Optical superlattices—a strategy for designing phase-shift masks for photolithography at 248 and 193 nm: Application to AlN/CrN

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This letter illustrates with AlN/CrN multilayers that optical superlattices, comprised of multilayers of a uv transmitting dielectric layer and a metallic layer, offer a systematic approach to design and fabricate partially transmitting, phase-shift masks for photolithography. From the measured optical constants of sputtered AlN/CrN multilayers, it was found that films had π-phase shift and tunable optical transmission between 5% and 15% at 365, 248, and 193 nm. We compared the optical properties of sputtered AlN/CrN multilayers to ''ideal'' superlattices, calculated from the measured optical properties of individual thick CrN and AlN layers, and to compositionally equivalent psuedobinary alloys of $(AlN)_{1-x}(CrN)_x$. Although optical properties for all three systems were nearly the same, which is attractive because it implies wide process lattitude, we found systematic differences that were attributed to their individual structures. A phase shift mask with 6% transmission at 365 nm was fabricated with a 1650-Å-thick (25 Å AlN+25 Å CrN) multilayer film.
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Microlithography,[1] used for patterning and fabricating microprocessors and memory chips with critical feature size as small as 0.25 μm, is one of the key technologies that makes the modern PC possible. Today these circuits are faster, denser, and cheaper than ever before. However, further reduction in feature size will require photolithography with shorter wavelength light (248 and 193 nm)[2] and the use of advanced optical enhancement strategies such as phase-shift masks[3–5] and optical proximity correction[4,5] schemes. A phase shift mask enhances the patterned contrast at the edges of small circuit features by destructive optical interference of light that passes through the mask with an adjacent band of light that propagates in air. Among the different types of phase-shift masks, those that combine light attenuation and 180° or π-phase shift in a single layer, known as attenuating embedded phase-shifters (AES),[6–10] are especially attractive because design and processing of the photolithographic mask are simplified, since fabrication steps are similar to traditional opaque Cr masks, which either let light pass or block it.

Although many materials[6–10] have been proposed for attenuating embedded phase-shift masks, there are critical shortcomings. The most serious is the inability to accurately ($<\pm 3°$) control the phase shift. Small phase errors are unacceptable in an AES mask, because they decrease the depth of focus and shift the optimum focus position.[11] Phase errors are caused by poor etch selectivity[8] with respect to the substrate, and more consequentially by difficulty in controlling the film's chemical composition.[6] Furthermore, the material's requirements for a partially transmitting phase shift mask are seemingly contradictory. At 248 and 193 nm a material is needed with lossy dielectric properties, whereas metallic character is needed to dissipate charge buildup, when electron beam writing is used, and to reduce optical transmissivity at 488 nm, where masks are inspected.

In this letter we demonstrate with AlN/CrN multilayers that optical superlattices[12] offer a systematic approach to design and fabricate partially transmitting, phase-shift masks with a single material's chemistry that is tunable at 248 nm, 193 nm, and at potentially shorter wavelength. Optical superlattices are comprised of an optically absorbing metal, multilayered with a uv transparent dielectric layer. The optical character of the metallic layer is that it is highly absorbing at longer wavelengths, good for mask inspection, and less absorbing in the uv, attractive for accurate control of optical transmission. Layer constituents can also be chosen from stable oxides and nitride pairs with etch selectivity to quartz. Examples of uv transmitting layers include AlN, HfO_2, and Al_2O_3, while RuO_2, CrN, and MoN are examples of metallic layers. Changing the ratio of these layers allows systematic control of chemistry and optical properties. Potential advantages include continuous metallic layers to reduce film resistivity and decrease transmission at the inspection wavelength; a broader process lattitude that minimizes phase errors, because control of chemistry is by layer thickness of stable oxides or nitrides, not by maintaining a critical reactive gas concentration; and simplified synthesis from elemental sputtering targets.

Multilayers of metallic CrN with uv transmitting AlN (band gap of ~6.2 eV) were made by simultaneous magnetron sputtering from separate metal targets of Al and Cr in partial pressures of Ar and N_2 to produce uv transparent AlN and metallic CrN layers with little sensitivity to minor changes in Ar/N_2 gas ratio. The chemical composition of films was adjusted by the relative thickness of individual layers, controlled by deposition rate and the time substrates on a rotating table were paused under each target. We deliberately grew AlN/CrN multilayers with a short superlattice periodicity of 50 Å, e.g., 20×(35 Å AlN+15 Å CrN) to promote optical homogeneity. With the periodicity much less than the lithographic wavelength, optical properties should be less sensitive to details of layer interfaces, and etching of the layers more uniform.

Figure 1 summarizes the optical constants, index of refraction (n), and extinction coefficient (k), of AlN/CrN multilayers with a periodicity of 50 Å and a total film thickness of about 1000 Å. The optical constants were determined from variable angle, spectroscopic ellipsometry, and uv/

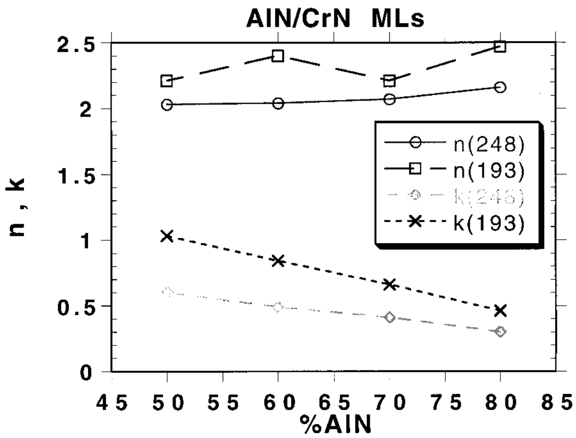

FIG. 1. Dependence of index of refraction (n) and extinction coefficient (k), measured at 248 and 193 nm for AlN/CrN sputtered multilayers with periodicity 50 Å and total thickness about 1000 Å on % AlN.

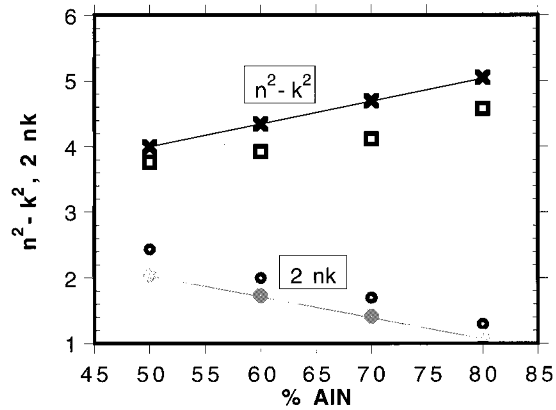

FIG. 3. Comparison of the real (n^2-k^2) and imaginary ($2nk$) parts of the dielectric constants of sputtered AlN/CrN multilayers and ''ideal'' AlN/CrN superlattices as a function of AlN concentration. Lines are drawn through the points corresponding to the ideal superlattice.

visible spectroscopy measurements,[13] combined with optical modeling.[14] Thicker, more transmitting AlN layers consistently reduced the extinction coefficient at 248 and 193 nm, whereas their effect on the index of refraction was proportionally smaller. From the optical constants, the film thickness, optical transmission, and reflectivity, corresponding to 180° phase shift, can be calculated[15] exactly. The phase shift through the film is given by the expression

$$\phi = \frac{180}{\pi} \arctan\left[\frac{\mathrm{Im}(T_a)}{\mathrm{Re}(T_a)}\right], \quad (1)$$

where T_a is the transmitted amplitude. For normal incidence from air into a film with thickness d and a complex index of refraction, $N=(n-ik)$ on a lossless substrate of index n_2, T_a is[15]

$$T_a = \frac{4N}{[(1+N)(N+n_2)\exp(iK)+(1-N)(N-n_2)\exp(-iK)]}, \quad (2)$$

where $K=2\pi d/\lambda$.

Figure 2 summarizes the optical transmissions at 248 and 193 nm calculated exactly for 180° phase shift in AlN/CrN multilayers. At 193 nm, 180° phase shift and 10% optical transmission occurred in AlN/CrN multilayers with 673 Å thickness and 80% AlN. 180° phase shift designs were achieved in a desirable range of optical transmissions (5%–10%) at both 248 and 193 nm. Up to an AlN concentration of 80%, there was a smooth, gradual dependence of optical transmission on chemical composition, characteristic of an ideally tunable material system. At 70% AlN, a 1200-Å-thick film, with a calculated phase shift at 248 nm of about 180° with 7% optical transmission, had sheet resistivity less than 500 kΩ/square, low enough for charge dissipation with electron beam writing, and an adequately low optical transmission (<40%) at 488 nm for mask inspection.

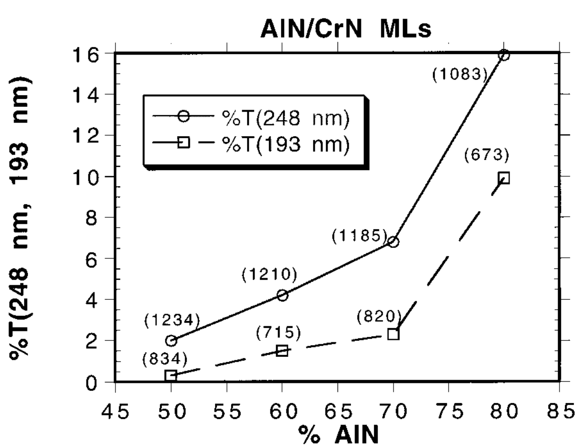

FIG. 2. Optical transmission calculated for AlN/CrN multilayers with 180° phase shift relative to propagation in air at 248 and 193 nm as a function of AlN concentration. Each point represents a unique film thickness (Å) indicated in parentheses.

It is informative to compare the optical properties measured in AlN/CrN multilayers to calculated ''ideal'' superlattices using the optical constants measured for thick (~100 nm) layers of CrN and AlN made with the same sputtering conditions. For optical superlattices with layers much thinner than the optical wavelength and normal incidence of light, Hunderi[16] has shown that the dielectric properties are well described by the effective medium approximation, $\epsilon_s = f\epsilon_m + (1-f)\epsilon_d$, where ϵ_s, ϵ_m, and ϵ_d are, respectively, the complex dielectric constants of the superlattice, the metal or absorbing layer (CrN), and the optically transmitting layer (AlN); f is the fraction of the absorbing layer, and ϵ is related to the usual optical constants by $\epsilon=(n-ik)^2$. Figure 3 then compares at 248 nm the calculated real (n^2-k^2) and imaginary ($2nk$) parts of the dielectric constant of ideal superlattices to values measured for sputtered AlN/CrN multilayers. The optical constants measured at 248 nm for individual layers of AlN and CrN were $n(\mathrm{CrN})=1.6$, $n(\mathrm{AlN})=2.4$, $k(\mathrm{CrN})=0.9$, and $k(\mathrm{AlN})=0.1$. This comparison highlights that ideal superlattices overestimate n and underestimate k in sputtered multilayers.

The difference in optical constants may be due to interfacial mixing or roughening of AlN and CrN layers in sputtered multilayers. Alternatively, the optical constants of AlN and CrN may be thickness dependent, differing from values measured for thicker films. The thickness dependence will require further study. To investigate the effect of mixing or roughening, we made pseudobinary alloys of $(\mathrm{AlN})_{1-x}(\mathrm{CrN})_x$ by simultaneously sputtering Al and Cr ni-

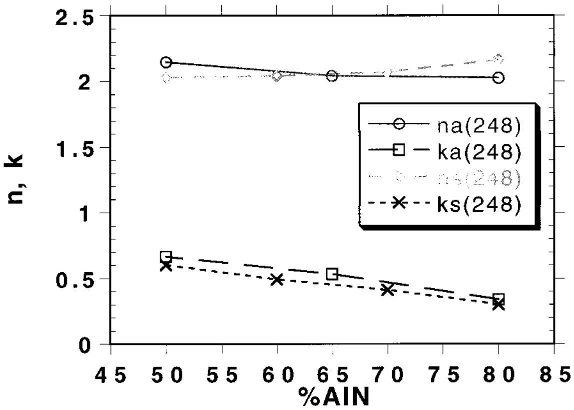

FIG. 4. Comparison of the optical constants for sputtered pseudo-binary alloys (n_a, k_a) of $(AlN)_{1-x}(CrN)_x$ and compositionally equivalent multilayers (n_s, k_s) of AlN/CrN at 248 nm.

trides onto quartz substrates. Although we found that differences in optical constants were relatively small, the extinction coefficients of alloys were systematically larger ($\sim$10%) than chemically equivalent sputtered multilayers, as shown in Fig. 4. Thus the interpretation of some interfacial mixing in sputtered multilayers is consistent with the trend k(ideal superlattices)$<k$(sputtered multilayers) $<k$(alloys). Interfacial mixing also agreed with the absence of prominent superlattice peaks in x-ray diffraction patterns of sputtered AlN/CrN multilayers.

Finally, using an interferometer[7] that measures phase shift directly at 365 nm, we designed a 180° phase shift mask for this wavelength with AlN/CrN multilayers. Using optical constants measured in films sputtered from 3-in. diam targets, we designed an 8%/π-phase shifter, which we calculated to be 1650 Å of (25 Å AlN+25 ÅCrN). We sputtered these periodic multilayers using 6.5-in. diam targets on a 5 in.×5 in.×0.90 in. quartz substrate. A pattern of lines for measuring relative phase shift and optical transmission was wet etched in the multilayers using a solution of perchloric acid and ceric ammonium nitrate (Cyantek CR7S) and AZ1375 (Hoechst Celanese) photoresist. Consecutive scans of relative phase shift are shown in Fig. 5. Experimentally, we obtained 175° phase shift and 6% transmission at 365 nm, both encouragingly close to the design values, since this was a single experiment.

In summary we have demonstrated that optical superlattices can be a materials platform for designing phase-shift masks with optically tunable properties at 248 and 193 nm. Specifically we showed that AlN/CrN films could be sputtered with π-phase shift and optical transmissions between 5% and 15%.

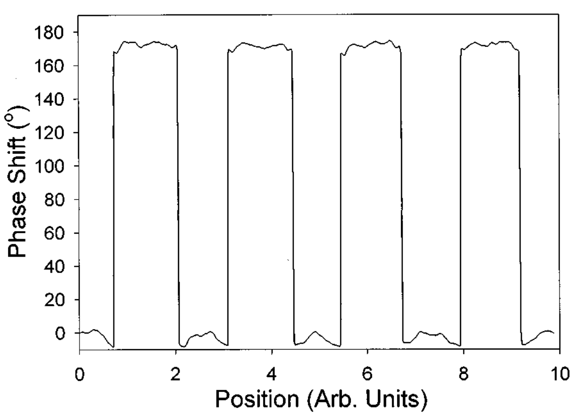

FIG. 5. Scan of relative phase shift, directly measured at 365 nm on lines patterned in an AlN/CrN multilayer mask, designed for 180° phase shift.

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