

# **Advanced Die-Level Assembly Techniques and Quality Analysis for Phase-Only Liquid Crystal on Silicon Devices**

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## **Abstract**

In this paper, quality analysis of the assembled phase-only liquid crystal on silicon devices (LCOS) devices is presented based on experiences using the flexibility and scalability of die-level assembly process. The research contents mainly consist of quality control and optimisation of liquid crystal (LC) filling process and device overall quality assessment including the thickness uniformity of LC layer with post-assembly inspection. To summarise, pre-production prototype phase-only LCOS devices with high quality has been developed in high reproducibility using a die-level assembly process, the robust glue deposition is performed, LC filling process in isotropic phase is presented and thickness variation can be controlled in the range of  $\lambda/4$ .

**Keywords:**

Liquid Crystal on Silicon, Phase-Only, Die-Level Assembly, Liquid Crystal Filling

**1. Introduction**

Liquid crystal on silicon devices (LCOS) assembly technology has been considered previously for ferroelectric liquid crystal devices <sup>[1]</sup> and nematic liquid crystal devices <sup>[2]</sup>. Commercial amplitude modulating liquid crystal on silicon (LCOS) devices utilise wafer-level assembly techniques <sup>[1]</sup> adapted from established LCD <sup>[3]</sup> high-volume production lines. For instance, the successful JVC D-ILA projectors use the VAN mode LCOS devices produced by wafer-level assembly process <sup>[4]</sup>. The wafer-level approach assembles large size glass panels on whole silicon wafers, and then the assembled samples are diced into individual LCOS modules. However, for phase modulating LCOS devices, the assembly quality is required to be better than that of amplitude modulating ones because the uniformity of optical response across the device is demanded for customised applications of high accuracy of wavelength selective switches (WSS) <sup>[5]</sup>, reconfigurable optical add-drop multiplexers (ROADMs) <sup>[6,7,8]</sup>, optical correlators <sup>[9,10]</sup>, adaptive optics in medical sciences (e.g. ophthalmology <sup>[11]</sup>) and defense industry <sup>[12]</sup>. Since many applications mentioned above are still in early stage of development, therefore the corresponding silicon backplanes are not widely available yet. Additionally

in order to meet the basic condition of proposed applications, glass substrates and LC materials are required in a different way. To summarise, most applicable and appropriate pre-production device prototyping<sup>[13,14]</sup> using die-level assembly process<sup>[15]</sup> is suitable to highly flexible and efficient for the selection of different devices and materials. The advantages of using die-level assembly process are not only allows individual examination and optimisation of each process step in the assembly processes for quality control of phase-only LCOS device fabrication, it is also an economical fabrication process using inexpensive commercial equipment in comparison with those used by wafer-level process.

The die-level advanced assembly process for the prototype of phase-only LCOS device is the procedure to ultimately attach the glass substrate and silicon substrate together. The previous reports involving a complicated multi-step procedure were described by Choubey<sup>[16]</sup> and D. Cuypers<sup>[17]</sup>. These includes mechanical and thermal treatments, optical inspection of the individual substrates, such as polyimide alignment treatment, glue dispensing, LC material filling and sealing etc. After these steps, the LCOS device is interfaced to external components so that it can be placed in an optical characterisation system for specified applications. However, the good quality of those assembled devices cannot be guaranteed because some of processes are manually manipulated. Therefore, a robotic semi-automatic machine<sup>[18]</sup> has been employed to complete the step-by-step packaging procedure of the die-level assembly of phase-only LCOS device with excellent

quality <sup>[14]</sup>. Fig.1 indicates the reported work <sup>[15]</sup> including pre-assembly inspection for the curvature match of the glass and silicon substrates and robust glue dispensing process. Baking program is utilised to evaporate the solvent of polyimide materials, rubbing process is to create “grooves” in order to align the LC materials on the substrate surface with desired orientation, glue-curing process under high efficiency UV exposure is taken to further age the adhesive sealing materials.

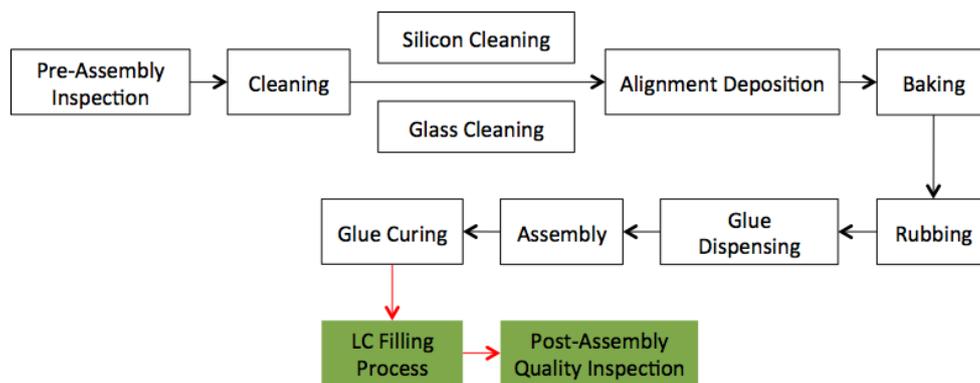


Figure 1: The designed assembly process for phase-only liquid crystal on silicon devices

In this research, further development of die-level assembly process for phase-only LCOS devices is presented, particularly on upgrading techniques on LC filling process and overall quality assessment. LC filling process using the designed equipment with a temperature-adjusted system and details of filling procedures are described in this report. In addition, an Olympus BX 51 microscope is employed during the experiment for LC layer inspection and its thickness measurement of assembled devices. As the result of

using advanced controllable die-level LCOS assembly process and quality inspection of gap thickness based on the previous designed assembly steps reported before, the in-house assembled phase-only LCOS device is eligible to achieve the necessitated tolerances for LC thickness ( $< \lambda/4$ ) with post-assembly inspection in high reproducibility. This not only implements our own research such as free space<sup>[19]</sup> and fibre switches<sup>[20,21]</sup> optical interconnects in crosstalk mitigation but also supplies to other research institutions and industrial users for system development and product evaluation.

## **2. LC Filling Process**

LCOS devices should be filled before mounting and bonding in order to avoid uncertain contamination to ingredients of LC materials. The alignment quality should also be assessed before filling process<sup>22</sup>. For example, the rubbing cloth might be left on the substrates during the rubbing process. Contamination from the sealing glue lead to two major effects: one is the creation of secondary electric layers that decrease the effective voltage across the LC layer; the other is the weakening of the alignment strength by bonding to the surface of the alignment material.

The filling hole with a premeditated size should be left so that the LCs can be efficiently filled without any blockage. In general, for non-linear LC materials, three major aspects of materials parameters should be considered: the birefringence, viscosity and

temperature requirement for the phase transition from the nematic to the isotropic. In practice, on one hand, heating might help for the filling process; however, composition of LC materials might be changed during the heating process and this leads to the reduction in the optical properties of LC materials such as birefringence and dielectric anisotropy [23,24,25]. On the other hand, if the isotropic phase temperature of the LC is not reached during the filling process, there is a possibility that the nematic filling flow will affect the alignment of the LC so that the molecules do not lie in the rubbed grooves. This will affect the LC off-state alignment and degrade the switching performance of the LCOS device ultimately. Therefore, an optimised heating process to the nematic phase is required with a high degree of experience. The steps change when different LC materials are applied. In practice, phase-only LCOS devices are filled with the LCs in the isotropic phase as fast as possible without changing the composition of LC materials.

The filling process uses in-house designed vacuum filling rig as shown in Fig.2. This filling rig consists of two heating stages (red), the LC container (blue), joystick (green) and pumping system (grey). The joystick is used to dip the needle into the LC material, and feed the device at the filling hole. It allows the device and the LC to be heated separately. The appropriate heating of the LC will speed up the outgassing process so that gas bubbles in the LC materials can be released more efficiently. This improves reduces the possibility of gas bubbles in the filled devices and the desired optical performance can be guaranteed.

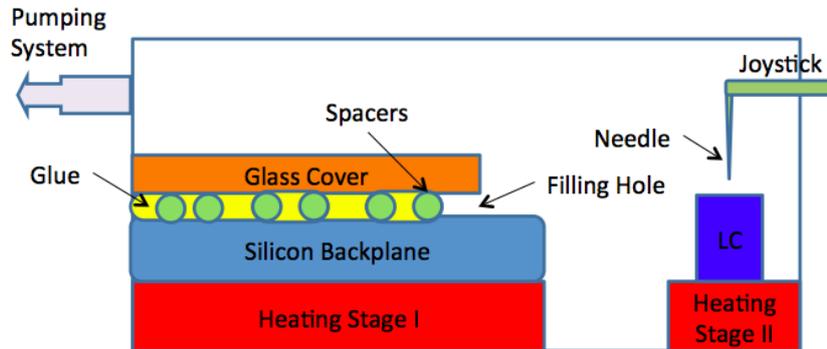


Figure 2: The cross-section schematic of the designed LC filling rig.

Inspection of the filled LCOS device reveals any problems in the assembly process, such as scratches on the substrates, filling flow effects, and glue deposition quality, etc. It is an essential step in the quality control of the LCOS device, offering feedback that will allow improvement of the assembly technique.

In Figure 3, pictures are taken by the BX51 microscope through crossed-polarisers in the dark state. Figure 3 (A) and (B) show a comparison between an empty and filled LC device. As can be seen in the empty device, the glue line is deposited uniformly and does not come into the contact with pixel array. Note: the visible stains are on the front surface of the glass outside the device. However, inspection of filled devices reveals alignment defects caused by microscopic damage to the alignment layer during handling. For example the scratches observed at the left upper corner on the glass substrate. The LC filling process spreading corrugations from the filling hole can also be inspected. These

corrugations are caused because the environmental temperature is not reached the clearing point (isotropic phase) during the filling process (so called “flow alignment”). Furthermore, it may occur if the speed of filling is too fast, due to either an abrupt release of the air pressure in the vacuum chamber, or an oversized filling hole because of poor control of the glue dispensing. In brief, the filling technique is a critical process requiring accurate temperature control and suitable gas releasing. Also it needs to be completed as quickly as possible in order to avoid changing the composition of the LC. Figure 3 (C) shows an example of a LCOS device filled with LC in isotropic phase, thus no flow alignment occurs, the planar alignment with  $2^\circ$  pre-tilt angle is obtained using the rubbing machine AZ-LCD MF7 .

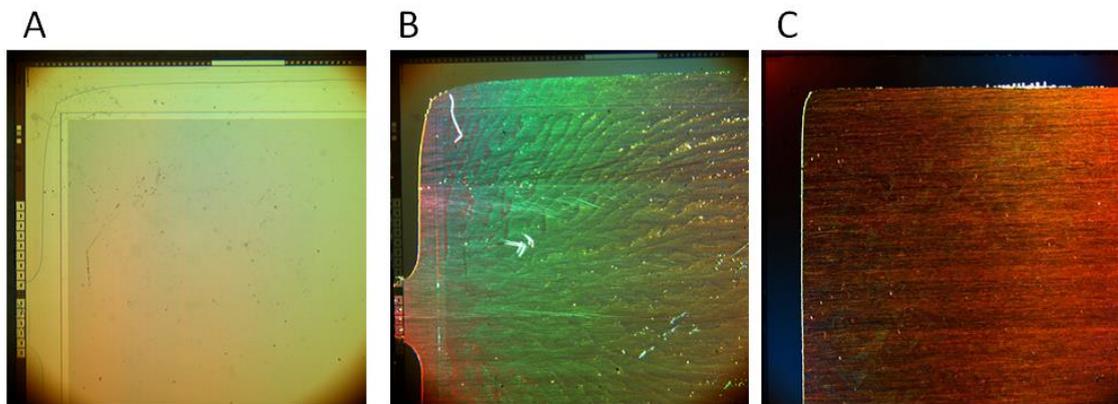


Figure 3: The comparison of LC filling process at the same area of a phase-only LCOS device between the empty and filled states ("A" and "B"), the typical example for the LC filling process in isotropic phase ("C").

### 3. Overall Quality Assessment

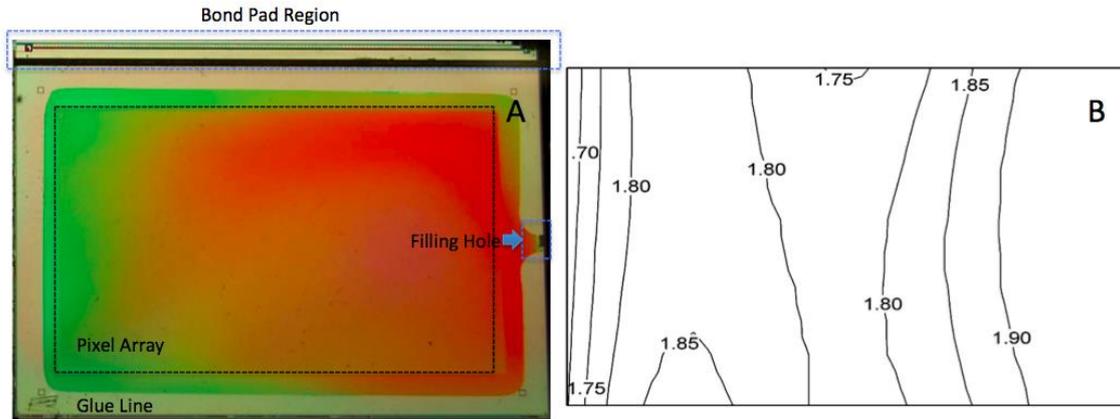


Figure 4: Interferogram (left) and the thickness measurement (right) of a high quality phase-only LCOS device using an Olympus BX51 microscope. Note: the interferogram is taken by the BX51 microscope through crossed-polarisers, the method of thickness measurement is summarised in the separate section at the end of this paper.

Table 1: Statistics of thickness for the device (Fig.4). The average LCOS thickness is 1.816 $\mu\text{m}$ ; the standard deviation is 90nm.

N total	Mean	Standard Deviation
15	1.82 $\mu\text{m}$	90nm

A die-level assembly process for assembling pre-production prototype phase-only LCOS devices of high quality has been developed by using a semi-automated programme-controlled robotic tool (S.E.T Technology Kadett). The overall assembly assessment can be summarised in three major parts which are device thickness uniformity, glue line robustness and in-cell characteristics including LC filling process, alignment rubbing etc.

Figure 4 is an example of the desired quality of devices to illustrate the overall quality of assembled device. In Fig.4, the interferogram is taken using mercury light (365-436nm) and Xenon arc light. The image was captured between cross-polarisers, including differential interference contrast (DIC) prism and objective. These two images normally indicate a number of characteristics of assembled cell. Firstly, average thickness uniformity of the device can be clearly evaluated by reflected colour variation from the pixelated area using Olympus BX51 microscope through cross-polarisers. For instance in Fig.4 (A), the red colour is observed in the most area and the rest is mainly in green. This specifies that the cell has a very good potentiality to achieve the desired quality of thickness uniformity and it is worthwhile to proceed the thickness measurement shown in Fig.4 (B) as the next step. Secondly, the glue dispensing characteristics shown in Fig.4 (A) is also inspected. The width of deposited glue line should be controlled wide enough (about 1.5mm-2mm) to seal the device firmly but without approaching the pixel area depending on the layout of the VLSI circuitry (20mm × 15mm). In addition, the size of the LC filling hole should be 1-3mm depending on the layout of pixelated array in order to maintain the device uniformity and guarantee an efficient material filling process. Thirdly, alignment layer obtained by rubbing the polyimide sufficiently in order to avoid reverse tilt <sup>[26,27]</sup> can be also established that when the LC behaviour can be obviously visualised by the colour differences at the boundary of applied voltages in Fig.5. Because of the colour uniformity shown in Fig5, it indicates that LC filling process have been

executed in isotropic phase. The thickness contour in Fig4 (B) is employed to the thickness measurement. The details of thickness measurement is shown in Tab1, where “N” denotes the device has been divided into 15 areas ( $3 \times 5$ ), the measurement for each area is calculated and then the mean value and standard deviation are obtained.

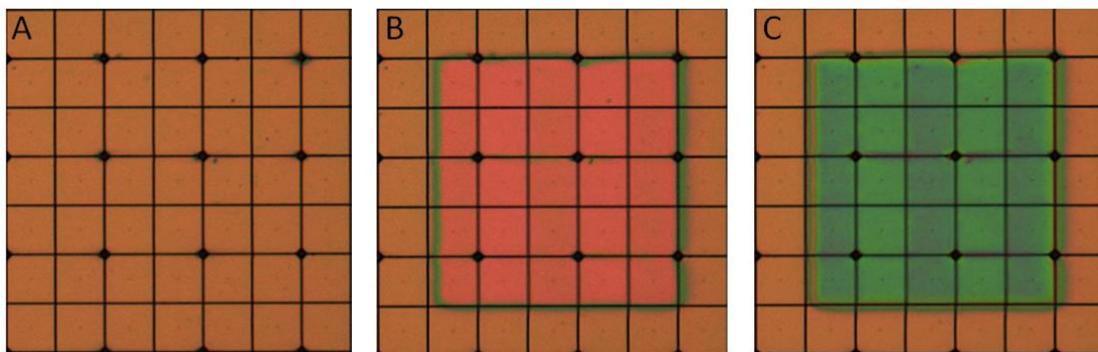


Figure 5: An enlarged view of a  $5 \times 5$  pixel array displayed with different voltages through cross-polarisers using BX-51 microscope. (A) without any applied voltages, (B) 1.4V is applied across the device and (C) 1.6V is applied to the same area. The pixel pitch is  $15\mu\text{m}$ .

#### 4. Conclusion

An established LC filling process and statistical overall quality analysis have been developed for die-level assembly process to ensure the excellent quality of pre-production prototype phase-only liquid crystal on silicon devices. A designed rig is able to implement the LC filling process with moderate filling speed, appropriate filling temperature so that the LC composites can be maintained and injected to the cell without

producing the damage to the alignment layer during the filling process. It indicates that 'Proof-of-principle' phase-only LCOS devices are successfully assembled with the flexibility in choosing the right LC materials and different silicon backplanes. More importantly, the quality of the assembled devices is comparable to that from a commercial high-volume production line. To summarize, the die-level assembly quality for phase-only LCOS devices can be produced with a number of distinguished features: (1) excellent spatial uniformity (less than of  $\lambda/4 \approx 150$  nm), (2) robust glue sealing process and effective UV exposure to maintain the seal strength, (3) LC materials uniformly aligned with no “flow alignment” effect, and (4) quality assurance of individual devices by inspections at each assembly stages.

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### **Method:**

Robotic tool are from S.E.T called K1 Kadett, the die-level assembly process has been performed in class 100 and class 1000 clean room. Thickness measurement using the BX-51 microscope is introduced.

The cell thickness of an empty device was measured using an interference method. When the cells are illuminated, some of the incident light is reflected directly, and some is transmitted and reflected from the back of the glass plate. There is a phase difference  $\delta$  between rays of wavelength  $\lambda$  given by:

$$\delta = \frac{2d \cdot n}{\lambda} \quad (1)$$

where  $n$  is the refractive index, and  $d$  is the cell thickness. It is assumed that the intensity of further reflections is negligible. At certain wavelengths, a phase difference of some odd multiple of  $\pi$  occurs, causing the two sets of rays to interfere destructively and result in minimum transmission. For two consecutive wavelengths that satisfy this condition in air ( $n = 1.00$ ):

$$\delta_{i+1} - \delta_i = 2\pi = 2d \left( \frac{1.00}{\lambda_{i+1}} - \frac{1.00}{\lambda_i} \right) \quad (2)$$

This suggests that plotting successive values of  $1/\lambda_{\min}$  against integer steps will give a straight line with slope of  $1/2d$ . In the cell thickness calculation, the minima were found using MATLAB. Local minima were found based on their first and second derivatives,

and more accurate values were obtained for the minima by approximating each ‘valley’ as a parabola. This was necessary because some of the minima were asymmetric or noisy. The thicknesses were evaluated using a least squares regression. As an example, the transmission spectra for one of the cells both empty and filled are shown in the Fig.5. A correlation coefficient of 0.9999 or better for each linear regression performed on data from each cell confirms the above equation.

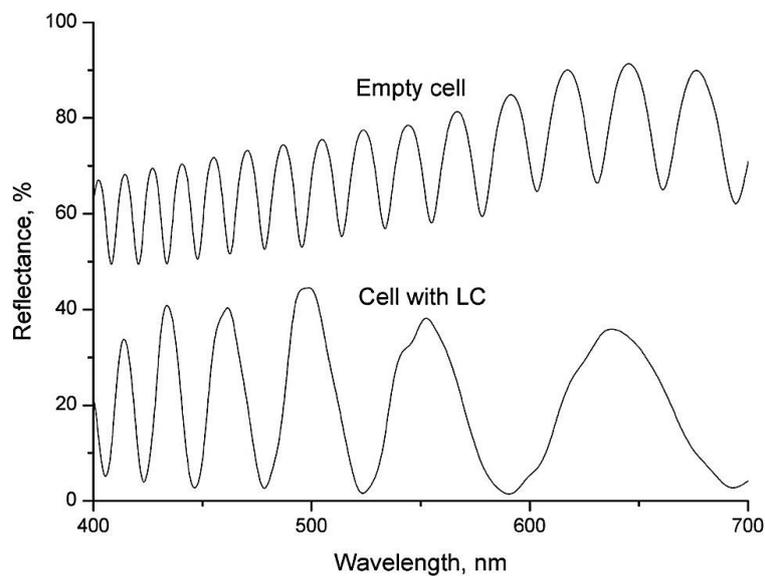


Figure 5: Reflection spectra for an empty device and a device filled with LC between crossed polarisers.

The spectra of a cell filled with LC show clear points of minima at near-zero intensity corresponding to phase shifts of  $2\pi$ . The wavelengths  $\lambda_m$  at which these occurred were used to calculate the phase shift across the spectrum by interpolation.

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