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Defects, Flexoelectricity and RF communications: the ZBD story

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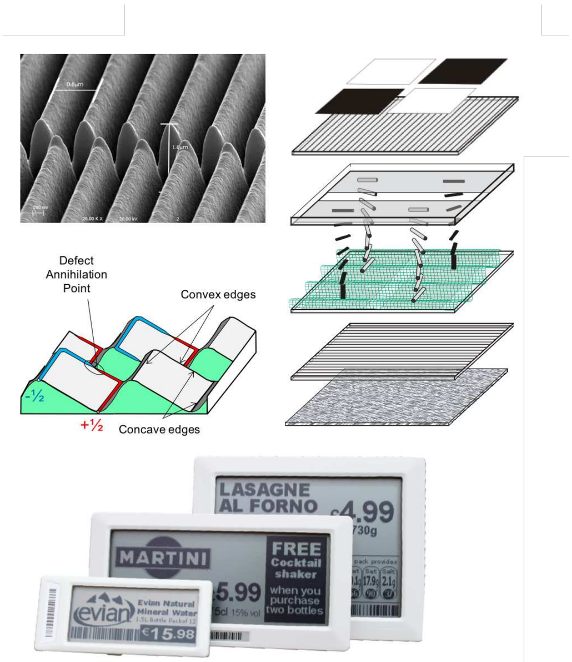
The Zenithal Bistable Display (ZBD) was the first liquid crystal device mode to be commercialised that uses nematic disclinations in a constructive fashion, to use the flexoelectric effect inherent to all liquid crystals but at the time was considered too weak an effect to be useful, and to transfer nano-replication methods to the LCD manufacturing environment. The genesis of the invention and spin-out company *ZBD Displays Limited* will be described, and the evolution of that company from licensing model, through fabless manufacturer to display provider and finally to a system provider for the retail sector. The story may be useful not just to those interested in the science behind a rather unusual LCD, but also those involved in taking technology from laboratory to manufacturing, from idea to commercial success.



Key words: Nematic LCD, Bistability, Grating, topological defects, flexoelectricity, Manufacturing, Business models, RF Communications, Low power displays, retail displays, electronic-shelf-edge labels.

1 Introduction

History is a difficult subject for any scientist to convey. Even for a personal history, a scientist's primary need for truth is impeded by the subject's complexity and the forgotten. Particularly testing for an account written by a major protagonist such as this is the addition of emotion: conceit to exaggerate one's own role; idealism that forgets disasters and remembers the triumphs; convenience that writes from a personal viewpoint; cowardice that excludes the uncomfortable or the potentially libellous; re-sequencing of the narrative for brevity and the storyteller's art. I try to resist these traps but undoubtedly fail. At least, everything reported is true in my opinion.

So why might a liquid crystal scientist be interested in the story of ZBD? The Zenithal Bistable Display was the last successful invention from the world-renowned Displays Group at *Royal Signals and Radar Establishment* (*RSRE*) in Malvern, though made when the UK MoD's electronics research institution had joined with the aircraft, naval, and army research establishments to form the *Defence Evaluation and Research Agency (DERA).* A surface relief grating with a homeotropic surface condition is used to align a conventional nematic liquid crystal [1]. Rather than lie parallel to the grooves, as Berreman had shown previously, [2] the homeotropic anchoring forces the director into an elastically deformed state. If the grating is sufficiently deep, the director either follows the surface and averages out to a vertically aligned condition, or some of the elastic energy is relaxed by the formation of -½ and +½ disclinations at the convex and concave surfaces of the grooves, respectively. This Defect or D state as it was termed, has a much lower pre-tilt, depending on the shape of the grating, whereas the Continuous or C state is near vertically aligned, regardless of surface shape. Switching between these bistable states is done by coupling to the local surface flexoelectricity induced in the nematic by the high degree of elastic deformation close to the grating: a positive pulse with respect to the grating surface latches into the low tilt, D state, whereas a negative pulse causes the defects to annihilate and form the high tilt, C state.

The invention and operation of such a device should be relevant to the liquid crystal scientist. However, what makes this invention unusual and of wider interest is the subsequent formation of the UK Civil Service's first Venture Capital-backed spin-out company, *ZBD Displays Ltd*; the development of that technology from an impractical device that was difficult to repeat to a display manufactured at many millions of units per year; and the evolution of that company which allowed it to survive when its competitors failed, through two world recessions, to become the world leader in its chosen market today. The story includes lessons for any scientist or technologist wishing to maximise the impact of their research, and take the rarely trodden path from Laboratory to Board room.

Common to all success is hard work, deep thinking and above all, a quality team. Indeed, my role in this accomplishment is but a part, and acknowledgement must be made to the brilliant technologists, managers and investors that drove this story. The technological innovations described originate from many, but of particular importance are Rich Amos, Dave Walker, Steve Beldon and Emma Wood. Above all, no ZBD history would be complete without acknowledging the experimental genius of Guy Bryan-Brown, who continues to impact the technology. As shall be shown, the company's evolution was guided by a series of managers: Henri-Luc Martin, Clive Mayne, Shaun Gray and Andrew Dark. Particular thanks go to Mayne and Gray who steered ZBD through a technological down-turn in each case, and who were instrumental in developing the manufacturing and marketing, respectively. ZBD has also been blessed with experienced and patient investors, none more so than Dr. Bob Hook of *Prelude* and *Esprit*.

1. "The Peace Dividend"

The year 1989 witnessed a lot of change in the world. Having founded the Displays Group at *RSRE* in the early seventies, and provided fundamental direction to the work on liquid crystals and, importantly, to the world's first amorphous silicon thin-film transistor (TFT) LCD, Cyril Hilsum was then Chief Scientist at *GEC Hirst Research Centre*. He had recruited me in 1985 as a young physicist working for Mike Clark and Alan Mosley, and seconded me to *RSRE* under the Supervisorial guidance of Peter Raynes. I had enrolled for an external PhD in the Chemistry Department at the *University of Hull*. My academic co-supervisor had been Prof George Gray, *the* giant in the field of liquid crystals, someone with whose work I had already been familiar with even as an undergraduate, and a major reason that I was happy to enrol in a chemistry department, despite my physicist origins. However, George was to retire from academia in 1989, and be replaced by John Goodby, from Bell Laboratories in the US. Of course, John's work on smectic liquid crystals was world leading and well known to me too, but I was yet to meet the man, one of the most successful of a distinguished set of co-workers from Gray's group in the nineteen seventies. Over the next decade, I worked very close with John, as described in the edition of Liquid Crystals dedicated to George Gray [3] particularly whilst developing ferroelectric liquid crystals for High-Definition Television (HDTV) operation with Sharp. However, the following account describes work done both alongside that work with John and subsequently. Much of what is to be described will explain to John why he lost close contact with one of his first Ph.D. students for over a decade.

1989 also saw rather larger changes in the world at large. The fall of the Berlin Wall, reunification of Germany and end of the cold war were to have a major impact on what was to happen in the following decade. *RSRE* received the majority of its income from the UK Ministry of Defence, with funding for flat-panel, low power displays one of its priorities. The momentous worldwide events gradually changed this emphasis. The so-called "peace-dividend" was a concept that government funded research teams would now find new, commercial avenues to target.

The impact of this change was felt hard across the community, including the field of Displays.

It was at this point that one of John's peers from the Gray group of the 1970s became particularly important. Damien McDonnell had defined the relationship between mesogenic structure and cholesteric helicity whilst at Hull. By then at RSRE, he took on a more managerial role, and eventually lead the search for more commercial funding. He joined the team lead by the MoD Head of Intellectual Property, Bob Beckham, which included the Displays Group Superintendent Norman Apsley, and the main inventor of the technologies, Peter Raynes, the team began to chase patent royalties for the use of pre-tilt in TN cells and for Supertwist Nematic displays, both invented at *RSRE* during the 1970s and early 1980s. As the first company to sign an agreement, *Sharp* won a favourable deal provided that they reinvest some of the royalties directly back into the Displays Group at *RSRE*. Not only did this secure funding for on-going basic research but also created a relationship with Sharp Japan that was to last the following decade, leading to the HDTV programme on Ferroelectric Liquid Crystals described in [3].

At the onset of this Royalty Reinvestment Programme, McDonnell suggested the topic of grating aligned liquid crystal devices. He was familiar with the previous work of Flanders *et al*, where controlled alignment had been produced using 320nm pitch gratings [4]. Separately, George Durand and co-workers had recently described an Azimuthally Bistable Nematic device based on SiO alignment [5]. Evaporating inorganic dielectric layers such as SiO or MgF at 30° to 60° to a surface normal leads to degenerate, planar alignment with zero pre-tilt in the plane perpendicular to the evaporation. Increasing the evaporation angle to about 75° leads to a high pre-tilt (~30°) alignment parallel to the evaporation plane. Bistable alignment was achieved for a band of angles and evaporated layer thicknesses, where both 0° and 30° pre-tilt alignment states coexisted with alignment planes angled to each other. Combining two such surfaces so that tilted and planar states opposed each other gave bistable director profiles with opposite directions of splay/bend, allowing flexoelectric switching between the two surface stabilised states. At that first project meeting, McDonnell made the rather ingenious suggestion that a grating surface with two orthogonal directions (i.e. a bi-grating) would be able to support the azimuthal bistable states [6]. Adding blaze to one of the surface oscillations would then give pre-tilt, and Durand's device could be mimicked but with a more reproducible surface. At the beginning of 1992, Martin Bancroft from my team was assigned to begin the investigation on grating aligned liquid crystals.

Soon after, McDonnell admitted his main worry with the project to me: no matter how successful we were at creating a bistable bi-grating surface, it would remain a secondary invention to Durand's original prior art. He tasked me to consider alternative methods for achieving a bistable nematic display. The approach seemed obvious: to avoid the prior art one could not rely on azimuthal bistability and hence a mechanism for achieving a zenithally bistable device was needed. Naïvely, I though this best done by dividing the alignment layer into tiny domains of planar and homeotropic surface conditions, potentially through mixing planar and homeotropic surfactants together. Avoiding flexoelectricity would then be simpler, since a zenithal bistable device could be latched between the vertical and horizontal states using a dual-frequency liquid crystal, where the dielectric anisotropy $\Delta\varepsilon$ swapped from positive to negative with increasing frequency. In March 1992, I filed an internal *RSRE* invention record on a zenithal bistable nematic surface and device, but never attempted mixing surfactants to demonstrate whether it was practical or not.

2. The Invention

I was not interested in grating alignment for bistability only. I hypothesised that a grating coated in a homeotropic surfactant would also provide useful alignment to a ferroelectric SmC* phase: the homeotropic alignment would ensure that the smectic layers were parallel to the plane of the cell, but the grating would favour alignment of the SmC(*) tilt either parallel or perpendicular to the modulation. However, Bancroft was struggling to fabricate gratings, so he was sent to the Physics Department at *Exeter University*, where Professor Roy Sambles was using metallised gratings to couple surface plasmons into liquid crystals. There, Bancroft met the young post-doctoral researcher delivering that project: Dr. Guy Bryan-Brown. His contract was due to end in September 1992, at which point he was to take up a post in the Photonics group at *DERA*. On Bancroft's return, we intercepted this offer and suggested Bryan-Brown be recruited to the Displays Group instead to work on Grating Aligned Nematic Devices.

Bryan-Brown soon settled in, working closely with Carl Brown who modelled the effect of grating shape on alignment properties to compare with Bryan-Brown's experimental data. A particular aim of the work was to control the pre-tilt of the director through increasing the blaze angle of the grating. A more reproducible and controllable pre-tilt would be useful for application in mono-stable displays such as supertwist Nematic (STN). Two regimes were investigated: degenerately planar aligned bi-gratings (where the director could be forced to lie perpendicular to a blazed grating by the action of a higher aspect ratio grating normal to it), or using the homeotropic mono-grating, again with blaze. In both instances, two solutions were found: either a Continuous state for low aspect ratio, shallow gratings or a Defect state for high aspect ratio, deep structures, figure 1. Brown and Bryan-Brown were disappointed to report that the target of 7° pre-tilt remained elusive regardless of the blaze angle, and that the gratings were not likely to be suitable for STN application. I was more upbeat, having spotted that an intermediate grating aspect ratio, where the Continuous and Defect states had similar elastic distortion energies, would provide the zenithal bistable surface that I had been seeking. In February 1995, Brown modelled the bistable grating director profile, figure

1a), and we suggested to Bryan-Brown that he fabricate opposing zenithal bistable gratings and use a two-frequency nematic to latch between the states.

The year 1995 was an *Annus Mirabilis* for Bryan-Brown. He was already working on using the homeotropic grating [a] to induce a twist in a negative Δε, hybrid-aligned nematic (the Voltage Controlled Twist or VCT effect) and using oligomers to give slippery surface planar anchoring. Both of these pieces of work led to publications in *Nature,* [7] and [8], respectively, therefore it wasn't until September of that year that he had a chance to attempt a zenithal bistable device. Fortuitously or through experimental brilliance [b] Bryan-Brown took several initial steps that made the first devices far better than I could have predicted. He took a deep, homeotropic blazed grating similar to that he was using for the VCT device, but assembled it opposite a standard homeotropic surface and filled the 3μm spaced cell with the positive Δε nematic mixture ZLI-2293. The mixture cooled into the low-tilt D state, but on application of pulses of different polarity, he found selective latching between the D (hybrid aligned) and the C (vertically aligned) states. The Zenithal Bistable Display was realised [9].

Initial progress was rapid. The first time that Bryan-Brown demonstrated the device to me, he suggested that the latching mechanism depended on the flexoelectricity. I showed how the latching thresholds could be greatly reduced using a bipolar pulse, suggesting that the magnitude of the flexoelectric term at the surface would be increased by the dielectric effect of the leading pulse with the positive Δε liquid crystal, and priming latching in the trailing pulse. It was also at this time I first suggested dropping the word *Nematic* from the name of the display, thereby enabling the acronym ZBD and pronunciation "*Zebedee*". Soon after the invention, the group was approached by *Hewlett Packard (HP) Laboratories* in Bristol, who were looking for a partner to work on flexible liquid crystal displays. The team were new to liquid crystals and offered a multi-year contract to combine our expertise in liquid crystals with their access to electronics and end users. When the project started in October 1995, *HP* was informed of both ZBD and the bi-grating Azimuthal bistable display, but HP chose to concentrate on the latter. This rather slowed

[a] Although invited, I did not believe that I was an inventor of VCT, since I had subsequently found an earlier paper that used homeotropic gratings: M. Nakamura and M. Ura (1981) J. Appl. Phys., **52** (1), pp 210-218.

[b] Bryan-Brown states that the effect was actually a discovery rather than through a designed experiment. Whilst studying the homeotropic grating in an STN configuration, he found that he could only induce the high tilt state by applying electrical pulses. Despite the effect being restricted to just a tiny fraction of the cell he was observant enough to realise its importance.

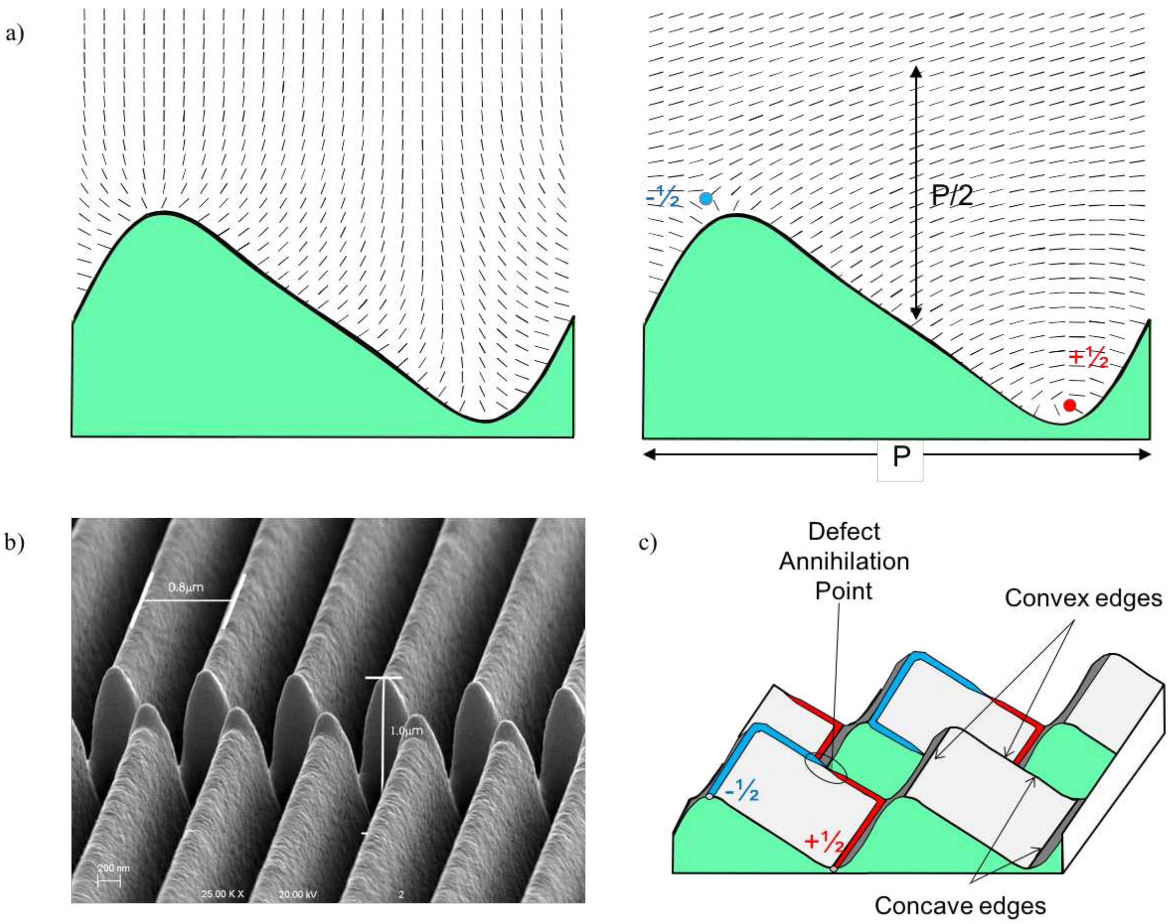


Figure 1. Stabilising Defect and Continuous States at a grating surface. a) The Original modelling from reference [9]; b) SEM of a typical grating showing the π-phase shifts or slips [10]; Schematic representation of how slips stabilise defect loops through the addition of extra convex (for - ½ defects) and concave (for + ½ defects) surfaces in the direction perpendicular to the grating. These are spaced randomly with an average periodicity of about 6μm.

the development of ZBD, as it progressed alongside the *HP* collaboration.

Over the following two to three years, the basics of addressing [11, 12] and greyscale [13] were developed, and an improved twisted nematic (TN) geometry defined, where the opposing surface was a rubbed polyimide and the grating aligned parallel to it, to give a TN in the low tilt D state, and an untwisted Hybrid Aligned Nematic (HAN) in the C state, figure 2. The twisted nematic geometry offered enormous benefits. In addition to the higher cell gap, achromatic performance and wide-viewing angle (particularly in reflection, where the HAN state self-compensated), this geometry solved what had been a major issue. Grating pitches of between 0.6μm and 1.0μm were readily fabricated using photolithography. However, the deep structures that were required for bistability give high optical form-birefringence at these pitches, significantly impeding the dark-state and contrast ratio when the polarisers are set at 45° to the grooves, as required for the HAN white state. Operating in the TN mode allowed the polarisers to be set parallel and perpendicular to the grating, where the form-birefringence is removed by index matching the grating material to the ordinary index of the liquid crystal, figure 2. If this geometry was used with a negative $\Delta\varepsilon$ liquid crystal, the distracting optical flash observed in the image whilst updating could also be removed [14]. Other inventions included the use of random arrays of bistable gratings or pillars with different orientations to form a bistable diffracting, refracting or scattering states [15]. Some ideas remained unpatented: these included: use of conductors both covering and below the grating to concentrate the field at the same surface where latching occurred; alternating planar and homeotropic alignment, similar to the original invention record but where a regular array of stripes is used instead of random mixing; zenithal bistability from a grating with planar anchoring perpendicular to the groove direction, to give a low pre-tilt C state and high pre-tilt D state. I also became concerned that the temperature range of the ZBD would be limited, since the defect loops running along the top and bottom of the grooves were only weakly pinned between areas of D and C states. I suggested that the grooves should be "broken" at regular intervals, either using holes or bridges in the grooves, or most effectively by using phase shifts, or "slips" of the grating structures, figure 1b) and 1c). Initially, we considered this to be useful technical know-how that should not be published, and therefore remain unpatented. Several years later, when in conversation with Karl Amundsen of *E-Ink*, he too suggested added pinning sites to the grooves. On returning to the UK, I quickly filed the "Broken" ZBD patent [10].

The first stage of the *HP* project ended in early 1997, but the team was struggling to produce an azimuthal bistable bi-grating display. This was concerning because a successful demonstrator was needed to convince *HP* management that continued funding of the *DERA* project was worthwhile. We decided to use *ZBD* to produce an addressed prototype, and targeted making a first publication jointly at that year's Society of Information Display Conference. John Rudin from *HP* dutifully applied the addressing waveforms to our completed 32 x 32 transmissive demonstrator, figure 3a) and was included as an author on the first ZBD paper [16]. With hindsight, it appears unwise to have made this the first publication. The patent had entered its PCT stage, and a companion paper in *Nature* or some other prestigious journal could have been attempted. However, the

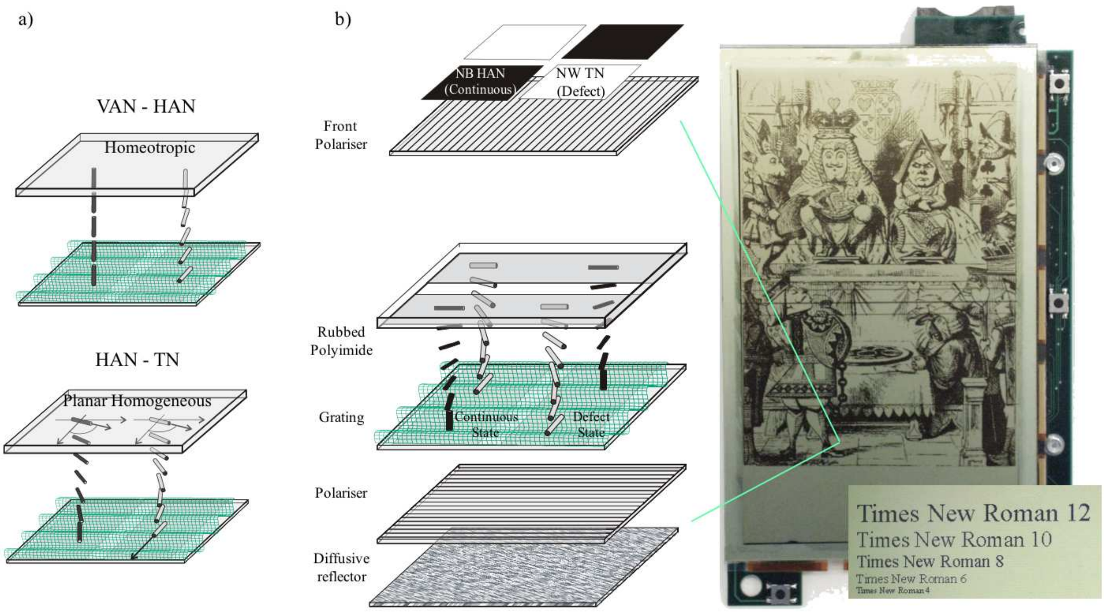


Figure 2 Optimising the ZBD geometry; a) VAN operation using a grating opposite a homeotropic surface, and TN operation when opposite a planar homogenous surface. b) A 7" diagonal 200dpi ZBD operating in the 90° TN mode, together with the polariser arrangement.

commercial reality of having to secure on-going funding from HP, and a naïve belief that this would be helped through demonstrating a working relationship through a joint publication were more important factors at that time. It remains a source of discontent to Bryan-Brown, Brown and myself that a respected first publication was not made, particularly because of the high number of future publications with incorrect citations to subsequent work of other authors, sometimes by authors not wishing to condescend to referencing a conference proceedings or patent. This discontent was compounded when the efforts to attract further *HP* funding failed, and they chose instead to continue funding work on grating aligned bistability through a variety of studentships at Universities in place of the, by then, struggling *DERA*. By 1998, Carl Brown had left *DERA* for academia, I was redeployed on other projects and the opportunity to publish had passed until the project could find a sounder footing.

It was not just funding that was the issue. The patent search had yielded prior art from *Bell Laboratories* from the 1980s. In particular, a patent from Julian Cheng and Gary Boyd seemed to include opposing grating surfaces with zenithal bistable states stabilised by defects [17, 18]. Looking back from the Internet age, it seems peculiar that we, the ZBD inventors, could have missed such a large body of work on bistable nematics. However, on studying the literature more carefully, it became apparent that the similarities to ZBD were superficial. The *Bell Labs* bistable states were stabilised by the bulk elasticity of the cell. Similar to the π-cell [19], parallel aligned directors lead to a horizontal state when the pre-tilt is low, where the director predominantly splays from one surface to the other, with the central director being parallel to the cell plane. If the pre-tilt is much higher, a vertical state is formed, where the director is predominantly bent from one surface to the other and the central director is normal to the cell plane. The Cheng and Boyd invention relied on achieving intermediate pre-tilts (claiming between 22.5° and 67.5°) where the elastic energy of the splay and bend states are approximately equal. Alternating the pre-tilt directions across the surface gave disclinations that would pin either the vertical or horizontal state after switching with a two-frequency nematic liquid crystal. No alignment layers were available with such high pre-tilts, so Cheng and Boyd cleverly tilted the surface itself to form a saw-tooth grating on each surface, each with planar alignment in the direction normal to the grooves. The grating needed a pitch similar to that of the cell gap (~10μm) and an aspect ratio of about 0.5. The top and bottom surfaces needed to be in-phase, to form a series of square cross-sectioned containers for the liquid crystal.

ZBD was clearly different. Bistability arose from a single surface alone, a surface that could be used opposite any other conventional alignment surface and still give two stable pre-tilts. The deformation of the liquid crystal was restricted to the vicinity of the surface, and decayed to become a uniform director profile within a distance typically about half of the grating pitch (i.e., within half a micron, figure 1). One of the bistable states was continuous, and did not exhibit disclinations close to the grating peaks and troughs. Latching was achieved by coupling a DC field to the flexoelectric terms induced by the near-surface deformation. The patent examiners in all of the major countries where the patent was filed agreed with these arguments and, after delaying grant for as long as I dared to allow a series of protective divisionals [9], the US patent was granted in March 2004.

3. "I'll give you five million dollars"

The search for commercial funding meant that visiting the Society of Information Display conference in the US became a yearly ritual. There is a large trade show alongside the conference, where exhibitors market new display related technology, from early prototypes to that year's main product launches. The 1998 conference was held in Anaheim, California, and the *DERA* Displays Group took a booth. Alongside sales material relating to DERA's Ferroelectric Liquid Crystal TV technology [3], VCT, [6] and the reconfigurable holographic display based on the *Active Tiling* of an FLC Optically

Addressed Spatial Light Modulator [20], was the 1" diagonal ZBD demonstrator. Each of these innovations garnered interest, but I was particularly struck when demonstrating ZBD to the effervescent Nick Darby from *Dow Chemical Ventures*, when he volunteered "I'll give you $5M for that technology". I pondered this for several days during the course of that conference. Sitting next to Bryan-Brown on the return flight home, I suggested that we leave DERA, seek venture capital funding and form a spin-out company; Bryan-Brown immediately agreed to join me and the process was begun.

I do not believe that forming a spinout company was a novel idea within *DERA* at that time. The peace dividend had brought a constant move towards commercial activity and the private sector. Some years earlier, the Chief Executive, John Chisholm had written to all staff stating that there were no plans to privatise *DERA*, which initiated the rank and file within the organisation to that very concept. In the Electronics Sector, to which the Displays Group was part, Superintendent Norman Apsley had set up a team to evangelise and enable these commercial activities. I met with Apsley on my return from SID and told him of my plan: he was instantly pleased and put me in contact with Robin Godfrey, who was leading the commercial exploitation team. Under Godfrey's tutelage, Bryan-Brown and I toured various UK venture capitalists. All were interested, but none more so than Dr. Rob Hook of *Prelude Venture Capital* in Cambridge. In late 1998, he was the first to put an offer to *DERA,* having formed a consortium of investors including *Dow Chemical* from Michigan, US (perhaps Nick Darby had been serious after all) and *The Technology Partnership (TTP) Ventures* from Royston, UK.

The ensuing negotiations were to take over eighteen months. Having neither funded the original work nor subsequent proposal submissions, the *MoD* still had to be convinced that ZBD had no Defence use. Moreover, the proposition that inventors use their invention to form a spinout company of which they would receive a share prompted investigation by the UK *National Audit Office* to determine whether it was right for civil servants to benefit personally from taxpayers' money. The spinout could not have been possible without the founders declaring that they would leave *DERA* regardless of the outcome, and that *DERA* would therefore lose all knowhow associated with what would then become a useless technology. The period 1998 to 2000 was the height of the 'dot-com' boom, and we were certain that the on-going delay would be seriously detrimental to the technology's potential. Moreover, competitors *E-ink* and *Nemoptic* had been formed from the electrophoretic displays team at *MIT* and Durand's team at *Orsay*, respectively. Time seemed to be running out – even now, two decades later, that delay seems to have been fundamentally damaging. The founders were particularly attracted to VC Bob Hook: he is a very sharp-minded yet agreeable character, with years of experience as a Director at *Cambridge Consultants* in the 1970s, before founding *Prelude Venture Capital* in 1984. What set Hook apart as an investor was his patience: it was not until May 2000 that

DERA was ready to begin the final negotiations, deploying Commercial Director David Steeds to manage the transactions on *DERA's* behalf.

During this time, Hook had asked to be introduced to the full ZBD team. This included Emma Wood, Pete Brett, Jon Hughes and manager Alistair Graham. I was uncertain that we all needed to join the company, but Bryan-Brown was adamant. Hughes was nearing retirement and so the risk proved too much, but Wood, Brett and Graham all wished to make the leap. After agreeing our individual shares, I entered into negotiations with both *DERA* and the venture capitalists. Negotiations were more difficult with *DERA* than the VCs. Typically for such large organisations (20,000 research scientists and engineers), several different objectives needed to be satisfied. The business unit's position was similar to that of the venture capitalists: their aim was to maximise future value, balancing the equity share appropriately to ensure the founding team remained motivated without setting unrealistic expectations for future spin-outs. They attempting to speed the negotiation to the earliest settlement. Senior Management at *DERA* believed that there would be many instances of future spin-outs, and so timing was less important; the priority for them was to set the correct precedent for those future entities and minimise the benefits to both VC and founders. There was some confusion over whether the future privatisation of *DERA* would benefit from a demonstration of the ability to create successful spin-outs, or whether its own value would be perceived to have been reduced through loss of control of successful technologies. Lastly, the local management of the Displays Group had a different view too. They saw no advantage to losing key staff, equipment and future projects, and were reticent about the process.

Whilst negotiations proceeded, we needed to give the nascent company an identity. I was devoid of good ideas for the company name: Zenithal Efficient Displays (ZED); Malvern Displays; Green Displays. Eventually, Hook suggested that we already had a good name with ZBD, and that the company should be called *ZBD Displays Ltd*. Settling on this compromise (I remain uncomfortable with the repetition of the D for Displays) we founded the company on 27th July 2000, becoming the UK Civil Service's first venture backed spin-out company, figure 3.

The company relocated to the recently formed Malvern Hills Science Park, adjacent to the *DERA* Malvern site. This enabled us to continue to access the laboratories within *DERA* to do fabrication work. Alistair and I had a small laboratory area by the offices, to do electro-optic work, addressing and electronics. The hard work was about to begin.

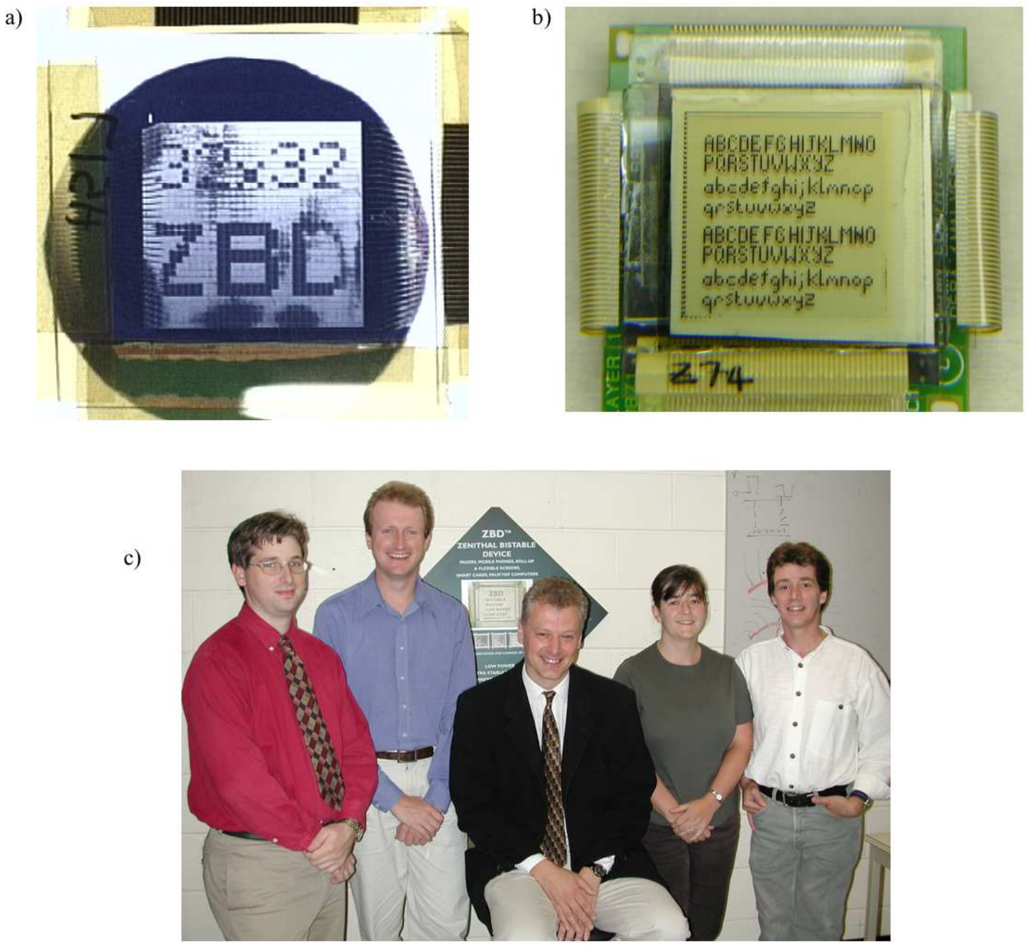


Figure 3 Founding of the company: a) The original 32 x 32 ZBD Demonstrator shown at SID 1997 worked in transmission; b) The ZBD Displays Ltd. Founding team on the day of spinning out (Alistair Graham, Guy Bryan-Brown, Cliff Jones, Emma Wood and Pete Brett); c) The 2000 1" diagonal 90 x 83 demonstrator working in reflection but still with the VAN configuration. It was designed to mimic the screen for the Nokia 3310 mobile phone, but with higher resolution

5 Licensing

By 2000, full colour LCD monitors were beginning to make inroads against the incumbent cathode-ray-tube, and laptops were growing in complexity and performance. However, LCD could not achieve video frame rates and replacing CRT in TV looked unlikely, particularly since Plasma Display Panels seemed a better choice for high-end flat-panel TV. The mobile phone market was beginning to become a significant industry driver, but the constituent displays were still Black and White with limited information content, based mainly on STN. Rather than carry an expensive mobile phone, many still had pager units that would receive text information only. A new device, enabled by STN, was the Personal Digital Assistant (PDA), a precursor of today's tablet or smart phone and best exemplified by the *Palm V*. This product, released in March 1999, had a 160 x 160 pixel monochrome STN display, and allowed pen input using a basic resistive touchscreen. The battery for such products was relatively large, typically weighing 270g with only 650mAh charge at most, yielding only 10 – 12 hours use even when the display backlight was turned-off and the STN operated in reflective mode. As remains pertinent today, reflective colour displays were too dim for normal operation. The performance of TFT for reflective, monochrome LCD was not sufficiently better than STN to warrant the large increase in cost that it would then have involved.

The inherent ultra-low power for the bistable ZBD was a natural fit for such applications. Moreover, the ZBD reflectivity, contrast ratio and viewing angle greatly surpassed that of STN. The latching threshold of ZBD allows a line of information to be written using a conventional 20V STN driver within less than 1ms, but because the information is then latched until the next time an addressing signal is applied, there is no limit to the number of lines that can be addressed. Unlike STN, for which fabrication limits prevented commercialisation of much more than 240 lines of information, ZBD displays of 1000 rows or more were readily achievable, albeit for a 1s frame rate. As with the other passive matrix TN and STN displays, ZBD had design flexibility of shape, form factor and image content, needed for many niche markets where the expense of tooling TFT was prohibitive. However, ZBD offered the superior optics to STN, ultra-low power and, if the grating could be made cheaply enough, a display price similar to STN. This estimate was based on the facts that ZBD had the manufacturing tolerances of TN but used an STN driver and liquid crystal and that ZBD did not require compensation films but needed the grating to be fabricated.

Although TFT themselves remained prohibitively expensive for many low-cost applications, plastic displays presented severe problems for TFT and seemed condemned to low image contents provided by segmented displays achieved with passive matrix TN. The temperature limitations and yield issues associated with a multi-mask lithographic process on substrates that would swell at each step seemed destined to prevent TFT from being applied to plastic. Plastic ZBD would not be threatened by STN either due to the high tolerances for surface flatness and accurate cell gap STN needs. Not only did plastic ZBD promise rugged, lower weight and thinner displays ideal for portable products, and therefore provide a route into those markets, but novel applications were possible. Amongst these was the smart-card display, including secure credit cards where the number changes after each transaction; subway or travel cards that display the available credit; loyalty cards that show the number of points accumulated; membership cards with the renewal date indicated; driving licences that show the number of points accrued. Ideas for new applications for zero-power plastic reflective displays flourished: price tags; name tags; conference badges; airline tickets with barcode, gate and boarding time; medical indicators; Kanban tracking of products through a factory; floor tiles that indicated routes for individuals through large buildings and hospitals, interactive toys and game; SmartMedia cards (or what would now be flash-memory sticks) with displays incorporated to name, indicate content and available data space; a car key fob, indicator to show whether the car had been locked and the fuel level status. There were so many potential applications that McDonnell could have been excused for once claiming that "*by 2020, you won't even remember what paper was*".

One of the first things that an entrepreneur must consider is the business model. The great variety of potential applications naturally suggested a licence approach for *ZBD*. This model has low upfront costs and could produce high profit margins. Typically, a company might expect 3% to 5% on all display sales by the LCD manufacturer, although this level is required for all of the licenses needed for the product, so would usually be somewhat lower. Naturally, higher revenues become possible if licences can be won for the final product and not just the display component. Where ZBD was tackling STN replacement, such as in mobile phones or PDA, licences from the component only would still be competitive due to the high sales volumes. For the more esoteric products where ZBD was the enabling technology, the possibility of more valuable product licences could be explored. The patent portfolio had to be strengthened, and so divisionals on the primary patent were filed, eventually providing for *any* LCD with a bistable surface where at least two of the stable states were in a plane that included the surface normal. Of the seven initial filings, the portfolio was increased to a total of twenty patent families, and the term ZBD was granted as a registered trademark.

The company also began to court interest from potential users of the ZBD technology. *Swatch* were working on a smart-watch project with *Microsoft* and needed a low power display capable of showing graphical content. Israeli electronic shelf-edge label (ESEL) manufacturer *Eldat* saw the potential to add graphical output to their IR driven ESEL system that were popular in supermarkets across Europe. This early interest seemed to justify our choice of the licensing business model.

Our most important tasks of this period were to recruit an experienced CEO. Despite a thorough search with a technology head-hunter, we still had not found the right candidate by January 2001. A strategy session was held close to the *Prelude* premises in Cambridge that month, with a number of contributors brought in to help ensure a wealth of new ideas. These included Henri-Luc Martin from *Dow*. He had just finished a project on anti-counterfeiting of DVDs and was seeking a new opportunity. He immediately made a good impact on investors and team alike, and was soon offered the CEO position. Henri-Luc is highly energetic, something he needed to be in the ZBD post: he retained family commitments in Midland, MI and so commuted monthly to Malvern, working a full and busy week there, before returning to the US and more conventional hours. With the recruitment of company chairman Colin Garrett, an experienced CFO Richard Scanlon, and the strengthening of the technology team through the addition of Rich Amos and Steve Beldon, the company was set to begin raising a more serious funding round in August 2001.

A main conclusion of the January 2001 strategy meeting was to focus on one product and deliver the best demonstration of ZBD's capabilities. Many potential markets were considered: I particularly favoured either the smart watch or ESEL, because of the commercial interest we had already received for these two products. However, the consensus view was to concentrate on the E-book reader (EBR) market. Today, after the success of the *Amazon Kindle*, this product choice seems clear. However, at that time, EBR displays were limited to rather poor demonstrators based on the bistable cholesterics, with a yellow on black appearance that was rather difficult to read and unlikely to compete against paper. ZBD aimed to compete with a B&W 7" diagonal display that had a very high resolution (for that time) of 200dpi resolution, to help make the reading experience as close to paper as we could achieve [22]. The low cost of the display was to be emphasised by including two 7" panels hinged together in a book-like form, partly to protect the glass, but mainly to attract the book lover to our product, figure 4.

Whilst the team concentrated on producing the EBR demonstrator, CEO Henri-Luc Martin, CFO Richard Scanlon and I concentrated on writing a business plan. Throughout August and September 2001, we struggled to put this thinking into a coherent plan, working hard together, both in Malvern and Michigan, to raise the £5M or so needed for our next stage. We believed that we needed a dual-pronged approach to our model, targeting large existing markets such as mobile communications to ensure that the licenses were sufficient, whilst realising that accessing the niche markets enabled by ZBD could yield much higher margins. Like a clarion call heralding the end of the technology (dot.com) boom that had occurred around the *fin de siècle,* the *Al Qaeda* inspired atrocity in Manhattan and Washington DC on 11th September 2001 had a far bigger effect than our individual efforts could make. Perhaps it was not just the technical downturn: our model lacked focus, with potential investors failing to believe that we could both (or either) transplant STN from its incumbent market lead and introduce new products such as smartcards and EBR, when there was no infrastructure for us to supply into. Whichever the cause, our fundraising efforts failed despite touring much of the venture capital community across the UK, Europe and occasionally the US. We relied on our existing investors *Prelude*, *TTP* and *Dow* to fund our next stage. On reflection, this failure to attract new money must have preyed on our investors, and caused both CEO and CFO to leave within eighteen months. Blame did not seem to be directed to me or to the technology. By mid 2003, the investors decided to elect me to the Board and promote me to become Chief Technology Officer, CTO.

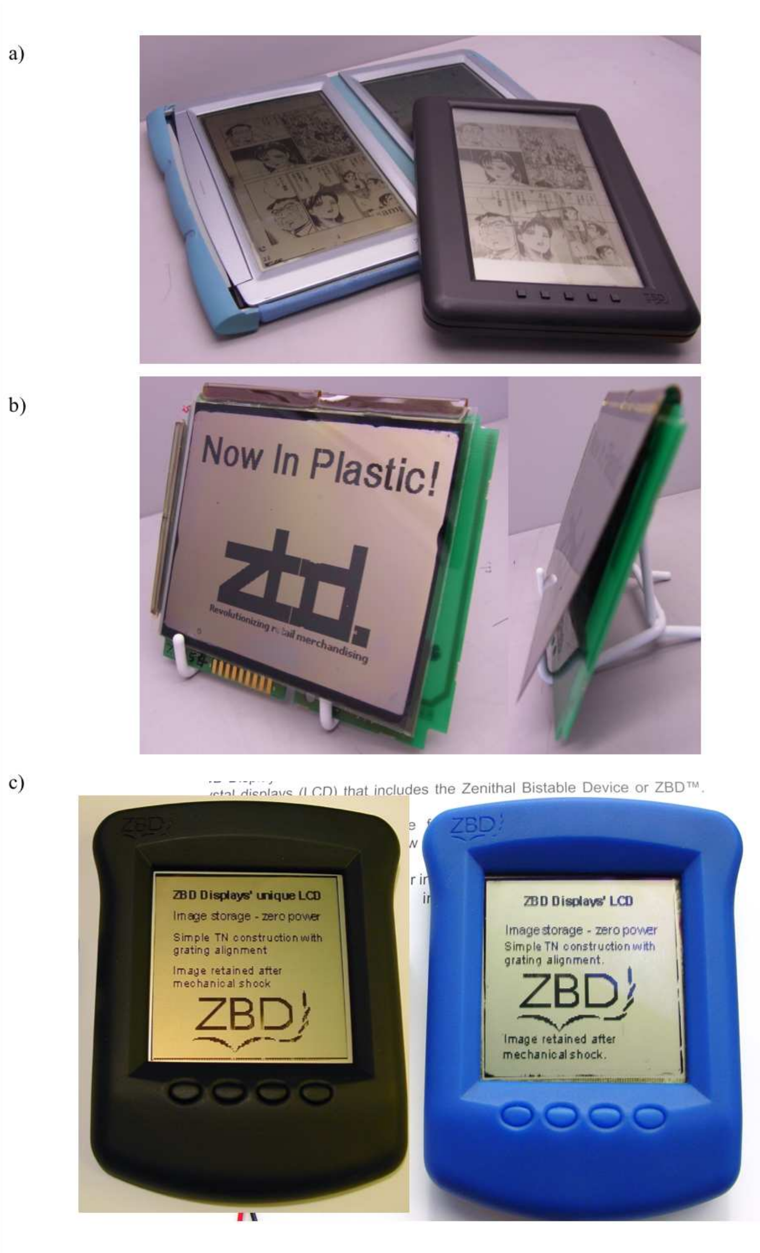


Figure 4 Progress made during the first two-years. a) Two page ZBD E-book Reader (Z-book) concept and the 7" demonstrator. These were among the first demonstrators to include the TN ZBD variant. b) Plastic VGA display [21]. c) Improvements to the optics and manufacturing dominated the R&D in this period, represented by move from the black to blue demonstrators as shown. The use of embossing for the demonstrator on the right allowed a transparent photopolymer and the improved, near sinusoidal grating shape with low pre-tilt and consequently wider viewing angle. These early prototypes used a display that mimicked that used in the *Palm V* PDA.

During the period 2002 to 2003, we relocated to much larger premises on the Malvern Hills Science Park. We built a large clean-room, divided between a Class-100 production room with Class 10 areas, and a Class 1000 for R&D. Above the cleanrooms are the offices, meeting rooms and a large well equipped laboratory for electro-optic assessment and display characterisation. This site remains part of the company today, and at its height housed twenty-five scientists and engineers. The company began to become better organised, with me overseeing the technology, Graham in charge of the electronics, Brett running the Cleanroom, and Scanlon running all operational aspects, leaving Martin to manage the investors, potential collaborators and partners, and overall strategy. A product development manager Manoj Thanigasalam was recruited from the electronics industry. Soon after, Graham left the company, being replaced by a team of electronics consultants with whom Thanigasalam had worked previously.

The product related technical work began to concentrate in a number of important areas [23]:

1. Gratings were still made directly onto the display glass using photolithography, but we found an improved photoresist that removed a yellowish tinge to the white state (compare figure 3c with the improved photoresist of figure 2b).
2. A team began to be recruited to move grating fabrication to the more practical and ultimately low cost method of embossing.
3. Our work with *DERA* theoretician Victor Hui had shown that the pre-tilt of the D State depended on the ratio of the closest separation between defects on the surface to the surface integral of the grating across a full pitch [13]. Greyscale might be possible through the movement of defects to different pinning sites on the side of a more complex shaped grating, thereby stabilising different pre-tilts. This approach, however, proved impractical and simple pitch modulations were used instead [24, 25]. Greyscale became a major theme of this period, culminating in the demonstrator shown in figure 5. Several inventions were made including the use of fractional dither weightings when combining digital and analogue grey levels [26] and optimised grid patterns for the areas of differing thresholds that negated the requirement for accurate registration between grating and electrodes [27].
4. A more important consequence of the Hui theory was the implication for achieving lower pre-tilts for the D state. The best viewing angle for the TN configuration requires a low pre-tilt, one just sufficiently high to ensure that one sign of tilt and handedness of twist always results after a switching event (as with any TN). The C to D transition is

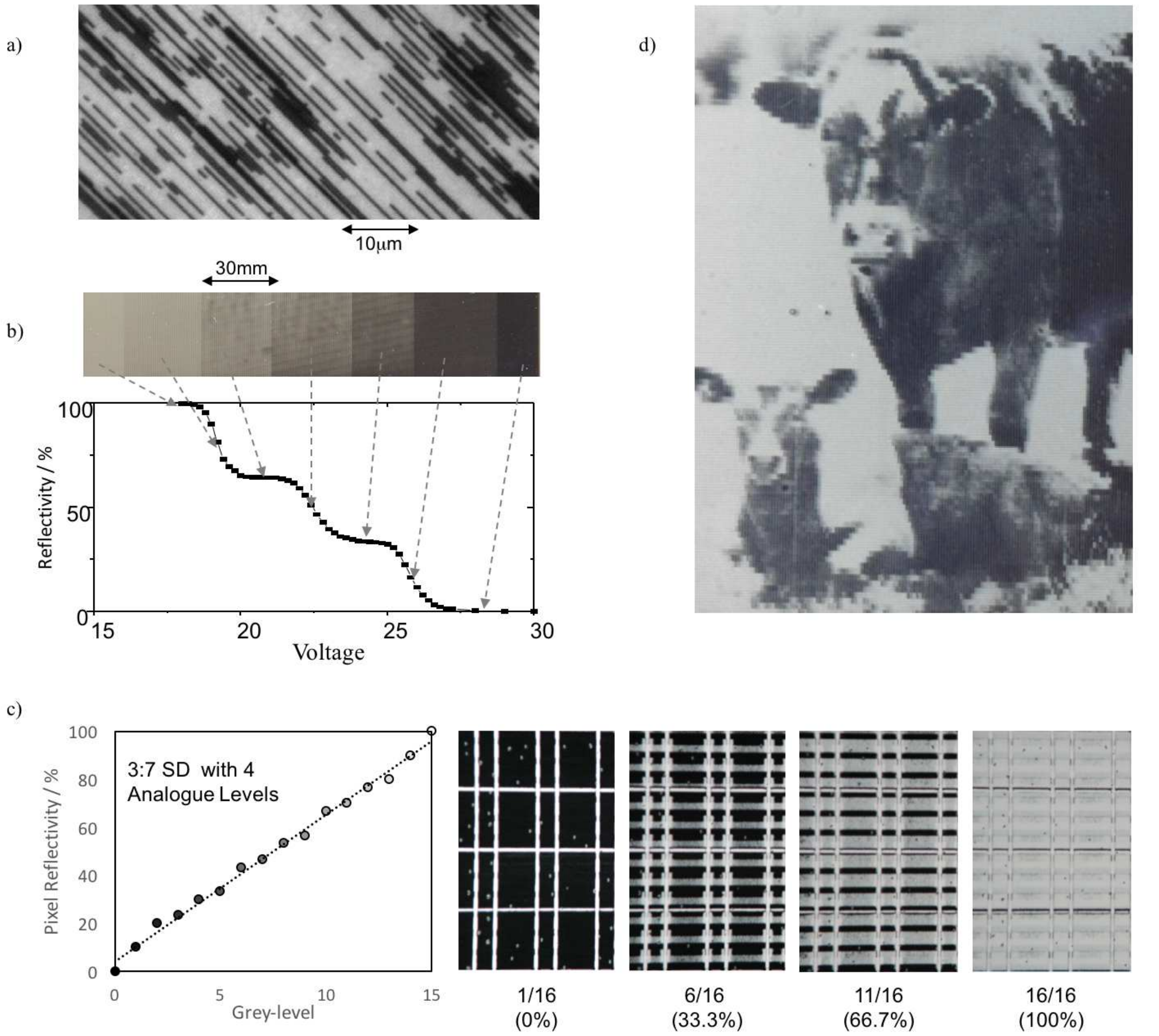


Figure 5 Greyscale in ZBD [25]. a) As with most bistable LCD, the latching transitions have partial latching where microscopic domains of one state are stable in the other. As shown, ZBD domains follow individual grooves, and so can be a few square microns in area. b) The threshold voltage can be controlled by small changes in grating pitch. Here pitches of 0.6μm, 0.8μm and 1.0μm are used to produce three thresholds and four analogue grey levels. Combining this with one 50% partial latched level for each pitch gives seven greys, shown over a 5" diagonal panel. c) Higher greys are achieved by combining analogue levels with spatial dither. The demonstrator shown in d) has sixteen greys using four analogue levels from the different pitches, and two spatial dither bits on the columns. Rather than use the standard 1:4 dither which is optimum for 4 analogue levels, a fractional 3:7 spatial dither was used [26] to reduce line losses in the least significant

mediated by the nucleation of a ±½ defect pair at the steep-edges of the profiled surface. Symmetric gratings lead to two defect pairs being nucleated on either side of the grating peak when the field is applied; although the equivalent polarity defects are favoured by the surface curvature (- ½ to the grating peak and + ½ to the grating trough), the two like defects from opposite sides of the grating repel each other and prevent the Defect state from stabilising. Thus, some asymmetry or blaze is always required for latching between the bistable states to be effected, asymmetry that inherently gives some pre-tilt to the Defect state. The easiest gratings to fabricate are square in cross-section. Near-square gratings give very high pre-tilts, since the closest separation of the opposing defects is less than half of the surface integral (or simplistically, half the pitch). This leads to pre-tilts of between 30° and 50°. The optimum shape is as close to a sinusoid as possible, as shown in figure 6a. This gives a single concave and convex point of curvature per unit pitch, each close to half the pitch away from each other, and therefore with a low pre-tilt. In this instance, the pre-tilt is dictated solely by the blaze angle, and can be as low as 3° - 4° without losing bistability. Fabricating such a shape controllably and reproducibly took a major effort, and the solution includes significant company know-how.

5. An important attribute of ZBD operation is that it works using standard nematic liquid crystals. The use of flexoelectricity in the latching mechanism might imply that mesogens with wedged or bent shaped molecules would be advantageous, to maximise the sum of the flexoelectric coefficients e_1 and e_3, respectively. Assuming the elastically deformed director profile near to the grating surface decays to a uniform orientation at about a pitch length P from the bottom of the grooves, the latching time is may be estimated from:

$$\tau \sim \frac{\gamma_1 P d}{(e_1 + e_3)V} \approx \frac{(0.2Nsm^{-2}).(10^{-6}m).(5.10^{-6}m)}{(10.10^{-9}Cm^{-1}).10NmC^{-1}} \approx 10\mu s \qquad (1)$$

In practice, the type of deviations to the calamitic rod-like shape that might increase $e_1 + e_3$ would likely also give a deleterious increase of the twist viscosity γ_1. This means that the best route to low voltage or fast operation is through increases to $e_1 + e_3$ through increases of the molecular dipoles. Thus, many of the same design rules for optimising STN liquid crystal mixtures apply. From 2001 to 2004, *ZBD* worked closely with *Merck* in Southampton UK to produce mixtures tailored for the bistable device. Particularly high values of $(e_1+e_3)/\gamma_1$ were found for highly polar compounds such as PZU-V2-N shown in figure 6b. A series of low voltage, fast switching mixtures were made using such additives [28 – 30] leading to 20V latching times of around 500μs, figure 6c. This work on highly flexoelectric liquid crystals went further than that required for simple ZBD devices, defining mixtures with low birefringence for operation in single polariser mode ZBD [31] and low conductivity mixtures for use in dual-mode ZBD when driven by TFT [32].

6. Reflective LCD are formed using a rear polariser combined with a diffusive aluminium or silver mirror. Image parallax occurs, wherein shadowing around the image occurs because the mirror is separated from the image plane by the thickness of the rear glass. This was minimised in later ZBD products by using an asymmetric display design, with 0.6mm glass at the rear, and protective 1.1mm glass as the front plate. However, reflective colour requires all image parallax to be removed and the reflectivity to be maximised. These requirements in turn required that a single- polariser geometry is designed, enabling use of an internal mirror on the rear plate, and reduced absorptive losses associated with the second polariser. In such a geometry the D state is arranged to the quarter-wave condition to give plane polarised light oriented at 90° to the front polariser after traversing twice through the material [33]. Making the internal mirror semi-reflecting also allowed transflective devices to be produced.

Soon after the original ZBD patent, I had realised that a surface that was inherently bistable could be applied opposite any other surface to provide a variety of novel devices. For example, a ZBD grating arranged to give the defect state parallel to an opposing high pre-tilt monostable surface could form a π−cell [35], where the bend state would always form after latching into the D state from the high-tilt C state. Alternatively, two ZBD surfaces could be used opposite each other, to allow latching between a vertically aligned state and the low tilt TN state [35]. This arrangement is ideal for transmissive devices, where both the VAN and TN states have wide viewing angles. Because the electric field inverts at the opposing surfaces, gratings with different thresholds are needed to allow independent addressing when the appropriate signal sequence is applied. The use of standard liquid crystal arrangements, such as the TN, also means that the ZBD can be used in a dual-mode [36], either continuously updated or selectively latched and the image stored. For example, combining a ZBD surface opposite an active matrix TFT plate allows full-greyscale video

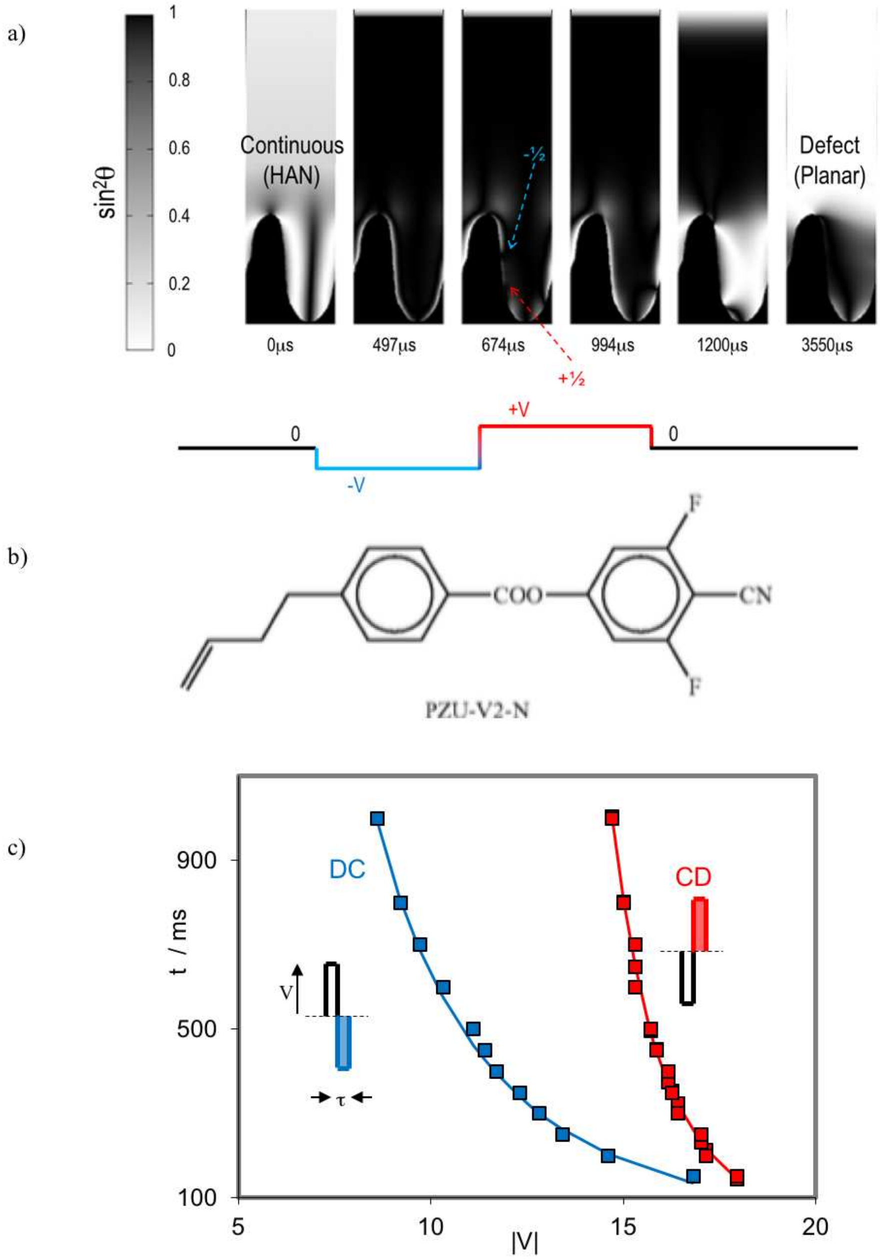


Figure 6 ZBD Latching. a) c) Theoretical modelling of ZBD latching done in collaboration with Care and Spencer [34]. The model used a Lattice Boltzmann model to solving the 2D dynamics, and the Qian-Sheng method for dealing with defect creation and annihilation. b) Example of a low viscosity compound with high flexoelectric coefficients [29]. c) Latching characteristic for proprietary Merck mixture MDA-1551 in a 5μm spaced VAN- HAN cell at 25°C.

images to be displayed when the grating is latched to the Defect state (i.e. the TN geometry) but can then can be latched into a bistable or storage mode to show the image (albeit with reduced grey-levels) but without further power use. Applications such as digital cameras and mobile phones were well suited for this and in 2003 *ZBD* worked with a multinational consumer electronics giant in Japan to deliver a TFT driven dual-mode ZBD demonstrator.

6 "Fabless" Manufacturing

The original technical plan used to form the spin-out company listed a variety of commercial manufacturing methods used in the Si IC industry that had the potential to fabricate sub-micron pitch gratings onto the inner surface of an LCD. These methods included projection photolithography, holographic lithography and hard-contact photolithography. However, right from the outset both McDonnell and Bryan-Brown had realised that the lowest cost route to fabrication would be an embossing technique, similar to that used to stamp the holograms onto paper currency.

The ZBD grating presented several challenges. The low-pitch (800nm) gratings are deep (1080nm) and require accurate reproduction of the blazed sinusoidal shape. This discounts the use of conventional hot-foil embossing techniques and required a photo-embossing method to be developed, similar to that used for optical light guiding films on road-signs or holographic wrapping paper. Perfecting the solution for this took several years, involved most of the technical team and scientists from several suppliers, but was especially due to the efforts of Guy Bryan-Brown, Rich Amos and Emma Wood.

Of particular importance for operation in an electric field-driven device is the minimisation of the grating "offset": any unwanted layer of dielectric material between the bottom of the grating grooves and the indium tin oxide (ITO) electrodes. Not only would such offset increase the operating voltage but, more importantly, minute variations would limit the addressing window of a practical display. For small offsets Δh, the maximum variation in the applied voltage ΔV is approximately:

$$\Delta V \approx \frac{\varepsilon_G \varepsilon_{||}}{\left(\varepsilon_G d + \varepsilon_{||} \Delta h\right)} . \Delta h . V \qquad (2)$$

Typically, the cell gap d is about 7μm, $\varepsilon_G \approx 4$, $\varepsilon_{||} \approx 50$ and the operating voltages V about 20V. Equation (2) predicts that only 50nm of offset variation would change the voltage by 0.7V.

As with all bistable LCD, [37], ZBD is addressed a line-at-a-time by applying a strobe voltage V_S to the addressed row synchronously with data of appropriate polarity $\pm V_D$, whilst holding all of the other non-addressed rows at 0V. Each pixel on the addressed row either experiences a high resultant voltage $V_S + V_D$ or a low resultant $V_S - V_D$. Setting the strobe V_S midway between the onset and completion of latching ensures that the data discriminates between pixels that need to change, and those that do not. No latching occurs on any of the other rows, where the resultant is $\mp V_D$, until the strobe scans onto that line and the new, appropriate data applied to the columns simultaneously. Usually [37], the addressing pulse has one polarity (for example, a positive pulse with respect to the grating may induce the continuous to defect transition) and is preceded by a blanking pulse of the opposite polarity. The blanking pulse is of sufficiently high voltage that one state is selected regardless of the data being applied. In that way, a line is blanked into one state, and then either latched to the opposite state or not during the addressing period. A panel will suffer variations in the latching voltages, perhaps through a change in temperature from one side to the other, or perhaps inherent to the panel itself (such as that caused by Δh, or resistive losses along the electrodes). Equation (1) indicates that the latching voltage is temperature dependent (related to $[exp(1/k_B T)]/S$). Although difficult at low temperatures, changes of the addressing signal due to changes of temperature should be minimised. For example, the temperature sensor incorporated into the ZBD driver ASIC has an absolute accuracy of $\pm 5°C$. In these circumstances, it is important to provide sufficient data voltage so that:

$$V_d \geq \frac{(V1)_{MAX} - (V0)_{MIN}}{2} \quad (3)$$

where V1 is the voltage required for complete latching to the selected state for a pulse width τ and V0 is the onset at which the first sign of latching can be seen. The subscripts MAX and MIN refer to the points on the panels where the voltage is maximum (for example, at the lowest temperature and with the highest Δh) and minimum (highest temperature and zero Δh), respectively. Not only must the addressing cope with these variations across the panel but across all panels output by the production line, usually with minimal testing. Using a high data voltage to maximise the operating window increases the power usage of the display. Moreover, for large displays, the data applied across the long frame time could cause unwanted latching to the C state through the effect of the RMS voltage coupling to the positive $\Delta\varepsilon$ of the liquid crystal. In practice, data of about 5V is used and the temperature range maximised by minimising variations of grating shape and consistency, and ensuring fabrication gives no offset (Δh <10nm). Steve Beldon and his team collated results from many hundreds of displays, from 2" to 7" diagonal panels, from batches made over several years to develop addressing schemes that worked across the widest of operating ranges.

The basic route for grating production is to replicate a perfect grating millions of times using UV embossing [38]. The process, shown in figures 7 and 8) begins with creating a master grating in a dedicated Class 1 area in the Malvern cleanroom. This is

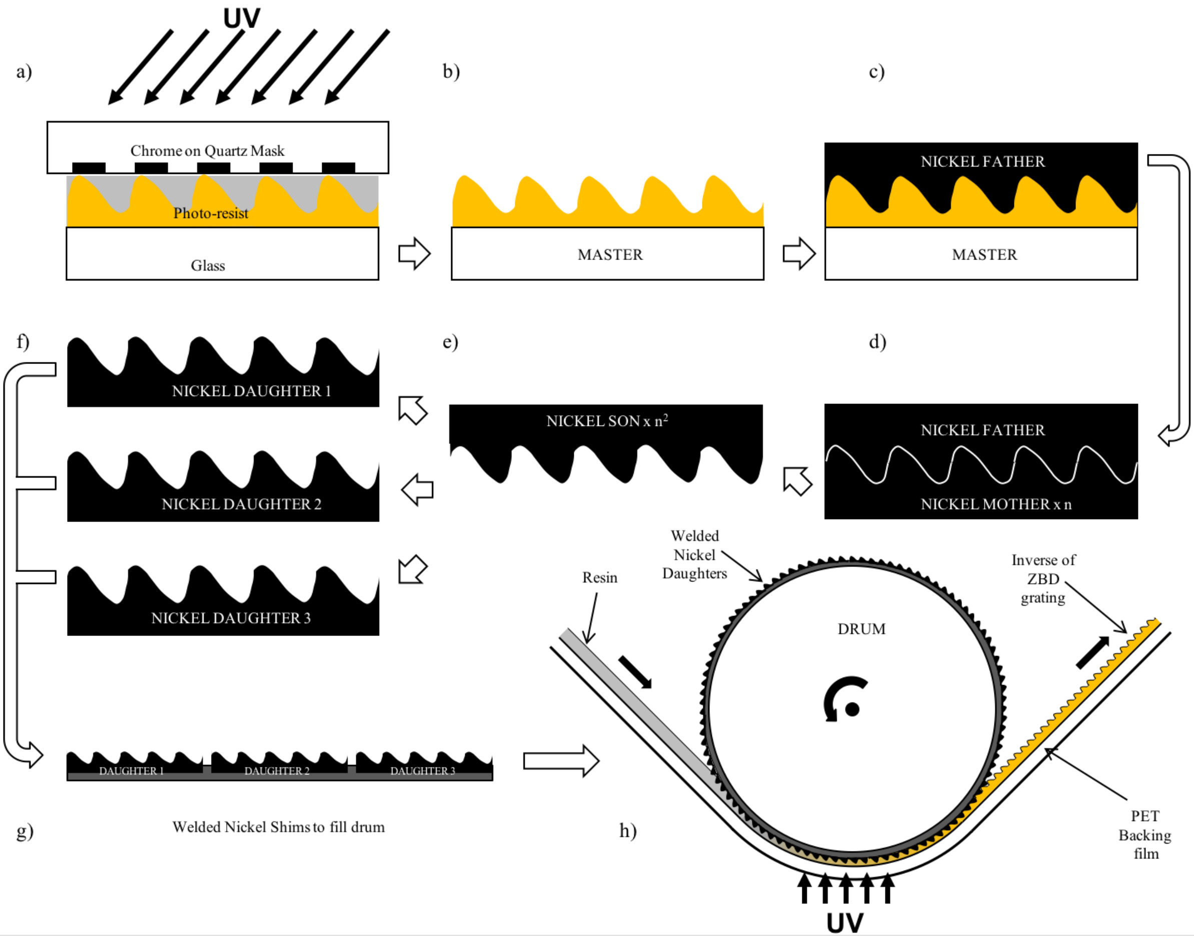


Figure 7 Production of the ZBD embossing film for use in grating manufacture. a) Direct contact photolithography into a photoresist using collimated DUV and a chrome on quartz mask. Blaze is produced by illumination at a slight angle. b) Once developed, the completed master is inspected for any defects, uniformity and the correct shape from the first order diffraction colour. c) Nickel alloy is sputtered onto the master surface and then used to electroform a nickel Father. Once complete, the original master is removed (and destroyed). d) The Father grating is used to produce a number of Mother shims by electro-forming. Adhesion between shims is prevented by the nickel oxide that forms on exposure to air. e) Each mother can form Sons, and in turn, f) each Son to produce many Daughters. g) A number of "female" generation shims (here daughters) are welded together to form a much larger shim. h) The welded shims are mounted onto a drum which is used to UV emboss into a resin spread onto a PET backing film. The final grating on the film has the "male" grating shape.

formed in a photo-resist layer spin-coated onto a glass using hard-contact photolithography. The resist is exposed to a 248nm wavelength collimated Deep UV source through an 8” chrome-on-quartz mask, with the appropriate mark-to-space ratio and slip pattern pre-defined. The near-sinusoidal shape was achieved by careful selection of the photo-resist, together with control of the multiple UV exposures and thermal sequences. Blaze is introduced by illuminating at a fixed angle of about 4°. The depth of the photo-resist was sufficiently high to prevent the groove troughs from becoming square which happens when the etching reaches the underlying quartz. This depth played little other role in the grating design. More important factors were the lack of dust in the process (since defects would un-necessarily be repeated throughout all displays) and grating uniformity. These were checked, respectively, using manual inspection and by measuring the zero-order diffraction colour for transmitted white light and comparison to both theory and SEM results from previous samples.

Once a perfect master is fashioned, it is shipped to a DVD supplier who copies it into a Nickel shim by first sputtering an atomic layer of Ni alloy onto photo-resist surface, and then electroforming a nickel backing to form a 300μm to 500μm thick *father*. The *father* shim is peeled away from the original photo-resist master, which is then discarded. After washing unwanted photo-resist from the shim, it is then used to electro-form many copies, called *mothers*. Separation of nickel shims from each other at each electro-forming step is easy because of the oxide layer that forms on exposure to the air. Indeed, this process can be repeated from the *mothers* to form *sons*, and to form *daughters* from these *sons*, etc. Each “male” element of the family would have the reflection symmetry to the original master, whilst “females” would replicate it (nearly) perfectly.

It would then be possible to use the nickel shim directly at the LCD production line, to emboss into photo-polymer onto the glass. However, because zero-offset is required, this could lead to shim damage as the nickel is pressed into close proximity to the glass under pressure. Dust or other particulate on the mother-glass surface would create high-pressure spots that would permanently damage the nickel shim, forming repeating defects on all subsequent displays. Moreover, this particulate would cause “tenting” of the shim[c], leading to large circular areas of offset around the central dust particle. Such ‘ringed-offset’ defects would

[c] Tenting refers to the deformation of the shim around the particle. A rigid shim would deform only slightly, bending around the particle to touch the glass surface at a large distance from the particle. A flexible shim, such as film, deforms elastically either side of the particle, touching the surrounding surface much closer to the particle. The size of the region of offset around the particle is directly related to both the size of the particle and the rigidity of the shim.

easily be noticeable in the display, as evident from equation (2). These problems are resolved by introducing an intermediate step into the fabrication, wherein the nickel is used to stamp the grating into a UV-hardened resin layer coated onto backing film, figures 7 and 8. This film is then shipped to the LCD manufacturer and used to emboss the grating directly onto the glass. Because the film is flexible and embossing is done under pressure, most particulate that occurs either at the film or display manufacturing steps is embedded directly into the resin or photopolymer without significant tenting. A 5μm particle might lead to a sub-50μm 'ringed-offset' defect, which would not be visible on the display or effect performance in any significant fashion. Note, because of the film step, a "female" nickel shim gives the "male" shape on the film, thereby leading to the desired "female" grating shape on the mother-glass.

Although possible to use each sheet several times, the cost of the film was sufficiently low to allow single use embossing [38]. This allows a simple two-step process where the embossing and UV curing steps are separated. First, the photo-polymer is deposited onto one end of the mother-glass, film is placed over the glass and the laminate put through an embossing roller. This squeezes the liquid photo-polymer along the grooves, allowing the grating groove tops to touch directly onto the ITO and ensure zero offset: Δh <<10nm. There is a range of plate speed S and roller pressures (in turn related to the Young's modulus of the roller rubber coating E, the force applied per unit length W and the roller radius R) that meet this condition perfectly. The upper limit of speed (lower pressure limit) is the point at which the offset increases above zero, found empirically to be governed by the relationship:

$$\Delta h \sim \frac{(\eta S R)^{0.6}}{E^{0.4} W^{0.2}} \qquad (4)$$

where η is the viscosity of the photo-polymer before cure. The low speed / high pressure limit was set by the resin hardness, where distortion and catastrophic collapse of the grating structure occurs. Optimising the process and resin material allowed the speed target to be reached, wherein each plate is embossed and cured at a similar rate to the conventional rubbing process, thereby maintaining the same process *Takt* time and allowing the ZBD process to fit within an STN production line.

Once the roller has passed from one side of the glass to the other, the film is held in place by capillary action. After UV curing the laminate, the film is peeled away. In addition to being simple, this approach also allows the grating to be automatically patterned onto the glass using selective adhesion [39] as shown in figure 8. The grating must be deposited only onto the viewing areas, avoiding the glue-seals and bonding ledges. Using a simple UV-O_3 pre-treatment of the film, the resin can be arranged to adhere preferentially to the photopolymer cured in contact with it so that the grating is removed from the glass at the peeling step. For the viewing areas where the grating is required to remain on the glass, a combination of surfactants with terminal acrylate groups are ink-jet printed onto the appropriate areas prior to the embossing process steps. In addition to bonding to the glass, the acrylates bond cohesively to the acrylate photo-polymer during the curing process. This radically increases the adhesion of the grating to the glass in these areas only, so that when the film is peeled, the grating is left behind only where required.

Once complete, the grating on the mother-glass would be coated with a homeotropic surfactant using a vapour deposition process. This was done in a purpose built chamber, where batches of plates were exposed to a uniform flow of moist air containing the appropriate level of a long chain alkyl-tri-chloro-silane. The silane condenses onto the photopolymer surface, to which it bonds covalently after a 180°C bake. Its surface density, and hence the resulting homeotropic anchoring energy and latching voltage [34] were controlled by

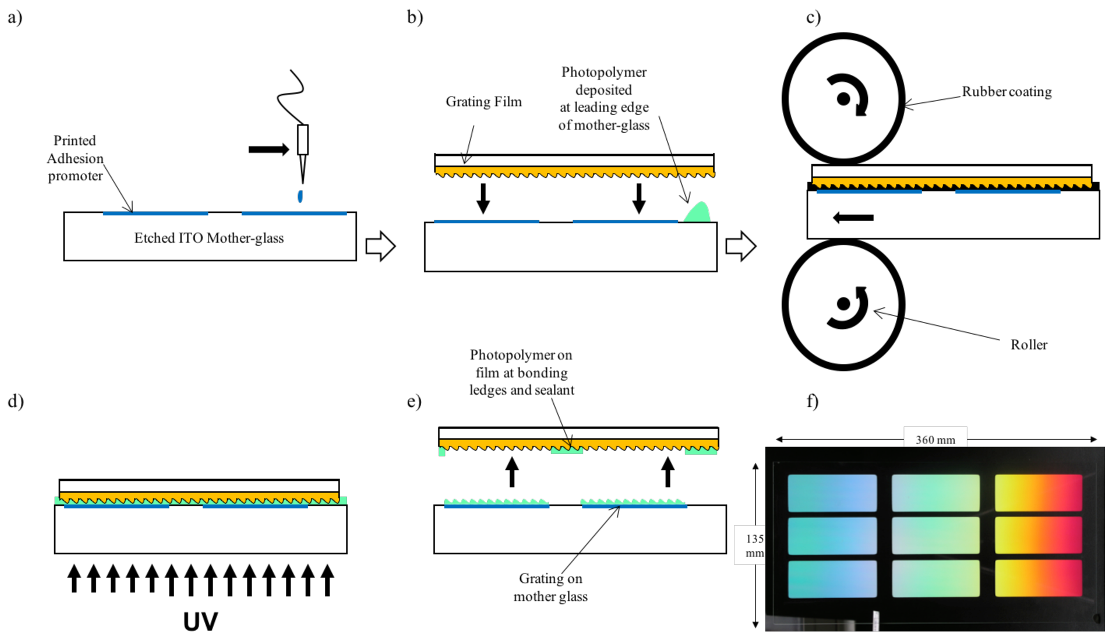


Figure 8 Grating fabrication at the LCD Manufacturer, using selective adhesion and embossing. a) The patterned LCD mother-glass for one plate of the LCD laminate is ink-jet printed with adhesion promoter to define the grating areas (corresponding to the viewing area). b) The homeotropic photo-polymer is syringe deposited at the leading edge of the mother-glass and the film placed on top. c) The mother-glass and film are passed between embossing rollers to squeeze the photo-polymer across the surface. d) The film is held in place by capillary forces whilst the plate is UV cured. E) The film is peeled from the mother-glass, leaving film where the adhesion promoter was printed, and removing excess from the bonding ledges and glue seal areas.

measuring the amount of HCl vapour produced as the silane reacts with surface oxygen in the presence of water, reaching the correct termination point after a period typically between 90s and 120s.

The completed ZBD plate would then be laminated with a rubbed polyimide plate in the conventional fashion, and all other steps remained the same as those used for TN or STN. This proved important to keeping investment low, since only a few $10k of dedicated equipment were needed. Critically, it allows the manufacturer to switch instantly between ZBD and TN / STN production, thereby fitting into the existing fabrication schedules as the ZBD sales grew from nothing.

In late 2002, the fabrication process had progressed sufficiently to consider transferring to a far-eastern manufacturer. Damien McDonnell introduced me to the CEO of *Varitronix Ltd* in Hong Kong: C.C. Chang, who was immediately interested in our proposition. Soon began the decade-long relationship between *ZBD* and *Varitronix* that led to the first large scale manufacturing and marketing of ZBD related products. When C.C. retired in 2005, new CEO Tony Tsoi closed most of *Varitronix's* R&D projects, but retained the interest in ZBD, indeed moving its operation from the R&D laboratories in Hong Kong to the manufacturing line in Heyuan, deep in the countryside of Guangdong province. Members of our team had an almost permanent presence at both sites during the technology transfer process.

As this process begun, the investors made another important choice: recruiting Clive Mayne to become firstly Chief Operations Officer and, three months later, our second CEO. A founder of *Red M*, Mayne had successfully brought electronic products to market prior to joining *ZBD* and had the necessary experience to help *ZBD* move from prototype to product. He brought a sense of focus, helping migrate the company from seeking licenses for its patents to a "fabless" manufacturer. *ZBD* would market our display to end-users, with supply provided by *Varitronix*, who could sell panels only to *ZBD*. For any OEM to choose to fit ZBD into a new product, all effort on their behalf had to be minimised otherwise the activation energy for choosing the *ZBD* technology would be too high. In particular, this meant providing the electronics part of the display, and Mayne brought with him a team of electronics and firmware engineers led by David Dix. Mayne also realised that we needed to concentrate our deep understanding of ZBD operation to helping *Varitronix* achieve the necessarily high yields for us both to achieve our cost targets. Any R&D that was not related to achieving a stable LCD supply chain was dropped, including what had begun to be a promising project with the large Japanese consumer electronics company on dual-mode TFT driven ZBD.

Despite Malvern being designated one of the UK's *Areas of Outstanding Natural Beauty* and what we scientists would consider an ideal environment to live and work in, the company never did attract a CEO to live and be based in Malvern. Mayne based himself in an office close to Windsor, locating the electronics team there, one hundred and fifty kilometres from the rest of the technology team in Malvern. This meant making both regular flights between UK and China and drives between Malvern and Windsor. As the company grew, the Malvern site remained roughly constant in size whereas the Windsor office needed to relocated to Ascot in 2009, to gain more space for the burgeoning sales and marketing teams. In 2013 another relocation was required to still larger premises in Bracknell.

A key part of Mayne's strategy was the introduction of 6σ-related principles of process improvement to the company. To enable this, we defined a series of key operating parameters and every item produced by the manufacturer was tested. For example, three quantities were measured for each LCD at room temperature: onset and full latching voltages from continuous to defect states (*V0* and *V1* respectively), and the maximum data voltage allowed. The three quantities were stored on the database as the centred voltage *V*, and voltage spread *ΔS*, and V_{RMS}:

$$V = \frac{V1 + V0}{2} \;\; ; \;\; \Delta S = \frac{V1 - V0}{2} \;\; ; \;\; V_{RMS} \qquad (5)$$

together with all information concerning the process (film, shim, time, position on glass, assessor, test rig, etc.). Process capability parameters Cp and Cpk for each of the three parameters allowed quick visualisation of whether the process was correct or whether the displays were insufficiently uniform to be addressed over the temperature range using the addressing scheme. Individual displays could not be tuned, but each had to fit with one or two sets of parameters. As the process and its consistency improved, the amount of testing decreased. Firstly, measurement of V_{RMS} was dropped after process improvements led to a V_{RMS} Cpk > 2 for a long period. The accuracy required for V0 and V1 was continually reduced, until eventually display consistency was sufficiently good to allow a simple Pass - Fail test, and more thorough testing reserved for samples only.

To implement this, Mayne recruited product engineer Richard Hoodless, with whom I worked very closely over the following six years to achieve a high-yielding production process, both in the film supply chain and for production of LCD. The technical team needed a more coherent division of labour, so Rich Amos managed mastering and grating design, Emma Wood managed film production, Steve Beldon managed test and addressing, Richard Hoodless managed the LCD and LCM (Liquid Crystal Display Module, being the completed panel including mounted polarisers and drivers), and David Dix running associated electronics, software and plastics.

This period was far from problem free. Theoretical modelling done in collaboration with *Sheffield Hallam University* [34, 40] showed that, for a sinusoidal grating, changes to the grating full-width-half-maximum of less than 10nm could cause a measurable change to the latching voltage *V*. This was no problem for the mastering, where such variations could be detected and discarded before entering the supply chain. However, during one particularly difficult period, a third-party supplier to a component of our film supply chain changed their product, which impacted our ability to make film of sufficient quality. Tracking this down, whilst continually depleting existing film stocks, took over six months and was very stressful for everyone involved.

A longer-term issue was the vapour phase surface silanisation process. This process often drifted and gave unusually large panel variations, both within a batch and across individual panels. Whilst reviewing the problem, investor and chemist from *Dow*, Nick Darby pointed out that the photopolymer that we had designed was devoid of the appropriate bonding sites for the silane, and that we were relying on impurities in the photopolymer. This was something that John Goodby will not be impressed with: our conceit as liquid crystal physicists to believe that any chemistry related problems would be simple for us to resolve. In 2006, we added the excellent, experienced industrial chemist Dave Walker to our team, and quickly resolved our surface treatment issue. However, the whole process still did not fit: whereas all of the other ZBD production steps sat neatly on the LCD production line, surface treatment remained a batch process, both for the vapour phase deposition and subsequent oven baking. We had realised for sometime what the best solution would be: re-design of the photopolymer to provide inherently homeotropic alignment with the correct anchoring energy. Now equipped with a first-rate chemist, that challenge became feasible. Bryan-Brown, Walker and I dedicated much of 2006 and 2007 to solving this issue, and in early 2008 we were ready to swap the production process to the new homeotropic photopolymer.

As display numbers increased, new problems would arise. For example, Master and Nickel variations led to voltage differences that could be as high as 2V. This was solved by designing a two-bottle mixture of the homeotropic photopolymer, one with low anchoring energy and one high. Each batch of film would be labelled with the correct photopolymer to use, thereby compensating for any variation in the film process.

Over the years, the mastering process continued to increase its yield, and because yield is unimportant for this step, we allowed further complexity to be added. The first step was to include three 6” x 5” grating areas aligned in proximity onto a single master. This meant that each sheet of film could stretch from one side of the Generation 2 sized glass used by the LCD manufacturer, greatly simplifying the process (since a single deposit of photopolymer at the glass edge could then be used). Seams between the individual gratings still limited the glass layout for the different displays that we offered. By 2010, seamless mastering had been perfected, removing restrictions on film placement, display size or glass layout.

Whilst the manufacturing processes developed, business development efforts continued but without sales success. Potential customers always returned to two issues: could ZBD make an attractive reflective display with colour; and, what volume of displays was required before ZBD would reach STN prices. Without colour, ZBD seemed destined to compete directly with STN for the low power B&W market, and without hitting the cost target early, contracts would not be won. There had been some attempts at introducing reflective colour to portable TFT LCD, such as in the *Colour Game Boy* by *Sharp*. These used microstructures to trade viewing angle for reflectivity, and hence provide up to 20% reflectivity in the viewing direction. Although feasible for ZBD, the approach did not provide satisfactory performance: it was better to concentrate on applications that could be satisfied with B&W, but where power and high image content were critical.

One such application was Electronic Shelf Edge Labels, which was beginning to be established across Europe, partly because of the adoption of the euro currency and the need to display two inter-related but changing prices. Having acquired *Eldat*, market-leader *Pricer* from Sweden approached *ZBD* in 2006. They sold a label system to retail customers with large supermarket and hypermarket chains. Their labels were segmented TN that allowed updates of pricing only, reserving product details to a separate paper label. *Pricer* were interested in using larger display devices to display occasional information such as promotional offers. Their communication system used IR to send information to the any of the 50,000 labels in a store, sent from a series of transceivers located along each aisle. Although the system was designed for low data rates, sending price only to each label, *Pricer* believed that the addition of occasional displays that offered more information would be beneficial. The application requires the TN display to be permanently on, 24 hours per day and 7 days per week. A small, segmented TN would have a battery life of 5 – 7 years, but including graphical information using an STN would reduce this to a month or less: bistability was essential. At this time, the choices for bistability were limited. *E-ink* displays were too expensive for such a low-cost application, requiring a TFT to address the threshold-less electrophoretic film. Bistable cholesteric displays were an unattractive yellow on black (or blue on white) and were subject to erasure when pressed. *ZBD's* nearest competitor was French company *Nemoptic,* who used a bistable twisted nematic that latched between 0° and 180° states by flow-induced breaking of the anchoring on one of the surfaces. This device needed cell gaps below 2μm, and lagged behind us in their manufacturing progress and cost. *ZBD* offered *Pricer* the most realistic route to providing low cost, high performance products.

The display size chosen was a 5" diagonal, 240 x 320 based display, driven by three commercially available TAB mounted STN drivers. Once the project had begun in earnest, what might seem like a small issue arose, but it proved one that was to have major consequences for both companies. *ZBD* needed access to the label micro-controller to provide the information for the necessary addressing waveforms. This microcontroller contained proprietary knowhow of *Pricer,* related to their IR communications. This created an *impasse* that could only be resolved by including separate microcontrollers, one for the display and one for the communications. *Pricer* re-designed the circuit board to form an appropriate slot where the ZBD controller would be located, and *ZBD* began the process of designing and procuring its own driver board from a Far Eastern electronics manufacturer. *ZBD* had inadvertently entered the LCD product business.

7 Product and System Supplier

Whilst writing the 2002 business plan and settling on e-book readers as one of our options, we explored adapting our business model to become a supplier. Such niche markets offer the rich and brave the opportunity to forge an early market lead not only through timing but targeting an application where the technological advantages are most closely matched. For *ZBD*, the e-book reader market was such a match, offering much lower power than STN, better optics than bistable cholesterics, lower cost than *Nemoptic* and much lower cost than *E-ink*. The issues were route-to-market and content provision, hurdles that from the UK seemed too great to cross. Indeed, struggling *E-ink* reversed its fortunes in 2007 by partnering with content provider *Amazon* and the launch of the first *Kindle* E-Book reader.

Electronic-shelf-edge labels (ESEL) were different: they already had a strong market base in Europe and content was managed either by the larger stores themselves, or through a network of providers across the continent. Now that *ZBD* was producing circuitry with a microcontroller, an ESEL product required the addition of a communication system, plastic casings, and a means for selling and distributing those products to the end-user. RF based-communications using the Industrial, Scientific and Medical (ISM) bands between 862 to 928 MHz had the potential for a low-cost system with sufficient bandwidth for sufficiently complex static images. Importantly, the range was hundreds of metres and not 'line-of-sight' such as an IR solution, meaning that even the largest of hypermarkets could be addressed using a single transceiver unit.

Through our link with *TTP Ventures*, *ZBD* licensed software developed by *The Technology Partnership (TTP)* and began to adapt it for the ultra-low power requirement needed to reach a target battery life of over seven years. A spoke-and-hub network was essential, with each label spending the majority of its time in the lowest power mode and both RF and display drivers off. After several seconds, the label would wake up and listen for a brief time for an appropriate signal from the control transceiver. Minimising the awake time is critical for low power, which in-turn requires very accurate synchronisation between the label and transceiver timers. Rather than use higher cost components in the label, this is achieved by re-synchronising each label using the transceiver signal pulse itself, using any of several methods that were invented [41], such as the method shown in figure 9. When a display update is needed, the RF remains on whilst the data is downloaded to a buffer, the display controllers powered and the addressing done. Once complete, a receipt signal is sent to the transceiver and the ESEL powered down. Not only would ZBD provide individual labels, but also the communications transceiver and software, marketing it under the trade name *Bounce*™. David Dix was critical to all of this work, designing the RF system, running the electronics and software teams, managing the design and production of the plastics, and playing a key role interacting with end-users.

Retrospectively, the choice of using the ISM band and the development of the *Bounce*™ system are amongst the most important in *ZBD's* history. Our ESEL competitors *Pricer* and *SES* used IR or low frequency RF, respectively, and were limited in bandwidth. Their systems were one-way systems, where each label always remained passive. In practice, this often results in a high proportion of labels going unchanged; the two-way nature of *ZBD's Bounce*™ means that any label that does not respond initially is recognised by the system, and can be readdressed until the acknowledgement is received. Importantly, these competitor systems required the retailer to make significant capital outlay upfront for the communications infrastructure. This was not just a cost problem: it restricted the range of customers to large retailers only. Once *ZBD* began to market its system, we quickly found pull from mobile phone outlets previously unable to afford to fit-out a store with only a hundred labels or so, let alone provide good-looking futuristic displays that could show each product specification for the ever-changing models on offer.

ZBD found its early adopters with these small retailers that could now afford to implement ESEL systems for the first time. This low initial outlay also allowed larger stores to use labels in limited areas of the store only, usually those areas where the added value and impact was maximum. In spring 2008, Bryan-Brown and I travelled to central London to the *Peter Jones* flagship store of UK retail giant *John Lewis* to see our first ESELs in use. Later that year, at the SID *Displays Week* tradeshow in Los Angeles and the tenth anniversary since the company's conception, we took a stand to launch ourselves to the displays community. To maximise our impact, we transported 560 of our 110mm diagonal QVGA ESELs (marketed as *epop*™, meaning electronic-point-of-sale*)* and set up a 4m diagonal tiled array from 20 x 28 array of the 320 x 240 products. Each *epop*™ would display an example label from one of our retail customers, updated wirelessly using *Bounce*™. Eye-catchingly, the textual content of each individual label was analysed and then used to form a larger image, as shown for the word 'ZBD.' in figure 10a; observers were intrigued and impressed [42]. Clearly, *ZBD* was equipped with high yield manufacturing, stable supply chain, serious investors and an interested target market.

Mayne had delivered on the manufacturing, communication and plastics, but was relatively inexperienced at delivering

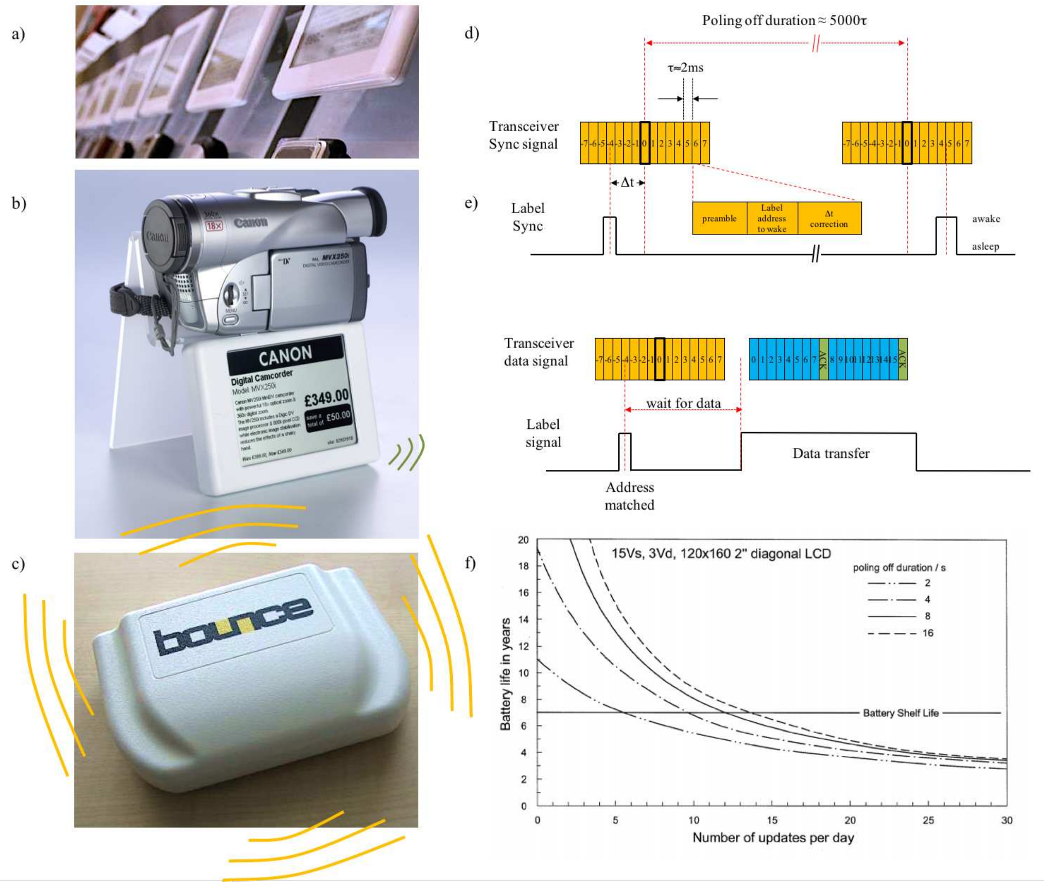


Figure 9 Ultra-low power RF communication protocol, *Bounce*™ [41]. a) A series of *epop* labels wake up every several seconds, listen for their address whilst correcting any lag due to drift caused by the low cost RC oscillator, and then return to sleep. b) The label(s) that require(s) an image updating is awakes to receive the data, and send out acknowledgement signals back to the communications system. c) The bounce communicator is a small unit that covers over 100m radius, includes an accurate crystal oscillator to ensure accurate time signals are maintained, and is connected to the Ethernet to allow information transfer with databases in the back-office or head-office. e) Synchronisation for a low cost label where timing drifts by Δt due to errors in the RC oscillator is done using a series of sub units each of duration τ. Each label reads both the identification code for the labels that need updating, and the relative timing between label and communicator. f) If the identification code matches that of the label, it wakes up after a sufficient period to receive the data in a series of bundles. The data is loaded into memory, and when complete the label switches on the display drivers and proceeds to update the image. g) Calculation of battery life for two low-cost button cells operating with various poling periods between synchronisation pulses, for a 2” 100dpi label. Given a battery shelf life of 7 years and an average update of 10 images per day, the poling duration was optimised at about 8s. This duration dictated the time taken to address all of the labels in the store that needed new images.

Figure 10 Marketing the ZBD technology. a) ZBD at SID 2008. The 43-million pixel display: 560 QVGA *epop* labels addressed using the ZBD proprietary *Bounce* RF communications system. b) Most publications were in trade magazines, rather than technical journals. Items from the Malvern concept centre included c) displays with different colour options, d) an operational colour shutter that allowed three colours to be displayed on an *epop* label, and e) a 14” wide shelf-strip demonstrator.

the sales and distribution channels, and left in September 2008. New CEO Shaun Gray was recruited to replace Mayne in late 2008, soon after our triumphant return from SID. Before this change, we continued to consider selling displays to non-retail sectors, whilst restricting the retail market to ourselves. The board now decided to concentrate wholly on the retail sector and become a system provider. Gray was an experienced CEO who was truly expert at marketing in the retail sector. *ZBD* was about to change gear.

The most urgent element required was a dedicated ASIC driver. Large displays are readily driven from TAB mounted STN driver ICs connected to vertical and horizontal bonding ledges. The 110mm diagonal devices, for example, used two 160 output drivers on the columns and one 240 row driver on the columns, controlled by a separate microcontroller and large circuit board to allow access to the drivers along both sides. Not only does this type of arrangement add cost, but it leads to wide borders around the display. These factors prohibit this approach for small displays, precisely where the largest segment of the ESEL market was: 30mm to 60mm diagonal labels. Whereas previously we had considered restricting our business to larger labels only, as a system provider we had to invest in a dedicated driver chip that would allow access to much higher sales. With new found confidence and funding from our investors we began to develop a dedicated ZBD driver. Throughout 2009, we worked with *Solomon* in Hong Kong to produce an ASIC that could drive a 96 x 240 pixel ZBD label across the temperature range -10°C to 60°C. The chip is mounted directly onto a single bonding ledge on the short side of the display, thereby allowing a much smaller circuit board not only through the removal of many of the components now integrated into the ASIC. The rows are output directly from the chip whereas the column signals are routed around the edge of the panel and connected to the opposing face of the LCD using one-dimensional conducting glue. This allows much thinner edges on three of the display sides. In 2010, ZBD launched its 50mm *epop 50* and 70mm *epop 55* units and began to sell labels in far higher volumes.

Gray was not satisfied: despite our far lower label prices, our customers were now accustomed to the high viewing angle and excellent white state of electrophoretic E-ink displays that they used in their *Kindles*. Our Sales team was under continuous pressure to improve the optical appearance and Gray delivered an ultimatum that without a solution, my job (and that of everyone in the company) was endangered. Bryan-Brown and I considered scores of potential solutions, from the esoteric use of phosphorescence, quantum dots, or the diffraction itself from the grating when not index matched to the liquid crystal, to the mundane use of more costly 3M reflective polarisers. The solution came from our chemist, Dave Walker. He noticed that, when testing different liquid crystal mixtures in the same cell gap (used for comparison) some materials gave a much whiter D state than others. Between the first and second Gooch-Tarry maxima for green light, there is a cell gap where blue wavelengths are close to the second maximum and the red light close to the first

[43], figure 11b). The white balance is greatly enhanced, simply by increasing the cell gap from 5μm to 7μm, with only a minor decrease in perceived reflectivity (due to the increased blue and red light contributions) and a sensitivity to cell gap that is well within the tolerance allowed by the any LCD manufacturer.

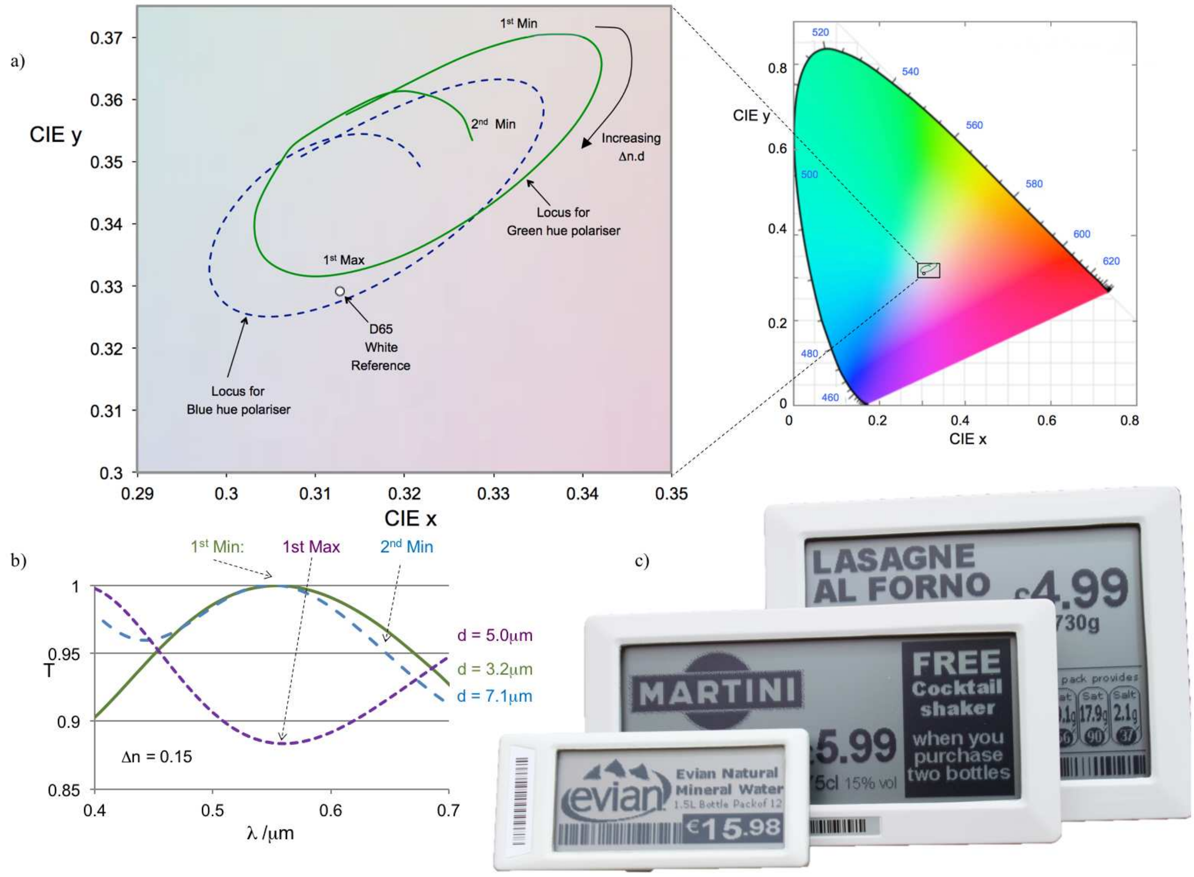


Figure 11 Optimising the ZBD White state. a) CIE diagram with the locus for the TN white state colouration as a function of retardation, Δn.d [43]. Loci for standard and slightly blue tinted front polarisers are given. This shows that the latter comes very close to the white state standard when operating close to the Gooch-Tarry "first maximum". b) Gooch-Tarry curves for first and second minima conditions and the intermediate first maximum. Rather than give peak transmission in the green, maxima at blue and red wavelengths give a more pleasing white. c) This is evident from the various ZBD *epop* displays from around 2011. A number of improvements were made, including operating at the first maximum, removal of the front protective plastic, asymmetric glass thickness to reduce parallax but maintain good shock stability, and haze-free front polarisers with a blue tint. The *epop* 50 at front uses the *Solomon* ZBD driver.

As sales began to grow, our priority was always to reduce panel costs. Initially, this was mainly increasing the LCD yield. During this time, pressure was maintained on the electronics and plastic suppliers, negotiations made easier by the increasing sales volumes. Once our LCD yields reached the high nineties, it became essential to leverage through having multiple suppliers. Although relatively straight forward for the electronic components, plastic fabrication, polariser and liquid crystal materials, this was much more challenging for the film supply chain and LCD manufacturers. Replicating and improving these critical elements to the supply chain were both a major effort and accomplishment made by the Malvern Technical Team during this period. The company's success is due to it hitting both cost and performance targets for the labels.

Another big change to the company in this period was the increase in both marketing and sales activities, figure 10f. The head-office in the South East of England was moved to bigger premises near Ascot, marketing manager Sarah Todd was recruited, and our first US-based sales team set up. Gray's strategy was to build a partner network across Europe with point-of-sale services and software suppliers that already had strong ties to customers in individual countries or territories. This meant that local experts dealt with variations in law, language and custom. It proved a most successful approach, rapidly leading to implementations across the continent, firstly with small stores that *Pricer* and *SES* could not serve, and by 2012, beginning to affect these competitors at the core of their business. The US strategy was different for a number of reasons. There was no existing ESEL infrastructure, label prices needed to be lower, and the logistic difficulties were naturally lower. Hence, *ZBD Inc.* was set up and a local ZBD sales team recruited across the country.

An essential part of Gray's market strategy was to have a Technical Roadmap, producing demonstrators that helped focus technologist, sales person and customer on what was potentially possible, aided through the instigation of a concept centre at the Malvern site. This included larger and smaller displays to those available as products, light-guiding covers and adjustable plastic mounts to help maximise legibility for all shelf levels, and novel colours such as a gold reflector used for high end jewellers. Demonstrators made in 2012 included a 14" x 1" shelf-strip display (made possible by the seamless master) with a minimal 2mm seam for use along the length of a supermarket shelf, figure 10e. Also a low cost three colour LCD was fabricated, where segments of the B&W could be switched to black and red to highlight promotions. This worked using a segmented TN with a single red polariser laminated to the front of the ZBD with an index-matched adhesive. The effect of red-leakage of the red-polariser was minimised by tuning the cell gap of the ZBD to give it a blue-tinge to the white state, so that the combination of ZBD and TN gave the same good B&W states, albeit at the slightly darker red state as shown in figure 10d.

As yields and costs of standard ZBD approached those of STN, the technical work could move to extend the performance ranges. As a supplier to the food-sector, it was particularly important to offer labels capable of operating inside a Freezer. Market research from our end-users showed that, despite being set to -22°C, freezers would often have regions at -28°C or lower. This proved particularly challenging to solve, since the standard photopolymer had a glass transition at about -20°C and the grating shape would only provide a total temperature range of 75°C. Thus, separate versions were sold to the supermarkets, with standard products operating from -10°C to +60°C (marketed as 0°C to +50°C) and freezer versions -28°C to +45°C (marketed as -25°C to +30°C). Clearly, the cost of the freezer version was inherently higher, since it had to be built in separate lots, but this was something that the market accepted.

8 Solution Provider

From the outset, Shaun Gray's vision was for *ZBD Display Ltd*. to become a total solution provider. It was important not only to maximise the performance to price ratio of our labels, but to provide everything that would make the customer's decision to buy easier: plastic mountings for the large variety of shelves; plastic covers to highlight promotions and special offers; Bluetooth beacons that allow the shopper to interact online at the point-of-purchase. Above all was the desire to enhance the control software sitting above the label communication system *Bounce*, and provide as much utility for the retailer as possible. This ranged from stock control (from shoppers being informed of items in stock at the shelf-edge, to the label indicating location information for staff during restocking periods), to active price optimisation (where pricing can be adjusted automatically due to demand level, stock level, or propinquity to a particular sales event or sell-by date).

These ideas were a long way from the original ZBD invention, and began to lead the management team to consider using other display technologies, and relying on the RF solution as the company's major differentiator. Oddly, I was in favour of introducing a label using an E-Ink display, whereas Gray was far more conservative. I saw it as means by which the end-user could judge whether to pay the higher price for an *E-Ink* EPD or whether the *ZBD* LCD performance was sufficient. *E-Ink* was clearly the benchmark by which reflective displays were being judged. As Lambertian reflectors, electrophoretic displays both take light from all directions and reflect light to all directions. This leads to a high reflectivity when illuminated from every direction; a condition often found where label buying decisions are made, such as the Boardroom. Things are different in the supermarket aisles. Reflective LCD use reflective polarisers that scatter the light in a much tighter viewing cone, usually centred on the angle of specular reflection. This means that the LCD has a significantly higher reflectivity than E-Ink when viewed closer to the specular condition, though is much poorer at wider angles and when illuminated by a diffuse source.

Supermarket shelves are lit from above and read from straight on: ideal for LCD and ZBD, particularly when appropriately tilted for the different shelf heights. Although promotional photographs of the labels looking along a whole aisle favoured the optics of E-ink displays, in reality ZBD gives superior optical performance for this application and at the lower price. However, as E-Book Reader sales were retreating following the success of tablet computers such as the i-Pad, *E-Ink* would eventually be forced to lower their film costs and so I believed that *ZBD* would be best prepared by using both types of display.

Where Gray and I did agree was that *ZBD* had a highly capable technical team that could deliver new display technology as well as any in the world. In mid-2012, we approached Cincinnati spin-out company *Gamma Dynamics*, who had a novel electro-wetting display based on a porous film separating layers of conducting black ink and clear fluid. Applying an electric field of one polarity caused the ink droplets to change wetting angle, thereby pushing through the pores of the film and displacing the clear fluid, whereas the opposite polarity field would reverse this movement. Demonstrations showed exceptional reflectivities well exceeding those achieved by E-ink, and considerably better than the ZBD LCD even under typical directed illumination. *Gamma Dynamics* recognised in ZBD both a potential end-user and a company that could help turn their early stage demonstrators into products. Not only were we expert in production of the film, we understood electrical driving of bistable panels better than any, and had a supply chain able to adapt quickly.

As our sales increased, *ZBD* began to win accolades. No longer were the prizes for promise but were now for achievement. We were fifth in the Sunday Times Technology Track for 2012, and 2nd in the Deloitte European fastest growing companies. The ZBD display technology was recognised by the Institute of Physics with the 2012 Innovation Award. Change was not limited to the market. Bob Hook had retired and sold *Prelude* to *DFJ Esprit Ventures*; new investors *Lansdowne Partners* and *Trillium* (representing *Collar Capital*) were then dominant shareholders, replacing chairman Colin Garrett for the experienced Howard Ford. Amidst the award ceremonies, Gray left the company, and the Board needed someone to complete the company's evolution into a total solution provider. Andrew Dark had been a Non-Executive Director from early 2008 and was ideal to deliver this transition. From 2012 onwards, new CEO Andrew Dark has grown the sales business greatly, extending the partner network worldwide, including North and South Americas, Asia, the Middle East and Australasia, as well as continuing to strengthen its core in Europe. In 2014, the company rebranded to *Displaydata Ltd.* and introduced electrophoretic displays to its oeuvre. Today, the company is the world leader in graphic electronic shelf edge labels, having launched in 2016 three-colour labels based on the electrophoretic micro-cups from *Sipix*, acquired by *E-Ink* in 2012. Given that this represents a multi-billion dollar market, *Displaydata Ltd.* still promises ample reward for the patience of its investors. Work still continues both at Displaydata and at the University of Leeds on the ZBD technology, both for display and non-display applications. For example, the company has continued to improve the optical appearance of its ZBD labels through the use of novel scattering films and has re-started work on dual mode TFT ZBD.

The evolution of the company is summarised in Table 1. It shows that each change of business model required a new champion. This revitalised confidence in the company from its investors at each stage, particularly since each change followed periods of great difficulty. As the investment grows, so must the ambition and market access. Retrospectively, it is evident that each CEO precipitated the changes that lead to their own replacement. With renewed investor confidence comes a period of growth, indicated by the increasing need for office space. Rebranding is important, usually just involving a new website and logo, but sometimes with a completely new name.

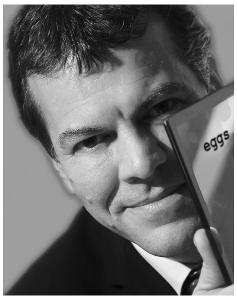
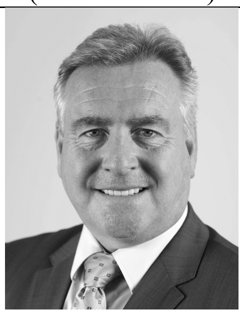
9 One Flew Over the Cuckoo's Nest

Immediately before founding ZBD, and again in 2010, I had been approached to take a chair at a UK university. Neither offer came at the right time: leaving at either stage would have been critically damaging to the company. By mid-2012, our yields were sufficiently high for me to begin to rethink, and I told new chairman Howard Ford of my longer-term intentions. In late 2012, I proposed to the Board a long-term research programme partnering with *Gamma Dynamics* to bringing electro-wetting displays to our labels. They declined, logically wishing to reap the benefits bought by the investment already made. It was clear that my work was completed: leaving the company would have little long-term negative impact and that I was ready for the long-postponed move to academia.

John Goodby had been an inspiration to me, since his days as my Ph.D. supervisor and throughout our joint work on smectic liquid crystals in the 1990s. He is the type of academic I would aim to emulate: inventive and possessing the ability to see a broad vision and yet personable and interesting. In spring 2013, I contacted John and he steered me to Helen Gleeson at Manchester. Having won an Advanced Fellowship from the EPSRC that targeted industrialists wishing to move into an academic environment, I moved to the School of Physics at Manchester in November 2013.

After nearly fifteen years of concentrating on a single technology, and being focussed on the world of bistable displays and the retail sector, I was mostly unaware of the advances being made in the world of liquid crystals. Of particular interest is the body of work where defects play a role in liquid crystal behaviour, whether occurring around nano- and micro-particles in nematic dispersions, droplet suspensions and photonic structures, or being used to stabilise different configurations in two and three dimensions. Defects have changed from being something that is automatically avoided to

Table 1 The Evolution of ZBD Displays Ltd.

Period	Business Model	CEO (CFO)	Head office location	Logo
2000 – 2003	Licensing	 Henri-Luc Martin (Richard Scanlon)	Malvern Hills Science Park, Worcestershire	ZBD
2004 – 2008	Fabless Manufacturer to Product Provider	 Clive Mayne (John Dernie)	Windsor, Berkshire	ZBD
2008 – 2012	System Provider	 Shaun Gray (Carl Plucknett)	Ascot, Berkshire	zbd.
2013 – Present	Solution Provider	 Andrew Dark (John Varney)	Bracknell, Berkshire	Displaydata

parts of the lexicon of liquid crystal effects. But this new liquid crystal world has so much more to offer, from novel phases such as the twist-bend nematic or dark conglomerate phases, to non-display applications, such as printed liquid crystal lasers or RF antennas. These innovations will lead to new technologies seeking to step from the academic into the commercial world. Perhaps, the lessons learnt from the successful spin-out, Displaydata, will be helping guide to those making this exciting and rewarding path.

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