Amorphous carbon films for use as both variable-transmission apertures and attenuated phase shift masks for deep ultraviolet lithography

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We describe the development of amorphous carbon (a-C) films grown by magnetron sputtering for use in optical elements for sub-0.25-μm deep ultraviolet (DUV) lithography. We have measured the transmittance of a-C films deposited onto quartz substrates as a function of film thickness, and find that the films are ideally suited for use in variable-transmission apertures that can be used to improve DUV process latitude: we can achieve essentially any transmittance (T) desired in the range $0<T<100\%$ by controlling the film thickness (t) in the range $200>t>0$ nm with subnanometer precision. We also find that the transmittance remains stable after prolonged exposure to high intensity DUV radiation. We describe a masked deposition technique to produce variable-transmission apertures using a-C films of various thicknesses, and also discuss the use of these films in attenuated phase shift masks, given that we can simultaneously achieve $\sim 6\%-8\%$ transmittance and a phase shift of 180° at either $\lambda = 248$ nm or 193 nm. © *1999 American Vacuum Society.* [S0734-211X(99)08203-7]

I. INTRODUCTION

Recently we presented experimental results demonstrating a technique using a variable-transmission aperture (VTA) for improving process latitude (i.e., depth of focus and resolution) in deep ultraviolet (DUV) (248 nm) lithography.[1] The VTA, consisting of a particular, two-dimensional spatial arrangement of amorphous carbon (a-C) films of various thicknesses (and thus various transmittances) deposited onto a quartz substrate, is placed between the source and the mask in a DUV stepper and is used to control the distribution of light incident on the photomask, and thus the distribution of light diffracted from the features on the mask and reaching the wafer plane. The two-dimensional spatial transmission function of the VTA (i.e., as determined by the two-dimensional film thickness function) is designed for optimal process latitude for the feature geometry specific to a given photomask.

We describe here how these a-C films are produced with subnanometer thickness control using magnetron sputtering, and present measurements of transmittance as a function of film thickness at $\lambda = 248$ nm. We also describe measurements of the film transmittance over time after prolonged exposure to high-intensity DUV radiation. These results are presented in Sec. II, while in Sec. III we describe the masked deposition technique we have developed to produce the VTAs just discussed. We summarize our results in Sec. IV, and also discuss the use of these films in attenuated phase shift masks, in light of the observation that we can simultaneously achieve $\sim 6\%-8\%$ transmittance and a phase shift of 180° at either $\lambda = 248$ or 193 nm.

II. FILM PREPARATION AND CHARACTERIZATION

The films described here were grown by dc magnetron sputtering in argon of 99.999% purity using a deposition system having subnanometer film thickness control for the production of multilayer x-ray optics that has been described previously.[2] The system is cryo pumped (the background pressure was $5.0 \pm 0.1 \times 10^{-6}$ Torr) and the argon pressure was maintained at 1.5 mTorr with a closed-loop gas-flow system using a capacitance manometer and a mass-flow controller. The power to the 50-cm-long $\times$9-cm-wide planar magnetron source containing a solid graphite target (99.999% purity) was fixed at 400 ± 7 W. The deposition rate under the conditions just described was found to be 0.05 nm/s, and was computed from film thicknesses determined by x-ray reflectance analysis that is described below. Film thicknesses were adjusted with subnanometer control by varying the (computer-controlled) rotational velocity of the substrate (which faces downward) as it travels over the source (which faces upward, 10 cm below the plane of the substrate).

X-ray reflectance measurements are made as a function of grazing incidence angle at a fixed wavelength using a four-circle diffractometer with a rotating anode x-ray source having a Cu target, and a pyrolytic graphite monochromator tuned to the Cu-$K\alpha$ line near 8 keV (1.54 Å). Reflectance measurements are typically made for incidence angles in the range of 0°–3°, which generally corresponds to a span of roughly seven orders of magnitude in reflected intensity. The angular resolution of the diffractometer is $\sim 0.02°$, and measurements are typically made every 0.01°, which is sufficient to resolve the thickness fringes for films as thick as ~ 50 nm. Fits to the x-ray reflectance data, performed with IMD software package,[3] are used to determine film thickness and roughness. With this technique, the measured reflectance versus incidence angle data are compared with a theoretical reflectance curve computed using an algorithm based on recursive application of the Fresnel equations; the formalism described by Stearns[4] is used to account for the effects of interfacial roughness (or diffuseness). Nonlinear, least-

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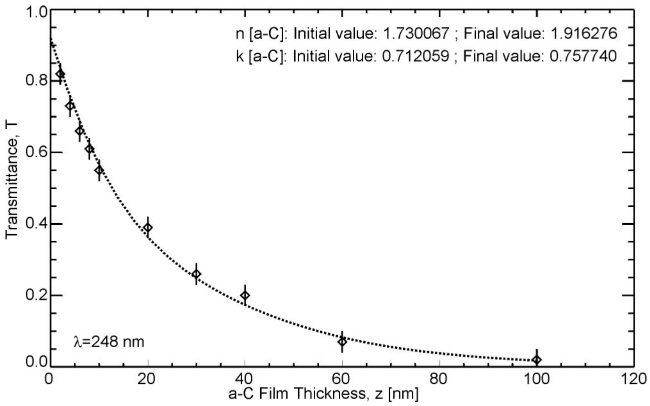

FIG. 1. Measured transmittance (diamonds) of a-C films deposited onto quartz substrates at a photon wavelength of $\lambda = 248$ nm. The calculated transmittance (dotted line) is also shown, and is computed from the best-fit values of the optical constants $(n\ k)$ as indicated.

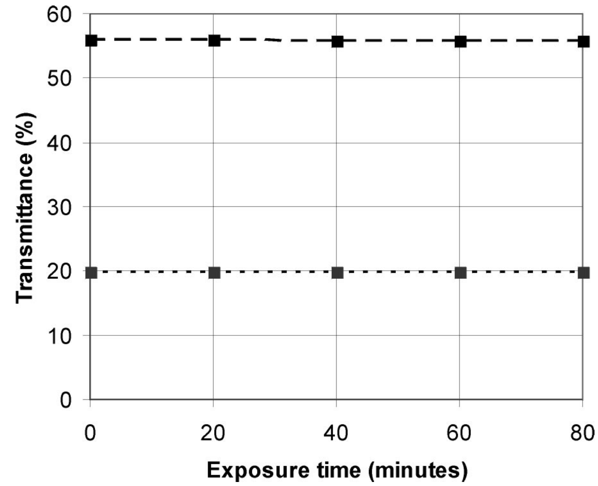

FIG. 2. Measured transmittance for two a-C films as a function of time after exposure to high-intensity 248 nm radiation as described in the text.

squares curve fitting (based on the X^2 test of fit) is used to determine the film thickness with a precision of approximately ± 0.1 nm.

Films of various thickness in the range of $2 < t < 100$ nm were deposited onto 15-cm-diam $\times 0.5$-mm-thick quartz substrates, and their normal-incidence transmission was measured using a Hewlett-Packard UV diode array spectrophotometer with collimating optics; the precision of the measurements is $\pm 3\%$. The resultant plot of transmittance versus thickness is shown in Fig. 1. The transmittance ranges from approximately $T = 82\%$ for a 2-nm-thick film to $T = 2\%$ for a 100-nm-thick film. We have fit the transmittance data using IMD to determine the values of n and k (the real and imaginary parts of the complex index of refraction) for the a-C films: the best fit values so obtained—$(n,k) = (1.916, 0.758)$–differ somewhat from the values $(n,k) = (1.730, 0.712)$ given by Palik.[5] Using the best-fit optical constants, we note that a 200-nm-thick film would have a transmittance of $T = 0.065\%$.

To determine the stability of these films, the transmittance was also measured as a function of time. Samples were inserted into the illuminator of an Integrated Solutions DUV exposure tool and irradiated with light at the exposure wavelength (248 nm). The power at the wafer plane during exposure was ~ 140 mW/cm^2 (as measured with the 10-nm-thick sample inserted into the beam). The resultant plot of transmittance versus time is shown in Fig. 2 for two samples; there is no measurable change in transmittance after 80 min of exposure. This would correspond to approximately 450 device wafers assuming 50 die/wafer at a dose of 30 mJ/die, and thus suggests that these films are well suited for long-term use as optical elements in device fabrication.

III. MASKED-DEPOSITION TECHNIQUE FOR VTA FABRICATION

The VTAs used to obtain the results described in Ref. 1 consist of a concentric ring pattern of a-C films of various thicknesses, deposited onto a 150-mm-diam$\times 0.5$-mm-thick quartz substrate, shown schematically in Fig. 3(a). The film thickness in each of the four rings indicated in Fig. 3(a) was adjusted (by varying the rotational velocity of the substrate over the source as described in Sec. II) in order to achieve the desired transmittance values shown in Fig. 3. So, for example, the thickness of the a-C film comprising the outer ring was set to 20 nm, in order to achieve 40% transmittance, and so on for the films used in the other rings. Each film was grown separately, using stencil masks to expose only the relevant portion of the aperture during each deposition cycle. A photograph of the VTA, mounted in the holder needed for installation in an Integrated Solutions Model 8800 Deep Ultraviolet step and repeat exposure tool, is shown in Fig. 3(b). Also shown in Fig. 3(b) are the stencil masks used to produce the VTA.

The masked-deposition technique to control the two-dimensional film thickness profile just described can be used to produce many different types of VTA patterns, and is not limited to the concentric-ring-type pattern shown in Fig. 3(a). For example, we have recently developed dipole, tripole, and quadrapole VTAs, which are shown in Figs. 3(c)–3(e). By varying the pole position in this type of VTA, we are able to optimize the illumination (thus increasing the process latitude) for specific feature geometries: for example, the dipole VTA is well suited for a continuous grating geometry, while the tripole could be used for a hexagonal array geometry; the quadrapole VTA could be used to optimize process latitude in so-called Manhattan geometries. We will describe elsewhere specific improvements in process latitude obtained with the VTAs shown in Figs. 3(c)–3(e).

IV. CONCLUSIONS

We have described the fabrication by magnetron sputtering of amorphous carbon films, and have shown how the DUV optical properties of these films were measured. Because of their desirable optical properties and their excellent stability to high-intensity DUV radiation, these films are well suited for use as optical elements in high-throughput DUV steppers for sub-0.25 μm lithography. We have used these

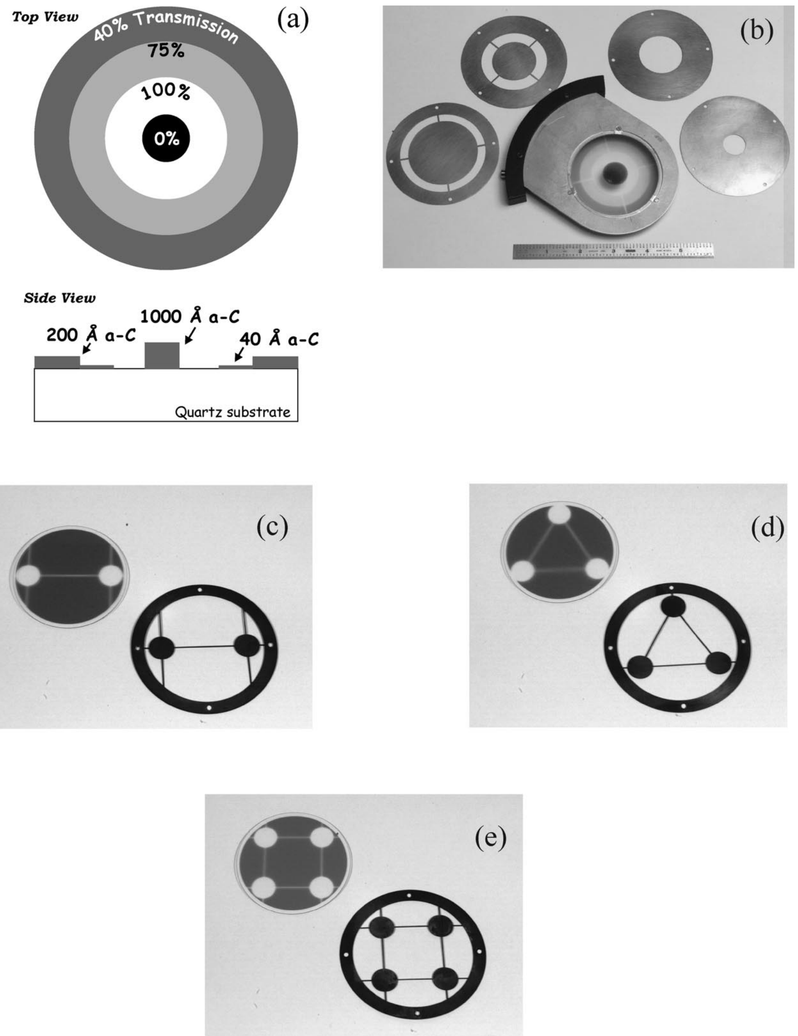

FIG. 3. Schematic diagram of (a) a concentric-ring-type variable-transmission aperture. A photograph of the actual aperture is shown in (b), along with the stencil masks used during fabrication, described in the text. (c) Dipole, (d) tripole, and (e) quadrapole apertures are also shown, along with the stencil masks used for fabrication.

films to produce variable-transmission apertures that are designed to improve process latitude in DUV lithography, and have described a masked-deposition technique used to fabricate such apertures. Finally, we note that these films are also ideally suited for use in attenuated phase shift masks for DUV lithography:[6] using the optical constants determined from the measured transmittance, described in Sec. II, we calculate that a ∼75-nm-thick *a*-C film should have a transmittance of ∼6% at $\lambda = 248$ nm and should give rise to a phase shift on transmission of 180°. Similarly, we estimate (using the optical constants from Ref. 5) that a ∼58-nm-thick film should also have a phase shift of 180° and a transmittance of ∼8% at $\lambda = 193$ nm. Therefore, these films can also be used for attenuated phase shift masks at $\lambda = 193$ nm.

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