DESY Summer Student Program 2008 Report

Radiation damage Tests with front end electronics on Field-Effect Transistors (FETs) for further development of a Hybrid Pixel Array Detector (HPAD)

Raphael Grifone

Supervisor: Heinz Graafsma

Abstract

The fourth generation of photon sources, the European X-ray Free-Electron-Laser (European XFEL) with its outstanding brilliance will be the machine for scientific resurge in near future. And it will be the first time in photon science a detector is planned and constructed specially for the specifications of the source.

One of the challenges of the European XFEL project is the number of 10^{12} photons per pulse, giving strong scattered signals onto the detector. If Silicon is used as a sensor, a significant fraction will be transmitted and hit the front end readout structure. For that radiation hardness is a big issue in the development of new detectors.

This document reports my work on radiation hardness measurements of metal–oxide– semiconductor field –effect transistor (MOSFET). I compare a p-channel and an n-channel Surface Mounted Device (SMD) unit during my experiment.

Contents

Contents
<u>1 Introduction3</u>
1.1 Self-Amplified Spontaneous Emission (SASE) FEL
1.1.1 Structure and properties of the European XFEL
<u>1.2 The Analogue Pipe-Line Hybrid Pixel Array Detector (HPAD)4</u>
1.2.1 Challenges
2 Physical principals of photon absorption
3 Experimental setup
<u>3.1.1 Measurement</u>
3.2 Differences to a Free-Electron-Laser7
<u>4 Results</u>
4.1 Discussions11
5 Conclusion & Outlook
<u>6 Appendix12</u>
<u>6.1 Pictures12</u>
<u>6.2 Bibliography15</u>

1 Introduction

During my participation in the Summer Student Program at the German Synchrotron (DESY) I was assigned to the detector workgroup of Dr. Heinz Graafsma, which is a department of the Hamburger Synchrotron Laboratory (HASYLAB). In the two months of the program it was my task to perform several pre-studies for further measurements of a readout chip for the HPAD, measuring the radiation hardness of p-channel and n-channel MOSFET.

For the investigation I built up an experimental setup at a HASYLAB laboratory using an X-ray tube, as source, a double slit system and various detectors for measurements.

My work includes the calibration and characterisation of the X-ray beam of the used setup. And I get familiar with different kinds of detectors, like a photosensitive paper, Photodiode, CCD-Camera and an Energy Dispersive Detector (EDD).

The aim of this experiment was to get an idea how ionising radiation causes damage in a metal-oxide-semiconductor field –effect transistor structure.

In the first paragraph I like to explain what XFEL means and what it is about HPAD. Then I briefly explain the physics behind my experiment. I spend a big part on the experiment, to describe my course of action in detail.

Finally I present the outcome of the measurements.

1.1 Self-Amplified Spontaneous Emission (SASE) FEL

1.1.1 Structure and properties of the European XFEL

The Machine begins on the DESY site (Hamburg) with infrastructure and the injector complex and goes through a tunnel to the end at the X-FEL site in Schenefeld (Schleswig-Holstein) where the experiments take place; see <u>Pictures</u>: "Bird view of the European XFEL". From an injector the electrons will travel through a 2100 meter long linear accelerator in superconducting TESLA technology. The electron bunches are much longer than the desired wavelength to avoid complications and difficulties during acceleration. After the electrons got their final velocity at 20GeV the beam splits at switchyards to provide different kind of experiments. On a total distance of 1200 meter the beam passes several undulators to produce a monochromatic, coherent laser like light. That for the beam has to be cut into equally spaced pieces, which is very difficult. They realised that in three steps; Step 1: modulation of the beam Energy, Step 2: Modulation of the Current and finally Step 3: produce of Radiation. The emitted Photons by the wiggler looks like a bunch train; see <u>Pictures</u> "Bunch train structure". Some outstanding numbers:

- Wavelengths down to atomic scale $\lambda \sim 1 \text{\AA}$ and
- Pulse length of sub-picoseconds with
- Brilliance more than 10²¹ photons/sec/mrad²/mm²/0.1% bw

The last important number in regard to the detectors I like to mention is the Intensity of the emitted radiation.

For a fully coherent superposition we get that the Intensity I is proportional to N_e^2 times N_p^2 , with N_e : number of electrons per bunch and N_p : number of magnet poles.

Compare this with an undulator where $I \sim N_e N_p^2$, which has much les Intensity.

With these values scientists will be able to reach a new field of investigation, like study on ultra fast coherent diffraction. This gives the possibility to make "movies" for example of molecular processes and so on.

The bunch train structure is also very important to the detector development. Because the images have to be stored in the read out structure until the bunch train passed. But during this duration leakage currents will occur.

With a total of 10^{12} - 10^{13} Photons per pulse a common structure, like a bio molecule, will be destroyed after one pulse, but that's enough to get good diffraction results. That was demonstrated at ultra fast coherent X-ray diffraction by *1H. Chapman et al. Nature Physics 2, 839 (2006).*

That brings us to the major problems and the consequences on detector construction.

1.2 The Analogue Pipe-Line Hybrid Pixel Array Detector (HPAD)

The HPAD hybrid pixel detector is based on an ASIC readout structure which is bumpbonded to a silicon-sensor. In principle the readout structure contains a variable gain input stage and an analogue pipe-line for each pixel to store the images during the bunch train.

Based on CMOS technology the readout structure contains several functional blocks, like an analogue pipeline and other logics for temporarily storing the images. The ASIC operates in charge integration mode. The number of images, which can be taken, depends on the pipeline depth. The proposed Front end module contains a 200x200um Silicon sensor, to build a prototype with 32x32 pixel submitted on a Multi Project Waver (MPW) out of it.

HPAD will be able to target: Coherent Diffraction Imaging (CDI), Single Particle Imaging (SPI) and X-ray Photon Correlation Spectroscopy (XPCS).

hpad_0.1—test structure

A first test structure, called hpad_0.1 chip is developed to perform pre-studies on the readout chip to verify the implemented structures. The chip will be wire-bonded to a test structure for further measurements on the behaviour of the electronics.

1.2.1 Challenges

Ionizing radiation cause several processes, as described under 2 Physical Principals.

The major problems will be leakage currents in the ASIC readout chip. We predicted, that the leakage at the drain and source structures of the FETs will be acceptable. More difficult to estimate are the tunnelling electrons, for example through the SiO_2 dielectric of the analogue storage arrays or the transistor gates. If we loose charge somewhere there we will loose information's or in worst case the complete image.

With the specifications of the European XFEL it is expected to shoot approximately 10^{16} photons (~10keV) during three years of use per pixel of about 100um² area. This results in a deposited Dose above one Giga Gray in the sensor surface and roughly a factor 10 less at the read-out chip.

2 Physical principals of photon absorption

What caused the damage and what kind of damage will occur?

When a photon hits solid matter several processes take place, depending on the energy of the incoming photon. There are three major interaction mechanisms taking place in solid states:

Photoelectric absorption, Compton scattering and pair production

In detail, photoelectric absorption predominates for low-energy gamma rays (up to several hundred keV), pair production predominates for high-energy gamma rays (above 5-10MeV), and Compton scattering is the most probable process over the range of energies between these extremes.

For energies used in the European XFEL (about 12keV) the photoelectric absorption is the predominating process in Silicon solids. So we can neglect processes such as Compton scattering and pair production.

Photoelectric absorption

During the photoelectric absorption process, a photon interacts with an absorber atom which assimilates the photon completely. In its place, an energetic photoelectron is ejected by the absorber atom from one of its bound shells with an energy given by the incident photon energy minus its binding energy.

The absorption itself is a process which strongly depends on the number of possible interaction atoms given by the density of a material, the absorber thickness and a material constant, called absorption coefficient which represents the probability of absorption for a given Energy of the incoming photon. The Intensity given in photons per second is predictable using the so called absorption law:

$$I = I_0 \cdot e^{-\mu (E) \cdot \rho \cdot x}$$

For X-rays of sufficient energy, the most probable origin of the photoelectron is the most tightly bound or K shell of the atom. The interaction can only take place, if the nucleus absorbs the momentum of the incoming photon because of momentum- and energy conservation, but this recoil energy is very small and usually can be neglected. That's why the photoelectric absorption cannot take place with free electrons, only with the atom as a whole.

What we obtain is an excited atom. But it relaxes immediately in two main feasibilities, emission of fluorescent photons or Auger electrons. The emittance of a characteristic photon is more likely than for Auger electrons. Also the Auger electrons have extremely short range because of their low energy. Unlike a neutron- or a charged beam (e+, e-), where the particles can travel a long path through an absorbing material, scattered or diffracted by several atoms or a nuclei.

The vacancy that is created in the electron shell will quickly be filled by electron rearrangement. This means an electron-hole pair occurs in the atom.

Absorbed Dose

The Dose is equal to the deposited energy per unit mass in a medium, and has the unit Joule per kilogram or Gray (Gy). The absorbed Dose is a measure of the energy deposited in a medium by ionizing radiation, like X-rays.

3 Experimental setup

During my stay I built up my own experimental setup to perform the measurements. I used as a source an X-ray tube with a Molybdenum cathode. A double slit system characterises the beam position precisely and creates a defined rectangular of the beam. I used a small focused beam of the size of the radiated transistors. <u>Pictures</u>: "The experimental setup" shows the used setup inside the shielding hutch of the laboratory. At the exit window of the X-ray tube comes an automatic shutter and a short collimator was preinstalled. The slits are made out of Tantalum, to avoid florescence and Bremsstrahlung in the beam. I used step motors to control

and change the positions of the slits. As close as possible to the tube in respect to the slit system, I position the different Detectors in the same distance of about 15cm from the tube. All components were fixed to a mounting rail to keep a precise position over the entire experimental time of several days.

3.1.1 Measurement

At the beginning I measured the Spectrum of the source, which comes out of the X-ray tube in the lab. For that I used a so called Vortex-50EX detector, with 4096 bins/channels. So each channel has 10eV bandwidth. I accomplished all my measurements with a fixed accelerator voltage of 30kV and 50mA current at the X-ray tube.

To measure the Transistor characteristics I got familiar with the Semiconductor Parameter Analyzer (HP 4156A). The HP 4156A is an electronic instrument for measuring and analysing the characteristics of semiconductor devices. Of interest is the calculated threshold Voltage and the corresponding Forward Transconductance.

What do these parameters tell us?

V_{Th}—Threshold Voltage

This is the gate-source voltage at which collector current begins to flow. V_{Th} has a negative temperature coefficient, meaning that as the transistor heats up, the collector current will turn on at a lower gate-emitter voltage.

For the experiment, the threshold voltage represents the appearing leakage currents inside the semiconductor structure, which responds to the damage caused by radiation.

gm — Forward Transconductance

Forward Transconductance relates collector current to gate-emitter voltage. Forward Transconductance varies with collector current, collector-emitter voltage, and temperature. A high Transconductance corresponds to low plateau voltage and fast current rise and fall times.

With the use of the HP 4156A I got the linearly extrapolated threshold voltage with gate and drain connected to one voltage source. Source and bulk are connected to ground and the voltage is swept in order to find the maximum slope of the square root of the drain current as a function of the gate voltage. Around this operating point the Analyser performed a linear regression to find the threshold voltage. The voltage sweep has to be positive for n-channel devices and negative for p-channel devices. The intercept with the abscissa is taken as V_{Th} .

During my measurements I irradiate a DMOS Transistor (N-Channel), Type ZVN3310F in comparison to a DMOS Transistor (P-Channel), Type ZVP3310F. See <u>Outcomes</u>. At a first step I played with the CCD-camera to get familiar with the setup.

For the alignment of the beam position and size I used a Photodiode and photosensitive paper, to calibrate the exact position of the beam. I designed a multipurpose detector holder with a hole in the centre, to locate a Photodiode in the middle of the beam. But you can also adjust a MediPix-detector and the test structure to the holder. After I adjust the beam size to a 400x400um rectangle in the centre of the Detector holder, I put the EED detector, called Vortex, window at the place of the holder. The Vortex detector measured the Spectrum of the X-ray tube; to calculate the Intensity in the same position of afterwards irradiation experiments, see <u>Outcomes</u>. To avoid radiation damage to the detector, I used a 100um thick slit in front of the Beryllium window of the Vortex detector.

After that I replaced the detector holder and exchanged the photodiode by one of the transistors to irradiate. For the measurements I fixed the transistor from behind the holder using tape, to keep it in place. Immediately after each irradiation I took the transistor out of the experimental hutch and measured it with the Parameter Analyzer. This procedure was to be repeated until the threshold voltage reached saturation. Also further exposure would take more than one day and for it no time remained.

After I finished the irradiation period I stored the MOSFET under room temperature in the Laboratory, to determine if there will be measurable annihilation processes taking place in the substrate after a view days.

3.2 Differences to a Free-Electron-Laser

At a first point of view an X-ray tube is something totally different to the European XFEL, but we will see why it makes sense to use the results for a FEL.

The differences could not be bigger, experiments using an X-ray tube began with C. Röntgen in the 19th century and now we are talking about a Free-Electron-Laser the newest generation of X-ray source builds by man.

In my experiment I used a white beam to shoot on a target and not a highly monochromatic beam. But what counts is the absorbed number of photons in the target, with a given energy. This knowledge is necessary for the calculations on the Intensity of the beam and the deposed Dose in the material.

As described under Experimental setup the cathode is made out of Molybdenum, which Spectrum has its characteristic K^{α} peak at about 17keV, what is close to the proposed FEL energy of about 12keV.

4 Results

To get an idea of the Dose absorption in the HPAD chip I calculated the expected Dose depending on the thickness of different materials. For interest is Silicon (Si) and Silicon oxide (SiO_2) , the two main components of major concerns. It's shown nicely that the highest Dose will be absorbed by a thin surface layer; see <u>Pictures</u> "Theoretical Absorption". You can easily see that the absorption in a few micrometer thick layers is 100 times higher in comparison to a bulk material of about 500um.



My first results of measurement show the out coming flux in photons per second of the X-ray tube. I corrected the measurement with the not absorber photons in the detector, which depends on its thickness. As expected from the theoretical data given by X-ray Oriented Programs (XOP) one found a broad slope, caused by Bremsstrahlung in the cathode material and two sharp peaks K^{α} and K^{β} , see Picture: "Molybdenum Spectrum". From that I calculated the total Intensity of the tube.

The primary experiment, the radiation hardness measurements of the MOSFET took me several days irradiating the transistors day and night. A selection of my measurement is saved in the files: MESx.DAT, with x representing the time of irradiation.

For the analytical calculations I plotted the square root of the drain current as a function of the gate Voltage, using the Semiconductor Parameter Analyzer, see <u>Measurement</u>.

With Origin 7.5 I plotted the two measured parameters, the threshold Voltage V_{Th} and Forward Transconductance gm depending on the deposited Dose in the transistors and also for the irradiated time, see graphs underneath. Out of the Datasheets I got for the ZVP3310F a threshold voltage range from -1.5V to -3.5V for a given drain current equal -1mA. For the ZVN3310F there is a given range from 0.8V to 2.4V for the threshold voltage.



p -channel Measurements $V_{Th} = V(dose)$

The curves show an exponential decay. A double exponential function like

$$y = y_0 + A_1 \exp(-(x-x_0)/t_1) + A_2 \exp(-(x-x_0)/t_2),$$

gives a good approximation of the data sets. This means that there are two processes and fittings show that the coefficients A_1 and A_2 are in the same dimension of about 1.5, so they can not be neglected.



n – channel Measurements $V_{Th} = V(dose)$

It comes out that the major damage obtains in the early stage of a view kilo Gray or a correlate irradiation time of about 15 minutes. While the n-channel respond more sensitive on the irradiation than the p-channel MOSFET does. This different response comes from the design and the working principle of these two transistor types. The ionising process in the silicon oxide layer during the irradiation creates more and more free electrons, which create a channel, were a current can flow. These free electrons must be "pushed" down into the substrate to pinch of the channel.

For a certain dose both devices get into saturation, because of the fact that the substrate will be fully ionised.



p-channel Measurements V_{Th}= V(time)

The measured data points 7 of the n-channel transistor are obviously wrong, this happened due to the fact that the curves where shifted so much to the left, that the Semiconductor Parameter Analyzer did not calculate the linear regression correctly.



n – channel Measurements $V_{Th} = V(time)$

One can see a annihilation for both types. But for the n-channel device the process acts faster, because free electrons have a higher mobility than "electron holes". So the electrons will easily recombine in the positive doped substrate of an n-channel device.



n – channel Measurements gm= gm(dose)

The plot above shows the measured forward Transconductance per absorbed Dose for an n-channel device. The kink at data point 7 is a measurement error, which I discussed above.



n –channel Measurements gm= gm(time)

The development of the forward Transconductance versus irradiation time is in good approximation linear on a logarithmic time scale. This corresponds to the theoretical behaviour of a FET under irradiation. The kink at data point 7 is a measurement error, which I discussed above.

4.1 Discussions

I tried hard to keep the error possibly small, but I think there are several alignments which can be improved, such like a more professional isolated and soldered probe. Also I neglect the effects caused by the air between the tube and the transistor, so one has to correct the beam intensity by absorption processes.

The transistors did not explode or disperse, not even after days of irradiation. Also no visible damage appears on the package, but the experiment shows that there is serious damage to the MOSFET even for low irradiation of a view kilo Gray. That is six magnitudes below the proposed Dose at the European XFEL.

5 Conclusion & Outlook

I learned a lot of daily life science and the problems to grapple with during the work and especially the measurements. So I got a good expression, what it's like to be a part of a large research facility and I enjoyed it very much. I'm thinking of coming back soon.

Especial thank to my supervisor Heinz Graafsma for a brilliant support during my stay at DESY and also to the entire detector group, cheers. I loved doing my work honestly. My time as a summer student was a fruitful experience that provided me with the skills and knowledge to go ahead with a scientific career. It was a pleasure to work with you.

Next step will be the first experiments with the developed test structure hpad_0.1, but unfortunately without me.

I'm looking forward to hear about these measurements and the out coming results.

Maybe it will be of interest to have a closer look on the annihilation process taking place in the structure. To speed the processing up, one could heat the chip during measurement breaks, for example.

6 Appendix

6.1 Pictures



Bird view of the European XFEL







The experimental setup



Theoretical Absorption of a thick layer

6.2 Bibliography

- Claus Grupen; Grundkurs Strahlenschutz. Praxiswissen für den Umgang mit Radioaktiven Stoffen, Springer-Verlag GmbH
- Glenn F. Knoll; Radiation Detection and Measurement (3rd edition), John Wiley & Sons, Inc.
- c/o: Ulrich Trunk; The hpad_0.1 Manual; Version 0.4α
- c/o: Heinz Graafsma; The Analogue Pipe-Line Hybrid Pixel Array Detector Proposal
- Hewlett Packard; User's Task Guide Semiconductor Parameter Analyser (3rdedition)
- Hewlett Packard; User's Manual Semiconductor Parameter Analyser (3rd edition)
- ◆ Zetex Semiconductors; Package information SOT23, Issue 4
- Zetex Semiconductors; Datasheet ZVP3310F / ZVN3310F -SOT23 p- / n- channel enhancement, mode vertical DMOS FET, Issue 3
- IBM; CMOS8RF Design Manual –Conducting Film Thickness