# NEAR-FIELD PHOTOLUMINESCENCE AS HIGH RESOLUTION DIAGNOSTICS OF SEMICONDUCTOR STRUCTURES

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## ABSTRACT

Scanning Near-field Optical Microscope, in which an uncoated single-mode fiber tip is used both as nanosource to excite the semiconductor sample and as nanoprobe to investigate characteristics of the structure and to pick up the photoluminescence (PL) reflected from the sample, is applied for the diagnostics of the defects in semiconductor devices. Using the high lateral resolution of the microscope with fast micro-photoluminiscence response, it is possible to locate non-luminescence defects in a multiple quantum well grown by molecular beam epitaxy. Near-field characteristics of measured spectral PL intensity are also discussed.

## KEY WORDS

Scanning near-field optical microscope, photoluminescence, quantum well structure, spectral photoluminescence intensity, subwavelength resolution

## INTRODUCTION

It has been shown [1] that the reflection scanning near-field optical microscopy (r-SNOM) can be applied in spatially resoluted local photoluminescence (PL) measurements. Primary reasons [2] for such work were to study the spectroscopy of low dimensional quantum structures such as quantum wires, quantum dots, etc. These applications require a very high spatial resolution and low temperature PL system. Therefore, it is principal to use a metallized fiber tip with a well defined small aperture at the fiber apex (end of the sharpened fiber probe). Subwavelength resolution in PL measurements has been reported by different groups [3, 4].

The purpose of the current work is to report a simple and cheep setup, easy to use, of high resolution photoluminescence system for general diagnostics of semiconductor devices. For this purpose, we have designed a room temperature micro-PL system using an uncoated fiber tip. The main part of the setup is based on the hybrid mode r-SNOM, in which the fiber tip serves as a nanosource for illumination of the sample surface or for excitation of local PL, and for collection of the reflected light from the sample and/or the reflected photoluminescence, which is normally very difficult to implement in the scheme with metallized fiber. In the microscope with metallized probe, there is a power limitation in delivering excitation light to 2 mW approximately because of the ohmic heating in the tip [5] and because of the excitation of the surface polaritons on the metal cladding and the degradation of the received signal [6].

In the proposed setup, however, one can deliver high power excitation light to the surface, because minimal mode conversion loss occurs and substantial power reaches the tip if the taper is sufficiently tailored [7, 8]. Moreover, the designed setup has very high PL collection efficiency even though it has poorer spatial resolution than that of using metallized fiber probe tip. Therefore, the optical arrangement and luminescence processing electronics can be greatly simplified.

Using this technique one can identify defects in a molecular beam epitaxy grown GaAs/AlGaAs multiple quantum well (MQW) structure, which are unintentionally introduced during the fabrication process due to incomplete fabrication environments and/or improper substrate preparation.

## EXPERIMENT

The experimental setup is shown in Fig.1.

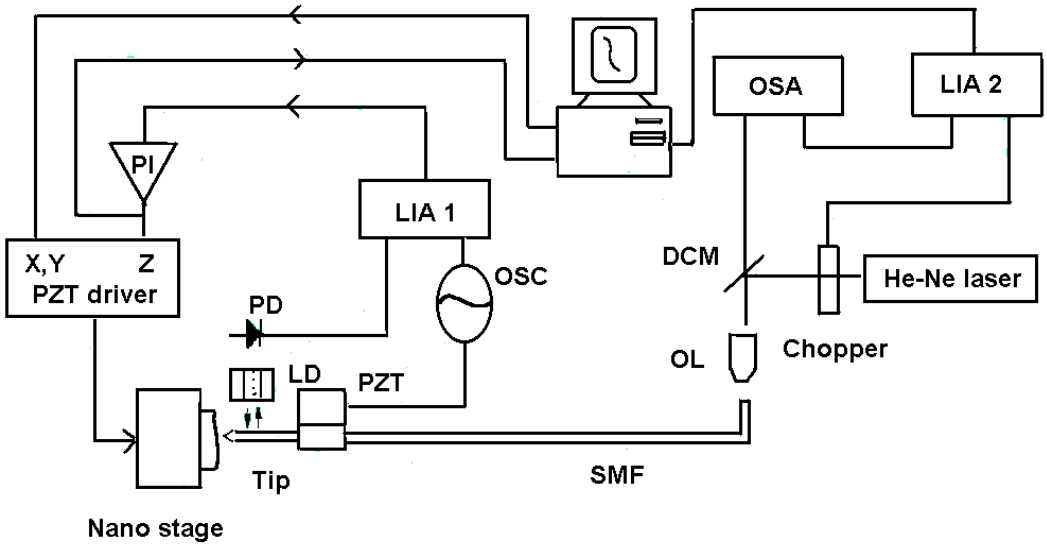


Fig.1. Experimental set-up.

The fiber tip probe used in the experiments was fabricated from the single mode fiber by the pulling method and/or by the selective chemical etching. The diameter in apex (extremity of the fiber tip) [8] was typically in the range of 50 - 100 nm. The microscope operated in the hybrid illumination-collection mode . The light form the fiber was collected, after the reflection on the sample surface, by the same fiber. But the distance control of the microscope has been modified. Instead of the shear-force control mechanism, we have used the intensity modulation effect in the laser diode (LD), which mainly originates from phase modulated weak feedback, to measure the amplitude of vibrating fiber tip. Using this technique we can construct a small size PL system which can also fit in a small size cryogenic chamber. As shown in the Fig. 1, small part of the laser light form the one facet of LD was reflected by the vibrating fiber tip and fed back into the LD resonator. The lasing dynamics of the LD in the presence of optical feedback is very complicated nonlinear problem. For weak feedback, however, the dynamics can be linearized. It can be shown that the output light from the other facet of the other facet is sinusoidally modulated by the vibrating tip.
The intensity modulated output beam from the other facet of the LD was monitored by a photodiode and the signal from the photodiode was synchronously detected using a lock-in

amplifier. After a proportional and integral operation, the output signal from the amplifier was fed back into the *z*-axis control port of the three-axis nanopositioning piezoelectric flexure stage (Physik Instrumente 517.3LC) with capacitive sensor, in which the MQW sample was mounted. The distance between the tip and sample surface was regulated by closed feedback control loop. *x* and *y* control ports of the nanopositioning stage were interfaced to the computer to scan the MQW sample. The control signal for the distance regulation was stored in the computer while the surface was scanning. Topography of the surface was retrieved from the distance regulation data stored in the computer.

The excitation light for the PL is delivered to the MQW sample using the optical arrangement shown in fig. 1. Light form 5 mW He-Ne laser was reflected by the dichroic mirror with high reflectance at 632,8 nm and wide band transmittance for PL light, and launched into the single mode fiber with tip. The distance between the apex and sample was maintained at 10 nm by the constant current mode mechanism. The PL light reflected from the MQW sample was picked up by the same fiber and sent back through the dichroic mirror to the PL processing unit - optical spectrophotometer. Most of residual excitation light was reflected on this mirror. We have used the spectrophotometer for two purposes: to take the micro-PL spectrum at any specific point on the sample and narrow band detection of spectral PL intensity while the sample was scanning. In the latter case, we set the spectrophotometer in the 0 nm sweep mode and the magnitude of the narrow band spectral PL intensity was measured by the built-in photodiode in the spectrophotometer. The center frequency of the spectrophotometer was 840 nm, at which the PL spectrum for the MQW used in this study has its peak intensity. The bandwidth for the spectral PL intensity measurement was adjusted to be 10 nm, which is narrow enough to identify defects in MQW sample, since the full width half maximum of the typical PL spectrum is 30 nm approx. Excitation light was intensity modulated by using an optical chopper, and the output photoelectric signal from the spectrophotometer was synchronously detected using lock-in amplifier. In this way, we are able to obtain both the maps of spectral PL intensity and topography of the MQW sample. The signal of spectral PL intensity picked up by the fiber tip is sufficiently large to reduce the scanning time significantly. In our current arrangement, scanning time was only limited by the time delay in data communications between two lock-in amplifier and computer. The total data acquisition time for each data point was 20 mn aprox.

Spectral PL intensity and the corresponding topography maps ware taken in various regions of the sample. Spectral PL intensity may vary because of: (a) PL peak shift due to inhomogeneity of MQW and (b) local defects caused by improper fabrication. Therefore, if there was a significant spectral PL intensity change during the scanning, we moved the probe to that specific point and obtained the PL spectrum to identify the defect. In this way, we are able to locate non-luminescent defects in our MQW sample.

## RESULTS

The non-luminescent defects observed in our experiments have a strong correlation with the topographic structure of the surface as expected. It is interesting to note, however, that there are some non-luminescent defects which do not show any correlation with the surface topography. A map of spectral PL intensities of the region which contains the topography independent non-luminescent defect and the corresponding surface topography map are shown in Fig. 2a and 2b, respectively. In the map of spectral PL intensity, the lighter shade represents the higher intensity, while the lighter shade in the topography map represents the higher topography.

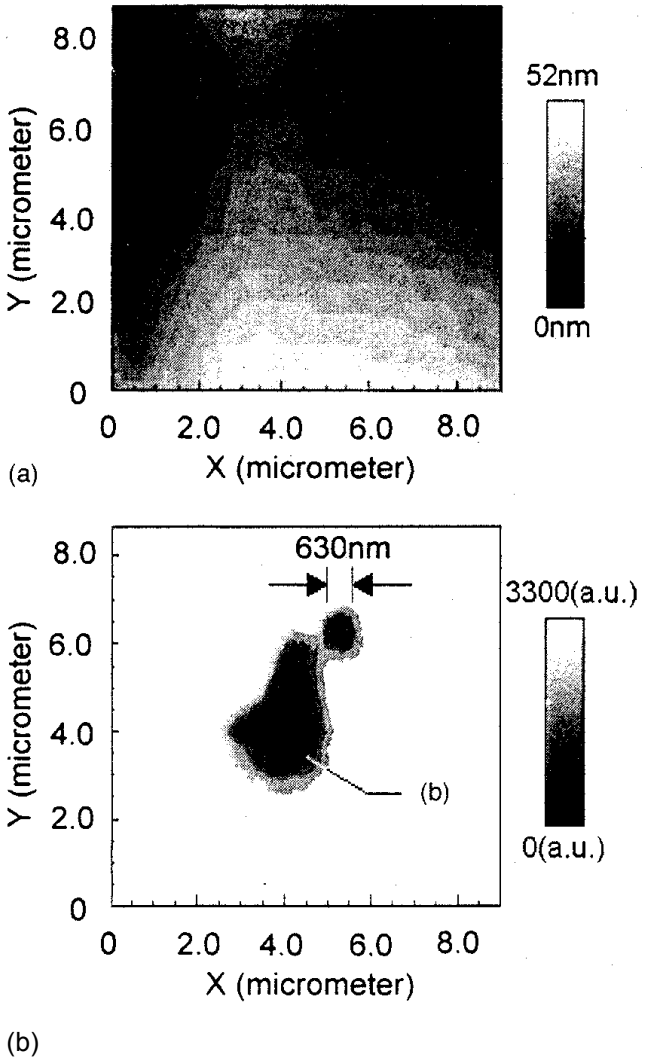


Fig 2.: (a) Spectral PL intensity map of the topography independent non-luminescent defect, (b) Corresponding surface topography map

The PL spectrum at the point specified as (a) in the lightly shaded region in Fig. 2a is shown in Fig. 3a, in which the PL peak occurs at 840 nm. The PL spectrum at point (b) in Fig. 2b is shown in Fig. 3b. Neither a significant shift in PL peak nor a broadening of spectral width has been observed in this room temperature measurement. No evidence of PL from the MQW was observed in the black region in Fig. 2a. Moreover, we cannot observe any sign of PL from GaAs or AlGaAs. From these results we can conclude, that two black images in Fig. 2a represent topography independent non-luminescent defects. In general, to the best of our knowledge, defects caused by improper growth processes, gallium droplets for example, play an important role in roughness formation and we believe they result in topography dependant non-luminescent defects. At the present time, we do not know exactly the growth mechanism for the topography independent non-luminescent defects. However, we believe these defects originated from improper fabrication processes since subsequent diagnostics using a transmission electron microscopy indicate the primary constituent of defects are Ga and Mo.

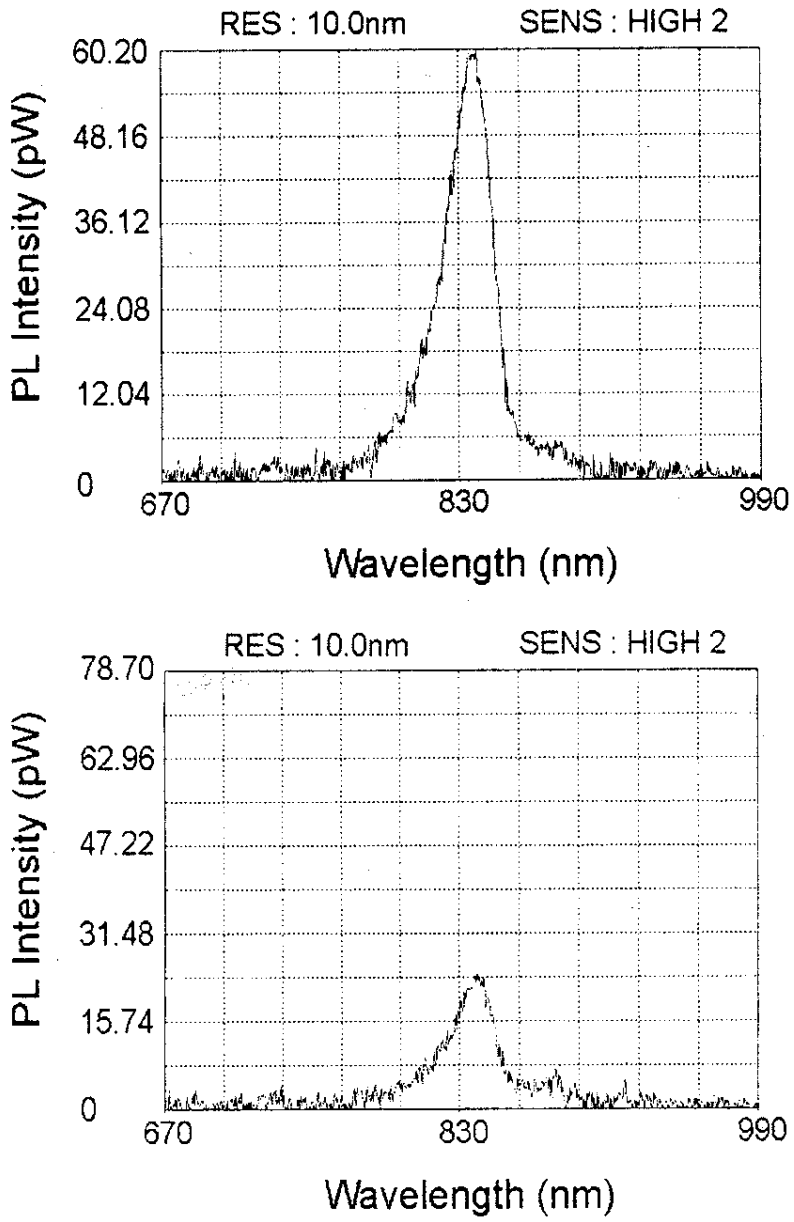


Fig.3.: PL spectrum at the point (a) in Fig. 2a (above) and (b) at the point (b).

The MQW samples used in this experiment were not designed to study absolute spatial resolution for the PL measurement, and we do not intend to discuss the resolution in detail. However, we would like to briefly mention the near-field contributions in spectral PL intensity signal since we have experimental results which cannot be explained by the far-field model [9]. One can use their geometrical configuration for the reflection measurements to analyze far-field contributions in exciting and collecting PL from each luminescent quantum well layer. In our calculation, the sub-sequential absorption of excitation light in the barrier and well layer of the MQW sample were taken into account. The far-field model can be modified for the PL measurements as

$$I_s \propto \sum_{m=1}^{M} \frac{R_s D^2 \{\exp[-m\alpha_b d_b - (m-1)\alpha_w d_w]\}}{\{D + 4[H + h + md_b + (m-1)d_w tg\,\theta]\}^2} \qquad (1)$$

where $d$ represents the thickness and $\alpha$ the absorption coefficient for excitation light. In Eq. (1), the subscripts $b$ and $w$ stand for barrier and well layer, respectively, $M$ is a number of layers in MQW structure, and $D$, $H$, $R$ and $h$ have the same meaning as used in [9].

Spectral PL intensity has been measured as a function of tip-surface distance $h$. The result is shown in Fig. 4. The dotted line in Fig. 4 is the theoretical fit based on Eq. (1). As one can see in Fig. 4, the experimental result fits very well to the far-field model for a relatively large tip-sample separation. The far-field model, on the other hand, cannot explain the rapid increase in spectral PL intensity with decreasing tip-sample distance in the range less than 200 nm. These short range spectral PL intensity characteristics may be explain qualitatively by introducing near-field contributions to the excitation and PL light. The near-field component of the excitation light at the uncoated fiber tip transfers into propagating waves by the presence of the MQW surface, and plays a major role in the generating carriers. The tip can collect up near-field components of radiating dipoles in the quantum well layer, because they are very close together. In addition, one can measure the near-field effects very efficiently in this set-up, because the corresponding wavelength of the strong excitation light and weak luminescence possess different values, and hence interferes caused by stray reflections of the excitation light were eliminated.

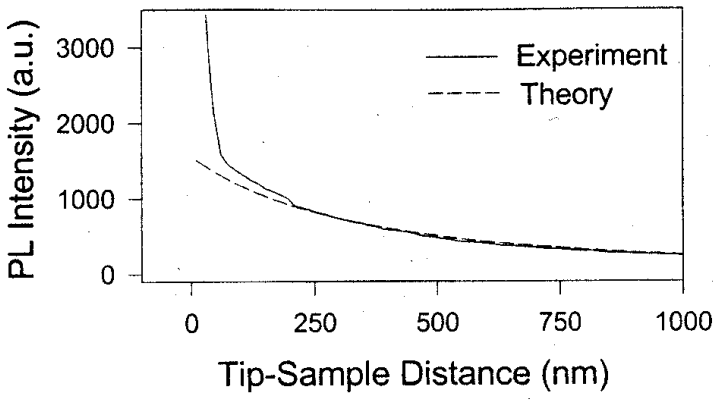


Fig.4.: Spectral PL intensity as a function of tip-sample distance $h$.

## CONCLUSION

In summary, a near-field micro photoluminescence system using uncoated fiber tip has been presented. Using this technique, we are able to identify the non-luminescence defects as small as 630 nm in the sample of multiple quantum well structure. In theory, this resolution can be obtained in the far-field photoluminescence system. In practice, however, it requires a very sophisticated imaging system to obtain diffraction limited resolution. The sample used in this preliminary research is not appropriate for drawing conclusion about the spatial resolution. Nevertheless, we believe, however, that the lateral spatial resolution of this system could be better, because we have seen a significant near-field contribution in the spectral photoluminescence intensity signal.

## ACKNOWLEDGMENTS

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