Hydrogenated amorphous silicon nitride based photonic light emitting devices

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ABSTRACT

We have observed visible photoluminescence from hydrogenated amorphous silicon nitride (a-SiN_x:H) as well as the enhancement and inhibition of this photoluminescence in a microcavity formed with metallic mirrors. The a-SiN_x:H was grown both with and without ammonia. The photoluminescence of the a-SiN_x:H grown without ammonia is red. The photoluminescence of the a-SiN_x:H grown with ammonia is blue-green. In this paper, we report on the enhancement and inhibition of the photoluminescence from a half wavelength thick dielectric a-SiN_x:H microcavity. The distributed Bragg reflector mirrors were fabricated using alternating pairs of quarter wavelength thick silicon oxide and silicon nitride. The photoluminescence is enhanced by at least an order of magnitude at the dielectric a-SiN_x:H microcavity resonance at 710 nm. The minimum resonance linewidth is 6 nm, which corresponds to a quality factor of 118. The maximum rejection bandwidth is 150 nm. The enhancement and inhibition of the photoluminescence is understood by the modified photon density of states of the dielectric microcavity. The linewidth of the photoluminescence is also narrowed with respect to the linewidth of the bulk a-SiN_x:H, again due to the presence of the electromagnetic modes of the dielectric microcavity. The resonance enhancement and inhibition of the photoluminescence in a-SiN_x:H opens up a variety of possibilities for optoelectronic applications such as color flat panel displays or active resonant cavity enhanced devices for wavelength division multiplexing.

Keywords: Fabry-Perot, microcavity, distributed Bragg reflector, amorphous silicon, photoluminescence, resonators, thin films, spontaneous emission, optoelectronics, plasma enhanced chemical vapor deposition.

1. INTRODUCTION

The possibility to control the emission properties of materials with the use of optical microcavities is continuing to attract the attention of the photonics community.^{1,2} Optical microcavities can now be realized in solid state systems such as organic materials³ and semiconductors.⁴ Semiconductor microcavities are used in resonant cavity enhanced (RCE) optoelectronic devices, which are wavelength selective and ideal for wavelength division multiplexing (WDM) applications.⁵ The simple planar Fabry-Perot resonator is the most widely used geometry in semiconductor microcavities.⁶ As they alter the optoelectronic properties of photonic gain media, semiconductor microcavities can be used in very low threshold lasers and very efficient light emitting diodes (LED's).⁷ Semiconductor microcavities have been used in the realization of the low threshold vertical cavity surface emitting lasers (VCSEL's),^{8,9} external-cavity surface emitting lasers,¹⁰ microdisk,¹¹ and microwire¹² lasers. Semiconductor microcavities have also been used in efficient RCE light emitting diodes.¹³

2. EFFECT OF THE MICROCAVITY

The cavity alteration of the spontaneous emission was first proposed for radio waves.¹⁴ Afterwards, the optical microcavity alteration of the spontaneous emission was proposed¹⁵ and observed in organic microcavities.¹⁶ Alteration of spontaneous emission in semiconductor microcavities was also observed¹⁷ and calculated.¹⁸ In this, so called, weak coupling (of the photon and exciton modes) regime, the cavity mode linewidths are smaller than the exciton linewidth. The spontaneous emission spectrum is altered due to the redistribution of the density of optical modes by the presence of the microcavity. However, in the strong coupling (of the photon and exciton modes) regime, the cavity and exciton linewidths are

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comparable, and (vacuum Rabi) splitting of the cavity and exciton modes occurs.¹⁹ The strong coupling in optical microcavities was also proposed.²⁰ This was followed by the observation²¹ and the theory²² of strong coupling in semiconductor microcavities.

3. PHOTOLUMINESCENCE OF AMORPHOUS SILICON

Semiconductor microcavity effects (in the weak coupling regime) have also been applied to porous silicon (π -Si) after the observation of room temperature visible photoluminescence (PL) made π -Si a potential optical gain medium.^{23,24} Microcavity controlled PL in π -Si has been observed experimentally^{25,26} and calculated theoretically.²⁷ Microcavity controlled PL has been observed in π -Si inorganic-organic structures,²⁸ as well as Si/SiO_x superlattices.²⁹ Microcavity controlled electroluminescence (EL) of π -Si has also been reported.^{30,31} These developments justify the renewed interest in silicon (Si) as a potential optoelectronic material. With modern process techniques, it will be possible to integrate lasers, photodetectors, and waveguides into optoelectronic Si motherboards.³²

Similar to π -Si, hydrogenated amorphous silicon (a-Si:H) also exhibits room temperature visible PL.³³ In addition, planar waveguides are being realized from a-Si:H.³⁴ An advantage of a-Si:H is that, it can be deposited by plasma enhanced chemical vapor deposition (PECVD) on almost any substrate at temperatures below 500 K, which makes it compatible with the microelectronic technology. Recently, we have observed room temperature visible PL from Si rich hydrogenated amorphous silicon nitride (a-SiN_x:H).³⁵ Room temperature PL of an optically $\lambda/2$ thick layer (where $\lambda = 710$ nm at the PL maximum) of a-SiN_x:H is shown in Fig. 1. The red-near-infrared PL of the bulk a-SiN_x:H has a broad linewidth of 240 nm. This broad linewidth shows that, a-SiN_x:H has potential as a novel photonic gain medium.

Fig. 1 Room temperature photoluminescence of a-SiN_x:H.

4. MICROCAVITY EFFECTS ON THE PHOTOLUMINESCENCE OF AMORPHOUS SILICON

We have also observed the enhancement of PL in a planar a-SiN_x:H microcavity realized with metallic mirrors.³⁶ The a-SiN_x:H used in the microcavity can be grown both with and without ammonia (NH₃). For the Si rich samples (grown without NH₃) the PL is in the red-near-infrared part of the optical spectrum, while for the nitrogen rich samples (grown with NH₃ and annealed at 800° C) the PL is in the blue-green part of the optical spectrum.³⁷ While the exact mechanism of the occurrence of the PL in bulk a-SiN_x:H is still under discussion, we have suggested in Ref. 37 the use of a quantum confinement model.³⁸ There, it was proposed that, our samples consist of small a-Si clusters in a matrix of a-SiN_x:H. The regions with Si-H and Si-N, having larger energy gaps due to strong Si-H and Si-N bonds, isolate these a-Si clusters, and form barrier regions around them. The PL originates from the a-Si clusters. In this paper, we report the control of PL in an

a-SiN_x:H microcavity realized with dielectric mirrors. The microcavity is formed by sandwiching the active a-SiN_x:H layer between two distributed Bragg reflector (DBR) mirrors. The microcavity resonance wavelength was designed to be at the maximum (710 nm) of the bulk a-SiN_x:H luminescence spectrum.

Fig.2 Schematic of the a-SiN_x:H microcavity.

5. MICROCAVITY DESIGN AND FABRICATION

The microcavity was designed to have a $\lambda/2$ active layer of a-SiN_x:H sandwiched between two passive DBR mirrors. The DBR mirrors are composed of passive (not light emitting) nitrogen rich a-SiN_x:H layers and a-SiO_x:H layers. The optical thickness of these layers are $\lambda/4$. The active (light emitting) layer composed of silicon rich a-SiN_x:H is placed in between the DBR mirrors. Figure 2 shows a schematic of the a-SiN_x:H microcavity. The $\lambda/4$ passive nitrogen rich a-SiN_x:H layers are shown in black, while the $\lambda/4$ passive a-SiO_x:H layers are shown in white. The active $\lambda/2$ central layer of silicon rich a-SiN_x:H is shown in grey.

Fig. 3 SEM of the a-SiN_x:H microcavity

During the growth of the microcavity, first, the bottom DBR was deposited by PECVD on the silicon substrate using 14 pairs of $\lambda/4$ alternating layers of a-SiN_x:H (with refractive index = 1.72 and metric thickness = 104 ± 5 nm) and a-SiO_x:H (with refractive index = 1.45 and metric thickness = 124 ± 6 nm). For the nitrogen rich a-SiN_x:H deposition, ammonia (NH₃) with a flow rate of 10 sccm, and 2% silane (SiH₄) in nitrogen (N₂) with a flow rate of 180 sccm were used. For the a-SiO_x:H deposition, nitrous oxide (N₂O) with a flow rate of 25 sccm, and 2% SiH₄ in N₂ with a flow rate of 180 sccm were used. After the deposition of the bottom DBR, a $\lambda/2$ layer of silicon rich a-SiN_x:H (with refractive index = 2.03 and metric thickness = 163 ± 8 nm) was deposited. For the silicon rich a-SiN_x:H deposition, only 2% SiH₄ in N₂ with a flow rate of 180 sccm was used. Afterwards, the top DBR was deposited, using 14 pairs of $\lambda/4$ alternating layers of a-SiO_x:H and a-SiN_x:H. The radio frequency (RF) power was 20 W, and the deposition chamber pressure 1 Torr during the continuous deposition process. Figure 3 shows a scanning electron micrograph (SEM) of the a-SiN_x:H microcavity. The dark $\lambda/4$ layers are nitrogen rich a-SiN_x:H, while the bright $\lambda/4$ layers are a-SiO_x:H. The central $\lambda/2$ layer of silicon rich a-SiN_x:H also appears bright.

6. RESULTS AND DISCUSSION

Figure 4 shows the measured (solid curve) and the calculated (dotted curve) room temperature reflectance spectra of the a-SiN_x:H microcavity. The room temperature reflectance measurements were made at 0° with respect to the surface normal with a resolution of 0.1 nm. There is good agreement between the measured and the calculated reflectance spectra. There is a microcavity resonance at 710 nm with a linewidth of $\Delta\lambda = 6$ nm and a quality factor of $Q = 118$. For calculating the reflectance spectra a transfer matrix model (TMM) was used.³⁹ In this model, we used the structure of the microcavity depicted in the schematic of Fig. 2. The stop bandwidth was estimated to be 150 nm, and the resonance linewidth was estimated to be 6 nm, both of which are in agreement with the experimentally observed results.

Fig. 4 The measured (solid curve) and calculated (dotted curve) reflectance spectra of the a-SiN_x:H microcavity.

Figure 5 shows the room temperature spectrum of the a-SiN_x:H microcavity. PL The room temperature PL spectra were also measured with a resolution of 0.1 nm. The PL spectra were later corrected for the responsivity of the spectrometer and the photomultiplier tube. An Ar⁺ laser with a wavelength of 514.5 nm and a power of 150 mW was focused with a 15 cm focal length cylindrical lens on the samples. The PL spectra were taken at $0 \pm 3.6^\circ$ with the laser at 30° with respect to the surface normal. During the PL measurements the temperature of the sample is not controlled and there might be local heating, which reduces the PL efficiency, and broadens the PL linewidth.⁴⁰ However, local heating would not considerably affect the general shape and features of the a-SiN_x:H gain spectrum. As seen in the PL spectra, even though there might be local heating, we are observing strong PL from the sample.

Fig. 5 The photoluminescence spectra of the a-SiN_x:H microcavity.

There is good agreement between the reflectance spectrum of Fig. 4 and the PL spectrum of Fig. 5. Both the reflectance and the PL spectra show a microcavity resonance at a wavelength of 710 nm. This resonance has a linewidth of $\Delta\lambda = 6$ nm and a quality factor of $Q = 118$. The PL is enhanced by the microcavity resonance, which correlates well with the minimum of the reflectance spectrum.

In order to clarify the effect of the microcavity and to demonstrate its advantages with respect to the bulk a-SiN_x:H, we can compare the PL of a $\lambda/2$ thick layer of bulk a-SiN_x:H (Fig. 1) with the microcavity PL spectrum (Fig. 5). The comparison of the spectra in Figs. 1 and 5, which were obtained under the same experimental conditions, shows that the effect of the microcavity is twofold. First, the wide PL emission band (240 nm) is strongly narrowed to 6 nm. Second, the resonant enhancement of the peak PL intensity is more than one order of magnitude with respect to the emission of the $\lambda/2$ thick layer of bulk a-SiN_x:H. In addition by choosing the appropriate width of the a-SiN_x:H active layer and DBR's it is possible to select the emission wavelength of the microcavity by taking advantage of the broad spectral emission of the a-SiN_x:H active layer.

7. CONCLUSIONS

In conclusion, we have demonstrated that a-SiN_x:H microcavities with DBR mirrors can be successfully realized by PECVD. The PL of the a-SiN_x:H is both narrowed and enhanced at the microcavity resonance with respect to the PL of the bulk a-SiN_x:H. This narrowing and enhancement of the PL can be understood by the redistribution of the density of optical modes due to the presence of the microcavity. The microcavity narrowing and enhancement of luminescence in a-SiN_x:H opens up a variety of possibilities for optoelectronic applications such as color flat panel displays or active resonant cavity enhanced devices for wavelength division multiplexing.

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