Si Micromachined Optical Encoder Based on Grating Imaging

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SUMMARY

Using micromachining technique, an integrated optical encoder has been fabricated for the measurement of linear displacement. Grating imaging phenomenon has been used in the displacement sensing. The index grating of the sensor consists of the transmission type Si grids, which are etched through by the reactive ion plasma. On the Si grids, arrays of line photo-detectors are installed by ion implantation. The two gratings, photo-detectors, light emitting diode, and preamplifier circuit chip are stacked perpendicularly to the optical axis. The encoder signal with a high contrast has been obtained from the integrated sensor.

Keywords: Optical sensor, Displacement sensing, Grating.

INTRODUCTION

In several mechanical systems, optical encoders are indispensable devices for sensing precise displacement [1]. Recently, with the requirement for high precision in the displacement measurements, encoders using optical interference of the light diffracted from the scale grating have been introduced [2]. In general, however, these encoders are bulky. On the other hand, in order to install optical encoders in the industrial systems, compact encoders with low cost are preferable. Advanced micro-encoder has been fabricated [3]. Likewise, the simple Moire encoders with two gratings superimposed with an air gap are still important in many practical applications. Lately, improved Moire encoders having modulated-pitch gratings were proposed for suppressing the harmonic noise of the encoder signal [4,5]. On the other hand, in the optical system similar to the Moire encoder, the grating imaging effect was used previously [6,7], in which the encoder signal was insensitive to the change of the air gap between the two gratings under incoherent illumination. The grating imaging effect was further investigated on the basis of the optical transfer function for the displacement encoder [7,8]. We carried out preliminary experiment about micromachined encoder based on grating imaging [9]. In the experiments, simple transmission grating was fabricated from Si substrate.

In this paper, we propose an integrated Si micromachined encoder using grating imaging phenomenon. Two gratings, photodetectors, light emitting diode (LED), and preamplifier circuit chip are integrated by stacking them.

PRINCIPLE AND FABRICATION

Figure 1 (a) shows the conventional encoder and Fig.1 (b) shows the encoder proposed in this study. Five components of the conventional encoder are stacked in the proposed encoder. Figures 2 (a) and (b) show the schematic front views of the designed two index gratings (Type 1 and Type 2, respectively). The Si substrate is etched through to form the index gratings. In each grating line, which is a thin Si beam, two kinds of phase shifted line photodiodes are installed using Si micro-fabrication technique. The index grating is illuminated from backside and the light passes through the slits between the grids (Fig.2(c)).

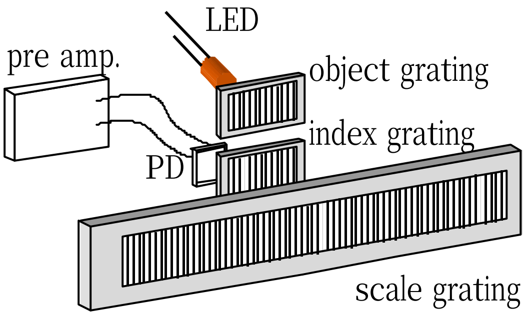

Fig. 1(a): Conventional encoder

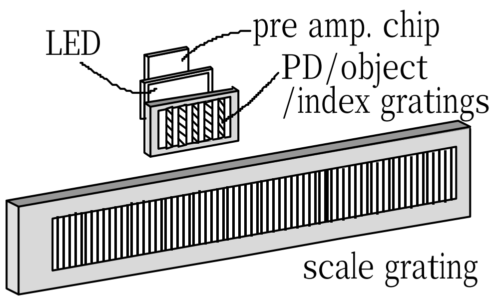

Fig. 1(b): Proposed encoder

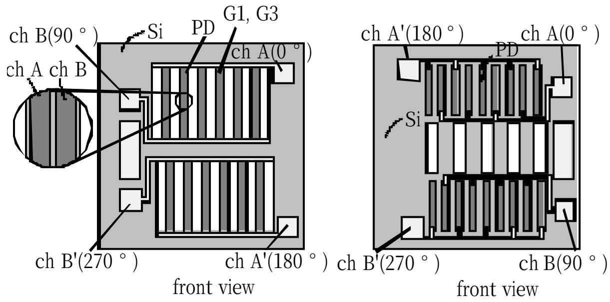

Fig. 2 (a): *Designed index (Type 1,left)*
(b): *Designed index (Type2, right)*

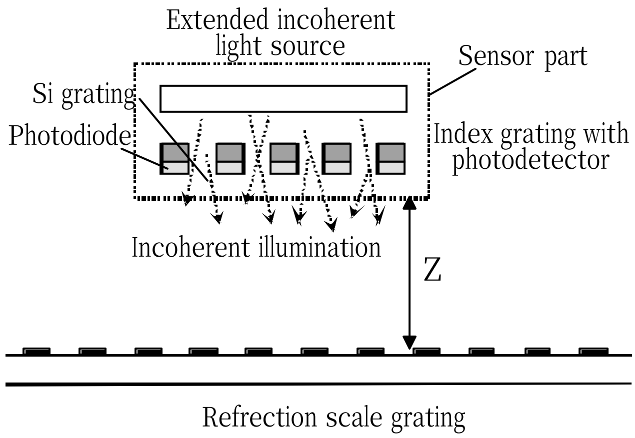

Fig. 2 (c): *Cross-sectional view of the encoder*

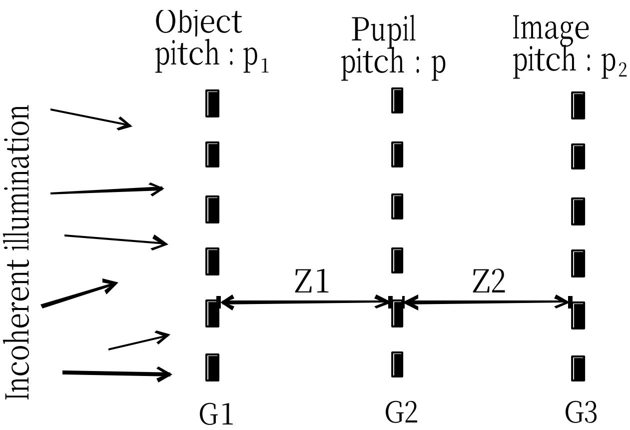

Fig. 3: *Equivalent optical configuration of the proposed encoder*

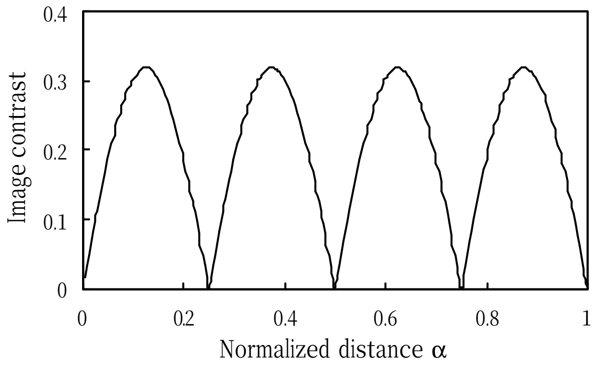

Fig. 4: *Signal contrast as a function of* a

In Fig.3, the equivalent optical system is described by the three gratings placed in tandem at the same distances z between the gratings. When the first grating (index grating) is irradiated with spatially incoherent light, the index grating pattern is transferred by the center grating (reflection scale grating) on to the image plane (which is equal to the plane of the index grating). The center grating of the three gratings works as a pupil for imaging. The optical transfer function of the pupil grating is given under our experimental conditions as follows [7],

$$F(s) = \Pi(2sp)\exp(ip\,2s\,\mathrm{m}p)\left[1 \mp \left(s - \frac{\mathrm{m}p}{lz}\right)\frac{lz}{2e}\right]$$

$$\times \mathrm{sinc}\left\{4es\left[1 \mp \left(s - \frac{\mathrm{m}p}{lz}\right)\frac{lz}{2e}\right]\right\}$$

$$\textit{for sign}(+)\ \frac{\mathrm{m}p}{lz} \le s < \frac{\mathrm{m}p}{lz} + \frac{2e}{lz}, \qquad \textit{for sign}(-)\ \frac{\mathrm{m}p}{lz} - \frac{2e}{lz} \le s < \frac{\mathrm{m}p}{lz}.$$

Here, s is the image frequency, p and $2e$ are the pitch and the slit width of the pupil grating, respectively, z is the distance between the gratings, ? is the wavelength of light and m is an integer. The function ?(x) represents a comb function which becomes unity when x is equal to integers.

When the image frequency is equal to the object frequency ($s=1/p$) and the slit width is assumed to be half of the pitch ($e=p/4$), The image contrast calculated as a function of the normalized distance $a(= zl/p^2)$ is shown in Fig.4. The image contrast is always positive under the optical conditions, which means that the image is located at the position of the geometrical shadow. Therefore, in the case of polychromatic illumination, the images generated by the respective wavelengths are superimposed constructively, and thus the image contrast is not degraded by the polychromaticity of the light source under these conditions. Moreover, the maximum value of the image contrast does not decrease with increasing the distance between the gratings, and thus the displacement can be measured at a distance z much larger than that used in the conventional Moire encoder.

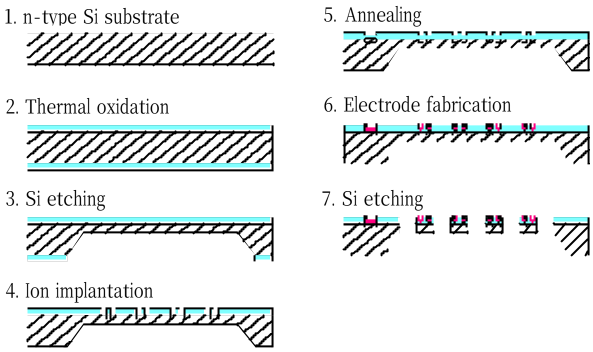

Fig. 5: *Lithographic process*

Figure 5 shows the sequence of the lithographic processes for fabricating the index grating of Type 1. Starting from a n-type Si substrate (1), a SiO_2 film is formed by wet oxidation (2). From the rear of the wafer, the wafer thickness is reduced by TMAH wet etching (3). The etched area is 4mm×6.0mm and 160mm thick. Next, the line photodiode is fabricated on the etched area by implanting B ions (4). After annealing (5), the Al electrode is patterned (6).The grids with the line photodiodes are then fabricated by etching through with inductively coupled reactive plasma (7). The pitches of the gratings fabricated in this study are as shown in Fig.6.

FABRICATED SENSORS

The fabricated index gratings are shown in Figs. 6(a) and (b) for the index gratings of Types 1 and 2, respectively. The light reflected from the scale grating is detected with the photodiodes installed on the grids of the index grating in the case of Type 1. Therefore, the areas of light emission and detection are nearly same. Two line photodiodes are installed on one grating line to obtain the 90 degree phase-shifted signals. Another set of the phases-sifted signals is obtained from the index grating located below as shown in Fig.6(a).

In the Type 2, the photodiode arrays is placed in the upper and lower parts of the etched grating, The light is emitted from the etched grating. The light reflected form the scale grating is detected in the two photodiode regions for obtaining two sets of phase-shifted encoder signals.

Figure 7 shows the designed preamplifier for obtaining the two phase-shifted signals from the four channel photodiodes. Figure 8 shows the two encoder signals (one is phase-shifted by 90 degree from the other) obtained from the four outputs of the photodiodes. The signals vary sinusoidally as a function of the lateral displacement.

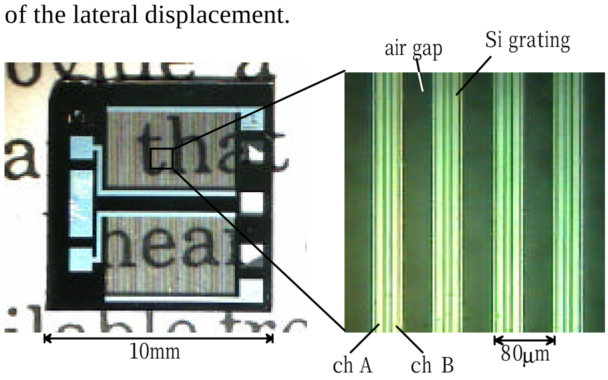

Fig. 6 (a): *Fabricated index grating (Type 1)*

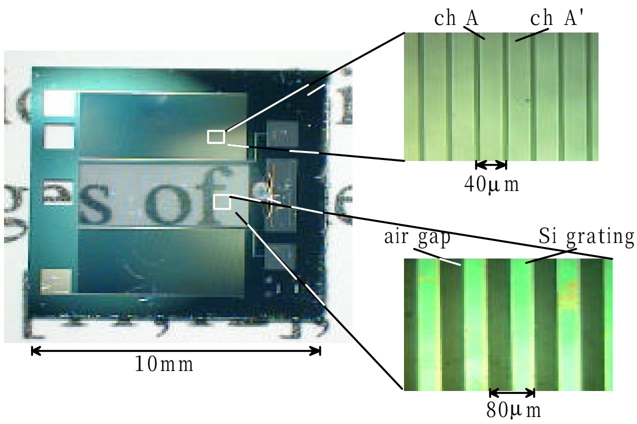

Fig. 6((b): *Fabricated index grating (Type 2)*

In Fig.8, Lissajous figure of the two encoder signals is also shown. The signals with the phase difference of 90 degree are clearly obtained. The contrast of the encoder signal approaches to a constant value in the measured region when the gap z increases.

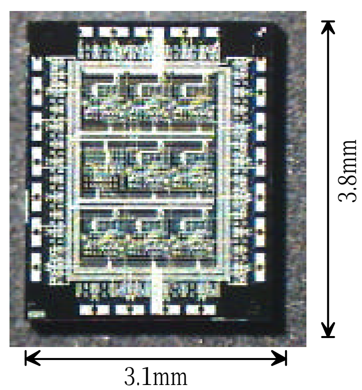

Fig. 7: *Designed pre-amplifier*

At the distances between 1mm and 30mm, the encoder signals with a high contrast were obtained. In the Type 1, the signal contrast decreases somewhat faster than that of Type 2 with the increase of *z*. The two photodiode regions (ChA,B region and ChA'B' region) are close to each other in Type 1, the light reflected from the scale grating is mixed somewhat at a large z. Using the index grating of Type 2, the results similar to those shown in Fig.8 were obtained.

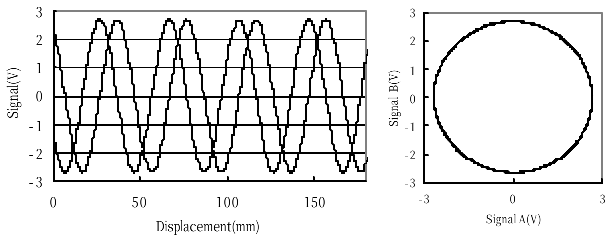

Fig. 8: *Encoder signals and Lissajous figure*

According to the results obtained above, an integrated sensor as index grating has been fabricated which is schematically shown in Fig.9. The sensor consists of the index grating (Type 1) with four kinds of photo-diode array, LED, and preamplifier circuit chip, which are stacked perpendicularly to the optical axis. The LED has been fabricated specially as an incoherent light source from GaAs wafer. The emitting area is as wide as the index grating. Front view of the fabricated sensor is shown in Fig.10. The square LED emitting light is seen bright behind the upper index grating in Fig.10. The four encoder signals with phase differences of 90 degrees have been obtained and successfully used for the displacement measurement with the division better than *p*/10.

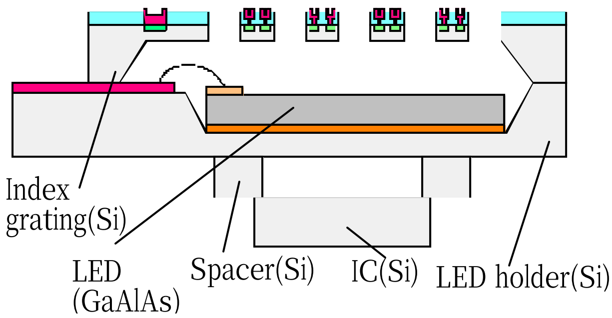

Fig. 9: *Integrated sensor as index grating*

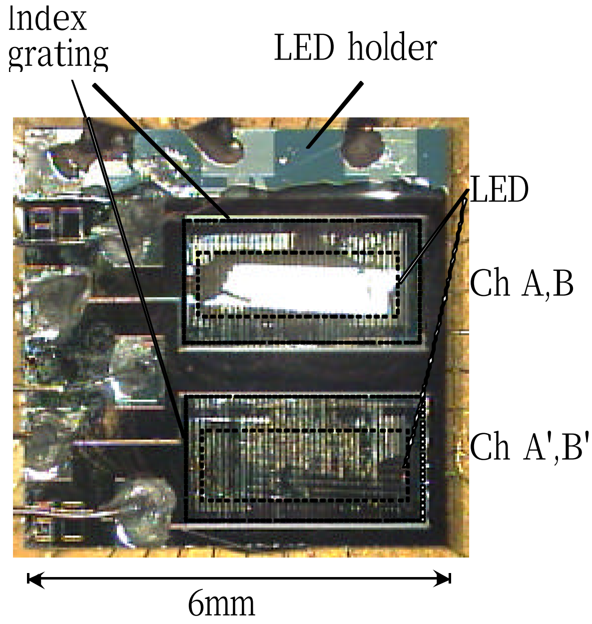

Fig.10: *Micrograph of the fabricated integrated sensor*

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