Suppression of Compressive Stress in Hydrogenated Amorphous Carbon Films Using Carbon Nanoparticle-Embedded Sandwich Structures

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Minimizing intrinsic film stress in protective films is crucial in dry etching processes for semiconductor fabrication. Hydrogenated amorphous carbon (a-C:H) films are widely used due to their mechanical strength, chemical stability, and ashing compatibility. However, the deposition of thick, high-density films often induces large compressive stress, leading to delamination and reliability problems. Conventional approaches for stress reduction include post-annealing and the incorporation of different metal atoms/nanoparticles. However, these methods involve high-temperature processing and contamination risks, making them unsuitable for semiconductor manufacturing.

To overcome these limitations, we have demonstrated a new approach in which carbon nanoparticles are embedded within the thin film, effectively reducing stress without introducing thermal or contamination concerns. So far, we achieved the stress reduction with a-C:H/CNP/a-C:H sandwich films using a multi-hollow discharge plasma chemical vapor deposition (MHDPCVD) and capacitively coupled plasma (CCP) CVD [1,2]. In this study, to study the evolution of film stress during the growth of the second a-C:H layer in the sandwich film, and to quantitatively evaluate the impact of carbon nanoparticle (CNP) surface coverage on stress reduction, we formulated the stress reduction behavior as a function of the CNP coverage ratio.

Sandwich films were deposited on Si (100) substrates via CCP CVD using Ar/CH_4 gas mixtures. The flow rate of Ar and CH_4 was 19 sccm and 2.6 sccm, respectively. The pressure was set to 0.3 Torr. The a-C:H layer was deposited using 13.56 MHz excitation at the lower electrode. The CNP was deposited using 28 MHz excitation at the upper electrode. Both peak-to-peak voltage were set to 280 V. The first a-C:H layer thickness was 154 nm and the second a-C:H layer thickness, t_s, was varied from 0 to 180 nm. The surface coverage of CNPs, C_p, was estimated via TEM and defined as $C_p = \pi r_p^2 n_p$, where r_p is the average radius of the CNP, and n_p is the number of CNP per unit area. The C_p was controlled at 0 %, 4.4 %, 8.9 %, and 15.9 %. The film stress was quantified by curvature measurements based on Stoney's equation, while surface morphology was characterized via atomic force microscope (AFM).

Our results demonstrate that increasing C_p significantly reduces the compressive stress—from 1.59 GPa at C_p = 0 % to 1.02 GPa at C_p = 8.9 % at the same thickness of the first and second a-C:H layer—highlighting the critical role of CNP-induced sandwich structure. When the thickness of the second a-C:H layer was varied with C_p as a parameter, the stress evolution exhibited different trends depending on C_p. For C_p = 0 %, the compressive stress increased linearly with the second a-C:H layer. For C_p = 4.4 % and 8.9 %, the stress initially increased in a similar trend to that of C_p = 0 % during the early growth stage of the second a-C:H layer; however, beyond a threshold thickness, the trend of stress increase became more gradual. Additionally, AFM analysis further revealed that, in the presence of CNP, the surface roughness exhibited a maximum at a specific thickness of the second a-C:H layer. This critical thickness closely coincided with the position at which the slope of stress increase and the surface roughness both began to decrease. These observations suggest that the presence of CNP influences the growth behavior of the second a-C:H layer, and that the transition in growth mode might be associated with stress relaxation. Furthermore, it was revealed that the stress reduction effect can be expressed as a function of C_p, the thickness of the first a-C:H layer, and the total thickness of the a-C:H/CNP/a-C:H sandwich films.

References

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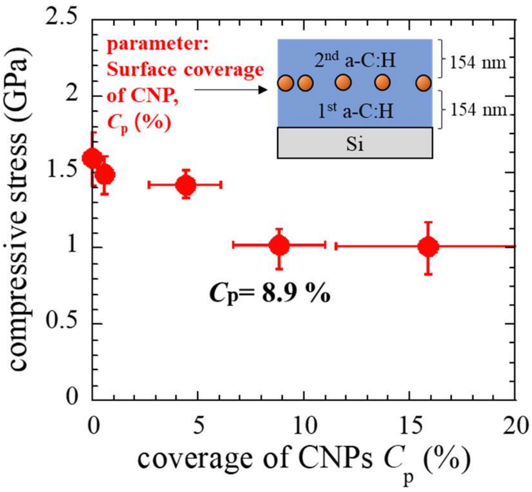

Figure1. Compressive stress of a-C:H/CNP/a-C:H sandwich films as a function of the surface coverage of CNP. The thickness of the first and second a-C:H layer was set to 154 nm in thickness.