Chapter 1 Introduction

1-1 Motivation

In advanced optical storage systems, the optical spot size and shape directly affect the recording density and signal quality. The smallest recording length varies from 0.8 μm in compact discs (CDs) to 0.4 μm in digital versatile discs (DVDs), even to 0.15 μm in Blu-ray Discs (BD). As the optical spot in the storage system becomes smaller, it is more difficult to measure the quality and spot size directly. Traditionally, a far-field CCD measurement is used, as shown in Fig 1-1. From the traditional measurement, the laser beam is first focused by the beam expander and lens, the laser spot image can be captured by CCD and the optical distribution can be analyzed by image processing software. In a more advanced setup, a CCD sensor was used to measure the spot [1] using the principle similar to the knife-edge method. However, the resolution of the CCD measurement is limited by the diffraction effect and the resolution of CCD.

In order to measure the near-field optical distribution in applications such as high density optical data storage and photonic band gap devices, the detector must be located within the near-field range of about 100nm. The resolution of the detector must also be smaller than the scale of the distribution. In fact, to get more reliable data, the optical detector should have a resolution much smaller than the near-field distribution range. For example, the near-field scanning optical microscope (NSOM) [2], as shown in Fig 1-2, has been used to measure nanometer scale optical distributions. However, the resolution of NSOM is limited by the aperture of the probe; NSOM also has disadvantages such as difficult fabrication processes and fragility of the near-field probes, complexity of the systems due to low light throughout.

In light of the disadvantages of traditional near-field optical microscopes, a MEMS-based optical spot knife-edge scan system is proposed as a more compact and robust device for near-field or tight spot measurement. The proposed device has a smooth and sharp knife-edge plate. A photo detector fabricated on the micro actuator is used to scan across the optical field and transform the optical signals to electrical ones. By analyzing the electrical signals, the optical spot size and distribution can be determined. In the MEMS-based device, the distance between the photo detector and knife-edge plate can be less than a few μm. Alternatively, the detector can be fabricated on the plate. Therefore, the measurement resolution limited by the diffraction effect in traditional far-field system can be minimized.

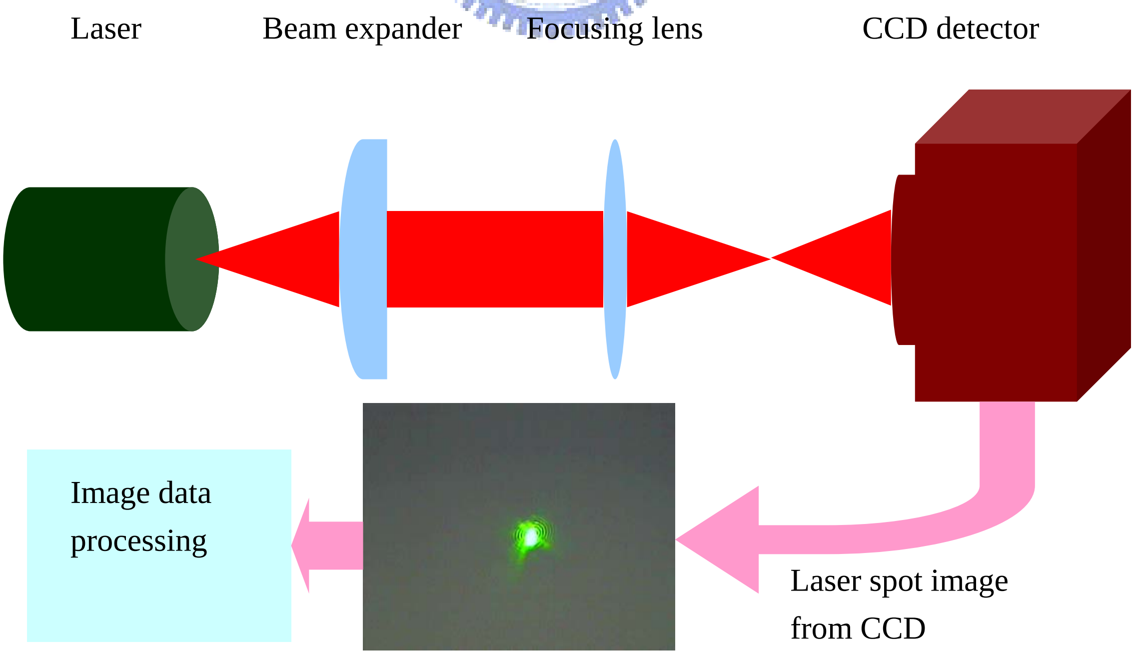


Fig 1-1 Traditional far-field CCD optical spot measurement system

The micro optical spot scan system also serves as a demonstration of an integrated optical microelectromachanical system (optical MEMS). In current optical MEMS applications, such as digital mirror device (DMD) developed by Texas Instrument (TI) for projection display or the optical switch arrays for optical communication, the electrical and opto-mechanical systems are two individual and independent systems. They can be only integrated in a multi-chip way to form the whole system. The reliability and performance can be reduced while the cost can be increased. In the proposed micro optical spot scan system, the opto-mechanical devices, photo detectors, and control and signal processing circuits can be integrated monolithically to form a photonic system on chip (PSOC), as shown in Fig 1-3.

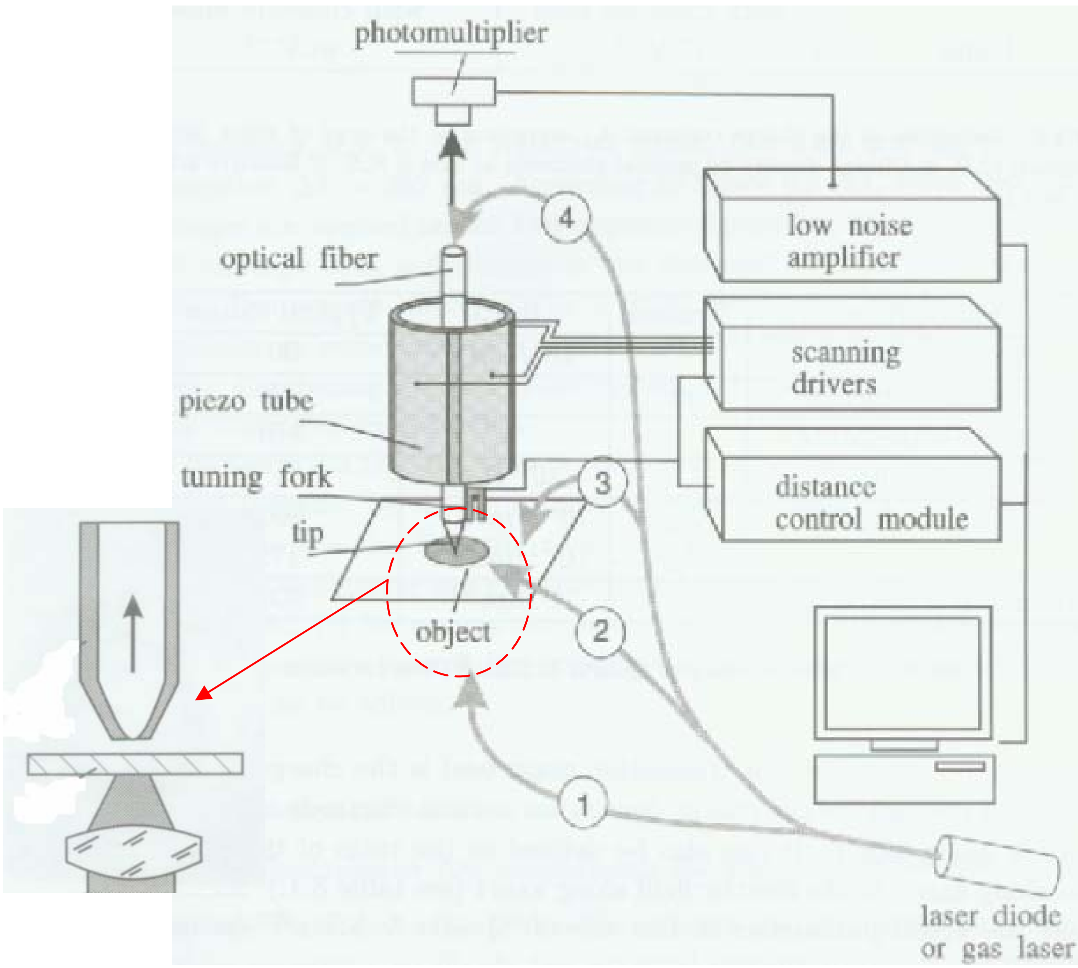


Fig 1-2 Schematic of a near-field scanning optical microscope (NSOM) [2]

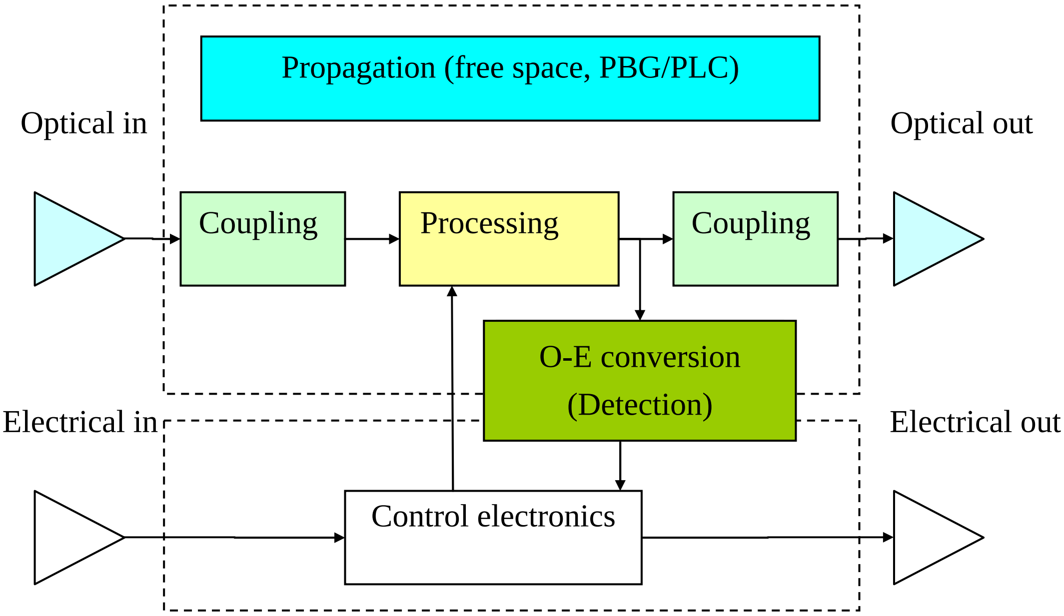


Fig 1-3 Photonic system on chip (PSOC) architecture

1-2 Knife-edge scanning method

A knife-edge spot scan system contains a knife-edge plate driven by an actuator and a photo detector placed behind the knife-edge plat, as shown in Fig 1-4(a). When the plate with a sharp edge scans across the optical spot, the photo detector located behind the plate collects the energy not obstructed by the plate and transform the energy to a photocurrent.

The photocurrent $I(x_0)$ 、power distribution of the spot $P(x)$ and position of knife-edge plate x_0 are related by(Fig 1-4(b))：

$$I(x_0) = a\int_{x_0}^{\infty} P(x)dx \tag{1-1}$$

$$P(x) = \frac{1}{a}\frac{dI(x)}{dx} \tag{1-2}$$

where a is the sensitivity of the photo detector. The optical spot distribution can be obtained from the derivative of derive the photocurrent $I(x_0)$ (electrical signal) measured by the photo detector Eq 1-2. The spatial resolution of the scanning system is decided by the sharpness of the edge and the position control system; it is not limited by the pixel or computer size.

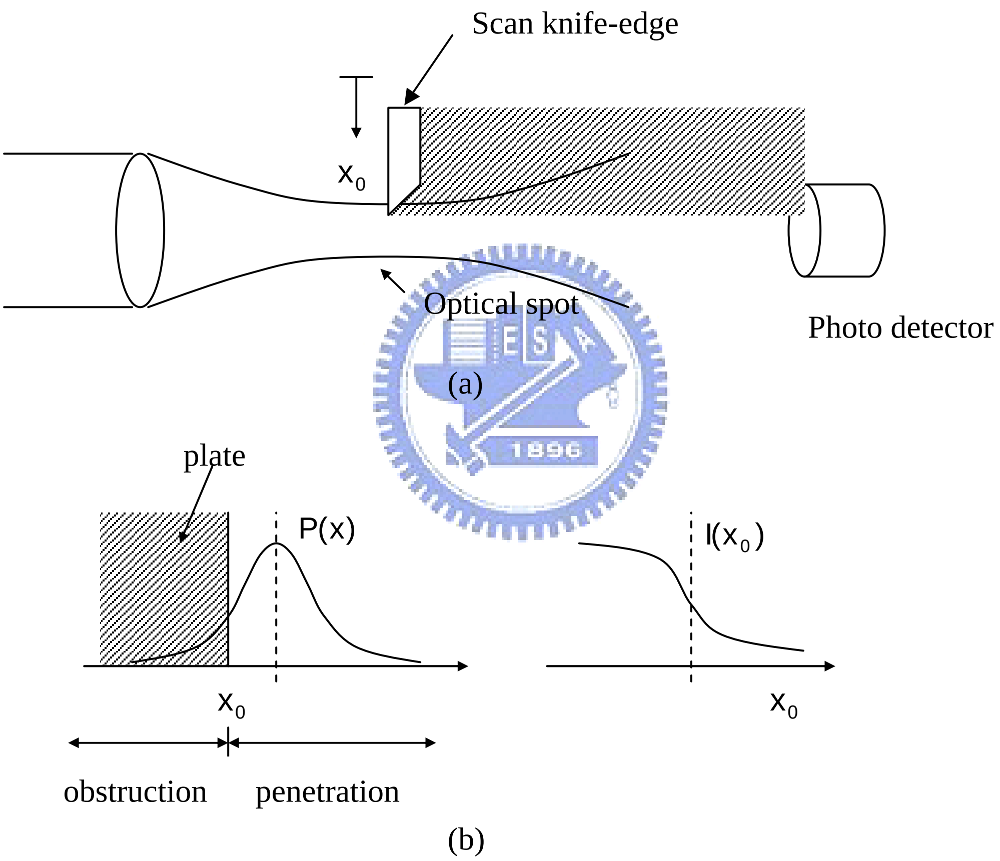


Fig 1-4 (a) Scanning knife-edge system schematic, (b) relation between optical power distribution $P(x)$ and readout photocurrent signal $I(x_0)$

1-3 <111> Silicon wafer crystallography and microstructure fabrication

MEMS technology is used in the proposed system to make the distance between the knife-edge plate and detector smaller than 1μm. In order to measure near-field distributions, if the detector can be fabricated directly on the plate, the distance becomes minimal. In this case, the plate and actuator material should be a suitable material for photo detectors and compatible with IC technology. Therefore, single crystalline silicon (SCS), should be used. Since the carrier lifetime and mobility in photo detectors have better performance than in poly or amorphous type silicon. In this thesis, <111> silicon substrates are used because the device orientation in <111> silicon is least sensitive to the crystallographic orientations as mentioned in ref [3]. The wafer cost is also lower than SOI wafers.

<111> silicon has been used to fabricate various devices [4], [5], [6]. To understand the principle of <111> silicon fabrication, consider the six (111) planes in a <111> silicon wafer, as sown in Fig 1-5(a). These (111) planes represent six of eight (111) planes, the others being the top and bottom planes. The six (111) planes are tilted at positive or negative 19.47^{o} from the wafer normal as indicated. The (111) planes are the slow-etching planes in KOH or TMAH solutions and are used as the etching stop when releasing the structure. The fast-etching planes are (110) planes. Six of twelve (110) planes in <111> silicon substrates can be found by rotating the equilateral triangles in Fig 1-5(a) by 30^{o} in either clockwise or counterclockwise directions, as shown in Fig 1-5(b). The others are aligned to the (111) planes, as shown in Fig 1-5(c). The difference between the (110) planes in Fig 1-5(b) and (c) is

intersection angle to the bottom <111> plane. In Fig 1-5(b), these (110) planes are vertical to (111) plane; while in Fig 1-5(c), the (110) planes are tilted at 54.7^{o}. Due to the intersecting <111> planes vertically, the (110) planes in Fig 1-5(b) are the fastest etching planes and the (110) planes in Fig 1-5(c) will be slower than those in Fig 1-5(b). To fabricate released MEMS structures on <111> silicon wafers, two reactive ion etch (RIE) are needed. One is used to define the MEMS structure and the other is used to define the releasing gap.

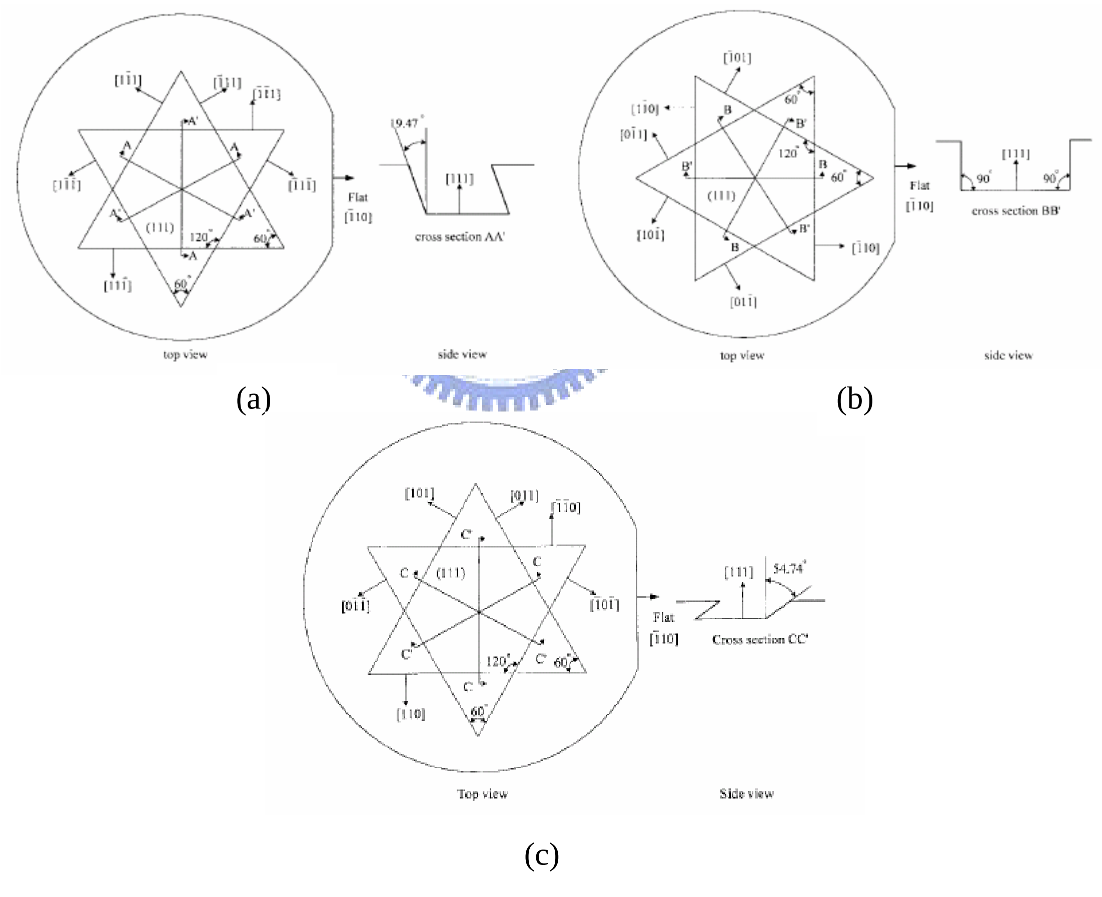


Fig 1-5 Crystallography of <111> silicon (a) <111> direction (b) six normal (110) planes(c) six oblique (110) planes

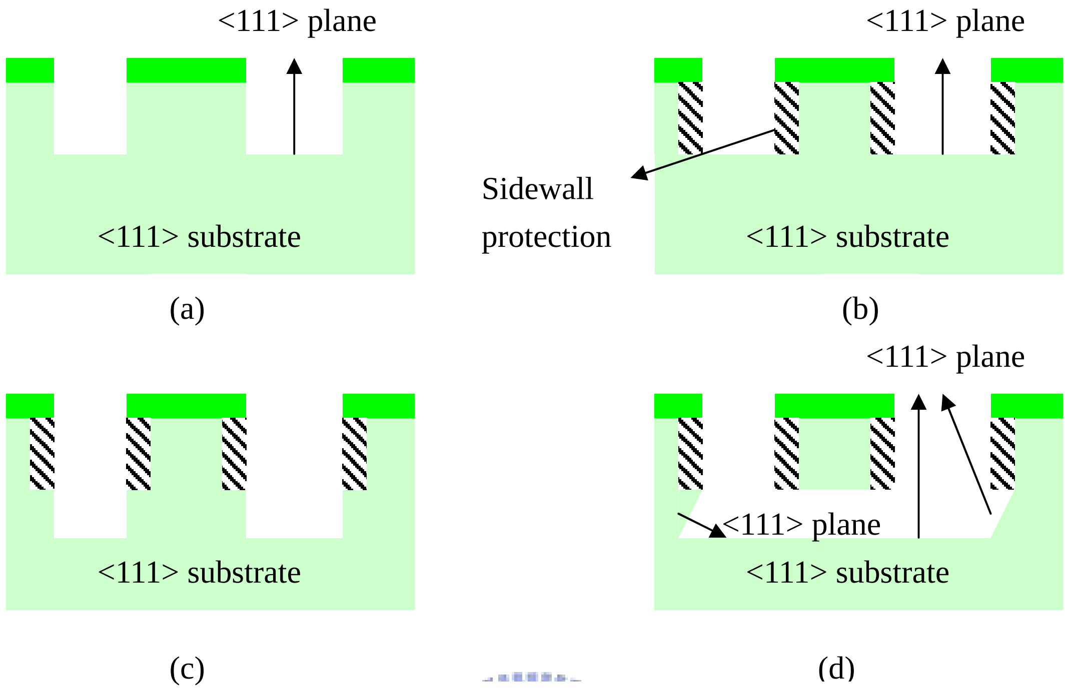


Fig 1-6 <111> silicon fabrication process: (a) pattern transfer and first RIE, (b) sidewall protection, (c) releasing gap definition by second RIE, (d) releasing in alkaline solution

The processing begins with a pattern transfer by first RIE, as shown in Fig 1-6(a). Next, the sidewalls in the first RIE structure must be protected for subsequent releasing steps, as in Fig 1-6(b). Then, the second RIE is used to define the releasing gap, as shown in Fig 1-6(c). Finally, the MEMS structure is released in alkaline solution, such as KOH or TMAH, as shown in Fig 1-6(d).

1-4 Literature survey

Earlier works on integrated optical microelectromechanical systems and devices fabricated on <111> silicon substrates are discussed.

1-4-1 Optical microelectromechanical system

The micro optical pickup head in Fig 1-7 is based on the free-space micro optical bench proposed by Wu, et al. [7]. It includes both optical and electronic devices, such as light source, lenses, beam splitter and reflective mirrors. However, the light source (laser diode) is integrated with the optical components by bonding.

In the standing-wave microspectrometer shown in Fig 1-8 by Kung, et al. [8], the photocurrent can be measured directly from module, although the optical detector and MEMS device are still combined by the bonding technique.

An integrated optical pickup head, which integrates planar integrated optics and optical detector, was demonstrated by Ura, et al., as shown in Fig 1-9 [9]. Because only the integrated optics is used, optical design and characteristics in the module have more limitation than free-space optical system. For example the optical coupling between wave guides and free space usually induce quite large energy loss.

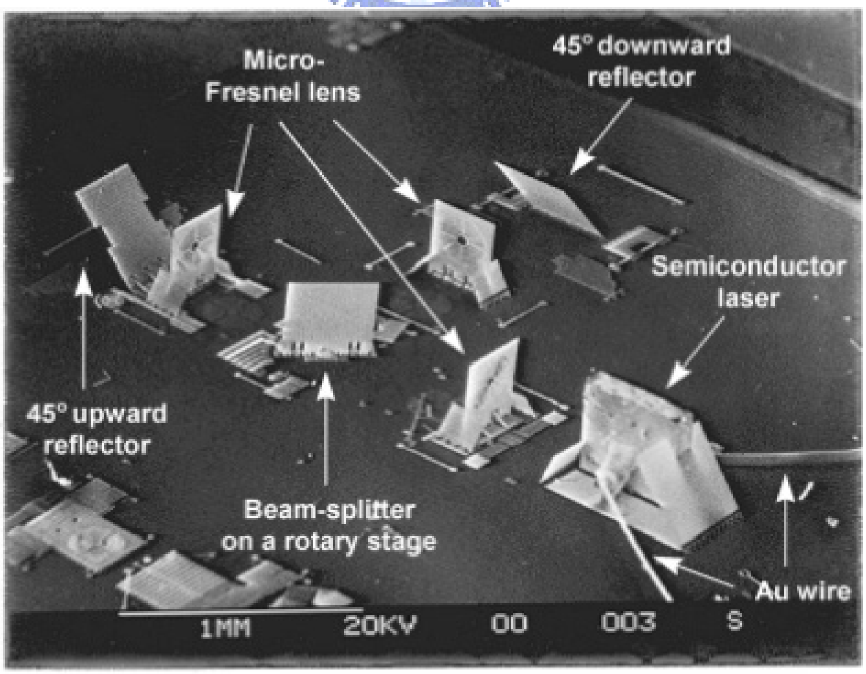
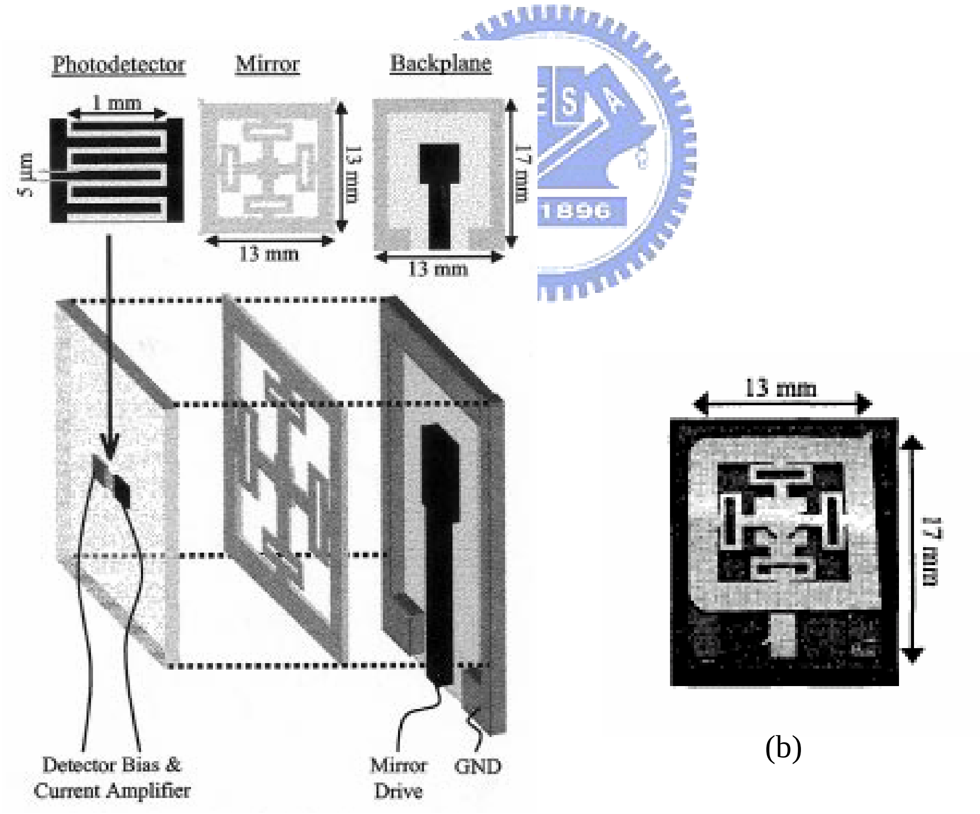


Fig 1-7 Free space micro optical bench [7]

Recently, complementary metal oxide semiconductor (CMOS process) process has been used to integrate optical components. In Fig 1-10 [9], Correia, et al. combined fixed tuned Fabry-Parot resonance cavity formed by a Al/oxide/silver stack and a detector in a single chip to form a micro optical spectrometer. However, the chip did not contain a movable MEMS actuator.

In the NSOM probe proposed by Sasaki, et al., as shown in Fig 1-11 [10], the waveguide and photodiode are integrated on a cantilever beam. In this system, the integration of micromechanical structure, micro optical components and optoelectric components were demonstrated.



(a)

Fig 1-8 (a) Standing wave microspectrometer schematic, (b) photograph of the MEMS component bonded with the mirror [8]

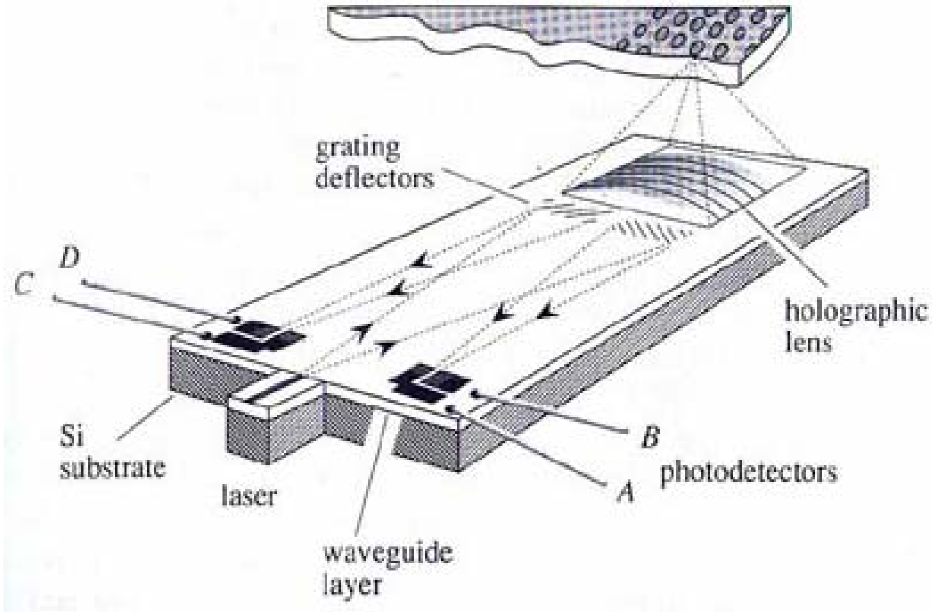


Fig 1-9 Integrated optical pickup head schematic [9]

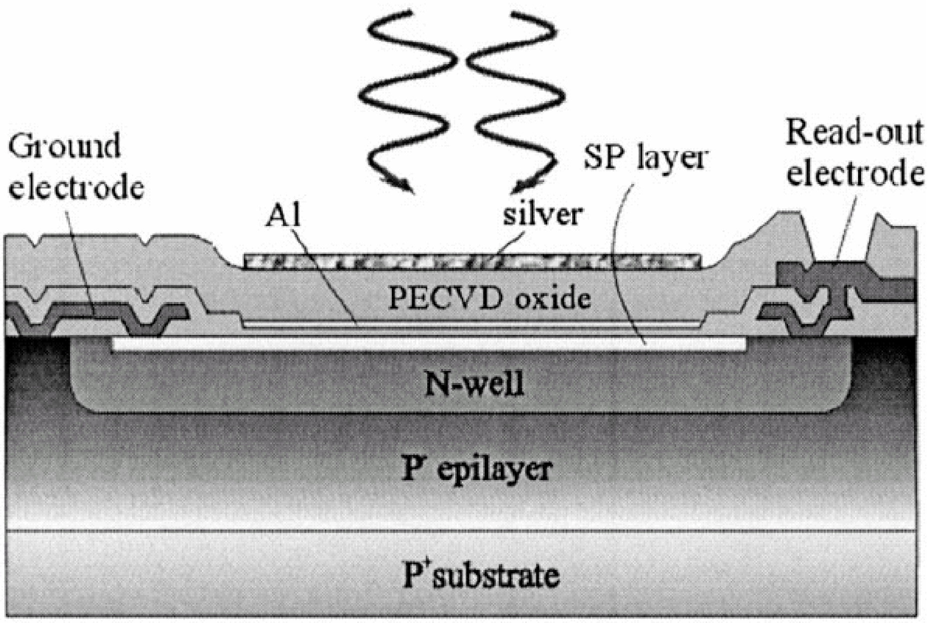


Fig 1-10 CMOS Fabry-Parot filter and photo detector [10]

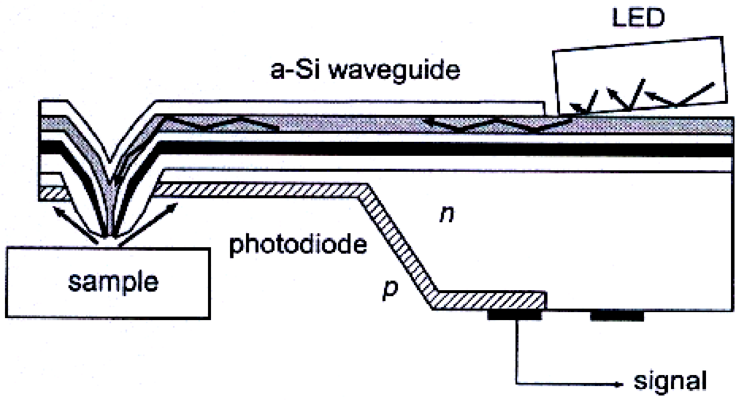


Fig 1-11 High efficiency NSOM probe [11]

1 – 4 – 2 Devices in <111> silicon substrate

A simple released structure fabricated by <111> silicon substrates are shown in Fig 1-12 [4]. In the figure, a circular plate is suspended by the three straight beams. More complex actuators and sensors have also been fabricated in <111> silicon substrates, such as the dual-mass spring resonator (DMSR) and the moving vibrating gyroscope (MVG), as shown in Fig 1-13, using the boron etching stop assisted lateral silicon etching process (BELST) proposed by Hsieh et al. [12]. In the process platform, heavy boron doping is used sidewall protection to define the MEMS structures. However, heavy doping and long drive-in time in the BELST process result in deep p-n junctions and reduce the absorption efficiency of photodiodes. Therefore, the process is inappropriate for the integration of IC circuit and actuators.

Another process proposed by Lee et al. [13], is the surface/bulk micromachining process (SBM). In this process, boron or phosphorous doping on n-type or p-type wafers to form the p-n junction is done by furnace diffusion and serves as the etching stop layer. Then, nitride and oxide with good step coverage are used to form the sidewall protection and serve as the electrical isolation layer. A simple comb actuator fabricated using the SBM process is shown in Fig 1-14. In this process, lower process temperature in forming sidewall protection is adapted, so the IC circuit can be integrated in a chip with the actuator without ruining the electrical properties of circuits.

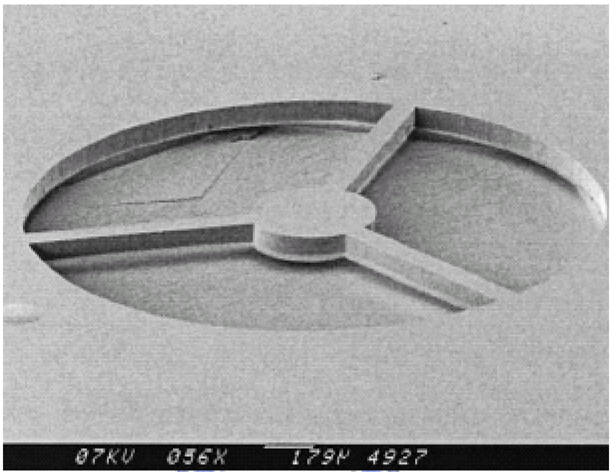
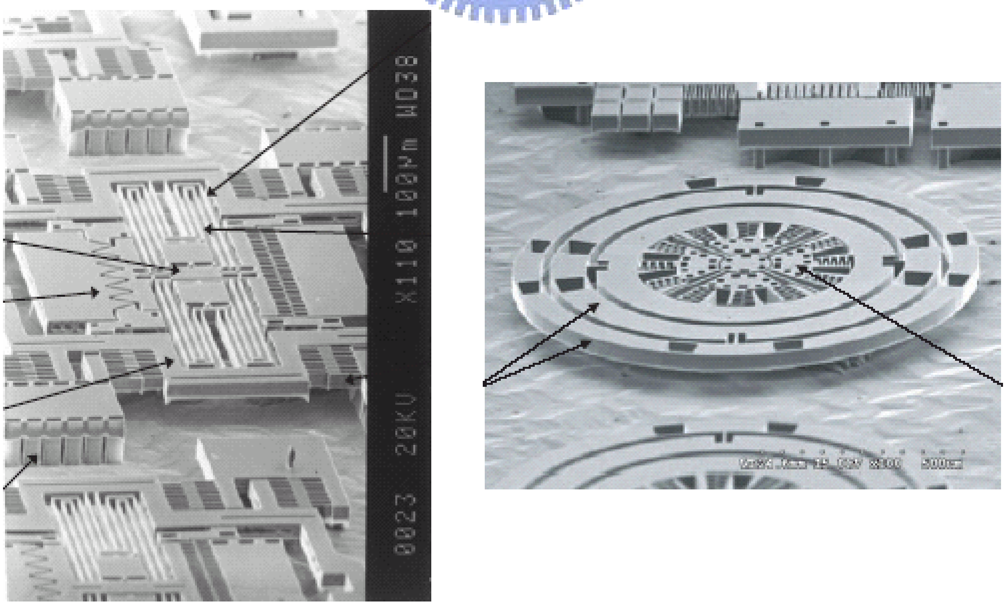


Fig 1-12 Released structure fabricated in a <111> silicon substrate



(a) (b)

Fig 1-13 BELST process application (a) dual-mass spring resonator (DMSR) (b) moving vibrating gyroscope (MVG) [12]

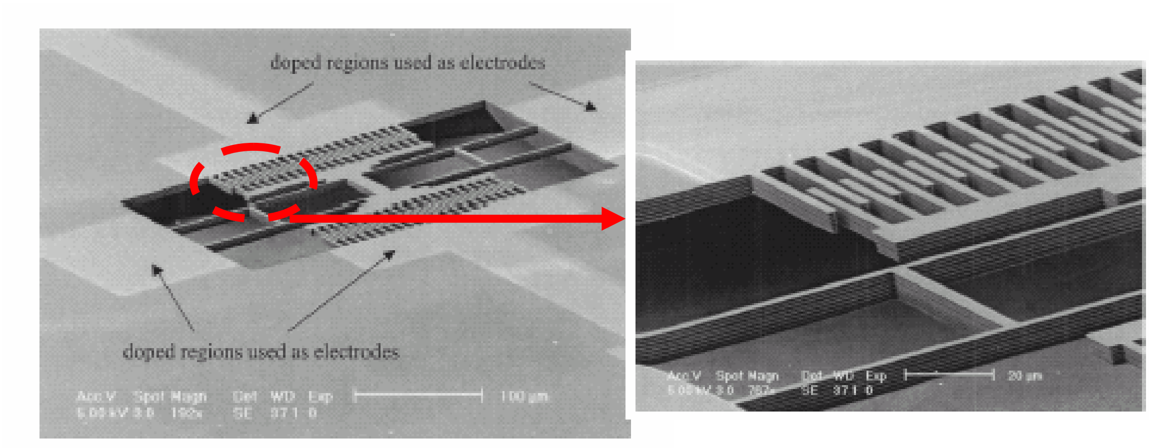


Fig 1-14 Comb drive actuator by the SBM fabrication process [13]

1-5 Objectives and thesis organization

The objective of the thesis is to develop a micro optical spot scan system to measure the optical spot based the scanning knife-edge method. A reflection type device fabricated with the Multi-User MEMS Processes (MUMPs) is to be used as quick prototyping and proof of concept. An absorption type device fabricated in <111> silicon is also to be developed to improve the responsivity of the photo detector and demonstrate the integration of electronic and mechanical components in the same chip.

In this thesis, the design and simulation will be given in Chapter 2. The fabrication technology is discussed in Chapter 3. Preliminary experimental results of such a MEMS optical measurement system are presented in Chapter 4. Finally, conclusion and future work are discussed in Chapter 5.