The Production of the ATLAS SCT Optical Links

A. R. Weidberg on behalf of the ATLAS SCT Collaboration

Physics Department, Oxford University, U.K.
t.weidberg1@physics.ox.ac.uk

Abstract

The on detector optical links for the SemiConductorTracker (SCT) have been produced and the assembly of the services to the support structures is nearly complete. Most of the off-detector opto-electronics has also been produced and has been used to successfully read out modules assembled on Barrels and Endcap disks. Many problems were encountered during the production and these will be described. The lack of modularity in the system design has been a major disadvantage and some suggestions for a simpler and more modular system for the optical links for an upgraded tracker at the SLHC will be discussed.

I. INTRODUCTON

Optical links will be used for the readout of the 4088 SCT modules and for the transmission of the Timing, Trigger and Control (TTC) data from the Read Out Driver (RODs) to the SCT modules[1]. All the on-detector components have been produced and all the harnesses for the Barrel and Endcap C have been mounted on the detector. The assembly of the harnesses for Endcap A is also nearly complete. The production of the off-detector opto-electronics is also nearly complete. This is based on a novel design for MT[1] coupled VCSEL[2] and PIN diode arrays.

The critical components and their performance are briefly summarised in section II. There were many unexpected difficulties encountered during production and some of these are described in section III. Some implications which would be relevant to the design of similar systems for SLHC are discussed in section IV and finally some conclusions are drawn in section V.

II. SYSTEM DESCRIPTION

The SCT opto-electronics system provides readout of the data from the SCT modules at 40 Mbits/s. The system also provides TTC data to all SCT modules[2]. Two VCSELs read out the data from an SCT module and redundancy is implemented in that if one VCSEL link fails all the data from one module is routed through the working link[3]. Redundancy is also implemented in the TTC system; if the TTC link to a module fails then a level is set to instruct the module to take its TTC data from a neighbouring channel.

[1] Mechanically Transferable splice.
[2] Vertical Cavity Surface Emitting Lasers.
[3] For unmodified barrel modules, if one link fails the data is read out from 11 out of the 12 ABCDs.

A. On-Detector Components

The on-detector system is based on the Taiwan opto-package which contains two VCSELs and one silicon PIN diode[3]. The VCSELs and PIN diode are coupled to the radiation hard fibre by using 45^0 angle polished fibres. The fibre used is a special radiation hard step index multi-mode fibre[4]. For the readout of the Barrel SCT the opto-packages are mounted on copper/kapton flex circuits together with the associated ASICs, DORIC4A and VDC[5]. These flex circuits connect to low mass aluminium/kapton power tapes (LMTs). A Barrel opto-harness is assembled out of 6 copper/kapton flexes and 6 pairs of LMTs. A photograph of a part of a Barrel harness mounted on a carbon fibre support structure is shown in Figure 2.

For the SCT Endcaps the fibres and opto-electronics are assembled separately from the flex circuits that bring in the power. This more factorised system can be used for the Endcaps because of the increased vertical clearances. The opto-ASICs are mounted on the SCT Endcap modules. The opto-package is produced on a PCB with a small connector that allows it to mate to the SCT Endcap module. Separate flex circuits are used to bring in the power to the module. These flex circuits use copper/kapton for the low current lines and copper clad aluminium twisted pairs for the high current lines.

The more factorised system for the Endcaps made it easier to produce the separate fibre harnesses and flex circuit sub assemblies with high yield. However once the electrical, optical and cooling services were assembled onto a disk, the resulting system was very complicated as illustrated in the photograph in Figure 4. After all the services were mounted it was extremely difficult to replace a flex circuit and almost impossible to replace a fibre harness.

The performance of the VCSELs is illustrated in the distribution of coupled power shown in Figure 3. With such large power, it is relatively easy to operate these links with low bit error rates (BER). The specification states that the BER should be less than 10^{-9} and all links were tested to give a BER of less than 10^{-10}. A few links were tested for longer periods of time and the BER was found to be less than 10^{-12}. The optical links have been used to read out the four barrels of the SCT during detailed and very successful evaluations of the module performance at Oxford and CERN. The links have also been used for similar studies of Endcap C at Liverpool and Endcap A at NIKHEF. All on-detector components have been qualified to be suitably radiation hard [4,6,7].

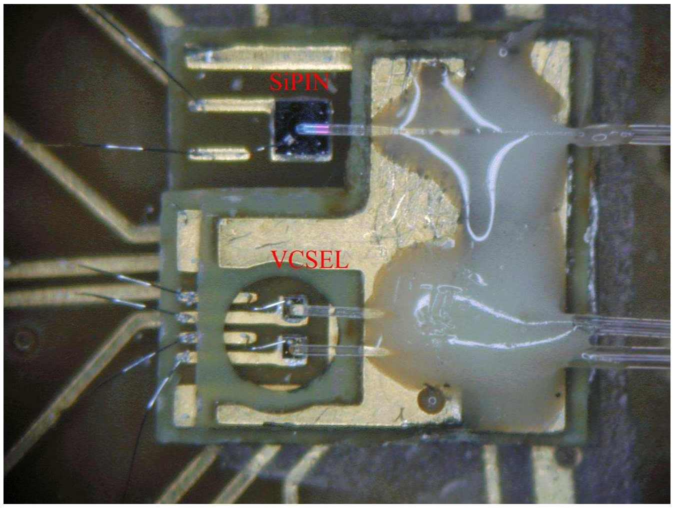

Figure 1 Taiwan opto-package with two VCSELs and one PIN diode, coupled to radiation hard fibres.

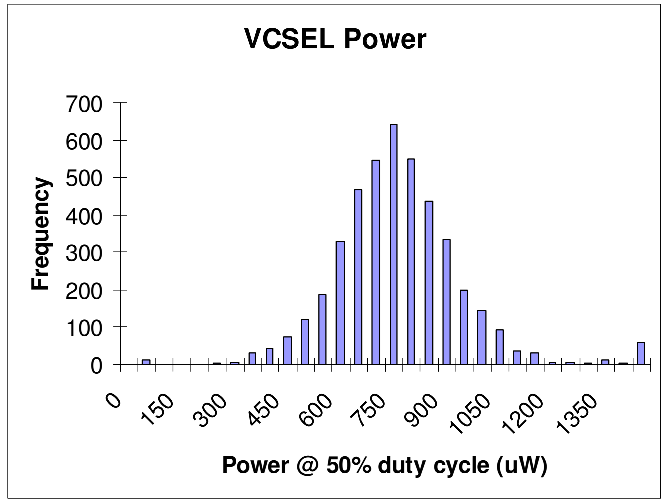

Figure 3 Distribution of VCSEL coupled optical power at 50% duty cycle for a sample of Barrel opto-packages.

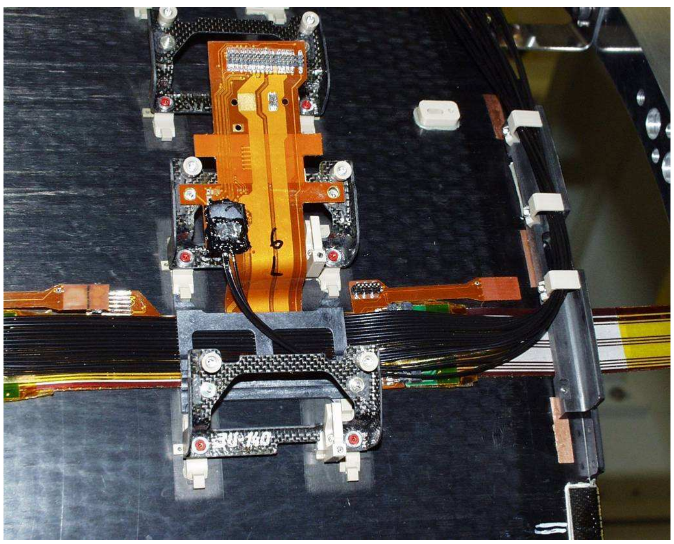

Figure 2 Opto flex circuit mounted on a Barrel. The opto-package is beneath the black plastic cover to prevent light leaks.

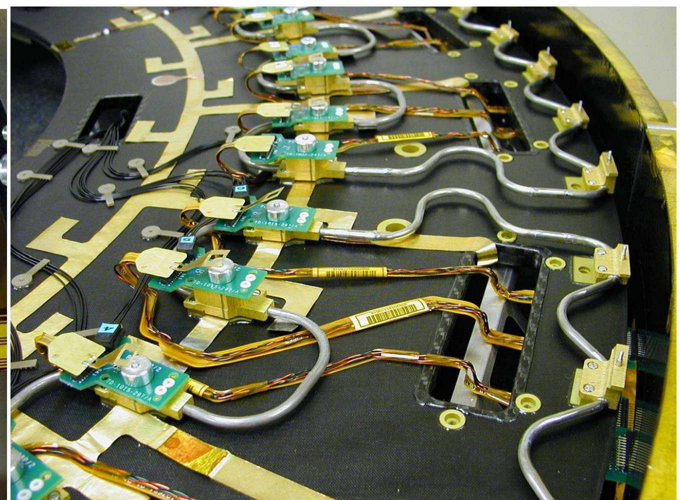

Figure 4 Photograph of section of a disk showing the power tapes, optical fibres and opto-package and the cooling pipes.

B. Off-Detector Components

The off-detector opto-electronics uses a novel packaging concept to allow an MT terminated fibre ribbon to connect to a 12 way VCSEL or silicon PIN diode array. This is illustrated schematically in Figure 5 below. The precision placement of the array chip relative to the MT guide pins, ensures that the fibres are aligned to the active components.

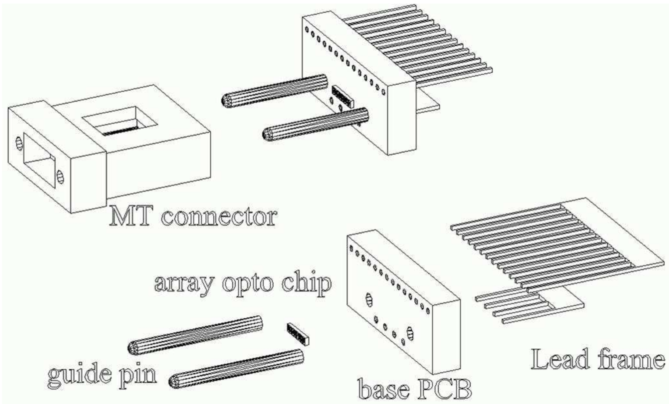

Figure 5 VCSEL and PIN array packaging schematic.

The DRX-12 ASICs are used to discriminate the signals from the PIN diode. The discriminator level can be adjusted for each individual channel. The BPM-12 ASIC is used to encode bi-phase mark data and drive the VCSELs. This then sends all the TTC data for one module down one fibre. The phase of the 40 MHz clock can be adjusted in order to optimise the efficiency of the front end ABCD ASICs. The trigger signal can be delayed by an integer number of clock cycles in order to ensure that the trigger timing is correct for each module. The amplitude of the VCSEL driving current can also be adjusted. More details of the off-detector opto-electronics are available in [8].

III. PROBLEMS ENCOUNTERED IN PRODUCTION

Several serious problems were encountered during production which are discussed in the following sections.

A. Complexity and Yield.

The barrel topology is such that 42 different geometries of harnesses are required, assembled from 16 distinct flavours of kapton flex circuits. Each harness contains 48 electrical connectors. Each of the 12 LMTs in a harness had to be soldered to a PCB. Initially this soldering was performed with a pulsed thermode soldering machine but it was not possible to achieve a sufficiently high yield. The soldering process was changed to a simpler one using a hot air gun and this achieved higher yields. Each harness was a complicated assembly which was therefore difficult to produce with high yield. This was compounded by the fact that it was very difficult to do repairs to a single item once a harness was assembled.

There was a mistake in the geometry for the layout of the flex circuits for two of the four barrels. The result was that there was an error of 2.8 mm in the location of the connectors for the module. This was only discovered after nearly all the harnesses had been assembled. This required connectors to be removed from the flex circuits and special translation PCBs added to the flex circuits. These problems could have been avoided if a simpler design had been used.

B. Cracks in Flex Circuits

The first problem with cracks was found in the Barrel kapton flex circuits. An example of a crack is shown in the photograph in Figure 6.

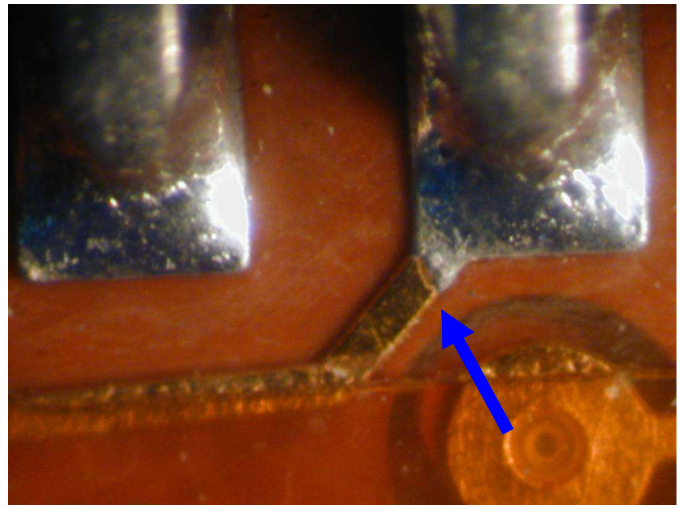

Figure 6 Photograph of a Barrel flex circuit showing a crack near a solder pad (see arrow).

The cracks tended to occur because the layouts were not optimised for robustness. This happened because there was insufficient time for the detailed optimisation of the layout. The cost in time and money of remaking all these circuits was prohibitive. It turned out to be possible to use ceramic stiffeners behind the connectors as a work around for this problem. However if there had been fewer flavours of flex circuits to design it would have been possible to optimise them to avoid these problems.

The next problems with cracks to be encountered were in the kapton flex circuits for the Endcaps. The kapton flexes alone were rather robust as were the copper clad aluminium (CCA) wires. The CCA wires were attached to the flex and then the flex was bent into the required 3D shape. Since the CCA wires were much more rigid than the kapton flex, this tended to cause cracks in the narrow copper tracks on the flex circuits. A more robust design would have separated the CCA wires from the flex.

An even more serious problem with cracks was found for the Al/kapton power tapes. There were no problems with the basic Al/kapton tapes but it turned out that the ends of the tapes were very fragile. The ends were electro-plated with a thin layer of Ni to allow a layer of Pb/Sn solder to be electro-plated. The tapes were then soldered to PCBs. A typical example of a crack in a 500 µm wide trace is shown in the photograph in Figure 7. The crack is not straight and is believed to follow the grain boundaries.

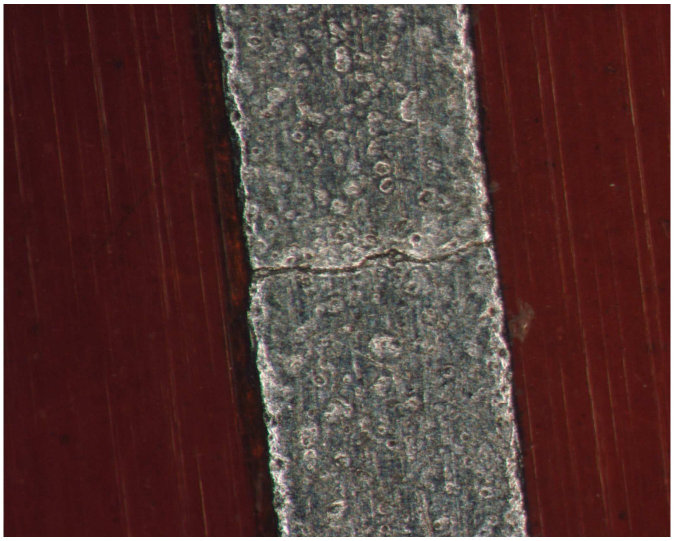

Figure 7 Photograph of a crack in a 500 µm wide track on an Endcap aluminium low mass tape.

The problems were so serious that it was decided to abandon the Al/kapton tapes for the Endcaps and use more conventional Cu/Espanex tapes.

From discussions with metal plating experts we believe that the fragility was probably due to hydrogen embrittlement of the aluminium. We are currently performing plating trials with samples in which we will try to use a bake out cycle at 190^0C to expel the hydrogen. If this is successful Al/kapton tapes would be an attractive option for SLHC.

C. Light Leakage

The silicon detectors are very sensitive to the light at 850 nm emitted by the VCSELs. Since the light from the VCSELs is by definition synchronised with the readout, the system is extremely sensitive to a very small fraction of light leakage from the VCSELs and fibres. Since the clearances between the opto-package and silicon detectors and other components is so small, custom covers had to be designed and manufactured using plastic injection moulding. The individual fibres are routed in black furcation tubing (coloured tubing turned out to be almost completely transparent at 850 nm). For the Endcaps the 12 way ribbons are close to the detectors so they had to be wrapped in aluminium foil.

D. Resonant Wire Bond Vibrations

Any bond wire in the SCT will experience a force if it is drawing current and it is at an angle to the solenoid magnetic field. The DC force is negligible, however any wire that is drawing current which varies in magnitude at a frequency that is close to resonance will undergo dangerous vibrations. This was studied in detail for the bond wires from the VDC ASIC to the VCSEL on the Barrel and from the VDC ASIC to the hybrid for the Endcaps. The results confirmed that long bond wires vibrating out of the plane of the bond wire loop will tend to break after a few minutes of operation on resonance[9]. The effects in the SCT are fortunately not expected to be so severe because of a combination of the length of the bond wires and the orientation with respect to the magnetic field. However in order to achieve greater safety, we are implementing a veto against fixed frequency triggers in the TIM[10] module.

E. Electro Static Discharge

The VCSELs, PIN diodes and ASICs are well known to be sensitive to Electro Static Discharge (ESD). We therefore tried to implement the standard precautions against ESD at all stages. The first ESD problems we saw were with the DORIC4A ASICs which were wafer tested before being assembled onto the flex circuits. The low yield of the DORIC4As after this assembly was eventually traced to ESD. A classic example of ESD damage on an ASIC is shown in the photograph in Figure 8. All the assembled flex circuits were discarded and the ESD precautions improved and this problem was not seen again.

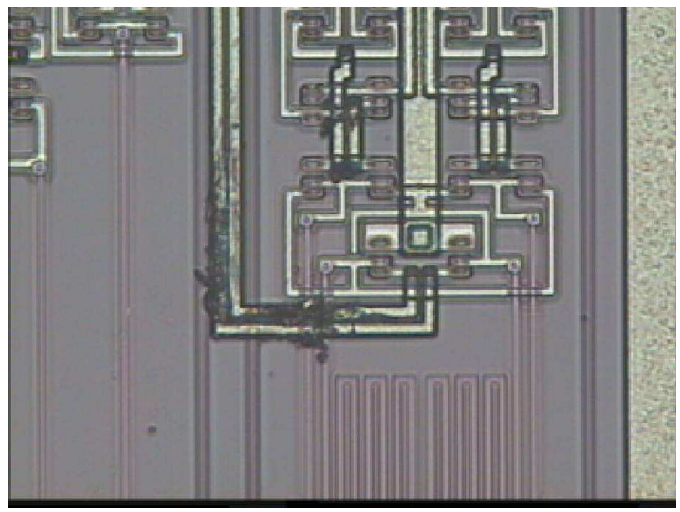

Figure 8 Microscope photograph of a DORIC4A ASIC showing clear evidence of ESD.

VCSELs are known to be very ESD sensitive. An ESD pulse will start to melt the layers in the Distributed Bragg Reflector (DBR) mirror and increase its opacity and hence reduce the light output[11]. Further damage can also increase the leakage current and hence shift the IV curve as illustrated in Figure 9[11].

Imaging damaged VCSELs requires transmission electron microscopy on a slice. However the reduced forward voltage provides a simple test for ESD to VCSELs. A low rate of ESD damage was observed for the VCSELs in the Endcap opto-harnesses. These VCSELs passed the initial burn-in and subsequent QA at Radiantech (Taiwan), RAL and Liverpool. After the modules were mounted on the disks at Liverpool the VCSELs were operated for a longer period of time and it is estimated that 10 VCSELs out of 1976 failed due to ESD. It is very difficult to localise the source of the problems. We have thoroughly reviewed the ESD procedures at all assembly sites and made several small improvements. We have not however been able to localise the origin of the problems.

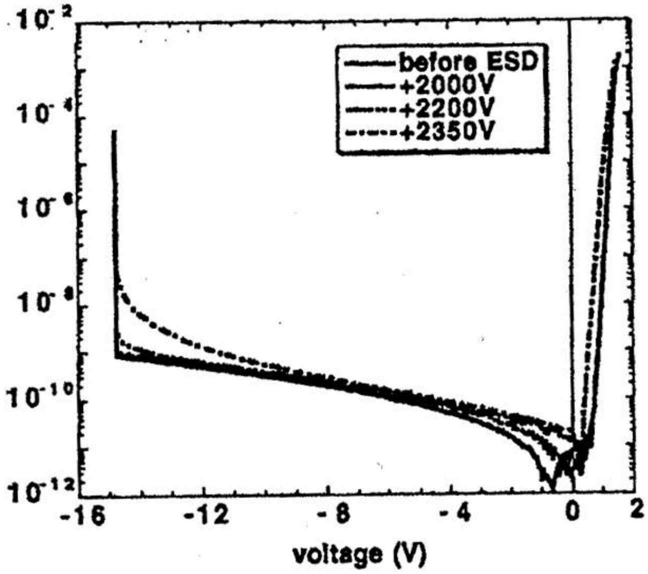

Figure 9 Current versus voltage curves for VCSELs before and after different levels of ESD.

Given the non-modular nature of the system, it is not possible to replace these damaged VCSELs and we are forced to rely on the redundancy system to readout the data. While this will not result in any immediate loss of data, there is a concern that lower levels of ESD might have reduced the lifetimes of many VCSELs.

IV. IMPLICATIONS FOR SLHC READOUT

The silicon tracker for the upgraded ATLAS detector at SLHC is expected to contain an order of magnitude more channels than the current detector. It is therefore neither practical nor affordable to simply scale up the present system by an order of magnitude. One attractive option would be to use more electrical multiplexing and much higher speed optical links. The current SCT links operate at only 40 Mbit/s, whereas current radiation hard optical links operate at 1.6 Gbits/s and future developments aim to achieve even higher speeds. If the high speed multiplexing and optical links were located at the end of the barrel or disk structures, then it should be possible to design a much more modular system. This would allow for any damaged items to be easily replaced at any time during the assembly of the detector.

VCSELs are an attractive option for the readout at SLHC because of their excellent radiation hardness but greater consideration would have to be given to ESD precautions if they were to be used.

V. CONCLUSIONS

The on-detector optical links for the SCT readout have been produced. All the components for the Barrel and Endcap C have been assembled and Endcap A is well advanced. The system has been used successfully for the readout of the Barrels and Endcaps. The performance of the Barrel and Endcap modules on the support structures is excellent and the percentage of working channels for the Barrel (Endcap C) is greater than 99.7% (99.7%). There were several unexpected difficulties encountered during production and it is clear that a simpler more modular system will be required for SLHC. The cause of the fragility of the nickel plated regions of the aluminium LMTs will have to be understood and cured, if this technology is to be used for SLHC. The design of the opto-electronics for LHC will have to take into account the extreme ESD sensitivity for VCSELs if they are going to be used.

VI. ACKNOWLEDGEMENTS

This work was supported by the Ministry of Education, Culture, Sports, Science and Technology and the Japan Society for the promotion of Science, The Research Council of Norway, Ministry of Higher Education, Science and Technology of the Republic of Slovenia, Plan Nacional de Fisica de Particulas y Aceleradores Spain, Swedish Research Council, Knut and Alice Wallenberg Foundation Sweden, National Science Council of Taiwan, ROC and the UK Particle Physics and Astronomy Research Council.

VII. REFERENCES

1 ATLAS Inner Detector Technical Design Report, CERN/LHCC/97-17.

[2] A.R. Weidberg, Status Report of the ATLAS SCT Optical Links, LECC 2001, CERN 2001-005.

[3] M-L Chu, EDMS, ATL-IS-AT-0009.

[4] Irradiation Studies of Multimode Optical Fibres for use in ATLAS front-end links. Nucl. Instr. Meth. A 446 (2000) 426.

[5] D. J. White et al, Radiation Hardness Studies of the Front-end ASICs for the Optical Links of the ATLAS SemiConductor Tracker. Nucl. Instr. Meth. A 457 (2001) 369.

[6] Radiation hardness and lifetime studies of the VCSELs for the ATLAS semiconductor tracker, Nucl. Instr. Meth. A497 (2003) 294.

[7] Radiation Hardness and Lifetime Studies of the Photodiodes for the Optical Readout of the ATLAS SCT. Nucl. Instr. Meth. A 456 (2000) 292

[8] M-L Chu et al, The Off-Detector Opto-electronics for the Optical Links of the ATLAS SemiConductor Tracker and Pixel Detector, Nucl Inst. Meth.A530 (2004) 293.

[9] T.J. Barber et al., Resonant Bond Wire Vibrations in the ATLAS SemiConductor Tracker, Nucl. Instr. Meth. A538 (2005) 442.

[10] J. Butterworth et al, TTC Interface Modules for ATLAS Read-Out, LECC 2004, CERN ATL-COM-ELEC-2005-001, 320-324.

[11] Neitzert et al, Sensitivity of Proton Implanted VCSELs to ESD Pulses, IEEE Journal Selected Topics in Quantum Electronics, Vol 7, No 2 March 2001.