Hydrogen passivation of Si and Ge rings

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Abstract

Si-based emitters have encountered several difficulties in emission efficiency, carrier injection, etc. We have attempted to apply hydrogen and water vapor remote plasma treatment (H2+H2O RPT) technique, which we successfully used to enhance PL of GaN and ZnO, to enhancing the PL intensity of three Si rings with radii of 2, 3, and 5 µm, a thickness of 0.34 µm and a width of 0.25 µm. H2+H2O RPT enhanced the PL intensity of two of the rings with radii of 2 and 5 µm. This may be ascribed to the hydrogen passivation of surface states of the rings in the as-etched state just after reactive ion etching, since we observed extremely strong emission of atomic hydrogen from the plasma. For the third ring with a radius of 3 µm, H2+H2O RPT has no substantial enhancement of PL intensity probably because of a less density of surface states of the third ring in the as-etched state. Contrary to Si rings, H2+H2O RPT had no effects on the current-voltage characteristics of a Ge photodiode. This may be due to no hydrogen diffusion into Ge, or a less density of surface states of the Ge photodiode in the as-etched state.

1. Introduction

Si CMOS Photonics has emerged as one of the most promising technologies to overcome many difficulties that Si-based Electronics has encountered. This technology requires several devices, among which a light emitter probably makes the most significant bottleneck in the technological development. Therefore, to develop efficient Si-based light emitters is one of key issues. However, Si-based emitters have encountered several difficulties in emission efficiency, carrier injection, etc [1, 2]. One of alternative ways is emission enhancement using resonator-based structures such as disks, photonic crystal cavities, etc [3, 4]. Recently, the group of University of Tokyo of the authors has observed that photoluminescence (PL) from Si ring resonators fabricated on SOI wafers was enhanced at room temperature, at least 50 times stronger than that of the surrounding Si slabs [5]. Sharp peaks in the PL spectra strongly suggested the Purcell effect as the enhancement mechanism. The group of University of New South Wales reported on high external PL quantum efficiencies from bulk Si with surface texture and efficient surface passivation [6]. This report strongly suggests that the appropriate passivation of surface states of Si ring resonators may further enhance their luminescence efficiency. The group of Okayama University of the authors observed that water vapor remote plasma treatment (H2O RPT) strongly enhanced PL of Mg-doped p-type GaN and Si-doped n-type GaN, and EL of p-n diodes with the layer structure of p-GaN:Mg/n-GaN:Si/sapphire [7, 8]. Very recently, similar enhancement has also been observed on visible emission from ZnO in our group. Since extremely strong emission of atomic hydrogen from H2O remote plasma was observed, these enhancing effects may be ascribed to the hydrogen passivation of non-radiative recombination center. We have undertaken this work to aim at the emission enhancement from Si and Ge ring resonators by applying the H2O RPT technique. The present paper is the first report on the results of H2O RPT experiments.

2. Experimental Procedure

We fabricated Si ring resonators with radii of 2, 3 and 5 µm on lightly doped SOI wafers, where the top Si
layer is 0.34 μm thick and the buried oxide layer is 1 μm. We made device patterning on SOI wafers using electron beam lithography, and then fabricated device structures of rings with a thickness of 0.34 μm and a width of 0.25 μm using reactive ion etching with SF6 and C4F8 gases. We operated microwave (2.45 GHz) H2+H2O plasma, typically with a power of 50 W and at a pressure of 350-400 Pa of a mixed-gas stream consisting of H2 at 40 sccm and H2O at 2 sccm, and carried out H2+H2O RPT in a horizontal quartz tube, where the rings were heated at ~70°C for 60 minutes downstream 15 cm apart from the plasma region. We performed optical emission spectroscopy to identify radicals and ions existing in the plasma, and observed extremely strong emission lines due to atomic hydrogen, as shown in Fig. 1. We measured PL of the rings at room temperature using microscopic PL spectroscopy system before and after H2+H2O RPT. We used an Ar ion laser at 514.5 nm as an exciting light source, and focused the beam to ~1 μm in diameter with a pumping power of 2 mW measured on the Si surface. Other experimental details were the same as published before [5, 7, 8].

3. Results and Discussion

Figure 2 shows PL spectra of a Si ring resonator with a radius of 2 μm, a thickness of 0.34 μm and a width of 0.25 μm before and after H2+H2O RPT. Before H2+H2O RPT, several sharp peaks are generated at the Fabry-Pérot resonance frequency, and the Purcell effect is suggested to enhance the PL intensity [5]. After H2+H2O RPT, the intensity of these PL peaks is further increased, strongly suggesting that H2+H2O RPT enhances the PL of the ring. For another larger ring with a radius of 5 μm, a thickness of 0.34 μm and a width of 0.25 μm, H2+H2O RPT has a similar enhancing effect on the PL intensity as shown in Fig. 3, where some of the PL peaks are sharpened by H2+H2O RPT. Such PL enhancement may be due to the hydrogen passivation of non-radiative recombination centers, such as surface states of the Si ring, interface states between the Si ring and oxide, deep states in the bulk of the Si ring. However, for still another ring with a radius of 3 μm, a thickness of 0.34 μm and a width of 0.25 μm, H2+H2O RPT has no substantial enhancement of PL intensity (Fig. 4). Since this ring had sufficient strong PL intensity even in the as-etched state, comparable with those of the other rings with radii of 2 and 5 μm after H2+H2O RPT, it is likely that H2+H2O RPT made no further enhancement of the PL intensity. If
Fig. 4 PL spectra of a Si ring resonator with a radius of 3 µm, a thickness of 0.34 µm and a width of 0.25 µm before and after water vapor remote plasma treatment (H₂+H₂O RPT), which makes no substantial enhancement of PL intensity.
	his is a case, the hydrogen passivation of surface states of Si rings in the as-etched state may be the cause of the PL enhancement effect of H₂+H₂O RPT. Anyway, further experiments are necessary to confirm the enhancement effect.

Contrary to Si rings, H₂+H₂O RPT had no effects on the current-voltage characteristics of a Ge photodiode. Since hydrogen does not diffuse into Ge by hydrogen plasma treatment according to [9], the hydrogen passivation of surface states of the Ge photodiode did not occur. An alternate explanation may be a less density of surface states of the Ge photodiode in the as-etched state.

3. Conclusions

We have applied hydrogen and water vapor remote plasma treatment (H₂+H₂O RPT) technique, which we have successfully used to enhance PL of GaN and ZnO, to attempt to enhancing the PL intensity of three Si rings with radii of 2, 3, and 5 µm, a thickness of 0.34 µm and a width of 0.25 µm. H₂+H₂O RPT enhanced the PL intensity of two of the rings with radii of 2 and 5 µm. This may be ascribed to the hydrogen passivation of surface states of the rings in the as-etched state just after reactive ion etching, since we observed extremely strong emission of atomic hydrogen from H₂+H₂O plasma. For the third ring with a radius of 3 µm, H₂+H₂O RPT had no substantial enhancement of PL intensity probably because of a less density of surface states of the third ring in the as-etched state. Contrary to Si rings, H₂+H₂O RPT had no effects on the current-voltage characteristics of a Ge photodiode. This may be due to no hydrogen diffusion into Ge, or a less density of surface states of the Ge photodiode in the as-etched state.

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