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A NOVEL STRUCTURE OF ALL-OPTICAL TYPE SILICON MICRORESONATOR*

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Abstract: A novel All-Optical type Silicon MicroResonator (AOSMR), with exciting and testing optical fibers is reported in this paper. It consists of a ridge optical waveguide and input and output optical fibers to pick up vibrations. The advantages include simplicity in structure and convenience in operation. Both theoretical analysis and experimental results showed that the new structure has large misalignment tolerance between the fiber and vibrator. The optical length of the fiber does not affect the output signal. In addition, the resonant frequency of the vibrator is independent of the internal stress of the silicon wafer.

Key words: all-optical type, microresonator, cantilever, ridge waveguide, optical fiber, pigtail
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INTRODUCTION

It is known that the application of an All-Optical type Silicon MicroResonator (AOSMR) or sensor is greatly restricted by the problem of optical coupling (Guckel et al., 1993; Pitcher et al., 1990). The vibrator surface is used for optical excitation and vibration pickup in a number of AOSMRs (Halg, 1992; Rao et al., 1992; Fatah, 1992). In this method, both exciting and testing pigtails have to be fixed on top of a cantilever beam, which is very difficult due to its limited area. The other approach is to transmit the exciting and testing signal simultaneously using an optical fiber. In this case, an optical coupler is needed. Hence the resonator becomes complex.

In this paper, a novel structure AOSMR with a ridge waveguide fabricated on the cantilever beam is reported. In order to form an independent optical circuit for the vibration pickup, both input and output fibers are connected to the ridge waveguide via standard V-grooves. An exciting optical fiber is fixed on the glass with a hole, and is bonded with a piece of silicon wafer. By using the new structure, the pickup signal synchronizes with the cantilever vibration. The optical platform used in conventional methods is no longer needed. As a result, the experimental system and theoretical analysis for the pickup signal are simplified greatly.

STRUCTURE AND PRINCIPLE

The resonator in a resonant sensor normally consists of a vibrator and two other components for exciting and probing (i.e. pickup) the vibration. Excited and pickup laser beams in the novel AOSMR are introduced directly through input and output optical fibers (i.e. pigtails), as shown in Fig.1.

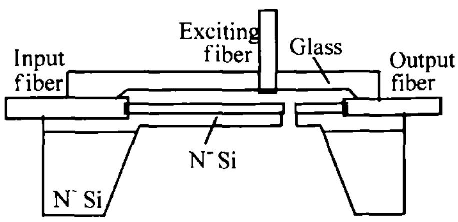

Fig.1 Schematic diagrams to show the new AOSMR structure with pigtails

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The vibrator is a cantilever fabricated on Si (100) using anisotropic wet and dry plasma etching. It is 2400 μm long, 400 μm wide and 15 μm thick, approximately. The cantilever structure is widely used as a vibrator for several reasons (Rao et al., 1992). Firstly, its resonance frequency is not affected by the stress in the silicon wafer. The free end of the cantilever may come off because of the stress. Secondly, its resonance amplitude is higher than that of a bridge. Assuming the same optical power is used to excite a cantilever and a bridge of the same size, the ratio of their maximum resonant amplitudes can be expressed as: (Rao et al., 1992)

$$\frac{Y_{max}}{Y'_{max}} = 30.92\left(\frac{L_c}{L_b}\right)^2 \tag{1}$$

Where Y_{max} and Y'_{max} are the maximum amplitudes of the cantilever and bridge, respectively, L_c and L_b are the length of the cantilever and bridge, respectively. The equation indicates that when $L_c = 0.5L_b$, the amplitude of the cantilever vibration is 7.73 times the bridge vibration. And thirdly, when the gap between the exciting fiber end and the vibrator surface is about 30 μm, the bridge vibrator does not work. In contrast, the cantilever vibrator can produce an about 42dB resonant signal peak above the noise level (Rao et al., 1992). Even if the gap was adjusted to approximately 200 μm, a resonant signal near 40 dB was also observed. This means that there is a large misalignment tolerance between the fiber end and the cantilever surface. Our study has also confirmed this point.

Based on vibration theory, the resonant frequency of a silicon cantilever beam f is given by

$$f = 0.167 \times \frac{h}{L^2}\sqrt{\frac{E}{\rho}} \tag{2}$$

where E is Young's modulus, L is the density of silicon, L is the length, and h the thickness of the cantilever.

When an intensity-modulated laser beam is focused incident to the surface of a cantilever, some of the optical energy is absorbed, causing locally periodic heating in the spot. This can result in periodic expansion and contraction of the cantilever, leading to periodic distortion of the beam. Thermal waves are then generated and propagated on the cantilever, and hence the elastic waves on the beam (Fatah, 1992). The optical energy is transformed into mechanical energy in this process.

Analysis of the cantilever response to the optical excitation showed that the resonant amplitude of the cantilever is closely related to the location of optical excitation. Commonly the suspended end of the cantilever is chosen for the excitation (Yu et al., 1998).

The optical signal probe consisted of an input multimode fiber, a ridge waveguide and an output multimode fiber. The vibrator was made of N^-/N^+-type (100) epitaxial silicon. The cantilever with a ridge waveguide was fabricated on an epitaxial layer. The layer with $10^{16}cm^{-3}$ doping concentration was grown on an around $10^{18}cm^{-3}$ substrate. The refractive index difference between the epitaxial layer and the substrate can be calculated from the formula (Soref et al., 1986)

$$\Delta n = -\left(\frac{q^2\lambda^2}{8\pi^2c^2n\varepsilon_0}\right)\left(\frac{N_e}{m^*_{ce}} + \frac{N_h}{m^*_{ch}}\right) \tag{3}$$

where q is the electrical charge, λ is optical wavelength, n is the refractive index of pure Si, ε_0 is the permittivity of free space, N_e and N_h are the free electron and hole concentrations, respectively. m^*_{ce} and m^*_{ch} are the conductivity effective mass of electrons and holes, respectively. A refractive difference index of about 10^{-3} could be achieved in this study, as calculated by using the above formula. A resulting planar waveguide was formed in the epitaxial layer.

The ridge stripe on the surface of the cantilever was produced by photolithography followed by etching. The ridge was 20 μm in width and 2 ~ 3 μm in height. Since the refractive index of the stripe was slightly higher than that of the slab waveguide, the optical beam was limited and transmitted within the strip.

The V-grooves were fabricated at two ends of the ridge waveguide to fix pigtails. The interface between the V-groove and the ridge waveguide is (111). Because the included angle between the (111) interface and the (100) ridge waveguide surface was 54.74 degrees, good contact between the end face of the optical fiber and the ridge waveguide surface could not be achieved; leaving an about 50 μm, gap similar in size to the gap of the ridge waveguide at the cantilever.

The probe loss due to the existence of two gaps can be calculated. For the fundamental mode with Gaussian distribution, its amplitude is as follows (Yariv, 1985).

$$E(z) \propto E_0 \frac{w_0}{w(z)} \exp\left[-\frac{r^2}{w^2(z)}\right] \quad (4)$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2} \quad (5)$$

where w_0 is the radius of the beam waist, $w(z)$ is the radius of the beam spot at an arbitrary position, z_0 is the confocal parameter of a Gaussian beam and z is its optical axis. From equation (5), it is estimated that the spot size increases by 7% when a laser beam comes through the gap. According to equation (4), and using the normal distribution function (Ding et al., 1998).

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2} \quad (6)$$

$$p = \frac{1}{\sigma\sqrt{2\pi}} \int_{x_1}^{x_2} \exp\left[-\frac{(x-a)^2}{2\sigma^2}\right] dx = \phi\left(\frac{x_2 - a}{\sigma}\right) - \phi\left(\frac{x_1 - a}{\sigma}\right) \quad (7)$$

where a is the symmetry point of the normal distribution curve, x_1 and x_2 are left and right half-width of the ridge waveguide section, σ is the radius of the beam spot at both ends of a gap. From equation (7), it is found that the attenuation of the optical power at the gaps was only about 2.3%.

Since the included angle of 54.74° causes total internal reflections of the probing beam at the end face of the ridge waveguide, the laser beam cannot propagate properly. In order to solve this problem, dry plasma etch to depth is about 10 μm so that the end face of the ridge waveguide is perpendicular to the cantilever surface.

When the modulating frequency of the exciting laser beam was far from the resonant frequency, the cantilever showed extremely limited response to it, and was practically in equilibrium. The probing laser beam transmited smoothly through the input fiber, the ridge waveguide and the output fiber to a detector. The signal, which underwent interruption at the gap collected by the detector, was almost a direct signal. If the modulating frequency approximates the resonant frequency of the cantilever, the response increases and the cantilever vibrates, leading to transverse deviation of the flexible part of the waveguide. The output signal changed alternately from bright to dark, and its frequency equalled that of the cantilever vibration. When the modulating and resonant frequencies were exactly the same, the amplitude of the cantilever vibration was the greatest, and hence the transverse deviation was also the largest. In this case, the amplitude of the alternating optical signal received by the detector was considerably high.

EXPERIMENT AND ANALYSIS

The technique used for making the vibrator was similar to that for the ordinary micromechanical components. The N^-/N^+ type Si (100) epitaxial wafer was oxidized with the pyrolytic method (Fig. 2a). Rectangular pits and the V-groove were then fabricated on the top and bottom of the wafer (Fig. 2b) followed by the formation of the ridge waveguide over the rectangularpit, (Fig. 2c) using two-sided photolithography and anisotropic wet etch. Then the dry plasma etch was used to form a silicon cantilever over the rectangular pit and to modify the interface between the V-groove and the ridge waveguide (Fig. 2d, e).

The excitation fiber of the resonator was fixed on the glass with a small hole. A groove was made on the glass to ensure the vibration of the cantilever. The glass was then bonded to the wafer with the cantilever. Finally the excitation and pickup fibers were fixed in the hole and the V-groove. Fig. 3 shows a resonator sample.

The experimental setup for the optical test of a silicon microresonator is shown in Fig. 4, where M is the modulating electrical source, EL and IL are the excitation and interrogation laser, respectively. FO is the focusing objective, PD is the infrared photodiode, LA is the lock-in amplifier and R is the resonator sample.

The electrical source consists of a voltage regulator, a signal generator and modulation circuits. The generator directly controls the amplitude and the frequency of the modulated signal.

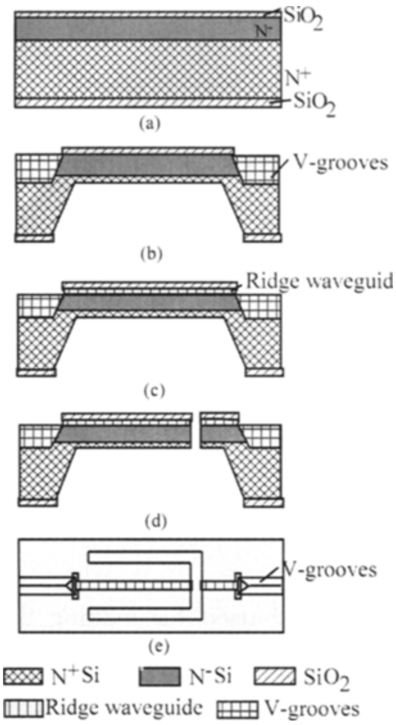

Fig. 2 The schematic diagrams of the structure and the brief fabrication process of the resonator
(a) oxidation of the wafer by the pyrolytic method;
(b) two-sided photolithography;
(c) etching the ridge waveguide;
(d) dry plasma etching of the cantilever;
(e) top view.

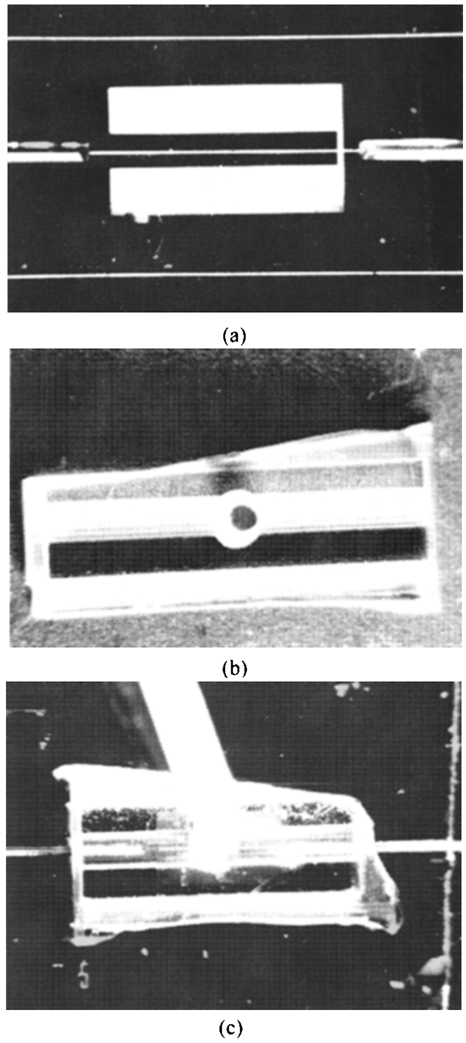

Fig. 3 Micrograph of the resonator
(a) micrograph of unmounted vibrator
(b) micrograph of unmounted glass
(c) micrograph of mounted resonator

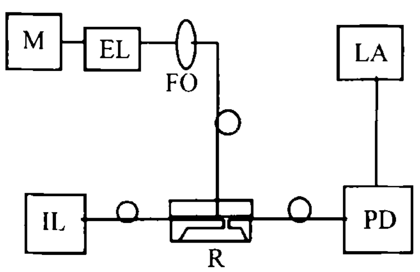

Fig. 4 Scheme of the experimental setup

The modulation signal was applied to the excitation laser through the modulation circuit. The laser beam was then modulated and coupled into the multimode fiber with a focusing objective. The modulated beam propagates through the fiber and illuminated the suspended end of the cantilever.

In the mean time, the 1.3 μm probing laser beam from the interrogation laser (IL) transmitted through the input multimode fiber, the ridge waveguide, and the output pigtail and reached the detector (PD). The optical signal was then transformed into an electrical signal, which was subsequently read by the lock-in amplifier (LA).

When the frequency was tuned far from the resonant frequency of the cantilever, the cantilever could not vibrate or only oscillated slightly, the signal received by the detector was almost cons-tant, leading to zero output of the lock-in amplifier. As the frequency gradually approached to the cantilever's mechanical resonance point, the amplitude of the vibration increased, to maximum at the resonance point. In this case, the output signal from the lock-in amplifier was also increased gradually to the maximum. By tuning the frequency and measuring the amplifier output, a curve of amplitude against frequency (A-F) was obtained as shown in Fig.5.

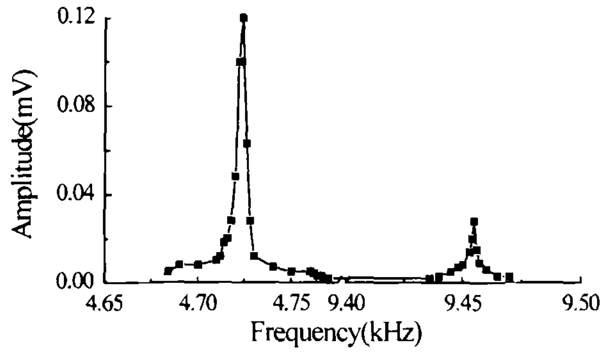

Fig.5 A-F curve of the AOSMR

The experimental result, showed that the resonant frequency of the microresonator was about 4.724 kHz, which was close to the calculated result of 4.36 kHz using equation (2). The difference could led due to the deviation from ideal size of the cantilever used. In fact, the size after the process cannot be the same as that we designed, especially the thickness, because the etching-stop technique was not adopted. Besides this, the influence of the ridge stripe on the cantilever was not taken into account in the calculation.

From the A – F specific curve, a Q value of the resonator can be calculated according to its definition:

$$Q = \frac{\omega_n}{\omega_2 - \omega_1} \quad (8)$$

where ω_n is the resonant frequency of the main vibration mode of order n, ω_1, ω_2 is the vibration frequency at half maximum of the A – F curve. In this study the Q value was larger than 940. It is expected that the Q value will be even higher if the oscillator is put into a vacuum.

CONCLUSIONS

The optically excited resonance of the all-optical type silicon microresonator with the cantilever structure was studied in detail. Our theoretical analysis and experimental results showed that:

The new microresonator is compatible to micromechanical and optical waveguide technology. A ridge optical waveguide was introduced into the new structure successfully. This means an independent optical circuit for the vibration probe. The coupling and testing of the vibration is simplified largely.

The way the signal probe works is distinctive due to the introduction of the ridge waveguide in the new structure. The deviations of the cantilever result in ridge waveguid misalignment and lead to an alternative light. The probing signal is therefore a frequency signal, which is independent of the effective optical length of the pigtail. This is of great value for realizing a practical sensor system for remote measurement.

Because the multimode fiber is used as the pigtail of the all-optical type resonator, the misalignment error tolerance between the end of the probing fiber and the ridge waveguide is greater. On the other hand, the misalignment error tolerance between the exciting fiber and the cantilever surface is also greater due to the larger vibration amplitude of the cantilever structure. The higher misalignment tolerance benefits the realization of the AOSMR greatly.

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