SUMMER 2002

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APPLICATIONS
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MODULATORS

TOKAMAK PLASMA DIAGNOSTICS

A PEM-based Stokes Polarimeter for Tokamak Plasma Diagnostics

by Dr. Theodore C. Oakberg, Senior Applications Scientist

Hinds Instruments photoelastic modulators (PEMs) have played an important role in nuclear fusion energy research. A Stokes polarimeter using a special dual PEM system is used with "tokamak" plasma fusion reactors for determining characteristics of the magnetic field and the plasma. This technique is called "Motional Stark Effect Polarimetry" or the "MSE Diagnostic."

Tokamak Plasma Fusion Reactors

A "tokamak" is a device for containing a plasma (ionized gas) using a strong magnetic field. Originally conceived by Soviet scientists Igor Tamm and Andrei Sakharov, it is today the most promising of several such magnetic containment devices. The tokamak is the focus of an intense worldwide effort to control nuclear fusion for electric power generation.[1]

The plasma (an ionized gas of the heavy hydrogen isotopes deuterium, H^2, and, on rare occasions, tritium, H^3)[A] is enclosed in a vacuum chamber in the shape of a torus (donut). The idea is to "contain" the plasma at the very high temperatures required for nuclear fusion (about 100 million degrees C) using magnetic fields. One of these magnetic fields, the "toroidal" field, is produced by large current-carrying coils around the torus. The magnetic flux from these coils is also toroidal in shape, and the field lines "fill" the torus cavity (Figure 1a).

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Dual PEM Systems for Polarimetry

Photoelastic modulators have historically been used in polarimetry. When the PEM is used as a polarization analyzer, it is generally useful to use a dual PEM system. A dual PEM system can characterize any polarization state by obtaining all four Stokes vectors simultaneously. By using a dual PEM system, the unparalleled high sensitivity, spectral range and stability of photoelastic modulators (PEMs) can be applied to study polarization.

One of the first uses for the PEM was astronomical polarimetry. Applications can also be found in Stokes polarimetry and Optical Rotation. Other polarization analysis PEM applications include laser light characterization and magnetic field diagnostics in tokamaks throughout the world.

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ABOUT THE SCIENTISTS

Dr. Fred Levinton	Nova Photonics, Inc.
Dr. Robert C. Wolf	Max-Planck Institut für Plasmaphysik

Dr. Fred Levinton received his B.Sc. Degree in physics from McGill University, Canada, and his Ph.D. in physics from Columbia University. He developed the motional Stark effect (MSE) diagnostic for measuring the magnetic field in high temperature plasmas which was implemented at the Princeton Plasma Physics Lab. Dr. Levinton received the American Physical Society's *1997 Award For Excellence In Plasma Physics Research* for the concept and development of the MSE diagnostic. He is currently with Nova Photonics, Inc.

Robert C. Wolf received his Diploma from the University of Aachen and his Ph.D. from the University of Düsseldorf in 1993. In 1996 he became associated with the ASDEX Upgrade tokamak, one of the magnetic confinement fusion devices of the Max-Planck-Institut für Plasmaphysik in Garching, Germany, and there developed the Motional Stark Effect polarimeter. At present he is working at the Joint European Torus tokamak, the world's largest facility of its kind, as task force leader responsible for the program concerning improved confinement regimes. In September 2002 he will move to Forschungszentrum Jülich to become one of the directors of the Institut für Plasmaphysik.

[A] Most research tokamaks use only deuterium, a stable isotope of hydrogen. Future power-producing fusion reactors will likely use tritium as well as deuterium. As of the date of this article, the use of tritium has been tested only at the TFTR tokamak at Princeton and the JET facility in Culham, U.K.

...PEM-based Stokes Polarimeter for Tokamak Plasma Diagnostics

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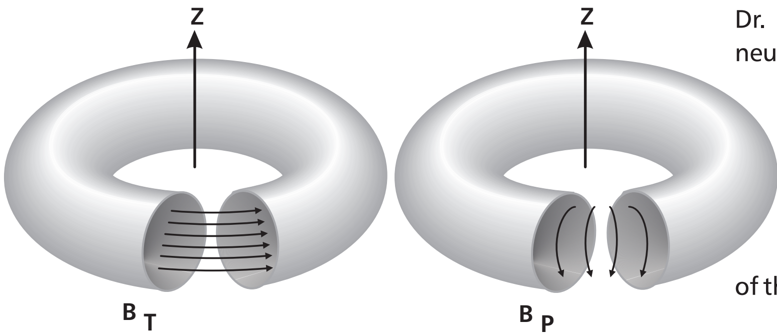

a) Toroidal magnetic field *b) Poloidal magnetic field*

Figure 1. Magnetic fields in a tokamak

The second field, called the "poloidal" magnetic field, is produced by a strong current in the plasma. This field has the unique property that it is weakest at the center of the current distribution and strongest at the periphery of the current distribution. The direction of the poloidal field is shown in Figure 1b.[B]

The strength of this poloidal magnetic field vs. position is of great interest to plasma scientists, since it can shed light on the stability of the plasma and the distribution of the current density inside the plasma. The PEM-based Stokes polarimeter offers a means of determining the magnitude of the poloidal field vs. position in the plasma. [2-4] This has led to improved understanding and performance of tokamak plasmas.[5]

In a power-producing tokamak reactor, the plasma will consist of ionized H^2, H^3 and free electrons. Since all the particles in the plasma are electrically charged, the magnetic field is able to contain them. The kinetic energies of the H^2 and H^3 ions must be high enough that during some collisions, the electrostatic forces of repulsion can be overcome and the two colliding particles can get close enough for a fusion reaction to take place. A typical fusion reaction is:

$$H^2 + H^3 \rightarrow He^4 + n^1 + energy$$

The energy released (as kinetic energy of the particles) from each "successful" collision is about 17.6 MeV.

[B] Both the toroidal and poloidal magnetic fields serve to "contain" the plasma. This containment is a consequence of the laws of electromagnetism, which predict that a charged particle when moving at right angles to a uniform magnetic field will follow a circular path, returning to its original position. If the particle has a velocity component parallel to the field, the path of the particle will be a helix, with the center of the helix being parallel to the magnetic field. Even non-uniform magnetic fields can "contain" charged particles if the proper conditions of particle speed, mass, electric charge and magnetic field strength are met.

Development of the PEM Stokes polarimeter for tokamak plasma diagnostics

The PEM Stokes polarimeter that is used with tokamaks was invented by Dr. Fred Levinton with the assistance of the late Dr. James Kemp of the University of Oregon. A beam of neutral deuterium atoms is injected into the tokamak plasma. The atoms become excited and emit the red "Balmer alpha" light at about 656 nm. The light of interest is polarized perpendicular to the magnetic field in the vicinity of the light emitting atoms. The polarimeter measures the direction of polarization of the light and thus may be used to determine the direction of the magnetic field.

Modern versions of the dual PEM feature a 20 kHz PEM and a 23 kHz PEM mounted in a single optical head enclosure with their retardation axes at 45 degrees with each other. The optical head material is frequently plastic, since the forces induced on metal enclosures by a rapidly changing magnetic field can be very strong.

The ASDEX Upgrade tokamak, details of the Stokes polarimeter installation

A typical PEM Stokes polarimeter installation is at the ASDEX (Axially Symmetric Divertor Experiment) Upgrade tokamak at the Max Planck Institute for Plasma Physics at Garching in southern Germany. Dr. Robert Wolf was the scientist responsible for the installation of this polarimeter system.

The ASDEX Upgrade tokamak is designed specifically for experiments on magnetic divertors. Divertors are devices for removing unwanted (impurity) ions from the plasma. The toroidal chamber has a major radius of 1.65 meters and a minor radius of 0.5 meters. Toroidal field strengths are typically 2 to 3 Tesla and the plasma current is typically a million amperes.

An important component of all tokamaks is a coil located at the center of the torus. A tokamak "run" begins with the chamber being filled with H^2 gas at very low pressure. A rapidly changing current in the coil at the center of the torus provides a strong induced electromotive force inside the torus. Any existing free electrons are sufficient to ionize the rest of the gas and produce a plasma. The plasma then becomes the "secondary winding" of a transformer with the plasma current being determined by the rate of change of the current in the center coil (primary) and the resistivity of the plasma. Electrical resistance heating provides the initial heating of the plasma.

Additional heating of the plasma is required to achieve the high temperatures required for nuclear fusion. One method is by injecting neutral deuterium atoms into the plasma at high speeds (i.e. high kinetic energies). Electrically neutral atoms must be injected, since ions would be repelled by the magnetic field. The neutral atoms eventually become ionized and become part of the plasma.

A top view showing the torus vacuum chamber, the neutral deuterium beam and the dual PEM is shown in Figure 2.

The light from the deuterium beam is reflected by a mirror into the polarimeter optics. The light is focused using two lenses through the dual PEM and the polarizer to a fiber optics array. There are 10 lines-of-sight, each with a line of 6 fiber optic bundles for measuring the light polarization direction at 10 points along the H^2 beam. The array pattern of the ends of the fiber bundles is also shown in Figure 2.

In the mid-plane of the torus, the toroidal magnetic field component $\mathbf{B_T}$ at each point lies in the mid-plane and the poloidal magnetic field component $\mathbf{B_P}$ is perpendicular to the mid-plane (Figure 3). The toroidal field is produced primarily by the large electromagnets and is therefore known. (Subtle perturbations of this field occur due to the motion of the electrons and ions in the plasma, but these can be calculated.) If the tilt angle γ_p of the net magnetic field ($\mathbf{B_T} + \mathbf{B_P}$) can be determined, the magnitude of the poloidal field component $\mathbf{B_P}$ may be calculated according to the following equation:

$$\gamma_P = \tan^{-1}\left(\frac{B_P}{B_T}\right)$$

Not all of the H_α spectral line can be used. The deuterium atom experiences a strong electric field due to its motion in the magnetic field ($\mathbf{E = v \times B}$). This splits the line into different components according to the Stark effect. (This phenomenon is called the "Motional Stark Effect".) Only the σ components are used; these are perpendicular to the net magnetic field and their central wavelength is independent of the field strength. If the light is viewed perpendicular to the direction of the induced electric field, the light is linearly polarized. The spectral bandwidth of the filter/detector must be limited to 0.2 to 0.3 nanometers to accept only the σ components of the H_α spectral line.

It is also necessary to view the beam line at some angle other than perpendicular to the beam. A Doppler shift of the spectrum line is needed to separate the highest energy component of the injected atoms from lower velocity components as well as H_α radiation from the plasma edge and radiation from charge-exchange reactions.[C] Each channel (line-of-sight) therefore requires measurement of a narrow spectral band at a different central wavelength.

Typical toroidal and poloidal field strengths are shown in Figure 4. The intersection of the beam line and each line-of-sight defines a particular point on the mid-plane inside the plasma where the magnetic field is measured. Since the toroidal field strength is known, measuring the direction of the polarization of the σ component of the light determines the strength of the poloidal field component. From the distribution of the poloidal field vs. position inside the plasma, it is possible to calculate the current density distribution inside the plasma. This is very important information to the scientists who are studying the tokamak plasma.

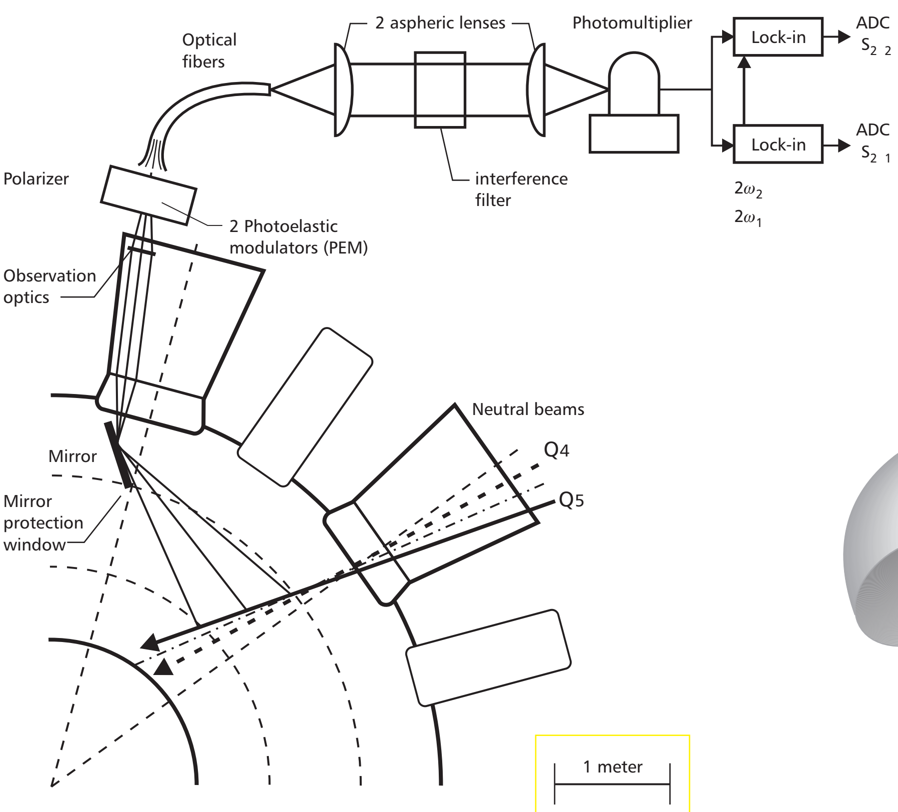

Figure 2. Neutral deuterium beam, details of the ASDEX Upgrade Stokes polarimeter.

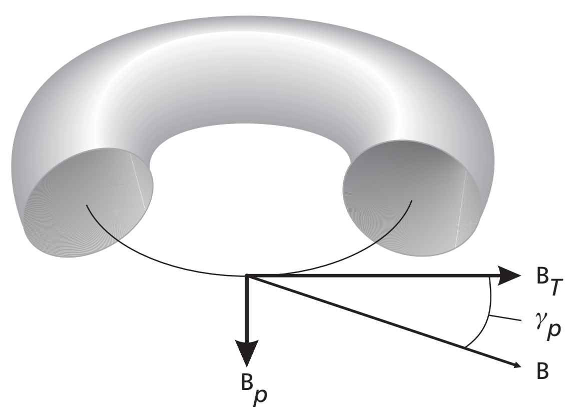

Figure 3. Geometric relationship between the toroidal field, poloidal field and pitch angle γ_p.

Novel system design details

There are a number of unique design features associated with this and other tokamak PEM polarimeter systems.

1 Protecting the PEM electronic heads from strong magnetic fields.

The PEM electronic heads are susceptible to strong magnetic fields. It is therefore necessary to locate the electronic heads some distance away from the dual optical head, or magnetically shield the electronic heads or both.[D] The coaxial head-to-head cables are 15 meters long for the ASDEX Upgrade tokamak installation.

2 Optical signal transmission via optical fibers

Optical fiber bundles are used to conduct the light from the PEM assembly to the individual detectors (photomultiplier tubes or PMTs). The intensity modulated light signals are carried to the control room where the detectors and associated electronics are located. The polarization of the light is lost in the fibers, but this is an advantage, since the type of PMTs being used are polarization sensitive.

3 Fine tuning of wavelength selection

An aspheric lens collimates the light coming from the end of the fiber bundle which passes through an interference filter and another lens to the photomultiplier tube. Each interference filter has a spectral bandwidth of about 0.2 to 0.3 nm. The center wavelength of each filter is "tuned" by varying the filter temperature and/or tilting the filter. Each channel has a single PMT which is connected to a pre-amplifier with a gain of 10^5 volt/amp. Each pre-amplifier is then connected to two lock-in amplifiers, one at 40 kHz and the other at 46 kHz (twice the oscillation frequencies of the PEMs).

4 Real-time data analysis

The output of each lock-in amplifier goes to an A-D converter. Data is sampled at a rate of 1 kHz. At the present, ASDEX Upgrade data is reduced at the end of the run. It would be possible to perform real-time data analysis and use the information in a feedback loop to control the reactor. This may be tried with the ASDEX Upgrade in the future.

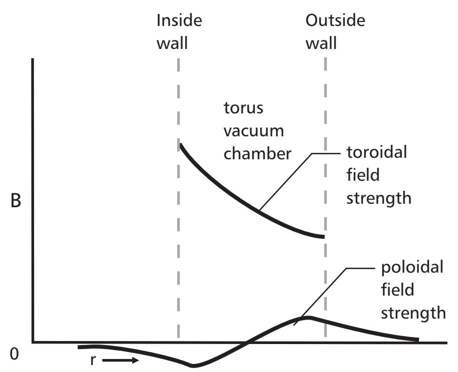

Figure 4. Relative intensities of toroidal and poloidal magnetic fields, vs radial position.

Summary

Stokes polarimeters using a dual PEM are an important part of the diagnostics of tokamak plasmas in installations around the world. Hinds Instruments employees are proud of the role our product plays in nuclear fusion research. We at Hinds Instruments are very grateful to Dr. Fred Levinton of Fusion Physics for developing this application of the photoelastic modulator and for his assistance with this article. I am personally grateful to Dr. Robert Wolf for his assistance in helping me understand the operation of the tokamak and the details of the Motional Stark Effect polarimeter and for his assistance in preparing this article.

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Hinds Instruments Teams with International SEMATECH to Develop an Instrument that Characterizes Birefringence in Calcium Fluoride for 157 nm Microlithography

In recent years, optical lithography has continued its transition to shorter wavelengths in order to produce more advanced microchips. The next generation of optical lithography systems will use F_2 Excimer lasers operating at 157 nm. Due to its unique optical properties and readiness for large-scale production, calcium fluoride (CaF_2) is the only practical optical material available for use in stepper and scanner lenses at this wavelength. Consequently, linear birefringence in CaF_2 components has emerged as an important quality parameter for the optical lithography industry.

In May 2001, as part of a project with International SEMATECH, researchers at the National Institute of Standards and Technology (NIST) reported intrinsic birefringence in CaF_2 that affects lens design and images at the wafer level in 157 nm microlithography systems. This news came as an unwelcome surprise to the optical lithography industry. Prior to this discovery it was commonly assumed, incorrectly, that CaF_2, belonging to the cubic crystal group, was an "isotropic" material.

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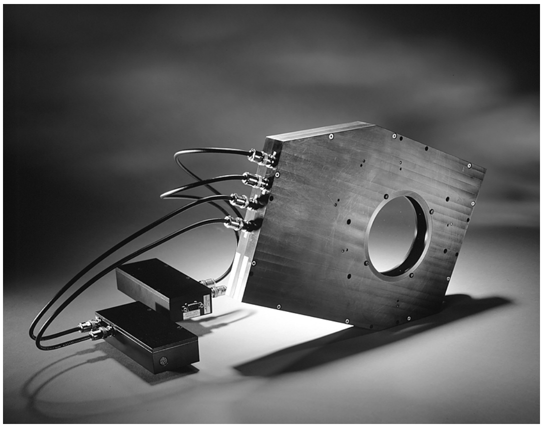
[C] The magnitude of the Doppler shift in wavelength is proportional to the component of the particle velocity along the direction of the line of sight.

[D] Hinds Instruments recommends that the electronic heads be located in a magnetic field no stronger than 100 Gauss or 0.01 Tesla.



Dual PEM Systems for Polarimetry

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Dual PEM Models

Hinds Instruments has five standard dual PEM systems for applications that require different useful apertures and measurements in different spectral regions. The dual PEM models are:

- *I/FS50-55*
- *II/FS42-47*
- *I/FS47-50*
- *II/ZS37-50*
- *II/FS20-23*

The I/FS50-55 and the I/FS47-50 systems use the series I PEM with fused silica as the optical material. The series I PEM has a rectangular shaped optic that has a useful aperture that is limited by the height of the optic. These small systems are useful when the light source has a small beam diameter.

Most of the dual PEM systems utilize the series II PEMs, which contain octagonal shaped optical elements. The series II PEMs meet higher requirements for magnitude of modulation and offer symmetrical distribution of PEM retardation over a larger aperture range.

The II/FS20-23 and the II/FS42-47 systems also employ high quality fused silica as the optical material and have a transmission range of 170nm to 2.6μm. Both models are useful for quarter and half wave retardation in the UV, visible and near IR light spectral regions. Of the two models, the II/FS20-23 system has the benefit of a larger aperture. This is especially useful if the light source has a large beam diameter or more than one light source is to be imaged through the optic. The II/FS42-47, on the other hand, provides a more compact optical head configuration.

The II/ZS37-50 has ZnSe as the optical material. This provides a transmission range from 514nm to 18μm. This PEM has applications in the infrared region of the light spectrum. It is used to analyze both broadband light sources and infrared lasers, such as the CO_2 laser.

Like all Hinds PEMs, these systems provide the unique benefit of a wide acceptance angle (> ± 20 degrees), a good transmission for a wide wavelength range, high power handling capabilities and a high polarization sensitivity. The table below compares the technical specifications for all of the dual PEM systems.

Applications for Dual PEM Systems

Polarization Analysis and Stokes Polarimetry

The most common use for a dual PEM system is to analyze the polarization state of a light source. There are different ways to represent light polarization. One of these is to use Stokes vectors or parameters (I, Q, U and V). Using the 1f and 2f reference signals from each of the controllers, a dual PEM system is able to provide all four of the Stokes para-meters simultaneously. Any light polarization can be charac-terized by using these four parameters. For more informa-tion, please see the Stokes Polarimetry application note on our website.

Astronomical Polarimetry

One of the first uses of the photoelastic modulator was astronomical polarimetry. Dr. James Kemp, late Professor of Physics at the University of Oregon, used PEMs to study the polarization of light from nearby stars and features on the sun, such as sunspots. The four Stokes parameters (I, Q, U, V) give a complete description of the polarization state of these stellar light sources. For more information on this application, please refer to Hinds Instruments' PEM Newsletter #1 on our website.

Tokamak

Hinds Instruments manufactures a dual PEM system specifically designed for Motional Stark Effect (MSE) diagnostic polarimeters associated with tokamaks. A detailed description of this application is the feature article of this newsletter.

Dual PEM systems provide the capability to make real time polarization analysis measurements. These systems are available in a wide variety of materials and configurations to support many diverse applications. A Hinds sales engineer or application scientist will be glad to explain any of these options. Please contact us with any questions or comments.

Technical Specifications for Dual PEM-90 Systems

Model	Optical Material	Nominal frequencies	Spectral Range	Range of λ/4 Retardation	Range of λ/2 Retardation	Useful aperture
II/ZS37-50	ZnSe	37 - 50kHz	550nm - 18μm	550nm - 18μm	550nm - 10μm	13mm*
II/FS20-23	Fused Silica	20 - 23kHz	170nm - 2.6μm	170nm - 2.6μm	170nm - 2.5μm	45mm*
II/FS42-47	Fused Silica	42 - 47kHz	170nm - 2.6μm	170nm - 2.6μm	170nm - 2.6μm	23mm*
I/FS50-55	Fused Silica	50 - 55kHz	170nm - 2.6μm	170nm - 2μm	170nm - 1μm	16mm
I/FS47-50	Fused Silica	47 - 50kHz	170nm - 2.6μm	170nm - 2μm	170nm - 1μm	16mm

***Useful aperture is defined as the area for which the average retardation is 90% of the retardation at the center. For more information, please contact Hinds Instruments.**

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- **Dual PEM Systems**
- **HINDS Teams With SEMATECH**

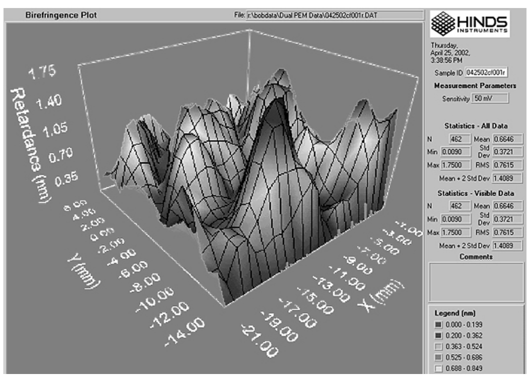

Figure 5. Intrinsic Birefringence of CaF_2 at 157nm

HINDS Teams With SEMATECH

(continued from page 4)

To respond to this issue, Hinds has extended its core competency in low-level visible birefringence measurements to develop a system to characterize birefringence in any optical material transparent at 193 nm or 157 nm. We were awarded a contract with SEMATECH to expedite the development of the DUV birefringence measurement system. They have tasked Hinds to provide the semiconductor industry with measurement metrology for QC, as well as lab R&D use, for characterizing the interaction between DUV light and CaF_2 in lithography imaging systems.

Data from a prototype DUV birefringence measurement system was reported at International SEMATECH's 157nm Technical Data Review this May in Dallas, TX. One of our senior application scientists, Dr. Bob Wang, showed 2-D images as well as contour maps which vividly displayed both the magnitude and corresponding fast axis angle of residual and the recently discovered intrinsic form of birefringence in CaF_2 at 157 nm. An example is shown in Figure 5. This data represents the first multidimensional characterization of CaF_2's birefringence at 157 nm resulting from our collaboration with SEMATECH. Dr. Wang's preliminary findings, measured at different crystal orientations, confirmed high levels of intrinsic birefringence. Furthermore, the 2-D birefringence maps of the entire surfaces of CaF_2 cubic samples measured at the (110) orientation demonstrated significant variation in birefringence, possibly due to residual birefringence in those samples. Lower levels of birefringence, with significant variation in magnitude and angle, were also observed for the (001) orientation.

One design solution that has been proposed to reduce the intrinsic birefringence at 157 nm is to couple lenses in the imaging system at offsetting orientations. Dr. Wang demonstrated the validity of this approach. He presented data from two stacked cubes that had the same orientation (110) with a resulting total mean birefringence of 54 nm. When one of the cubes was rotated by 90°, the total birefringence was drastically reduced to below 1 nm/cm.

Hinds is aggressively pursuing the development of a DUV birefringence measurement system and has an engineering model in development. A commercial system capable of measuring samples as large as 400 mm diameter x 270 mm thick is scheduled to be available during the second half of 2002.