Industry consensus is that calcium fluoride (CaF$_2$) is the only practical optical material for use in stepper and scanner lenses for 157-nm lithography. It has always been challenging to produce high optical quality CaF$_2$ with low stress-induced birefringence. In addition to this stress-induced birefringence, John Burnett and his colleagues at NIST discovered intrinsic birefringence in CaF$_2$ along the <110> crystal axis to be 11.2 nm/cm at 157.6 nm. This news came as an unwelcome surprise to the optical lithography industry, which had incorrectly assumed that CaF$_2$, belonging to the cubic crystal group, was an isotropic material.

In an intrinsically birefringent material, linearly polarized light experiences different indices of refraction along different crystal axes. Birefringence can also be introduced by external or residual stresses in bulk materials. At very short wavelengths (i.e., 157 nm), CaF$_2$ shows stress-induced birefringence and a much stronger intrinsic birefringence (also known as spatial dispersion birefringence). Birefringence in CaF$_2$ introduces performance issues for high performance lithography applications.

Birefringence is traditionally measured by passing a light beam through a sample that is placed between crossed polarizers. The light intensity is usually detected as the sample is rotated through 360°. The magnitude of birefringence is related to the difference between the maximum (fast axis is 45° from the polarizers' axes) and minimum (fast axis is parallel or perpendicular to the polarizers' axes) signals. This method has several disadvantages, including a long measurement time and a low accuracy. The requirement of rotating a sample for every sampling spot makes birefringence mapping impractical for industrial applications.

Photoelastic modulator (PEM) technology offers a better alternative to the crossed polarizer technique. The PEM modulates the incoming light polarization at a high frequency (nominally 50 kHz). When the modulated light passes through a birefringent sample, light polarization will always be changed regardless of the fast axis orientation of the sample. We have extended this technique to analyze polarization changes over two channels, determining both the birefringence magnitude and fast axis angle in less than 2 s. The speed of the PEM approach opens the door for birefringence mapping of entire optical samples in industrial applications. It is possible to further increase measurement speed by adding an extra lock-in amplifier to the signal processing scheme.

In addition to speed, PEM technology offers extremely high accuracy in measuring birefringence (good to within 0.005 nm). It is well-known that common light sources have intensity fluctuations on the order of several percent. This fluctuation can affect the accuracy of birefringence measurement in traditional methods. The PEM approach measures the ratio of the modulated signal to average light intensity, so light source fluctuation does not impact the measurement accuracy.

In collaboration with International Sematech (Austin, TX), we have recently extended the birefringence measurement capability into the optical lithography applications. The resultant birefringence measurement system (the Exicor) can be used at all DUV lithography wavelengths (157, 193, and 248 nm). Using this system, we have mapped the birefringence in a variety of CaF$_2$ samples at 157.6 nm, for example tracking the birefringence map of a CaF$_2$ cube that was measured when the light beam propagated along the <110> crystal axis (see figure).

The intrinsic birefringence in CaF$_2$ at 157.6 nm is determined by the crystal structure. The solution for the optical lithography industry is to offset birefringence by arranging different optical components at the proper angular orientations. Testing the worst case when light propagates along the <110> axis, we stacked two CaF$_2$ cubes with the same dimensions with their intrinsic birefringence axes being offset by 90°. The total birefringence measured is <0.2 nm/cm, indicating that this approach is a viable solution.

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References

A data plot of birefringence in a CaF$_2$ cube shows 400 data points ranging from 13.5 nm/cm to 10.5 nm/cm.

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