Cavity-Q measurements of silica microsphere with nanocrystal Si active layer

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Abstract– Cavity Q of silica microsphere with nanocrystal silicon active layer is investigated. Q factor of up to 8×10^5 is observed, and loss due to nc-Si is identified as not dominating the loss mechanism.

I. INTRODUCTION

There is an increasing interest in silicon-based photonic technology, as evidenced by recent reports [1,2]. A significant roadblock to developing such silicon photonic technology is the relative optical inactivity of the silicon-based materials, including Si itself, SiO_2 , and SiN_x . This has led to intense search for Si-compatible, optically active materials, and also into ways of making Si itself optically active [3, 4]. An interesting material is nanocrystalline Si (nc-Si). It has a much higher optical activity in the visible range due to quantum confinement effects, allowing it to be used as a light source [5], and recently, evidence of stimulated emission has been reported, making development of Si laser plausible. In addition, nanocrystal Si can also act as sensitizers to Er, enabling development of low-cost optical amplifiers, and also as a non-linear optical element.

However, nc-Si can scatter light no matter how small they may be, as well as cause absorption of signal light due to the interface states. Such loss mechanisms are inherent to any optical system that relies on Si nanocrystals, and can significantly affect the performance of possible devices. However, so far there has been a little work on the scattering and loss mechanisms of nc-Si, in part because they are difficult to manufacture on long enough of a scale to measure the loss accurately.

In this paper, we report on measurement of cavity-Q values of high-Q silica microsphere cavities with an nc-Si active layer at $1.54 \mu\text{m}$. Such silica microspheres can have extremely high Q values that exceed 10^8 , enabling an accurate measurement of even very weak loss mechanisms. We find that silica microsphere cavities can have cavity Q values as high as 8×10^5 even with an nc-Si active layer. Dependence of the cavity Q values on the annealing

conditions and composition of nc-Si layer indicate that nc-Si themselves are not the dominant scattering center in the active layer, indicating that with proper design and fabrication, low-loss optical components with nc-Si may be realized.

II. EXPERIMENTAL

The high-Q silica microsphere is fabricated at Stanford University. A CO_2 laser beam is focused on the tip of a piece of silica fiber. The tip is melted and by surface tension reshapes itself into a sphere of about $150 \mu\text{m}$ diameter attached to the sphere by a thin neck.

Subsequently, a layer of amorphous SiO_x is deposited onto the microsphere surface by inductively-coupled plasma enhanced chemical vapor deposition (ICPECVD) using Ar, SiH_4 and O_2 as source gases. The thickness of the SiO_x layer was $140 \pm 10 \text{ nm}$. During deposition, the spheres were rotated along its axis during deposition, ensuring uniformity of the deposited layers. Subsequently, the spheres were annealed for 1 hr at temperatures ranging from 650 to 1100 °C to precipitate nc-Si. After high temperature annealing, all samples were hydrogenated by a 1 hr anneal at 650 °C in forming gas (10:90 mixture of $\text{H}_2:\text{N}_2$) to passivate defects. For comparison, a piece of Si wafer was also deposited with SiO_x layers at the same time and underwent the identical annealing procedures for analysis.

The composition of the films were analyzed with Rutherford backscattering spectroscopy (RBS). The precipitation of nc-Si was analyzed with X-ray Photoelectron Spectroscopy (XPS) and transmission electron microscopy (TEM). Photoluminescence spectra of the films were measured using the 488 nm line of an Ar laser, Cs:InGaAs PMT, and employing the standard lock-in technique.

The cavity-Q factors of the microsphere were measured using a tunable external-coupled cavity laser and a tapered fiber.

III RESULTS.

Figure 1 shows the optical microscope image of a sphere with nc-Si active layer, confirming the uniformity of the deposited layer. Figure 2 shows the scanning electron microscope image of the surface layer, confirming the smoothness of the deposited film surface.

Figure 3 shows the dependence of the PL spectrum of a film with 10 % excess Si on the annealing temperature. No significant PL emission is observed unless the annealing temperature reaches 1100 °C, consistent previous report.

Such emergence of strong nc-Si PL peak is associated with emergence of well-formed *crystalline* Si nanoclusters. This is shown by Figs. 4 and 5, which show the XPS spectra and the TEM image of the annealed films, respectively. We find that even as-deposited films shows presence of Si-Si bonds, indicating presence of Si nanoclusters. However, the XPS spectra also show presence of many suboxide phases, which do not disappear until the annealing temperature reaches 1100 °C. At that point, however, crystalline Si nanocluster become visible in TEM, as is shown in Fig. 5.

Figure 6 shows the dependence of the PL spectra on the film composition. We find a monotonic redshift in the PL intensity with increasing excess Si content, consistent with previous reports that increasing excess Si content results in larger nc-Si clusters.

Figure 7 shows the dip in the transmission intensity of the probe beam due to the coupling with the whispering gallery mode of the microsphere. From the width of the dip, we can obtain the Q factor of the microcavity.

Figure 8 shows the values of the microcavity obtained from the width of the transmission dip. We find that for pure silica film, the Q factor of the microcavity remains as high as 2×10^7 . The Q-factor decreases strongly, however, if a Si-rich active layer is deposited. Interestingly, we do not observe any consistent dependence of the value of the Q-factor upon nc-Si size. In fact, as the anneal temperature dependence of the 10% excess Si sample shows, the highest value of the Q-factor seems to be obtained for the sample with the largest nc-Si size.

IV. DISCUSSION

Many possible factors can lead to reduction of the Q-factor of a microcavity, not the least of which is inevitable damage introduced to the surface during handling. However, the fact that the microcavity with pure silica layer has a Q-value of 2×10^7 indicates that it is possible to retain very high Q values for the microcavities even with deposition, annealing, and subsequent trans-pacific transportation. Therefore, it is very likely that the relatively low Q-values of the microspheres with nc-Si active layer is due to the loss mechanisms associated with the layer. However, the fact that there is little dependence of the Q-value on the nc-Si size indicates that scattering

due to nc-Si is not the dominant loss mechanism. Indeed, the films with the largest nc-Si – the films with highest excess Si content and with highest annealing temperature – show the highest Q-value, or the lowest loss value. Therefore, it is likely that the signal loss is dominated by some other mechanism such as interfacial scattering or absorption by interfacial states (since nc-Si itself cannot absorb the 1.54 μm light). Further research is needed to clarify exactly which mechanism is dominant. Note, however, that such mechanisms are not intrinsic to nc-Si themselves. Therefore, the results presented in this paper show that there no intrinsic, high-loss mechanism associated with nc-Si, and that practical low-loss optical devices based on nc-Si may be possible.

Figure 1: Optical microscope image of a microsphere with deposited nc-Si active layer. Note the uniformity of the deposition.

Figure 2: SEM image of the deposited layer. Note the smoothness of the surface.

Figure 3: Dependence of the PL spectra of the nc-Si film with 10% excess on the anneal temperature

Figure 4: Dependence of the XPS spectra of the nc-Si film with 10% excess on the anneal temperature. Note the presence of Si-Si bond in as-deposited film

Figure 5: TEM image of the nc-Si film with 10% excess Si after 1100 °C anneal. Crystalline nc-Si indicate by the circles

Figure 6: Dependence of the PL peak on the excess Si content. All films were annealed for 1 hr at 1100 °C

Figure 7: Normalized transmission dip at whispering gallery mode of the microsphere.

Figure 8: Dependence of cavity Q factor on the PL peak wavelength (e.g., nc-Si size) and the anneal temperature

V. CONCLUSION

In conclusion, we have measured the cavity Q of a silica microsphere microcavity with nanocrystal Si active layer. We find that a Q factor as high as 8×10^5 may be obtained even with the active layer. Furthermore, the data indicate that the nc-Si are not the main reason for the reduction in Q, indicating the possibility of using nc-Si as a basis for practical, low-loss optical devices.

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