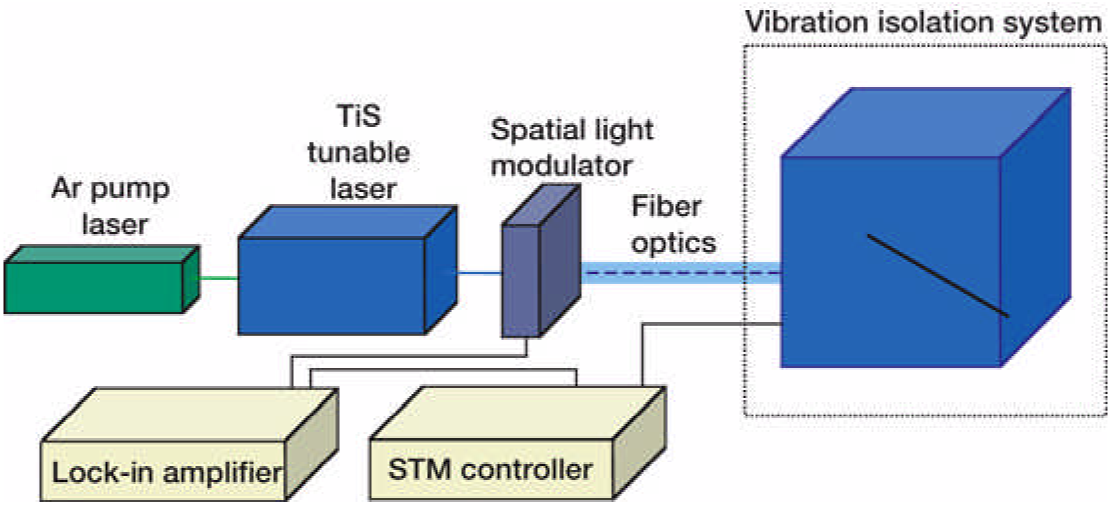
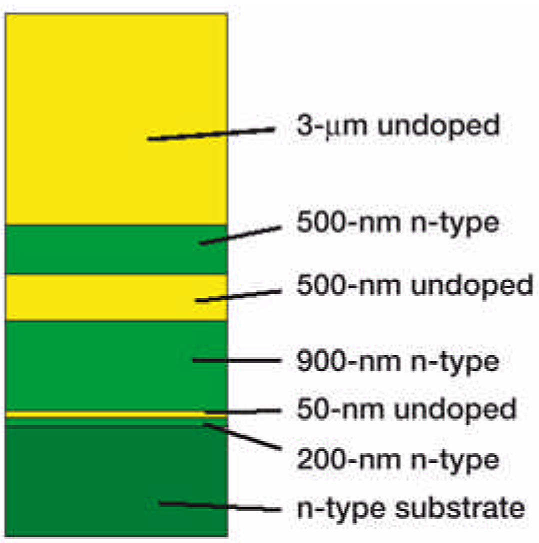
Scanning Tunneling Optical Resonance Microscopy Developed

The ability to determine the in situ optoelectronic properties of semiconductor materials has become especially important as the size of device architectures has decreased and the development of complex microsystems has increased. Scanning Tunneling Optical Resonance Microscopy, or STORM, can interrogate the optical bandgap as a function of its position within a semiconductor micro-structure. This technique uses a tunable solid-state titanium-sapphire laser whose output is "chopped" using a spatial light modulator and is coupled by a fiber-optic connector to a scanning tunneling microscope in order to illuminate the tip-sample junction. The photoenhanced portion of the tunneling current is spectroscopically measured using a lock-in technique. The capabilities of this technique were verified using semiconductor microstructure calibration standards that were grown by organometallic vapor-phase epitaxy. Bandgaps characterized by STORM measurements were found to be in good agreement with the bulk values determined by transmission spectroscopy and photoluminescence and with the theoretical values that were based on x-ray diffraction results.

Combining the localized spectroscopic illumination provided by a fiber-optically coupled solid-state Ti:S laser with the imaging and electronic characterization capabilities of scanning tunneling microscopy provides a technique for determining the in situ semiconductor optical bandgaps of these small systems. The scanning tunneling microscope (STM) can be used to identify small semiconducting regions of a material or system by monitoring the change in tunneling current as a function of position. It is possible to enhance the tunneling current in these semiconducting regions by illuminating the semiconductor surface with light of sufficient energy. The photoenhancement results when the wavelength or energy of the illuminating photons is such that the valence electrons in the sample can absorb these photons and be promoted into the conduction band where they can contribute to the tunneling current. The use of a tunable solid-state laser allows the wavelength of the illumination to be continuously tuned and directed into the system via a fiber-optic device that can be directed onto the tip-sample region. By chopping the laser light with a spatial light modulator (SLM), one can measure a voltage proportional to the tunneling current by a lock-in amplifier at the SLM chopping frequency. The output of the lock-in is then monitored as a function of the wavelength of the illumination. The onset of the photoenhanced tunneling current then provides a direct measurement of the optoelectronic bandgap of the material (i.e., the individual quantum dot, carbon nanotube, semiconductor quantum well, etc.) or region of the material that is being imaged in the STM. See the STORM apparatus in the schematic on the left.

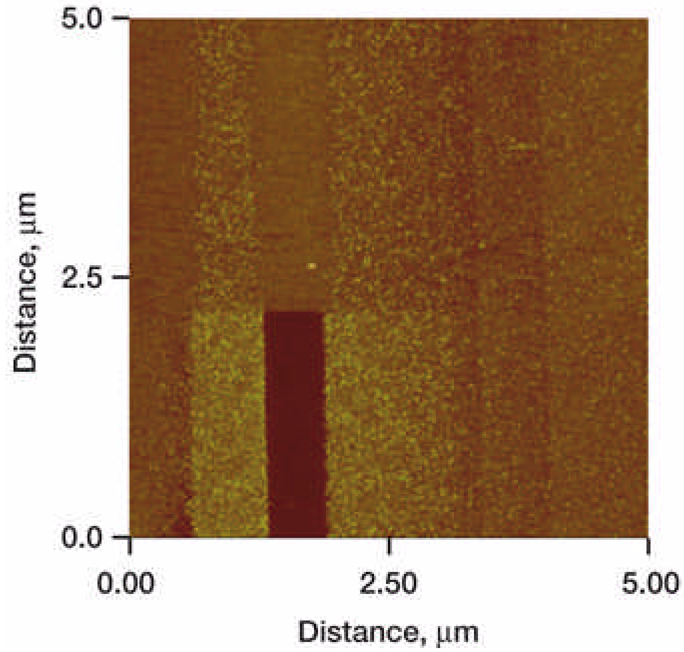


Left: Schematic of STORM setup. STM, scanning tunneling microscope.
Schematic showing argon pump laser, TiS tunable laser, spatial light modulator, fiber optics, vibration isolation system, lock-in amplifier, and STM controller.



Cross-sectional STM image of layered InP sample. The top half of the image has no illumination, and the bottom half is illuminated with white light.
Diagram showing layers (top to bottom) in InP sample: 3-micrometers undoped, 500-nanometers n-type, 500-nanometers undoped, 900-nanometers n-type, 50-nanometers undoped, 200-nanometers n-type, and n-type substrate.

The scanning capability of STORM was investigated at the NASA Glenn Research Center using samples grown with a number of layers with varying doping concentrations. The figure on the right shows the growth profile of the layered InP sample. The following figure shows an enhancement in the bandgap differ-ences between the individual layers when the sample was illuminated with white light. The direct-current illumination was initiated in the middle of the scan shown in this figure.



Growth profile of layered InP sample.

Other areas of investigation that will be enhanced by an increased capability to probe optoelectronic properties at the nanoscale include the combination of multiple nanomaterials in close proximity to each other. We have sought to covalently couple semiconductor quantum dots with single-wall carbon nanotubes. By taking advantage of the dangling bonds produced on the ends of the carbon nanotubes during purification of the raw soot, we can introduce organic functional groups at these sites. Standard covalent coupling techniques can then be used to create a bond between the carbon nanotube and a complementary functional group introduced on the surface of the quantum dot.

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