Image Monitoring In-situ of Alpha Particles by CR-39 Detector

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***Abstract*-Photothermal deflection is described in this article to detect the change in the thermal and optical properties of the track nuclear detector CR-39 when irradiated to alpha particles. The probe laser beam deflection was found to decrease with the increase of time of exposure to alpha particles. A novel technique, in-situ image analysis of the photothermal deflection spot is presented to assess the detection of the CR-39 to any nuclear particle or radiation instantaneously. This technique offers the ability to acquire data very rapidly and can be used for monitoring any source of nuclear radiations immediately.**

Keywords-Photothermal Deflection Sspectroscopy; CR-39; Alpha Particles; Image Processing; In-situ Monitoring

I. INTRODUCTION

Photothermal deflection spectroscopy (PDS) is an attractive optical contactless method for determining both thermal and optical parameters of the tested material. The system operates on the pump-probe technique, with pump laser is used for an initiation of the surface thermal deformation and it is chopped mechanically, while the probe laser is deflected by passing through the thermal lens. This technique, PDS, is nondestructive and contactless method and provides a higher sensitivity than transmission measurements because rather than observing small changes in a large quantity, absorption induced heating is detected directly [1]. On the other hand, the measured deflection can provide, besides thermal and optical parameters [2], with carrier transport properties such as lifetime of photo-induced free carriers [3], detailed analysis of the defect structure of thin films [4,5]. Nuclear track detector CR-39 offers many advantages to other detectors besides their low cost and simplicity in exploitation, preferred ion detector like alpha particles and insensitive to gamma and x-rays [6], dosimetric determination [7]. These detectors require long processing time and extensive chemical etching [8]. Instead of etching, scanning electron microscopy was proposed to investigate the trace of alpha particles [9]. CR-39, the solid state track nuclear detector (SSNTD) will be studied systematically in terms of the incident ions (the α-particles) for different time of exposure. An image processing of laser probe spot of PDS will be also presented as alternative method of time wasting chemical etching of the detector CR-39 when irradiated by alpha particles to demonstrate the potentiality of the recurrence signal acquisition and subsequent processing of the image. This technique will provide fast and remove the necessity of bi-cell photodiode and lock-in amplifier. Also, in this technique, time-resolved PDS measurements for thermal and optical properties can be evaluated, and to our knowledge, this is the first to be implemented. On the other hand, in-situ is a preferred technique of monitoring any source of nuclear radiation, ours will provide this ability, as demonstrated here.

II. THEORY

The pump power is periodically modulated and is absorbed by the sample. This power is converted into heat with temporal variation of temperature and result in a change of refractive index gradient. The probe laser beam will undergo a deflection due to the thermal lens formed by the index gradient. The detected photothermal deflection when passing through it will carry the surface information. The information includes thermal diffusivity, absorption coefficient, and thickness of the thin film. The PDS signal is given by [10]:

$$S = T_r\left(\frac{L}{n_o}\right)\frac{dn}{dT}\left(\frac{dT(z_o)}{dz}\right)e^{i\omega t} \tag{1}$$

where T_r is the detector transducer, $\frac{1}{n_o}\frac{dn}{dT}$ is the relative index of refraction change with temperature of the sample, ω is the angular modulated frequency, L is the interaction length, and z_o is the distance of the probe beam from the sample surface. $T(z)$ is the ac temperature rise above the average temperature in the deflecting sample. Therefore, from the measured PDS signal as a function ω, it is possible to extract the thermal properties of the sample. The temperature rise $T(z)$ can be written as [10]:

$$T(z) = Q\exp(-\sigma z) \tag{2}$$

where

$$\sigma = (1+j)(\omega/2D_{therm})^{1/2} = (1+j)/\mu_{therm} \tag{3}$$

μ_{therm} is the thermal diffusion length, and D_{therm} is the thermal diffusivity of the sample. Q is the complex temperature rise above the average temperature on the sample surface. It depends on the optical and thermal properties of the sample.

The amplitude A of the PDS signal is finally given [10]:

$$A = \frac{\sqrt{2}}{n_o}\frac{dn}{dT}\frac{L}{\mu_{therm}}\left(Q_r^2 + Q_i^2\right)^{1/2} e^{\frac{-z_o}{\mu_{therm}}} \tag{4}$$

where Q_r and Q_i are the real and imaginary parts of Q, respectively.

III. EXPERIMENT

The experimental setup is shown in Fig.1. The pump laser was CW, 300 mW diode pumped solid state laser Nd:YAG and at the second harmonic wavelength at 532 nm. This laser uniformly hits the detector CR-39 and was 4.2 cm wide to diminish lateral heat flow generated by the pump laser. The laser beam was modulated at a frequency (40.2 Hz) by mechanical optical chopper (Thorlab model MC1000) for the measurements of exposed CR-39 detectors. A Gaussian, TEM00 laser probe beam of 1 mW, 632.8 nm was adjusted by means of three axes inclination micropositioning device to be parallel to the sample surface. A position sensor (bi-cell photodiode) was used to determine the amplitude and phase of the probe beam deflection. The output of the position sensor was fed into the lock-in amplifier (EG&G Princeton Applied Research Model 5209) via a differential detecting and amplifying circuit. The signal was then recorded by the digital storage oscilloscope (UT 2102C). Repeated measurements were accomplished in order to minimize the noise. Lenses were used to focus the beams in an accurate manner after choosing the appropriate focal lengths and to adjust the focal waist of the beams. A digital camera was replaced the photodiode for image recording and a computer for data collection and storage for image analysis by Matlab.

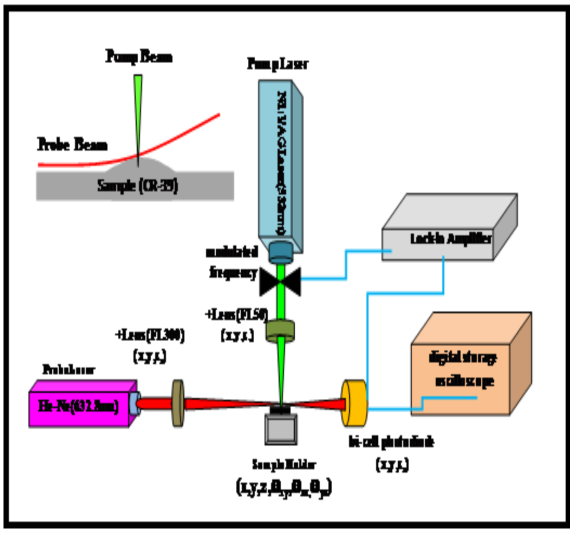

Fig. 1 Experimental setup and optical alignment for photothermal deflection.

CR-39 detector is a clear and colourless plastic, and α-particles of energy greater than 100 keV may damage the bulk material of the detector leaving etchable tracks [6]. In our experiments, the source of α-particles was a pellet of Americium-241 with energy (1.5 MeV) which will definitely leave a track in the detector. Transparent films, as might be not argued about it, is difficult to measure its variation in its refractive index or absorbance directly, unless with the PDS. Each piece of CR-39 detector was placed above the Americium source and exposed normally. The time of exposure were taken from (0-6 min) to increase the penetration depth or the damaged track in the detector due to α-particles fluence. After exposing no etching, process was carried out. Then each piece of CR-39 of definite time of exposure was placed in the setup for PDS measurements and image analysis. In this investigation, the track properties of CR-39 will be revealed without the need of etching but by PDS and image analysis as a possible technique for direct determination of nuclear radiation and dose. This technique discussed in this article will consider any growth asymmetry and surface texture of the CR-39 when PDS carried out as well as the image analysis. Any roughness on the surface may produce speckle and diffraction pattern which can be directly observed. This is another feature of the proposed method. Further investigations concerning the exposure of the CR-39 to other ions, and overexposed will be considered.

IV. RESULTS AND DISCUSSION

The dependence of photothermal deflection on the chopping frequency (modulated frequency of the pump laser) is illustrated in Fig.2. Thermal lens, and hence the photothermal deflection decreased with the $1/f$ (f is the frequency of modulation). This can be interpreted as, when frequency was increased, the temperature of the CR-39, especially the central region, was decreased, and also the thermal length which in turn will decrease the thermal lens giving a low deflection. The frequency of modulation was adjusted with both control device of the Thorlab instrument and the lock-in amplifier reading. The decrease in the photothermal deflection against the square frequency was found a quadratic dependence rather than a linear dependence.

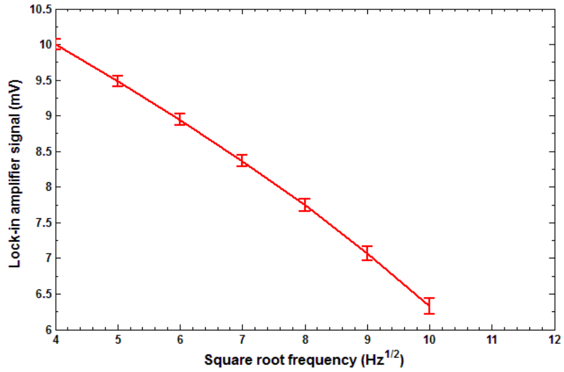

Fig. 2 Photothermal deflection of unexposed track detector CR-39 depending on the square root frequency.

To assure the measurements carried out in this investigation, the above study (deflection versus frequency) has to be done in the first place. The pump beam when modulated by frequency the thermal diffusion length (μ_{therm}) in the sample is defined as $\sqrt{D_{therm}/\pi f}$, where D_{therm} is the thermal diffusivity of the sample (cm^2/s) [11].

Phase and amplitude measurements of the deflected probe beam laser with modulation by the chopper were recorded with the aid of lock-in amplifier and the digital oscilloscope.

Fig.3 shows the effect of alpha particles (energy 1.5 MeV) on the recorded deflection of the lock-in amplifier. The exposed detector CR-39 for only (1.5 min) had shown this reduction in the deflection, but the behaviour still kept the same, i.e., increasing the deflection with pump power. The unexposed CR-39 had shown a sharp increase in the deflection above a pump power of (160 mW). The detector CR-39 had shown a pronounced peak in the absorption spectrum around the wavelength of pump laser, when a (VIS-IR) absorption spectroscopy was performed.

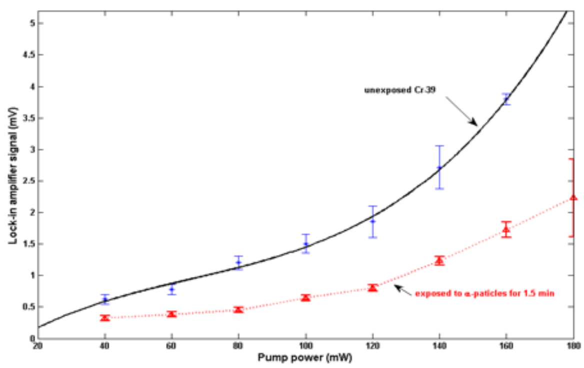

Fig. 3 Photothermal deflection of unexposed CR-39 (line in black) and exposed to alpha-paticles for 1.5 min (line in red) in terms of pump power.

The recorded deflection for the detector CR-39 for different of exposures for alpha particles of energy (1.5 MeV) and keeping the power of the pump laser at (140 mW), is illustrated in Fig.4.The deflection decreased with the increasing time of exposure to alpha particles, and this can be interpreted as that the absorbance of the CR-39 had decreased with the increasing time of exposure. When an ionizing particles cross the nuclear track detector, it produce damages at the level of polymeric bonds at its trajectory, forming the so-called “latent track”, and the damage depends on the ratio Z/β [10], where Z is the particle charge and β is the velocity of the particle.

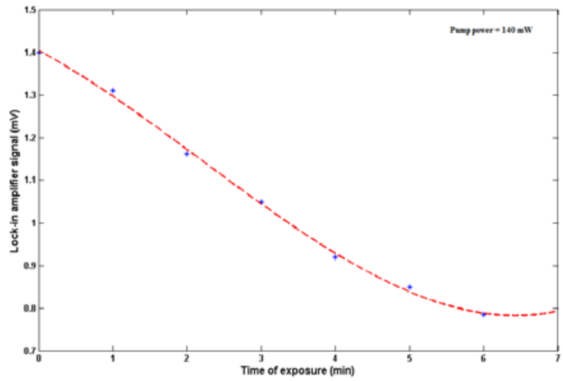

Fig. 4 The variation of deflection measured by the lock-in amplifier with the exposure time for constant pump power of 140 mW

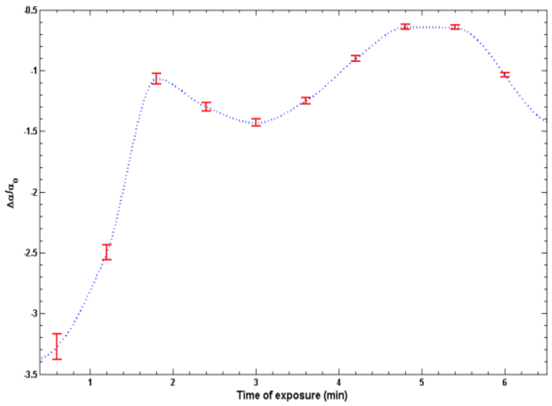

Fig. 5 The change in the absorption coefficient normalized to (α_o) the absorption coefficient of unexposed sample as a function of exposure time.

The deflected signal recorded in the Fig.4 can be converted to absorption coefficient by following equation [12]:

$$\alpha = -\frac{1}{d}\ln\left(1-\frac{S}{S_o}\right) \tag{5}$$

where d is the sample thickness, S is the output deflected signal, and S_o its saturated value, i.e., when the light is completely absorbed (unexposed sample). The calculated change in the absorption coefficient of the CR-39 for different time of exposure to the alpha particles normalized to the saturated value is illustrated in Fig. 5.

The variation of absorbance difference of the nuclear detector CR-39 was decreased as a result of the damaged track in the detector due to α-particles fluence. These results suggest the possibility of using the detector for the estimation of α-particles fluence.

Another interesting parameter that can be calculated from the PDS results is the thermal diffusivity D_{therm} from the amplitude of the PDS and the modulated frequency [13]. The thermal diffusivity is the physical quantity that can characterize the heat diffusion in the CR-39 due to conduction. More experiments are carrying on measuring the thermal diffusivity D_{therm} .

These parameters have to be verified by another technique or experimental method in order to demonstrate the reliability of the adopted PDS and to compare between corresponding parameters values.

The image of the deflected spot is shown in Fig.6 with and without the irradiation of alpha particles. These plots will then be processed by our software written for this purpose and will be as illustrated in Fig.6b. This, in-situ, measurements have the ability to acquire data rapidly and allow as many as possible to be averaged and one single result will be given with excellent repeatability. Computer programming takes very short time compared to any other technique.

With the image technique, it is possible to provide us the thermal properties of the sample under test. Also, it has the advantages of sensitivity and ability, in a non-contact manner, for collecting information of the sample.

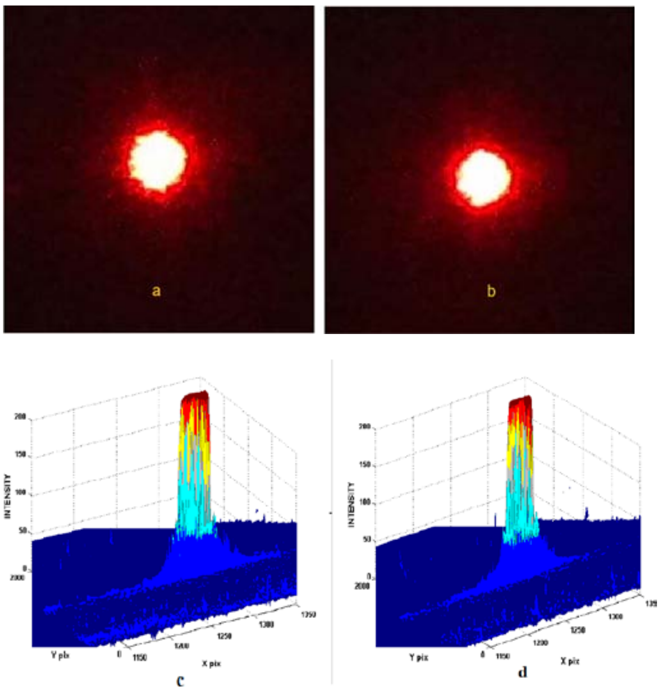

Fig. 6 The transform of image spot of the deflected laser beam into laser light intensity, (a) without irradiation, (b) with alpha irradiation, (c) light intensity for (a), and (d) is the light intensity for (b).

The next step is to find what changes have been found in the transformed image compared to the stored data for the unexposed CR-39 and to evaluate its variation with the energy of the nuclear particles or with the time of exposure. Many parameters were found in this study when the data were analysed, one of them is the variation of laser intensity FWHM (referred to as laser spot radius in pixels) with time of exposure. This laser spot radius was decreased, as can be seen from the Fig.7, with increasing time of exposure. Time of (1min) up to (2 min) showed rapid decrease in the width of the laser spot due to the irradiation to alpha particles of energy (1.5 MeV) and showed little decrease when the sample was irradiated above this time.

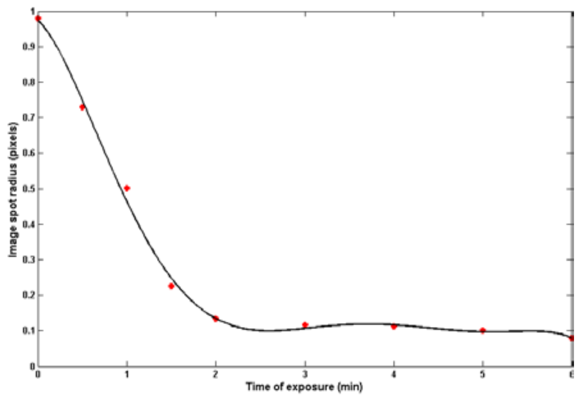

Fig.7 The laser spot variation with the exposure time of irradiation.

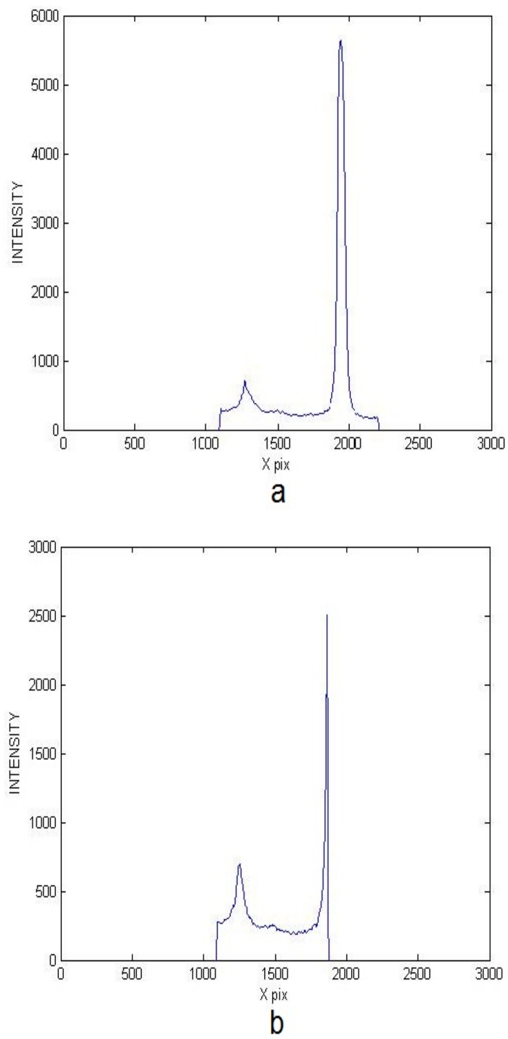

Fig.8 presents the conversion of the laser profiles (a) without pumping and (b) with pumping of 300 mW. A shift in the location of peak intensity was due to the pumping.

The software has the ability to convert an image into any kind of data. To illustrate this ability, Fig.8 shows the converted image in one dimension in terms of pixel in order to estimate the FWHM of the curve and to show how this FWHM varies with the pump power. This estimation will be treated as an overall effect of photothermal deflection analysis for the detector CR-39 rather than using the usual manner of calculations of deflections in terms of the stimulus. The shift in the location of the peak intensity of the two plots can be observed from the figure which can be interpreted as an effect of pumping, which is another feature of the deflected spot.

The influence of pump power on the laser spot of the deflected probe beam is presented in Fig.9. The shift in spot was calculated from the program in terms of pixels and this shift was extremely dependent on the power of the pump. At high power of the pump, a noticeable flatness can be observed due to thermal expansion in the CR-39 film and will introduce no further influence on the thermal lens.

The pump power when modulated by chopping frequency, the induced thermal waves has short penetration depth and gives much information of the surface thermal properties [14]. This information is much easy recorded by the image technique as given above. The argument about this novel approach will be more studied thoroughly and published shortly.

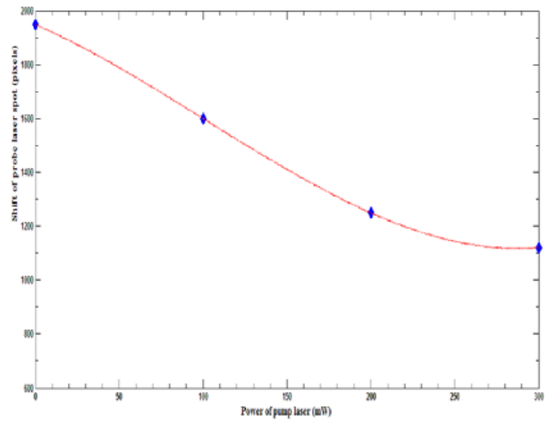

Fig. 9 The shift in the probe laser spot as a function of the power of pump laser calculated by the image analysis.

V. SUMMARY

Photothermal deflection spectroscopy technique is developed for thermal characterization of materials and based on the principle of generation of a thermal wave through periodic heating of the sample surface by a modulated (pulsed) laser beam, followed by detection of laser probe beam of the signal induced by the local temperature increase. As this technique fully uses optical beam, the samples under investigation can be evaluated without making any contacts.

The PDS experiments in this article were performed on CR-39 nuclear track detector (SSNTD) with frequency of modulation was sufficient to obtain the required resolution as well as for image analysis. Thermal properties of this detector, optical absorption coefficient and thermal diffusivity are of major importance, since these parameters were found in our experiments to be altered with the irradiation of α-particles.

Optical and thermal properties of CR-39 were found by PDS and image technique before exposing the pieces of the detector to the α-particle source, the Americium-241 with energy (1.5 MeV) that was sufficient to leave a track in the detector. When the results of PDS experiments were collected, the influence of nuclear irradiation on the detector was clearly noticeable. The influence on the following parameters, the absorption coefficient, and the thermal diffusivity were observed. The change in the absorption coefficient may be used for the assessment of the nuclear radiation dose and its fluence. Thermal diffusivity and thermal diffusion length, on the other hand, were evaluated and their variations with the time of exposure to α-particles need more attention and more experiments are carrying on.

Image analysis of the deflected probe laser spot was the novel technique is presented in this study. This technique was able to detect any variation in the optical or physical properties of the CR-39 detector even during the irradiation to the α-particles. No etching process, no time consuming, and in-situ monitoring or detection of nuclear radiation is provided with this technique. The image analysis can detect a small dose of radiation and very sensitive to α-particles down to less few seconds. Image processing showed a rich data to be analysed that can relate these data to the kind of exposure and its dose and exposure time. This suggests a future proposal for the image analysis for gamma radiation or other nuclear particles such as neutrons or protons.

In conclusion, we have presented a method to determine quantitatively the optical absorption coefficient of CR-39. The high sensitive PDS based on the analysis of both amplitude and phase of the photothermal deflection spectroscopic signal enabled to determine the absorption coefficient and diffusivity of the nuclear detector CR-39. Image analysis was successfully implemented as in-situ measurements for optical and thermal properties of the sample under test. The sample might be thin film, polymer, multilayered structure, and even liquid.

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