



Scanning Tunneling Optical Resonance Microscopy

Optoelectronic properties of semiconductors are to be probed on the nanoscale.

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Scanning tunneling optical resonance microscopy (STORM) is a method, now undergoing development, for measuring optoelectronic properties of materials and devices on the nanoscale by means of a combination of (1) traditional scanning tunneling microscopy (STM) with (2) tunable laser spectroscopy. In STORM, an STM tip probing a semiconductor is illuminated with modulated light at a wavelength in the visible-to-near-infrared range and the resulting photoenhancement of the tunneling current is measured as a function of the illuminating wavelength. The photoenhancement of tunneling current occurs when the laser photon energy is sufficient to excite charge carriers into the conduction band of the semiconductor.

Figure 1 schematically depicts a proposed STORM apparatus. The light for illuminating the semiconductor specimen at the STM would be generated by a ring laser that would be tunable across the wavelength range of interest. The laser beam would be chopped by an achromatic liquid-crystal modulator. A polarization-maintaining optical fiber would couple the light to the tip/sample junction of a commercial STM.

An STM can be operated in one of two modes: constant height or constant current. A STORM apparatus would be operated in the constant-current mode, in which the height of the tip relative to the specimen would be varied in order to keep the tunneling current constant. In this mode, a feedback control circuit adjusts the voltage applied to a piezoelectric actuator in the STM that adjusts the height of the STM tip to keep the tunneling current constant. The exponential relationship between the tunneling current and tip-to-sample distance makes it relatively easy to implement this mode of operation.

The choice of method by which the photoenhanced portion of the tunneling current would be measured depends on choice of the frequency at which the input illumination would be modulated (chopped). If the frequency of modulation were low enough (typically < 10 Hz) that the feedback circuit could respond, then the voltage applied to the piezoelectric tip-height actuator could be measured by use of a lock-in amplifier locked to the modulation (chopping) signal. However, at a high modulation frequency (typically in the kilohertz range or higher), the feed-

back circuit would be unable to respond. In this case, the photoenhanced portion of the tunneling current could be measured directly. For this purpose, the tunneling current would be passed through a precise resistor and the voltage drop would be measured by use of the lock-in amplifier.

The optimum modulation frequency can vary from specimen to specimen and with changes in the local environment. However, in general, the high-frequency approach is preferable because it affords the ability to filter out unwanted contributions to the tunneling current due to thermal effects. These effects include thermovoltage due to differential heating of the tip and specimen, thermal expansion of the tip, and thermionic emission.

To achieve the highest resolution, the STORM apparatus must be vibrationally isolated from its surroundings. The STM portion of the apparatus would be completely enclosed in a vibration-isolation chamber specifically designed to filter out low-frequency vibrations (which are particularly problematic in scanning probe microscopy), audio frequencies, and stray light. A standard Pt/Ir STM probe tip would be used to minimize ef-

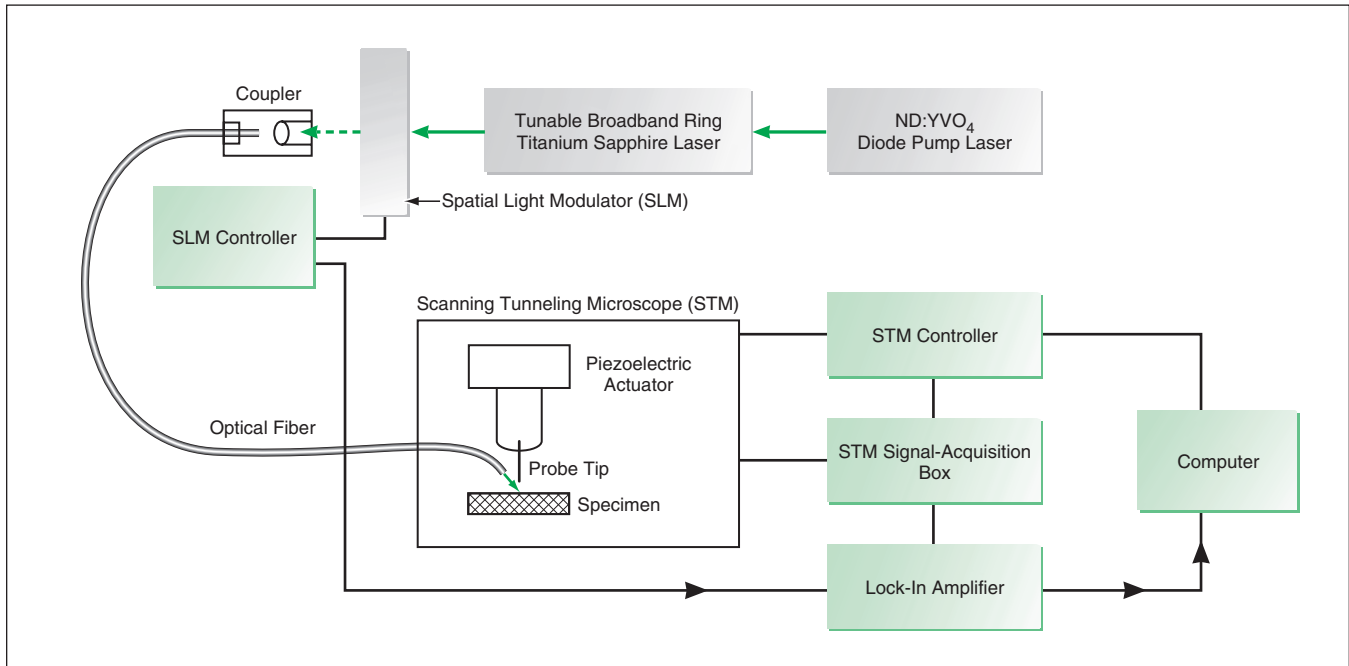


Figure 1. A STORM Apparatus would implement a combination of traditional scanning tunneling microscopy (STM) with tunable laser spectroscopy.

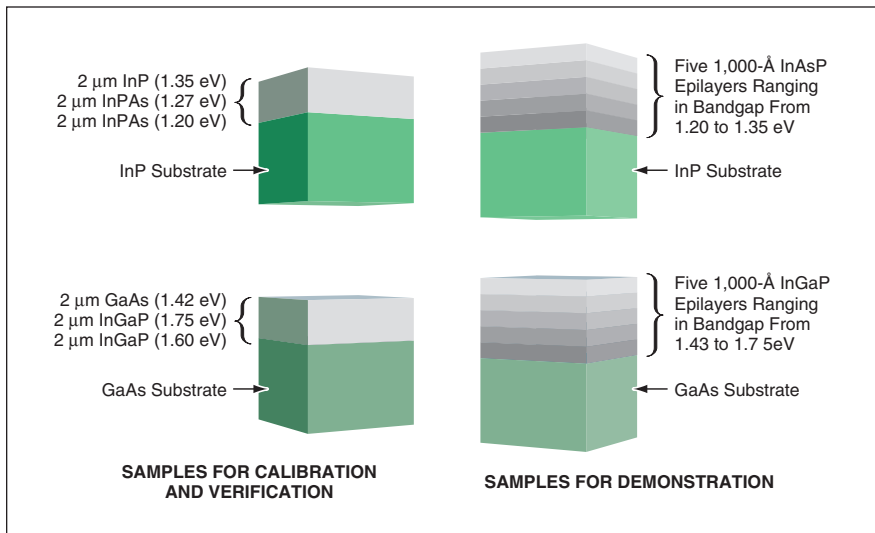


Figure 2. Heterostructures containing single and multiple III-V epilayers are to be evaluated by use of STORM.

fects of deterioration of the tip and interactions with the illumination.

Initially, in a proposed demonstration, a prototype STORM apparatus would be used to measure the local bandgaps on well-characterized metal/organic chemical-vapor-deposited epilayers composed of elements from periods III and V of the periodic table (“III-V epilayers”). $\text{InAs}_{1-x}\text{P}_x$ and $\text{In}_{1-x}\text{Ga}_x\text{P}$ can be grown with extremely precise stoichiometry so as to provide a range of bandgaps that are accessible to the wavelength range of a tunable solid-state laser included in the proposal.

In principle, the optical bandgap of $\text{InAs}_{1-x}\text{P}_x$ should vary from 0.36 to 1.35 eV and the optical bandgap of $\text{In}_{1-x}\text{Ga}_x\text{P}$ should vary from 1.35 eV to 2.27 eV as x is raised from 0 to 1. In practice, lattice mismatches make it impossible to achieve these ranges. However, it is possible to provide a set of samples having

bandgaps ranging from 1.2 to 1.75 eV. It is planned to grow initial single control epilayers of these materials (see left side of Figure 2) and characterize them by use of standard techniques. Single-crystal x-ray diffraction (and scanning electron microscopy with energy-dispersive spectroscopy) will be used to determine the stoichiometric coefficients of these samples. The relationship between the stoichiometry, lattice parameters, and optical bandgaps in these materials has already been established to a high degree of certainty. In addition, Hall-effect and four-point probe measurements will be performed to determine the electrical properties of the materials. These materials will constitute, in effect, a calibration set for initial qualification of the proposed STORM apparatus. The optical bandgaps measured by use of STORM on cleaved cross sections of the

individual epilayers will be compared to their known values.

Subsequently, the individual epilayers of the calibration set would be incorporated into multilayer heterostructures (see right side of Figure 2). The entire cross-sectional surfaces of these multilayer stacks would be scanned by STORM and the “turn-on” wavelength of each layer would be determined by the spectroscopic illumination technique of STORM. It is planned to grow several analogous structures with decreasing layer thicknesses for use in studying how the turn-on characteristics and optical bandgaps of the individual layers vary with decreasing thickness and comparing them with quantum-mechanical theoretical estimates based on the bulk properties of the materials.

It is also planned to use STORM to measure the size dependencies of the optical bandgaps of isolated nanocrystals. Two specific types of systems that will be studied are semiconducting quantum dots and high-purity single-wall carbon nanotubes. These systems are the foci of several current projects at Glenn Research Center.

This work was done by Sheila Bailey and Dave Wilt of Glenn Research Center, Ryne Raffaele and Tom Gennett of Rochester Institute of Technology, Padetha Tin of the National Center for Microgravity Research NASA GRC, and Janice Lau, Stephanie Castro, Philip Jenkins, and Dave Scheiman of Ohio Aerospace Institute. Further information is contained in a TSP (see page 1).

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland Ohio 44135. Refer to LEW-17344.



The Micro-Arcsecond Metrology Testbed

Optical-path measurements must be precise to within tens of picometers.

NASA's Jet Propulsion Laboratory, Pasadena, California

The Micro-Arcsecond Metrology (MAM) testbed is a ground-based system of optical and electronic equipment for testing components, systems, and engineering concepts for the Space Interferometer Mission (SIM) and similar future missions, in which optical interferometers will be operated in outer space. In addition, the MAM testbed is of interest in its own right as a highly precise metrological system.

The designs of the SIM interferometer and the MAM testbed reflect a requirement to measure both the position of the starlight central fringe and the change in the internal optical path of the interferometer with sufficient spatial resolution to generate astrometric data with angular resolution at the microarcsecond level. The internal path is to be measured by use of a small metrological laser beam of 1,319-nm wavelength,

whereas the position of the starlight fringe is to be estimated by use of a charge-coupled-device (CCD) image detector sampling a large concentric annular beam. For the SIM to succeed, the optical path length determined from the interferometer fringes must be tracked by the metrological subsystem to within tens of picometers, through all operational motions of an interferometer delay line and siderostats. The purpose