Degradation of carrier lifetime in irradiated lasers

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ABSTRACT

The effect of radiation damage on carrier lifetime in 1310nm InGaAsP/InP multi-quantum-well lasers irradiated with 0.8MeV neutrons, was investigated for fluences up to 6.9×10^{14}n/cm^2. The damage to the carrier lifetime was studied by measuring the transient response of irradiated lasers to incident optical pulses of 1064nm and 532nm wavelength, and by relative intensity noise measurements. The carrier lifetime was determined to be degraded to a similar extent in both the InGaAsP laser cavity and the surrounding InP material following radiation damage.

Keywords: Semiconductor laser, radiation damage, carrier lifetime, transient response.

1. INTRODUCTION

InGaAsP/InP lasers operating at 1310nm are being considered for applications in diverse radiation environments such as readout data-links in high energy physics experiments[1] and diagnostic data-links in nuclear fusion applications[2]. A series of studies of displacement damage effects[3-5] and transient response[2,6] are being carried out to validate this type of device for these applications. In this paper we study the transient response of neutron irradiated lasers to determine the extent and effects of carrier lifetime degradation due to displacement damage.

With displacement damage, host atoms are moved from their lattice sites in collisions with incident energetic particles or other recoiling atoms[7]. Defects are therefore introduced into the crystal lattice giving rise to energy levels into the band-gap. Such defects can be efficient sites for non-radiative recombination, with the net effect of a decrease in the carrier lifetime. In a semiconductor laser the additional non-radiative recombination due to radiation damage competes with radiative recombination for the injected charge carriers and the laser threshold current is increased if the carrier lifetime decreases through radiation damage[8].

The transient response technique is one of several methods[9] that can be used to determine the carrier lifetime in lasers. In the case of transient response to illumination with short, intense pulses of 1064nm or 532nm light, there can occur several transient effects that are also sensitive to the carrier lifetime. The photon energy at 1064nm is 1.16eV, and therefore the light is absorbed only in the InGaAsP active volume where the band-gap is 0.95eV (compared to 1.35eV in the InP). The transient response at 1310nm therefore exhibits a fast positive pulse, due to the radiative recombination of the photo-generated carriers, followed by relaxation oscillations. The frequency of these oscillations is related to the carrier lifetime in the InGaAsP and it was compared, in this study, with the resonant frequency of the relative intensity noise (RIN) spectrum, which is also sensitive to the carrier lifetime in the laser cavity.

For 532nm incident optical pulses the laser light output at 1310nm can be extinguished totally, as a result of breakdown of the confinement action, allowing carriers to leak around the active volume[2,6]. Following a brief turn-on delay there is then some extra light output at 1310nm, resulting from diffusion of photo-generated carriers from the InP material into the active volume. The duration of this additonal output pulse at 1310nm is directly related to the carrier lifetime in the InP material.

The goal of this investigation was therefore to measure the effects of neutron damage on the transient response and then to determine whether the damage effects, such as the threshold increase, could be related specifically to carrier lifetime degradation in either the InGaAsP active volume or the InP layers.

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2. EXPERIMENT

The lasers under test were Alcatel 1310nm InGaAsP/InP multi-quantum-well devices supplied in open-packages (allowing lateral illumination of the die) with single-mode fibre pigtails. The lasers have a BRS (buried ridge stripe) structure similar to that described in Ref. [10]. Light-current (L-I) characteristics measured before irradiation indicated that the laser threshold currents were 8-10.5mA and the output efficiencies were 30-50µW/mA (for power emitted from the fibre).

Irradiation of 5 samples with neutrons (average energy = 0.8MeV) was done at the Prospero reactor[11] at CEA Valduc. By varying the distance of the different devices to the reactor, the devices were irradiated to various neutron fluences over a period of 6 hours. The irradiation was made at ambient temperature (20-30°C) and the devices were irradiated short-circuited. The fluences received were 1.4, 3.0, 4.4, 5.6, and 6.9 x10^{14}n/cm^2 (for devices 1 to 5 respectively). The gamma background was 750Gy per 10^{14}n/cm^2. This dose was not expected to have caused any significant damage in either the laser diode or the short fibre pigtail[12].

The L-I characteristics of the lasers were remeasured approximately 3 weeks after irradiation, then again following 115 hours of annealing at 15mA bias. The latter annealing step was made so that the devices would have a stable threshold current during the time required to make a full set of transient response measurements.

The setup for the transient response measurements to incident optical pulses is illustrated in Fig. 1[2]. Pulses of 30ps width are generated, at either 1064nm or 532nm, in a Nd:YAG laser and focused onto the lateral face of the laser under test. The optical response, in terms of the output of the laser under test for a given bias current, was measured through a 22GHz photodetector and 40GHz sampler. A second photodetector was used to provide dosimetry measurements of the incident 1064nm or 532nm optical pulses. The transient response to 1064nm and 532nm pulses were measured for various incident optical pulse amplitudes and different bias currents. At 532nm the range of (optical) dose rates was 7-50x10^{10} rads/s and the current was varied 2-44mA above threshold. At 1064nm the ranges were 1.3-16x10^{9} rads/s and 22-44mA above threshold. Measurements were made before and after irradiation (after the annealing under bias). A limited set of transient response measurements at 1064nm were also made before the annealing step, but the threshold current was annealing too quickly at this stage to take a full set of data points.

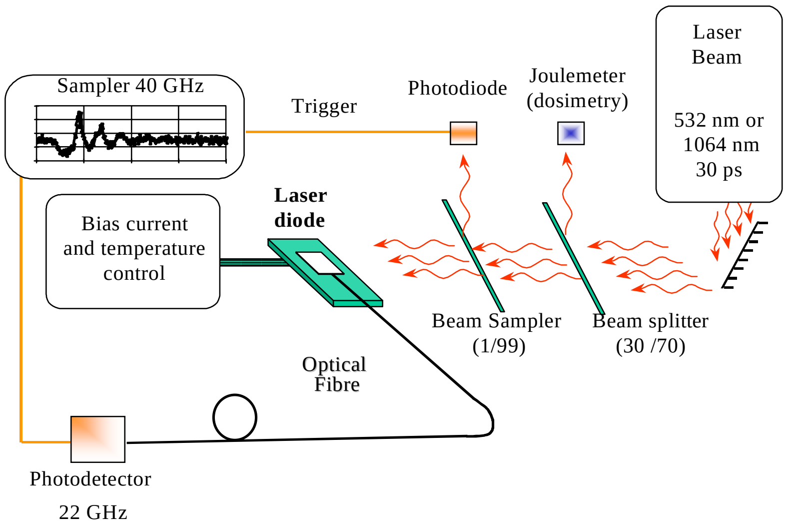

Fig.1: Experimental setup for transient response measurements

3. RESULTS

3.1. Threshold current damage

The L-I characteristics shown in Fig. 2 illustrate the effect of radiation damage and annealing on the (static) performance of the lasers. There is the usual increase in threshold current due to radiation damage that is approximately linear with fluence, as shown in Fig. 3. The effect of 115 hours of annealing under 15mA forward bias was that ~55% of the damage recovered in each device.

The output efficiency of these devices was not significantly affected by the neutron damage. There were some small variations in the slope of the L-I characteristics, but these were most likely due to fluctuations in the optical coupling achieved at the FC/PC connectors.

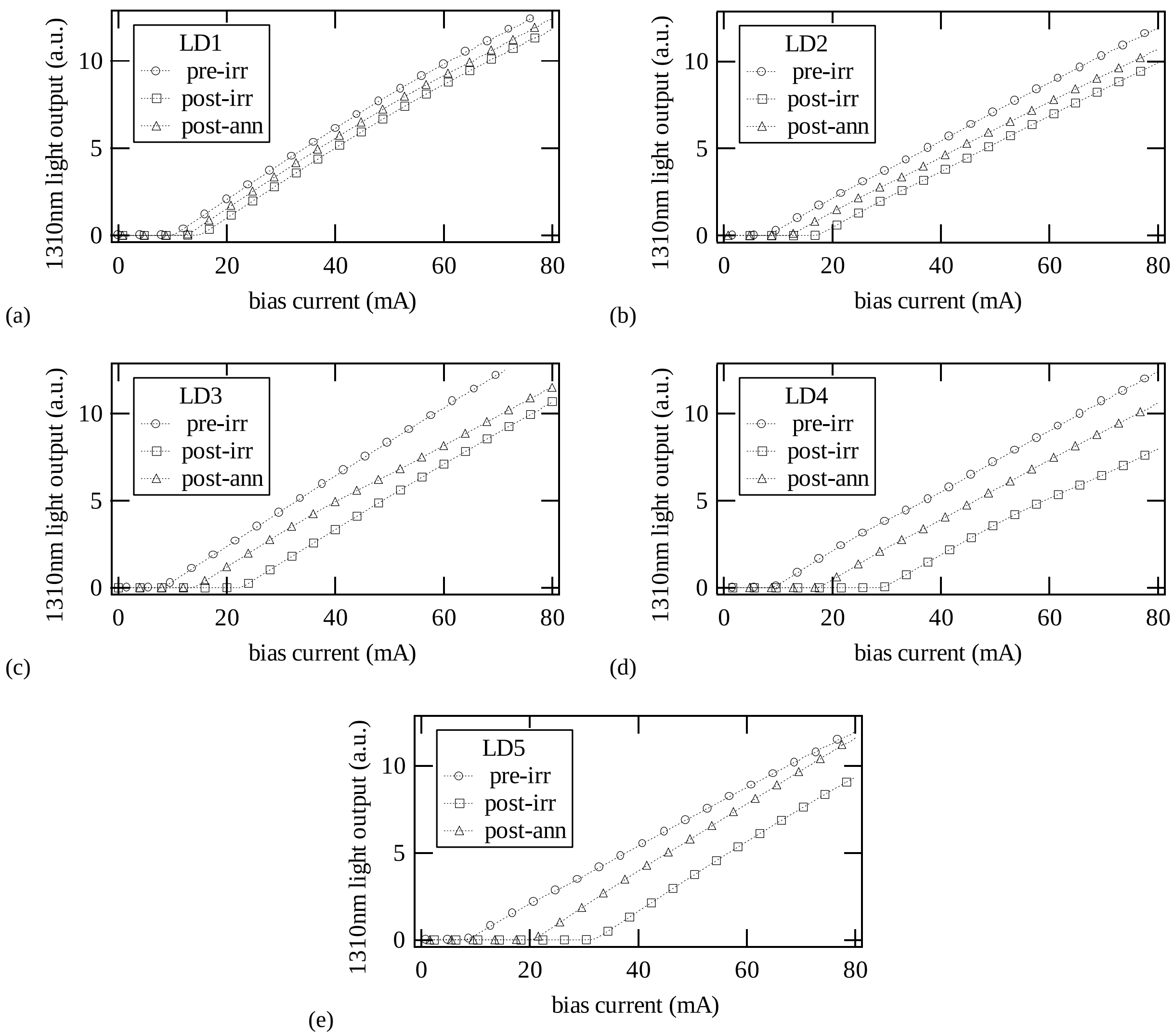

Fig. 2: Laser L-I characteristics before and after irradiation and after annealing. Plots (a) to (e) are for devices LD1 to LD5 respectively with the neutron fluences given in the text.

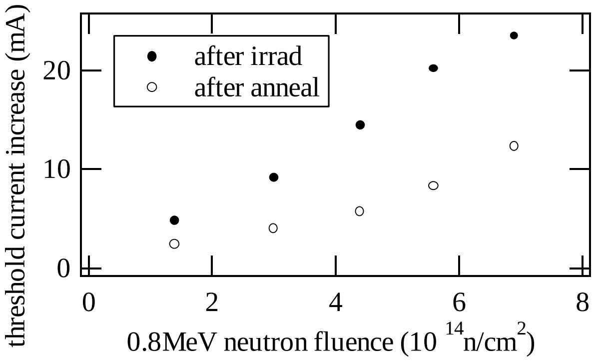

Fig. 3: Laser threshold current increase versus neutron fluence (before and after annealing).

3.2. Transient response to 1064nm incident optical pulses and RIN measurements

An example of the response to optical pulses of 1064nm wavelength is given in Fig.4. There is a sharp positive peak due to the additional stimulated recombination of the photo-generated carriers, followed by relaxation oscillations.

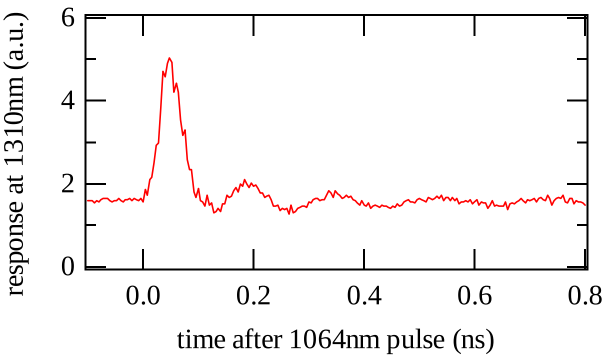

Fig.4: Example of the transient response at 1310nm to 1064nm incident optical pulses.

Fig. 5 shows the relaxation oscillation frequency (Ω_R=2πf) dependence upon bias current for the different devices, before and after irradiation, and after annealing under bias. The relaxation oscillation frequency is related to the carrier lifetime τ at the threshold current I_{thr} by[9],

$$\Omega_R^2 = \frac{K}{\tau}\left(\frac{I}{I_{thr}} - 1\right) = \frac{K}{\tau I_{thr}}(I - I_{thr}) \qquad (1)$$

where K is a constant parameter related to the particular type of laser, that is not expected to change due to radiation damage.

In Fig. 5 there is an indication that the frequency after annealing was slightly lower than the other data but this effect is not significant when compared with the experimental uncertainty. Because of the difficulty experienced in measuring the frequency of the relaxation oscillations, we therefore decided to compliment these data with measurements of the resonant frequency of the relative intensity noise (RIN), which can be measured more directly and accurately.

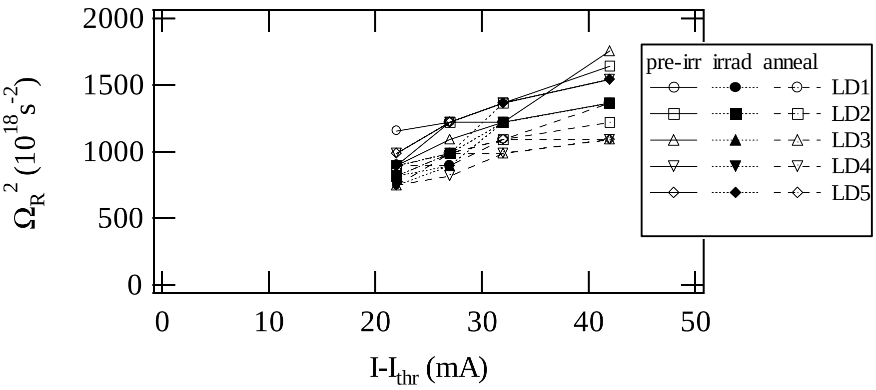

Fig. 5: Relaxation oscillation frequency dependence upon bias current before and after irradiation, and after annealing.

The laser RIN was measured as a function of frequency for all the irradiated devices (after annealing) as well as for two devices that had not been irradiated. Fig. 6 shows a typical noise plot illustrating the characteristic resonance and Fig. 7 shows the resonant frequency of the RIN spectrum for all the devices, as a function of current above threshold. For the RIN measurements it was necessary to use a lower range of current values (0-22mA above threshold, compared to the 1064nm transients measured at 22-44mA above threshold) as the resonance becomes less distinct with increasing bias current above threshold.

The resonant frequency is expected to be close to the frequency of the relaxation oscillations measured in the transient response[9] and the RIN data can therefore be combined directly with the 1064nm transient measurements. We can now conclude more firmly that there was no significant difference between the data for the irradiated and unirradiated devices.

One consequence of this finding is that the bandwidth of the lasers is not significantly affected by radiation damage, at least up to the fluences tested. This is an important result in terms of the laser performance in the planned applications. Secondly, the product of carrier lifetime and threshold current, according to equation (1), must be constant. The plot of Ω_R^2 versus $I-I_{thr}$ has a slope of $40\times10^{18}s^{-2}$. Using typical values of the parameters that determine the factor K for InGaAsP lasers given in Ref. [9], the product of lifetime and threshold current is $\tau.I_{thr}\approx43$ns.mA. Therefore, in the case of the most irradiated lasers, where the threshold current increased to from 8mA to 31mA after irradiation, the carrier lifetime was reduced from approximately 5.4ns to 1.3ns.

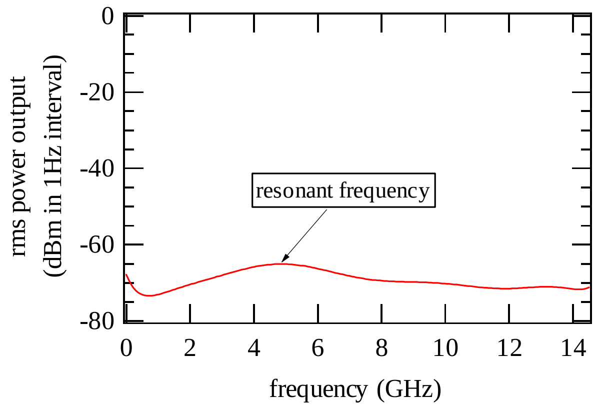

Fig.6: Typical noise characteristic of the lasers under test showing the resonant peak that corresponds to the frequency of relaxation oscillations.

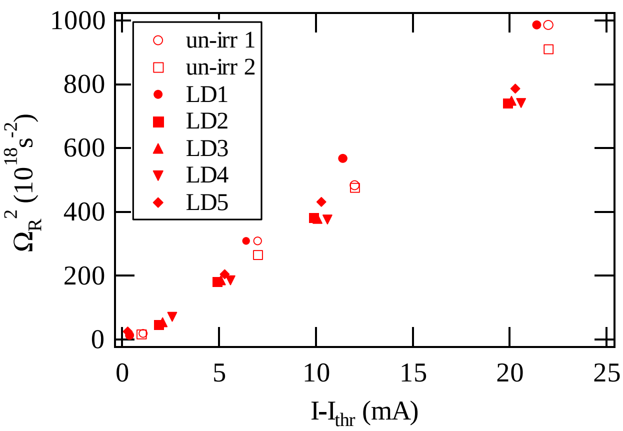

Fig.7: Variation of resonant frequency of RIN with current above threshold in irradiated and unirradiated lasers.

3.3. Transient response to 532nm incident optical pulses

The transient response of the laser diode under test to the 532nm optical pulses is illustrated in Fig. 8 before and after irradiation (including the additional annealing step). These data are for a laser bias of 12mA above threshold and incident pulses corresponding to a dose rate of 5.7×10^{11}rad/s. Other measurements were made at higher bias current values and various dose rates, with similar effects overall. The transient response included a suppression (turn-off) of the laser action for approximately 0.3ns in all devices, before and after neutron irradiation, followed by a second effect which is an increase in the overall laser light output at 1310nm, before the laser output returns to the original level.

The turn-off effect is due to the loss of resistivity of the InP confinement layers when illuminated by the 532nm pulse; this has been confirmed in measurements of the resistivity of InP samples irradiated with different dose rates of 532nm incident light[6]. The turn-on delay is related to the carrier lifetime[9]. However the carrier lifetime could not be directly determined from the 532nm induced transient response, as one of the other important parameters, the magnitude of current in the laser active volume during the 'turned-off' period, was not known.

Of perhaps greater importance than the turn-on delay is the second effect present in the transient response to 532nm incident light. This is the extra light that is emitted after the laser action returns, which is due to the diffusion of photo-generated carriers into the active InGaAsP volume from the surrounding InP material. The time to return to steady state is representative of the carrier lifetime in the InP material around the active InGaAsP volume. This settling time is plotted in Fig. 9 for lasers biased at 12mA above threshold; it is defined as the period measured from the start of the incident 532nm pulse to the point where the output at 1310nm returns to its initial steady-state value.

The return to steady-state took up to 3ns before irradiation whereas after irradiation it occurred more rapidly, for example <1.5ns in the most irradiated device, along with an attenuation of the extra light power emitted at 1310nm. Both of these effects are consistent with a decrease in carrier lifetime in the InP material following neutron irradiation. Defects introduced by radiation damage into the InP cause an increase in the rate of non-radiative recombination and therefore fewer carriers would diffuse into the active volume and the laser would also return more quickly to its steady-state condition.

As the laser threshold current can be written as[9],

$$I_{thr} = \frac{qVn_{thr}}{\tau} + I_L \tag{2}$$

where q is the charge of an electron, V is the volume of the active region, n_{thr} is the density of carriers at threshold, τ is the carrier lifetime in the laser cavity (at threshold) and I_L represents leakage of current around the active volume, the degradation of the lifetime in the InP material could therefore contribute to the increase in the laser threshold current after radiation damage through an increase in the leakage current component.

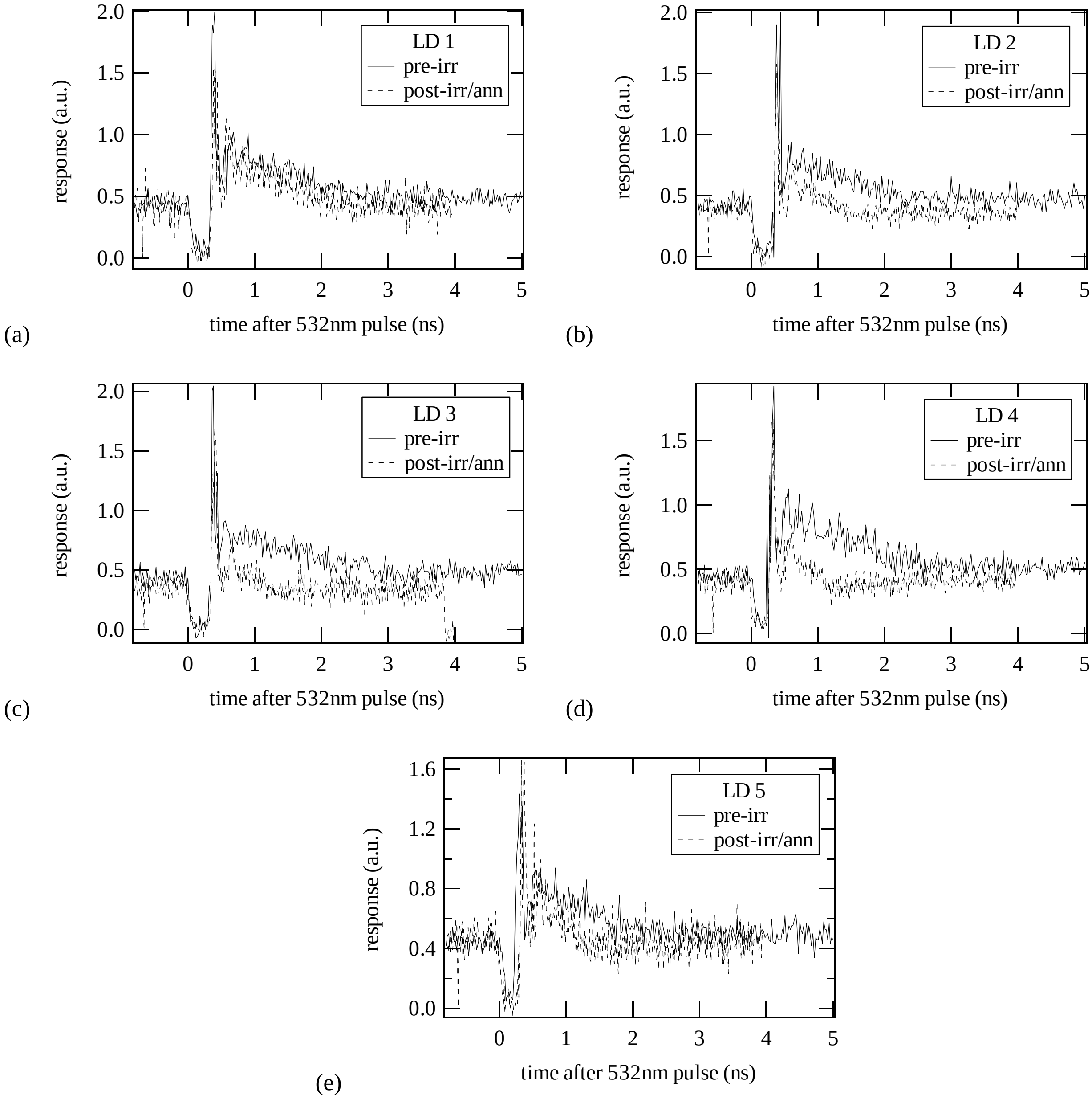

Fig.8: Transient responses to 532nm pulses measured as the output of the lasers under test at 1310nm. Plots (a) to (e) are for lasers 1 to 5 before and after irradiation.

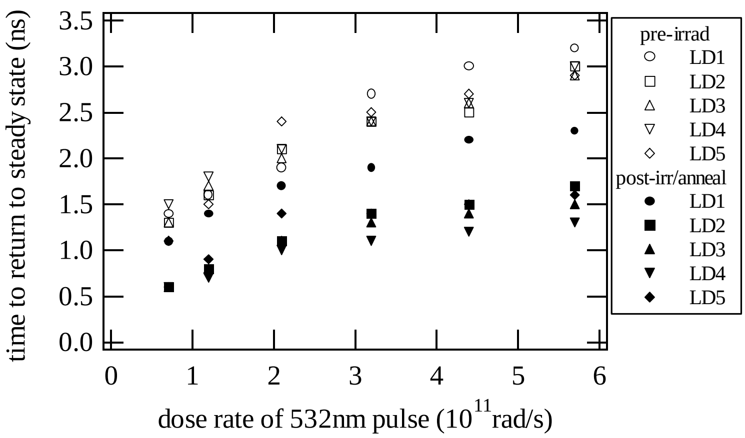

Fig. 9: Time to return to equilibrium after 532nm incident optical pulse, for different incident power levels (dose rates), with lasers biased at 12mA above threshold.

4. SUMMARY

The effect of a decrease in carrier lifetime following displacement damage with 0.8MeV neutron irradiation was confirmed in InGaAsP/InP 1310nm lasers, based on the transient response to high dose rate incident optical pulses of 1064nm and 532nm wavelength, and laser RIN measurements. The RIN measurements also demonstrated that the bandwidth of the lasers was not degraded by neutron fluences up to $6.9x10^{14}n/cm^2$.

Carrier lifetimes in both the InGaAsP active volume and the InP confinement layers were degraded after neutron damage. In conclusion the threshold current damage is not only due to carrier lifetime degradation in the InGaAsP active region but is also likely to be due to lifetime degradation in the surrounding InP material.

5. ACKNOWLEDGEMENTS

The authors would like to thank Alcatel for providing specially packaged samples and assisting with the RIN measurements, Robert Grabit, Bernard Maulini and Loic Baumard for constructing the supports for the samples, and the staff of Valduc for making the neutron irradiation and dosimetry measurements.

6. REFERENCES

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