MINIMIZING SPATIAL-DISPERSION-INDUCED BIREFRINGENCE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit of the filing date of copending Provisional Patent Application Nos. 60/303,898, filed on Jul. 9, 2001, and 60/309,192, filed on Aug. 1, 2001.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

This invention was made by employees of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties.

FIELD OF THE INVENTION

The present invention concerns birefringence in crystals used in optical systems, and more specifically to mixed solid solutions of fluoride crystals in order to minimize spatial-dispersion-induced birefringence in components of optical systems.

BACKGROUND OF THE INVENTION

Fluoride crystals, such as calcium fluoride, strontium fluoride, and barium fluoride, are widely utilized in high precision optics, including UV optical lithography. These crystals exhibit high transmittance within a broad range of wavelengths from the infrared through the UV, below 157 nm. Accordingly, these crystals are used in various kinds of optical elements for precision UV optics, including lenses, prisms, and beam splitters.

A major complication presently associated with crystals used in precision optical systems is a phenomenon known as birefringence. Birefringence, also known as double refraction, refers to the dependence of refractive index on light polarization direction. Most crystalline materials are naturally birefringent and have anisotropic optical properties due to their asymmetric crystalline structure. However, it is generally thought that crystals with cubic-symmetry crystal structure are constrained by their high symmetry to have no inherent birefringence and have isotropic optical properties. As a result, these cubic crystals were believed to be ideal for use in precision optical systems. Birefringence in these crystals used in optical systems is generally thought to be primarily caused by mechanical stress or strain incorporated during the crystal fabrication process, and substantial efforts have gone towards reducing this stress-induced birefringence.

However, it has been recently discovered that cubic crystals such as calcium fluoride, barium fluoride, and strontium fluoride have an intrinsic birefringence, in addition to the above-mentioned stress induced birefringence as disclosed in John H. Burnett, Zachary H. Levine, and Eric L. Shirley, "Intrinsic Birefringence in 157 nm Materials," in R. Harbison, ed., **2**[nd] International Symposium on 157 nm Lithography, (International SEMATECH, Austin, Tex., 2001); John H. Burnett, Zachary H. Levine, and Eric L. Shirley, "Intrinsic Birefringence in 157 nm Materials," in R. Harbison, ed., Calcium Fluoride Birefringence Workshop, (International SEMATECH, Austin, Tex., 2001); John H. Burnett, Zachary H. Levine, and Eric L. Shirley, "Intrinsic birefringence in calcium fluoride and barium fluoride," Phys. Rev. B 64, 241102 (2001) (hereinafter "Intrinsic birefringence in calcium fluoride and barium fluoride"), all incorporated herein by reference. This birefringence is caused by the symmetry-breaking effect of the finite wave vector q of the photon, and is known as spatial-dispersion-induced birefringence, or intrinsic birefringence. This phenomenon was first discussed by H. A. Lorentz in 1878. It was first convincingly demonstrated in 1971 in Si from J. Pastrnak and K. Vedam, in Phys. Rev. B 3, 2567 (1971) (hereinafter "Pastrnak") and in GaAs from P.Y. Yu and M. Cardona, Solid State Commun. 9, 1421 (1971), both incorporated herein by reference, but the implications for precision UV optics were not explored.

The problem of intrinsic birefringence must be addressed in precision UV optical systems incorporating crystalline optics because the magnitude of the birefringence in the UV is larger than the present industry specifications, e.g., for 157 nm lithography as was reported by A. K. Bates, in Proceedings of the First International Symposium on 157 nm Lithography, ed. by R. Harbison (International SEMATECH, Austin, 2000), p. 377, (hereafter "Bates") incorporated herein by reference.

This complication presents serious challenges to optical engineers because, unlike stress-induced birefringence, intrinsic birefringence is inherent to the material, and thus cannot be reduced by material improvements in a single material.

Four main problems result from this intrinsic birefringence. The first problem is that a different refraction occurs for the two polarization components at the lens surface, which causes a ray bifurcation at each lens. A second problem is that each polarization component accumulates a different phase as it transverses the crystal, resulting in phase-front distortion. A third problem is that an index anisotropy necessarily accompanies the birefringence. These combined effects of intrinsic birefringence cause blurring of the image, which limits the achievable resolution. A fourth problem is an alteration of the polarization state of light as it traverses the optics, which is significant for optical systems using polarized light. Accordingly, there exists a strong need to correct the problem of intrinsic birefringence in crystals used in high precision UV optical systems.

BRIEF SUMMARY OF THE INVENTION

The present invention concerns a method to eliminate or reduce the intrinsic birefringence in cubic crystals made from Group II fluorides, namely CaF_2, SrF_2, BaF_2, and MgF_2. The method is based on the discovery that CaF_2 has a value of the intrinsic birefringence of opposite sign to that of SrF_2 or BaF_2. As a result, mixed solid solutions of these materials, e.g., $Ca_{1-x}Sr_xF_2$, $Ca_{1-x}Ba_x$, F_2, $Ca_{1-x-y}Sr_xBa_yF_2$, $Ca_{1-x-y}Sr_xMg_yF_2$, will have its intrinsic birefringence nulled at a given wavelength with appropriately chosen values of x (and y).

In accordance with one aspect of the present invention, a composition includes a mixture of CaF_2 crystal and a second crystal, said composition having minimal spatial dispersion induced birefringence at a selected wavelength within the UV range.

In accordance with another aspect of the present invention, a method for making a non-birefringent material includes selecting a wavelength, and mixing CaF_2 crystal with a second crystal to form a composition having minimized spatial dispersion induced birefringence at the selected wavelength.