patterned phase change memory matrix with an integrated selector [**3.5**]. Researchers also developed a new method for the electrodeposition of mono- and few-layer 2D transition metal dichalcogenides (TMDCs) [**G4**,**3.6**]. 2D TMDCs are an emerging class of semiconductors whose properties depend on the combination of metal and chalcogen, as well as the layer thickness, with emerging prospects in multiple high-tech devices. Our gold fingerprinting PE activity was developed to demonstrate electroplating into the pattern formed by a person's fingerprint as a visual analogue to patterned templates used for next generation electronic devices.

3. References to the research

3.1 Halometallate Complexes of Germanium(II) and (IV): Probing the Role of Cation, Oxidation State and Halide on the Structural and Electrochemical Properties. P. N. Bartlett, G. Reid, *et al. Chem. Eur. J.* 2014, **20**, 5019–5027. https://doi.org/10.1002/CHEM.201400179

3.2 Electrodeposition of Semiconducting Chalcogenides – $Ge_2Sb_2Te_5$ Phase Change Memory. P. N. Bartlett, A. L. Hector, G. Reid, *et al. Mater. Horiz.* 2015, **2**, 420-426. https://doi.org/10.1039/C5MH00030K

3.3 Supercritical fluid electrodeposition, structural and electrical characterisation of tellurium nanowires. P. N. Bartlett, A. L. Hector, G. Reid, *et al. RSC Adv.* 2017, **7**, 40720-40726. https://doi.org/10.1039/C7RA07092F

3.4 Exploration of the smallest diameter tin nanowires achievable with electrodeposition: sub 7 nm Sn nanowires produced by electrodeposition from a supercritical fluid. P. N. Bartlett, A. L. Hector, G. Reid, *et al. Nano Letters*, 2018, ***18***, 941–947. https://doi.org/10.1021/acs.nanolett.7b04330

3.5 Towards a 3D GeSbTe phase change memory with integrated selector by non-aqueous electrodeposition. A. L. Hector, G. Reid, P. N. Bartlett, *et al*. *Faraday Discuss*. 2019, **213**, 339-355. https://doi.org/10.1039/C8FD00126J

3.6 Large-area electrodeposition of few-layer MoS_2 on graphene for 2D material heterostructures. G. Reid, P. N. Bartlett, *et al. ACS Appl. Mater. Interfaces,* 2020, **12**, 49786–49794. https://doi.org/10.1021/acsami.0c14777

Key grants:

G1 EPSRC Programme Grant EP/1033394/1, 'Complex Nanostructures by Supercritical Fluid Electrodeposition', P. N. Bartlett (PI), A. L. Hector, G. Reid, 2011-2016, £5,140,372.

G2 EPSRC Programme Grant EP/N035437/1. 'ADEPT – Advanced Devices by ElectroPlaTing', P. N. Bartlett (PI), A. L. Hector, G. Reid, 2016-2021, £6,331,952.

G3 EPSRC: EP/I010890/1, 'Phase Change Memory Materials via Non-Aqueous Electrodeposition into Nano-structured Templates', G. Reid (PI), P. N. Bartlett, A. L. Hector, 2010-2014, £901,440.

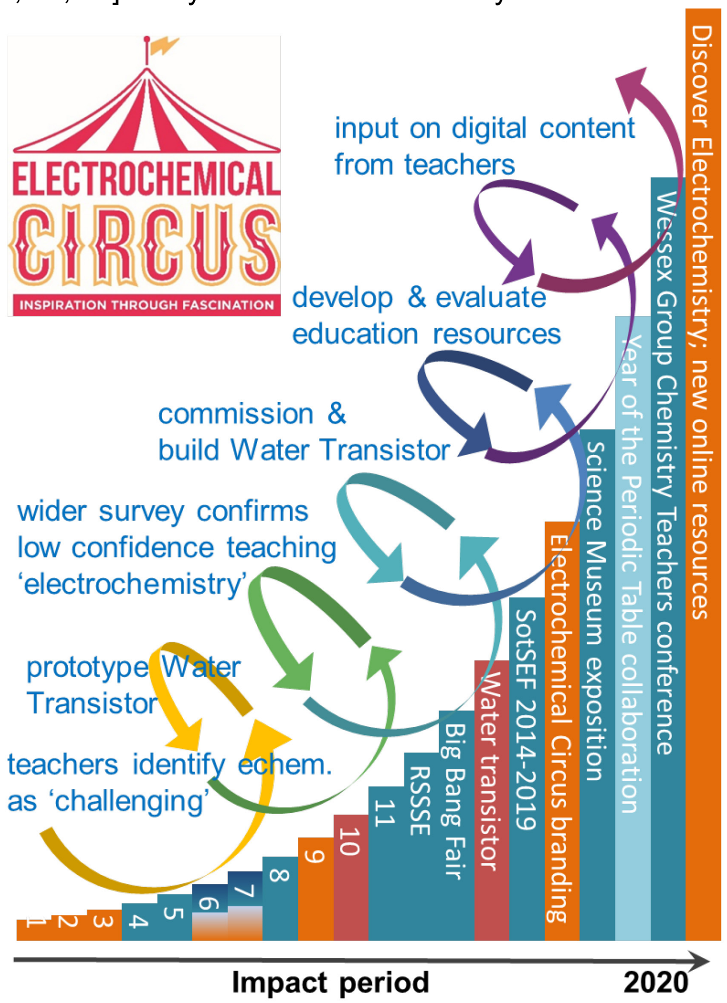
G4 EPSRC: EP/P025137/1, '2D layered transition metal dichalcogenide semiconductors by non-aqueous electrodeposition'. G. Reid (PI), P. N. Bartlett, A. L. Hector, 2017-2021, £799,813.

4. Details of the impact

The role of electrochemical processes in the fabrication of electronic devices on which society is wholly reliant is poorly appreciated. In 2014, School of Chemistry researchers embarked on a public engagement programme to address the imbalance between a lack of public knowledge of transistors and electrochemistry and the ubiquity of consumer devices that were only made possible through advances in these fields. In engaging the public in their pursuit of novel electrodeposition technologies for the next generation of electronic devices, the team set two key objectives: introduce new audiences, including schoolchildren, to electrochemistry and inspire them to learn more; enhance and sustain public knowledge of electrochemical principles and their intrinsic relevance to daily life. Three key principles underpinned the approach: dedicated funding, team-based delivery and rigorous evaluation to guide continuous feedback and improvement. A 0.3 FTE public engagement role was costed into the ADEPT [**G2**] grant. A further £30,000 came from the ESPRC Impact Acceleration Account, along with an Institute of Physics grant and UoS internal funds. Engagement ideas were generated across the School of Chemistry and volunteers, including UGs, were invited to participate in delivery. The programme was designed and evaluated according to Arts Council England's Generic Learning Outcomes, with a focus on two criteria: 'Knowledge & Understanding' and 'Enjoyment, Inspiration, Creativity'. Outcomes shaped an iterative design process, allowing methods and exhibits to evolve. The overall programme, centred around the

Electrochemical Circus and Water Transistor, reached an in-person audience of >100,000 over the impact period, delivering 6,000 direct, face-to-face interactions between researchers and the public. Learning outcomes are detailed below.

Enhancing public understanding of electrochemistry at large-scale science events: Initially researchers developed two interactive demonstrations that formed the core of their public engagement at large-scale science events. They built the mobile Water Transistor, a physical analogue of an FET, to demonstrate how switches inside computers function. It used water to represent electrical charge, with pressurised squeezing affecting flow through a long, thin balloon. It reflected the underlying research principles and the motivation for research on the electrodeposition of nanostructured semiconductors [**G1**,**G3**,**3.1**,**3.3**]. They also created an activity that demonstrated how gold is electroplated from solution. Naturally occurring oils on people's fingers were used to template gold deposition around the fingerprint pattern and people took home their own gold-plated fingerprint. This represented the templated electrodeposition process used to produce semiconductors for phase change memory, infrared detection, and other applications (**3.2-3.5**). The 3-minute activity provided an opportunity to discuss the underpinning science at a level of complexity appropriate to age or knowledge levels, the relevance of this chemistry to modern electronic devices and how UoS researchers were advancing the technologies. Both demonstrations visited the National Big Bang Fair 2014, the Royal Society Summer Science Exhibition (RSSSE) 2015 and Southampton Science and Engineering Festival (SotSEF) 2014-2019. Footfall of >40,000 people and 6,000 face-to-face interactions were recorded across these events **[5.1]**. Data collected at RSSSE 2015 showed that as a result of engaging with SCFED research, there was the following transfer of knowledge: an increase in the number of people who could identify a supercritical fluid as 'a hot, dense gas' from 5% to 54%; an increase in those who identified electroplating as 'a bottom-up, atom-by-atom process' from 28% to 46%; and an increase in those who correctly identified a transistor as 'an electrically-operated switch' from 34% to 69% [**5.1**]. The gold fingerprinting activity was as popular with children as it was with industry professionals and proved a versatile vehicle for engaging with varied publics. The souvenir fingerprint ensured the impact of the interaction lasted longer than the activity itself. Representative comments from people who interacted with the demonstrations included: "awesome"; "it's fascinating, thank you so much"; "very informative and well explained" [**5.1**].



1) teachers' conference; 2) initial survey of teachers; 3) teacher focus groups RSC conference; 4) activities prototyping; 5) gold fingerprinting refinement; 6) UG and PG demonstrator training; 7) Light-Up Poole; 8) GIF design and Twitter engagement; 9) suitcase of curiosities; 10) KTN Materials Expo; 11) portable Water Transistor design.

Design of a permanent exhibit to increase audience diversity, further improve public knowledge of transistors and sustain impact beyond annual events: The mobile Water

Transistor went through five design iterations to make improvements on the basis of audience feedback. Building on lessons learned, in 2017 the team commissioned interactive exhibit specialists Science Projects to build a permanent, large-scale Water Transistor exhibit at Winchester Science Centre (WSC). Researchers took this decision in order to engage a broader audience (WSC targets 5-12 year olds and their families) on a consistent, daily basis. The exhibit was installed in Jan. 2019. At 6 m long and 2 m high it occupies a prominent position in the main visitor space. Modules demonstrate how transistors help computers make calculations and allow people to 'race' transistors used in electronic devices to see how fast they are. A video explains the underpinning research [**3.1**-**3.4**], how UoS researchers are developing nano-transistors for even faster electronic devices, and introduces the researchers involved. Feedback is gathered via a touch screen panel. Using observation data, the number of people interacting with the Water Transistor from Jan. 2019 to Mar. 2020 was >75,000 based on an average of 30 visitors per hour [**5.2**]. This equates to one in three visitors to WSC. The video was played 5,420 times, and there were 11,629 responses to the feedback questionnaire. Key outcomes [**5.2**] were: 77% of people found the water transistor enjoyable to use; 65% said it helped them to understand how transistors work; 64% correctly identified transistors as electrically operated switches; 79% recognised that transistors are faster than humans; and 71% understood that computers are fast because of transistors. Further evaluation [**5.2**] was carried out in person by a student intern in summer 2019; 96% of adults either strongly agreed or agreed with the statement 'I enjoyed using the water transistor'. Data revealed clear evidence that the exhibit increased public awareness of the role of the transistor in everyday consumer electronics, and how electrochemistry research can enhance our lives. Before interacting with the exhibit, only 35% of people recognised the word transistor and knew of its role in modern electronics, but afterwards this proportion increased to 80% and 75%, respectively. Furthermore, 84% agreed they had learnt something new about computers/transistors; 89% said they had a better understanding of how chemistry improves our lives; 71% were inspired to find out more about electronics; 74% recognised that UoS scientists are working on new devices; 95% of people would recommend the water transistor to others. Ben Ward (Chief Executive, WSC) highlighted "*the value of incorporating real, recent, internationally-published research in the exhibit*" [**5.3**].

Water Transistor at WSC

Creating the Electrochemical Circus to widen access and inspire further STEM study: In 2017, in order to both widen access to children less likely to attend science venues, and strengthen wider appeal of the programme, existing activities were consolidated under a new Electrochemical Circus brand. A range of activities were brought together, including making batteries out of fruit, the passing of a current through a red cabbage to explain electrochemical reactions and the Suitcase of Curiosities, a collection of objects related to electrochemistry research relevant to [**3.1-3.6**]. PGR/ECR electrochemists and undergraduate chemistry students at UoS were trained as Electrochemical Circus volunteers. Data from SotSEF 2019 [**5.4**] showed that of those visitors surveyed after interacting with the Electrochemical Circus, 71% identified that electrons move from high to low potential; 94% of people understood that an electrical current refers to the flow of electrons through a circuit; >90% identified that electrons flow through an electrolyte, a metal wire, a lemon, but not a chocolate bar; 72% understood that electrodeposition is a process during which metal ions in the solution move to form a layer of metal atoms on the electrode; 87% said they were interested in learning more about electrochemistry. A large majority of people surveyed (87%) did not identify as having high levels of prior electrochemistry knowledge. The team was presented with the 'Wow Factor' award by the SotSEF organising committee.

The Water Transistor formed the centrepiece of a series of Electrochemical Circus school visits at WSC in June and July 2019. Harder-to-reach pupils were targeted specifically according to widening access criteria and workshops were designed to complement the schools' own science curricula. A total of 128 Year 8 pupils and eight teachers attended. Questionnaires [**5.5**] demonstrated the following changes in understanding: that electricity can be made by chemical reactions (from 43% to 70%); that digital electronics depends upon transistors (from 30% to 80%); that transistors are electrically operated switches (from 29% to 74%); and that computers are 'clever' because transistors are fast (from 36% to 88%). Data collected at follow-up visits to schools in

December 2019 showed retention of this knowledge: 45% of pupils remembered that transistors are electrical switches; 51% of pupils remembered that computers are fast because of transistors. Pupils rated their overall enjoyment of the Electrochemical Circus at 4.2/5. On our return to the schools we asked students what they remembered from their summer WSC visit: 95% of students remembered visiting the centre, 86% said that they had enjoyed their visit, and 81% remembered meeting scientists at the WSC. Students remembered the individual activities, with gold fingerprinting being remembered by almost all (98%) students; some students still had their gold fingerprints in their wallets and purses and showed them to the team.

In 2019, the Electrochemical Circus featured at two festivals. The first was *Light Up Poole!* Digital Arts Festival (February 2019), with the aim of engaging an audience that might typically favour arts events over science. A total of 1,071 people took part in The Photon Shop, a series of activities relating to the science of light. Gold fingerprinting was presented in the context of electroplating to make materials for infrared sensing. It featured prominently in the overall evaluation data as an activity that the audience had enjoyed and understood [**5.6**]. In addition, 100% agreed that the event was enjoyable and would recommend it to others; 90% said that they had learnt something new about science; 81% gained a better understanding of what scientists do; 87% were inspired to find out more about science; and 71% of visitors were more likely to consider studying science or recommend science to others. The Electrochemical Circus visited the Science Museum in April 2019 to take part in CHEMFEST, in celebration of the International Year of the Periodic Table. Visitor numbers were 7,000 (4,000 adults, 3,000 children) and the UoS team created >800 gold fingerprints over a four-day residency. The event coordinator said [**5.7**]: "*The families had a great time and it's amazing to have something so memorable to take home with them. I know many were also inspired by electrochemistry, a field many were unaware of how vast and important it is.*"

While demonstrating impact of public engagement on uptake of STEM subjects is extremely difficult, the evaluation of the Electrochemical Circus included a survey question with a 5-point Likert scale asking how likely people were to consider further study or encouraging others towards further study of science. These showed an increase from 18% to 31% in positive responses [**5.5].**

Engaging online audiences in electrochemistry [**5.8**]: In 2019 the UoS research team worked with Errant Science to create animated gifs as a novel way to communicate key electrochemical principles to a new online audience. The animations were published via the Electrochemical Circus Twitter account. The first animation (April 2019) featured the Daniell Cell and achieved 11,554 impressions, 3,389 media views, and 693 engagements. A second animation communicating the electroplating process (July 2019) achieved 7,266 impressions, 1,082 media views, and 231 engagements. There was particular interest from teachers in the UK and overseas, with most highlighting the content to their A Level/AP Chemistry students. The second animation (July 2019) featured the reduction of gold at the electrode during electroplating and was designed to complement the gold fingerprinting activity. It achieved 6934 impressions, 1050 views and 186 engagements, and was described as being '*superbly explained*'. The account reached 345 followers, with 120 of those being linked to the two animations.

Feedback from 80 teachers stimulated further developments through the production of a bespoke set of teacher resources in response to a need identified by researchers in the UoS Chemical Education Research Group (S. Barnes, PhD Thesis, UoS, 2020) [**5.9**]. Electrochemistry was the theme for the 2020 Wessex Group Chemistry Teachers' Conference (100 delegates), with a Keynote presentation by P Bartlett that was well received (100% of respondents rated the talk as 'good' or 'excellent' [**5.10**]). Feedback at this event and from teacher focus groups was used to create a series of resources hosted at *discoverelectrochemistry* [**5.11**]; Robert Campbell (former Chemistry teacher and current lead on the secondary science PGCE course at St Mary's University says, "*recommending the Discover Electrochemistry website to trainee teachers has been invaluable*", describing them as "*a critical tool to support teachers develop their confidence in teaching electrochemistry*" [**5.12**]; Dr Emma Wright (KS5 Science Coordinator, Queen Elizabeth's Girls' School) says, "*genuinely, the resources are brilliant and I will use them every year*" [**5.13**].

5. Sources to corroborate the impact

5.1 Report: Big Bang Fair (2014), RSSSE (2015), SofSEF (2014-19); **5.2** Report: Water Transistor exhibit; **5.3** Letter: Chief Exec. WSC; **5.4** Report: Electrochemical Circus; **5.5** Report: Electrochemical Circus school visits; **5.6** Report: *Light Up Poole!;* **5.7** Statement: Science Museum; **5.8** Impact: Twitter engagement; **5.9** Teaching Electrochemistry; **5.10** Teachers Conference; **5.11** Discover Electrochemistry; **5.12** Letter: PGCE course leader; **5.13** Letter: KS5 Science Coordinator.