Chapter 3

Fabrication Technologies and Measurement Instruments

The fabrication techniques utilized to fabricate the designed microoptical components will be firstly described in this chapter. These techniques include VLSI semiconductor process, replication with plastic molding, and half-tone mask technology. The instruments, such as scanning electron microscope (SEM) and atomic force microscope (AFM), for characterizing the surface profile and roughness of a microoptical element will be depicted then. Followed by the description of a Conoscopic system, which is utilized for evaluating the image performance of portable displays with the developed microoptical components.

3.1 Introduction

The fabrication technologies of microoptics are getting more and more advanced. With the development of fabrication technologies, smaller and precise structure becomes possible to be fabricated, yielding more and more flexibility in component and system design. The VLSI (Very Large Scale Integration) semiconductor fabrication processes and plastic molding techniques are two well-established processes with the capability of well control in precision and fidelity. Most of all, these mature processes are efficient and economical fabrication technologies to realize the microoptics design in practical applications, satisfying the demands of high quality, high throughput, and low cost. Therefore, we utilized these well developed and economical processes to fabricate the light control films, which will be described in chapter 4, to effectively increase the brightness and contrast ratio for various portable LCDs. Additionally, in chapter 6, the semiconductor fabrication process including mask generating, thermal re-flowing, spin coating, exposure and development were also used to demonstrate the light collecting capability of micro-tube array structure in a transflective LCD.

In chapter 5, a bi-prism reflector (image-enhanced reflector) with continuous surface relief was proposed to enhance the image quality for transflective TFT-LCDs and Ch-LCDs. However, by using binary mask, traditional VLSI process is not easy to form a continuous surface profile of the microoptical elements. Therefore, the technique can directly produce the microoptical elements with continuous surface relief in only one mask step, half-tone mask technology, was developed. Half-tone mask is also a kind of binary masks in which the critical dimension is smaller than the resolution limit of the optical exposure system. Thus, the main advantage of half-tone mask is not only the easy control of the writing and further processing since only binary structure are written but also the higher optical efficiency and lower complexity of process owing to the continuous surface profile of the microoptical elements, with only one mask needed.

The characteristics and performance of these optical components, such as fidelity to the geometric design, uniformity of surface variation were measured by typical semiconductor measurement systems, such as scanning electron microscope (SEM) and atomic force microscope (AFM). The functions of these microoptical components designed for display applications were evaluated by the display characteristic evaluation systems, conoscopic system (ELDIM EZContrast 160R), to measure the improvements in performance of displays. We shall describe the major features of the above mentioned instruments in this chapter.

3.2 Fabrication of surface relief microoptical components

Making microoptical elements by creating a surface relief pattern is presently a common practice of microoptics. Due to multitude of applications for surface relief microoptical components, a range of materials, pattering techniques and actual relief fabrication tools are available, as shown in Table. 3-1[60]. For the continuous and binary surface relief structures, there are different pattern designs and fabrication processes, respectively. Combining the selections of materials, patterning, and tooling techniques, the fabrication procedures can be obtained to meet the requirements with compromise between design specification and fabrication practicality of the designed microoptical components in this thesis, as presented in Table. 3-1.

Except direct tooling techniques, all these processes are similar to the VLSI fabrication processes. The patterning processes include normal lithography/direct writing to produce the binary pattern on the photoresist (PR) layer. After the development, the desired features are patterned on PR layer. Then the fabrication processes transfer the structure from PR to the substrate. However, for the continuous surface relief optical components, the e-beam/laser direct writing with the thermal reflow and gray-tone mask technology are developed for different applications.

The selection of the most suitable material for each specific application depends on the required performance and cost of microoptical device. If the cost is aimed to be few cents, as is the case for high volume production, only plastic materials –polymers with the molding fabrication process can be selected, thus setting an upper limit to optical precision and performance, such as surface uniformity and substrate birefringence. If low volume products is involved, a broad rage of materials are available, such as silica glass, quartz, bulk plastic, or thin film deposited on a transparent substrate.

Table. 3-1. List of materials, patterning, and fabrication tools of continuous and binary surface relief structure.

Binary surface relief structure		
Fabrication technologies		**Applications in this thesis**
Mask patterning	sets of e-beam masks lithography	Light control films (Chapter 4)
	sets of laser masks lithography	
	laser writing	
	e-beam writing	
Structure fabrication	Reactive ion etching (RIE)	Light control films (Chapter 4)
	lift-off	
	wet etching	
	ion milling	
Continuous Surface Relief Structure		
Fabrication technologies		**Applications in this thesis**
Mask patterning	E-beam direct writing	
	Laser direct writing	
	E-beam/ Laser mask lithography (Binary relief on PR) + Thermal reflow (Binary → continuous relief)	Micro-tube array (Chapter 6)
	Gray-tone mask lithography	Image enhanced reflector (Chapter 5)
Structure fabrication	Reactive ion etching (RIE)	
	lift-off	
	wet etching	Micro-tube array (Chapter 6)
	ion milling	
Direct tooling	Electric-discharge machining (EDM)	
	Laser tooling	Image enhanced reflector (Chapter 5)
	Diamond tooling	
Materials		
Fabrication materials		**Applications in this thesis**
Mass production	plastics	
	metal master ↓ plastic molding	Light control films (Chapter 4)
Low volume production	thin film or coated dielectric	Image enhanced reflector (Chapter 5) and Micro-tube array (Chapter 7)
	bulk dielectric	

3.2.1 Semiconductor process and plastic replication for binary relief optical components

The fabrication process to produce a microoptical structure on Si-wafer include mask generating, lithography, and etching is similar to VLSI fabrication processes. Therefore we can implement our fabrications in the National Nano device Laboratory (NDL). First we plot the binary pattern for the designed microoptical elements. Then, generate the pattern to a photo mask in an electron-beam (e-beam) or laser pattern generator. The third step is the VLSI lithography/etching process to produce the desired structure on Si-wafer. Consequently, the designed microoptical component structure is generated.

The detail processes of lithography and etching include initial cleaning, coating PR, UV exposure with G-Line (436nm) stepper, develop, fixing, and RIE etching, as shown in Fig. 3-1. First step is initial clean. Wet cleaning processes are necessary to obtain an ultra clean wafer surface for subsequent fabrication. Then the coating of photoresist will be applied. The wafer is placed on a vacuum chuck in the coater and the photoresist is dropped onto the center of the wafer. A uniform and thin photoresist layer can be coated on the wafer surface after spinning the wafer. Following is Exposure step. The mask pattern is transferred onto the wafer by the projective system with a five times reduction. The exposed wafer is loaded into the development system after exposure. Consequently the desired structure will show up in the photoresist. Etching is then employed to transfer the desired structures from the developed pattern to a wafer. Regions not covered by the photoresist are removed during the etching treatment. Finally, the remained photoresist are stripped by O_3 plasma and the fabricated microoptical structure is represented on the Si wafer.

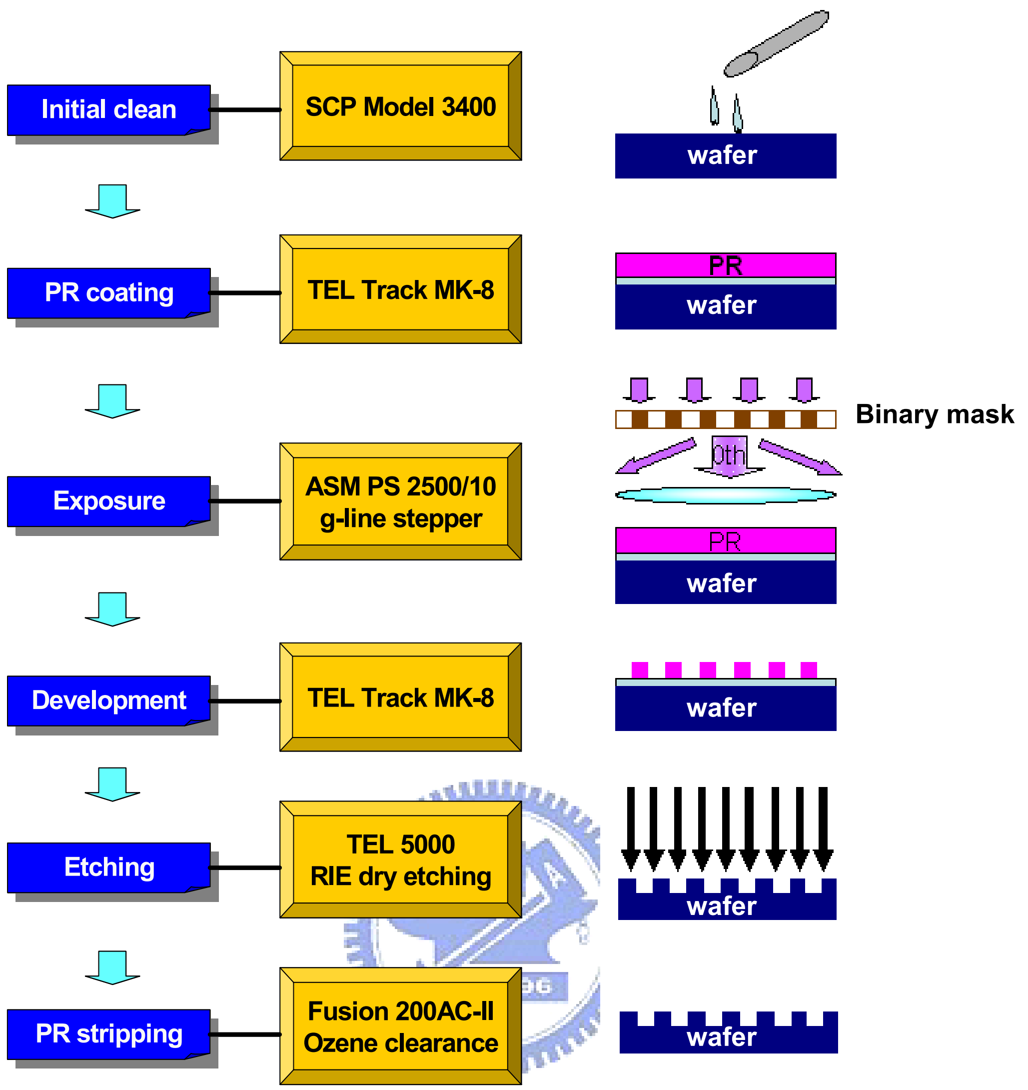


Fig. 3-1. Detail processes of lithography and etching to realize the technology of half-tone mask.

The above mentioned process is suitable for generating the microoptical structure on Si-wafer. However, for the cost concern and mass production, replication is necessary. Fig. 3-2 illustrates an overview of the major replication technologies[61]. To replicate the original structure on Si-wafer, a Ni shim is formed by electroplating as a master. From this first Ni master, second and third generation masters can be formed. The stamper hot embossing and roller hot embossing are well established technologies for replication of surface relief elements with depths up to ~1μm. Deeper structures can be replicated as well by UV-casting or injection molding, which have demonstrated good results for elements with a minimum segment size of 5μm and a relief depth of 5μm.

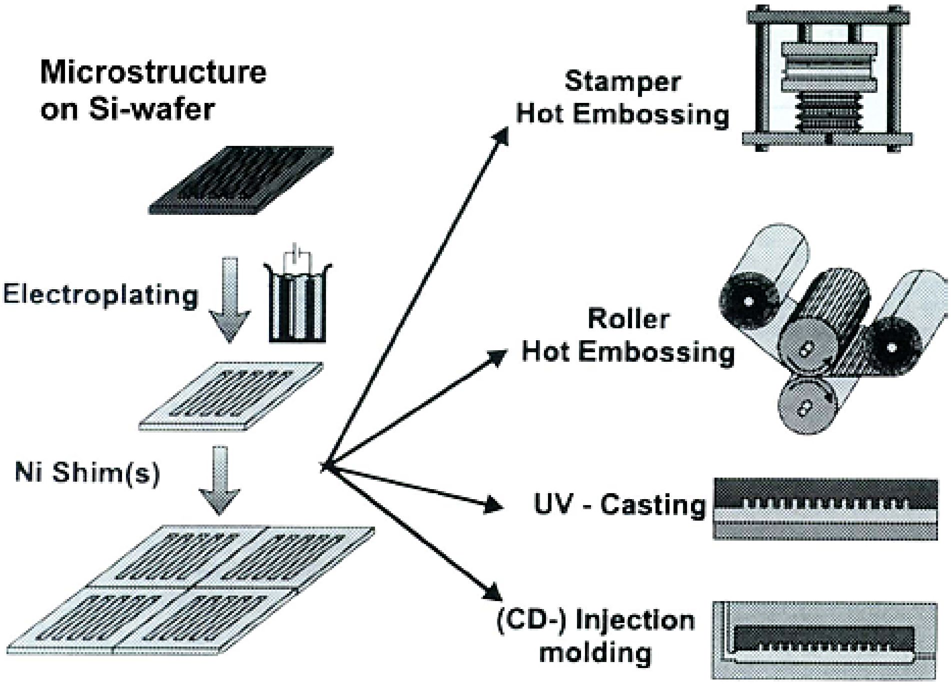


Fig. 3-2. Replication processes and the corresponding techniques [61].

The light control films in Chapter 4 are fabricated by using the mentioned techniques. Utilizing a standard VLSI process, the binary pattern of designed structure are generated on a Si wafer. Then the patterns are economically replicated on a 100μm thick plastic thin foil using the stamper hot embossing.

3.2.2 Half-tone mask technology equipped with Excimer laser micromachining for continuous relief structures

Conventional well-developed VLSI technology uses a set of sequential binary masks to build up discrete phase levels of microoptics. M binary masks can produce 2^M binary relief levels by means of successive photoresist spinning, exposure, development, etching steps, as shown in Fig. 3-3. Nevertheless, due to the limitation of alignment accuracy, the error introduced from alignment, coating, exposure, development and etching will increase rapidly with the increase of the mask number. The misalignment leads to the degradation of efficiency. Therefore, the drawback of requiring M-sequential processing iterations for 2^M phase levels, the time consuming, alignment sensitive, processing complex, are among the main concerns.

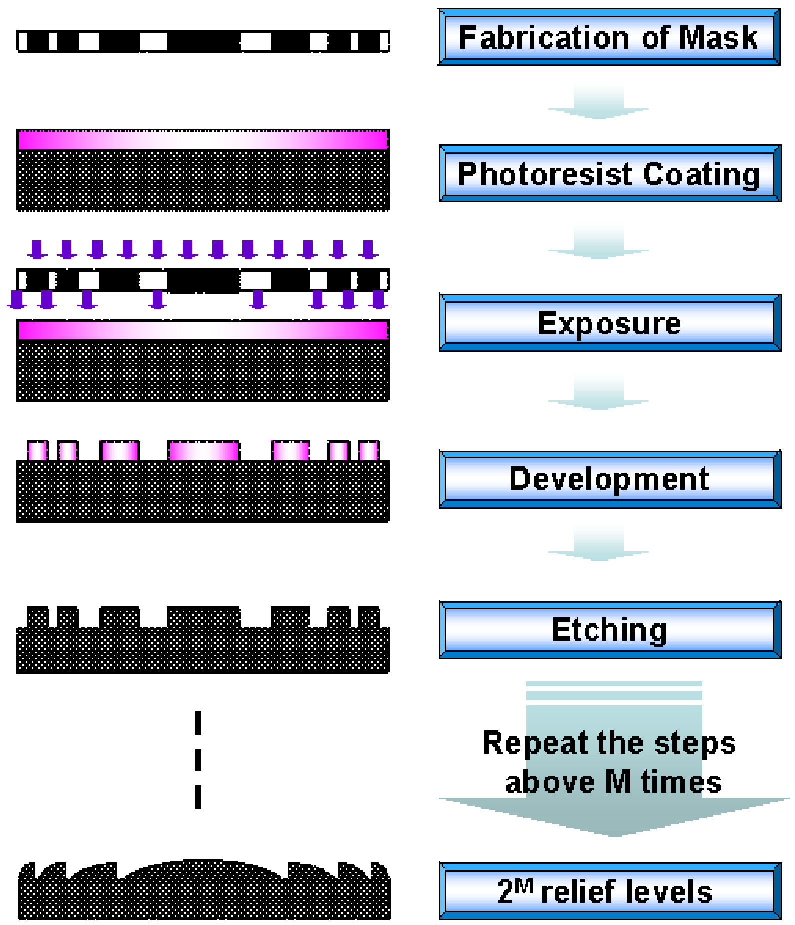


Fig. 3-3. Flow of the traditional multi-binary mask lithography.

Half-tone mask technology[62] was developed with merits of easy fabrication, precise control, compatible with semiconductor process, and shows great potential for mass fabrication cost-effectively. Half-tone masks are binary masks in which the critical dimension is smaller than the resolution limit of the optical exposure system.

Gray levels are encoded through the density and diameter of binary structure, as shown in Fig. 3-4. The continuous profiles are achievable through this technique by using only one mask.

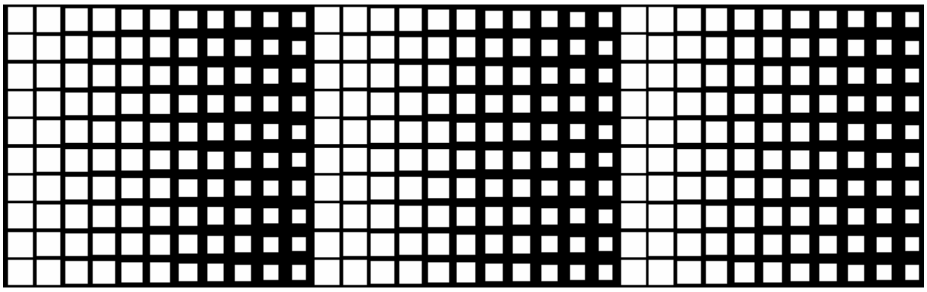


Fig. 3-4. Coded half-tone mask.

The half-tone mask is usually equipped with an optical exposure system to project the topology pattern onto the substrate. The excimer laser micromachining system was chosen to fabricate the structure due to its dry etching [63]. The pattern of the half-tone mask can be rapidly decomposed and ablated on transparent polymer substrates such as polycarbonate, PMMA and photoresist. Besides, energy of laser pulse, number of shot, and pulsing rate can be accurately controlled resulted in a higher degree of precision. Hence, a continuous profile of elements can be fabricated precisely and cost-effectively.

In this thesis work, we utilized the Excimer laser micromachining equipped with half-tone mask at National Precision Instrument Development Center (PIDC) to fabricate a micro-biprism reflector in chapter 5. The used laser system is an Excitech 7000series excimer laser workstation. The schematic diagram of Excitech7000 is shown in Fig. 3-5. The laser is a KrF excimer laser which operates at 248nm. The maximum energy per pulse is typically equal to 0.7 J, the pulse duration is approximate 20ns, and the maximum repetition rate is 100Hz. In order to control the machining energy with program, the emitted excimer laser beam first passes through the attenuator, and the value of attenuator is between 0 and 1. The value 0 implies the laser will not be shot. Due to the intensity profile of an excimer laser output is quite non-uniform, beam forming optics and beam homogenizer inside beam delivery system are used to produce a uniform intensity field on the mask plane. This step can create a highly uniform (±5% RMS) illumination of 12×12mm region on the mask plane. Then the mask plane is imaged on the substrate to ablate the substrate with 4x or 10x demagnification by UV objective with 0.1 or 0.2 NA, respectively.

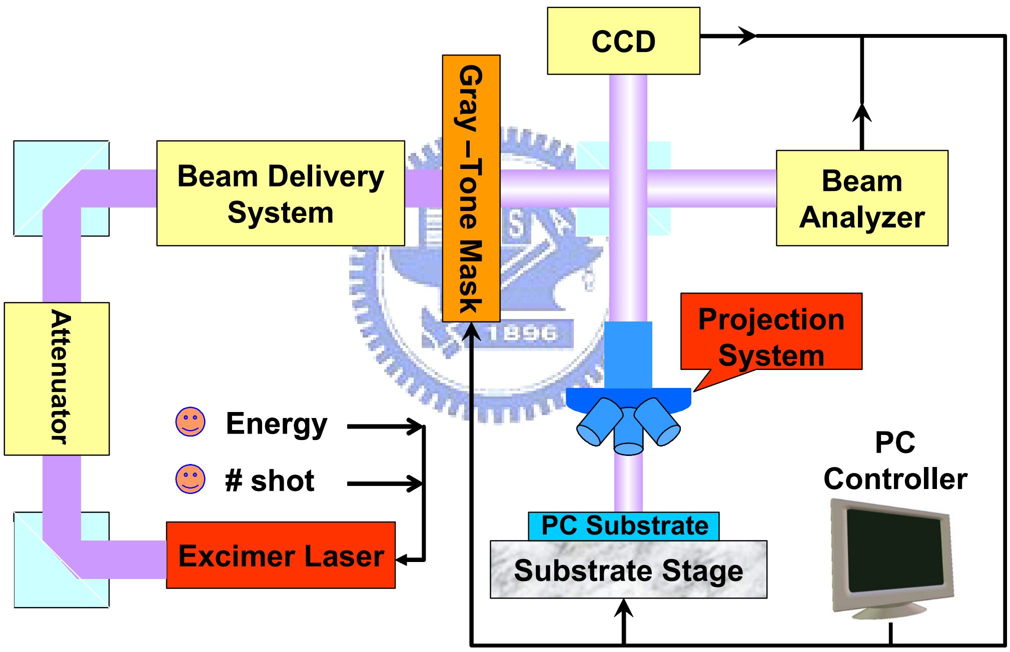


Fig. 3-5. Schematic diagram of excimer laser micromachining system.

The gray-tone mask technique makes use of the dependence of the ablation rate on the energy dose. The constant energy density at the mask plane is modulated by a mask with locally different transparencies according to the topology of the desired structure. The projection of the modulated energy distribution onto the material surface of the substrate results in locally different ablation rates, as shown in Fig. 3-6.

The desired structure can be machined using these locally different ablation rates and a previously calculated number of laser pulses. The accuracy of this method is highly influenced by the homogeneity of the laser beam at the mask plane, the reproducibility of the properties of the ablated material (e.g. ablation rate) and the properties of the gray scale mask. The roughness originates mainly from the superposition of the ablated edge profile of the separate pulses.

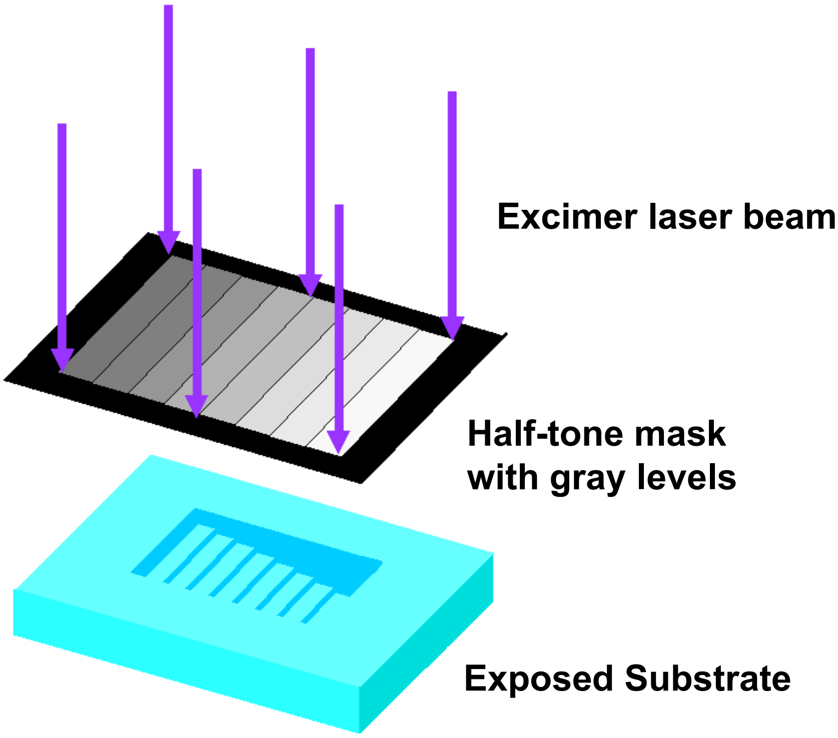


Fig. 3-6. 3D structure fabricated by projection of a gray scale mask.

We can summarize that the half-tone mask can modulate the input excimer laser beam with gray levels by using the projection system which serve as the low pass spatial filter, the continuous profile of microoptical elements is feasible after photo-ablation as shown in Fig. 3-7. The excimer laser micromachining process is not as complex as the semiconductor fabrication process. After focus adjustment, then the excimer laser beam modulated by half-tone mask will ablate the polymer substrate, usually PC or PMMA substrate to form the desired structure.

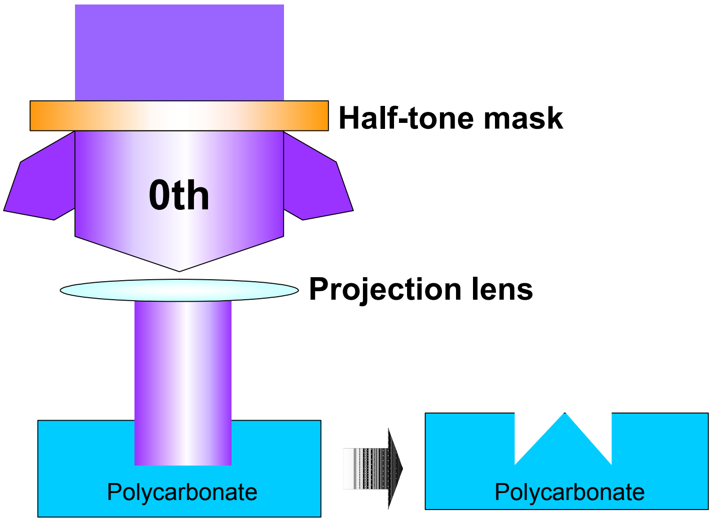


Fig. 3-7. Concept of half-tone mask in excimer laser micromachining system.

3.3 Measurement instruments

3.3.1 Scanning electron microscope (SEM)

A scanning electron microscope (SEM) is an essential instrument to measure the accuracy and fidelity of the fabricated microstructure. It scans electrons reflecting onto a fluorescent screen across the target where the image is captured by a camera and enlarged. Electrons are much smaller than atoms, so a scanning electron microscope paints a razor-sharp image of the target, and the feature variation of few Å can be observed. This is useful for mapping details of objects that optical microscopes cannot resolve. Using the electromagnetic lenses to focus the accelerated electron beam, the diameter of electron beam can be converged to the dimension of 10^{-3} um. The secondary electrons are generated where the focused accelerated electrons bombard the sample. Detecting the secondary electrons can determine the location of bombardment. Simultaneously, the focusing electron beam scans the surface of sample, with the aid of scanning coil, to map the feature of measured area.

In our work, a HITACHI S-4000 SEM was used to measure the quality of our fabricated microstructure elements. The line width, etching depth, and surface uniformity can be accurately measured.

3.3.2 Atomic force microscope (AFM)

AFM consists of a sharp tip mounted on the end of a flexible cantilever spring. Forces from the sample act on the tip and generate some measurable change in the cantilever, such as deflection or shift in resonant frequency. To form an image, the interaction between the sample and tip is mapped to the monitor as a function of position mechanically scanning the sample relative to the tip in a raster pattern into the photo-detector. By detecting the difference in the photo-detector output voltages, changes in the cantilever deflection or oscillation amplitude are determined. A schematic diagram of this mechanism is depicted in Fig. 3-8.

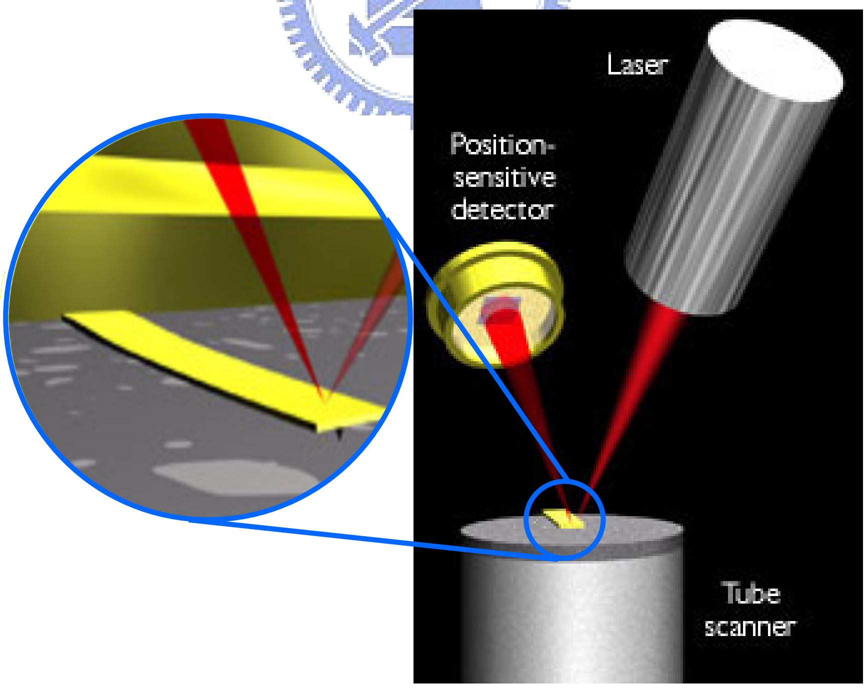


Fig. 3-8. Concept of AFM and the optical lever: (left) a cantilever touching a sample; (right) the optical lever.

There are two major operation modes for AFM:

(1) ***Contact mode***: Contact mode is the most common method to operate the AFM. As the term suggests, the tip and the sample remain in close contact as the scanning proceeds. One of the drawbacks of remaining in contact with the sample is that there exists a large lateral force on the sample as the tip is dragged on the specimen.

(2) ***Taping mode***: Tapping mode consists of oscillating the cantilever at its resonance frequency (typically hundreds of kilohertz) and positioned above the surface so that it only taps the surface for a very small fraction of its oscillation period. The laser deflection method is used to detect the root-mean-square (RMS) amplitude of cantilever oscillation. The advantage of tapping mode over contact mode is that it eliminates the lateral, shear forces present in contact mode, which enables tapping mode to image soft, fragile, and adhesive surfaces without damaging them.

3.3.3 Conoscopic system

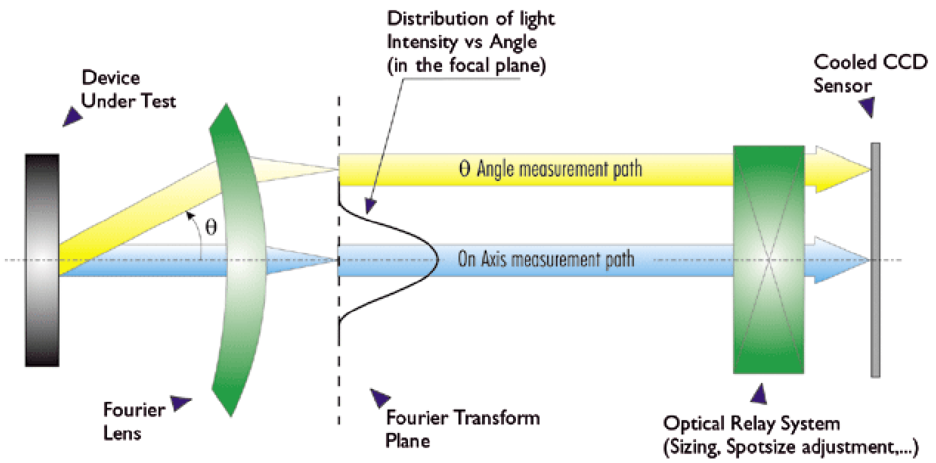
The conoscopic instrument for measuring the optical properties of brightness and contrast ratio at different angles are essential in the LCDs research and development. ELDIM EZContrast 160 is a conoscopic measurement system which utilizes Fourier transform lens to transfer the light beams emitted from the test area of different angles to the CCD array. Therefore, the angular properties can be easily measured on the CCD sensor plane.

The ELDIM EZContrast 160R which has diffuse and collimated illumination types with a plane detector consisting of various directional CCD sensors to detect the transmissive and reflective light is utilized to measure the luminance, contrast, color of the imaging devices at one time. The schematic diagram of the display measurements setup in both transmissive and reflective mode of ELDIM EZContrast

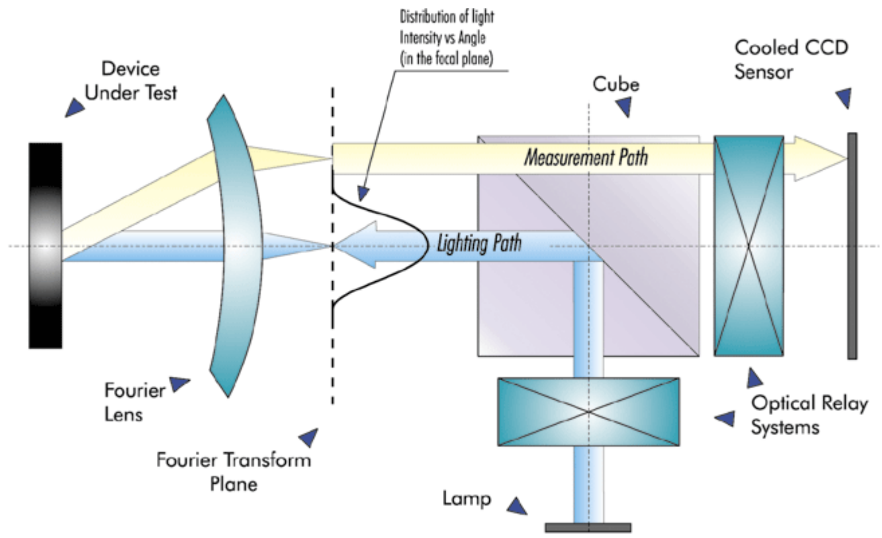
160R are as shown in Figs. 3-9(a) and (b), respectively.

The options for testing under illumination are based on the combination of Fourier Optics and cooled CCD sensor head. As shown in Fig. 3-9(a), the measurement is used for transmissive mode LCDs, where the first lens provides a Fourier transform image of the display surface. Every light beam emitted from the test area with a θ incident angle will be focused on the focal plane at the same azimuth and at a position x=F(θ). The angular characteristics of the sample are thus measured simply and quickly, without any mechanical movement. On the other hand, as shown in Fig. 3-9(b), an optical relay system combined with a beam-splitter cube enables to conjugate the light source plane with the Fourier plane. The light source distribution function allows controlling the angular distribution of illumination. Beside, the light through the system can extend up to the viewing cone of the Fourier lens (+/- 80° or +/- 60°).

When we developed the microoptical components for portable LCDs, the light distribution and contrast ratio are two important parameters to be evaluated. ELDIM EZContrast 160 conoscopic system was utilized to measure these parameters to determine the performance of the displays.



(a)



(b)

Fig. 3-9. Display measurement setup of ELDIM EZContrast 160R (a) transmissive and (b) reflective mode.