Deep-ultraviolet laser microscope reveals diamond's nanoscale transport behaviors

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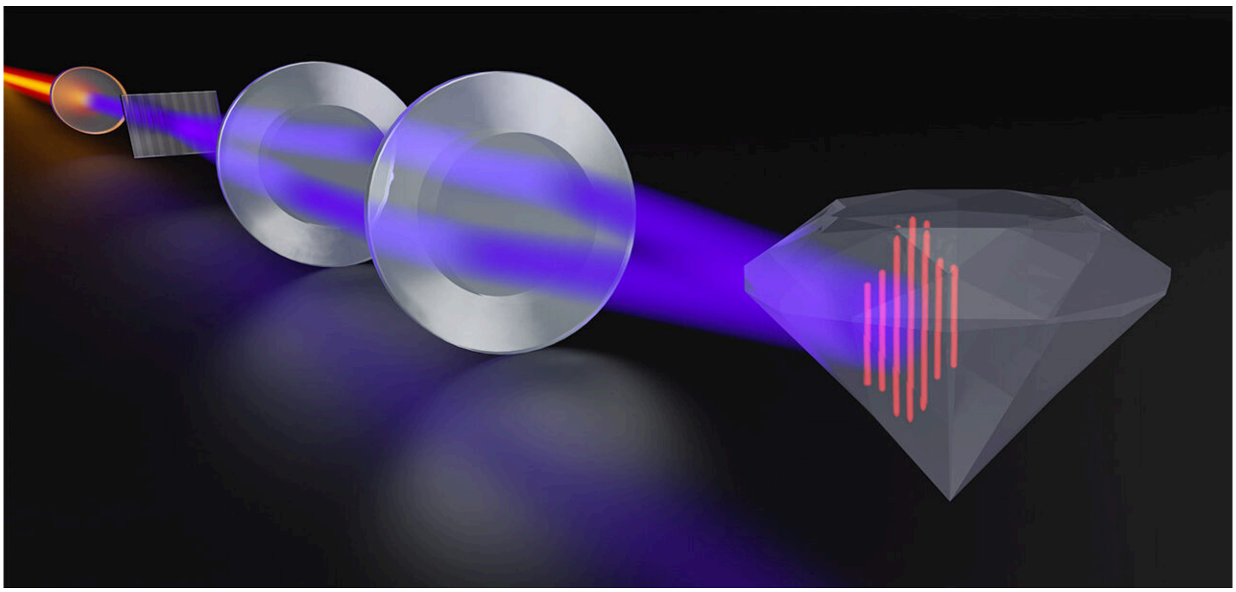

A diffractive optic creates two DUV beams, which are focused and interfered on a sample surface (diamond) using a 4f imaging system to generate a microscopic sinusoidal excitation profile. Credit: Steven Burrows/Murnane and Kapteyn groups

Ultrawide-bandgap semiconductors—such as diamond—are promising for next-generation electronics due to a larger energy gap between the valence and conduction bands, allowing them to handle higher voltages, operate at higher frequencies, and provide greater efficiency compared to traditional materials like silicon.

However, their unique properties make it challenging to probe and understand how charge and heat move on nanometer-to-micron scales. Visible light has a very limited ability to probe nanoscale properties, and moreover, it is not absorbed by diamond, so it cannot be used to launch currents or rapid heating.

Now, researchers at JILA, led by JILA Fellows and University of Colorado physics professors Margaret Murnane and Henry Kapteyn, along with graduate students Emma Nelson, Theodore Culman, Brendan McBennett, and former JILA postdoctoral researchers Albert Beardo and Joshua Knobloch, have developed a novel microscope that makes examining these materials possible on an unprecedented scale.

The team's work, published in *Physical Review Applied,* introduces a tabletop deep-ultraviolet (DUV) laser that can excite and probe nanoscale transport behaviors in materials such as diamond.

This microscope uses high-energy DUV laser light to create a nanoscale interference pattern on a material's surface, heating it in a controlled, periodic pattern.

Observing how this pattern fades over time provides insights into the electronic, thermal, and mechanical properties at spatial resolutions as fine as 287 nanometers, well below the wavelength of visible light.

Murnane states that this new probe capability is important for future power electronics, high-frequency communication, and computational devices based on diamond or nitrides rather than silicon. Only by understanding a material's behavior can scientists address the challenge of short lifetimes observed in many nanodevices incorporating ultrawide-bandgap materials.

A challenge from an industry partner

For Nelson and the other JILA researchers, this project began with an unexpected challenge from materials scientists from one of their industry collaborators: 3M.

"3M approached us to study an ultrawide material sample that wasn't compatible with our existing microscopes," Nelson says. The team then collaborated with 3M scientists Matthew Frey and Matthew Atkinson to build a microscope that could image transport in this material.

Traditional imaging methods rely on visible light to see the microscopic composition and transport behaviors in semiconductors and other materials, which is effective for studying materials with smaller bandgaps.

However, materials like diamond, often used in electronic components, have a much larger energy gap between their valence and conduction bands—typically exceeding 4 electron volts (eV)—making them transparent to lower-energy visible and infrared light. Higher-energy photons in the ultraviolet (UV) range or beyond are required to interact with and excite electrons in these materials.

Visible-light setups also struggle with spatial resolution, as their longer wavelengths limit the ability to probe the nanoscale dimensions relevant to modern devices.

These limitations inspired the team to think outside the box for their imaging setup.

"We brainstormed a new experiment to expand what our lab could study," says Nelson.

The result was a multi-year effort to develop a compact microscope that uses DUV light to generate nanoscale heat patterns on a material's surface without altering the material itself.

Diving into the deep ultraviolet regime

To generate the DUV light, the team first started with a laser emitting pulses at an 800-nanometer wavelength. Then, by passing laser light through nonlinear crystals and manipulating its energy, the team converted it step-by-step into shorter and shorter wavelengths, ultimately producing a powerful deep-ultraviolet light source at around 200 nanometers wavelength.

Each step required precise alignment of laser pulses in space and time within the crystals to achieve the desired wavelength efficiently.

"It took a few years to get the experiment working during the pandemic," says Nelson, describing the trial-and-error process of aligning light through three successive crystals. "But once we had the setup, we could create patterns on a scale never before achieved on a tabletop."

To produce the periodic pattern, called a transient grating, the researchers split the DUV light into two identical beams using a diffraction grating.

These beams were directed onto the material's surface at slightly different angles, where they overlapped and interfered with each other, forming a precise sinusoidal pattern of alternating high and low energy. This interference pattern acted as a nanoscale "grating," temporarily heating the material in a controlled way and generating localized energy variations.

This process allowed the team to study how heat, electrons, or mechanical waves—depending on the material—spread and interacted across the nanoscale grating. The periodicity of the grating, which defined the distance between these high-energy peaks, was closely related to the wavelength of the light source, allowing researchers to get shorter periods by using higher energy (and shorter wavelength) light.

The periodicity could be tuned by adjusting the angles of the beams, enabling detailed studies of transport phenomena at microscopic scales. For example, in this experiment, the team achieved grating patterns as delicate as 287 nanometers, a record for laser tabletop setups.

Testing the new DUV microscope

Once the DUV transient grating system was operational, the team focused on validating its accuracy and exploring its capabilities. Their first test involved thin gold films, which served as a benchmark material due to their well-understood properties.

The researchers used their system to generate nanoscale heat patterns, launching acoustic waves at the film's surface. By analyzing the frequency and behavior of these waves, they extracted material properties such as density and elasticity.

To confirm their results, Nelson developed computer models simulating how the gold film would behave under similar conditions. The experimental data matched her predictions closely, providing a strong validation of the system's precision.

"Seeing the experiment work and align with the models we created was a relief and an exciting milestone," Nelson says.

Next, the team used their new DUV microscope to look at diamond, a material prized for its exceptional electronic and thermal properties. Previous techniques for studying diamond often required physical alterations, such as adding nanostructures or coatings, which inadvertently changed its properties. The DUV system eliminated this need, enabling the team to study diamond in its pristine state.

Using their new setup, the researchers observed how charge carriers—electrons and holes—diffused across the diamond after being excited by the DUV light. This process revealed new insights into the nanoscale transport dynamics of diamonds, particularly at nanometer scales.

Beyond validating the system and exploring diamond's properties, the team's findings shed light on broader questions of nanoscale heat transport. At such small scales, heat doesn't always behave as predicted by traditional physical models, which assume a smooth, continuous flow.

Instead, nanoscale transport can involve ballistic and hydrodynamic effects, where energy carriers like phonons can travel in a straight line without scattering or can spread like water flowing through channels.

As researchers continue to refine these techniques and explore new materials, this advancement could play a crucial role in the development of high-performance power electronics, efficient communication systems, and quantum technologies. In the quest to push the boundaries of modern devices, diamonds may not last forever—but their impact on nanoscience certainly will.

More information: Emma E. Nelson et al, Tabletop deep-ultraviolet transient grating for ultrafast nanoscale carrier-transport measurements in ultrawide-band-gap materials, *Physical Review Applied* (2024). DOI: 10.1103/PhysRevApplied.22.054007

Provided by JILA

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