What are Liquid Crystals?

Liquid crystals are usually formed by rod-shaped molecules.

They are true liquids BUT they have some order—they are part way between solid crystals and conventional isotropic liquids.

**Nematic liquid crystals** are the simplest they only have orientational order. Nearly all commercial liquid crystal displays use nematic liquid crystals.

**Smectic liquid crystals** have some positional order too and tend to form layers.

**Smectic A liquid crystals** have molecules perpendicular to the layers.

**Smectic C liquid crystals** have molecules tilted in the layers. They can be ferroelectric.

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**STL Achievements**

- STL developed nematic liquid crystal displays for manufacture at ITT components Group at Leeds
- STL developed possibly the first Liquid Crystal over Silicon (LCOS) displays using nematic liquid crystals
- STL developed the first Smectic A Displays for manufacture at ITT Courier, at Phoenix
- STL pioneered the development and licensed Ferroelectric Smectic C displays
The ABC of the STL LCD team over the years

Peter Ayliffe developed electronic drive schemes for both Smectic A and LCOS devices.

Laurie Bidulph did some of the original work on fabricating twisted nematic devices at Harlow in preparation for transferring to production at ITT Components Group in Leeds. Bill Crossland has one of the twisted nematic devices that we made at STL in 1978 as prototype for the factory at Leeds still works.

Martin Birch was a key figure in development of LCOS VLSI backplanes. He transferred to Thorn EMI Labs and then to 4th Dimension Displays.

John Brocklehurst was Department Manager when the Smectic A device technology was being developed for transfer to ITT Courier in the USA. John transferred to Thorn EMI Labs and at a later stage worked for Thomas Swan Ltd on an optical correlator developed by Tim Wilkinson in Bill Crossland’s group at Cambridge in the 1990’s.

Rab Chittick joined the STL group to develop amorphous silicon photoconductors for optically addressed liquid crystal spatial light modulators. This interest continued at Cambridge and Rab worked for a time with there.

Terry Clapp worked in the Optical Transmission Group at STL, and participated in many discussions concerning liquid crystals. On leaving STL Terry became an employee of Dow Corning Ltd and was a co-founder of CAPE (Centre for Advanced Photonics and Electronics) at Cambridge. Terry worked closely with Bill Crossland’s group at Cambridge and championed both LCOS and Smectic A technology in CAPE and at Dow Corning. New materials for both Smectic A and LCOS devices were developed by Dow Corning in the 1990’s. The lead engineer at Dow Corning at Midland, Michigan in the USA was Jon Hannington, who in the early 1980’s (or late 1970’s?) was a materials scientist at STL in the old Van der Graaf building.

Dave Coates was the chemist of the group and developed the Smectic A liquid crystal materials and dyes. He left to head the LCD Development group at BDH Ltd, Poole, which was subsequently taken over by Merck. Later he became Chief Engineer of Magink Ltd developing liquid crystal advertising signs.

Neil Collings brought skills in optics to the group and worked on optical correlators, neural networks and optical switching using LCOS. Neil left STL to join the Institute of Optics in Neuchatel, Switzerland. He returned to the UK to work for Bill Crossland at Cambridge in developing holographic projection using LCOS. He now works for Two Trees Photonics on holographic projection for head-up displays.

Mike Coupland started the Liquid Crystal Displays (LCD) Group circa 1971. At the same time that RSRE at Malvern was starting a major effort on LCDs because it was thought that they may one day replace the CRT.

Bill Crossland was the Technical Group Leader for most of its history (1971 to 1992) after which he joined Cambridge University as Nortel Professor of Photonics in the Dept of Engineering, where he co-founded CAPE (Centre for Advanced Photonics and Electronics) along with Terry Clapp (ex STL) and Bill Milne (Head of Electrical Engineering). Aspects of the work continued at Cambridge.
Ken Darton made significant contributions to the circuit design of the silicon back plane of the STL LCOS devices.

Tony Davey was the resident expert on liquid crystals and transferred the Smectic A device assembly technology from Harlow to ITT Courier in Phoenix. He transferred to Cambridge and worked between 1993 and 2010 on liquid crystal materials for all applications, including Smectic A, LCOS, holographic projection and optical switching.

Pete Graves was a good friend and mentor, and was responsible for organising the transfer of equipment and facilities to set up Bill Crossland’s facility at Cambridge.

Pat Gunn helped develop LCD assembly processes in the early days.

Sadie Hughes developed processes for assembling LCOS devices. She transferred these processes to our collaborators at Colorado University in the USA, which ultimately became the US FLC LCOS company, Displaytech Ltd.

Joe Morrissy was the original engineer appointed by Mike Coupland to start work on liquid crystals 1971. Joe moved to USA in the 1980’s when the STL Smectic A device was put into manufacture at ITT Courier, Phoenix, Arizona. Later he joined an LCOS display start up in Phoenix called III/V Systems. Joe subsequently worked for a number of LCOS companies in the USA.

Barbara Needham joined the group as a display engineer and was a co-inventor of the Smectic A device. She helped develop ferroelectric liquid crystals (FLCs) and then left to join Philips to set up an LCD manufacturing plant in the Netherlands. At a later date Barbara joined other STL expatriates (Peter Ross, Martin Birch and John Seaver) at Thorn EMI Labs to develop the FLCs transferred from Harlow. In the 1990’s Barbara worked with Bill Crossland in Screen Technology Ltd., in Cambridge.

Jack Peters was Department Manager championing the Group for many years. Everyone associated with the Group will remember his encouragement and leadership.

Hedley Rokos made significant contributions to the circuit design of the silicon back plane of the STL LCOS devices.

Peter Ross worked on drive schemes for FLCs. He developed the automatic equipment that discovered the ‘Tor-V-min’ scheme for driving FLCs that was later developed further at RSRE, Thorn EMI and by Sharp in Japan. Peter moved to Thorn EMI Laboratories at Hayes, Middlesex along with most of the FLC and LCOS IP personnel.

John Seaver was a skilled assembler of LCDs and developed Smectic A assembly processes at Harlow with Tony Davey. He transferred to Thorn EMI and then to 4th Dimension Displays where was responsible for LCOS device fabrication.

Peter Selway guided the LCD Group through its most difficult times and ensured that the technology and personnel continued to develop.

Adrian Sparks designed and built the FLC spatial light modulator modules that STL sold to research labs around the world.

Chris Walker worked with Tony Davey on dopants for Smectic A devices. The compounds that they developed are still used today.

With apologies to anyone who we’ve failed to mention. It’s been a while!
Developed (1974-79) an early **manufacturing process for Twisted Nematic Displays** at ITT Component Group, Leeds. This was still operating in the late 1990’s.

Developed ‘**bistable** displays using smectic liquid crystals to avoid the use of switching transistors.

**Light scattering Smectic A displays** (1978 to 1985) developed for ITT Courier. Since used by: Polydisplay (Scandinavia) for road signs; Halation (China for point of sale etc.) and is now being developed by Dow Corning for electronic Windows.

*The STL Smectic A display preceded TN TFT displays. It was the first liquid crystal A4 full page text display. It could change a page of text in about 1.5 seconds. In 1981 when it was exhibited in New York, a simpler and smaller TFT TN display was also exhibited by TP Brody. However, the TN-TFT display came to dominate flat panel display industry, in part because it could operate fast enough for television.*

**Ferroelectric Smectic C displays** (1981 to 1990) developed under UK JOERS Alvey Project. TV displays were licensed by Sanyo and Sharp (via CRL and RSRE). Published in Ferroelectrics 122, 63, 1991. They have not been commercially successful.

**Liquid Crystal over Silicon (LCOS) devices** (1978 to 1990) with single crystal silicon VLSI backplanes. Currently the basic technology of high quality cinema projectors (e.g. Sony VPL, Compound Photonics Inc.) holographic projectors (Two Trees Photonics Ltd) and fibre-optic switching (ROADMS) systems > (Finisar Inc., Cambridge Photonics and ROADMAP Ltd.)

*LCOS devices have come into their own in the last 10 years in displays and in telecommunications.*

Research on LCOS and Smectic A liquid crystal devices continues at Cambridge University Engineering Dept. (Professor Daping Chou).

Dow Corning develops new materials and applications for Smectic A scattering devices.
1971 Liquid Crystal Display Group initiated by Mike Coupland, encouraged by RSRE, Malvern, who believed they might replace the CRT. Joe Morrissey was the original member of the group. Bill Crossland joined soon afterwards.

1978 Original STL patents on LCOS (Liquid Crystal over Silicon) displays (STL Labs Patent 8329807, under RSRE contract 711B/4751-D).

1972 to 1980 STL developed manufacturing technology for Twisted Nematic Displays and transferred it to ITT Components Group at Pudsey, Leeds, UK.

1981/82 The first LCOS demonstrator built at STL. In addition to Adrian Sparks within the group -- Ken Darton and Hedley Rokos made contributions from outside the Display Group. Backplane made at ITT Semiconductors at Footscray. Only one photo of one working demonstrator exists from this time.

1985 Presented STL Smectic flat panel text display at New York SID Conference.

*The same Conference where Clive Sinclair showed his miniature CRT based TV and T. P. Brodie presented the first thin film transistor driven liquid crystal display.*

1985 The STC Smectic A flat Panel Display was awarded the Finniston Award for the most outstanding product based on a recent scientific advance.

1985 to 1990 Jack Peters managed the group and steered it with skill and confidence during this time.

1986/86 STL transferred Smectic A flat panel technology to ITT Courier, Phoenix, Arizona. Factory subsequently purchased by Alcatel and closed.

1986 to 1989 Proposed and developed large multiplexed ferroelectric liquid crystal displays at STL. Initiated and then lead the UK JOERS Alvey project on this topic.

1988 The first LCOS device using ferroelectric liquid crystals were built in STL in collaboration with Edinburgh University (176x176 pixels on a 10mm VLSI chip). Key contributions were made by Martin Birch and Peter Ayliffe.

1988 to 1990 STL display patents were licensed to Thorn EMI Central Research Laboratories (CRL). Peter Ross, John Brocklehurst, John Seaver, Martin Birch and (later) Barbara Needham moved to CRL and developed ferroelectric television displays based on the JOERS Alvey addressing scheme. These were licensed to far eastern companies.

CRL Opto with Martin Birch and John Seaver founded the only UK LCOS company, now called 4th Dimension Displays.

1991 John Brocklehurst, John Seaver and Martin Birch continued work on SLMs that had been started at STL, using patents licensed from STL.

*In 1997 John Brocklehurst left CRL to start up his own company, John Seaver and Martin Birch moved to Forth Dimension, and Barbara Needham moved to Screen Technology Ltd. John Seaver and Martin Birch have both since died.*

1992 Final break-up of STL Display Group. Bill Crossland became the inaugural Nortel Professor of Photonics in the Engineering Department of the University of Cambridge, and Tony Davey became Leverhulme Research Fellow in Bill’s department.

1993 The “Optically Connected Parallel Machine (OCPM)”. LCOS Optical Switch using fixed holograms built by a UK consortium led by STL and British Aerospace (BAe).

Project finished at Cambridge.

1996 The “Terabit Holographic Optical Routing Switch” (THORNS) LCOS holographic switch built at Cambridge.

1998 Terry Clapp and Dow Corning helped found the Centre for Advanced Photonics and Electronics (CAPE) and partner Cambridge University in developing new organo-siloxane Smectic A materials and devices.

2005 (approx) LCOS holographic switches become a core technology for the Internet. WDM ROADMS built by Cambridge Photonics Ltd, and Finisar Inc. in the USA.

2013 LCOS Holographic head up displays, designed by Two Trees Photonics, available in Jaguar LandRover cars.

2015 Smectic A electronic shelf labels, designed by Halation Ltd, installed in Chinese supermarkets.
Mainstream Flat Panel LC Display Developments

Commercial liquid displays use a thin layer of nematic liquid crystal between sheet polarisers. They manipulate polarised light.

**Twisted nematic** displays rotate the polarisation direction.

An **active backplane** of switching transistors must be used to address large pixel arrays.

**In phase switching** displays are similar, but remove the twist. Their pixels are switchable $\frac{1}{2}$ waveplates. They are harder to manufacture, but give improve viewing angle.

*Nematic* display need a separate switch for each pixel. They relax when the voltage is removed.

For 30 years, flat panel display industry was based on twisted nematic liquid crystals and amorphous silicon (a-Si-H) thin film switching transistors (TFTs).
Liquid Crystal Over Silicon (LCOS Devices)

The first devices at STL used circuitry on a silicon VLSI chip as a backplane to electrically address a thin layer of liquid crystal material.

STL was granted patents in 1978.

It was first proposed for handheld text devices.

Current devices may have backplanes with >50 million silicon gates on a chip measuring a few square centimetres. The whole electronic system is integrated onto the chip.

They are now used for cinema projectors, micro projectors and holographic projectors, and telecommunications devices.

Ferroelectric liquid crystal LCOS devices are binary and very fast.

First devices made in partnership between STL and Edinburgh University around 1990
LCOS Projectors

**LCOS Cinematic Projectors**

Most high quality cinematic projectors project from LCOS devices, (one for each colour RGB) e.g. Sony VPL projectors and JVC DILA projectors.

Currently - the only native 4K projectors are liquid crystal projectors using LCOS.

Pixel density can be 10 million per square centimetre

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**Holographic 3D LCOS Projectors**

In the late 1990s, Cambridge supplied LCOS devices (and also optically addressed spatial light modulators (OASLMs), also originally developed at STL) to Qinetiq to build a holographic 3D display.

Ford Thunderbird replayed as a full colour 3D hologram. Required >10 Giga pixels per second. This was achieved by active tiling onto OASLMs.

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Early 640x512 pixel LCOS fabricated at Cambridge
LCOS Projectors

Holographic HUD | 2D LCOS Projectors for automotive head-up displays

In theory, images can be projected from phase-only Holograms with no light loss.

In practice efficiencies near 50% are achieved (<10% for conventional projection).

Focal points can be on a line (1D), a plane (2D) or a volume (3D)

In principle no light is lost, this is energy redirection.

Photonics & Sensors Group

LCOS holographic 2D projectors originated at Cambridge in the late 1990s

With Acknowledgments to Jamie Christmas & Two Trees Photonics

Designed holographic HUDs using phase-only LCOS devices. They are currently in production for Jaguar Land Rover.
LCOS Fibre-to-Fibre Switching Devices

**LCOS switch using fixed holograms and fast LCOS shutters (1988 to 1992) at STL**

A 65 x 64 fibre optic crossbar switch (28dB loss) used fixed phase-only holograms as beam splitters and combiners, with fast LCOS shutters for switching.

Proposed by STL, built by a consortium including STL and lead by BAe.

A fast switching FLC LCOS device was made by STL/Cambridge.

**LCOS low-loss dynamic holograms Switches (1993 to 2002)**

Following the transfer of technology from STL, in the late 1990s, Cambridge supplied LCOS devices (and also optically addressed spatial light modulators (OASLMs), also originally developed at STL) to Qinetiq to build a holographic 3D display.

Programmable phase-only holograms are written directly to the LCOS device.

The holograms (or gratings) steer the beam from one fibre to another with little light loss.

ROSES, (Reconfigurable Optical Routing Switches) and THORNS (Terabit Holographic Optical Routed Network Switches) Projects supported by Nortel & Thomas Swan (Cambridge Photonics)
LCOS Fibre-to-Fibre Switching Devices

LCOS Wavelength Selective Switches (WSSs)

Wavelength Selective Switches (WSS) are the key components of reconfigurable add-drop multiplexers (ROADMs) for wavelength division multiplexed WDM) systems.

LCOS holographic beam steering devices are now a core technology for these applications and a core component of the internet.

Cambridge Photonics Ltd developed optical modules based on this LCOS technology.

Modules were brought to the market by FINISAR who are the largest player in the Optical Communications market with 17% of the $8B market

ROADMAP Systems Ltd.in Cambridge is developing a new generation of devices.
Smectic A dynamic scattering was discovered at STL in the mid-1970s at STL when it was observed whilst attempting to orient a Smectic A liquid crystal with an electric field. The light scattering could be reversed by dielectric re-orientation.

The scattering and transparent states are all indefinitely stable, but can be changed when a suitable voltage waveform is applied. This enables very large array of pixels to be addressed by switching one row at a time.

This can only be achieved with conventional nematic liquid crystals (which relax when the voltage is removed) if a transistor switch is included at each pixel.

For this reason Smectic A displays manufactured at STL were probably the first page oriented text displays, the first ‘full A4’ panel text displays.

Because the liquid crystal switches line-at-a-time it takes >1 second to change a page of information. Thus they are not suitable for television displays.

However the development of amorphous silicon transistors technology (TFTs) in the mid-1980s provided transistor switching arrays for use with twisted nematic liquid crystal displays that could be switched fast enough for television.

These superseded Smectic A display displays and dominated the display industry for more than 30 years.

The unique property of Smectic A displays is that they only consume electric power whilst the information is changing. They also do not use polarisers and are therefore can be bright in natural illumination.

These properties have enabled them to be used in a number of ‘niche’ markets that have developed as display technology has diversified.

They are suitable for displays where active matrix addressing is difficult i.e. ultra high resolution displays, very large display (e-posters and windows), and displays for viewing in natural light.

Principle of Multi-stable Smectic A Displays

Schematic of SmA liquid crystals

AC low frequency (~50Hz; >60V RMS)

Clear State LC

Scattered State LC

Schematic of state changing conditions

\[
[V_{th(clear)}]^2 = \frac{2\pi \cdot K_{11} \cdot d}{\varepsilon_0 (\varepsilon_0 - \varepsilon_\infty) \cdot \lambda_0}
\]

AC high frequency (1-22kHz; >60V RMS)

\[
[V_{th(scat)}]^2 = \frac{2\pi \cdot K_{11} \cdot d}{\varepsilon_0 \cdot \varepsilon_\infty (1 - \frac{\sigma}{\sigma_0}) \cdot \lambda_0}
\]
Smectic A at STL/STC

Terminal display & Low Power Tablet display panels made at STL in the mid 1980s

Large A4 size (7.7 x 10.1 inch) panels with 420 x 780 pixels were built at STL.

For a brief period a production unit was set up by ITT Courier at Tempe in Arizona, USA circa 1985.

The applications targeted included a very low power reflective e-books display.

‘Chip-on-glass’ electronic drivers

In the late early 1980’s integrated circuit drive chips using a custom merged technology were developed by the ITT BTM (Bell Telephone Manufacturing).

Low voltage control circuits were included on the same integrated circuit as high voltage drivers.

All control logic and level shifting was contained on the integrated circuits, each of which had the capability to drive 30 pixel rows or columns and was configured for automated tape assisted bonding onto the glass display panels. The prototype chip had an area of 27mm².

These were probably the first ‘chip-on-glass’ displays to be manufactured.

A recent account of the development of Smectic A technology has been given in: "Smectic A Memory Displays” in The 7th Liquid Crystal Handbook, by W A Crossland, A B Davey, D P Chu, T V Clapp, published by Wiley-VCH, 2012
New Smectic Displays

Road Signs and Street signage in Scandinavia

Originally licensed via STC, the Polydisplay AS, Norway Company was established in 1996.

They developed a plastic cell technology’ which they refer to as: ‘Electrically Addressable Smectic Liquid Crystal’

Signage in China, Halation Photonics Corporation, Suzhou

Prototype Halation WhiteonTM electronic shelf edge SAM displays

Prototype Silkink™ (Halation) point-of-sale window displays using colour filters

Current Halation product installed in supermarkets in China as of October 2015
**Smart Windows**

**Societal Needs**

Sustainable development has become a key aspect of legislative and governmental guidance.

The energy economy, water usage and the aesthetics of the built environment have become design issues.

Resource management, whole product life-cycle and cost and materials efficiency are key.

So, what can an Smectic A 'display' system do?

In 2008 a work-shop was held in Cambridge to evaluate the future of electronics in the Built Environment.

This identified the growth of:

- 'Media Facade'
- Solar-control-glazing
- Public information systems
- Privacy and security concerns

All of which created markets for a totally new class of Smectic A display.

**New Materials and Devices**

New materials for "Smectic A Scattering Devices" have been developed by Cambridge and Dow Corning. These materials have improved light scattering and life times. They are based on novel organo-silicon chemistry:

![Organosiloxane molecular structure]

**Application Specification**

Warranty of 20 years plus...

Environmental stability against sun, weathering, wind buffeting...

Electronics that can be sustained against installation and operation of decades...

Manufacturing innovation to enable large area; arbitrary shape and form (flat or curved) etcetera... all at a cost point appropriate to construction industry demands!

Water-clear to uniform white (or a colour of your choice)...

![Flexible plastic ETFE foils developed with very high clarity]

![Foils in scattering and clear states, overlaying printed pages]

![Comparative Light Scattering]
Smart Windows

Eden project: Example of an ETFE (ethylene tetrafluoroethylene) clad building

Solar control foils assembled over a window overlooking an adjacent office block. (Cambridge 2009)

Final Comment

LIQUID CRYSTAL work originating at STL is now important in: displays, optical switching, real time holography and solar control.

Structured materials based on liquid crystals (mesoscopic phases) are now being used to improve performance in such areas as: OLED (organic light emitting diode) display and barrier dielectrics and phase and amplitude modulators in microscopy for aperture control and sub-wavelength tomography...

...quite apart from being fundamental to all living systems

Terry Clapp