Development of a Micro Photoluminescence Measurement System for the Inspection of $GaAs/GaAs_{1-x}P_x$

Mu-Chiau Xie, Fang-Jung Shiou, Geo-Ry Tang, Shui-Fa Chuang*

National Taiwan University of Science and Technology

Department of Mechanical Engineering

shiou@mail.ntust.edu.tw

Abstract - This article mainly focuses on the spectrum measurement of the LED semi-conductor material $GaAs/GaAs_{1-x}P_x$, using Photoluminescence (PL) method, by integrating the optical path design, the mechanism design, the motion control, the image processing, and the positioning technology to accomplish the development of automatic measurement system. The innovative method of μ-PL is proposed in the optical path design. A microscope was used to focus the laser light to a tiny area and by enhancing the strength of laser light unit to increase the sensitivity of the luminescence. In the past, the examination of PL was used to do the image positioning and to collect the luminescence manually in two different platforms. This system design integrates these two light path systems, PL and image positioning, as one machine. So image positioning and luminescence measurement can be done in one machine simultaneously to save manpower and avoid the positioning error due to transporting the machine.

Keywords – Photoluminescence(PL), $GaAs/GaAs_{1-x}P_x$

I. INTRODUCTION

LED (Light Emitting Diode) is extensively being used in all kinds of lighting, such as LCD backlight, traffic light signal, display board, general lighting devices, car lighting devices, etc. It has the advantages of long life, small size, quick response, energy saving, and anti-vibration. In promoting energy saving and environmental protection, LED can be viewed as the next generation of lighting that can replace traditional fluorescent light. In recent years, with the rising of global environmental protection and energy saving concept and the support of the governmental policies, the LED industry has been up and coming. Many manufacturers have pitched into this industry, from the lithography process of the up-stream, the manufacture of the bare dies of the mid-stream, to the IC packaging of the down-stream, to complete an industrial chain.

With the fast growing of LED industry and manufacturing technology, many metrological techniques have been developed to increase the yield and improve the reliability on the production. Traditionally, there were many techniques for examine the semi-conductor components; for example, scanning electron microscope and electron beam pulse. However, these have been limited to the resolution and have the problem of damaging the components. Since the invention of laser, it has replaced the stimulation of the original electron beam pulse. The non-intruding measuring characteristic allows the samples have the minimum damage rate. Among all the measuring technologies of semi-conductor components' optics characteristics, common methods using laser as the stimulation source are Photoluminescence (PL) and Electroluminescence (EL), etc. This article will focus on the light path modification of Photoluminescence (PL). The measuring samples are GaAs/GaAsP quantum well structure. The material proportions involved would affect the characteristics of luminescence [1]. This article mainly focuses on the measurement system design and the correctness of the results.

II. PRINCIPLE

PL is a simple, reliable non-destructive measuring technology. An appropriate light source was selected to project onto the to-be-measured samples to stimulate the luminescence collected by a spectroscope. The information of the optical spectrum of the test specimens can then be investigated and displayed on the computer. By studying and analyzing the spectrum information, we can learn the material characteristics and defects of the samples. The stimulation principle is that when the light source projects on the to-be-measured samples, the energy of the light source we choose is higher than the energy gap of the samples. The electrons inside the samples would leap to high energy level and generate an electron-hole pair. This electron-hole pair will combine again by two different ways: radiated coupling and non-radiated coupling.

If the electron-hole pair is combined by non-radiated coupling, the energy is likely to disappear in the form of phonon or heat. If the electron-hole pair is combined by radiated coupling, the electrons that are to be leaped to high energy level in extremely short time will be released by phonon or lower to the lowest energy level of the conduction band by electron collision. Then the electron-hole pair can re-combine by several different paths and release photon, which we call it luminescence [2, 3], as shown in Fig. 1.

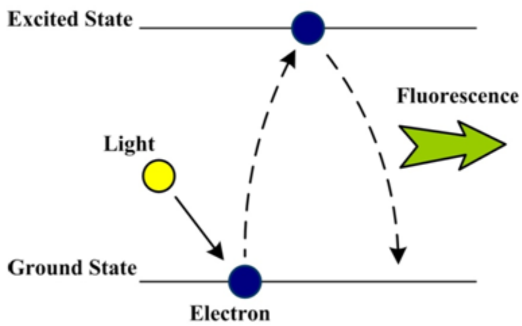

Fig. 1 Schematic diagram of PL principle

Energy gap is an important parameter in semi-conductor. It directly affects the lighting color of LED. Which laser wavelength should be selected and the wave tip position of the luminescence spectrum are all related with the energy gap of the sample. In order to select the appropriate laser to be the stimulation light source, we must calculate the size of the energy gap corresponds to the laser wavelength. The commonly used stimulation light sources are He-Cd Laser, Ar-ion Laser, and Green light laser. Generally, the wavelength closer to the blue light has the larger the laser energy gap and wider stimulation range of semi-conductor energy gap. The experiment quality would be better with higher price. In consideration of the budget and the effectiveness, this experiment adopted the green light laser with wavelength of 532 nm. Based on the conversion formula of energy gap and wavelength,

$$E_g = \frac{1240}{\lambda}(eV), \tag{1}$$

we get the energy gap of 2.33 eV of this laser. Most of the common used LED materials are smaller than this energy gap.

III. SYSTEM STRUCTURE

The developed measurement system mainly includes several optics components and motion platforms. The optics components include laser, spectroscope, bandpass filter, long wave pass filter (LWP filter), lens, mirrors, microscopy objective, beam splitter, CCD camera, etc.

Spectroscope is a scientific instrument that can analyse complicate light into spectrum line. After chromatic dispersion by gratings, a CCD light sensor array was used to detect the light intensity of different wavelength position. Spectroscope can be used to measure faint luminescence. The calibration results of the used spectroscope wavelength are as shown in the line chart (Fig. 2). The biggest different wavelength after calibration was 0.3nm. A Bandpass Filter was adopted to filter out the light beyond 532nm to get a pure laser single wavelength. A LWP Filter is the optical component that can filter out the light smaller than the cut-on wavelength. There are two LWP filters used in the developed system for filtrating laser light.

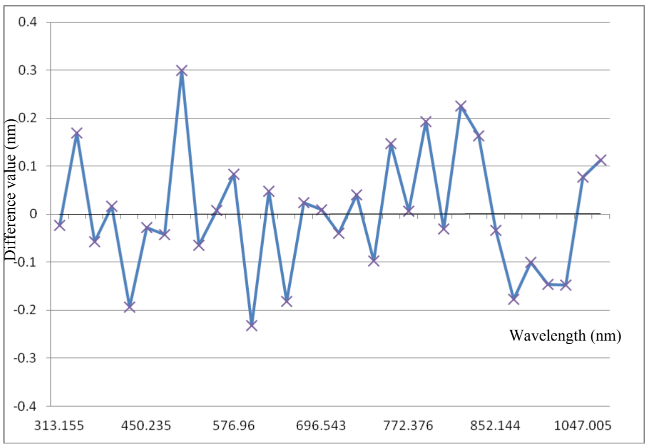

Fig. 2 Calibration results of the used spectroscope

Laser is used as the stimulation light source of photoluminescence. The energy gap must be larger than that of the sample material to be tested. Normally, the laser wavelength between green light and blue light is used. The green light laser with 532nm wave length was adopted in this study. A microscopy objective is used to focus laser beam and to collect luminescence. This system uses an objective lens with the magnification ratio of five to minimize the laser light spot below 300μm through microscope technology. The used CCD Camera has the spatial resolution of 1280 x 960 pixels equipped with zoom lens and extension ring for the camera to acquire sample image. The imaging principle is the same as the microscope system: it can receive upside down enlarged virtual image. A lens has been installed in front of the spectroscope to focus the luminescence into the optical fiber and then pass to the spectroscope from the optical fiber. For the purpose of doing photoluminescence along the same optical axis and gaining the image, a beamsplitter is needed in the optical path to realize light splitting effect. A special designed mirror with a hole of 7 mm in diameter in the middle is used in this system. This hole allows laser to pass through. Furthermore, the reflective side of the mirror, which is a very important component in the light path, can reflect the luminescence, as shown in Fig. 3. The two-axis motion platform for positioning adopts five-phase stepper motor with a travel of 120 mm. A set of software programmed with NI-Lab VIEW is for integrating images and controlling the motor.

The interactive relationship between the components and the light path is shown in Fig. 4. When taking image and automatic positioning, the laser is shut and the circular light source is open. Sample image can pass through the hole in the middle of the mirror from Microscopy Objective. Then reflecting from the Beamsplitter, passing the Long Wave Pass Filter to filter out laser light, and finally form an image on CCD Camera chip through zoom lens, to transfer the image to the computer. When doing photoluminescence, the circular light is shut and the laser is open. The laser beam first passes through Bandpass Filter to filter out useless wavelength. Then, focus through Microscopy Objective onto the sample. The luminescence was stimulated from the sample, which passes through Microscopy Objective, then reflects onto the lens from the reflection of the mirror. The luminescence goes through Long Wave Pass Filter to filter out laser light, focuses on optical fiber, and then transits to the spectrum by optical fiber. Finally, the spectrum data of the luminescence is transmitted to the computer. The 3D model of the developed system is shown in Fig. 5. After setting up the system, the whole system will be packed into a black box to avoid the possible influence of the environmental light while measuring.

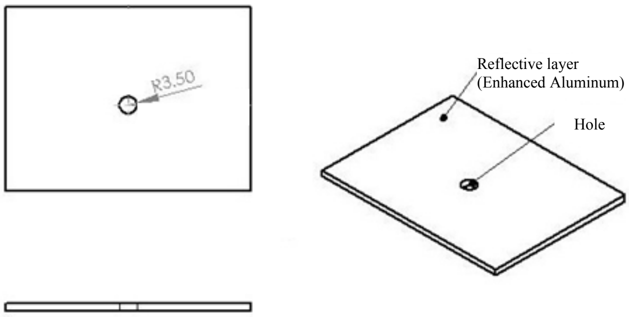

Fig. 3 Schematic diagram of the mirror with a hole

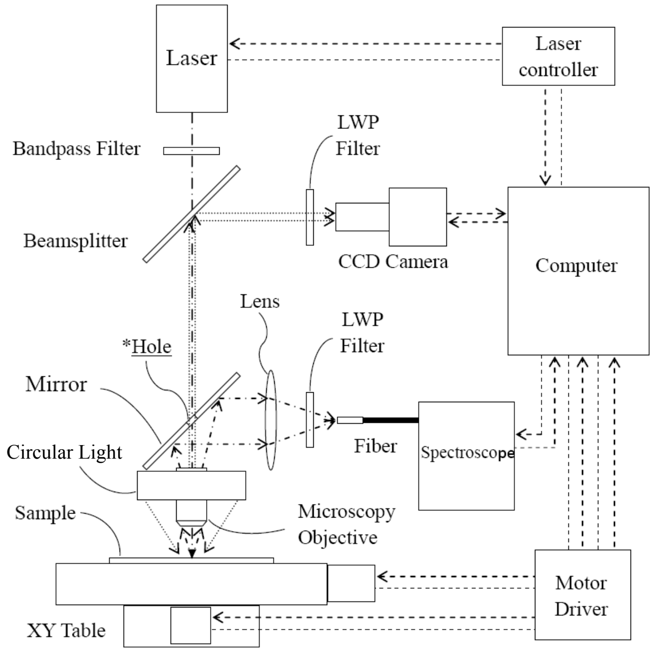

Fig. 4 Schematic diagram of the developed system

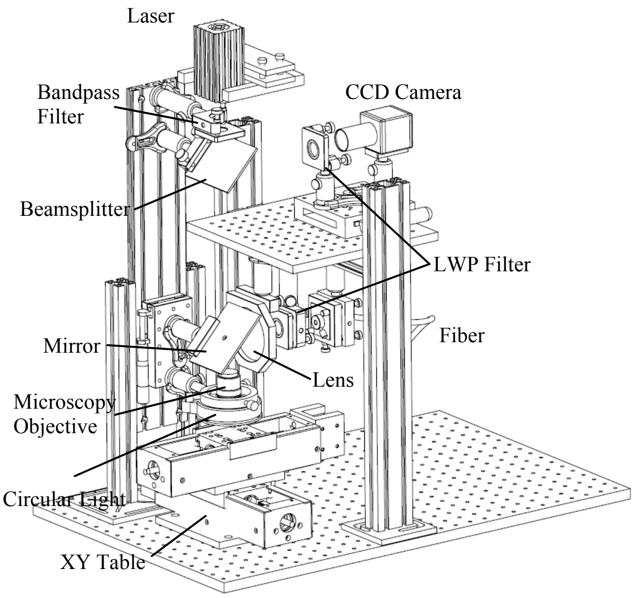

Fig. 5 Schematic diagram of the measurement system design

IV. RESULT

The image principle of this system is similar to the microscope: the upside down magnifying virtual image can be seen. We take the calibration plate with tiny square lines as the sample for taking the image on the system. Fig. 6 shows the result of the image actually taken by this system. The size of each square pattern (cell) on the calibration plate is about 300 μm. The black shadows on the four corners are the parts being shielded out when the image is passing through the hole of reflecting mirror.

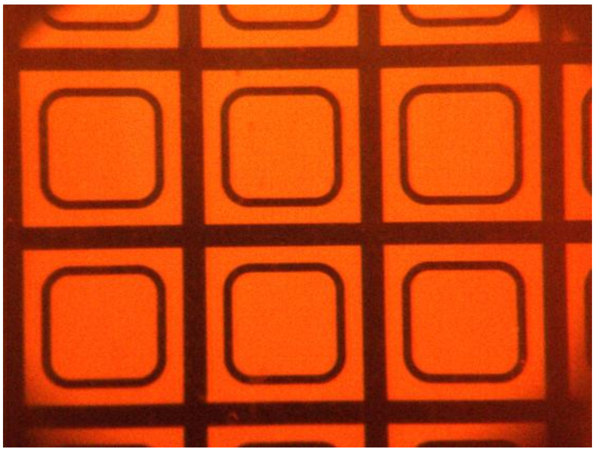

Fig. 6 Image of a calibration plate

The purpose of the developed system is to position the specimen by image acquisition, and then to measure the photoluminescence. So we need to calibrate the position from the laser spot to the image centre of each cell. Fig. 7 is the result of the laser spot after calibration. The laser spot appears in the middle of the image. What's more, you can see the laser interfering stipes on the image. The reason why there are interfering stripes is the overlapping effect of the laser incident and the reflected laser on the same spot. The reflected laser is produced by optics mirror set. The unit conversion factor is F≒1.07μm, meaning the size of each pixel is 1.07μm. The biggest Field of View (FOV) in the image is 1.37mm×1.03mm.

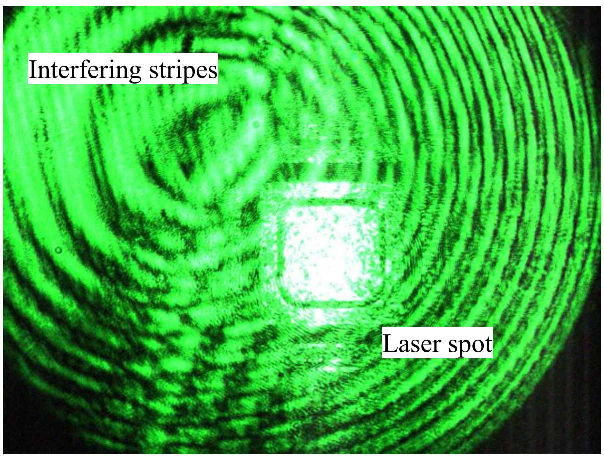

Fig. 7 Image of laser spot projected onto a cell

In order to know if the developed photoluminescence measuring system is workable, we compare the result of the same sample using traditional photoluminescence system with that of this experiment to make sure if the stimulated luminescence peak position is consistent and if the strength of the luminescence is greater.

The experiment in this article has been carried out in room temperature. The material of the sample is the $GaAs/GaAs_{1-x}P_x$ quantum well structure, where x is the material proportion and the value is 0.21, constructed by GaAs and GaP, and grown on the base plate of GaAs by MOVPE (Metal Organic Vapor Phase Epitaxy). GaAs is the main material for making red LED. The way to produce quantum well or quantum point structure in semi-conductor component can increase the efficiency and lighting strength effectively. Its material characteristic is often being studied.

Because most of the components of semi-conductor are complicated, generally multi chemical composition is used. In other words, it is composed of many different elements. For three-chemical composition semi-conductor, the empirical equation [4]

$$E_g = E_{g0} + bx + cx^2 \tag{2}$$

is used to calculate energy gap. E_{g0} is the energy gap of the main material; b and c are the parameters obtained from the experiments. To calculate the energy gap of the sample, we find out the empirical equation [5] of material $GaAs_{1-x}P_x$ proposed by Swaminathan and Macrander in 1991 can be used:

$$E_\Gamma = 1.424 + 1.172x + 0.186x^2 \,. \tag{3}$$

Substituting x into the formula, the calculated direct energy gap E_Γ is 1.678eV. The wavelength was than calculated about 738.84nm from the conversion formula (1) of the energy gap and the wavelength. The energy of the stimulated luminescence is smaller than the energy gap of the sample. The reason is that when the material absorbs the photons, part of the energy is wasted in the process of electron-hole pair re-combination. From the conversion formula of the energy gap and the wavelength we can know that the smaller the luminescence energy, the larger the wavelength. Therefore, it can be inferred that the stimulated wavelength of this sample is approximately at the position of 738.83 nm.

Fig. 8 shows the result using the traditional photoluminescence structure to measure the sample. It is clearly seen there is a protruding peak at the position of 876nm wavelength. This is the luminescence we want to measure. The strength of the peak light of the sample luminescence is about 1001. The light intensity is a relative strength (arbitrary unit, a. u.). Fig. 9 shows the spectrum measured by the developed system of the same sample. The luminescence spectrum is successfully detected under the structure. The peak position is approximately at 876nm, which is in consistency with the peak position detected under the traditional structure. As a result, the detected spectrum data is correct. Furthermore, the received luminescence intensity is 1941, 2 times the strength of the traditional structure. The strength has obviously stronger.

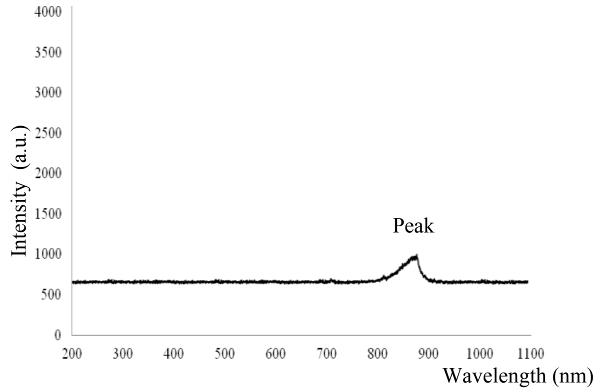

Fig. 8 The $GaAs/GaAs_{1-x}P_x$ spectrum detected by traditional PL

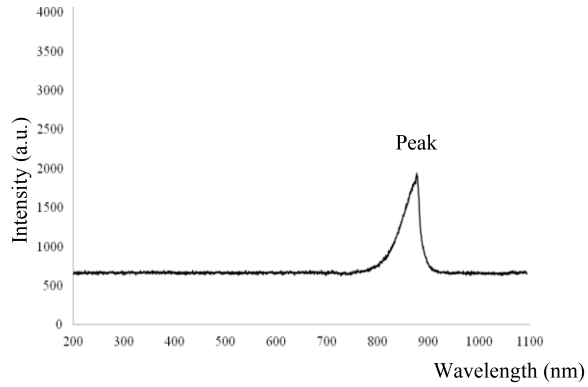

Fig. 9 The $GaAs/GaAs_{1-x}P_x$ spectrum detected by the developed system

V. CONCLUSION

Photoluminescence measuring technique is extensively used on the components of semi-conductor. All kinds of data are known by analysing the luminescence spectrum. When measuring with traditional photoluminescence, we can only observe the surface of the sample under a metallographic microscope, and then do the luminescence measurement on the photoluminescence system. As for if the laser hits on the desired position, it can be done only by feeling. This research successfully integrates the image acquisition with the photoluminescence measurement system. The experiment performer can measure the photoluminescence of the interested spot after observing the sample image without moving it.

The system has been preliminary implemented by the integration of the hardware, but still has space for further development. As for the researcher can have a deeper study on the LED semi-conductor material, a temperature control system, a wavelength adjustable laser, a vacuum sucker and vacuum chamber can be added. What's more, currently the size of this system is rather big. It could be improved from the optical path design, by adding a reflecting mirror or a splitting mirror into the image acquisition system to form the multi-reflection of the light path, to miniaturize the system.

REFERENCES

[1] Saime S. Cetin, Baris Kinaci, Tarik Asar, Ilknur Kars, Mustafa K. Ozturk, Tofig S. Mammadov, Suleyman Ozcelik, "Effect of different P/As ratio on the optical and structural properties of $GaAs_{1-x}P_x/GaAs$",

Surface and Interface Analysis, John Wiley & Sons Ltd, Chichester, (2010)1252-1256

[2] Timothy H. Gfroerer, in Encyclopedia of Analytical Chemistry edited by R.A. Meyers,"Photoluminescence in Analysis of Surfaces and Interfaces", John Wiley & Sons Ltd, Chichester, (2000) 9209-9213.

[3] I. Akasaki, H. Amano, M. Kito, K. Hiramatsu,"Photoluminescence of Mg-doped p-type GaN and electroluminescence of GaN p-n junction LED" , Journal of Luminescence, (1991) 666-670.

[4] X. H. Zhang, S. J. Chua, and W. J. Fan, "Band offsets at GaInP/AlGaInP(001) heterostructures lattice matched to GaAs" ,Applied Physics Letters, Vol. 73, (1998)1098-1100.

[5] V. Swaminathan, A. T. Macrander, Materials Aspects of GaAs and InP based Structures, Prentice Hall, Englewood Cliffs, N.J., (1991).