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An automatic probe station to test Silicon Microstrip Detectors

M.D. Gibson, P.W. Phillips*

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK

ABSTRACT

Equipment has been assembled to make automated, fast, repetitive electrical tests of Silicon Microstrip detectors. Custom software has been written using the LabVIEW package, bringing together off the shelf hardware from a variety of manufacturers to perform as one specialist instrument. The system has been used successfully to evaluate over 150 detectors for the DELPHI experiment and more than 30 prototype detectors for the forthcoming ATLAS Silicon Tracker. Some of the work performed for DELPHI is briefly described.

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* Corresponding Author. E-mail P.W.Phillips@rl.ac.uk

1. INTRODUCTION

Silicon Microstrip detectors are now a proven technology within the Particle Physics community. In experiments based at particle colliders their use for vertex reconstruction is commonplace.

With each successive generation of "Silicon Trackers", the size of the detector assemblies is seen to increase. The barrel of the latest DELPHI Silicon Tracker [1] uses 640 silicon plaquettes, whereas the barrel of the future ATLAS Semiconductor Tracker could contain of order 10,000 single sided silicon plaquettes.

For the early experiments using Microstrip detectors, the plaquettes were often tested manually. This is a time consuming and error prone procedure. As the numbers of plaquettes used continues to increase, automated testing becomes essential.

Several research institutes and most detector manufacturers have recently assembled systems similar to that reported here. Although the majority of detectors for future experiments will be supplied tested at source, verification of manufacturer's results remains an important part of the ATLAS SCT programme.

2. HARDWARE

A schematic of the Hardware is shown in Figure 1. Vacuum plumbing and such wiring as may be needed to make an individual measurement have not been shown.

The system is built around a Wentworth Laboratories AW1080 Automatic Probe Station, fitted with a Carl Zeiss/JVC Video Microscopy system using coaxial illumination. The probe station sits inside a light tight enclosure and, together with the electrical test equipment, is interfaced to a Macintosh computer using GPIB (General Purpose Interface Bus).

During routine operations the user sits at the computer, away from the probe station, and monitors progress on a video screen. A second monitor is located adjacent to the probe station for use during manual operations.

To make automatic step and repeat probe measurements, a single probe needle is mounted on a standard Wentworth probe card. The camera is aligned such that the needle tip is coincident with electronic cross wires. For automatic operation, it is important that the chuck (or sub-chuck) be adjusted to be parallel to the plane of XY travel. For operations requiring more than one probe needle, four Wentworth PR-240 manual probe bases are provided.

Test and measurement equipment has been assembled as summarised in Appendix 1. The two main units are a Hewlett Packard 4285A LCR Meter and a Keithley 237 High Voltage Source/Measure unit. This combination enables measurements of capacitance and current to be made as a function of voltage.

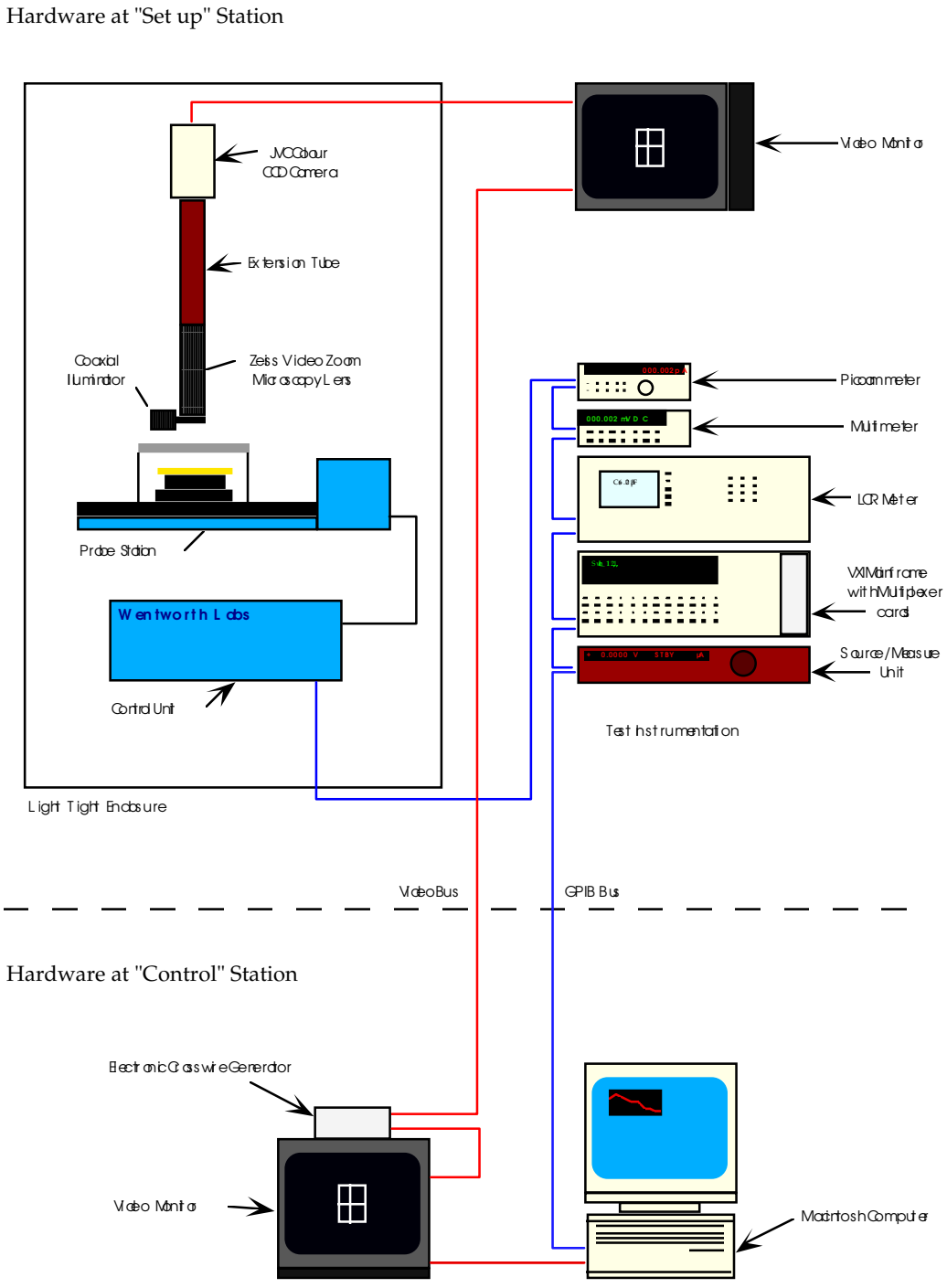

Figure 1: Schematic of Probe Station Hardware

These units were chosen bearing in mind likely requirements for testing detectors for the ATLAS experiment, namely:

- High Frequency Operation, approaching the LHC bunch crossing frequency of 40Mhz

- High Voltage Operation, necessary to ensure efficient charge collection during several years of detector operation in a high radiation environment

Although the Keithley unit can deliver a potential difference of over 1kV, its output is passed through a protection network which limits the maximum available potential to +/- 200 volts with respect to ground, in conformance with safety regulations. Similarly, the HP LCR meter can only withstand 40V potential difference across its terminals, so an external protection circuit has been added to make the system robust for 200 volt operation.

A Hewlett Packard 75000 VXI mainframe is provided. This unit presently contains two HP 66201 16 channel multiplexer cards. These cards enable signals from many probe needles (or bonded connections) to be routed to the instrumentation.

Other instruments are available for manual use only, including a Hewlett Packard 34401A multimeter and a Keithley 486 picoammeter. Both of these units have been purchased bearing in mind their GPIB capabilities, and will be integrated with the DAQ software as required.

The camera output is also connected to a high quality digital frame grabber to enable images of detectors to be recorded during testing.

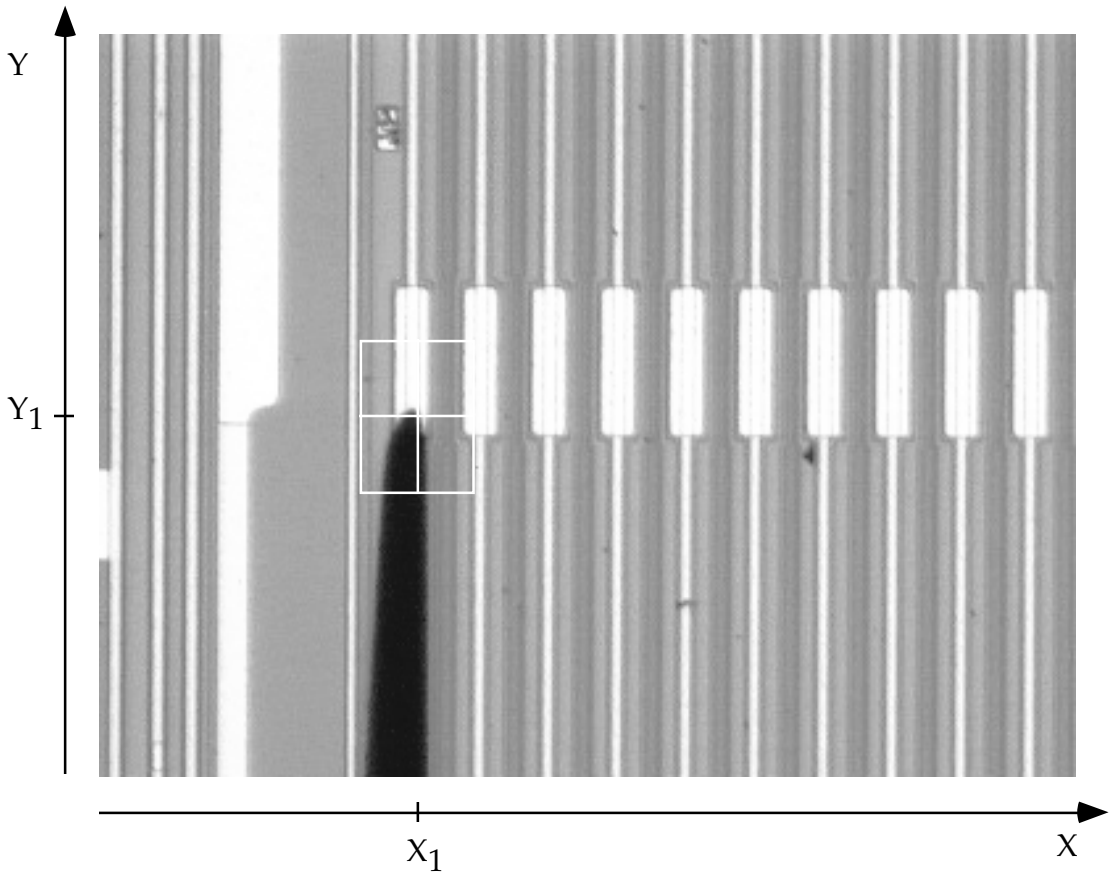

Figure 2: The Co-ordinate System

3. SOFTWARE

3.1. Shell

Software has been written using the LabVIEW®[1] package to provide a user friendly, graphical front end. Software drivers were available for the majority of the electrical test units in use, thereby saving development time.

The Step and Repeat function is built around the assumption that, for a given detector, there will be a number of bond pads equally distributed between one or two rows. The location of the nth pad is calculated to the following formulae:

odd strips $$(X_n, Y_n) = \frac{(N-n)(X_1, Y_1) + n(X_2, Y_2)}{N}$$

even strips $$(X_n, Y_n) = (X_e, Y_e) + \frac{(N-n)(X_1, Y_1) + n(X_2, Y_2)}{N}$$

given that

N	total number of pads to be probed
(X_1,Y_1)	position of first pad to be probed
(X_2,Y_2)	position of final pad to be probed
(X_e,Y_e)	Offset between odd- and even-numbered pads

for the co-ordinate system shown in Figure 2.

A manual rotation stage is used to align the detector to the system axes. The operator uses controls on the computer screen to move the detector under the camera until the crosswires, to which the needle has been aligned, are located over the first pad to be probed. This location is stored, and the procedure repeated for the final pad to be probed. The position of any pad in this series can now be calculated by the software, given that the total number of pads in the series is known.

The probe station chuck can be raised to bring the sample under test into contact with the probe needle. The system uses three "lift" values. The lowest value represents fully down. The middle value defines the plane used whilst aligning the sample: during normal operations, the camera is focused to this plane. The uppermost value represents the lift required to bring the probe needle into contact with the detector. This is determined empirically such that good contact is achieved without undue damage to the bond pad surface. The "Probe Lift" is adjustable in 2.5 micron increments, whereas the other two planes can be set in 25 micron steps only.

The operator can define a safety boundary. Any attempt to move outside this boundary with the chuck raised to the middle position will automatically drop the chuck to the lowest plane. This is useful, for example, if the detector under

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[1] LabVIEW® is a trademark of National Instruments Corporation, Austin, Texas.

investigation has been mounted in a frame to facilitate the connection of detector bias by wirebonding. Any accidental contact between the frame and the probe needle would damage the needle.

The software also includes the facility to return directly to any pad returning abnormal test data, and repeat the measurement. This is useful in the case of poor probe contact, such as may occur given a contaminated or uneven detector surface. A "STOP" Button is provided to interrupt the step and repeat sequence, should an error occur.

3.2. Test Functions

The software has been written from the start to be as general as possible. Each of the main test functions is performed by a subroutine with its own output window. Any combination of the following functions can be performed, either for a single location or for each location during a step and repeat operation:

3.2.1. Sweep [C(f)]

This routine returns parameters LCR1 (e.g. Cs) and LCR2 (e.g. Rs) from the LCR meter as a function of frequency. The LCR meter measures impedance and interprets the data as instructed by the user. For the majority of work performed so far the LCR meter has been used in the Cs-Rs mode. This measures a capacitance assuming that its series resistance is small compared to its parallel resistance.

In the case of an AC coupled detector, the parallel resistance is analogous to the DC resistance of the coupling oxide. If there is a pinhole defect in the coupling oxide, the parallel resistance falls dramatically and a large values of capacitance is returned.

Given the high resolution of the RAL system, as demonstrated later, a single capacitance measurement between each strip and the detector backplane can be used as a fast check of strip continuity.

3.2.2. Unbroken Stair [I(V)]

The Keithley 237 Source/Measure unit has internal software to generate a number of V(t) functions, or "Voltage Ramps", e.g. "Linear Stair". The LabVIEW software enables the user to concatenate a number of these V(t) functions to produce non-standard ramps. A current measurement is taken after each voltage level has been held for a programmed time interval.

This function can be used to measure Leakage Current as a function of voltage, V, or to test for pinholes in the coupling oxide of AC coupled Microstrip detectors.

3.2.3. Broken Stair [(C(f))(V)]

A frequency sweep is performed at each level of a voltage stair. A CV curve can thus be taken to determine the depletion voltage of a detector.

3.2.4. Pause

This facility was included to allow the step and repeat shell to be used together with non-interfaced hardware.

It is also possible to operate a relay switch during each stage of the testing operation, since different wiring arrangements may be required.

It should be noted that a reliable software current limit can be set for all operations involving the Keithley source/measure unit. This enables pinhole tests to be made in confidence, and protects against the accidental application of bias to a detector subjected to incident light.

3.3. Output

In its present form, the software will display a number of on line graphs including:

- LCR parameter 1 or 2 vs. Strip Number, n, for given Frequency, f
- LCR parameter 1 or 2 vs. Frequency, f, for given Strip Number, n
- Current, I, vs. Strip Number, n, for given Voltage ,V
- Current, I, vs. Voltage, V, for given Strip Number, n
- LCR parameter 1 or 2 vs. Strip Number for given Voltage, V
- LCR parameter 1 or 2 vs. Voltage, V, for given Strip Number, n

For any graph which can be displayed, an ASCII format file can be generated, such as can be read into a spreadsheet program. It is realised that for routine, production testing the present storage method is not the most efficient use of disk space. This will be addressed in a future version of the software.

There exist a number of accessory programs, again written in LabVIEW®, which generate plots of data from files saved by the probe station software. Examples of output from such programs are given in Figures 5, 7, 11 and 12.

4. SOME RESULTS FROM THE PROBE STATION

4.1. DELPHI RZ Plaquettes

4.1.1. Introduction

A sketch of a DELPHI RZ-320 silicon Microstrip detector[2] is shown in Figure 3. These detectors are used in the production of detector modules for the OUTER layer of the DELPHI Silicon Tracker [1].

These detectors are single sided, double metal, AC coupled designs. There are 1280 p+ diode implants in the p side of the detector. Above this an oxide layer is grown, and an aluminium layer (the Metal 1 layer) is deposited. Using a photoresist process, this is then chemically etched away to leave a number of metal strips. These are the readout lines, forming coupling capacitors through which charge collected by the diode implants can be transferred.

Above this, a film of polyimide 5μm thick is spun, and chemically removed where appropriate to leave contact windows down to the Metal 1 layer. Above the polyimide film, a second metal layer is processed to leave aluminium strips running perpendicular to the readout strips. Signals from the Metal 1 readout lines can be passed to readout electronics at the end of the detector by virtue of the Metal 2 "routing lines".

In this design two adjacent diode implants out of every four have Metal 1 readout lines above them. Each pair of readout lines is connected to one routing line through holes in the polyimide layer. Hence only half of the 640 routing lines are connected to readout lines, the remainder being left to allow connection to an adjacent plaquette in an assembled detector module.

A number of defects may occur during the fabrication of these devices. At the simplest level, the detector surface may be scratched, breaking a number of metal lines. Minor errors during the processing of the metal layers, or the polyimide layer, may result in a number of strips being shorted together. It is important that the dead area of each detector be kept as small as possible, hence the number of faulty strips must be carefully monitored. Most manufacturers of silicon Microstrip detectors now make measurements of the capacitance between each strip and the detector backplane to identify faulty strips at source.

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[2] Detectors of the similar RZ-640 design have also been tested by an identical method: this work is not described here.

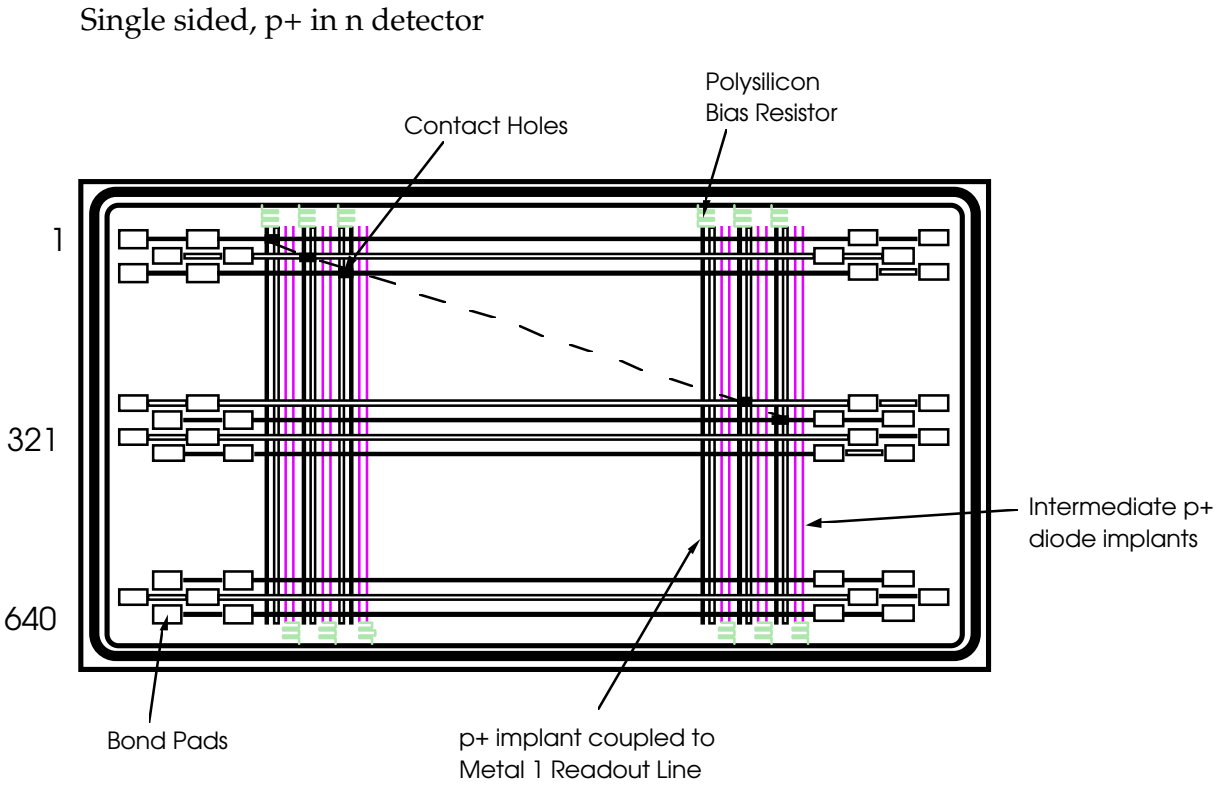


Figure 3: DELPHI RZ-320 Detector

The manufacturer of these devices was originally unable to measure the capacitance of routing lines not connected to readout lines: their test system was subject to random error of similar magnitude to the capacitance of these lines. Under ambient lighting conditions, the capacitance measured between a single Metal 2 routing line and the backplane of an unbiased detector is typically an order of magnitude less than that measured for a Metal 2 routing line connected to two Metal 1 readout lines. Hence the detectors were supplied with only the readout lines having been tested.

It had been assumed that the number of broken routing lines in the region not previously tested would not be statistically different from the number of broken routing lines in the tested region, but early results suggested otherwise. The first deliveries of RZ-320 detectors were evaluated by collaborators in Karlsruhe [2]. It was found that the resistance of lines in the top metal layer was often rather high, and unexpectedly large numbers of these lines were broken. The RAL probe station offered the possibility to obtain bulk statistics for these detectors quickly.

4.1.2. Method

The circuit diagram used for these tests is shown in Figure 4.

For the early tests, each detector was placed face up directly on the gold plated platter of the Wentworth probe station, and held down under vacuum. Later detectors were tested using an aluminium sub-chuck mounted on the probe station platter, topped with a conductive rubber sheet.

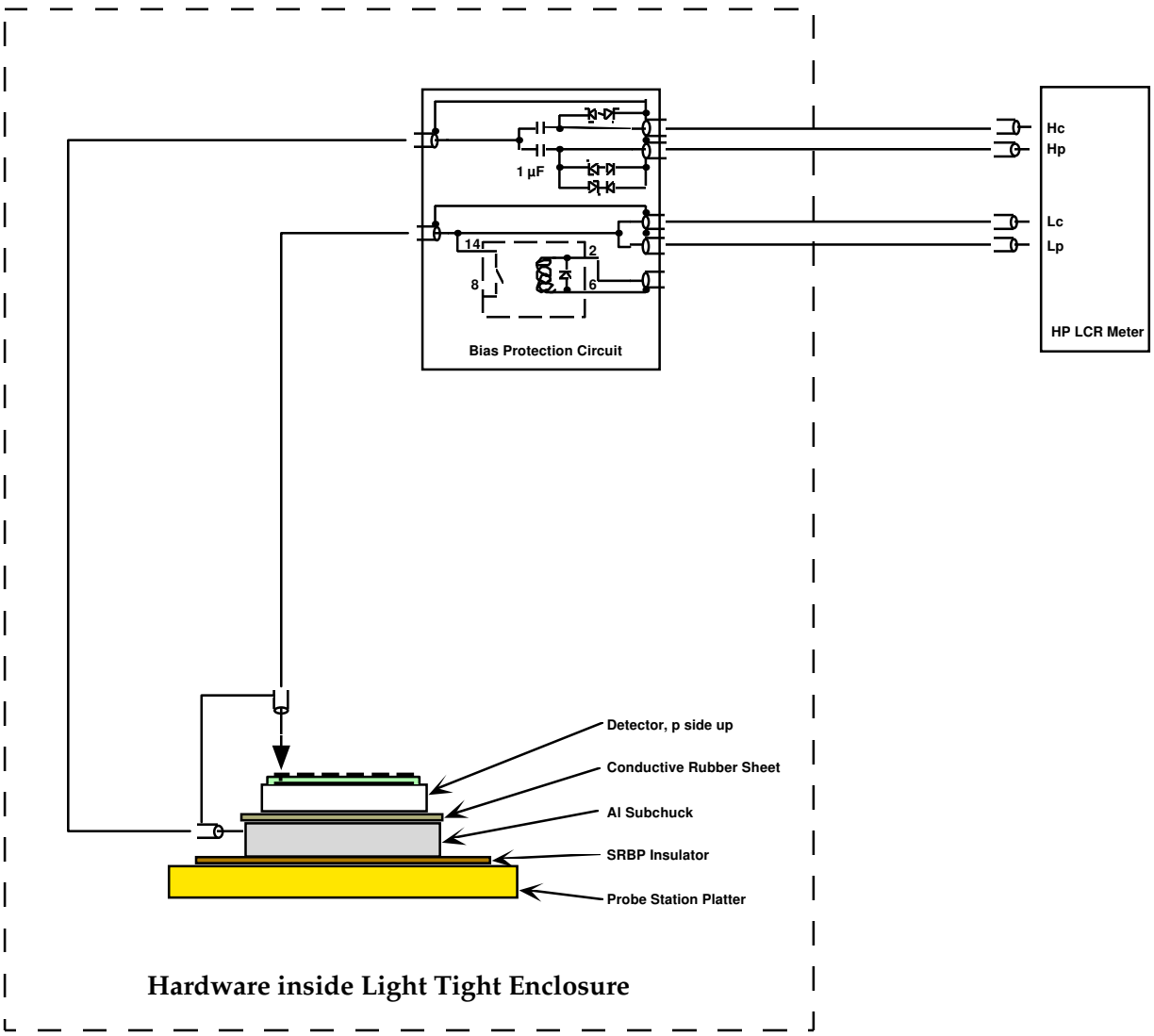


Figure 4: Circuit Diagram for RZ-320 Tests

A single needle mounted on a probe card was used to probe one bond pad of each strip in turn. At each location a single measurement of capacitance was made between the strip and the chuck (in contact with the detector backplane). Measurements were made without bias under ambient lighting conditions.

Any channels which returned abnormal data were retested to ensure that such results were not artefacts of poor probe contact. If necessary, strips were tested at both ends

to distinguish between broken lines in metal layers 1 and 2. Strip abnormalities were classified as follows:

- Broken M2 line $C < C_{M2}$ at both ends of the plaquette
- Broken M1 line or failed M1-M2 contact $C_{M2} < C < C_{norm}$ at both ends of the plaquette
- M2 short $C \approx n\, C_{norm}$ for n adjacent strips
- M1/M2 short $C \approx n\, C_{norm}$ for n non-adjacent strips
- Pinhole $C >> C_{M2}$ for a single strip

where C_{M2} typical value for an unconnected M2 routing line

C_{norm} typical value obtained for capacitance of a normal strip (i.e. routing line + 1 or 2 readout lines)

Broken M1 lines or failed M1-M2 contacts do not affect the transmission of signals from further along a detector module, and are deemed "non-propagating". Pinholes and M2 breaks are clearly "propagating" defects. Shorted strips often result in a current flow between two or more channels of readout electronics since no two input amplifiers sit at exactly the same potential. In practice, only one out of each group of shorted channels is connected to the electronics: for purposes of quality evaluation, one propagating defect was counted for every pair of shorted strips.

On the basis of the total number of propagating and non-propagating defects found, each detector was placed into one of three categories:

- PASS < 6 propagating defects AND <11 non-propagating defects
- HOLD < 8 propagating defects AND <11 non-propagating defects
- FAIL > 7 propagating defects OR >10 non-propagating defects

The HOLD detectors were kept in case insufficient PASS detectors, with less than 0.8% of their strips affected by propagating defects, were available. Detectors placed provisionally in either of these two categories were taken to Oxford University [3], where it was verified that the polysilicon bias resistors, bias current and leakage current of each device were to specification.

4.1.3. Early Results

A typical result for an early detector is shown in Figure 6.

Note firstly that slightly different values are obtained for the capacitance of odd and even strips. This is because odd-numbered routing lines are slightly longer than the

even-numbered ones, due to the arrangement of the bond pads. Ignoring broken channels, it can be seen from the data presented that the precision of measurement is better than 0.1pF. This particular detector was found to have a total of 13 broken lines in the Metal 2 layer.

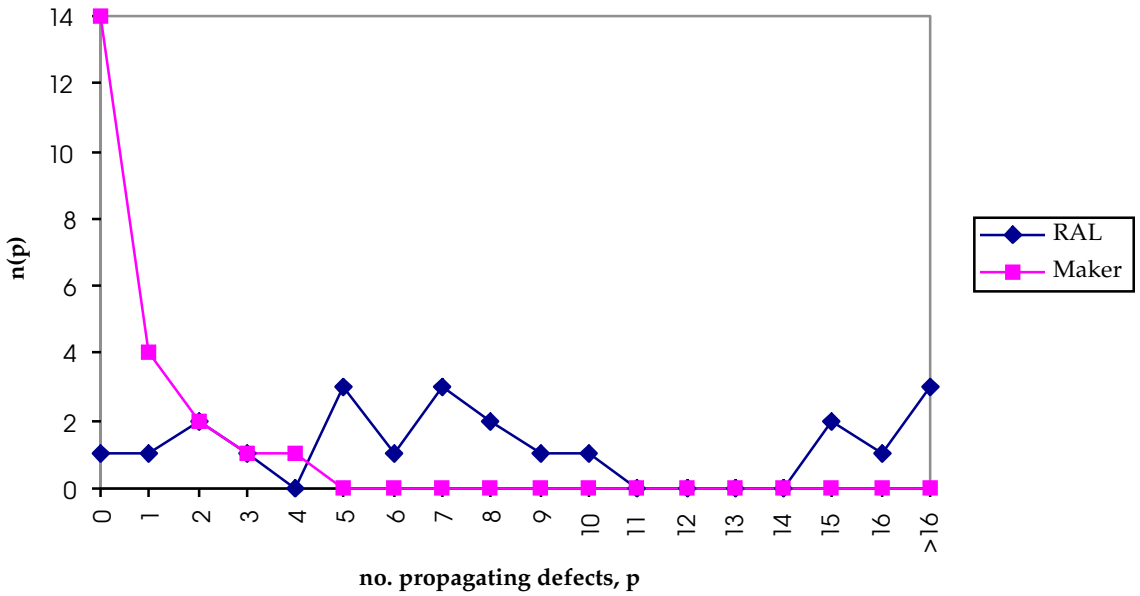


Figure 5: Propagating defects in Early RZ-320 Detectors

Figure 5 shows the number of propagating defects found for a sample of 22 early RZ-320 detectors tested at RAL. Data is also shown from the manufacturer, who tested only those Metal 2 lines connected to Metal 1 lines. One might have expected the RAL tests to yield a similar, but longer tailed distribution to that reported by the manufacturer. In the event a much broader and flatter distribution was established. Similar data was obtained for early RZ-320 detectors tested at other collaborating institutes.

It was eventually established that the early detectors had degraded after shipping, due to use of unsuitable packing material. The mechanism was one of attack of the polyimide layer by gas evolved from antistatic plastic sheeting. The manufacturer replaced the affected devices.

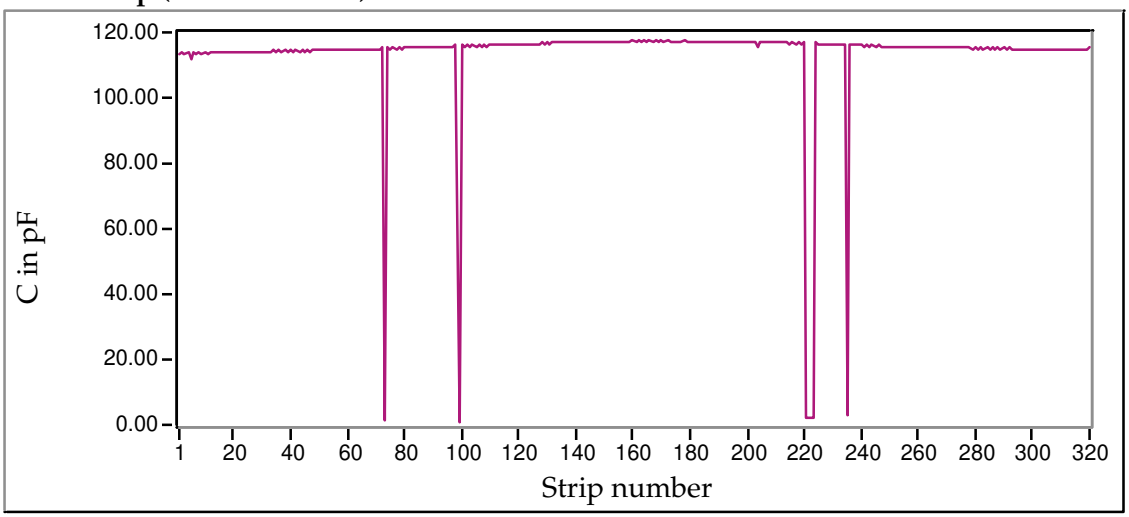
4.1.4. Later Results

A typical result for a later detector is shown in Figure 7. This particular plaquette was found to have only one defect, a broken line in the Metal 2 layer. The capacitance measured between each routing line and the detector backplane has increased slightly due to minor design changes in the bond pad region.

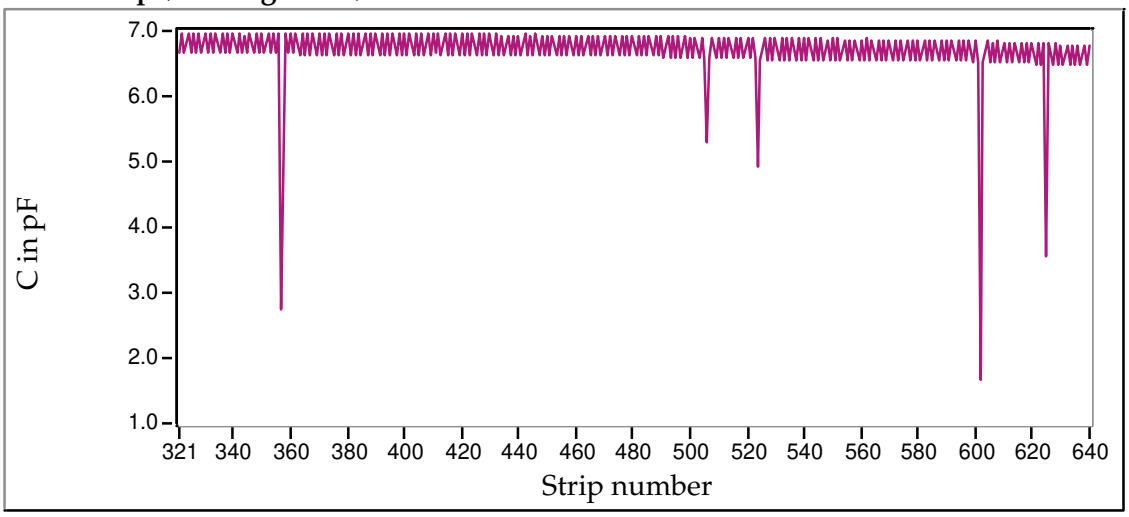
RZ-320 Test Sheet

Date:	8/12/94
Detector Type:	RZ 320
Detector No:	S1-32B
Side:	-
Tested by:	MDG

Cs vs Strip (Readout Lines)



Cs vs Strip (Routing Lines)



Comments

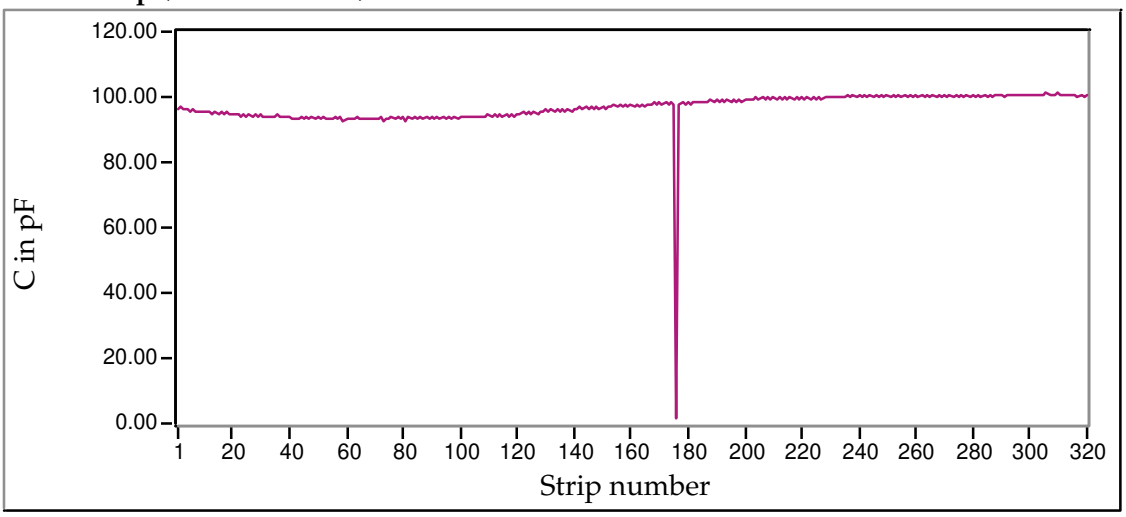
Readout lines: 8 broken M2 (5, 73, 99, 204, 221, 222, 223, 235)
Routing Lines: 5 broken M2 (357, 506, 524, 602, 625)

Figure 6: Typical Early RZ-320 Result

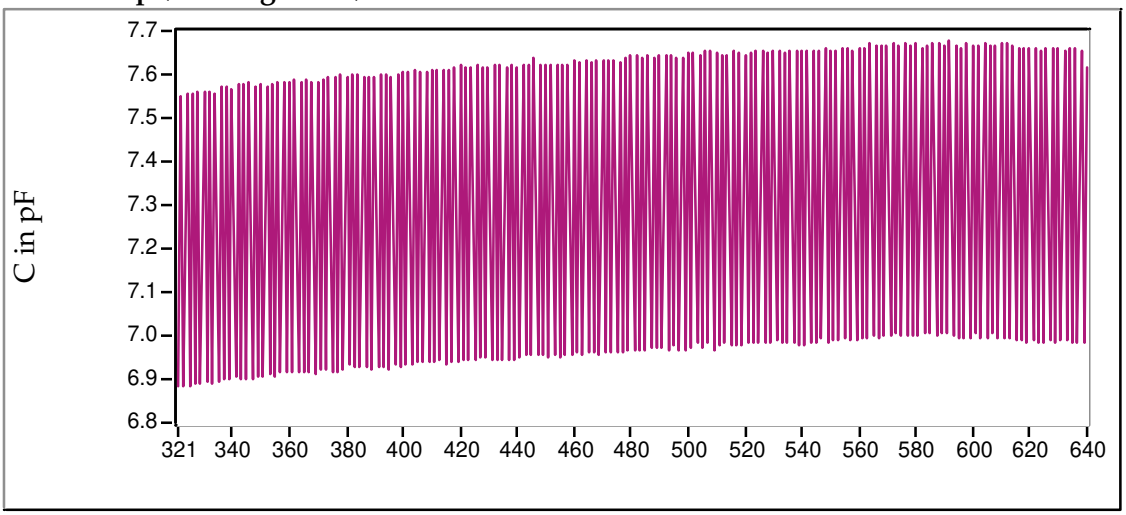
RZ-320 Test Sheet

Date:	12/1/96
Detector Type:	RZ 320
Detector No:	S4-219B
Side:	-
Tested by:	PWP

Cs vs Strip (Readout Lines)



Cs vs Strip (Routing Lines)



Comments

176 cut

Figure 7: Typical Late RZ-320 Result

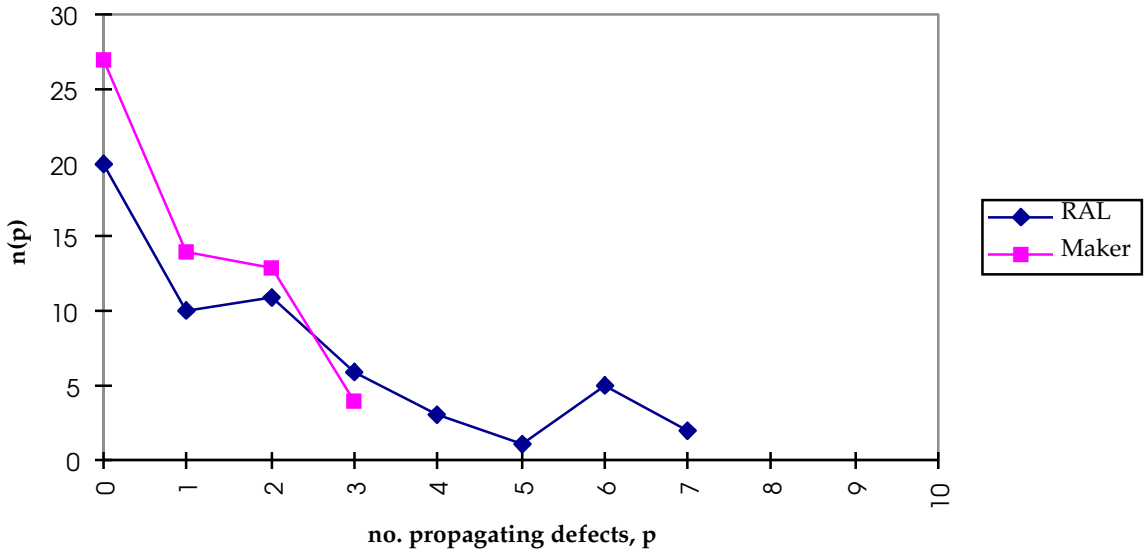


Figure 8: Propagating defects in Later RZ-320 Detectors

A histogram of the number of propagating defects found in all 65 later RZ-320 plaquette tests are shown in Figure 8. Again, the manufacturer's data is also shown, although for 9 of the detectors the manufacturer's data includes the number of broken routing lines. Only two detectors fell into the FAIL category, the remainder being categorised as PASS or HOLD.

By the time of the final shipment of 16 detectors, the manufacturer had upgraded their test equipment to identify defective routing lines. Nine detectors from this batch were tested at RAL, and the strips identified as defective matched exactly data provided by the manufacturer.

4.2. DELPHI DS Plaquettes

4.2.1. Introduction

A sketch of a DELPHI DS-385/79 silicon Microstrip detector[3] is shown in Figure 9. These detectors are used in the production of modules for the CLOSER layer of the DELPHI Silicon Tracker (formerly the DELPHI Microvertex Detector [1]).

[3] Detectors of the similar DS-385/60 design have also been tested by an identical method: this work is not described here.

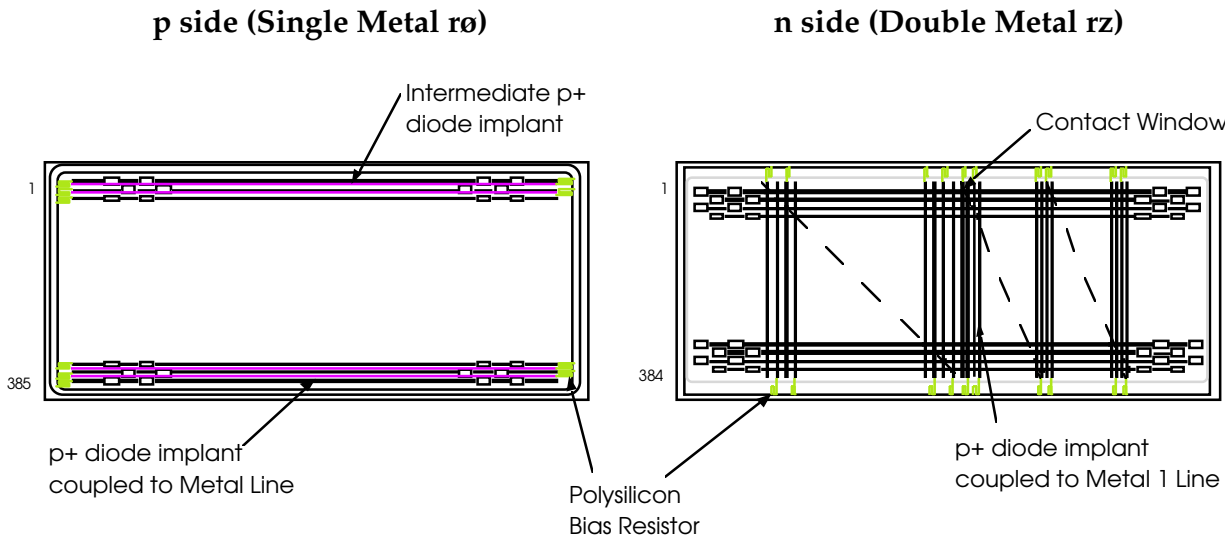


Figure 9: DELPHI DS-385/79 Detector

These detectors are double sided AC coupled designs. The p side is processed using a single metal technique to provide rϕ track information whilst the n side is processed using a double metal technique to provide RZ track information through readout at one end of the detector, similar to the single sided RZ detectors outlined above.

Silicon Microstrip detector readout systems generally expect the readout strips to be able to float to the nominal voltage level of the input amplifier, typically 3.5 volts. To fully deplete a silicon detector of this particular design the n side must be maintained at a positive potential of 60 volts or more. Should a pinhole defect develop in the coupling oxide on the n side, resulting in ohmic connection across the coupling capacitance of a particular strip, a large current flows into the readout chip. This disturbs both the function of the readout chip and the function of the detector, by virtue of the disturbed electric field. The performance of up to fifty strips may be affected by a single n side pinhole.

During the testing of these devices, the coupling oxide of each strip on the n side must be stressed to 100V to verify its ability to withstand operational voltages[4]. At the time of writing, the manufacturer was unable to perform this testing.

4.2.2. Method

A diagram of the circuit used at RAL is shown in Figure 10.

[4] In fact, pinholes are seen to form throughout a detector's life, although the probability of occurrence of new pinholes falls exponentially with time. The above test is still useful to identify "bad" detectors since those with manufacturing defects in the oxide layer will develop many pinholes immediately.

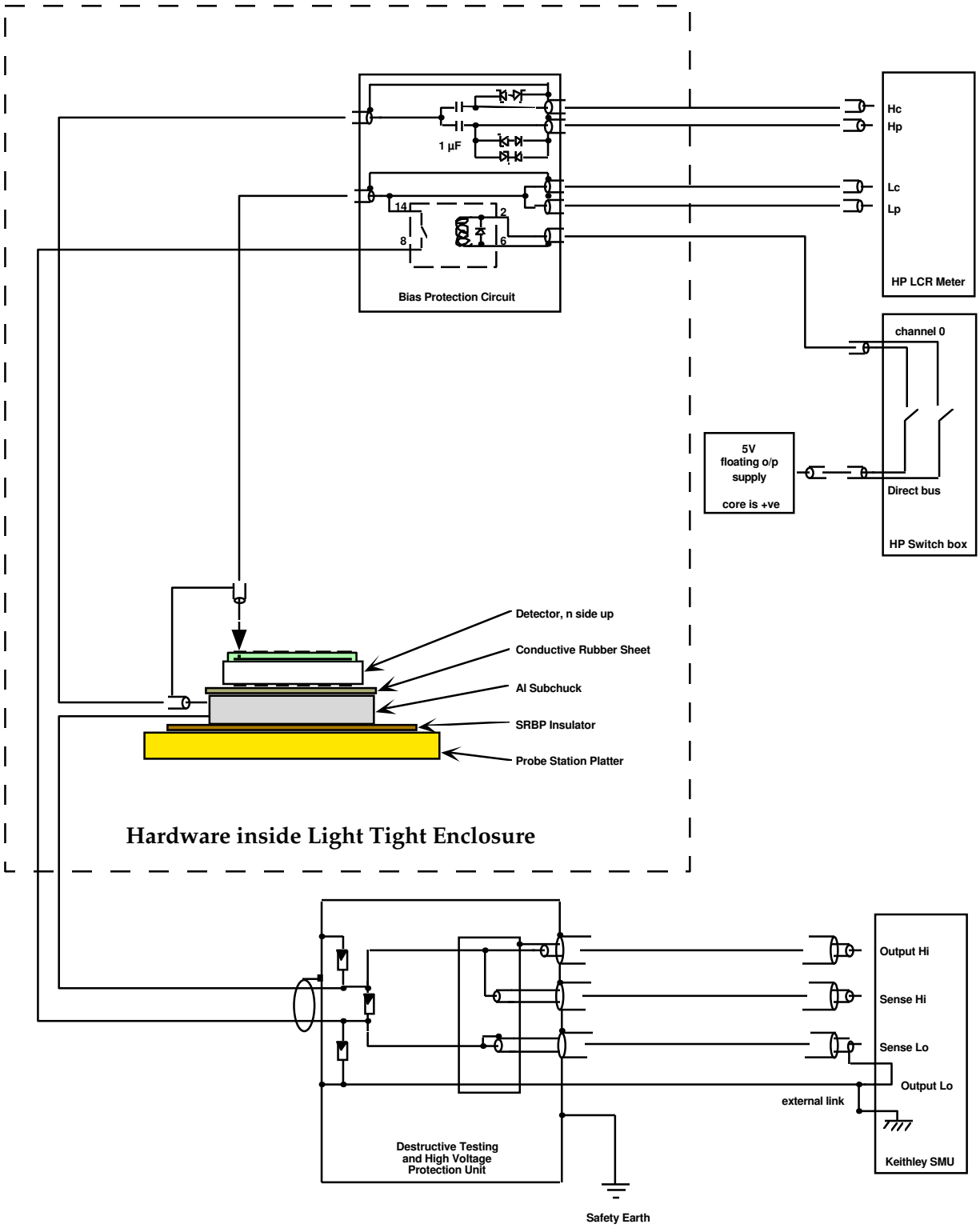


Figure 10: Circuit Diagram for DS-385/79 tests

Because both sides of these detectors have been processed, extra precautions were taken to prevent damage to the side not under investigation. Before each test, a sheet of conductive rubber was cleaned with alcohol and laid on top of a vacuum chuck on the probe station platter. A can of aerosol dust remover was then used to remove any

remaining particulate dust. The detector to be tested was then placed onto the rubber sheet, n side uppermost, and held under vacuum.

The detector was roughly aligned to the machine axes by means of a manual rotation stage on the probe station chuck, and the co-ordinates of the first and last probe positions were established by the operator. Next, the lift necessary to make good contact between probe needle and sample was determined empirically, raising the chuck in small steps until reliable capacitance measurements could be made for strips selected at random across the detector. At this stage, the light was turned off.

The software was set to perform the following sequence at each of the probe locations:

- Measure Capacitance
- Close relay, shorting the probe needle to ground potential.
- Ramp the p side of the detector to +100 volts with respect to ground. Under these circumstances the detector is forward biased, hence depletion does not occur. The silicon acts as a conductor and the n side floats to 100V. Hence the coupling oxide of the probed strip is stressed to 100 volts potential.
- Wait for the charging current to fall to steady state values.
- Make Current Measurement
- Ramp down to 0V
- Open Relay

Any strip for which the measured current was equal to the programmed current limit was deemed to have a pinhole defect in the coupling oxide. In the event that the capacitance measurement was so low as to suggest a probe contact failure, the strip was retested. Strips returning anomalous capacitance values were classified as outlined for the DELPHI RZ detectors.

If the n side of a detector proved unacceptable, no further testing was performed, otherwise the simpler p side was also tested. A single capacitance measurement was taken for each strip. Pinhole testing was not performed since the p side of a detector operates at a much lower potential than the n side. The single metal processing gives rise to fewer possible causes of defects than a double metal process, hence the classification of defects was more straightforward for the p side of these detectors.

The acceptance criteria for the DS detectors was simpler than that for the RZ detectors: no distinction was made between propagating and non-propagating defects. All detectors with less than 1% defective strips were taken Oxford University [3], where it was verified that their leakage currents were within specification.

4.2.3. Results

Typical results for a detector from batch S6 are shown in Figure 11 and Figure . Only one strip was found to be defective for this detector: a pinhole on the n side. All twenty detectors supplied from this batch were to specification regarding the total number of strip defects. No detector was found to have more than 2 pinholes on the n side.

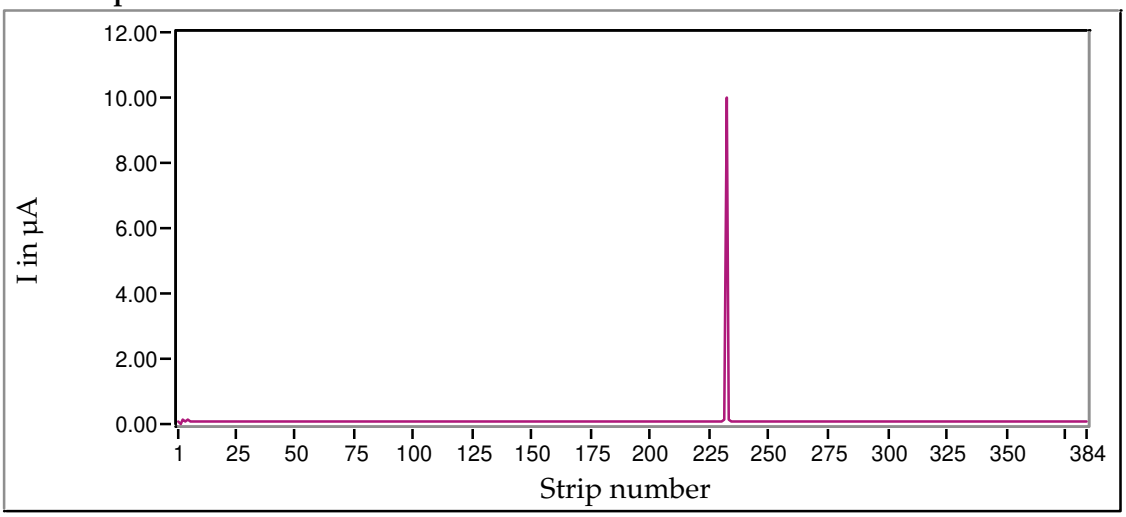
5. CONCLUSION

An automatic probe station was purchased and successfully integrated with test instrumentation. Its usefulness in a post-production environment has been proven. The ability to test detectors quickly and accurately has helped to reduce the dead area of finished detector modules and information fed back to manufacturers has helped to improve the quality of subsequent devices.

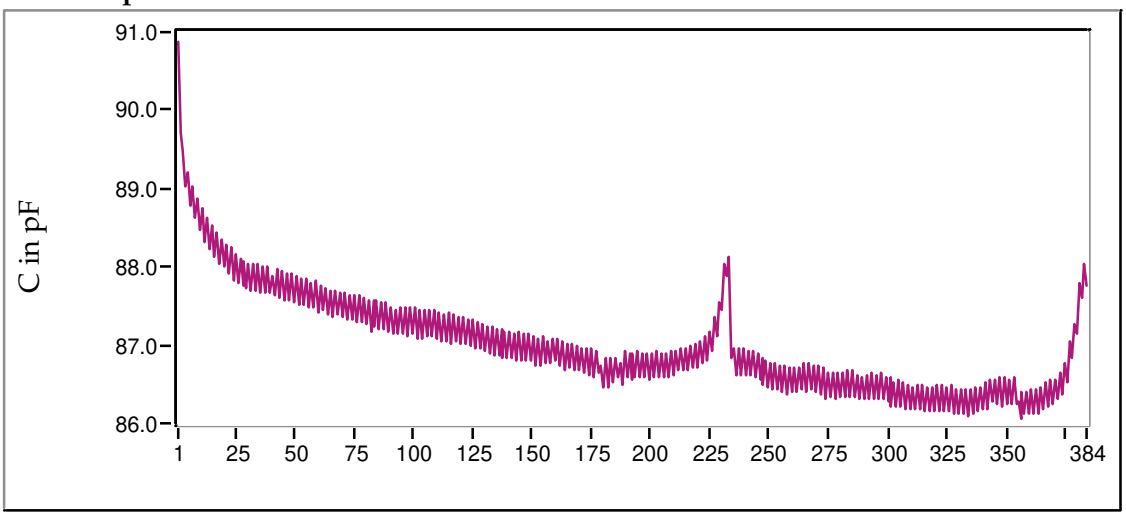
Pinhole Test Sheet

Date:	15/1/96
Detector Type:	DS-385/79
Detector No:	S6-10B
Side:	n side
Tested by:	PWP

I vs Strip



C vs Strip



Comments

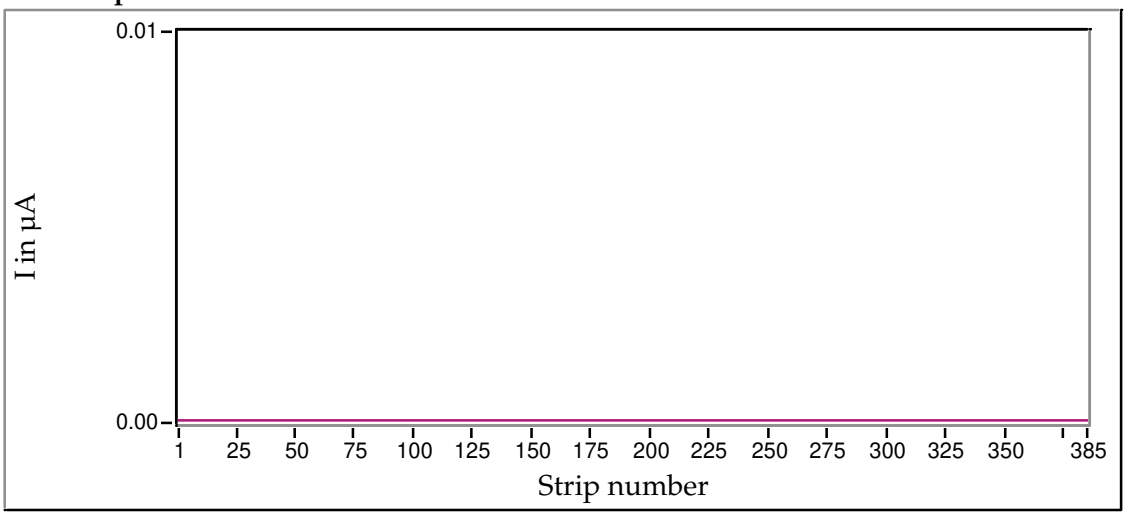
1 pinhole: strip 232

Figure 11: Typical n side Result from batch S6

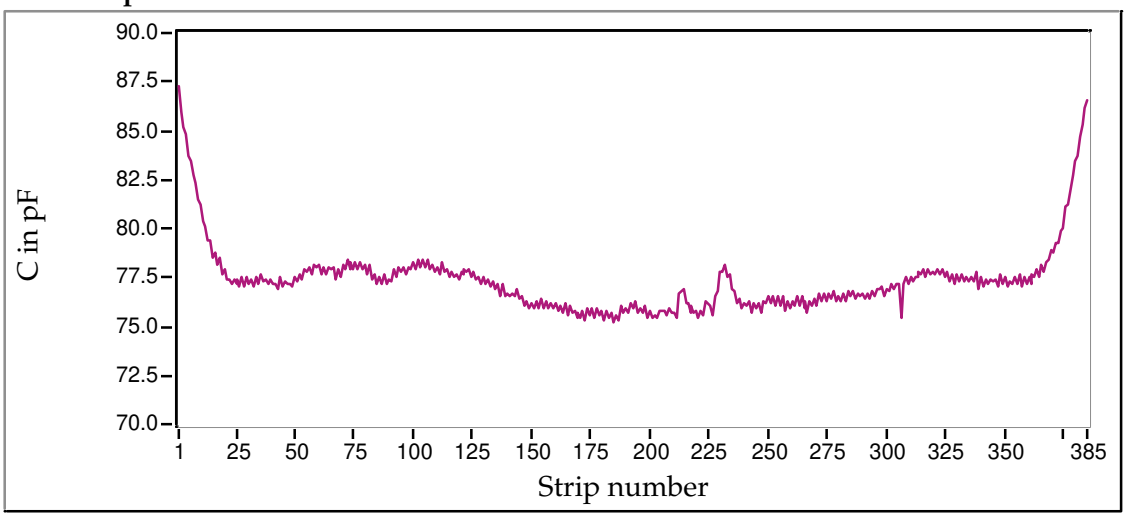
Pinhole Test Sheet

Date:	15/1/96
Detector Type:	DS-385/79
Detector No:	S6-10B
Side:	p side
Tested by:	PWP

I vs Strip



C vs Strip



Comments

Cs Scan: p side perfect
Pinhole test not performed

Figure 12: Typical p side Result from batch S6

6. APPENDIX 1: TEST AND MEASUREMENT EQUIPMENT

Item	Description	Key Features
HP 4285A	LCR Meter	HPIB controllable 75kHz - 30Mhz operation
HP 34401A	Multimeter	HPIB controllable
HP 75000 HP E1345A	VXI Mainframe, containing 16 channel Multiplexer (2 off)	HPIB controllable
Keithley 237	Source Measure unit	GPIB controllable Source 0 -1100 volts Measure I with 5 digit resolution Programmable Compliance (current limit)
Keithley 486	Picoammeter	GPIB controllable 10fA sensitivity
Kingshill	150V manual power supply	Linear supply, manual control. Used to apply bias in some applications.

7. REFERENCES

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