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Extreme ultraviolet polarizing optics using bare and aluminum-coated silicon carbide

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A deformable three-reflection system that uses a bare silicon carbide substrate can function as an in-line, high-throughput (>30%), 90° phase shifter in the 50–100 nm spectral range. For a given extreme ultraviolet wavelength, an aluminum thin film can be deposited on the silicon carbide substrate to suppress the parallel (p) or perpendicular (s) polarization on single reflection or to introduce quarter-wave retardation and equal reflectances for incident p- and s-polarized light.

1. Introduction

Because of the lack of suitable transparent birefringent materials, reflection-type polarization optical devices are important in the vacuum ultraviolet–extreme ultraviolet (VUV–EUV) and soft-x-ray spectral regions. One advantage of reflection devices is that mirror materials that are stable in the presence of EUV radiation can be used. (If a transparent or semitransparent birefringent material exists, such as MgF_2 in the 120–200-nm range, its performance may be affected by radiation damage to the medium.)

The use of in-line (insertion) reflection optical devices to convert in-plane-of-orbit synchrotron radiation from linear to circular polarization has received considerable attention recently (see, e.g., Refs. 1–4), and researchers are looking for mirror materials that can be used to achieve relatively high throughput. The same optical devices are also essential for the analysis or measurement of arbitrary elliptical polarization states (i.e., as components of Stokes parameter photopolarimeters).[5]

Silicon carbide (SiC) is a promising new material for reflection optics in the EUV spectral region because of high normal-incidence reflectance (30–50% in the 60–200-nm wavelength range), durability, and low coefficient of thermal expansion.[6,7] From the optical constants of SiC reported by Windt *et al.,*[8] we

show that SiC mirrors can be used in a deformable three-reflection system as a 90° phase shifter with a relatively high throughput (>30%) in the 50–100-nm spectral region. This throughput is higher than that attainable with any metal.[1,9] We also show that, at a given wavelength, the p or s polarization can be suppressed on single reflection by the use of light interference in an Al thin film deposited on the SiC substrate. Furthermore, a quarter-wave retarder (QWR) without diattenuation (i.e., with equal throughput for the p and s polarizations) can be designed by the use of the same Al–SiC film–substrate system.

2. In-Line Three-Reflection Quarter-Wave Retarder

An in-line three-reflection QWR is a device that introduces a relative phase shift of 90° between the p and s components of the incident monochromatic light. Incident linearly polarized light of the appropriate azimuth is converted to circularly polarized light when the p and s components of the emergent light have equal amplitudes.

The ellipsometric function, ρ, is defined as the ratio r_p/r_s of the p and s complex amplitude-reflection coefficients and is usually written in the form $\rho = \tan \psi \exp(j\Delta)$, where $\tan \psi$ is the p-to-s relative amplitude attenuation and Δ is the p-to-s relative phase shift on reflection.[10] We consider monochromatic linearly polarized light that is incident at an angle ϕ with its electric field vibration at an azimuth θ from the plane of incidence. For a given mirror material with complex dielectric constant ε, a cumulative differential phase shift of 90° (or an odd multiple thereof) can be achieved by an appropriate choice of the angle of incidence ϕ, called the principal angle and denoted by $\bar{\phi}$. The value of θ required to produce output circularly polarized light at $\bar{\phi}$ is called the principal azimuth and is denoted by $\bar{\psi}$.
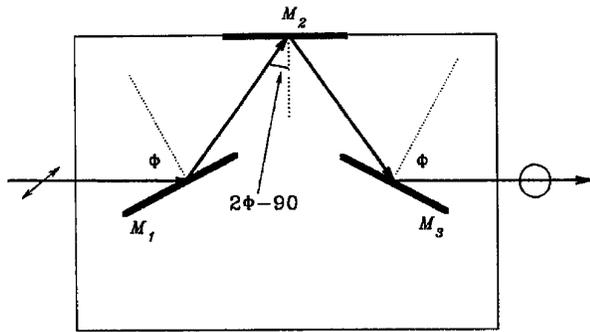
Fig. 1.   Geometry of the in-line three-reflection phase retarder.

Figure 1 shows the geometry of the in-line three-reflection system.   The three mirrors are assumed to be polished surfaces of the same substrate material, and the angles of incidence at the first and the third mirrors are equal because of symmetry.   The angle of incidence at the second mirror is equal to $2\phi - 90°$.   The entire system is rotatable around the incident light beam as an axis.

The net ellipsometric function is given by

$$\rho_n = \rho^2(\phi)\rho(2\phi - 90°), \tag{1}$$

where

$$\rho(\phi) = \frac{\sin \phi \tan \phi - (\varepsilon - \sin^2 \phi)^{1/2}}{\sin \phi \tan \phi + (\varepsilon - \sin^2 \phi)^{1/2}}. \tag{2}$$

For this three-reflection system to introduce a $\pm 90°$ differential phase shift, the real part of ρ_n is set equal to zero so that $\rho_n = \tan \bar\psi \exp(\pm j\pi/2)$.   The net intensity transmittance, or the overall throughput of the system, when operated as a linear-to-circular polarization transformer, is given by

$$T = \mathscr{R}_{pn} \cos^2 \bar\psi + \mathscr{R}_{sn} \sin^2 \bar\psi, \tag{3}$$

where

$$\mathscr{R}_{vn} = |r_{vn}|^2,$$
$$r_{vn} = r_v^2(\bar\phi)r_v(2\bar\phi - 90°), \qquad v = p, s. \tag{4}$$

To determine $\bar\phi$ analytically is difficult and cumbersome; therefore, the principal angle and principal azimuth are calculated numerically.   Note from Fig. 1 that $\bar\phi$ cannot be $<45°$.

The optical data reported by Windt *et al.*[8] are used to calculate the principal angle and the principal azimuth when chemical vapor deposition (CVD) SiC is used as the mirror material.   Figure 2 shows $\bar\phi$ as a function of λ in the VUV and EUV region.   There is more than one solution for the principal angle at each wavelength $\lambda > 10$ nm.   The cumulative differential phase shifts for the three solutions of $\bar\phi_0$, $\bar\phi_1$, and $\bar\phi_2$ are 270°, 270°, and 90°, respectively.   The largest principal angle, $\bar\phi_2$, is the more important, because the overall throughput at this angle is larger than it is at the other principal angles.   The net intensity transmittance at $\bar\phi_0$ and $\bar\phi_1$ is small ($<10\%$).
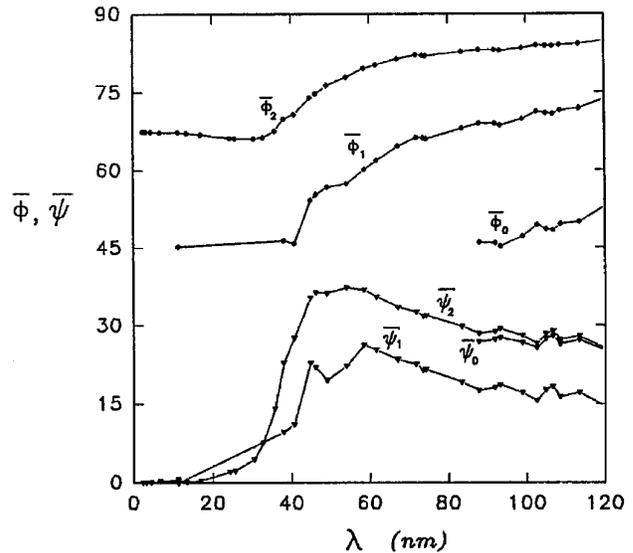

Fig. 2.   Principal angles $\bar\phi_i$ and principal azimuths $\bar\psi_i$ ($i = 0, 1, 2$) for CVD SiC mirrors as functions of λ in the VUV–EUV spectral region.   The optical constants of SiC are taken from Ref. 8.

Figure 3 shows intensity transmittance T of the system calculated at $\bar\phi_2$.   In general, the higher the principal azimuth, the higher the throughput, which is consistent with Eq. (3) because $|r_s| > |r_p|$.   To compare the calculated values of T for CVD SiC with those for Au (which is commonly used), we take the optical constants of Au also from Ref. 8.   Within the same spectral region, T for Au is $<T$ for SiC by a factor of 3 or more.   For example, at the He I wavelength of 58.43 nm, T of the SiC system is 44.7% whereas that of Au is only 8%.

3.   Reflection Polarizers and Phase Retarders that Use an Absorbing Thin Film on an Absorbing Substrate

Single-reflection retarders that use a transparent thin film on an absorbing substrate have been de-
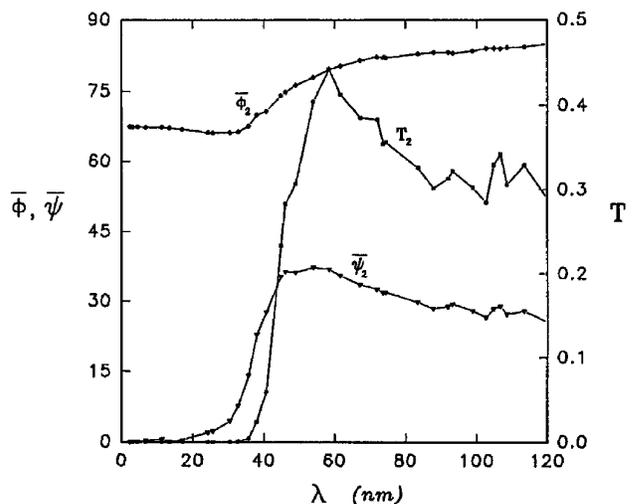

Fig. 3.   Largest principal angle $\bar\phi_2$, associated principal azimuth $\bar\psi_2$, and throughput T_2 for a CVD SiC three-mirror system as functions of λ.

scribed by Azzam and co-workers.[11,12] Thonn and Azzam[13] described dielectric-coated metallic mirrors for fixed three-reflection phase retarders in the IR spectral region, and Azzam and Kan'an[14] obtained variable-phase retardation in the IR by using a deformable three-mirror system with ZnS-coated Ag mirrors.

The change of polarization on single reflection from an optically isotropic surface is completely determined by ρ. For a light beam of wavelength λ incident at an angle ϕ from a transparent ambient (with $\varepsilon = \varepsilon_0$) onto an absorbing substrate ($\varepsilon = \varepsilon_2$), which is coated with an absorbing film of thickness d and $\varepsilon = \varepsilon_1$, the p and s reflection coefficients are given by[10]

$$r_v = \frac{r_{01v} + r_{12v}X_1}{1 + r_{01v}r_{12v}X_1}, \qquad v = p, s. \tag{5}$$

In Eq. (5), r_{01v} and r_{12v} are the ambient–film and film–substrate Fresnel interface reflection coefficients for the v polarization:

$$r_{ijp} = \frac{\varepsilon_j S_i - \varepsilon_i S_j}{\varepsilon_j S_i + \varepsilon_i S_j}, \quad r_{ijs} = \frac{S_i - S_j}{S_i + S_j}, \quad ij = 01, 12, \tag{6}$$

$$X_1 = \exp\left(\frac{-j4\pi d}{\lambda} S_1\right), \tag{7}$$

$$S_i = (\varepsilon_i - \varepsilon_0 \sin^2 \phi)^{1/2}, \qquad i = 0, 1, 2. \tag{8}$$

Because ε_1 of the film is complex, S_1 is also complex in general. For a given film thickness d, as ϕ is increased from zero (normal incidence) to 90° (grazing incidence), ρ traces a trajectory in the complex plane that starts at $(-1 + j0)$ for $\phi = 0$ and ends at $(1 + j0)$ for $\phi = 90°$. For $d = 0$ the contour is that of the bare substrate, whereas for large d (thick film), ρ traces a curve that is characteristic of bulk film material (because light does not penetrate to the film–substrate interface). To increase the range of d in which the film is semitransparent, one must make sure that the film material has a small extinction coefficient.

Consider a SiC substrate $[\varepsilon_2 = (0.401–j0.52)^2]$ that is coated with a thin film of Al $[\varepsilon_1 = (0.796–j0.0959)^2]$ at the He I wavelength $\lambda = 58.43$ nm. Here ρ is calculated at different thicknesses d as ϕ increases from 0 to 90°. In Fig. 4 these constant thickness contours (CTC's) are shown for $d = 0$, 32–42 nm, ∞. The spiralling constant angle of incidence (variable-thickness) contours (CAIC's) are also shown in the same figure for $\phi = 15$–75° in steps of 15°. Each CAIC starts on the $d = 0$ CTC and ends spirally on the $d = \infty$ contour. The spiralling is due to the low film absorption. The $\phi = 30°$ CAIC spans a large region of the complex plane. As d increases from zero, the CTC expands out in the upper half-plane. This is seen for $d = 32$ nm and $d = 34$ nm. Increasing d further causes ρ to go to ∞ and then come
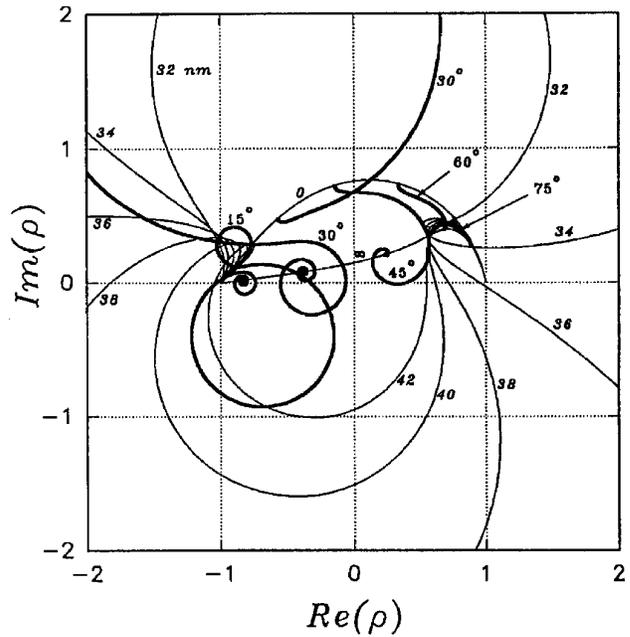

Fig. 4. Contours of constant film thickness d and constant angle of incidence ϕ in the complex ρ plane for single reflection by an Al–SiC film–substrate system at $\lambda = 58.43$ nm.

back in the lower half-plane. Most of the ρ complex plane is covered. Therefore, essentially any desired value can be assigned to ρ by means of the control of d and ϕ. To make a QWR with $\rho = j$, we look for d that is <32 nm. Making a QWR with $\rho = -$ requires a thickness of 38 nm < d < 42 nm. To make a p-suppressing reflection polarizer with $\rho = 0$, one can
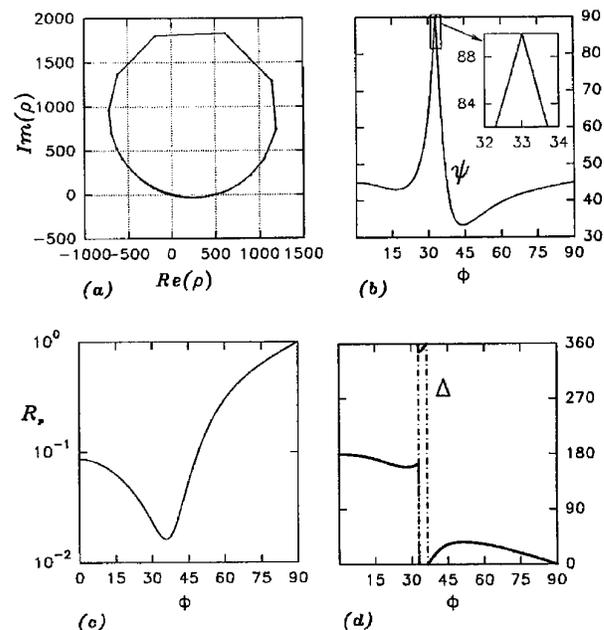

Fig. 5. (a) Re(ρ) versus Im(ρ) as angle of incidence ϕ is changed from 0° to 90° for the Al–SiC film–substrate s-suppressing single-reflection polarizer at $\lambda = 58.43$ nm. (b) Ellipsometric angle ψ versus ϕ. (c) Intensity reflectance R_p versus ϕ. (d) Differential reflection phase shift Δ versus ϕ.

Fig. 6. (a) Re(ρ) versus Im(ρ) as angle of incidence ϕ is changed from 0° to 90° for the Al–SiC film–substrate p-suppressing single-reflection polarizer at λ = 58.43 nm. (b) Ellipsometric angle ψ versus ϕ. (c) Intensity reflectance R_p versus ϕ. (d) Differential reflection phase shift Δ versus ϕ.
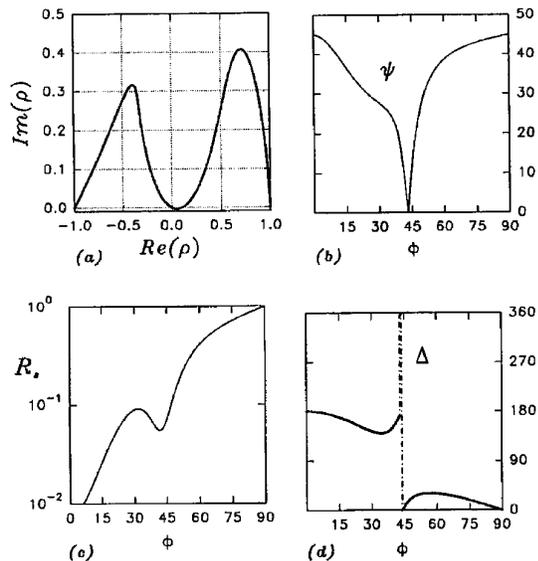
find a value of $d > 42$ nm. Finally, to cause ρ to go to ∞ (an s-suppressing reflection polarizer), we search for a value of d between 34 and 36 nm.

To suppress the s component in reflection (i.e., $r_s = 0$ and $\rho \rightarrow \infty$) we find $d = 35.12$ nm and $\phi = 33.03°$. For this thickness, the contour of ρ is shown in Fig. 5(a) and is nearly a circle. Figure 5(b) shows ψ as a function of ϕ; it is 90° at $\phi = 33.03°$. The intensity reflectance, R_p, is shown in Fig. 5(c) as a function of ϕ; it is 0.018 at $\phi = 33.03°$. Finally, Δ is
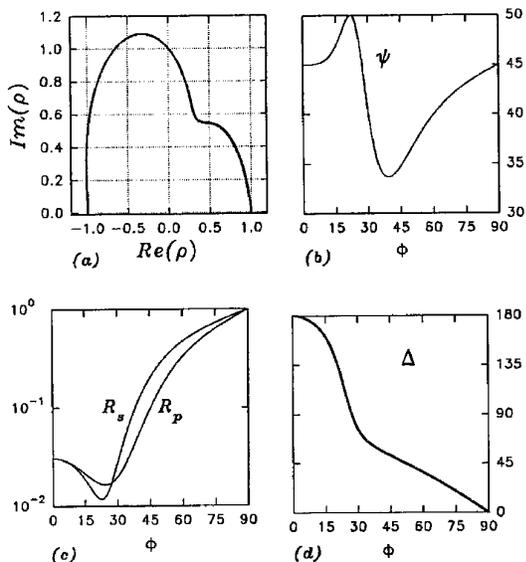

Fig. 7. (a) Re(ρ) versus Im(ρ) as angle of incidence ϕ is changed from 0° to 90° for the Al–SiC film–substrate single-reflection QWR ($\rho = j$) at λ = 58.43 nm. (b) Ellipsometric angle ψ versus ϕ. (c) Intensity reflectances R_p and R_s versus ϕ. (d) Differential reflection phase shift Δ versus ϕ.

shown in Fig. 5(d). Note the fast change in Δ around the polarizing angle of 33.03°.

To make $r_p = 0$, we determine $d = 55.8$ nm and $\phi = 43.9°$. The ρ contour, ψ, R_p, and Δ are all shown in Figs. 6(a), 6(b), 6(c), and 6(d), respectively. At the polarizing angle of 43.9°, $R_s = 0.057$. This reflectance level is adequate for certain applications.

Finally, we consider the design of a pure QWR so that $\rho = \pm j$. The solutions for the film thicknesses are 41.74 and 27.07 nm for $\rho = -j$ and j, respectively. We take the lesser thickness because the associated reflectance is larger. The angle at which $\rho = j$ for $d = 27.07$ nm is 27.2°. As the angle of incidence ϕ is changed, the ρ contour, ψ, R_v, and Δ are shown in Fig. 7. At $\phi = 27.2°$, $R_p = R_s = 1.7\%$. An error of ± 2 nm in the film thickness causes a corresponding error in the differential phase shift of $<8°$.

4. Conclusions

We have shown that by using CVD SiC mirrors, one realizes a three-reflection 90° phase retarder with largely increased throughput. This improvement is quite important in the EUV spectral region, where no transparent birefringent materials exist. In addition, this device is inexpensive when compared with more complicated designs that employ multilayer coatings. A pure QWR (without diattenuation) can be achieved on single reflection by an Al-coated SiC mirror at the expense of a reduction in reflectance.

Theoretically ideal interference-based single-reflection polarizers with low throughput for the unextinguished polarization (of the order of a few percent) are designed by the use of the Al–SiC film–substrate system at the He I EUV wavelength of 58.43 nm.

It should be noted that we have assumed perfectly smooth and clean optics throughout this paper, i.e., the absence of possible contamination (e.g., carbon) or oxide films on the plane surfaces of the bare or coated SiC mirrors. The actual performance of devices that are constructed according to the designs described here may be significantly affected by such films and by surface roughness.

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