

A practical guide for measuring and radiating diodes intended for research on intense x-ray radiation tolerant silicon detectors

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1 Introduction

1.1 Motivation

As large x-rays with higher and higher luminosities are emerging, there is a demand for more radiation tolerant detectors. This is especially the case with the upcoming European X-Ray Laser Project XFEL, which will supply low energy but high flux radiation. Silicon detectors have been a very successful type of detector in many high energy physics applications and are also aspired for upcoming x-ray light sources. Yet most of the detector research has been done in high energy physics and not much is known about radiation hardness at low photon energies with high

flux. It is even thinkable that silicon detectors turn out to be unsuitable for many applications in very high luminosity light sources. In [5] a systematic measurement procedure was proposed by irradiating pn junction diodes in certain well defined steps and after each step characteristic measurements of the diode are taken, which tells us something about defects in the silicon bulk, the semiconductor surface, the silicon oxide layer and so on at different radiation doses. These measurements are done with a special diode type, called a gated diode. During my participation at the DESY Summer Student Program I carried out such a measurement procedure with four different diodes, but will not be able to finish all proposed irradiation steps. This report is anticipated as a step by step guide on how such a measurement can be conducted given the infrastructure found at DESY so that other researchers in the future can continue or repeat this experiment and benefit from the practical experience I have gained in the past few weeks. This is why my report will concentrate on very practical issues (i.e. the proper usage of certain equipment found in the DESY labs) and only give a brief summary of the theory behind radiation defects found in diodes.

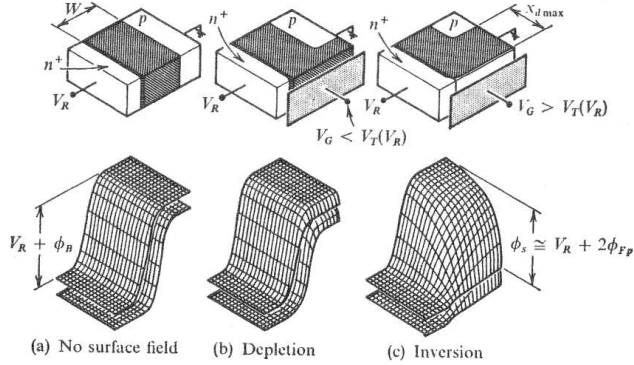


Figure 1: Depletion zone development and potential bending for different gate voltages

1.2 Theory

When a semiconductor is exposed to radiation, nuclear and chemical reactions take place and thus, by introducing defects into the material, dramatically change important characteristics of the semiconductor, i.e. the effective doping of the silicon. The defects play different roles depending on where they are generated. For example a defect in the depletion zone of a reverse biased diode will lead to a reverse current contribution because charge carriers can now be generated at such a defect. With the gated diode structure proposed in [2] it is possible to locate such defects. A gated diode is a pn junction and a metal gate that is separated by an insulator, as depicted in fig. 1. Let us first consider a pn junction without a gate or with a gate at an electric potential lower of that of the p substrate (fig. 1a). A depletion zone will form with the width according to the built in voltage of the semiconductor and the impressed bias voltage, as one would expect from a traditional diode. In fig. 1b the gate potential is increased to a potential higher than that of the p substrate and the charge carriers will be pushed away from the

surface under the gate, due to the electric field of the gate. This results in the build up of a depletion zone in this area. If we further increase the gate voltage (fig. 1a) then the energy bands in the semiconductor are bent to a level near the Fermi energy so that the electrons in the p substrate can jump into the conduction band and therefore move freely and act as charge carriers, thus inverting the p substrate right under the gate area. The voltage at which this takes place is called the inversion voltage. Therefore a measurement of the reverse bias current of the gated diode at different gate voltages can tell us which surface defect concentration the semiconductor has: at voltages lower than the inversion voltage the surface defects will contribute to the reverse current, because they lie inside the depletion zone. This additional current is called *surface generation current*. At voltages higher than or equal to the inversion voltage the surface defects cannot contribute to the reverse current, because now the area under the surface has been inverted and isn't depleted from charge carriers anymore. In this particular model we have neglected the effects of the insulator: if, for example, the insulator has positive trapped charges (i.e. due to radiation defects), then negative image charges will be induced into the silicon, requiring a higher gate potential than that of the p substrate to start to deplete the area just under the surface from charge carriers. The voltage of the potential needed to start the depletion of surface is called the *flat band voltage*¹ and can be determined by the voltage at which the surface defects start to contribute to the reverse current. Therefore the flat band voltage is an indirect measurement of properties

¹the number and location of trapped charges in the insulator is only one contribution to the flat band voltage

concerning the location and number of trapped charges in the insulator. The surface generation current, the flat band voltage and the inversion voltage are only three of many quantities one can derive from measurements with a gated diode with which we can gain information about changing diode characteristics with increasing irradiation. A more detailed description of characteristic diode quantities and their measurement with a gated diode is given in [2].

1.3 Overview

As we are interested in defects introduced by low energy but high flux light sources, the diodes need to be irradiated with intense x-ray radiation so the experiment can be conducted in a reasonable amount of time. The x-ray source used in this experiment was a synchrotron radiation beam. It was essential to understand this beam well enough to estimate what radiation dose was effectively deposited in the diode, if the diode was exposed to the radiation for a certain amount of time. Because the measurement of diode characteristics, like flat band voltage and surface generation current, take a lot of time and the facilities for measuring these quantities are not provided at the x-ray beam itself, a continuous observation of these properties while irradiation is not possible. Hence the diode is irradiated in certain steps. Before irradiating each diode the beam intensity is measured with a reference diode directly at the beam line. With this information the radiation time is calculated. After each irradiation step the diodes are taken to a lab with sophisticated equipment to measure characteristic diode curves, from which quantities like the flat band voltage and the surface generation current can be derived. To investigate annihilation effects the diodes were some-

Diode	Doping [cm^{-3}]	Depletion voltage [V]
CD22-50	$9.28 \cdot 10^{11}$	47.3
CD23-50	$1.17 \cdot 10^{12}$	72.0
CA03-50	$1.08 \cdot 10^{12}$	66.4
CA04-50	$1.11 \cdot 10^{12}$	68.4

Table 1: The characteristics of the diodes used in our experiment

times measured a second time after waiting a defined amount of time. Then the diodes went through another iteration of irradiation.

2 The Diodes

2.1 Diode Characteristics

The diodes used in our experiments are p⁺n diodes made out of detector grade silicon with a very low doping ($\approx 10^{12}cm^{-3}$) and therefore high resistivity ($\approx 5k\Omega cm$). The whole diode is about $280\mu m$ thick. The p⁺ side of the diode is structured and covered with a $1\mu m$ SiO₂ layer on which the metallic gate contacts reside. The exact doping of the irradiated diodes can be taken from table 2.1.

2.2 Diode Geometry

The geometry of the gated diode used in our experiments complies with the standard diode test field geometry used by the ROSE collaboration at CERN and is depicted in fig. 2. The diode that was irradiated is the lower right diode in the figure. Each of these diodes have five gate rings surrounding the actual pn junction in the middle. A more detailed description of this test field can be found in [3]. This test field and some other test elements are on each silicon die which is depicted in fig 3. It should be noted

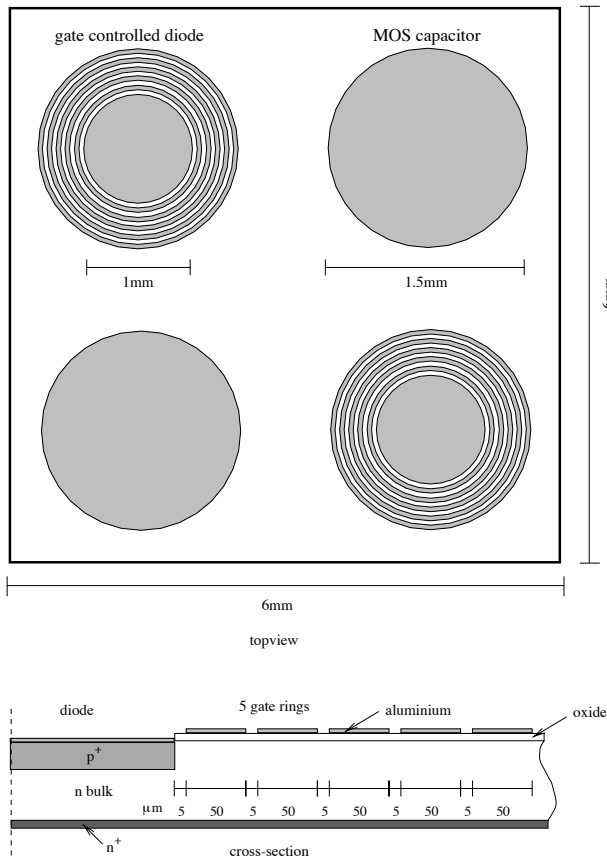


Figure 2: The test field structure of the diodes.

that the special geometry of the gated diode produces some complications when measuring, because the depletion zone doesn't grow in only one dimension with increasing gate potential, but more likely will grow in different directions into the silicon bulk simultaneously. This makes the evaluation of capacitance over bias voltage measurements an extremely non trivial task and hence this measurement was not conducted in our experiments.

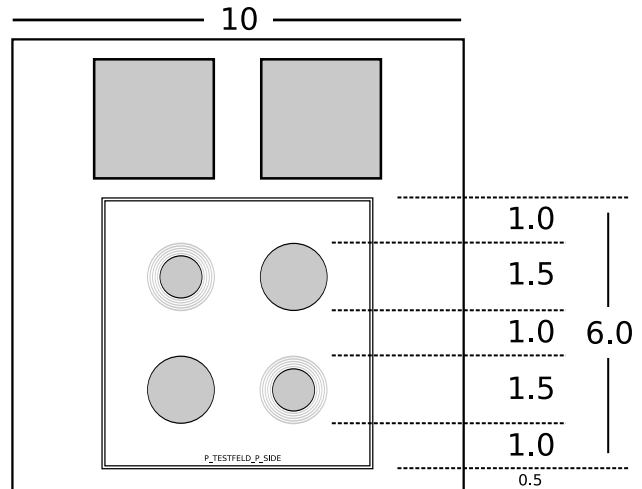


Figure 3: The die geometry. All units are in mm

Electrode	Assignment
Far left	Top bias
Left	First gate
Middle	Bottom bias
Right	second and third gate
Far right	fourth and fifth gate

Table 2: Electrode assignment as viewed from the top

2.3 The Ceramic

The die itself is glued and bonded onto a ceramic fixture depicted in fig. 4. The bonding connections are listed in table 2.

3 Irradiation Setup

3.1 Understanding the Beam

To determine the amount of time the diode has to be exposed to x-rays the radiation beam had to be well understood. The x-ray source used in this experiment was a synchrotron light source

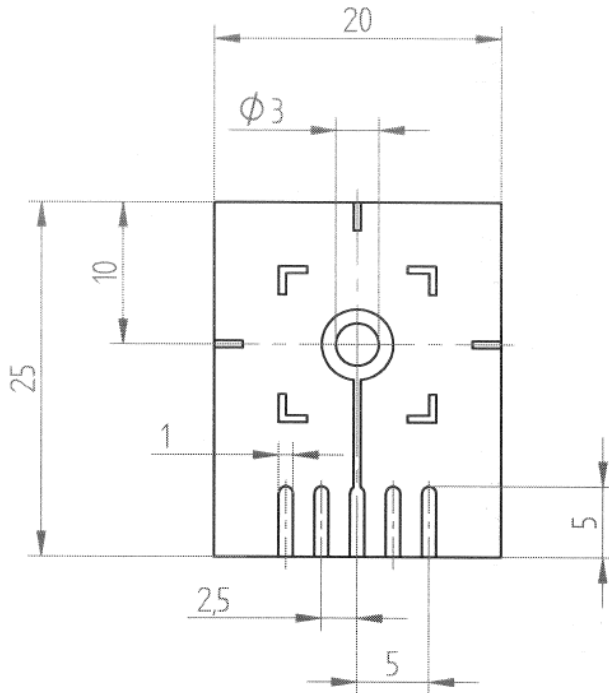


Figure 4: The ceramic holding the semiconductor die

Property	Value
Positron energy	4.45 GeV
Initial positron beam current	140 mA
Number of bunches	5
Magnetic field of bending magnet	1.2182 T
Critical photon energy	16.04 keV

Table 3: The beam parameters found at beam line F3

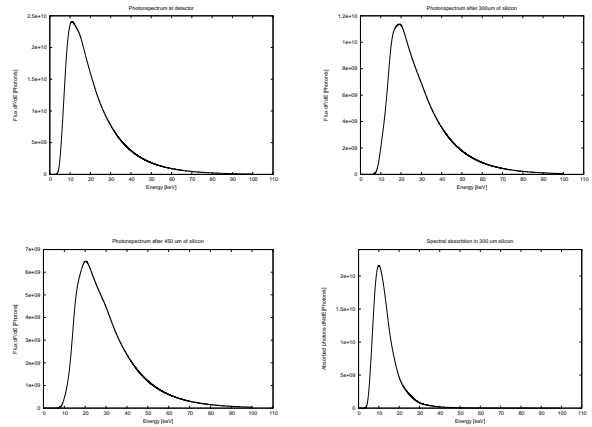


Figure 5: Energy spectras at different locations in the beam

at the HASYLab facility on the DESY site. HASYLab has several number of beam lines, all with different properties suitable for different kinds of experiments. The source of the synchrotron radiation is DORIS III, a 4.45 GeV positron storage ring. The radiation is produced by wigglers, undulators and bending magnets that are placed in the positron beam of the storage ring. The diodes were irradiated at beam line F3, a beam produced by a 1.2 Tesla bending magnet. The parameters of the beam line F3 are summarized in table 3. Materials like lenses and windows in front of the diode have a different absorption coefficient for different photon energies and this is why the intensity that arrives at the diode greatly depends on the source energy spectrum. The spectrum of synchrotron radiation produced by bending magnets can be calculated using relatively simple integrals [4]. But these formulas do not take into account that the positron beam is not point like, but spread in the plane perpendicular to the flight direction of the positrons.

There are applications available that consider this fact in the calculation of the energy spectrum. In our calculations the program SPECTRA was used [1]. Even though the program calculates the absolute expected photon flux for every energy, these absolute values are hardly reliable because the absolute value of photons produced at the source strongly depends on variable local beam operating parameters and these are hard to predict. Yet a normalized energy spectrum can be used to calculate the *deposited energy per photon*, which is a quantity for the energy fraction deposited in the silicon bulk of an exposed diode for every photon that is produced at the bending magnet considering all absorbers in front of the diode and the absorption of the different layers of the semiconductor itself. Some energy spectrums at different points of the beam path are depicted in fig. 5. Before every irradiation one can then measure the bias current increase when the diode is exposed to the beam which is proportional to the absolute energy that is deposited in the silicon bulk. Knowing this quantity and the deposited energy per photon mentioned above, we can simply calculate the number of photons that were produced at the radiation source and hence the absolute radiation dose the diode is exposed to. For the beam line F3 the empirical formula for the dose D can be given by eq. 1.

$$D = t_{exposure} \cdot I_{Diode} \cdot 6.848 \cdot 10^5 \frac{Gray_2}{C} \quad (1)$$

Unfortunately, the intensity of the beam also depends on the solid angle of the observer. In theory, the intensity over every horizontal angle should be constant because synchrotron radiation with the same intensity is produced at

²This formula is only valid for a 10 mm², 280 μm thick diode and the beam line parameters found at F3

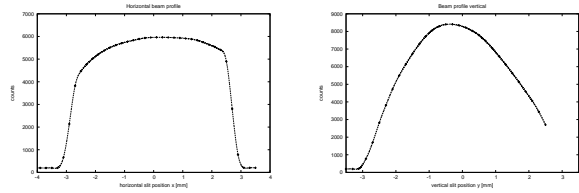


Figure 6: Vertical and horizontal beam profiles

every point of the flight path of the positron in the bending magnet. Yet measurements of the intensity of the beam over the horizontal angle showed a small variation. This is probably due to small misalignments of experiment tables or due to reflections at collimators. The vertical spatial intensity is not constant but can be calculated in theory (the intensity distribution is nearly gaussian like) with the same type of programs mentioned above. Again, the practical experiment shows a small variation to the calculated vertical spatial distribution. This is also most likely due to small misalignments or reflections of collimators. The measured spatial distributions are depicted in fig. 6.

3.2 Equipment found at the Beam Line F3

Because of the intense radiation of the beam, most of the experiment is located inside a so called beam hutch made mostly out of lead shielding (fig. 7). The hutch can only be entered if the main beam shutter in front of the hutch is closed. A special interlock system prevents the main shutter from being accidentally opened while people are still inside the hutch. Additionally, dosimeters are installed inside the hutches and if the radiation exceeds a certain level, the beam shutter will close automatically.



Figure 7: A beam hutch at HASYLab

This is why shielding inside the beam hutch is essential. For this purpose lead sheets and sandwich plates can be found at the beam hutch. The x-ray beam is guided through pipes inside the hutch and leaves the pipe through a yellowish window made of capton foil. Because the foil is very fragile, it is best to check if the foil is still intact before every irradiation. The beam pipes can be flushed with helium by opening a valve, labeled 'Strahlrohr'³, outside of the beam hutch right next to the beam hutch door. One should wait at least a half an hour until the beam pipes are sufficiently flushed once the pipe has been opened for maintenance or the the capton window had broken. Because the experiment must be controlled from outside the hutch, a BNC patch panel is installed on the in- and outside. A BNC terminal of the patch panel inside the hutch (mounted to the inner left hutch wall) is

³german for beam pipe

Motor Name	Number
Sample Table x	2
Sample Table y	3
Sample Table z	4
Collimator width	5
Collimator height	6
Collimator pos. y	18

Table 4: Motor number assignment

connected to the corresponding BNC terminal of the patch panel outside the hutch (located in the rack opposite of the hutch door). This way, electrical connections from your experiment inside the hutch can be guided to other equipment that reside outside of the hutch. The position of the experiment table in the middle of the beam hutch, the opening of beam slits and collimators can be adjusted by controlling appropriate motors with the beam line computer from the outside. Every motor has a number you refer to when you control them with the control software. Always check if you are really moving the motor you intended to because the motor and motor number assignment is subject to change frequently when other groups conduct their experiments. A table of the current motor number assignment is given in table 3.2.

3.3 The Setup

The diode irradiation setup is depicted in fig. 8. The bias of the diode is connected to a pico ampere-meter via the in- and outside patch bay. The pico ampere-meter is able to convert the input current to a proportional output voltage, which is connected to a voltage frequency converter that is located in the rack opposite of the hutch door. The frequency output is then connected to the input of the beam line computer

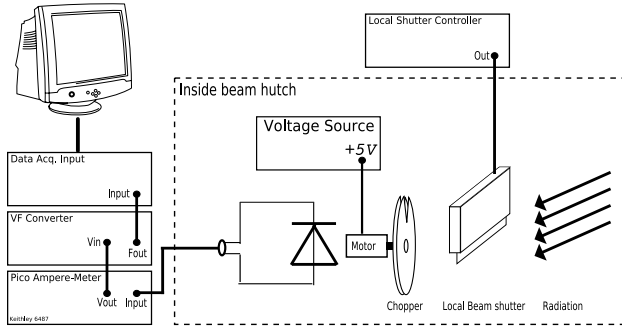


Figure 8: The setup while for measuring the beam intensity

data acquisition system that is also located in the rack. This data can then be recorded by the computer. A local beam shutter is installed into the beam line right in front of the irradiation table and can be controlled by the computer or by buttons on a shutter control device in the rack. This shutter is used to control the actual exposure time because the external beam shutter is far too slow to achieve short exposure times. Additionally the diode needs to be cooled and, if needed, the chopper needs to be connected to a power source. It should be noted that for the actual irradiation the diodes are not connected to any instruments. The current measurement is only done with a reference diode and used to calculate the exposure time. In our experiments the bias of the diodes that are meant for actual irradiation were left floating during exposure and this might have increased defect generation because excess currents may flow during irradiation. Another, maybe better option, would have been to tie the bias to ground.

3.4 More Details on Software and Equipment

3.4.1 The Irradiation Table and Chopper

During irradiation and setup the diodes need to be fixed in place and the diode needs to be connected to further instruments for the measurement of the beam intensity. For these requirements an irradiation table was built which is depicted in fig. 9. The ceramics (with the diodes bonded onto them) can be lowered into a slit and then fixed with a lever in the back of the table. Fixing the ceramic also connects the ceramic electrodes with lemo connectors mounted at the bottom of the table. This way the diodes can be exchanged in a matter of several seconds. Two collimators, one vertical and one horizontal collimator, can be mounted in front of diode in a special fixture on the top of the table. The collimators can also be exchanged in a matter of seconds, so one can switch between different collimator settings simply by having different collimator sets with different fixed slit sizes. The ceramic fixture is made out of copper and hollow in a way that cooling liquid can flow through it, thus cooling the diode. Because in the first radiation steps the dose up to which the diodes are exposed is relatively small a chopper consisting of two tantalum discs and an electric motor are mounted onto the table to reduce the beam intensity. The tantalum discs both have a small opening and are mounted in such a way that the relative angle of both chopper discs determines the size of the effective gap of the overall chopper. This way the beam intensity after the chopper can be reduced variably up to about 1/200 of the original beam intensity. The chopper can also be disassembled for higher dose rates simply by loosening four screws. The electric motor of

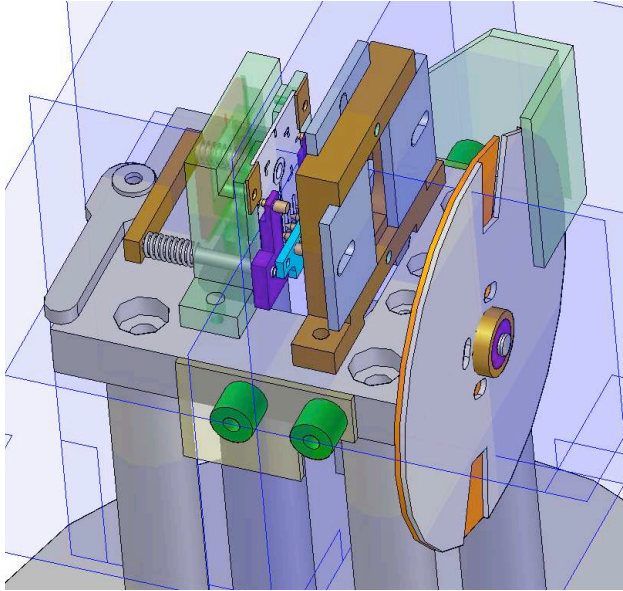


Figure 9: A schematic of the irradiation table

the chopper needs to be supplied with a maximum voltage of five volts. An extra power supply for the motor is located in the beam hutch and power connections for the motor are located on the bottom of the irradiation table. A fitting radiation shielding for the irradiation table can be found inside the beam hutch. The irradiation table needs to be enclosed with this shielding to ensure safe usage while the main beam shutter is open.

3.4.2 The Pico Ampere-Meter 'Keithley 6487'

A pico ampere-meter is used to measure the diode current from which the exposure time for a certain dose can be calculated. The pico ampere-meter that is used in our experiments is a highly sensitive ampere-meter from Keithley Inc. (Model 6487 fig 10). The instrument

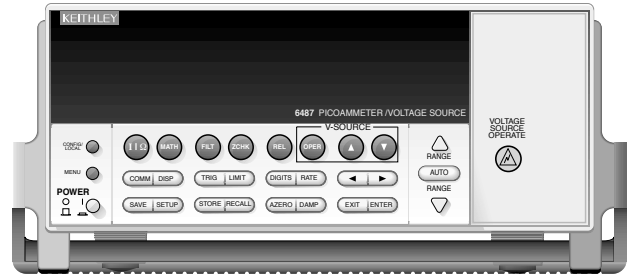


Figure 10: Overview of the Keithley 6487

additionally has the ability to output the measured current in a proportional voltage. After every power up the instrument needs to perform a so called zero check. For this you need to disconnect the input cables and press the 'ZCHK' button on the front panel of the instrument. To achieve the specifications that are given for the instrument by the manufacturer you need to let the instrument warm up for a maximum time of sixty minutes so it is best not to shut off the instrument if measurements are done frequently. During current measurements you can select different measurement ranges either manually or let the instrument select the range automatically by pressing the 'AUTO' button. It is **extremely important** to know that the output voltage is proportional to the number that is displayed on the screen of the device without the displayed unit in Volts and not the actual measured current. So if in one situation the screen displays 1.40 mA and in another it displays 1.40 nA the **same** voltage is applied to the output connections of the instrument (1.4 V). That is why the output voltage is range dependent. A further difficulty is that the overall range of the ampere-meter is limited to 20 mA and that after injection the diode current indeed does exceed 20 mA. This is why a simple 1/100 current divider is placed between the diode connections

and the pico ampere-meter if necessary. For low currents the auto mode of the instrument will fail because the current divider will produce different currents for different internal resistances for every range of the pico ampere-meter, thus resulting in a behavior that the instrument cannot find the appropriate range. That is why the current divider should only be used for currents higher than 1 mA. A third difficulty is the usage of the chopper, because the input current is not uniform but has very high peaks when the gap of the chopper allows the x-rays to hit the diode. For this particular situation a large integration time of the instrument should be selected. Do this by pressing the 'CONFIG' button, then the 'RATE' button and adjust the integration time to ten seconds using the arrow keys. Press 'SAVE' followed by 'ENTER' to save the setting. Do not use auto mode when the chopper is running because the current peak will cause the pico ampere-meter to switch its range setting. It must be noted that if the current divider is needed when measuring the diode current without the chopper it will still be needed if the chopper is installed, even if the current displayed is then far below 1 mA. This is because the peaks would still exceed the overall range of the instrument.

3.4.3 The Local Beam Shutter

To precisely control the exposure time of the diodes a local beam shutter was installed in front of the irradiation table. This beam shutter can be controlled manually or via the computer. The local beam shutter controller is mounted in the rack opposite to the hutch door and should not be confused with the external beam shutter controller mounted in the rack of the interlock system. A switch can set the local beam shutter

to 'Manual' or 'TTL' mode. In manual mode the shutter can be opened and closed with the open and close buttons on the shutter controller. In TTL mode the shutter is controlled via the computer. After having operated the shutter in TTL mode, one must close the shutter with the control software or manual mode will fail to function. The shutter has an opening and closing time of about 0.1 seconds.

3.4.4 The Cooling Device

In order to cool the diodes during irradiation a liquid cooling device is placed under the experiment table. The cooling liquid gets pumped from the cooling device to the irradiation table through small rubber hose and from there flows through the hollow copper ceramic fixture. It is not clear on how much the silicon is actually cooled by this setup, because the thermal conduction between the copper, the ceramic and the silicon is not known. Yet no evident thermal damage of the silicon was observed to this date. Before irradiation starts, you need to turn on the cooling device by flipping the main power switch and then adjust the temperature with the arrow buttons. The temperature should reach the desired temperature in a matter of minutes.

3.4.5 The Data Acquisition and Motor Control Software

During and at the beginning of every irradiation the experiment table must be moved, the external slits and collimators must be adjusted, data must be taken and the local beam shutter must be controlled. All this is done with the beam line computer located on the desk at the beam hutch. The data acquisition system can only count the number of pulses on one of the 16 input channels.

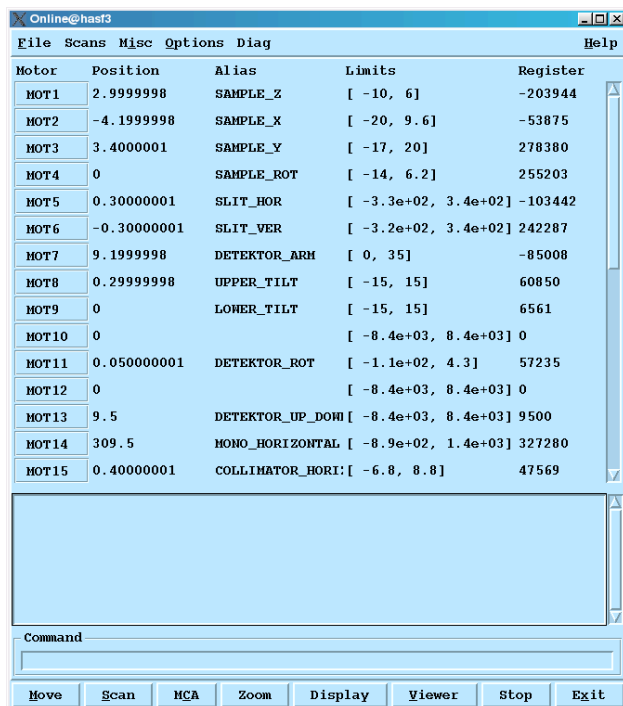


Figure 11: The main window of the control software

The input channels of the data acquisition are located in the lower half of the rack that is opposite to the hutch door. This might seem somewhat limited, but this limitation can be overcome with one of the many voltage frequency converters located in the rack. A voltage frequency converter creates pulses in a frequency that is proportional to the applied input voltage. To start the data acquisition system, open the software by executing the command online -tki in the unix terminal. A screenshot of the main window is depicted in fig. 11. In the 'Misc' menu you can select different motor sets, like collimators, slits and the table position. When selecting one of these menu items a window will open (fig. 12). Type in the new position in the text fields and

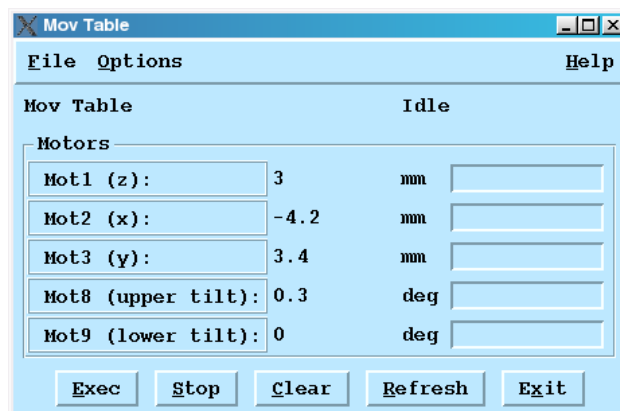


Figure 12: The motor window of the control software

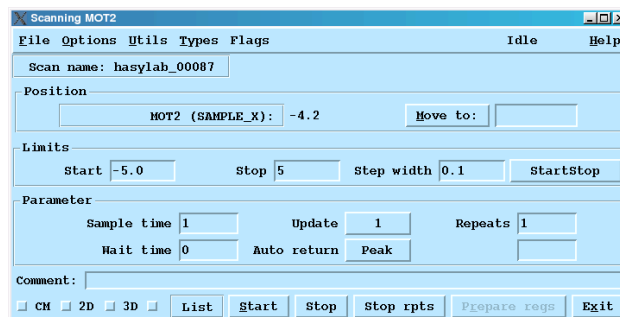


Figure 13: The scan window of the control software

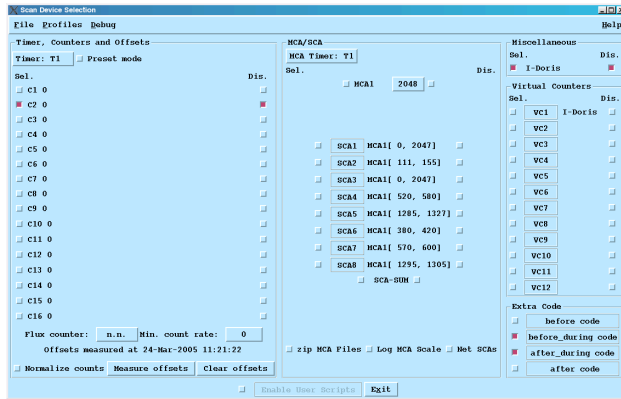


Figure 14: The scan settings window of the control software

click 'Exec' to move the motors. A count down will be displayed at the top of the window so you know when the motor has finished moving. **All values are given in mm.** To find the spatial maximum of the beam a scan must be conducted. For this click the 'Scan' button in the main window. In the open scan window (fig. 13 click on the button in the middle of the window to open a list of motors you want to automatically move during the scan. Select 'Dummy' from the motor list if you do not want to move a motor during the scan. From the menu 'Options' in the scan window select the item labeled 'Select scan devices'. A large configuration window will open (fig. 14). In the region labeled 'Timers, Counters and Offsets' select the channels of the data acquisition input that you want to record, for example if you want to measure the diode current then select the channel that the voltage output of the pico ampere-meter is connected to. It should be noted here that the channel numbers in the software are numbered differently (first channel is channel one) than the channel numbers labeled on the input device in the rack (first chan-

nel is channel zero). For our experiments we do not want the check box labeled 'Prefix mode' to be selected. In the region labeled 'MCA/SCA', no check boxes should be selected. In the region labeled 'Miscellaneous' select 'I-Doris' and 'Dis.' to record the DORIS current and have it displayed during measurement. No check boxes should be selected in the region labeled 'Virtual Counters'. If you want to open and close the local beam shutter during measurements select the check boxes 'before_during code' and the check box 'after_during code', located in the region labeled 'Extra Code'. Click 'Exit' to save your settings. In the main scan window type in the starting point, ending point and step width of the motor movement. The number located in the field labeled 'Sample Time' is the number of seconds the software waits and counts the pulses on the selected input channels before it saves this number to disk and moves the motor to the next position. For our experiments a sample time of one second was used. In the field labeled 'Wait time' one can type in the number of seconds the software should wait after motor movement before measuring the number of counts of the selected channels. This parameter is extremely important when the pico ampere-meter was set to an integration time of ten seconds, for example when using the chopper. In this situation the wait time should be at least ten seconds. All scans are automatically saved to disk in the active path from which the program was started.

3.5 The Irradiation Procedure

Following is a step by step guide for the procedure of irradiating diodes with a certain dose of x-ray radiation. Before starting all measurements please check with local HASYLab administration if you have all obligatory security per-

missions (i.e. beam shutter permission) to use the facilities at beam line F3. Once you are ready for irradiation turn on the cooling device under the experiment floor stand and set the temperature to 20°. The pico ampere-meter outside of the beam hutch should be turned on as well because it needs a certain warm up time to achieve it's full sensitivity. If the pico ampere-meter was off, it will need to perform a zero check, as will be indicated on the screen. Disconnect the input cables of the device and then press the 'ZCHK' button before reconnecting them. Check if the capton window at the one end of the beam pipe inside the hutch is still intact. If not, then ask for a replacement. If all beam pipes in the hutch are closed up properly then you can turn on the helium gas valve located outside of the hutch. If the beam pipe had been opened or the capton window was replaced then wait at least a half an hour before opening the beam shutter, so that the beam pipe is completely flushed. To focus the beam onto the lower right diode of the gated diode test field the local collimators on the irradiation table need to be adjusted. The upper plate of the vertical collimator should be closed all the way; the lower plate should be adjusted in such a way that the slit of the vertical collimator has a height of 4.0 mm. The left plate of the horizontal collimator should also be closed all the way; the right plate should be adjusted in such a way that the slit of the horizontal collimator has a width of 2.5 mm. Insert the collimator onto the irradiation table. It will only fit firmly if inserted in the correct orientation. Insert the reference diode (the reference diode that was used in our experiments has the serial number S04809) into the ceramic fixture of the irradiation table and secure it with the lever in the back. For a first good estimation of the exposure time, insert a reference diode current of 100 mA and the antic-

ipated dose increase into equation 1. If the estimated exposure time is too short (less than one second) you will now need to install the chopper with an appropriate adjusted gap width, so that the effective exposure time with the chopper is long enough (greater than one second). Do not turn on the chopper now. Connect the diode bias lemo connector at the bottom of the irradiation table to a BNC terminal of the patch panel located inside the beam hutch. Currently we connect the diode bias to the patch panel BNC connector number five. The signal from the diode is now routed to the corresponding BNC connector on the patch panel outside of the beam hutch. Connect this terminal directly to the input of the pico ampere-meter (without the 1/100 current divider) and set the ampere-meter to auto range. Now the diode current should be displayed on the pico ampere-meter screen. Switch the fluorescent light in the beam hutch on and off to see if the measured diode current reacts accordingly. Switch off auto range by manually selecting a range of 2 mA. Connect the output of the pico ampere-meter to the input of one of the voltage frequency converters located in the rack. The output of the converter needs to be connected to one of the channels of the input device of the computer data acquisition system which is also located in lower part of the rack. Currently we connect the converter to the channel that is labeled with the number one on the input device, which is referred to as channel two in the software. Start a scan with the beam line software selecting the dummy motor device. Is the recorded data reacting to the fluorescent light in the beam hutch? A common mistake is that the polarity of the output of the pico ampere-meter is inverted and the connector needs to be flipped. Now we want to move the tables and collimators into a default position, before we search for

Motor name	Motor Number	Position
Sample Table x	2	-4.5
Sample Table y	3	1.5
Coll. Width	5	6.0
Coll. Height	6	6.0
Coll. Pos. y	18	0

Table 5: Default motor positions

Scan Start	Scan End	Scan Step
Horizontal Scan		
-5	-1	0.2
Vertical Scan		
0.5	2.5	0.1
Sample time: 1 s		Wait time: 10s

Table 6: Scan parameters when searching for maximum beam intensity

the position with the maximum in beam intensity. The motor positions are listed in table 5.

Set the local beam shutter to manual control and make sure that the shutter is closed. Set the integration time of the pico ampere-meter to ten seconds and the range to 20 mA. Insert the 1/100 current divider between the diode current and the pico ampere-meter. Enclose the irradiation table with the proper lead shielding that is available in the beam hut. Make sure that the lead shielding doesn't block a part of the beam. If you will be using the chopper during irradiation then you need to set the power supply of the chopper motor to five volts by gradually increasing the voltage on the power supply. Turning the power on or off too fast can break the fragile motor. You should hear the motor running from the inside of the irradiation table. Open the main beam shutter. Now we need to move the experiment table to find the maximum beam intensity. Do this by doing two scans, one ver-

tical, one horizontal scan with the scan parameters listed in table 6. **Don't forget to open the local beam shutter before conducting the scans.** Look for the maximum of intensity in the recorded data of scans and set the position of the experiment table accordingly. If needed, then do a more detailed scan. Now, write down the measured diode current that is displayed on the pico ampere-meter. Multiply this value with a hundred to consider the current divider. Without the chopper, you should have a value ranging from 80 to 180 mA depending on the DORIS current that was present when measuring. Calculate the exposure time using the diode current, but do not forget to consider the installed current divider. Close the local and main beam shutter. If the chopper is used gradually turn off the chopper motor. Remove the lead shielding and replace the test diode with the diode that is to be irradiated. Disconnect the diode bias lemo connector. Enclose the irradiation table with the lead shielding and, if necessary, turn on the chopper again. Do not open the main beam shutter. First we need to be able to control the opening duration of the local beam shutter and thus we need to set the shutter to TTL mode and do a pseudo scan: this means that we initiate a scan just to open and close the shutter for the calculated exposure time. In the scan window select the dummy motor. Activate the scripts before and after sampling in the scan parameters window to enable software control of the shutter. Set the wait time to the maximum time of fifteen seconds. Set the sample time to the calculated exposure time. Set the start position of the dummy motor to zero, the end position to one and the step width to one. The parameters for this pseudo scan are summarized in table 7. The following will happen with these parameters: after clicking the scan button the software

Scan Start	Scan End	Scan Step
0	1	1
Sample Time:	$t_{exposure}$	Wait time: 15s

Table 7: Scan parameters to irradiate the diode

will open the local beam shutter after waiting for fifteen seconds. After the exposure time has elapsed the shutter is closed again and the procedure is run through a **second** time. This is because the software is programmed in such a way that at least two data points must be taken per scan. This means that one has exactly fifteen seconds to close the main beam shutter after the local shutter has shut after the exposure of the diode. One can hear the local beam shutter opening and closing from outside the hutch. Additionally the opening and closing of the local shutter is printed in a log field located in the main window of the measurement software. These fifteen seconds are not generous but sufficient enough to close the main beam shutter in time. Do a test scan before opening the main beam shutter to see if all parameters are set properly and no mistakes have been made. Open the main beam shutter and note the time and the DORIS current. Click the scan button to irradiate the diode and, as described above, quickly close the main beam shutter just after the local beam shutter closes for the first time after the exposure time. Wait for the scan to finish. Repeat the irradiation process for all diodes. Close the main beam shutter and, after setting the local beam shutter to manual mode, close it. Remove the last diode, turn off cooling and don't forget to close the helium valve outside the beam hutch.

4 Measurement of the Diode Characteristics after Irradiation

4.1 Measuring of Characteristic Curves

Currently it is not possible to measure the diodes at HASYLab. One must conduct diode measurements at the detector lab of the University of Hamburg, also located on the DESY site. There are three measurements that have been proposed for this experiment: an I_{oxide} characteristic curve, an IV characteristic curve and a MOS capacity characteristic curve. All curves are measured by varying the gate potential. In the first of the three measurements, the I_{oxide} characteristic curve, the bias current is measured in dependence of the gate voltage while the diode is reverse biased with a constant voltage. We expect a significant increase of bias current due to the surface generation current when the gate reaches the flat band voltage and a decrease of the same amount when the gate reaches the inversion voltage, as described in the theory part of this report. We repeat this measurement for different bias voltages. The second measurement, the IV characteristic curve, is similar to the first, but now the bias voltage isn't held constant but at the same potential as the varying gate potential. To understand the result of this measurement, let us first consider that the gate potential is held at a constant level and the bias voltage is increased. This situation would be like a standard IV characteristic curve measurement of a traditional diode and is an indicator for purity of the semiconductor. Let us now consider that the bias voltage is held constant and that the gate potential is varied. Now we have the same

situation as we had when we measured the I_{oxide} characteristic curve, with the only difference that inversion will never take place because by theory the inversion voltage must always be higher than the bias voltage and in this measurement the gate voltage is never higher than the bias voltage (remember that they are tied together), so inversion is never reached, and thus one expects a similar curve like the I_{oxide} measurement but without the decrease of surface generation current at the inversion voltage. The resulting curve is an overlap of both curves described above. In the third measurement, the MOS capacity characteristic curve, the capacity is measured in dependence of the second gate ring voltage⁴. In this measurement we expect the capacitance to stay constant except for a sharp drop of capacitance at the flat band voltage. In fact this measurement is used to be able to determine a more exact value for the flat band voltage of the diode. For a more detailed description of these measurements see [2].

4.2 Setup Overview

The detector lab of the University of Hamburg offers sophisticated equipment for measuring the characteristic curves mentioned above. The ceramics with the irradiated diodes glued onto them can be placed on a measurement table and are fixed by a vacuum pump. Needles around the table can be used to contact the ceramic electrodes. The needles and the table itself are located in a cupboard that can be closed to prevent environment light to induce a current in the diode. The needles are routed to BNC

⁴the third gate ring is bonded to the same electrode on the ceramic as the second gate ring during this measurement, so both second and third have equal potential during this measurement

connectors outside of the cupboard and can be connected to further measurement instruments. The equipment used in this experiment are an ampere-meter with a built-in voltage source, an LCR meter and an additional voltage source. Furthermore a device is used to switch between current and capacity measurements. The measurement equipment is then controlled by a lab computer to conduct automatic scans.

4.3 A More Detailed Description of Equipment and Software

4.3.1 The Measurement Cupboard

The measurement cupboard contains a table for the ceramics, needles to contact the electrodes on the ceramic and a microscope to check the position of the needles and the ceramic. The cupboard can be completely shut to avoid inducing a bias current produced by environment light. A light under the microscope can be turned on and off with a switch from the outside of the cupboard to be able to light up the working area. You can move the microscope with knobs that are located in the back of cupboard. When a diode should be inspected, place the diode in the middle of the table inside of the cupboard. The electrodes should be facing to the right. The ceramic can be fixed to the table by turning on the vacuum in the table with the white switch found at the right of the table base, near the back wall of the cupboard. Move the table with the two knobs next to the table to center the electrodes near the needles. Now the needles can be connected to the desired electrodes of the ceramic with the screws at the base of the needles. While this is done, observe the needles under the microscope. To ensure contact with the electrodes, it is best to pull the needle towards the needle base

BNC jack label	Needle Color
1	White
2	Yellow
3	Green
4	Blue
Chuck	Pink

Table 8: Color codes of the needles in the cupboard

after descending the needle onto the electrode. This will make a small scratch in the electrode that is visible under the microscope and ensures that there is no dirt between the needle and the electrode. Each needle is connected to a BNC jack on the outside of the cupboard. The jacks are numbered from one to four with an additional jack called 'Chuck'. The jacks are all connected to a needle inside the cupboard and are color coded (see table 8). By convention, 'Chuck' is connected to the reverse bias of the diode.

4.3.2 The Ampere-Meter

The ampere-meter used during the measurement of the characteristic curves is an ampere-meter with the model number 6517A from the manufacturer Keithley Inc. The ampere-meter is equipped with a built-in voltage source which can be controlled via software. After power up the ampere-meter needs a maximum of sixty minutes to achieve the sensitivity that is stated by the manufacturer. This is why the ampere-meter should only be turned off if it is not used for a longer period of time. Additionally the ampere-meter will need to perform a zero check after power up and this will be indicated on the screen of the device. To perform a zero check, disconnect all cables and then press the 'ZCHK' button. The ampere-meter has several measure-

ment ranges, the most sensitive being 2 pA, the highest being 20 mA. The range can be selected manually by using the arrow keys or the device can be set to find the appropriate range automatically by pressing the 'AUTO' button. Unfortunately the ampere-meter seems to have a small bug when the device is in AUTO mode: if the input current is exactly at the maximum of the selected current range (i.e. 20 nA) and stays constant at this value for longer than about a second, the device will not jump to the next range but display an 'Out of range' error message on the device's screen. During automatic measurement with the measurement computer the device is set to auto mode and if the above situation occurs then an invalid current of $3 \cdot 10^{37} A$ will be measured. There is no workaround for this bug and the false values must be corrected by hand by opening the data files in your favorite text editor.

4.3.3 The Bias Box

Connected to the front jacks of the LCR meter is a small silver box with which one can switch between capacity and current measurements. The device is called a bias box and the exact schematic can be found in [5]. When conducting an experiment both switches need to be flipped to the according state, either labeled 'IV' for current measurements or 'CV' for capacity measurements. There are two jacks on the bias box labeled 'lo' and 'high'. If the switches are set to IV mode the current flowing between these two jacks is measured by the ampere-meter that is connected to the jack labeled 'I' on the bias box. If the switches are set to CV mode the capacity between low and high is measured by the LCR meter. Additionally there is a jack labeled 'V' with which one can

set the potential difference of the low and high jacks. Usually this is connected to the built-in voltage source of the ampere meter because in almost all measurements the potential between high and low is varied via the automatic measurement system in the computer. Furthermore the jack labeled 'lo' is normally connected to the chuck jack of the measurement cupboard.

4.3.4 The LCR Meter

The LCR meter is used for the capacity measurement in our experiment. The LCR meter at the Detector Lab of the University of Hamburg is the 4284A by Agilent Technologies. The LCR meter is completely controlled by software and doesn't need to be used manually, except for calibration. The calibration that needs to be done in our measurements is an **open capacity calibration** and measures the capacity of the open terminals and cables. See fig. 15 for instructions on how this is done.

4.3.5 The Additional Voltage Source

There is an additional voltage source needed for the measurement of the I oxide characteristic curve, because in this measurement the diode bias potential is held at a constant value. In the detector lab the built-in voltage source of the pico ampere-meter 6487 from Keithley Inc. is used for this task. Like with the ampere-meter described above, the ampere-meter needs to perform a zero check after power up. This can be ignored by pressing the button labeled 'ZCHK' because no currents are measured with this device anyway. Unfortunately the device cannot be controlled by the automatic measurement system of the software, so the output voltage must be adjusted manually. To do this use the arrow

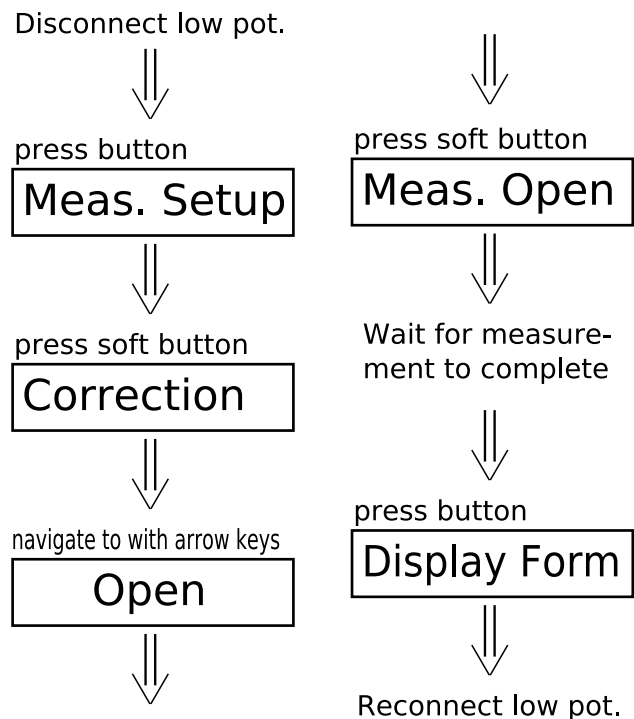


Figure 15: Flow chart on how to calibrate the LCR Meter for capacity measurements

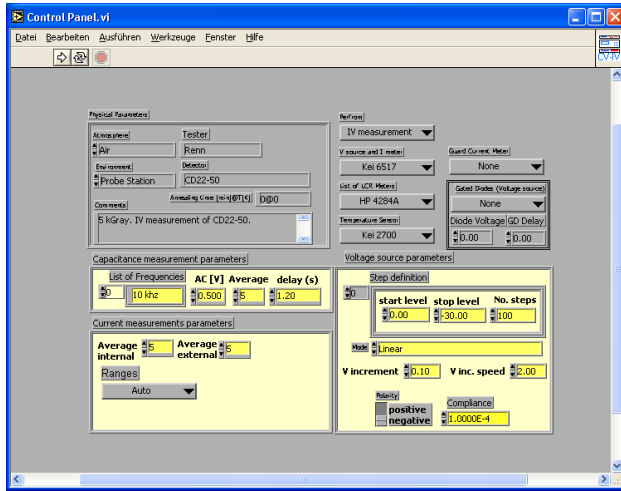


Figure 16: A screenshot of the main CVIV82 window

Popup menu label	Instrument Name
V source and I meter	Kei 6517
List of LCR Meter	HP 4284A
Temperture sensor	Kei 2700
Guard Current Meter	None
Gated Diode	None

Table 9: Equipment that needs to be selected in the CVIV82 software

keys in the front of the device and activate the output with the button labeled 'OPER'.

4.3.6 The Measurement Software

The software used to conduct the automatic measurements of the characteristic curves is called CVIV82 and a short cut to this application should have been placed on the windows desktop when your user account for the measurement computer was established. Many parameters can be adjusted in the main application window shown in fig. 16. In the upper left corner of

the window details about your measurement can be entered which later will be added as a remark in every measurement data file saved by the program. It is best to fill in the detector name, the name of the person who conducted the experiment and, in the comment field, the name of the characteristic curve that will be measured including the dose of radiation of the diode. In the upper right corner of the window select the measurement type you want to conduct from the popup menu and the instruments that shall be controlled by the software. The list of instruments that should be selected is listed in table 9. In the lower left corner of the window you can adjust two parameters: the frequency list for the capacity measurements and in which range the ampere-meter should measure the current. It is best not to change the range settings. Too add a frequency to the frequency list press the up arrow next to the frequency field. Type in the desired frequency including the frequency unit⁵. In the lower right corner of the window you can edit the scan parameters. The scan parameters refer to the way the gate voltage, produced by the built-in voltage supply of the ampere-meter, is varied during the measurement of the characteristic curve. The proper parameters for the measurement of the characteristic curves are listed later on in this report. To start the scan press the run button, labeled with a right arrow, from the very top of the window. A new window will open that interactively shows the result of your measurement. Near the top of this window you will see the path to which your measurement data is saved to. During the measurement the software sets the mode of the measurement equipment to

⁵the frequency unit can only be hz, khz or mhz, all in lower case letters with a space between the number and the unit

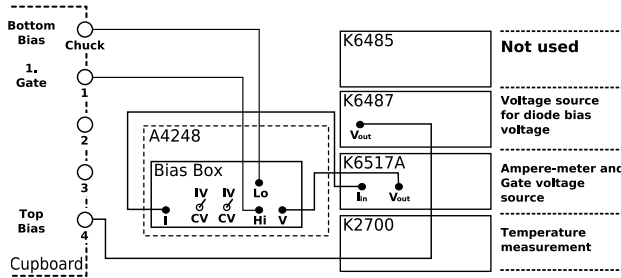


Figure 17: The setup for the measurement of the I_{oxide} characteristic curve

remote mode to be able to control the devices. In this mode the equipment will not respond to any buttons that are pressed at the equipment itself. All machines are put back to local mode once you close the whole application.

4.4 The individual Measurements

4.4.1 I_{oxide} Characteristic Curve

The setup for this measurement is depicted in fig. 17. Both switches on the bias box need to be set to IV mode. As always, the jack labeled 'lo' on the bias box needs to be connected to chuck. The jack labeled 'hi' is connected to the 1. gate of the diode. The additional voltage supply is connected directly (not via the bias box) to the forward bias of the diode. In the special case of the electrode geometry and electrode assignment of the diodes that we measured, it was convenient that the jack labeled 'hi' was connected to the BNC jack number one (white needle) of the cupboard and the output of the additional voltage source was connected to the jack number four (blue needle). The jack labeled 'I' is connected to the input of the ampere meter and the jack labeled 'V' is connected to the output of the built-in voltage source of the same

Parameter	Value
start level	0.00
No. steps	100
Mode	Linear
V inc.	0.10
V inc. speed	2.00
Unirradiated diode	
stop level	-20
Radiated diode	
stop level	-60

Table 10: Parameter values for the measurement of the I_{oxide} and IV characteristic curve

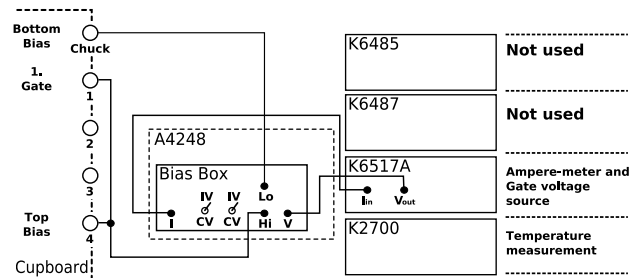


Figure 18: The setup for the measurement of the IV characteristic curve

ampere meter. Different measurement parameters must be used in the measurement software if the diode is irradiated or not. Additional measurements can be done at different diode bias voltages. The measurement parameters for the diodes in our experiment are listed in table 10. The parameters may vary from diode to diode.

4.4.2 IV Characteristic Curve

The setup for this measurement is depicted in fig. 18. Both switches on the bias box need to be set to IV mode. As always, the jack labeled 'lo' on the bias box needs to be connected to chuck.

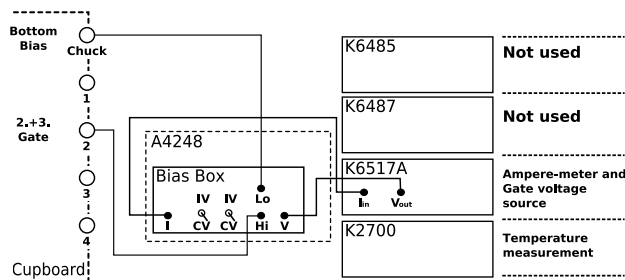


Figure 19: The setup for the measurement of the CMOS characteristic curve

The jack labeled 'hi' is connected both to the forward bias and the 1. gate. In the special case of the electrode geometry and electrode assignment of the diodes that we measured, these were connected to the jacks, labeled with the numbers one (white needle) and four (blue needle). The jack labeled 'I' is connected to the input of the ampere meter and the jack labeled 'V' is connected to the output of the built-in voltage source of the same ampere meter. The additional voltage source is not used. Different measurement parameters must be used in the measurement software if the diode is irradiated or not. The parameters are listed in table 10. The parameters may vary from diode to diode.

4.4.3 CMOS Characteristic Curve

The setup for this measurement is depicted in fig. 19. Both switches on the bias box need to be set to CV mode and, with the jack labeled 'lo' disconnected from the cupboard jacks, an open capacity calibration, as is described above, must be conducted before the measurement is started. After the calibration, the jack labeled 'lo' on the bias box needs to be connected to chuck. The jack labeled 'hi' is connected both to the second and the third gate. In the special case of the elec-

Parameter	Value
start level	-1.00
stop level	-30.0
No. steps	100
Mode	Linear
V inc.	1.00
V inc. speed	0.3

Table 11: Parameter values for the measurement of the CMOS characteristic curve

trode geometry and electrode assignment of the diodes that we measured, the jack labeled 'hi' on the bias box only needs to be connected to the jack with the number two (yellow needle) on the cupboard because the electrode that is contacted by needle two is bonded to both gates. The jack labeled 'I' is connected to the input of the ampere meter and the jack labeled 'V' is connected to the output of the built-in voltage source of the same ampere meter. The additional voltage source is not used. The measurement parameters for the measurement software are listed in table 11. The parameters may vary from diode to diode.

5 First Results

5.1 Interpretation of the Data

Not many measurements were finished when this report was written. Until now, the characteristic curves mentioned above were only measured for four different diodes at doses of 0, 1, 2 and 4 kGray. This is not much compared to the anticipated maximum dose of 1 GGray. For comparison, the I_{oxide} characteristic curves for the three doses have been plotted in fig. 20. One can clearly see that the surface generation current, which can hardly be seen for an unirr-

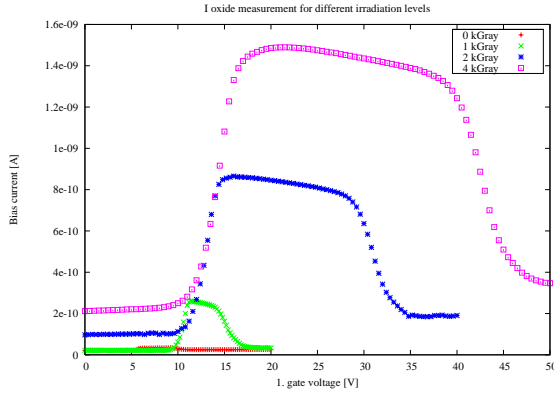


Figure 20: I_{oxide} characteristic curve for different radiation doses

Dose [kGray]	Surf. gen. [pA]	Flat band [V]
0	8.7	5.8
1	202	10
2	594	12.2
4	989	13.8

Table 12: Development of the surface generation current and the flat band voltage with higher doses for the diode CD22-50

diated diode, increases sharply once the diode is irradiated. This is an indication that strong surface defects are introduced to the semiconductor once the diode is exposed to radiation. For higher doses the surface generation current still increases but a lot more moderate. The flat band voltage is also increasing with higher radiation doses, which is an indication that charges have been introduced to the silicon oxide layer due to increasing radiation. The flat band voltages and surface generation currents can be derived from the measurements of the characteristic curves and are listed in fig. 12. Some mea-

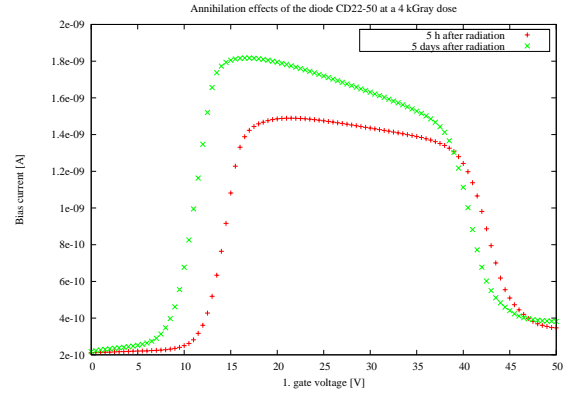


Figure 21: Annihilation effects of the diode CD22-50 at a 4 kGray dose

surements of characteristic curves were measured a second time before irradiating the diode again to see if after some time healing effects can be seen. The comparison of two measurements of the I_{oxide} characteristic curve of the same diode at the same level of radiation, but at a different times after irradiation have been depicted in fig. 21. One can see that the flat band voltage indeed had reduced, indicating that some charges in the silicon oxide had vanished over time. On the other hand, the surface generation current increased which is not clearly understood yet. Another surprising result is that the surface generation current reduces with higher gate voltages as one can see in the development of the current curve in the region between the flat band voltage and the inversion voltage, depicted in fig. 20. This is somewhat unexpected because more defects should be excited with higher gate voltages. This behavior wasn't observed for measurements done with the unirradiated diodes. One explanation is that the inversion voltage is different for

different regions of the diode due to the slightly variation in intensity of the beam for different vertical positions and thus some regions go to inversion earlier than others and their current contribution drops by their surface generation current earlier than others.

5.2 Conclusions

Even though we are at the beginning of the experiment, some interesting behavior can already be seen, that hadn't been predicted before. More measurements are needed to be able to suggest a profound explanation for these effects. Yet, as with every experiment, there is always room for improvement, if the experiment should be conducted a second time. Especially the chopper has introduced a large error in our measurements because the gap opening can't be determined as exact as one would like. A further disadvantage is that the chopper produces large peaks in the diode bias signal and therefore the ampere-meter must be set to high ranges even though the average current is fairly small. Future experiments should have a setup in such a way that the beam intensity can be reduced more efficiently. Additional errors are introduced by the fact that the exposure time is calculated with the current of a reference diode and not the diode that is being irradiated. The disadvantage of this procedure is that between the time after the current was measured with the reference diode and the time the next diode is ready for irradiation, the beam parameters will have slightly changed and therefore the calculated exposure time isn't accurate anymore. Even more: if an unexpected event occurs during irradiation, like a beam dump, then the actual dose cannot be determined. In the worst case this would introduce an error that is as large as the dose that the diode was to be ex-

posed to. Unexpected beam dumps are not even that uncommon at HASYLab because automatic beam dumps occur for security reasons, if a person opens an interlock door by accident. Therefore, for future irradiations, one should record the current of every diode during exposure to see exactly when an unexpected event occurred and with that derive the actual dose the diode was exposed to. If the demand for higher precision experiments is needed, one should ultimately switch to a setup where the characteristic diode quantities, like the flat band voltage and the surface generation current, is measured at the beam line itself.

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