Dielectric Resonators Based on Amorphous Silicon

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ABSTRACT

In this paper, we report on the design, modeling, fabrication, and characterization of dielectric microresonators based on hydrogenated amorphous silicon nitride and hydrogenated amorphous silicon oxide. The microresonators were modelled using the transfer matrix method (TMM). Quarter wavelength thick stacks of hydrogenated amorphous silicon nitride and hydrogenated amorphous silicon oxide were consecutively deposited using low temperature plasma enhanced chemical vapor deposition (PECVD). For the characterization of the dielectric microresonators the intrinsic photoluminescence of the amorphous silicon nitride is used. The photoluminescence is enhanced by at least an order of magnitude at the resonance wavelength of 710 nm. The minimum resonance linewidth is 6 nm, corresponding to a quality factor of 118. The maximum rejection bandwidth of the distributed Bragg reflector (DBR) is 150 nm. The enhancement and inhibition of the photoluminescence is understood by the modified photon density of states of the dielectric microresonator. The linewidth of the photoluminescence is also narrowed with respect to the linewidth of the bulk amorphous silicon nitride, again due to the presence of the electromagnetic modes of the microresonator.

Keywords: Fabry-Perot, microresonator, distributed Bragg reflector, amorphous silicon, photoluminescence, 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.^{6,7} 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).⁸ Semiconductor microcavities have been used in the realization of the low threshold vertical cavity surface emitting lasers (VCSEL's),^{9,10} external-cavity surface emitting lasers,¹¹ microdisk,¹² and microwire¹³ lasers. Semiconductor microcavities have also been used in efficient RCE LED's.¹⁴

2. DIELECTRIC MICRORESONATORS

The cavity alteration of the spontaneous emission was first proposed for radio waves.¹⁵ Afterwards, the microcavity alteration of the spontaneous emission was proposed¹⁶ and observed in organic microcavities,¹⁷ in the optical part of the electromagnetic spectrum. In addition, alteration of the spontaneous emission in semiconductor microcavities was observed¹⁸ and calculated.¹⁹ In this weak coupling (of the photon and exciton modes) regime, the interaction (Rabi coupling) strength is smaller than the microcavity mode damping (linewidth) and the exciton mode damping (linewidth). The spontaneous emission spectrum is altered due to a 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 interaction (Rabi coupling) strength is bigger than the microcavity mode damping (linewidth) and exciton mode damping (linewidth), and Rabi splitting of the microcavity and exciton modes occurs.²⁰ The proposition of strong coupling in optical microcavities,²¹ was followed by its observation²² and theory.²³

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3. POROUS SILICON MICRORESONATORS

Semiconductor microresonator effects (in the weak coupling regime) have been applied to porous silicon (π -Si), after the observation of room temperature visible photoluminescence (PL)²⁴ made π -Si a potential optical gain medium.²⁵ Steady state^{26,27,28} and temporally resolved,²⁹ single and multiple³⁰ microresonator controlled PL in π -Si has been observed experimentally^{31,32,33} and calculated theoretically.³⁴ The possibility of using π -Si microcavities as chemical sensors has been investigated.³⁵ In addition, microresonator controlled PL has been observed in π -Si inorganic-organic structures,³⁶ as well as Si/SiO_x superlattices.^{37,38,39} SiO₂/TiO₂ microresonators,⁴⁰ SiO_x/WO_y, and SiO_x/MO_y multilayers⁴¹ have been fabricated. Microresonator controlled electroluminescence (EL) of π -Si has been reported.^{42,43} Interference filters⁴⁴ and optical waveguides⁴⁵ have also formed from π -Si. Two-dimensional (2-D) photonic crystals have been fabricated in π -Si⁴⁶ and silicon nitride (Si₃N₄)⁴⁷ waveguides. 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^{48,49} for WDM applications.⁵⁰

4. AMORPHOUS SILICON NITRIDE MICRORESONATORS

Similar to π -Si, hydrogenated amorphous silicon (a-Si:H) also exhibits room temperature visible PL.⁵¹ In addition, planar waveguides are being realized from a-Si:H.⁵² 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).⁵³ While the exact mechanism of the occurrence of the PL in bulk a-SiN_x:H is still under discussion, we have suggested⁵³ the use of a quantum confinement model.⁵⁴ 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. Figure 1 shows a high magnification Atomic Force Microgram (AFM) of the a-SiN_x:H surface. The resemblance of the a-SiN_x:H to π -Si is remarkable.

Figure 1. High resolution AFM of the a-SiN_x:H surface.

We have also observed the enhancement of PL in a planar a-SiN_x:H microresonator realized with metallic mirrors.^{55,56} The a-SiN_x:H used in the microresonator 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.⁵⁷ Figure 2 shows the room temperature photoluminescence of a-SiN_x:H grown without NH₃.

Figure 2. Room temperature photoluminescence of a-SiN_x:H.

In this paper, we report the alteration of photoluminescence (PL) in an all dielectric a-SiN_x:H microresonator, and the measured and calculated reflectance of the all dielectric a-SiN_x:H microresonator. The microresonator is realized by sandwiching the active a-SiN_x:H layer between two distributed Bragg reflectors (DBR's). The microresonator resonance wavelength was designed to be at the peak (710 nm) of the bulk a-SiN_x:H PL spectrum.

5. MICRORESONATOR DESIGN AND FABRICATION

The microresonator was realized by a $\lambda/2$ active layer of a-SiN_x:H sandwiched between two passive DBR's. First, the bottom DBR was deposited by PECVD on the silicon substrate using 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). Figure 3 shows the schematic of the all dielectric a-SiN_x:H microresonator.

Figure 3. Schematic of the all dielectric a-SiN_x:H microresonator.

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 10 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. 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 gray. Figure 4 shows a scanning electron micrograph (SEM) of the a-SiN_x:H microresonator.

Figure 4. SEM of the a-SiN_x:H microresonator

6. REFLECTANCE MEASUREMENTS

Figure 5. The measured reflectance spectrum of the a-SiN_x:H microresonator.

Figure 5 shows the measured room temperature reflectance spectrum of the a-SiN_x:H microcavity. The room temperature reflectance measurements were made at 0±5° with respect to the surface normal with a resolution of 0.1 nm. The measured

reflectance spectra of Fig. 5 shows a microcavity resonance at a wavelength of 710 nm. This resonance has a linewidth of $\Delta\lambda = 6$ nm and a quality factor of $Q = 118$. In order to compare our experimental reflectance measurements, we have also calculated the room temperature reflectance spectrum of the a-SiN_x:H microcavity.

7. REFLECTANCE CALCULATIONS

The transfer matrix model (TMM) was used for the calculations.⁵⁸ In this model, we used the structure of the microresonator shown in Fig. 2 and 3. Figure 6 shows the calculated room temperature reflectance spectrum of the a-SiN_x:H microresonator.

Figure 6. The calculated reflectance spectrum of the a-SiN_x:H microresonator.

The calculated spectrum of Fig. 6 is in good agreement with the experimentally observed reflectance spectrum of Fig. 5. The resonance linewidth $\Delta\lambda$ and the quality factor Q can also be estimated using the multiplication of the electric field amplitude reflectivity coefficients r_1 and r_2 :

$$r_1 r_2 = \frac{\left(\frac{n_s}{n_{si}} \left(\frac{n_o}{n_n} \right)^{2q} - 1 \right) \left(\frac{n_s}{n_a} \left(\frac{n_o}{n_n} \right)^{2q} - 1 \right)}{\left(\frac{n_s}{n_{si}} \left(\frac{n_o}{n_n} \right)^{2q} + 1 \right) \left(\frac{n_s}{n_a} \left(\frac{n_o}{n_n} \right)^{2q} + 1 \right)} \quad (1),$$

$$Q = \frac{2\pi \left(1 + \frac{n}{\Delta n} \right)}{\ln(1/r_1 r_2)} \quad (2),$$

$$\Delta\lambda = \frac{\lambda}{Q} \quad (3),$$

where $\lambda = 710$ nm is the resonant wavelength, $n_s = 2.03$ the refractive index of the silicon rich a-SiN_x:H, $n_{si} = 3.77$ the refractive index of the silicon substrate, $n_a = 1.0$ the refractive index of air, $n_n = 1.72$ the refractive index of the nitrogen rich a-SiN_x:H, $n_o = 1.45$ the refractive index of a-SiO_x:H, $n = 1.59$ the average refractive index of a-SiN_x:H and a-SiO_x:H, $\Delta n = 0.27$ the refractive index difference of a-SiN_x:H and a-SiO_x:H, and $q = 10$ the number of pairs in each DBR. The estimated quality factor of $Q = 260$ and linewidth $\Delta\lambda = 3$ nm are close to the experimentally observed values.

8. PHOTOLUMINESCENCE MEASUREMENTS

The room temperature PL spectra were 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 $0 \pm 5^\circ$ 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.⁵⁹ 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 of Fig. 2, even though there might be local heating, we are observing strong PL from the sample.

Figure 7. The photoluminescence spectrum of the a-SiN_x:H microresonator.

There is good agreement between the reflectance and the PL spectra. Both the reflectance and the PL spectra of Fig. 5 and 7 show a microresonator 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 microresonator resonance, which correlates well with the minimum of the reflectance spectrum. In order to clarify the effect of the microresonator and to demonstrate its advantages with respect to the bulk a-SiN_x:H, we also show the PL of a $\lambda/2$ thick layer of bulk a-SiN_x:H in Fig. 2, obtained under the same experimental conditions as the PL of the a-SiN_x:H microresonator shown in Fig. 7. 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. A comparison of the spectra in Fig. 2 and 7 shows that the effect of the microresonator is twofold: first, the wide 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 microresonator by taking advantage of the broad spectral emission of the a-SiN_x:H active layer.

9. CONCLUSIONS

In conclusion, we have demonstrated that a-SiN_x:H microcavities with DBR's can be successfully realized by PECVD, and can be used for the control of the PL in a-SiN_x:H. The PL of the a-SiN_x:H is both narrowed and enhanced at the microresonator 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 microresonator. The microresonator narrowing and enhancement of luminescence in a-SiN_x:H opens up a variety of possibilities for optoelectronic applications such as resonant cavity enhanced light emitting diodes and color flat panel displays.

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