Micro knife-edge optical measurement device in a silicon-on-insulator substrate

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Abstract: The knife-edge method is a commonly used technique to characterize the optical profiles of laser beams or focused spots. In this paper, we present a micro knife-edge scanner fabricated in a silicon-on-insulator substrate using the micro-electromechanical-system technology. A photo detector can be fabricated in the device to allow further integration with on-chip signal conditioning circuitry. A novel backside deep reactive ion etching process is proposed to solve the residual stress effect due to the buried oxide layer. Focused optical spot profile measurement is demonstrated.

References and links

1. J. M. Khosrofian and B.A. Garetz, "Measurement of a Gaussian laser beam diameter through the direct inversion of knife-edge data," Appl. Opt. **22**, 3406-3410 (1983).
2. A. H. Firester, M. E. Heller, and P. Sheng, "Knife-edge scanning measurements of subwavelength focused light beams," Appl. Opt. **16**, 1971-1974 (1976).
3. F. Zamkotsian and K. Dohlen, "Surface characterization of micro-optical components by Foucault's knife-edge method: the case of a micromirror array," Appl. Opt. **38**, 6532-6539 (1999).
4. D. Karabacak, T. Kouha, C. C. Huang, and K. L. Ekinci, "Optical knife-edge technique for nanomechanical displacement detection," Appl. Phys. Lett. **88**, 193122, 1-3 (2006).
5. J. Murakowski, M. Cywiak, B. Rosner, and D. van der Weide, "Far field optical imaging with subwavelength resolution," Opt. Comm. **185**, 295-303 (2000).
6. M. Cywiak, M. Servın, and F. M. Santoyo, "Vibrating knife-edge technique for measuring the focal length of a microlens," Appl. Opt. **40**, 4947-4952 (2001).
7. S. Sumriddetchkajorn and N. A. Riza, "Micro-electro-mechanical system-based digitally controlled optical beam profiler," Appl. Opt. **41**, 3506-3510 (2002).

1. Introduction

The knife-edge method is a commonly used technique to characterize laser beam profiles [1], focused optical spots [2], and optical surfaces [3]. It is free from optical aberration due to the imaging optics and resolution limitation posed by the CCD or CMOS sensor arrays in most of the current beam profiling systems. Since the scanning actuator can be made with very high accuracy, it can be used in nano-optics [4] or subwavelength [5] optical measurement. In addition to direct profile measurement, this technique was also adapted to measure other characteristics of optical beams such as the focal length [6]. More recently, Digital micromirror device (DMD) from Texas Instruments was used to construct a knife edge scanning system without a mechanical scanner [7].

In conventional knife edge scanning setup, discrete components such as the scanners and the photo detectors are used to construct the system. Therefore the dimension and complexity of the system can not be reduced easily. The application of this technique in tightly confined optical fields or systems are thus limited. In this paper, we present a micro knife-edge scanner fabricated in a silicon-on-insulator (SOI) substrate by using the micro-electromechanical-system (MEMS) technology. In this device, a photo detector can be fabricated directly on the micro mechanical scanner to allow future integration with on-chip signal conditioning and

processing circuitry. The scale of the micro scanner with the integrated photo detector makes it possible to place the whole measurement setup in a near-field optical distribution or a compact optical system. The optical profiles that are difficult to measure otherwise can therefore be obtained more easily.

In this paper, a reflection type knife edge scanner and measured focused optical spot profiles are demonstrated. A novel backside deep reactive ion etching (RIE) process is also proposed to solve the residual stress effect in the buried oxide layer.

2. Principle and design

In a scanning knife edge system as shown in Fig. 1, a sharp knife edge plate scans across an optical field distribution. The photo detector placed behind the plate detects the partial optical energy which is not blocked by the plate. The photo current $I(x)$ measured by the photo detector as a function of the knife edge position x is given by:

$$I(x) = k \int_x^\infty P(x') dx',$$
(1)

where $P(x)$ is the optical field distribution, and k is the sensitivity of the photo detector (Fig. 2). The optical distribution can be found from:

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

If the field distribution is a Gaussian spot, the full width at half maximum (FWHM) of the spot can also be inferred from the distance between 12% and 88% of the full scale of the measured photo current $I(x)$, as shown in Fig. 2.
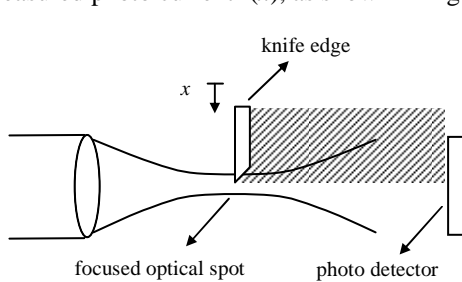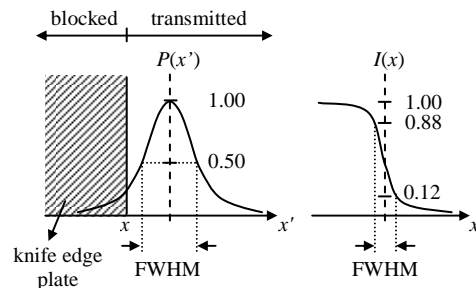

Fig. 1. Schematic of a scanning knife edge

Fig. 2. Spot profile $P(x')$ and measured signal

To implant a knife edge scanning system using MEMS technology, a micro actuator such as a comb drive actuator can be used to drive the knife edge plate, as shown in Fig. 3(a). If the scanning knife edge has a right-triangular shape, the spot can be scanned in two orthogonal directions. Three configurations can be implanted for the micro scanning system. The transmission type [Fig. 3(b)] is a miniaturization of the traditional system with the photo detector placed behind the knife edge plate. In the reflection type [Fig. 3(c)], a triangular reflective mirror is used as the knife edge plate. The partial light energy reflected from the mirror is detected by a remote photo detector. In the absorption type [Fig. 3(d)], a triangular photo detector is fabricated directly in the comb drive structure. The detector oscillates with the comb drive and serves as the knife edge plate. Among these configurations, the absorption type system has the highest level of integration. On the other hand, the reflection type system has a simple structure since no circuitry and detectors are fabricated in the device. Therefore, a prototype of the reflection type system is presented in this paper to verify the concept and design of the proposed MEMS-based scanning knife edge optical measurement system.
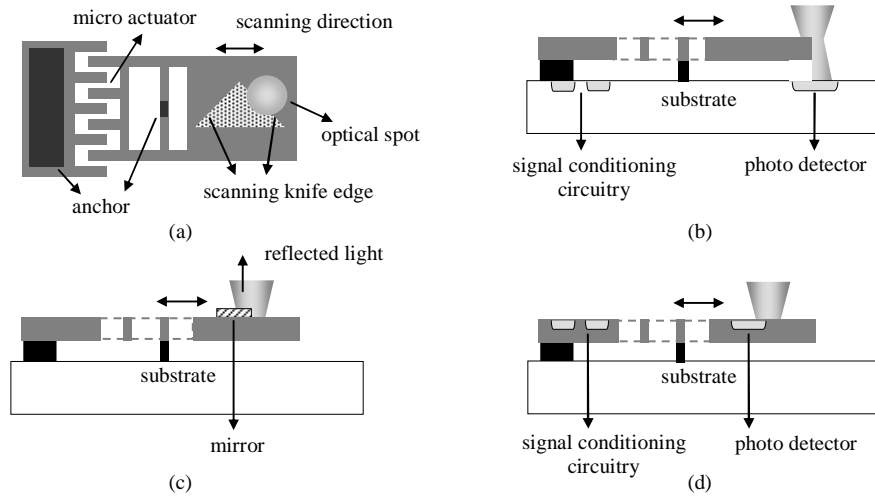
Fig. 3. (a). Top view of the micro spot profile measurement system, (b). transmission type, (c). reflection type, (d) absorption type

Since electronic devices are expected to be integrated with mechanical structures in future development, SOI substrates are used to avoid the high-temperature deposition process of additional structure layers after the fabrication of circuits and photo detectors in the SOI device layer. The single-crystalline nature of the device layer ensures high circuit performance and detector sensitivity. The mechanical structures fabricated in this layer are also free from residual stress, which greatly improves device design and reliability. The buried oxide also provides a good solution to isolate the electrical signal between sensors, actuators, and circuits.

As shown in Fig. 3(a), an electrostatic comb drive actuator is used to scan the knife edge plate. To measure the spot profile correctly, the scanning range needs to be large enough to cover the entire spot width. If the maximum spot size to be measured is about 5 μm, a scanning range of ±10 μm should be achievable for reasonable applied voltage. To reduce the required voltage, the comb drive can be driven at resonance. In such a case, a static actuator displacement of 0.1 μm is need for a typical quality factor $Q = 100$ for similar devices. If the maximum voltage is limited to 30 V, the actuator can be designed accordingly. As shown in the layout in Fig. 4, a folded flexure is used to reduce the device size. The triangular scanning region is implanted using a metal mask to reflect the light. Important device parameters, such as structure thickness, finger length, finger width, finger gap, etc., are summarized in Table 1.
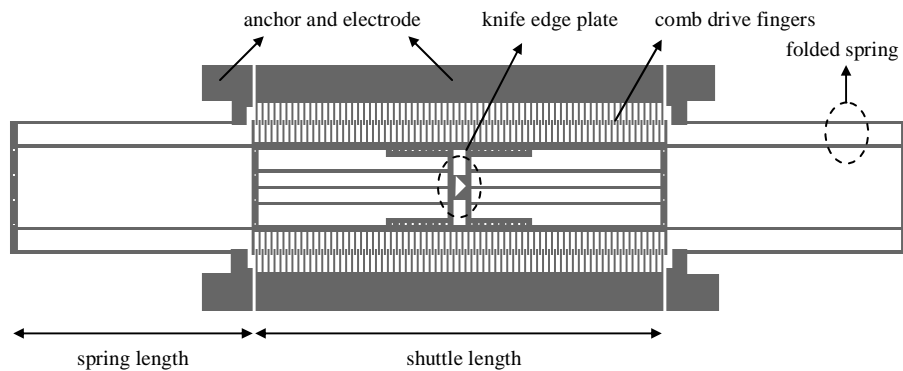

Fig. 4. Layout of the knife edge scanner in SOI substrates

Table 1 Geometry and performance parameters of the knife edge scanner

Parameter	Value	Unit	Parameter	Value	Unit
device thickness	20	μm	base of scanning triangle	30	μm
spring length	680	μm	height of scanning triangle	15	μm
spring width	10	μm	shuttle length	1110	μm
finger length	60	μm	shuttle mass M	6.6×10^{-9}	kg
finger width	4	μm	spring constant k_x	15.3	N/m
finger spacing	4	μm	quality factor	100	
finger number	70		static displacement at 30 V	0.1	μm
die area	1000×2500	μm^2	resonance displacement at 30 V	±10	μm

3. Device fabrication

The fabrication process is shown in Fig. 5. Dry etching is used in fabricating and releasing the structures to reduce the risk of stiction. Ion implantation is also included in this process so that both absorption and reflection type devices can be fabricated using the same process. As shown in Fig. 5, the photodiode is first fabricated by ion implantation in the center of the movable part, followed by aluminum deposition and patterning. The aluminum interconnect for the photo diode is routed on top of the spring. Next, the release pattern on the backside and then the comb structure on the frontside are defined by photolithography. Deep (RIE) is used to etch the defined patterns on the two sides sequentially. As shown in Fig. 5(c), only a ring is etched by RIE on the backside even though the entire region under the comb is to be removed. This process serves two purposes. First, a large block of the silicon substrate is retained to increase the rigidity of the substrate during process and handling. Therefore, the residual stress in the buried oxide in the SOI wafer does not destroy the delicate device layer. Second, all the deep RIE patterns on the backside can then be designed with equal width to avoid the RIE lag effect. After the RIE, the oxide is etched by HF vapor and the center block of silicon substrate drops automatically. Figure 6 shows a successfully fabricated and released device with the knife-edge pattern defined by a right-angle triangular opening in the metal layer. Whereas the pattern in the metal can be used as the reflection knife edge, the *pn* photodiode fabricated in the opened area can be used as the absorption knife edge.
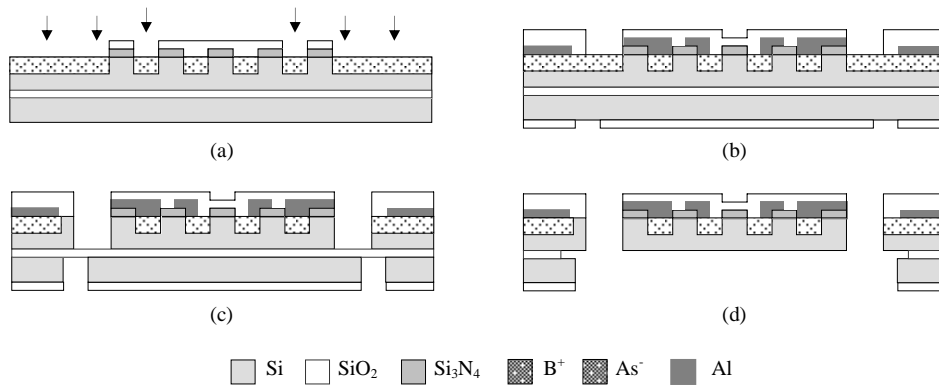

(a) (b) (c) (d)

Si   SiO$_2$ Si$_3$N$_4$ B$^+$ As$^-$ Al

Fig. 5. Fabrication processes

<div align="center">(a)   (b)</div>
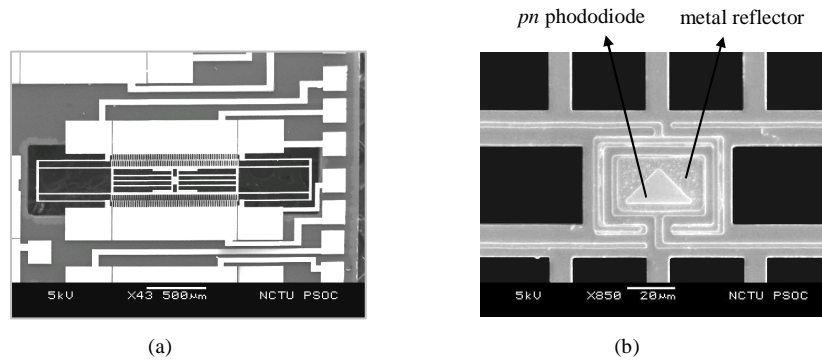
Fig. 6. Fabricated device: (a). overview, (b). knife edge plate

4. Measurement

4.1 Mechanical measurement

The mechanical characteristics of the fabricated comb drive actuator were measured by a MEMS motion analyzer (MMA). The frequency response is plotted in the Fig. 7. The resonance amplitude of 10 μm was found at 7.133 kHz, which was a little less than the simulated value of 7.58 kHz. The main reason is the reduced spring width (from the design value of 10 μm to the measured value of 9.7 μm) caused by the photolithography and etching errors. From the width of the resonance peak, the quality factor Q is about 137. Whereas both the spring stiffness and mass of the movable structure are reduced due to the etching process, the increased Q indicates an overestimated damping in the original design.
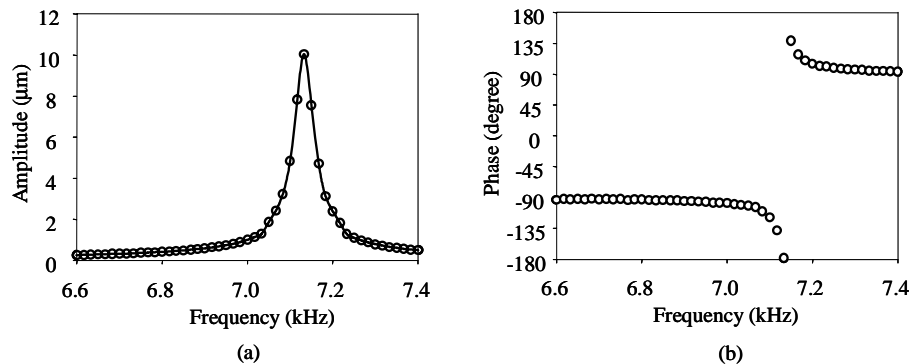

<div align="center">(a)   (b)</div>

Fig. 7. Frequency response of (a) amplitude, (b) phase

4.2 Optical profile measurement

The setup of the reflection type optical measurement is shown in Fig. 8. A He-Ne laser (633 or 543 nm) was used as the light source. A beam expander was used to expand the beam to fill the aperture of the focusing objective lens. The light reflected from the knife-edge plate was detected by a DC-coupled amplified photo detector (Thorlabs PDA 155). The micro knife edge scanner was mounted on a translation stage so that it could be moved along the optical axis to find the focal position of the objective lens. The biased actuator driving voltage $V(t) = V_0(1+\sin\omega t)$ and the detected knife edge signal $I(t)$ were recorded by an oscilloscope, as shown in Fig. 9. The scanning range of the plate was larger than the spot size. Therefore, the spot was scanned by the two orthogonal edges, the x edge and the y edge, of the knife edge plate and the spot profiles along the two directions could be obtained. In the periodic scanning, the plate scanned in both positive and negative directions to produce four knife edge signals in one scan period, as shown in Fig. 9.

The electrostatic actuation force is proportional to the square of the applied voltage; hence there is a second harmonic component in the driving force. Nevertheless, the second harmonic response is very small in the mass-spring-damper system when the operation is driven near the resonance. Therefore the driving force is proportional to the applied voltage. In the harmonic oscillation, there is a phase delay between the driving force, and thus the driving voltage $V(t)$, and the knife edge displacement $x(t)$. Near the resonance, the phase between $V(t)$ and $x(t)$ is very sensitive to the exact experimental conditions. Even slight deviation from the resonance can affect the interpretation of the results. In practice, the measured knife edge signal $I(t)$ was plotted against the recorded periodic driving voltage $V(t+\Delta t)$, where Δt was a parameter representing the exact phase between the two signals. Δt was adjusted until the positive and negative scan traces of multiple scans overlapped with one another, as shown in Fig. 10(a). The phase-corrected knife edge signal $I(x)$ could then be obtained by scaling the voltage swing to the measured maximum displacement. With such data processing, a typical knife edge signal $I(x)$ and its spatial derivative, the spot profile $P(x)$, are shown in Fig. 10. From the spot profile in Fig. 10(b), the spot size can be measured.

The profile measurement experiments were repeated with various combinations of light source and objective lens. The measurement results are summarized in Table 2. It can be seen that the measured spot size is very close to the theoretical diffraction limit. It should be noted that only a few of the recorded data points are marked in Fig. 10 for clarity. In traces shown in Figs. 9 and 10, there are actually more than 20 data points within a distance of 1 μm due to the large sampling rate of the digital oscilloscope compared to the low resonance frequency of the mechanical actuator. In this particular experiment, the spatial resolution is therefore about 50 nm. The resolution of this technique can be improved by either reducing the full scan range or increasing the data sampling rate.
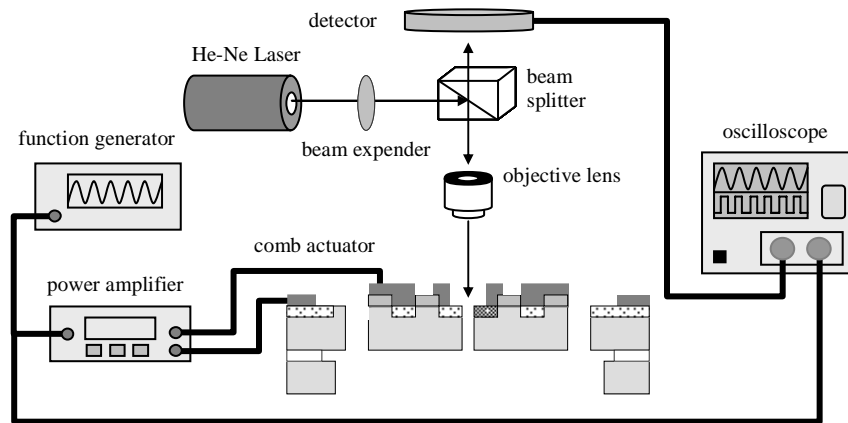

Fig. 8. Setup of the reflective type spot profile measurement

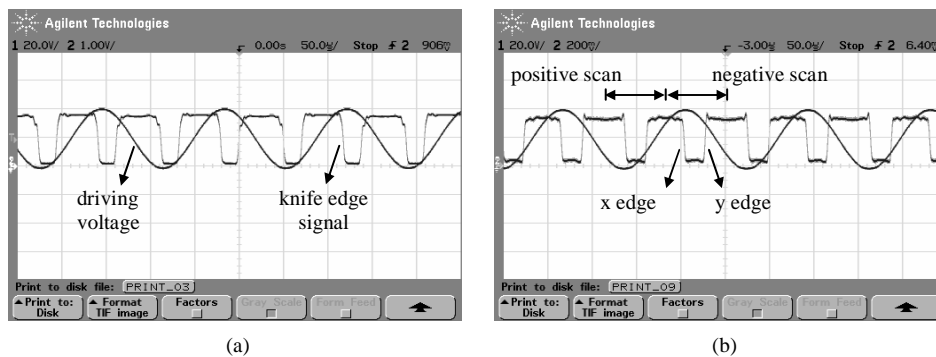(a)   (b)

Fig. 9. Measured knife edge signals of the spots focused with a (a) 20X and (b) 40X objective
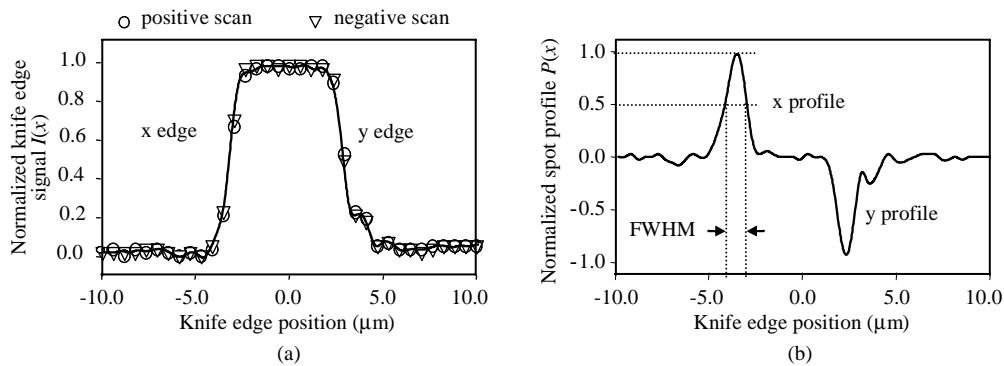
Fig. 10 (a). Measured knife edge signal, (b) derived spot profiles

Table 2 Measured and diffraction limited focused spot size

Wavelength	Objectives	NA	Diffraction limited spot size (FWHM)	Measured spot size (FWHM)
633 nm	20X	0.4	0.79 μm	0.90 μm
633 nm	40X	0.65	0.53 μm	0.57 μm
543 nm	20X	0.4	0.68 μm	0.82 μm
543 nm	40X	0.65	0.44 μm	0.50 μm

5. Conclusion

A MEMS knife edge scanner is proposed and demonstrated. The preliminary results from the reflection type device show that the spot size measured by the proposed device is close to the theoretical limits. The fabrication process allows the integration of photo detectors with the scanning knife edge plate. Further more, position sensing and data sampling circuits can be integrated with the MEMS structure by using CMOS-MEMS processes to allow real-time data processing. Such an integrated absorption type device is currently being fabricated and tested.

Acknowledgments