# Silicon-nitride Films Deposited by PECVD Method on Silicon Substrate for Next Generation Laser Interference Gravitational Wave Detector

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**Abstract:** We show optical properties and stress related mechanical loss for silicon nitride films deposited by plasma enhanced chemical vapor deposition (PECVD) method for application in the next generation laser interference gravitational wave detector.

**OCIS codes:** (310.0310) Thin flims; (310.6860) Thin films, optical properties; (310.6870) Thin films, other properties

Current high reflective coatings for mirrors of the laser interference gravitational wave detector are composed of $Ta_2O_5$-$TiO_2$ composite film as the high refractive index layer and $SiO_2$ as the low refractive index layer. The layers are deposited alternately on fused silica substrate by using ion beam sputter deposition method. The coatings and the substrate have low optical loss and low mechanical loss used in current detector operated at room temperature. Brownian thermal noise is the dominant noise source for the coatings. Cryogenic detector is under construction in KAGRA and is also proposed for the next generation detector for LIGO and ET to reduce the thermal noise. Thermal noise is related to the mechanical loss through the fluctuation-dissipation theorem [1]. For next generation cryogenic detector operated at 1550 nm wavelength, silicon is one of the candidate substrates due to its low cryogenic mechanical loss in contrast to the fused silica substrate that suffer from cryogenic mechanical loss leak. Ion beam sputtered $Ta_2O_5$-$TiO_2$ and $SiO_2$ coatings currently in use also have the same shortcoming. Seeking silicon-compatible high reflective coatings with good optical properties and low cryogenic mechanical loss is therefore important for developing the next generation detector.

Silicon-based IC fabrication technology is matured but still with fast innovative progress toward larger wafer. 18” silicon wafer process in IC industry is nowadays common practice and the size is larger than the proposed size of the mirror substrate for next generation detector. It would be advantageous if the thin films used in silicon IC for electronics purpose could serve as the coatings for the next generation detector such that multi-layer high reflective coatings on silicon substrate could be fabricated in the common IC fab. Most silicon IC thin films are deposited by using various inline chemical vapor deposition (CVD) methods. It is our purpose in a lager scope to study the optical and mechanical properties of those CVD thin films for application to the next generation detector. We report here, specifically, the optical and mechanical properties of the silicon nitride films fabricated by using the plasma enhanced CVD (PECVD) method.

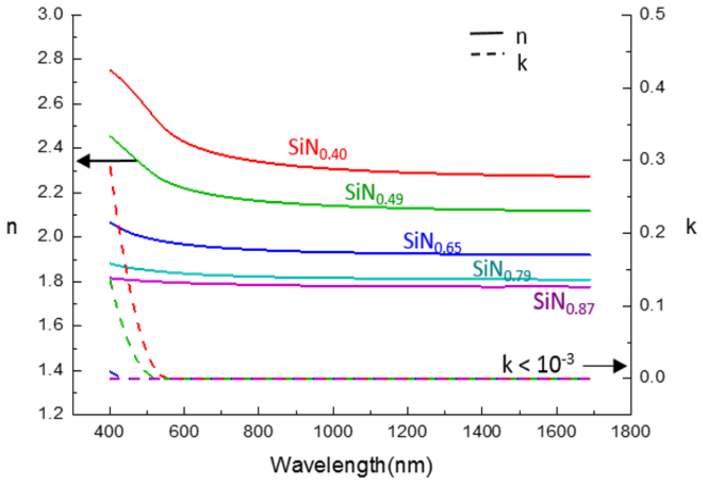

Fig.1 Refractive index and extinction coefficient of $SiN_x$ films with different composition.[2]

Silicon nitride ($SiN_x$) has wide composition range depending on the process parameters. Refractive index of the films also varies with the composition in a wide range. We used PECVD method with different $SiH_4$ and $NH_3$ flow ratio to fabricate $SiN_x$ with x ranging from 0.40 to 0.87. The corresponding refractive indices of the films varied from 2.28 to 1.78 at 1550 nm and the extinction coefficients were below detection limit of ellipsometer which is $10^{-3}$, as showed in Fig. 1 [2]. The wide range of refractive index implying that $SiN_x$ films can serve either as the high index layer or the low index layer in the multi-layer high reflective coatings by varying the composition.

The $SiN_x$ films are generally stressful [3]. More importantly, the high stress $SiN_x$ films were reported to have lower mechanical loss, particularly at cryogenics, for high frequency mechanical vibration, i.e. beyond MHz [4,5]. It is therefore important to study this property in the frequency range of the gravitational wave detector which is within few tens Hz to a few thousand Hz. Fig. 2 shows the composition dependent stress for our PECVD $SiN_x$ films. The stresses ranging from 120.2 MPa to 412.7 MPa and increased with increasing x. Notice that the stress values were that for the warped films/substrate in which the stress of the films were partially released due to warping. A method was developed [6] to deduce the loss angle of the films for which stresses are not released, i.e. equivalent to a “flat” film that is deposited on an infinite thick substrate. Fig. 3 shows the mechanical loss angle of the “flat” $SiN_{0.87}$ films [6]. Mechanical loss angles were in the $10^{-5}$ range that is lower than that of the 600℃ annealed 14.5% $TiO_2$-doped tantala, i.e. $2x10^{-4}$ [7,8], that is used as the high index layer for the current LIGO mirror coatings. Fig. 4 shows the loss angle of the “flat” films measured from the torsional mechanical vibration modes. The results indicate that stress indeed reduce the mechanical loss of the $SiN_{0.87}$ film.

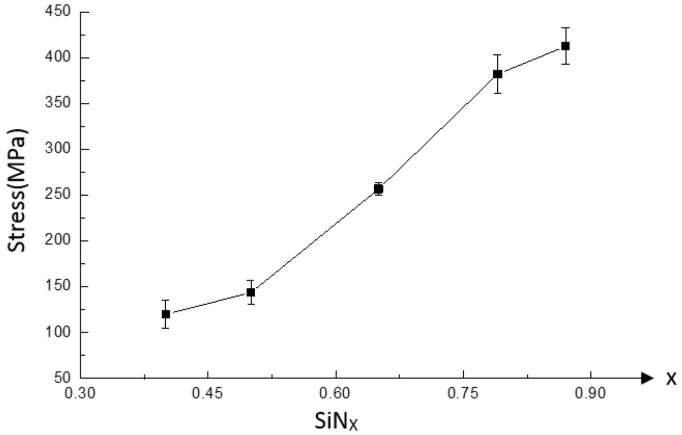

Fig.2 Composition dependent stress for $SiN_x$ film deposited by PECVD. [2]

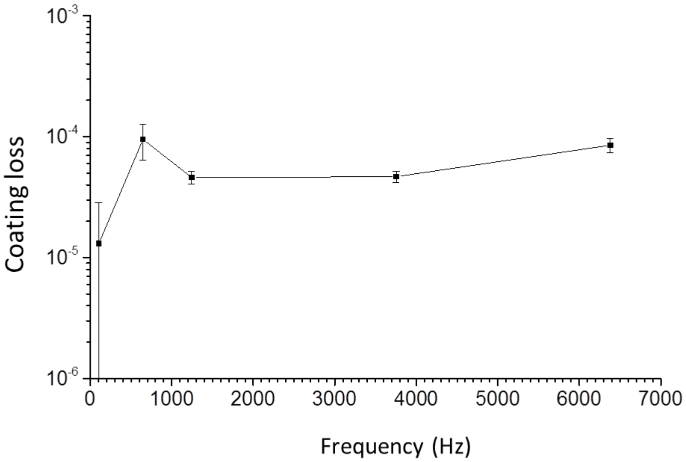

Fig.3 Loss angle of the “flat” $SiN_{0.87}$ film. [6]

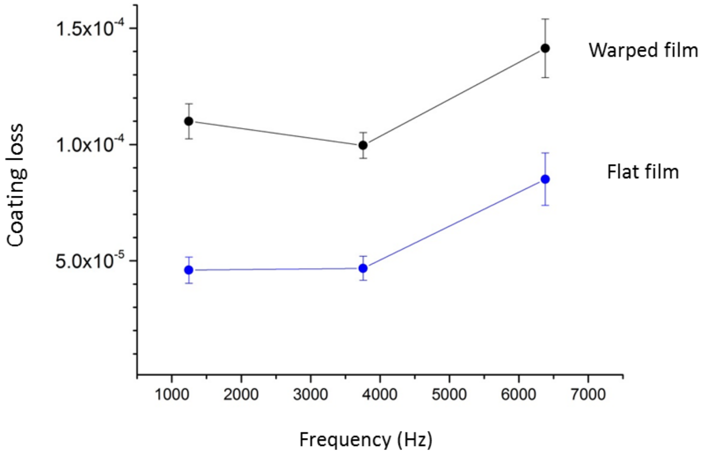

Fig.4 Flat film has lower loss angle than warped film in torsional modes. It indicates that stress reduce the mechanical loss of the $SiN_{0.87}$.[6]

We have fabricated a 2-layer and a 4-layer $SiN_{0.4}/SiO_2$ films on silicon substrate by using PECVD method, each layer has one quarter-wave optical thickness. Stress of the individual PECVD $SiO_2$ film has nearly equal but opposite stress as that of $SiN_{0.4}$ film [9], therefore, stress in these quarter-wave stack combinations were balanced. Stress in the balanced layer is higher than that in the warped layer. Preliminary measured loss angles of the multi-layer stacks are shown in the first row of table 1. Loss angle of the multi-layer stacks could also be calculated [10] by using the loss angle of the individual layers that were obtained from measurement of the warped films and the result is shown in the second row of Table 1. It is clear that loss angles of the high stress multi-layer combinations are lower than that of the low stress counterpart.

Table.1 Preliminary mechanical loss angle for quarter wave $SiN_{0.4}/SiO_2$ multi-layer structure at frequency of 108Hz.

| | 2-layer | 4-layer |
|---|---|---|
| High stress (measured) | $(4.42\pm1.83)\times10^{-5}$ | $(9.28\pm0.55)\times10^{-5}$ |
| Low stress (calculated) | $(3.08\pm0.74)\times10^{-4}$ | $(3.16\pm0.77)\times10^{-4}$ |

In conclusion, we showed optical properties and stress of the silicon nitride films for various composition deposited by the PECVD method. Preliminary results of the mechanical loss of the films and the quarter wave stacks of 2-layer and 4-layer indicating that higher stress reduced the room temperature mechanical loss. Future works including loss angle measurement in cryogenics temperature.

## Reference:

[1] H. B. Callen and T. A. Welton, "Irreversibility and generalized noise," Phys Rev **83**, 34–40 (1951)

[2] S. Chao, H. W. Pan, Y. H. Juang, S. Y. Huang, and L. C. Kuo, "Mechanical loss of silicon cantilever coated with a high-stress SiNx film," LVC meeting, Stanford University, Aug. 25 (2014). LIGO-G1400851

[3] A. Stoffel, A. Kovacs, W. Kronast and B. Muller, "LPCVD against PECVD for micromechanical applications," J Micromech Microeng 6, 1-13 (1996)

[4] D. R. Southworth, R. A. Barton, S. S. Verbridge, B. Ilic, A. D. Fefferman, H. G. Craighead, and J. M. Parpia, "Stress and silicon nitride: A crack in the universal dissipation of glasses," Phys Rev Lett **102**, 225503 (2009)

[5] B. M. Zwickl, W. E. Shanks, A.M. Jayich, C. Yang, A. C. Bleszynski Jayich, J. D. Thompson and J. G. E. Harris, "High quality mechanical and optical properties of commercial silicon nitride membrances,"Appl Phys Lett, 92, 103125 (2008)

[6] S. Chao, H. W. Pan, S. Y. Huang and L. C. Kuo, " Room temperature mechanical loss of high stress silicon nitride film measured by cantilever ring-down method on double-side coated cantilever," LVC meeting, Budapest, Hungary, Sep. 1st (2015). LIGO-G1501068

[7] I. Martin, H. Armandula, C. Comtet, M. M Fejer et al, "Measurements of a low-temperature mechanical dissipation peak in a single layer of $Ta_2O_5$ doped with $TiO_2$," Class. Quantum Grav. **25**, 055005 (2008)

[8] I. W. Martin, E. Chalkley, R. Nawrodt, et al, "Comparison of the temperature dependence of the mechanical dissipation in thin films of $Ta_2O_5$ and $Ta_2O_5$ doped with $TiO_2$," Class. Quantum Grav. **26,** 155012 (2009)

[9] H. W. Pan, Z. Z. Xie, L. C. Kuo, and S. Chao, "Mechanical loss of silica film on silicon cantilever deposited by PECVD method," LVC meeting, Pasadena C.A., Mar. 16th 2015. LIGO-G1500194

[10]R. M. Jones, *Mechanics of composite materials*, (Taylor & Francis 2nd 1999) pp.121-136