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FIRST RESULTS OF A COMPREHENSIVE LIFE TIME TEST OF IRRADIATED LEDS AND VCSELS

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Abstract

We present first results of a comprehensive life time test of irradiated Light Emitting Diodes (LEDs) and Vertical Cavity Surface Emitting Laser diodes (VCSELs). Following the encouraging results obtained in a previous life time test of neutron irradiated LEDs, we built an automatic measurement system that makes long term tests with a large number of LEDs and VCSELs feasible. After the irradiation of about 200 LEDs from two different manufacturers and of about 30 VCSELs with the high doses of neutrons and protons anticipated in the inner tracker of ATLAS, we report preliminary results on the radiation damage and the conditions required for its annealing. In addition, results of irradiation studies done by the Birmingham group are presented.

1. INTRODUCTION

One of the technologies proposed for the readout of the ATLAS SemiConductor Tracker (SCT) uses optical links based on Light Emitting Diodes (LEDs) [1]. Mounted close to the detector modules, these LEDs would be subject to fluences on the order of 10^{14} charged hadrons and 10^{14} neutrons per cm^2, and to an ionizing dose of about 10^5 Gy during 10 years of operation at LHC [2]. While sufficiently radiation hard LEDs suitable for fibre optic links seem to be available today [3], the use of Vertical Cavity Surface Emitting Laser diodes (VCSELs) has recently been suggested as a cost effective and presumably more radiation hard replacement for the LEDs.

The degradation of LEDs due to irradiation is primarily a bulk damage effect which is caused by the displacement of atoms from their original lattice sites. The amount of such displacement damage can be measured by the non-ionizing energy loss (NIEL) [4]. The initially generated vacancies and interstitials are subject to diffusion, leading both to vacancy-interstitial recombination (and thus to annealing) and to the formation of more stable defect clusters like e.g. vacancy-impurity complexes. These processes depend on the operating conditions of the LEDs during and after the irradiation, particularly on the forward current through the LED (injection annealing), since electron-hole recombinations at a defect may increase its mobility [5,6].

The crystal defects, which are present in the LED junction at a given moment, may act as non-radiative recombination centers, decreasing both the minority carrier life time and the fraction of radiative recombinations. Thus the light output of LEDs at a fixed operating current is decreased and for VCSELs the threshold current for lasing is increased.

While it is well known that the light output of LEDs may be decreased after irradiation, little information seems to be available about the influence of radiation on the aging properties and thus on the life time of LEDs. For the LEDs typically used for fibre optic applications, i.e. high radiance devices operated at high current densities, the dominant degradation mechanism is the inhomogenous development of crystal defects (dark line defects) acting as centers for non-radiative recombinations. Knowing that the development of dark line defects depends on initially present crystal defects and material impurities, the concern arises, that radiation-induced displacement damage in LEDs or VCSELs might lead to an increased growth of dark line defects and thus to a much shorter life time after irradiation.

In order to check if there is a large effect of irradiation on the life time of LEDs, we irradiated in an earlier life time test [7,8] a small number of GaAlAs LEDs (manufactured by ABB Hafo) with up to $1.4 \cdot 10^{14}$ n/cm^2. After the irradiation, an almost complete annealing of the radiation damage was observed. Five LEDs were subsequently operated in an accelerated life time test without seeing any degradation due to aging for a duration which was estimated to correspond to about 57 years of operation in the ATLAS SCT. Although these results are very encouraging, the conditions required for the annealing need to be clarified further, the test should be extended to include charged particle irradiation, and higher statistics are needed before a prediction concerning the reliability of LEDs can be made for the SCT. Therefore we have continued our tests, using an automatic measurement system in order to reach higher statistics [8,9]. In this paper, we report first short term results from these ongoing studies, and we present complementary results which were obtained in independent irradiation tests done by the Birmingham group [10].

2. EXPERIMENTAL PROCEDURE

2.1 The Scanning Machine

In order to make the necessary long term measurements of a large number of irradiated LEDs feasible, an automatic measurement system, called the scanning machine, was built with space and driver electronics for the simultaneous operation of up to 448 LEDs (or VCSELs). In the scanning machine, the LEDs are mounted with microlenses but without any further packaging in groups of eight on ceramic boards (figure 1), which ensure a good thermal contact.

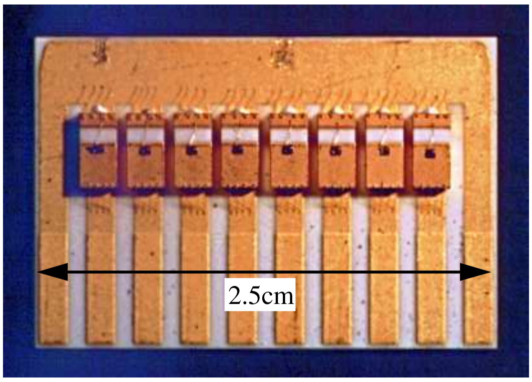

Figure 1: Picture of 8 ABB Hafo LEDs, each with a microlens (dark spot), mounted on a ceramic board for use in the scanning machine (see text).

Electrical contacts are made by wire-bonding. The light output is measured with a moving PIN diode at a distance of a few millimeters in front of the LEDs. The LEDs can be operated at forward currents up to 100mA, and, using Peltier elements, the temperature can be set in the range from -10^{o}C to 50^{o}C. For each LED, the forward current and voltage, the light output, and the fall and rise time can be measured automatically under computer control. For measurements at low temperatures, the scanning machine provides a tight volume with a nitrogen atmosphere.

2.2 Devices

For the operation in the scanning machine, LEDs and VCSELs were purchased from different manufacturers as shown in table 1. For the LEDs, the light output given in table1 is the average and RMS of the optical power that can be coupled into a 50µm core step-index fibre at the specified operating current which would be suitable for the SCT. For the VCSELs the typical light output measured with an optical head at room temperature is given.

Table 1: LEDs and VCSELs currently available for operation in the scanning machine.

Quantity	Description	Light Output
144	GaAlAs LEDs, ABB Hafo	17±5µW @ 10mA
320	GaAlAs LEDs, GEC	23±10µW @ 20mA
32	GaAs VCSELs, Sandia	typ. 0.7mW @ 3mA
48	GaAs VCSELs, Sandia	typ. 1mW @ 15mA

All devices listed in table 1 are non-commercial devices, and all of them have a peak wavelength of about 850nm. Except for the different packaging, the ABB Hafo LEDs correspond to the LEDs tested in the previous life time test. The GEC LEDs were developed by GEC (UK) on behalf of the Oxford group specifically for application at LHC. Two types of VCSELs (both in the form of 16-fold arrays) with a lower (2mA) and a higher (10mA) threshold current were purchased from Sandia National Laboratory (Albuquerque, USA) in collaboration with the ATLAS group developing the liquid argon calorimeter readout [11]. A larger batch of VCSELs with a threshold current below 1mA is expected to arrive in fall 1996. All VCSELs listed are GaAs based lateral oxidation devices, which are expected to be more reliable than the corresponding ion implantation ones [12].

In addition to the LEDs operated in the scanning machine, 5 pig-tailed GaAlAs LEDs (also manufactured by ABB Hafo) were reused from the previous life time test, where they had already been irradiated with $1.4 \cdot 10^{14}$ n/cm^2. These LEDs were used by the Birmingham group in order to measure the light output of LEDs during proton and neutron irradiation.

2.3 Irradiation

Up to now about 230 LEDs and VCSELs have been irradiated with either neutrons or protons in several runs at different facilities (table 2). Before the irradiation, the diodes were temporarily installed in the scanning machine for measuring the light output as a function of the forward current and the operating temperature. Some of the LEDs were subjected to a burn-in treatment before the irradiation by operating them at 50mA and 50^{o}C for one week. The irradiations were all done at ambient temperature but under

Table 2: Irradiation facilities and fluences reached.

Facility	Particles	Energy	Fluence (10^{14}/cm^2)
CERN PS	p	24 GeV	~ 0.1 ... 2.6
RAL ISIS	n	~ 1 MeV	~ 1 ... 5
Birmingham	n	~ 1 MeV	~ 6

different operating conditions of the LEDs/VCSELs (off, pulsed operation, DC operation). Except for the tests done by the Birmingham group, no measurements of the light output were made during the irradiation. After the irradiation, the diodes were reinstalled in the scanning machine, measured, and operated (with frequent measurements being made) for several days at different currents in order to study the annealing behaviour. For the long term studies, the diodes will eventually be operated for several months at higher temperatures in order to accelerate the aging.

3. FIRST RESULTS

3.1 Annealing of LEDs

A typical behaviour of a LED that was off during the irradiation is shown in figure 2: After an irradiation with $1.6\cdot10^{14}$ p/cm^2, the relative light output[1] of this particular ABB Hafo LED was decreased to a few percent. Operation of the LED for about 12 days at 10mA and 10^{o}C did not change the light output significantly. However, when the operating current was increased to 50mA, a fast annealing was observed, increasing the relative light output to about 40% within a few hours.

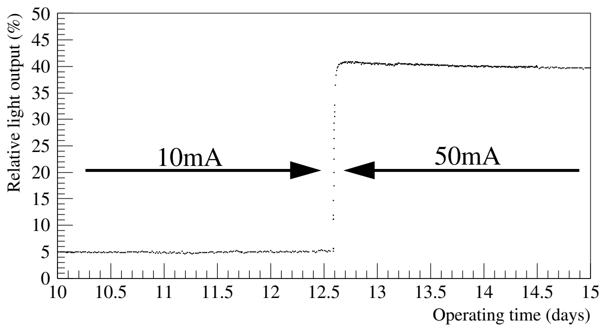

Figure 2: Relative light output of an ABB Hafo LED after the irradiation with $1.6\cdot10^{14}$ p/cm^2, as a function of DC operating time at 10^{o}C.

A different behaviour is shown in figure 3 for another ABB Hafo LED, which was irradiated with $3.2\cdot10^{14}$ n/cm^2: In this case, annealing took place already at a current of 10mA, raising the relative light output from ~10% to ~60%. However, when the operating current was increased from 10mA to 30mA after 6 days, an anti-annealing was observed, which decreased the light output to ~40%.

Both annealing and anti-annealing have been observed both after proton and after neutron irradiation. Although the behaviour described above can be understood qualitatively as being due to diffusion processes involving different types of defects, a quantitative modelling would require microscopic information about the defect types involved,

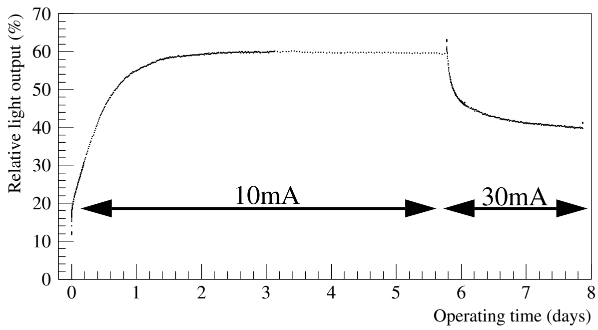

Figure 3: Relative light output of an ABB Hafo LED after the irradiation with $3.2\cdot10^{14}$ n/cm^2, as a function of DC operating time at 10^{o}C.

their electrical properties and their concentrations in the LED junction. Such information could be obtained e.g. from Deep Level Transient Spectroscopy (DLTS) [13] measurements.

If the LEDs are operated during the irradiation, as will be the case at LHC, depending on the radiation flux and the operating current, some or all of the annealing described above will take place during the irradiation. Consequently, the light output measured shortly after the irradiation is much higher than if the LEDs are off during the irradiation. However, the light output that is reached after an adequate annealing period seems to depend primarily on the maximum operating current applied and not on the operating conditions of the LEDs during the irradiation (see also section 3.3). An example of the light output measured during irradiation is shown in figure 4 for two ABB Hafo LEDs which were biased at 20mA.

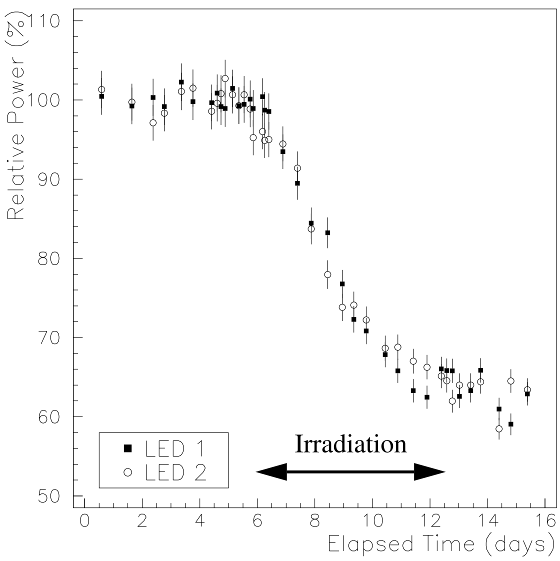

Figure 4: Relative light output of two ABB Hafo LEDs before, during, and after irradiation with ~$6\cdot10^{13}$ p/cm^2. During the whole irradiation period, the LEDs were biased with 20mA, except for short intervals, where measurements were made at currents up to 50mA [10].

1. The relative light output will always be given at the operating current specified in the last column of table 1, even though the annealing may be done at a higher current.

3.2 Annealing of VCSELs

So far only two 16-fold arrays of VCSELs could be irradiated. An example of a typical light output curve of a VCSEL with a threshold current of 2mA is shown in figure 5. The three sets of points denote the measurements made before and after irradiation, and after an annealing period of ~3 days of DC operation at 3mA and 30°C. During the irradiation with $2.1{\cdot}10^{14}$ p/cm^2 the VCSEL was not biased. As expected, the irradiation increased the threshold current from ~2mA to ~5mA, but during the annealing period the threshold current decreased back to almost the initial value.

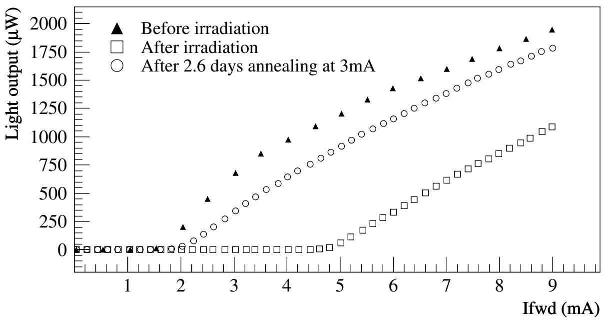

Figure 5: Typical light output curve of a VCSEL (2mA threshold) irradiated with $2.1{\cdot}10^{14}$ p/cm^2, before and after the irradiation, and after an annealing period of ~3 days at 3mA and 30°C. During the irradiation the VCSEL was off.

After the annealing, the relative light output at 3mA was ~55%, which, in terms of optical power that can be coupled into a fibre, still exceeds the light yield of typical unirradiated LEDs by about one order of magnitude.

3.3 Summary of Short Term Results

The short term results obtained so far are summarized in figure 6, which shows the relative light output of individual LEDs and VCSELs after the irradiation as a function of the neutron or proton fluence. The fluences for the irradiations at ISIS (with ~1MeV neutrons) and at the CERN PS (with 24GeV protons) are given by the top and bottom axis, respectively. Using the NIEL calculations in [14], these axes have been scaled such that the NIEL is the same for the corresponding neutron and proton fluences. Thus if the radiation damage in LEDs after the annealing can be parametrized by the NIEL, there should be no difference between the neutron and proton irradiation data in figure 6. Indeed, for the data available so far, the proton and neutron irradiation results agree fairly well, in spite of the large spread of the data, which is partly due to uncertainties in the dosimetry.

Because initially no difference was found in the annealing of ABB Hafo LEDs at -10°C and +10°C, and because at least on a short time scale no significant annealing was observed while the LEDs were not biased, most of the anneal-

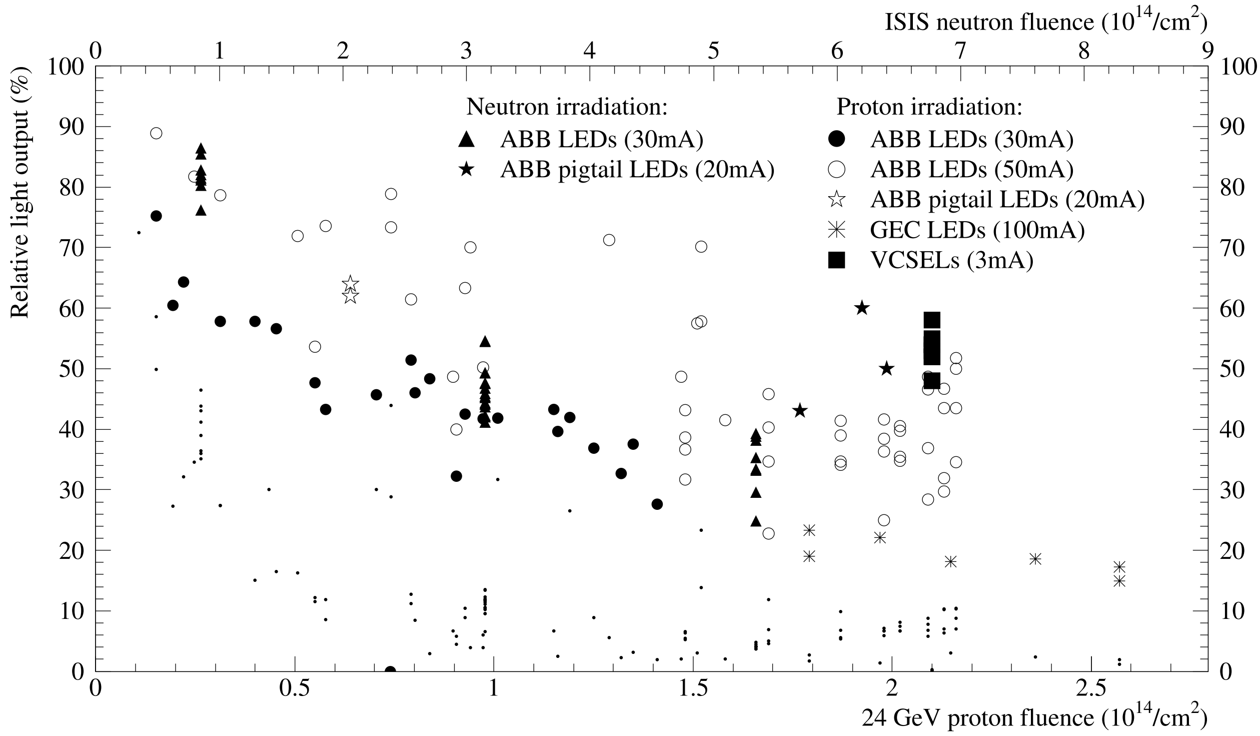

Figure 6: Relative light output of individual LEDs and VCSELs after the irradiation as a function of fluence. The little dots denote the first measurement made after the irradiation. The larger symbols show the relative light output when no further annealing was observed at the forward current indicated in the legend. Both proton and neutron irradiation data is shown (see text).

ing studies were performed at +10^{o}C for simplicity, although in the SCT the LEDs or VCSELs would presumably be operated at -10^{o}C.

The importance of injection annealing is evident from figure 6 when comparing the measurements of the relative light output before (dots) and after (larger symbols) the annealing. A comparison of the ABB Hafo LEDs, which were annealed at currents up to 30mA (full circles) with those operated at currents up to 50mA (hollow circles), shows that the latter generally reach a higher relative light output. Thus the degree of the annealing seems to depend on the maximum annealing current. For the GEC LEDs, a fast annealing similar to the one exhibited by the ABB Hafo LEDs was observed only at 100mA (stars), while at currents up to 50mA the annealing was much slower and was not yet complete at the time of this writing (not shown in figure 6). Further annealing studies with GEC LEDs are in progress in order to determine both the extent of the annealing and the current required.

After the irradiation, two out of 144 ABB Hafo LEDs gave no light and must be considered as dead. One of them was irradiated with $7 \cdot 10^{13}$ p/cm^2 and the other one with $5.3 \cdot 10^{14}$ n/cm^2. Whether their failure is due to radiation damage, or if they have been damaged e.g. mechanically, could not yet be completely clarified.

Finally, it is interesting to note that - within the relatively large spread of the data obtained so far - no significant difference was found in the relative light output after the annealing between LEDs that were biased with a DC or pulsed current during the irradiation (about one third of the LEDs) and LEDs that were off.

4. CONCLUSIONS

Up to now we have irradiated about 230 LEDs and VCSELs under different operating conditions with neutron and proton fluences comparable to those expected in the ATLAS SCT during 10 years of operation. The conditions required for the annealing of the radiation damage have been studied.

The short term results obtained so far indicate that the relative light output of ABB Hafo LEDs after these fluences would be on the order of ~30% to ~50%. In order to achieve sufficient annealing of the radiation damage, it may be necessary to operate the LEDs for short annealing periods of a few hours or days at elevated currents (about 3 to 5 times higher than for normal operation). This could take place e.g. during the yearly shutdown of the detector.

The few VCSELs from Sandia which were tested appear to be very radiation hard, but, since the reliability of VCSELs is a major concern, it must be emphasized that the results of the long term studies are not yet available.

Although the irradiation of further LEDs and VCSELs will continue, the emphasis will now be put on the life time studies so that results about the long term behaviour after the irradiation will be available within a few months.

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