4B20 Crib - 2015 - Text is longer than expected from candidates

Question 1: Radiometry: 6 out of 8 candidates answered this question. The average raw mark was 13.7 out of 20.

a) Well answered, but a few candidates confused the radiometric terms and surprisingly few knew what a lumen was. b) Well answered in general with a good knowledge of the two visual regimes and the function of the eye. c) Not so well answered with many confusing the CIE chart with the V(λ) curve. d) Quite well answered but few got the importance of the linewidth of the source. A few tried to argue etendu, which is not so obvious an advantage

Q1 a) [30%] Radiometry and photometry are, both, systems, terminology, mathematical relationships, measurement instruments and units of measure devised to describe and measure electromagnetic radiation and its interaction with matter. Radiometry is the pure measurement of radiation with respect to wavelength, whereas photometry is the measurement of radiation as seen through the response of the human eye. There are many different units in radiometry and photometry, some of which are now purely historical, but still cause considerable confusion. There is now a serious move all over the world to standardise these units under the SI system. It is important to note that the calculation of the radiation from complex shaped source such as a tungsten filament light bulb can only be approximated without the use of numerical simulation of the radiometric properties.

It is important that the nomenclature of radiometry is standardised, which seems to be the case in modern literature. For radiometric units, it is quite common to use the subscript *e* (Φ_e), to define the *energy* properties, whereas photometric units often bare the subscript *v* (Φ_v) to indicate the *visual* dependence of the units. This is a matter of choice. In the case of wavelength, the unit is standardised through the use of subscripts. If the radiometric quantity Φ is used without reference to wavelength then it has no subscript. If Φ is to be referenced to a wavelength λ. For every radiometric unit, there is a corresponding photometric unit, usually denoted by the use of the subscript *v* for visual. The difference between the two, is that the photometric quantities have been corrected for the wavelength response of the human eye. The response of the eye is given in terms of the spectral luminous efficiency V(λ), and is often referred to as the V-lambda curve. It is often more useful to refer to the **Radiation Luminous Efficacy** K_r, which is the ratio of luminous flux to radiant flux.

$$K_r = \frac{\Phi_v}{\Phi_e}$$

This ratio is like a normalisation of the radiometric and photometric quantities and explains the often-differing constant used in converting a radiometric value to its corresponding photometric equivalent. To add to the confusion, there is also a corrected version of the V-lambda curve produced as a supplement to that above, which shifts the peak response at 555nm by a factor of 1.0002. This is not used here and is usually only used in high accuracy situations. The peak efficacy as shown on the other axis peaks at a value of 683lm/W, hence we use this as the constant in converting photometric units. Other sources quote the figure 685lm/W and there are further variation on the theme.

The **Radiance**, L_e is the area and solid angle density of radiant flux or the radiant flux per unit projected area and per solid angle incident on, passing through or emerging in a specified direction from a specified point in a specified surface. Radiance has units watt/m^{2}sr and the defining equation is

$$L_e = \frac{d^2\Phi_e}{d\omega ds} = \frac{d^2\Phi_e}{d\omega ds_0 \cos\theta}$$

The luminous flux Φ_v is the basic unit of light power seen in the visible spectrum. It has units of **lumens** or **lm**.

The **candela** is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian. In other words, this definition states that at a specific frequency of green light, a monochromatic radiant intensity of 1/683 W sr^{-1} will produce a luminous intensity of 1 candela. Therefore, at this specific frequency of green light, 1 watt of radiant flux is directly equal to 683 lumens.

b) [25%] When a scene is viewed in good lighting conditions (illuminance levels > 50 lux) the spectral response of the eye is not affected by the actual level of illumination. These are the conditions for **photopic** vision, in which the visual process is entirely governed by cone receptors. There are three different types of cone receptor in the normal human eye, which have three distinct visual pigments, and these provide the basis for trichromatic colour vision, i.e. under photopic conditions, we have colour vision. The photopic condition is the most common one, the condition under which most observations are made and, most important from the photometric point of view, the eye is in a stable state.

Under very dim lighting conditions (illuminance levels < 0.05 lux) only the rods are sensitive and the eye operates in quite a different mode. This is the region of **scotopic** vision and extends down to the visual threshold which corresponds to an illuminance in the region of three microlux. Since there is only one type of visual pigment associated with rods (rhodopsin), there is no colour perception and the world is grey. However, this is also a situation in which the eye is operating in a stable condition. One of the anomalies of the scotopic range of vision is that an object may be visible 'out of the corner of they eye' (in the periphery) but invisible when viewed directly.

The ability of optical radiation to produce a visual response is termed the luminous efficacy of radiation, denoted *K.* It is defined as the quotient of luminous flux by the corresponding radiant flux, measured in lumen per watt (lm W^{-1}). $K = \Phi_v / \Phi_e$ There are two scales of luminous efficacy of radiation, one for photopic adaption *K* and one for scotopic adaption *K'*. Both *K* and *K'* are functions of wavelength; figure15 shows these functions, $K(\lambda)$ and $K'(\lambda)$, plotted against wavelength.

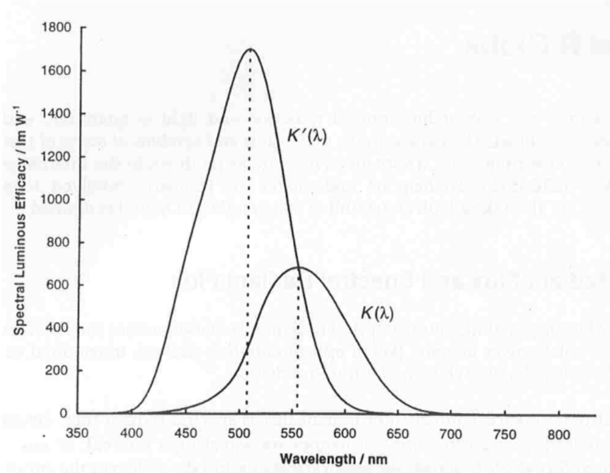


Figure . Spectral Luminous efficacy functions for photopic and scotopic vision.

To calculate the luminous flux in lumen produced by a radiant flux measured in watts, the radiant flux is weighted using the appropriate spectral luminous efficacy function *K(λ)* or *K'(λ).* Thus for photopic conditions:

$$\Phi_v = \int_{360nm}^{830nm} \Phi_{e\lambda}(\lambda) K(\lambda) d\lambda$$

$$\Phi_v' = \int_{380nm}^{780nm} \Phi_{e\lambda}(\lambda) K'(\lambda) d\lambda$$

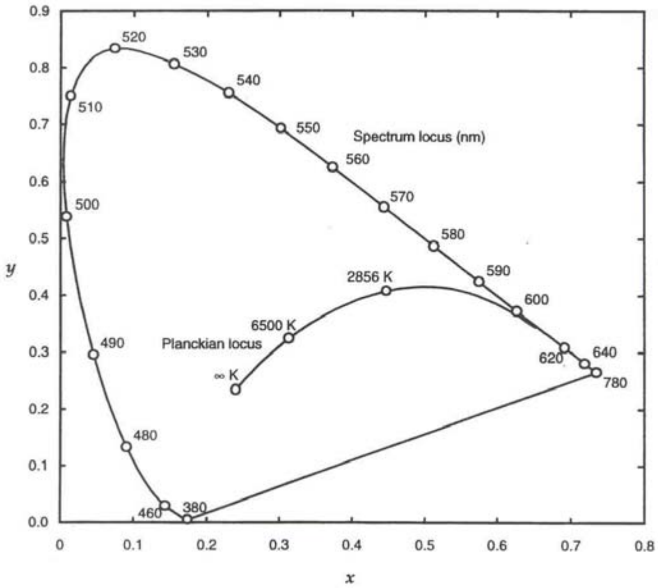
And for scotopic vision:

This means that there are two scales of luminous flux and hence two values of lumen, the photopic lumen and the scotopic lumen. It is not always realised that these are two totally different units. The scotopic scale is generally restricted for special situations where the eye is dark adapted, and so the interest in scotopic measurements is very limited.

c) [25%] The trichromatic nature of colour vision (the cones of the eye) means that a given colour stimulus can always be matched by a combination of a maximum of three suitable primaries. This physical fact is the basis for a system, adopted by the CIE in 1931, in which all colours of light stimuli can be plotted. Since the colour is only affected by the proportions of the three primaries [X], [Y] and [Z], the values can always be adjusted so that x + y + z = 1 where:

$$x = \frac{[X]}{[X]+[Y]+[Z]} \qquad y = \frac{[Y]}{[X]+[Y]+[Z]} \qquad z = \frac{[Z]}{[X]+[Y]+[Z]}$$

This permits the use of a two-dimensional plot, known as the x, y chromaticity diagram.



All humans perceive colour slightly differently, so the CIE (in 1931) introduced the standard colour matching functions $x(\lambda)$,y(λ) and z(λ).These serve a similar purpose to the $V(\lambda)$ function defined by the CIE for photometry , by ensuring that everyone makes measurements on the same basis.

When a display is designed, colour is nearly always generated by three primary colours such as read green and blue. The wavelengths of each primary can be plotted on the CIE chart to form a triangle known as the colour gamut. The total number of colours that can be generated by the display are limited by the area covered on the CIE chart. Colour outside the gamut cannot be displayed and this leads to visual error with the display such as a metarism where two different colours appear identical when displayed.

d) [20%] The corner coordinates of the CIE gamut represent the primary colours which are used as sources within the backlight. If a laser light source is used for a primary colour then it offers two advantages in terms of the CIE gamut

i) The wavelength of the laser is very well defined and forms a very narrow linewidth light source. If the correct types of laser are selected for the backlight, then the position of each corner of the CIE gamut will be right on the edge of the CIE diagram. This allows a very large triangle to be generated and therefore a very large number of colours giving a very bright and colourful display. Also the green wavelength can be chose to be very near the top of the CIE chart to give maximum gamut.

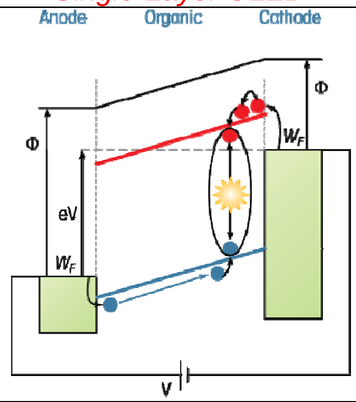
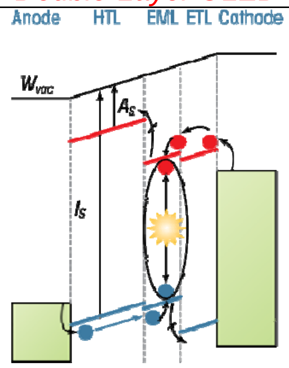
ii) The laser sources will have very narrow linewidths and therefore the colour component functions will not overlap, leading to less confusions and colour similarities such as metarism. The linewidth of the source is also the effective area of any point generated in the CIE chart which leads to purer and better defined colours.

Laser light sources can be modulated very quickly which allows for the backlight to be switched off quickly, generated a better dark state and higher contrast. It also opens up the possibility for a colour sequential backlight.

Question 2: AMOLED backplanes: 6 out of 8 candidates answered this question. The average raw mark was 12.5 out of 20.

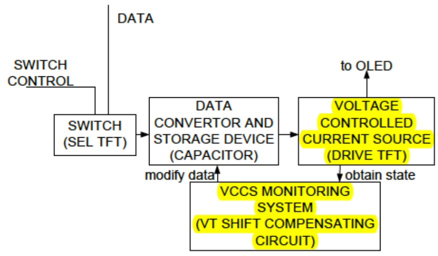
a) Generally well answered with a good understanding of hetrojunctions and good figures. Most got the different advantages. b) Bookwork section well answered. The better answers detailed issues such as the variation of voltage threshold compensation in AMOLEDs. c) Relatively poorly answered, with several candidates only listing a few attributes and several producing bogus tables. Few mentioned process temperature and claimed higher mobility. d) Poor section, most just copied diagrams from notes without further discussion or expansion.

Q2 **(a) [25%]**

<table>
<tr><th>Single-Layer OLED</th><th>Double-Layer OLED</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Energy levels in single layer OLED; W_{vac} denotes the vacuum level, W_F the Fermi level, and F the workfunctions. For equally efficient electron and hole injection and equal carrier mobilities, exciton recombination takes place near the middle of device. Otherwise exciton moves towards electrode of reduced efficiency thereby reducing emission efficiency.</td><td>Energy levels in a double heterojunction OLED; I_S denotes ionization energies and A_S the electron affinities. Here, materials are chosen to maximize injection and to pose a barrier for holes to reach the cathode and electrons to reach the anode.</td></tr>
</table>

(b) [25%]

<table>
<tr><td>In addition to the switching transistor used in the AMLCD pixel, the AMOLED pixel requires a current driving stage (since the OLED is a current-driven device) and a stage to compensate for V_T-shift in the TFT.

Yellow shaded bocks highlight the primary differences in terms of backplane requirements between the AMOLED and AMLCD.</td><td>
</td></tr>
</table>

(c) [25%] Oxide TFTs meet the primary requirements of:

• Low processing temperature: ~300˚C glass, ~350˚C metal foils, ~150˚C plastic.

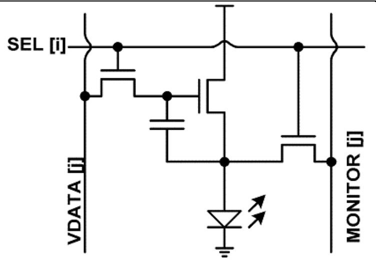
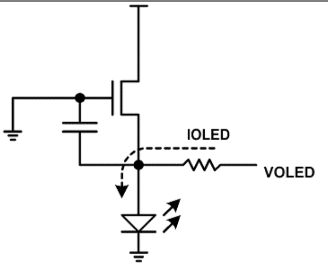
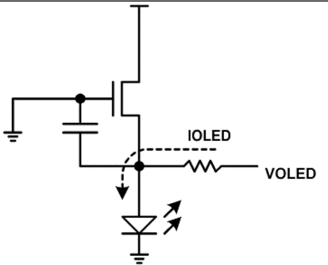
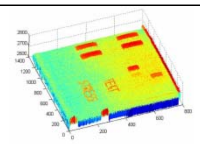
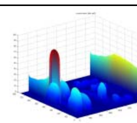
• TFTs with low leakage current, high ON/OFF ratio, low voltage operation, and small area.

• High uniformity/ device matching, high stability and lifetime.

Comparison of key performance attributes:

Attributes	a-Si:H	nc-Si:H	Poly-Si	Organic	Metal Oxide
Conduction	unipolar	ambipolar	ambipolar	unipolar	unipolar
Mobility (μ cm^2/V-s)	1 - 2	10 - 100	> 100	< 1	10 - 100
Stability (ΔV_T)	issue	stable	stable	improving	improving
V_T uniformity	high	high	improving	improving	high
Manufacturability	mature	RF PECVD?	scalability/yield	has potential	sputtering

(d) [25%]

<table>
<tr><th>Pixel circuit</th><th>TFT fault extraction</th><th>OLED fault extraction</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>• Uses V/I of the OLED and drive TFT as independent feedback signals
• Extra monitor and select lines
• External off-panel compensation</td><td>• Gate fixed to a voltage
• V/I is applied to the gate of TFT and the I/V is read back (here OLED is off).</td><td>• TFT is turned off by applying a voltage that makes the gate-source voltage of the TFT less than the initial V_T
• V/I is applied to OLED and I/V read back.</td></tr>
<tr><td>Snap shot of extracted data after one extraction cycle. Compensates for OLED/panel heating (caused by process non-uniformities, line resistances, etc.).</td><td></td><td></td></tr>
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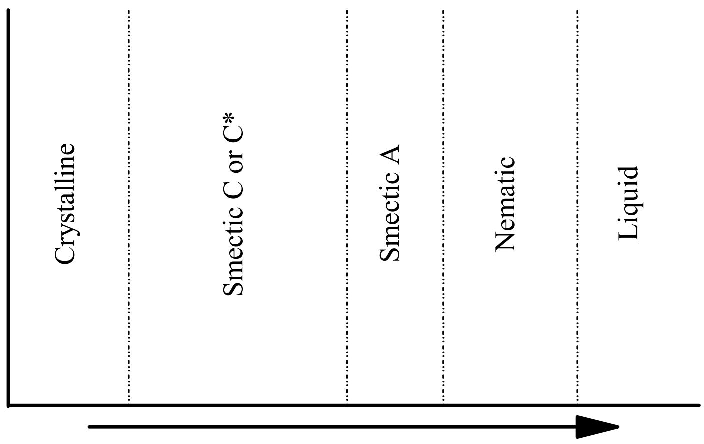
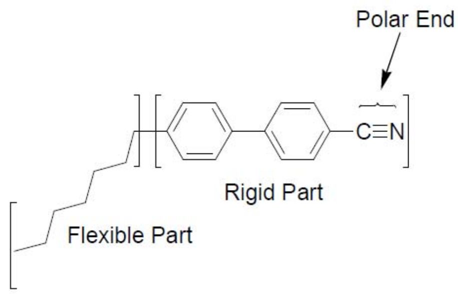
Question 3: Liquid crystal displays: 4 out of 8 candidates answered this question. The average raw mark was 9.25 out of 20.

a) Overall a good bookwork section, but a few tried to argue chirality and not many realized the importance of the overall molecular parts on its performance. b) Mostly well answered but only a few listed the key parameters that should be optimized. c) Well answered overall with a variety of different comparisons made. Most got the differences and the complexity of the electrode fabrication with IPS. One even mentioned S-IPS

Q3 a) [40%] Liquid Crystals are unique compounds with the properties of both liquids and crystals. They exist in mesophases, which have diffuse molecular order and orientation. The ordered or crystalline properties arise from the shape of the molecules and their interactions as they tumble about and is purely a statistical average of their motion. Common molecular shapes for liquid crystals are rod-like (calimatic) and disc-like (discotic). In calimatic LCs, phase changes are often initiated by temperature (thermotropics). Different liquid crystal compounds have difference mesophase combinations. Some are subtle and microscopic changes in order whilst others are much more dramatic.



In general, thermotropic liquid crystals have a similar molecular design to one another, consisting of a rigid part (commonly derived from aromatic rings), a flexible region (accomplished by long hydrocarbon chain(s)) and polar group(s). This is exemplified by 4'-hexyl-4-cyanobiphenyl, where the anisotropic geometry allows for preferential alignment along one spatial direction.



b) [30%] A single liquid crystal compound that can fulfil all the liquid crystal specifications for an active matrix display application is not possible. For example, compound 5CB has a melting point of 24 ^{0}C and a clearing point of 35 ^{0}C but the melting point of a binary mixture compound is less than either of its constituents and melting point of the mixture depends on the mixture ratio. At the eutectic point, the melting point reaches its minimum, however, the clearing point of the liquid crystal mixture is usually the linear average of the mixture composition. A mixture of two or more liquid crystalline compounds can offer a much larger temperature range that exhibits the nematic phase for a display application.

In addition to this phase range, many other physical properties, such as dielectric constants, dielectric anisotropy, elastic constant, birefringence and viscosity, also depend on the mixture ratio. Many of the liquid crystal mixtures are designed to provide optimum parameter for a particular application. For an active matrix display there are 4 main parameters which should be optimised by the mixture.

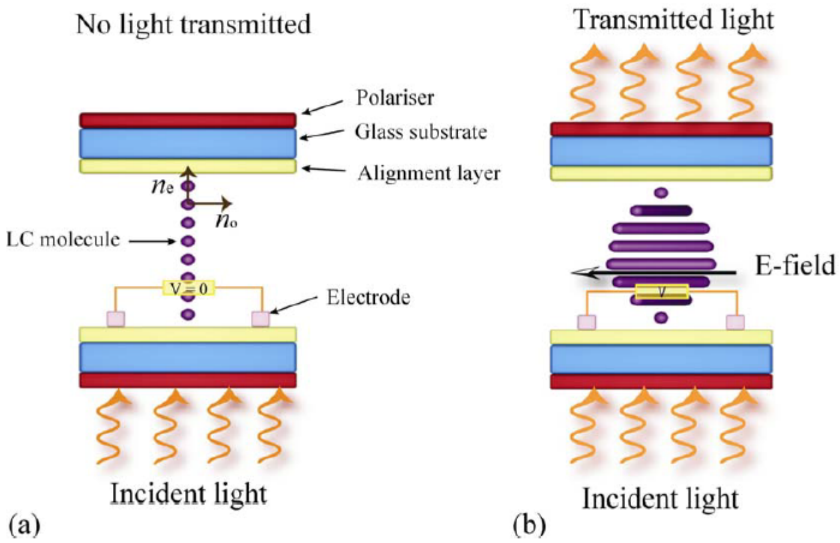
i) Temperature range - typically -10 to 80^{o}C

ii) Viscosity to minimise the response time of the display

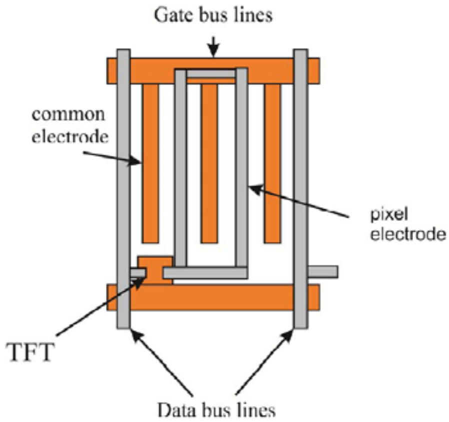
iii) Dielectric anisotropy - to reduce the switching voltage or field.

iv) Purity, ionic and polar groups are not allowed to minimise the conductivity

c) [30%] An IPS device exploits the wave-guide nature of twisted nematics. In this case the fringing field generated by inter-digitated electrodes causes the LC molecules to rotate in the plane of the cell.



When no electric field is applied the LC molecules adopt a homogenous alignment whereby the nematic director is parallel to the transmission axis of one polariser but perpendicular to it at the other. Therefore, incident light experiences no phase retardation and the light is absorbed by the analyser. However, when an electric field is applied across the electrodes located on one surface in the transverse plane the molecules are then forced to reorient, this facilitates transmittance through the analyser due to phase retardation. Since the switching mechanism is in the plane of the device the viewing angle is much wider than for conventional TN cells. The molecules are bounded at the substrates due to strong anchoring conditions.



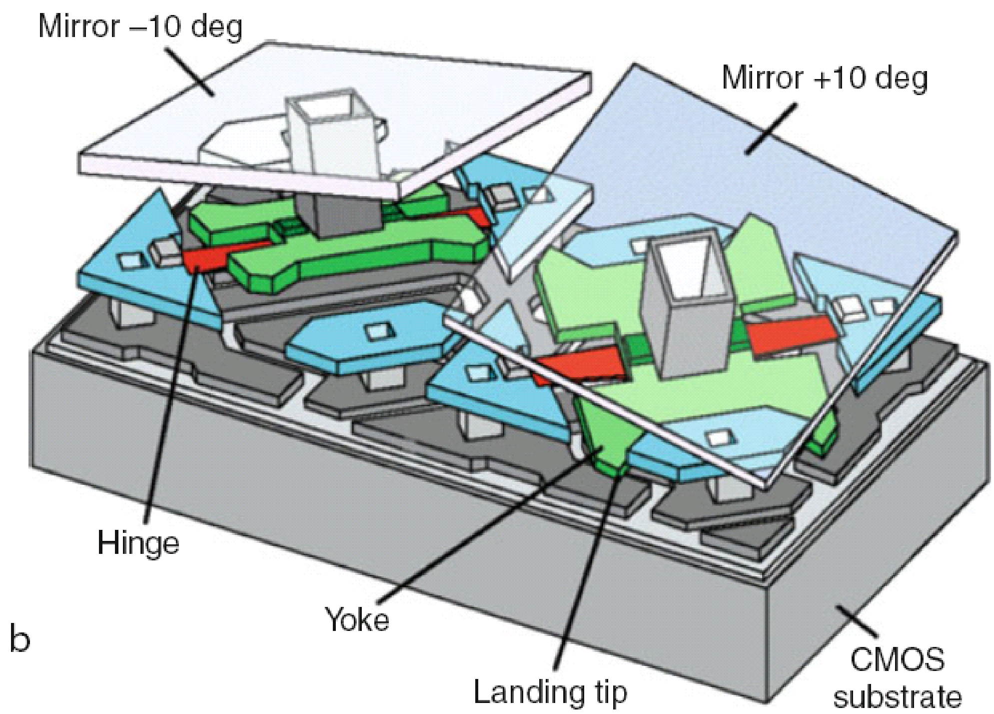
One drawback with IPS is that the electric field is not uniform: there are both vertical and horizontal components of the field. As a result, there is some out-of-plane rotation of the molecules. The dimensions of the electrodes and spacing are also important, particularly in terms of the transmission properties. In order to maximise the transmission, the width of the electrodes must be decreased and the separation must be increased.

For out-of-plane rotation the polar angle is different for different viewing angles. Since the effective birefringence depends upon the polar angle, this means that the transmittance varies with viewing angle. The azimuth angle, on the other hand, is relatively independent of viewing angle. Therefore, in-plane rotation of the molecules inherently has a wide viewing angle compared with out-of-plane technologies. However, a colour shift does exist for single domain IPS pixels. To minimise the colour shift with viewing angle, super-IPS LCDs have been developed whereby the electrodes form a chevron pattern: this improves symmetry and minimizes colour shift.

Question 4: Projection displays: 8 out of 8 candidates answered this question. The average raw mark was 14.6 out of 20.

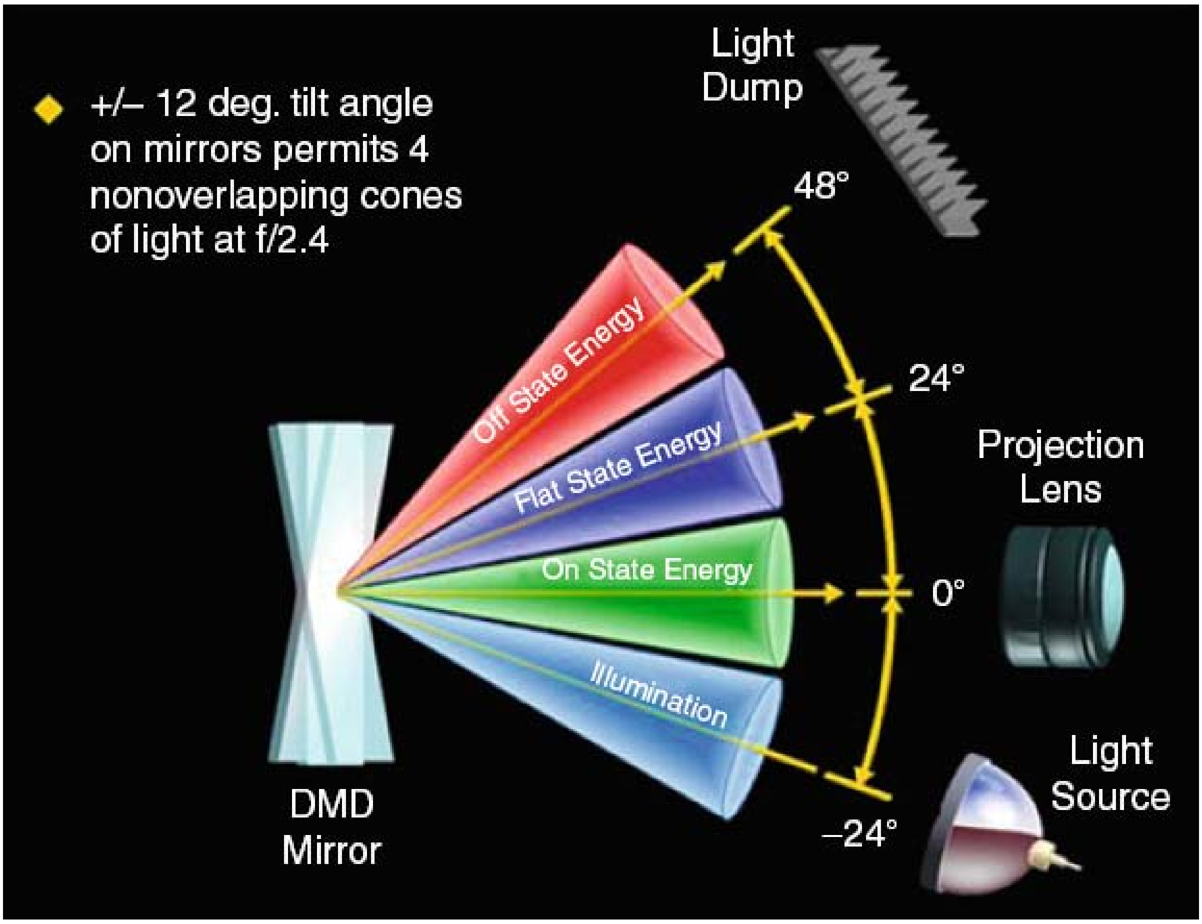
a) Overall good answers with some very entertaining diagrams of the DMD. Well defined modulation structure and angles. b) Most got the limits of binary and the role of PWM. Most also spotted the sensitivity of the eye and issues with colour breakup. c) Well answered in general, but several candidates listed two types of passive filters rather than active shutters.

Q4 a) [40%]

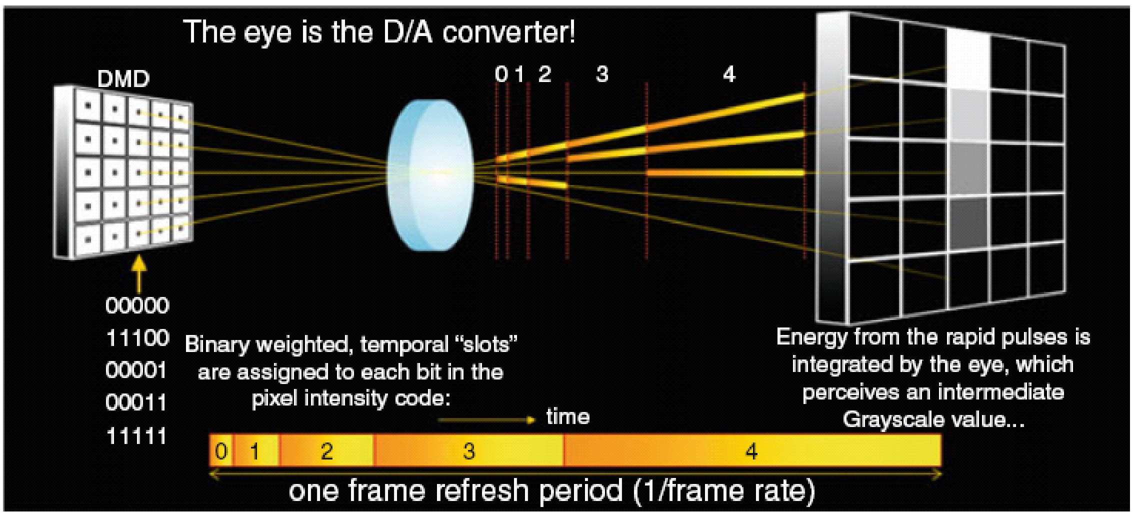


The square mirror is suspended between posts with a flat metallic torsion hinge. At rest, the mirror remains horizontal and flat. Underneath the mirror is a silicon memory cell (Static RAM) that stores a digital value (1 or 0) just like any computer memory cell. The difference between this RAM and a normal computer memory is that the outputs of the cell are wired to a pair of offset address electrodes on the surface of the silicon. These electrodes are wired so that a positive voltage appears on one side or the other depending on the memory value.

The differential voltage appearing between the mirror and the address electrodes causes the mirror to be attracted to tilt to one side or the other. The mirror moves all the way so that its tip touches down at a landing surface. The device is thus an electrostatic/torsion balance. The torsion in the hinge creates a restoring force to help the mirror return to its flat state once the mirror is released. The mirror can therefore be switched from tilted left to tilted right. The mirror angle is 12° from flat (in most versions). Mirror rotation from ‘‘1’’ to ‘‘0’’ is 12 + 12 = 24°. This movement allows a beam of light to be switched through 48°.



b) [30%] The main limitation of the DMD is that it can only steer light from an ‘‘on’’ to an ‘‘off ’’ condition where we have light or no light for every picture element (pixel). Hence it is only a binary intensity modulator. Computer graphics typically produce 8bit grayscale values that correspond to 256 brightness levels (2^8). This is produced on DMDs using the image equivalent of pulse width modulation.



The dithering of grayscales are then combined with the RGB colour components via a colour wheel to make a full colour image. The problem with this technique is the fact that the eye responds much faster to colour information that it does to intensity. The photo-sensitive layer which covers the inner surface of the eye is the retina. The retina is made up of large numbers of receptors which can be classified into two groups, named by virtue of their shape as rods (colour) and cones (intensity) and the cones respond faster than the rods. This leads to the phenomena know as colour breakup.

c) [30%] There are two basic techniques that can be applied to the DLP system. One is to switch the polarisation for each L and R view usually with an externally applied LC modulator. This requires passive glasses to be worn to filter out the L and R views. It also requires a non polarised light source (which the DLP is) and a polarisation maintaining screen The second option is to switch alternate L and R views on the DLP and then synchronise this with a pair of active shutter glasses to select which eye sees which view. This also works better with a polarised source but can work with any screen
The main limitation of this type of display is that they assume that each eye acts like a camera, which is not the case in reality. This leads to side effects such as headaches and nausea.