

# Scanning near-field optical microscopy

M. A. HERMAN\*

Institute of Vacuum Technology and Institute of Physics PAsC., Warsaw, Poland

The wealth of optical phenomena offers interesting opportunities in the world of nanometer dimensions. Many optical effects manifest themselves in a novel way if the relevant dimensions are small compared to the light wavelength [1]. Consequently, extension of optical characterization techniques into the nanometer regime seems to be an attractive possibility for nanotechnology of microelectronic structures [2]. Obviously, this is not possible by improving the conventional imaging techniques. The uncertainty principle, also known as the diffraction limit, prevents focusing on areas considerable smaller than the wavelength. This limit arises because electromagnetic waves interacting with an object to be imaged are always diffracted into two components [3]: (a) propagating waves with low spatial frequencies ( $<2/\lambda$ ), and (b) evanescent waves with high spatial frequencies ( $>2/\lambda$ ). Classical optics is concerned with the far-field regime where only the propagating waves survive whereas the evanescent waves are confined to sub-wavelength distance from the object corresponding to the near-field regime. Information about the high-spatial-frequency components of the diffracted waves is lost in the far-field regime and therefore sub-wavelength features of the object to be imaged cannot be retrieved. On the other hand, by operating a microscope in the near-field regime, the diffraction limit can easily be surpassed [3]. However, the necessary confinement of optical radiation fields can only be achieved by material structures with nanometer-sized dimensions, such as small apertures or slits, in the immediate vicinity of the object to be investigated. Although the possibility of near-field imaging had been recognized long ago, systematic investigations began only in the past decade [1].

In the first scanning near-field optical microscope (SNOM) a tiny aperture, illuminated by a laser beam from the rear side, was scanned across a sample surface, and the intensity of the light transmitted through

the sample was recorded. This arrangement, called aperture SNOM (a-SNOM), which is still the most popular one, provides the best-defined images with highest resolution is schematically shown in Fig.1, after Ref.4. To achieve a high lateral resolution, for example in the order of 25 nm ( $\lambda/20$ ), the aperture diameter has to be of nanometer size, and the aperture has to be maintained at a distance of less than 10 nm from the sample surface. The latter requirement arises because at increasing distance  $s$  from the aperture, the evanescent waves are damped out rapidly and the field intensity  $I$  decreases strongly according to the fourth power dependence of the field intensity on distance ( $I \sim s^{-4}$ ). This dependence, valid in the near-field regime, is in contrast to the adequate behavior in the far-field regime where the field intensity decreases quadratically with distance. Vacuum tunneling between a tiny metallic asperity at the foremost end of the aperture probe and the object to be studied was initially used as a servomechanism to maintain the optical probe in close proximity to the sample without actually touching it. Alternatively, the force interaction can be exploited as a servomechanism [4].

The optical probes of an a-SNOM system are usually formed by a sharpened glass or fiber tip coated with a thin metallic layer, leaving a sub-micrometer aperture at the apex [5–7]. As an alternative to glass or fiber tips, sharpened micropipettes coated with a thin metallic layer can serve as optical probes as well [3]. The micropipette apertures can either be illuminated from the rear side by a laser beam, acting as a light source, or they can be used as collectors for radiation from a small area of the sample which itself is illuminated as a whole. The experimental set-up for this "collection mode" SNOM (c-SNOM) is schematically illustrated in Fig. 2.

Another popular SNOM implementation is based on the tapping of an evanescent wave by an uncoated transparent tip [1]. The principle of operation is strongly analogous to that of the electron scanning tunneling microscope (STM), therefore, this arrangement is known as photon STM (PSTM). A sharpened optical-fiber tip probes the evanescent field above a dielectric

\* corresponding author: Institute of Vacuum Technology, 44/50 Długa Str., PL-00-241 Warszawa, Poland, phone: (+48)(22) 831-51-54, fax: (+48)(22) 831-21-60, e-mail: herman@alpha1.ifpan.edu.pl

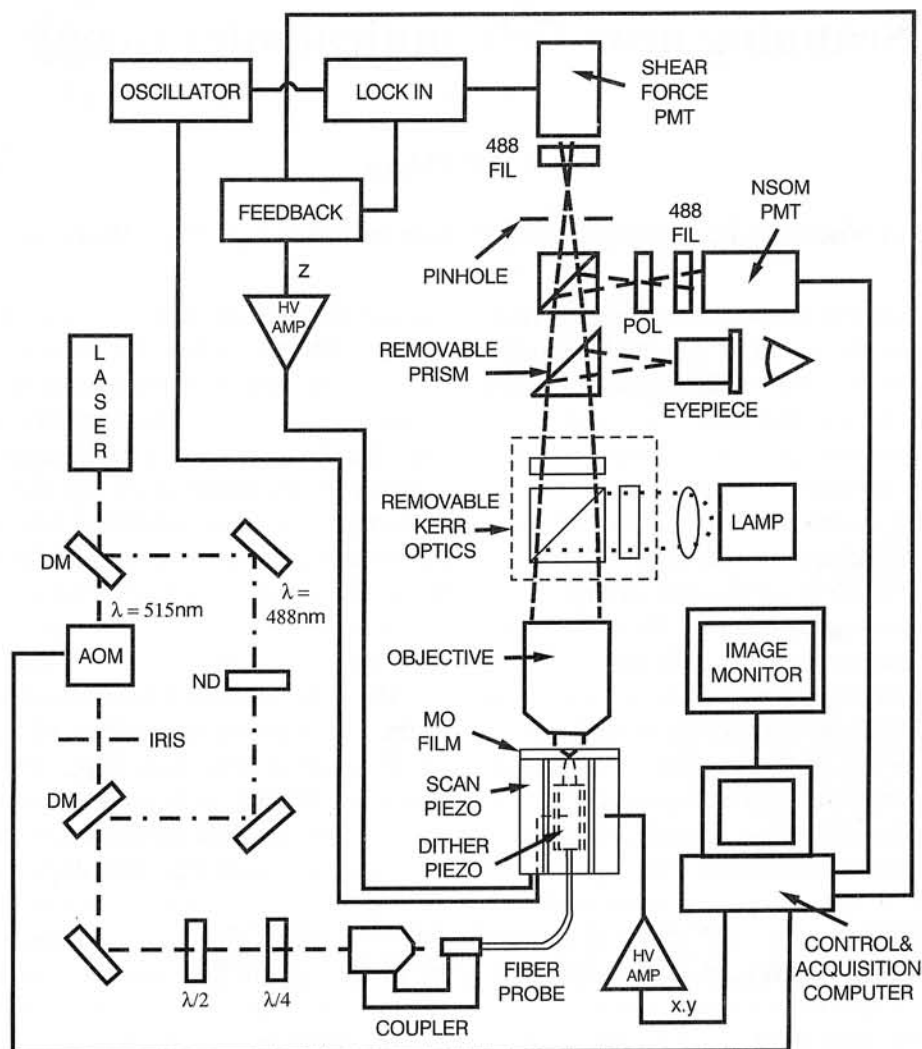


Fig. 1 Schematic of the system used for scanning near-field optical imaging and recording (after Ref. 4).

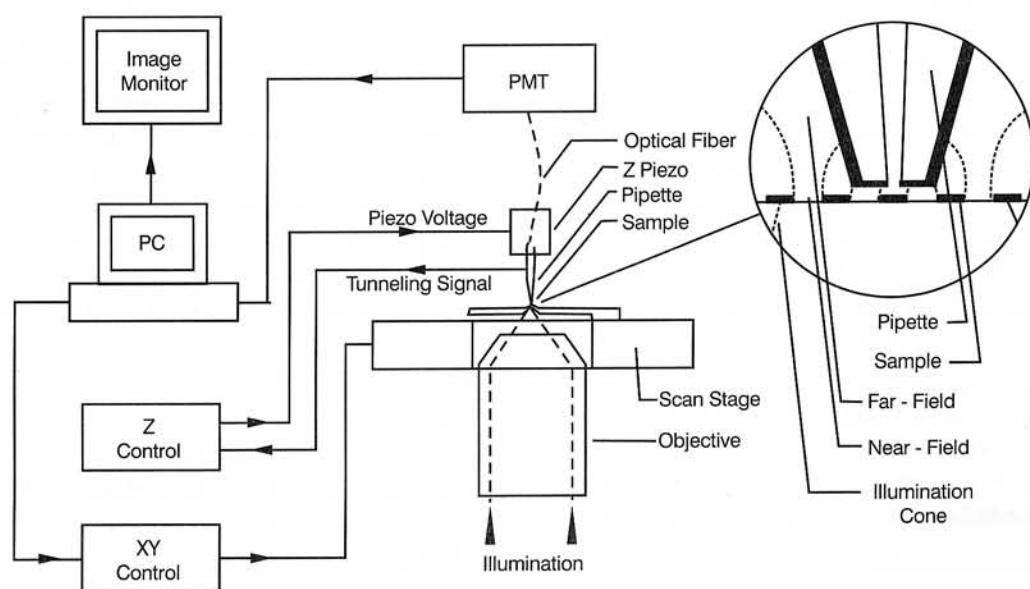


Fig. 2. A schematic diagram of an instrument used for c-SNOM (left side), and an expanded view of the light transmitted through a sample being collected in the near-field by an aperture (right side) (after Ref. 3).

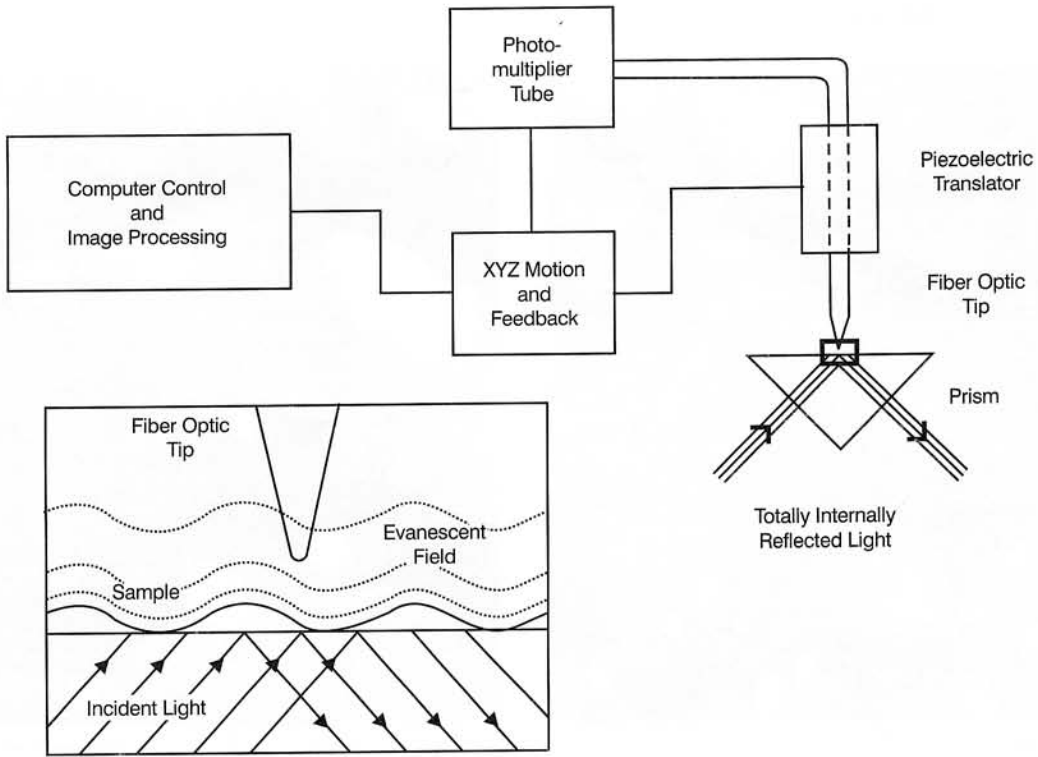


Fig. 3. Schematic diagram of the PSTM principle. The tip probes the sample-modulated evanescent field produced by an internally reflected light beam (after Ref. 3).

in which total internal reflection (TIR) is made to occur. As shown in Fig.3, the sample is placed on or forms the TIR surface and spatially modulates the evanescent field. The tunneling of photons to the tip end of the optical fiber is detected by a photomultiplier tube connected to the other end of the fiber, while the object surface is scanned relative to the tip by means of a piezo-stage. Constant intensity or constant height imaging can be performed similarly to STM [3]. SNOM and PSTM can be performed in reflection, as well as in transmission, the last one being of much larger practical importance. It can also be combined with all techniques known in classical optical microscopy including the investigation of luminescence and polarization as well as phase contrast [3].

SNOM, with its spatial resolution much better than the diffraction limit, is ideally suited for the optical investigation of inhomogeneous semiconductor structures on a lateral scale of about 100 nm. In such systems, different sizes of the structures result in different optical transition energies, which result in inhomogeneous broadening in conventional photoluminescence spectroscopy. Spatial resolved photoluminescence (SRPL) experiments, which may be performed with c-SNOM, allow, in contrast, a detailed investigation of individual structures [8]. In this field, quantum dots are interesting candidates because of

their discrete electronic energy levels, which should result in extremely narrow photoluminescence lines [9]. On the other hand, the self-organized growth of such dots [10] usually yields a size distribution, so that spatially averaging PL experiments result in inhomogeneously broadened transition lines, while SRPL experiments, in contrast, allow to study the specific spectroscopic characteristics of only a few or even of single dots. Fig.4 shows the topography of the self-organized  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$  quantum dots embedded in a GaAs matrix together with the simultaneously SNOM measured SRPL image [9]. In the topography small bumps 100-200 nm in diameter and about 3 nm in height are observed. They are more or less randomly distributed, and their dimensions and surface density (in the order of 5 bumps/ $\mu\text{m}^2$ ) are in agreement with transmission electron microscopic measurements performed on the same sample. The high signal variations in the corresponding overall SRPL image are directly correlated with the dot positions. Because of the lateral resolution in the SRPL better than 300 nm, the PL peaks can be assigned to groups of a few dots or to single dots. The small displacement between topography and SRPL features is assigned to an asymmetry of the SNOM tip apex [9].

In the past five-six years, SNOM has gained increasing attention in the field of characterization proce-

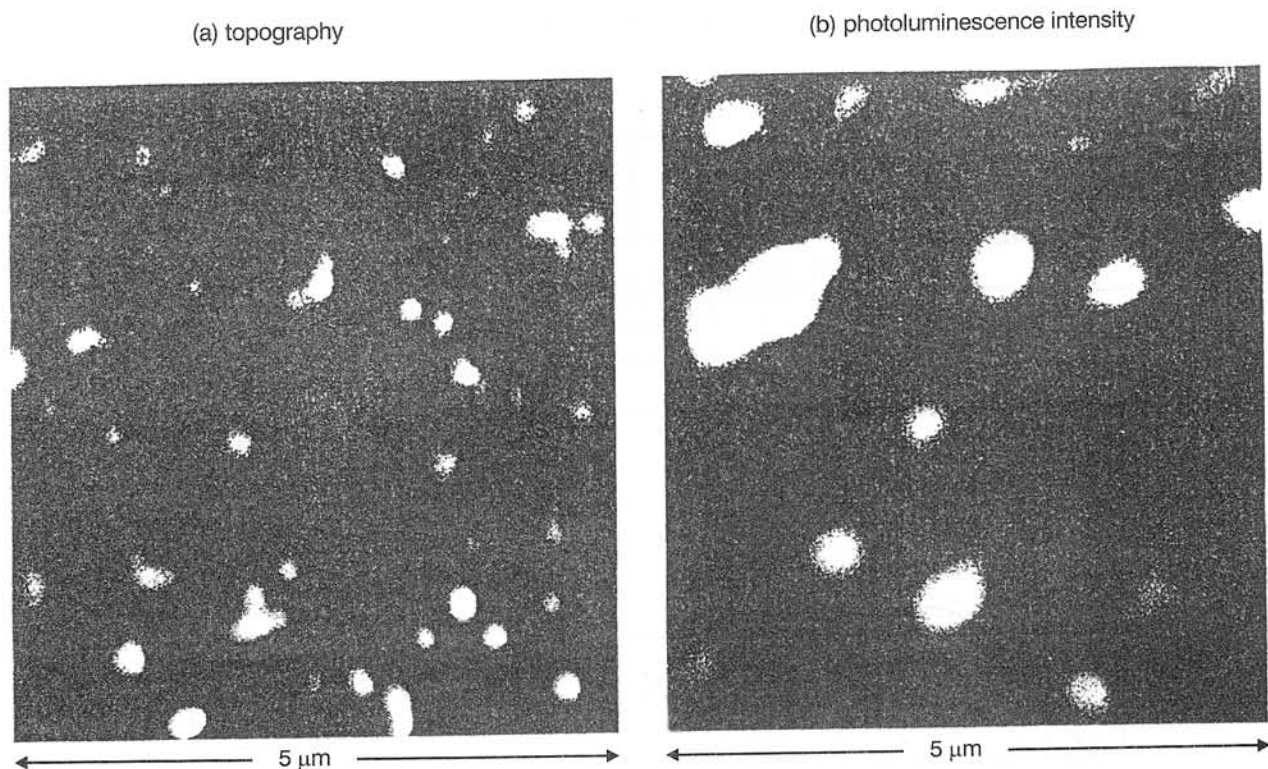


Fig. 4. SNOM imaging topography of the self-organized  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$  quantum dots embedded in a GaAs matrix (a) and the simultaneously measured, at 300 K, SRPL image (b) in top view (after Ref. 9).

dures of nano-scale objects. Besides the above described schemes, a number of others have been demonstrated [2]. It is worth to be mentioned, that near-field optical microscopy, in contrast to scanning tunneling (STM) or atomic force (AFM) microscopies, has resulted in a number of quite different implementations [1].

## References

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