Chapter 1
Introduction

1-1 Motivation

In the rapid progress of information technology, portable high-capacity optical storage systems have become more popular and important. The miniaturized pick-up head is one of the key components and has great influence on the performance of the system.

Figure 1-1 shows the schematic of a conventional optical pick-up head. It is composed of a laser diode, a grating plate, a polarizing beam splitter, a collimator, a mirror, an objective and photodiodes. The laser beam from the laser diode passes through the diffraction grating to produce two secondary beams needed to maintain the correct tracking of the spot. Then, the beam passes the polarizing beam splitter and is converted into a parallel beam by the collimator. After the quarter wave plate, the beam becomes circularly polarized. The beam is then focused onto the surface by the objective whose position is maintained by a servo mechanism. The reflected beam becomes orthogonally linearly polarized with respect to the source beam after passing through the quarter wave plate and then is reflected by the PBS into the detectors.

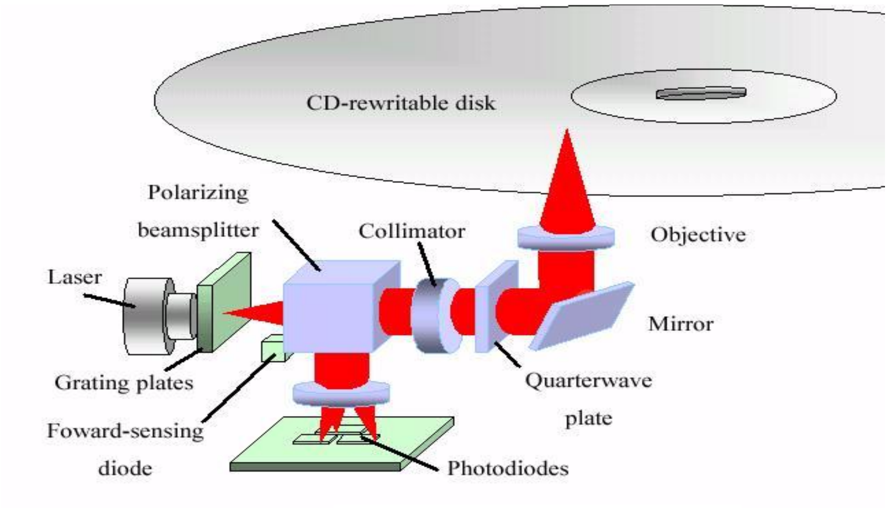

Figure 1-1: Conventional optical pick-up head.

Micro Electro Mechanical System (MEMS) is a technology employing semiconductor fabrication processes to fabricate miniaturized electro-mechanical devices. Compared with conventional devices, the miniaturized devices have the characteristics of shorter response time and less power consumption. In addition, MEMS devices and signal processing circuits can be fabricated on the same chip to reduce noise and signal distortion. MEMS technologies show prospective applications in optics, transportation, aerospace, robotics, chemical analysis, biotechnologies, medical engineering and microscopy using scanning micro probes [1].

Inasmuch as the conventional optical pick-up heads are fabricated by discrete components, concept of micro optical bench has been proposed [2] in order to fabricate a monolithic optical pickup head. For example, Figure 1-2 is a single-chip optical-disk pickup head developed by M. C. Wu et al. [2]. The pickup head consists of a semiconductor laser source (hybrid integrated with the help of three-dimensional alignment plates), three micro-Fresnel lenses, a beam splitter, and two 45 degree mirrors.

Figure 1-2: SEM micrograph of the monolithic optical-disk pickup head [2].

The MEMS based pickup of this research is composed of a laser diode, a coupling and beam shaping lens, a grating plate, a beam splitter, a focusing lens, focusing actuators and photo detectors, as shown in Figure 1-3. The optical system is similarly to the conventional one in Figure 1-1. All the optical elements are pre aligned during the design stage. That differs from the manual alignment in traditional pickup head fabrication processes. Since the height of MEMS structures are limited, multi-chip module can be used to fabricated the full functioning pickup head. As shown in Figure 1-3, the MEMS based optical pickup is composed of two chips bonded together: one is for the optical system, and the other for the vertical actuator.

Therefore, this thesis mainly contains two parts concerning the development of such a micro optical pickup. In the first part, wet etching is used to fabricate U-grooves and corresponding ridge structures as the precise horizontal alignment mechanism for the micro optical bench and the tunable focusing lens.

In the second part, silicon on insulator (SOI) wafers with almost zero stress are used in order to prevent the stress-induced curvature of micromirrors made by poly silicon. In addition, the tensile stress generated as the cross-linked SU-8 cools down from high temperature is used to fabricate stress beams to lift up the micromirror. SU-8 induced stress beams can avoid stiction and make it easier to lift up the micromirror by the probe. SU-8 is also used to fabricate anchors.

Integration of SOI and SU-8 in a surface-micromaching-like process can simplify the process. Finally, photodetectors are fabricated on the micro optical bench, as shown in Figure 1-3. A 135° micromirror can reflect the optical signals to the underneath detector. Therefore, the photodiodes are integrated with the 135° micromirror to detect optical signals.

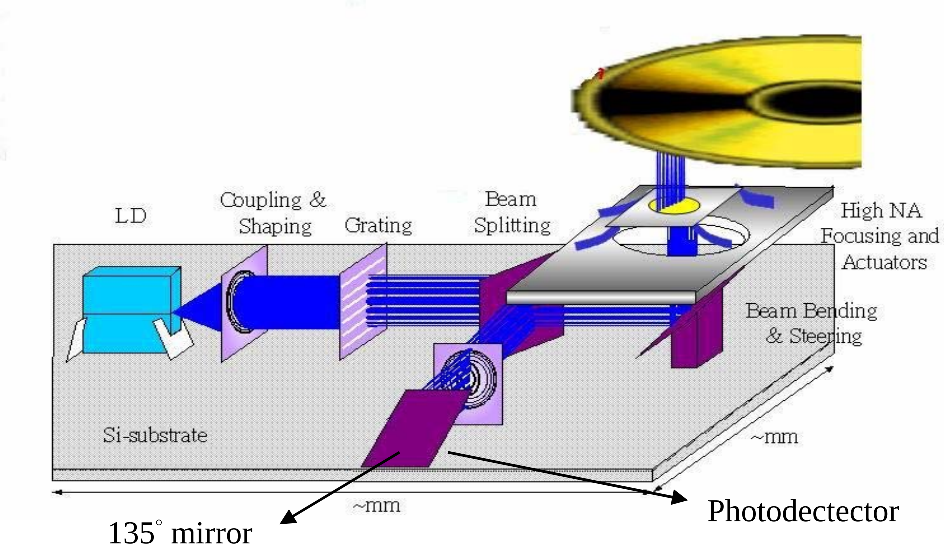

Figure 1-3: MEMS based optical pickup.

1-2 Literature survey

1-2-1 Self alignment structure

Self-aligned structures are widely used in bulk micromachining of single crystal silicon to fabricate the packaging platform for optical devices [3]. However, low cost assembly of the optical pick-up is the objective in the first part of this thesis. Wet chemical etching is adopted to fabricate the structures to align the optical bench. The structural nature of silicon makes it possible to fabricate precise three-dimensional shapes. In general, silicon has a high etching selectivity of (100) to (111) planes in anisotropic wet etching [4]. Consider a (100)-oriented silicon wafer protected by a thermal SiO_2 or a LPCVD Si_3N_4 film that was patterned and then subjected to an alkaline anisotropic etching. As Figure1-4 depicts, a rectangular structure is formed to the familiar (111)-faced, pyramid-shaped pit [4]. In this thesis, such structures are used to fabricate U-grooves and corresponding ridge structures to form the self-alignment mechanism.

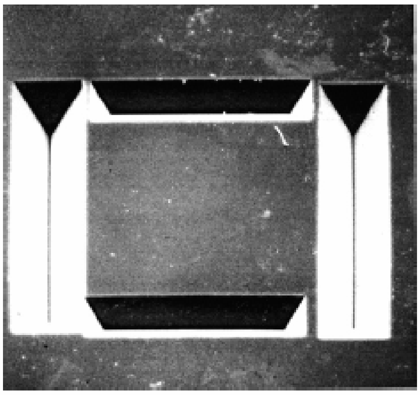

Figure 1. The (111)-faced pyramid-shaped holes on a silicon (100) wafer after the anisotropic wet etching.

Figure 1-4: (111)-faced pyramid-shaped holes on a silicon (100) wafer after the anisotropic wet etching. [4]

- **Silicon anisotropic etching in KOH**

KOH is the most commonly used anisotropic for silicon, although it may have an undesired roughness on the surface. Such surface nonhomogeneities can present major problems when micromachined silicon is used as a structural support, e.g. when micro machined trenches are used to fix and align optical fibers [5]. IPA has been proved to be an effective admixture to improve the smoothness of etched silicon surfaces [6]. However, the main drawback of KOH etchant is the poor compatibility with IC processes. Tetramethylammonium hydroxide (TMAH) is another anisotropic silicon etchant. It has much better compatibility with IC processes but its etching rate and selectivity are poor compared with KOH. Therefore, a non-poisonous and low-cost enchant, KOH water solution with isopropyl alcohol (IPA) will be adopted in this thesis.

- **Etching rate of KOH**

Etching rate is an important parameter in etching processes. Etching rate can be controlled by etching temperature or etchant composition. With the increase of etching temperature, the etching rate increases, too [6]. As far as high etching rate is concerned, the KOH concentration of 15 wt.% is optimal, but the roughness of etched surface is not ideal. In addition, KOH etching rate is also strongly affected by the crystallographic orientation of silicon [7]. Therefore, every parameter must be controled to get the desire etching rare.

1-2-2 Integrated device using SOI and SU-8

In this thesis, a novel fabrication process to integrate SU-8 negative resist on the Silicon-On-Insulator (SOI) substrates is proposed. In this surface-micromachining-like process, the device layer of the SOI substrate and the SU-8 layer are two structural layers, separated by an oxide sacrificial layer. The stress-free and single-crystalline nature of the top SOI layer and the transparency of SU-8 in the visible spectrum range make this process ideal for integration of mechanical structures, optical devices, photo detectors, and circuits.

Surface micromachining is an important technology in MEMS due to its design versatility and IC-like fabrication. Since the invention of the micro hinge [8], surface-micromachined devices have gained another degree of freedom in the vertical dimension. Based on this technology, many devices or modules, such as the micro optical bench [9], have been developed for micro-optical applications. Traditional surface micromachining uses thin poly-silicon as the structural and optical material. However, poly-silicon has several disadvantages for optical applications, such as residual stress in the films, opacity in the visible spectrum range, and poor performance as an optical detector. To increase the stiffness of the structure, SOI has been used with poly-silicon surface micromachining [10]. However, this is still a complex process and the high deposition temperature may affect the performance of detectors or circuits. Therefore, a novel fabrication to integrate SOI and SU-8 is proposed to solve the above shortcoming and provide a low-temperature and inexpensive process.

1-2-2-1 Self-assembly mechanism

MEMS devices are small and difficult to be assembled manually. Therefore, a self-assembly mechanism is very important. Several self-assembly technologies have been exploited and are discussed in the following.

(a) By surface tension

Devices can be self-assembled by the out-of plane rotation due to the surface tension torque obtained by melting thick pads of photoresist or solder. The fabrication processes are to pattern device first, and then pattern the photoresist or put solder on the rotation joints and melt it. Then the plate will be flipped up by the surface tension power when the photoresist or solder is melt, as shown in Figure1-5 [11].

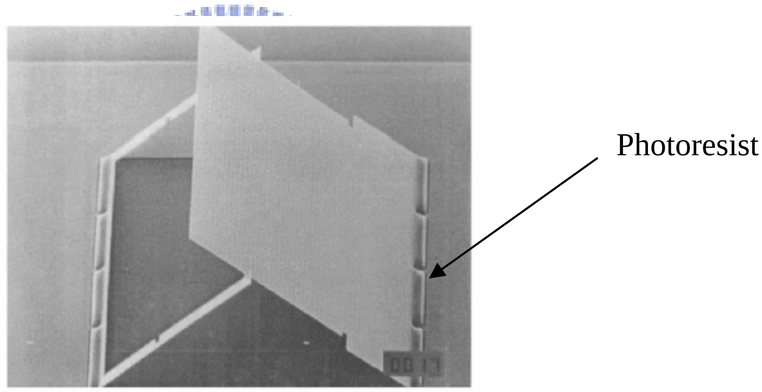

Figure 1-5: Self-assembly by photoresist [11].

(b) By ultrasonic triboelectricity

This method uses ultrasonic vibrations generated with an attached piezoelectric actuator to vibrate polysilicon plates on silicon nitride or polysilicon surfaces. The rubbing between the substrate and the structures creates contact electrification charge. The charge repulsion effectively stabilizes the surface micromachined flaps to the upright position as shown in Figure 1-6 [12]. Nearly perfect yield over the entire area can be achieved.

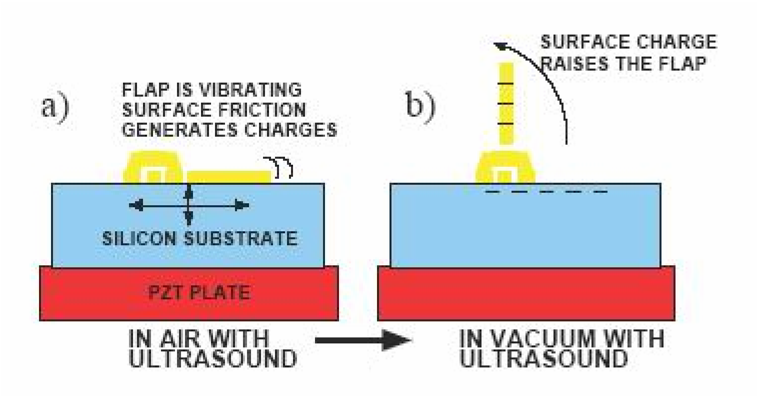

Figure 1-6: Sequence of actuation. (a) ultrasonic vibrations heat and charge the polysilicon parts. (b) electrostatic repulsion forces the plate up [12]

(c) By residual stress

The residual stresses that are inherent in thin films have been exploited to lift up a+nd assemble the micro structures [13]. The detail of residual stress beam is described in Section 2-3. In Figure 1-7, the typical assembly mechanism is composed of stress-induced beams and locking components [14].

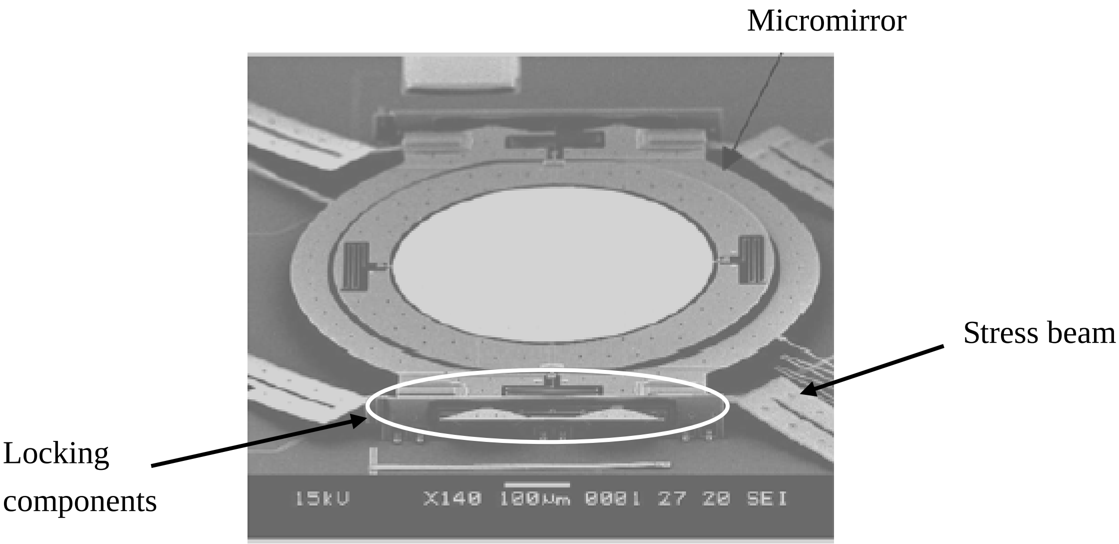

Figure 1-7: Typical assembly mechanism composed of stress-induced beam and locking components [14].

- **Bimorph stress beams**

Bimorph stress beams can be fabricated using different materials. For example, polysilicon/gold bimorph stress induced beams for three-dimensional self-assembly of MEMS device was reported in Ref [15]. However, as reported in Ref [16], the displacement of stress-induced beam would drop by 70% after 6 months because of metal relaxation.

Si_xN_y/polysilicon bimorph beams were evaluated using various reliability tests [17]. They were exploited to lift up and assemble the micro structures [14]. However, in the micro optical bench in this thesis, the Si_3N_4 layer is need for optical devices and its thickness is restricted.

SU-8/polysilicon bimorph actuator probe arrays integrated with a sensing part were proposed in Ref [17]. They were actuated employing the difference of the thermal expansion coefficients between polysilicon and SU-8.

In this thesis, a novel the bimorph stress beam made by SU-8 and single crystal silicon is proposed. The advantage of SU-8 includes 1. it can be used to fabricate optical devices such as micro lenses; 2. its processing temperature is low, so it does not affect the metal layer on the chip; 3.the thickness of SU-8 is easier to control; 4. the stress-free silicon layer can be used to fabricate flat structures.

1-2-2-2 SU-8 as structural material

SU-8 is an epoxy-based negative thick photoresist. The material has properties that are suitable for MEMS applications [18][19]. The most important characteristic is the high transparency in UV range. Compared with other thick photoresists, high transparency makes it possible to expose the photoresist up to much deeper range with conventional UV lithography equipment. Furthermore, it is possible to coat the material by conventional spin coater up to several hundreds of microns by single coating. Compared with other kinds of negative photoresist, SU-8 is much more stable to get the desired pattern. The key factor of SU-8 lithography is to control the amount of cross-linkage. As the amount of cross-linkage increases, the difference of solubility between exposed part and non-polymerized part increases. On other hand, it is hard to generate fine patterns in the case of low cross-linking density. Therefore, the amount of exposure and heat energy should be controlled not only by the thickness of film but also by the resolution of desired pattern. Additionally, SU-8 has a good endurance to the chemical and plasma, which allows more freedom in process design.

- **Stress effects**

In spite of the advantages mentioned above, SU-8 has a large stress. If it is excessively cross-linked, the patterns are distorted and sometimes adhesion failure occurs. Especially on some metals such as gold, copper, titanium and chromium, the adhesion problem is more serious than on silicon wafer or SiO_2 deposited wafers. SU-8 is also proven to have bad adhesion on silicon nitride film.

Wafer stress due to thick resist coatings is a key issue for many applications. After prebake, a small tensile stress is introduced by the difference between the thermal expansion coefficients of the wafer and SU-8. However, the main stress is generated as the crosslinked SU-8 cools down [20]. In this thesis, the tensile stress of SU-8 is used to fabricate the stress beam.

1-2-2-3 Photodiode

Recently, silicon photodiodes have been the focus of attention as a widely used standard detector, despite its sensible light wavelength is restricted from 100nm to 1100nm. Its applications induce CCD imaging, pattern recognition and front-end receiver of the Opto-Electronic Integrated Circuit (OEIC) [21,22]. This is due to its simple layout and ease to integrate with other circuitries on the same chip at low cost [23].

A simple theory for photocurrent generation is that light absorbed in the depletion region of a semiconductor diode produces electron-hole pairs, which will be separated by the applied or built in electric field. This phenomenon generates current flow in the diode. The electron-hole pairs that are generated outside the depletion region will swiftly recombine with the majority carriers and become undetectable. Therefore, photodiode with excellent performance should be designed with a wide depletion region. In general, the depletion width varies with the doping profiles. A lower doping concentration and a higher resistivity in the substrate are desirable for a wide depletion region. However, this approach is limited by the technology and fabrication processes, and it will certainly affect the performance of other circuitries when they are integrated in a single chip. If standard fabrication processes are used, layout design is the only parameter that allows optimizing the performance of photodiodes.

Six types of photodiodes have been proposed, as shown in Figure 1-8 [24]. For PD1 in Figure 1-8, the inside rectangular part is the n+ cathode of the diode. In order to get the maximum exposure to light, the ohmic contact is made only at the corner of the n+ region. In this layout, the PN junction is formed mainly between the bottom part of the n+ region and the p-substrate. For PD3, PD5, the n+ cathode region is formed along the p+ region as a rectangular ring. For PD2, PD4, and PD6, N-well is placed between the p+ and n+ diffusion region as shown in Figure 1-8. In Figure 1-9, the measured photodiode responsivity is plotted for three different layouts. For the same light intensity, PD5 shows the highest responsivity because the concentric square layout has more depletion region to produce electron-hole pairs. The dependency of photocurrent on the illuminated light intensity for four layout designs is illustrated in Figure 1-10. It can be clearly seen that N-well photodiodes are more sensitivity than the n+ photodiodes regardless of illumination intensity. This is due to two reasons: (a) N-well junction is composed of two parts, the sidewall (deeper than n+ region), the bottom area and hence larger depletion region, (b) N-well depletion region is much wider because its doping concentration is about two orders lower than the n+ region. Although the responsivity of PD1 is worse than other types, the layout design is easier. Furthermore, the fabrication process is simpler than the N-well types. Therefore, PD1 will be adopted to fabricate the photodiode.

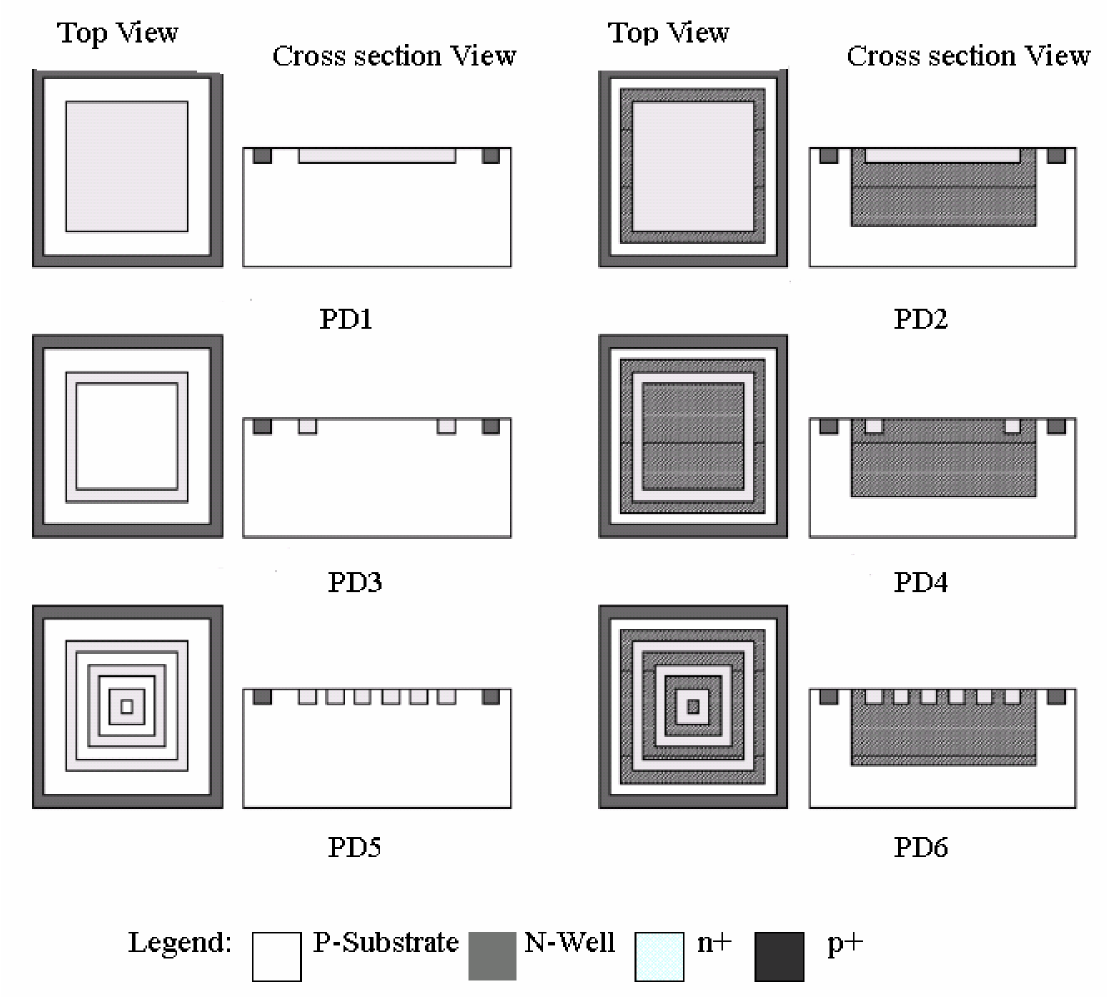

Figure 1-8: Top view and cross section of photodiode [24].

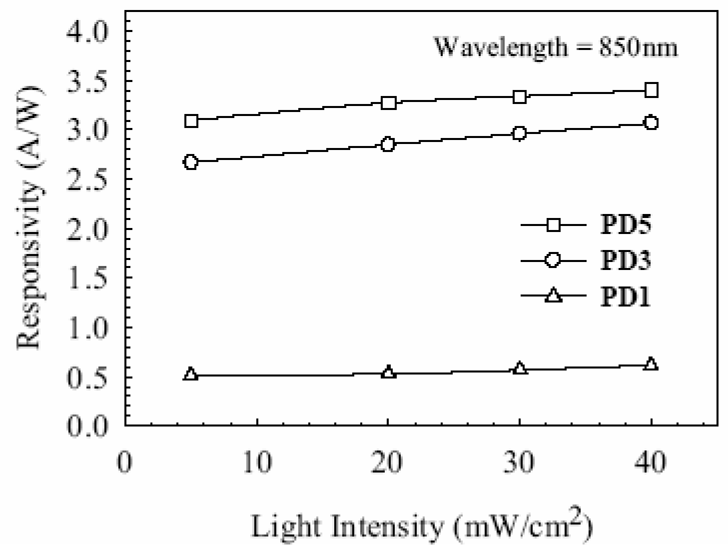

Figure 1-9: Measured diode reponsivity verses light intensity for three different layouts at V_{np}=1V [24].

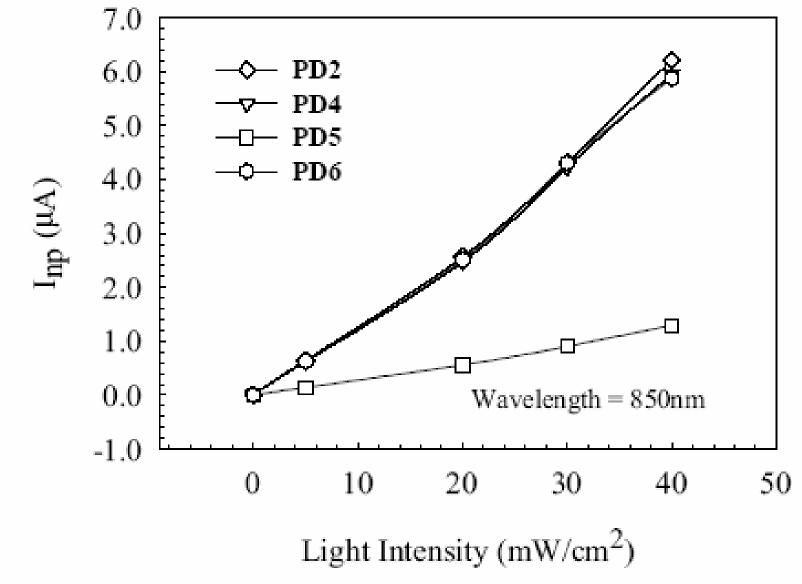

Figure 1-10: Measured photocurrent verses light intensity for four different layouts at V_{np}=1V [24].

1-3 Thesis overview

The objectives of this thesis are:

(a) Wet etching is used to fabricate U-grooves and corresponding ridge structures as the precise horizontal alignment mechanism for the micro optical bench and the tunable focusing lens.

(b) A novel fabrication process is proposed to take advantage of the single crystalline nature of SOI substrates and the easiness of processing and optical transparency of SU-8. An integrated device with a 135° mirror, latching mechanism, stressed lifting arm, and photodiodes are demonstrated.

The basic principles of the self-alignment structure and residual stress beams are presented in detail in Chapter 2. The fabrication processes and process issues are discussed in Chapter 3. The experimental results and discussions are presented in Chapter 4. Conclusions and future works are discussed in Chapter 5.