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PL enhancement of Si ring resonators by hydrogen plasma treatment

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1. Introduction

One of the most promising and challenging tasks in Si photonics is to combine optical and electrical functions on a Si chip.

Light sources are missing in Si photonics though detectors, modulators are well investigated. Light sources are considered to be the holy grail of Si photonics because of the great challenge of Si: the indirect band structure of Si. One of the ways to enhance the emission from Si is to use micro structures like micro rings[1] using Purcell effect[2]. Our group has succeeded in enhancing light emission by using Si ring resonators[1].

The enhancement of the spontaneous emission rate due to the Purcell effect, i.e., the Purcell factor F_p is expressed as

$$F_p = \frac{P\Gamma_r}{4\pi^2} \cdot \left(\frac{\lambda}{n_{eff}}\right) \cdot \frac{Q}{V_c} \qquad (1)$$

Where V is the modal volume, p the factor denoting the polarization anisotropy in the spontaneous emission, and Γ_r the relative confinement factor (=0.85)[3]. The quality factor Q is often used to characterize electrical resonance circuits and microwave resonators. High Q means more light can be confined in the structures. This parameter is defined experimentally as follow.

$$Q = \frac{2\pi(\text{stored energy})}{\text{energy loss per cycle}} = \frac{\lambda}{\Delta\lambda} = \frac{\omega}{2\alpha v_g} \qquad (2)$$

Where α is the attenuation coefficient, v_g the group velocity. As F_p goes up, the PL also goes up accordingly.

In order to enhance the light emission more from Si ring resonators, there can be 2 solutions. One is to exclude the non-radiative recombination center by removing the dangling bonds, and the other is to improve the quality factor of ring structures by smoothing the sidewalls resulting less light leakage.

Here, hydrogen plasma can be an option because hydrogen plasma treatment(HPT) can be an effective way to exclude non-radiative recombination center and also be thought to be an effective way to smooth the sidewalls[4]. In this paper, we propose that HPT should enhance the light emission from Si ring resonators.

2. Experiments

The ring structures with radius 1.4μm and width 0.20 μm were fabricated on lightly doped Si(100)-on-insulator (SOI) wafers. SOI was 525μm thick, the top Si layer was 340nm thick and buried oxide layer (BOX) layer was 1μm thick. The patterns of the rings were defined by EB (electron beam) lithography. After that, dry etching was done to etch the surface in order to get the ring structures. Then, piranha solution and HF were used to remove the damages originated from the dry etching. The HF solution used was $H_2O : HF(50\%) = 4 : 1$.

Fig.1 shows the remote hydrogen plasma system. We operated microwave (2.45 GHz) $H_2 + H_2O$ plasma, typically with a power of 50 W and at a pressure of 350-400 Pa of a mixed-gas stream consisting of H_2 at 40 sccm and H_2O at 2 sccm, and carried out $H_2 + H_2O$ remote plasma treatment in a horizontal quartz tube, where the rings were heated at 70~100ºC for 4 hours downstream 15 cm apart from the plasma region.

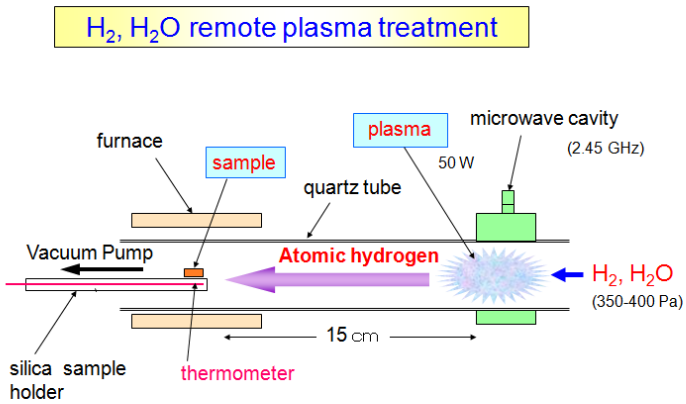

Fig.1. Remote hydrogen plasma system

We characterized the effect of HPT through measuring photoluminescence(PL) at room temperature by a microscopic PL spectroscopy (micro-PL). By measuring PL, we could know the intensity of light emission from Si ring resonators. The green laser with wavelength of 532nm was used to excite the Si ring resonators. Each PL was the sum of 5 times accumulation, and the laser spot is 1~2μm in diameter.

3. Results and discussion

The PL changes of ring resonators were shown in Fig.2. We have measured the rings several times and all of them showed almost the same spectrum, and Fig.2 shows typical PL. Three important results are shown: (1) hydrogen-plasma treated ring resonators showed higher PL baseline compared with that of ring resonators without HPT, (2) the PL of resonance peaks was significantly enhanced, (3) a month later after HPT, the PL of the Si ring resonators dropped to the original level. The reference ring, fabricated under the same condition as the ring with HPT, was used as reference. As a result, the resonance peak positions were slightly different each other caused inevitably by fabrication precision.

First, let us explain the result (1). The baseline enhancement after HPT clearly indicates that HPT reduced the non-radiative recombination center and thus radiative recombination rate was increased. This must be induced by removal of dangling bonds on and in the Si ring by hydrogen after HPT.

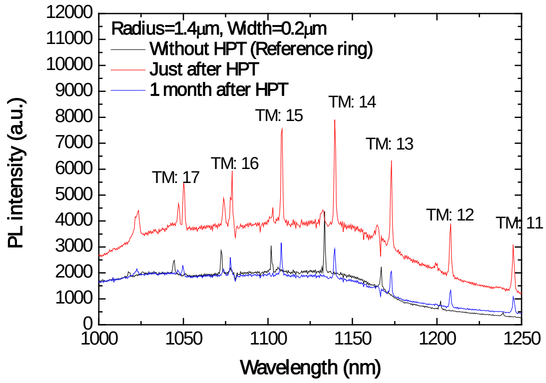

Fig.2. PL changes of hydrogen plasma treated Si ring resonators

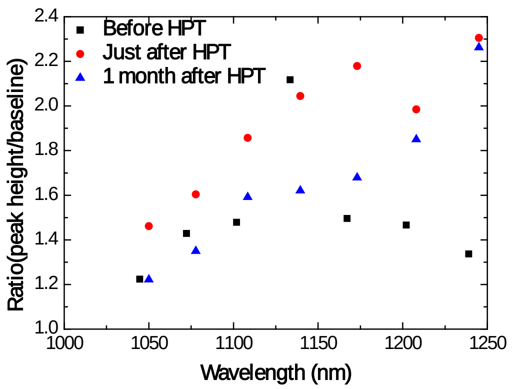

Fig.3. Ratio (peak height/baseline).

Next, we discuss the result (2); the enhancement of resonance peaks. Fig.3 shows the ratio of peak height and baseline of PL. We have confirmed that PL of baseline coincided with PL of waveguides with the same width previously, so we can consider baseline PL to be PL of waveguides. The ratio therefore shows how much PL sharp peaks were enhanced compared to PL of waveguides with the same width. The ratio is found to be higher with HPT than without. In other words, these resonance peaks become sharper with HPT, which means Q should increase after HPT. According to equation (2), attenuation coefficient α could have become lower after HPT, also, Q could have risen because of the smoother surface by HPT. However, because of the low wavelength resolution of the micro-PL system, Q could not be accurately calculated.

Finally, we discuss the result (3); the PL intensity drop of Si ring resonators. Fig.2 clearly shows that PL dropped 1 month after HPT. This result suggests that the hydrogen gradually detached after HPT. This means non-radiative recombination center increases in number as dangling bonds increases caused by detachment of hydrogen. From Fig.3, the ratio at longer wavelength still remains higher 1 month after HPT than without HPT. This result probably indicates that the effect of HPT still remains even 1 month after HPT to some extent.

4. Conclusions

We have investigated the effectiveness of HPT in enhancing the light emission from Si ring resonators. The PL intensity of Si ring resonators was enhanced just after HPT, however, the PL dropped close to its original level 1 month after HPT. There are two factors to explain these phenomena.

One is removal of dangling bonds. The PL enhancement was due to the attachment of hydrogen and removal of dangling bonds. That is to say that non-radiative recombination was suppressed just after HPT. The drop of PL could be due to the detachment of hydrogen resulting the increase in non-radiative recombination center.

The other explanation is changing Q. If the sidewalls were smoothed after HPT, Q should have risen. Fig.3 indicates that Q may have risen. However the resolution of micro-PL was not high enough for us to look into the accurate changes in Q. Investigation on Q is needed to confirm this factor.

More researches are needed to see whether Q changes or not after HPT by using higher resolution micro-PL and see how Q affects PL enhancement. In addition, more researches are needed to investigate PL stability of Si ring resonators and to investigate how hydrogen behaves on the surface of Si as time passes.

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