LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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ELECTRIC FIELD MEASUREMENTS USING SCANNING ELECTRON MICROSCOPE

Examiners: Professor Tuure Tuuva
Professor Erkki Lähderanta

Supervisor: Tuure Tuuva

ABSTRACT

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Electric field measurements using scanning electron microscope

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The main idea of this diploma work is to study electric field distribution on the micro level. For this purpose a silicon edgeless detector was chosen as the object of investigation and scanning electron microscope as an investigation tool. Silicon edgeless detector is an important part of installation for studying proton-proton interactions in TOTEM experiment at Large Hadron Collider. For measurement of electric field distribution inside scanning electron microscope a voltage contrast method was applied.

ACKNOWLEDGEMENTS

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1. Introduction

The main task of this diploma work was studying behavior of electric field at the edge of silicon detector using scanning electron microscope. This diploma is following two preceding diploma works [4, 5] made in Lappeenranta University of Technology, so the aim was set to obtain more precise data about electric field distribution in silicon edgeless detector, and to describe workflow more particularly. If You wish to know about technologies and phenomena mentioned in this work, You should refer to these aforementioned sources.

2. LHC

Large Hadron Collider is the largest and most significant experimental device in the world. It is a circular accelerator, constructed beneath the border between France and Switzerland, by CERN Organization (European Organization for Nuclear Research). The main part of it is represented as a giant tunnel with the length of main accelerator circle of 26.7 km. It was developed by scientists and engineers of more than 100 countries. There provide several experiments on different existing detector systems (see Figure 1), such as:

- ALICE - A Large Ion Collider experiment producing quark-gluon plasma by colliding lead nuclei;
- ATLAS - A Toroidal LHC Apparatus;
- CMS - Compact Muon Solenoid;
- TOTEM - Total Cross Section, Elastic Scattering and Diffraction Dissociation;
- LHCb - Large Hadron Collider beauty experiment;
- LHCf - Large Hadron Collider forward experiment;
- COMPASS (Common Muon and Proton Apparatus for Structure and Spectroscopy).

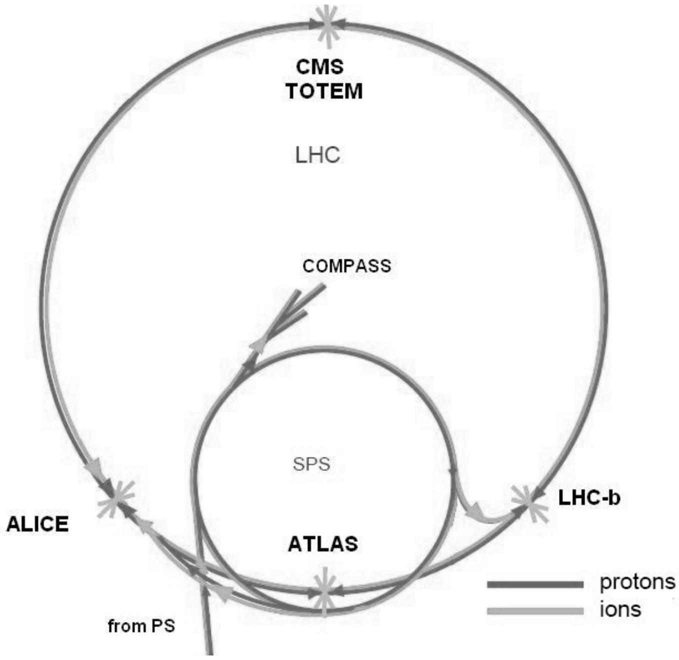

Figure 1. LHC Detectors.

2.1 TOTEM Experiment

The TOTEM Experiment will measure the total proton-proton cross-section with the luminosity-independent method and study elastic and diffractive scattering at the LHC. The purpose of the detectors in the TOTEM is a determination of high-energy proton trajectories [1]. Protons in this experiment fly to the detectors at extremely small angle with respect to the beam direction, so it was necessary to construct such a detection system, which could satisfy this requirement. This task was realized by two telescopes, one of them was placed at the end of CMS detector, and second one - in the shielding behind the CMS Hadronic Forward (HF) calorimeter [2]. Besides, these telescopes are supplemented with detectors called “Roman Pots” (this name was given by group of scientists from the Italy) (see Figure 3). Roman pots are located on the different distances from interaction point, nearest at the 147 meters, and the farthest at the 220 meters. [1]

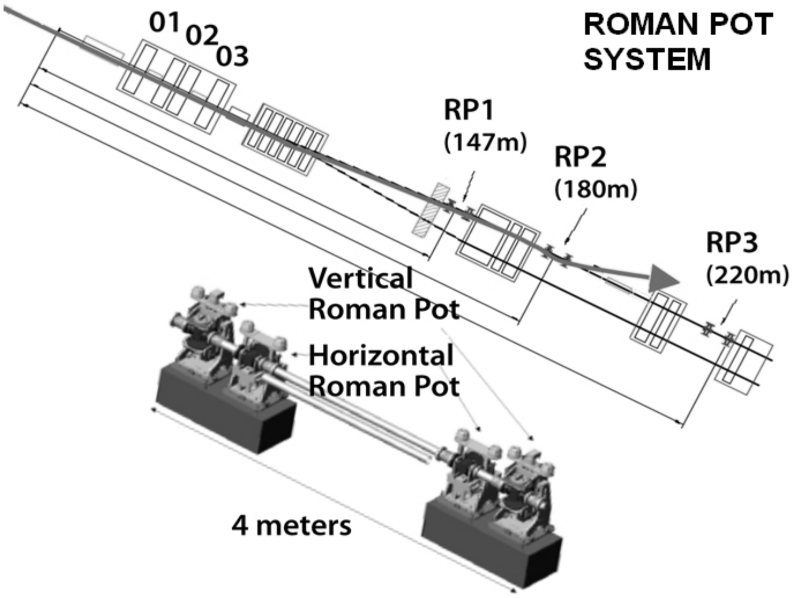

Figure 2. Schematic view of TOTEM detection system. (www.interactions.org)

Each group of detectors inside Roman Pots consists of two series of vertical detectors and one of horizontal detectors. The detectors in the horizontal pots overlap with the ones in the vertical pots, which correlate their positions via common particle tracks (see Figure 4). This feature is used for the relative alignment of the three pots in a unit. For the absolute alignment with respect to the beam, a Beam Position Monitor (BPM), based on a button feed-through technology, is integrated in the vacuum chamber of the vertical RP.

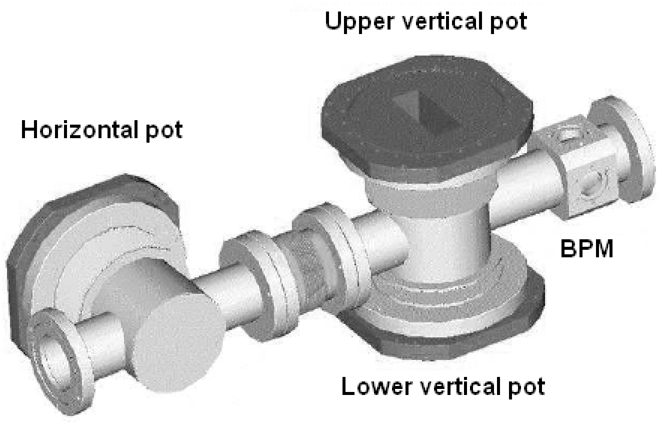

Figure 3. Vacuum chambers of a Roman Pot unit accommodating the horizontal and the vertical pots and the Beam Position Monitor. [2]

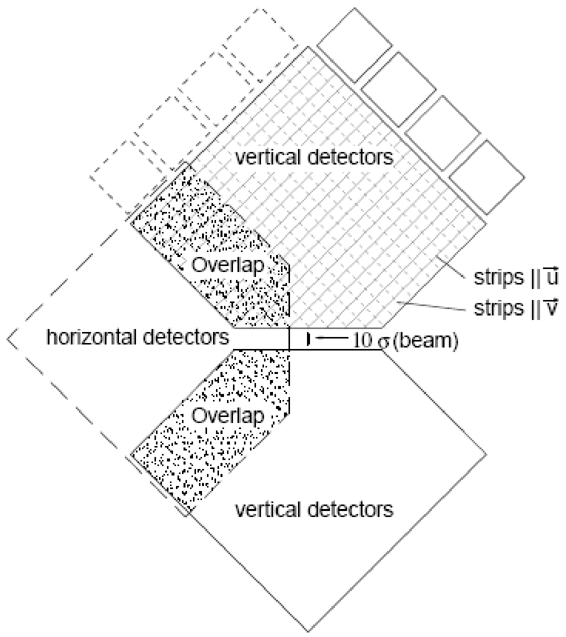

Figure 4. The overlap between the horizontal and vertical detectors. [2]

2.2 Detectors

Silicon edgeless detectors are the new type of detectors that have been designed for close-to-beam applications in high energy physics. Such an edgeless design of this device is needed in order to provide the minimal distance between the edge of detector and the active area of detector (see Figure 5).

These devices are microstrip detectors with 512 strips, with a pitch of 66 μm processed on very high resistivity n-type silicon wafer (>10 kΩ·cm), 300 μm thick (see Figure 6).

Standard planar silicon detectors have a typical insensitive border region around the sensitive area of 0.5 mm occupied by guardrings. This voltage terminating structure drops the voltage gradually between the detector sensitive area and the detector edge.

The basic idea of this new approach is to reduce the insensitive border below 100 μm by applying a large fraction of the detector bias across the detector chip cut through an outer current terminating ring (CTR) that collects the major part of the resulting surface generated current (see Figure 7). [3]

Figure 5. Silicon edgeless detector. [3]

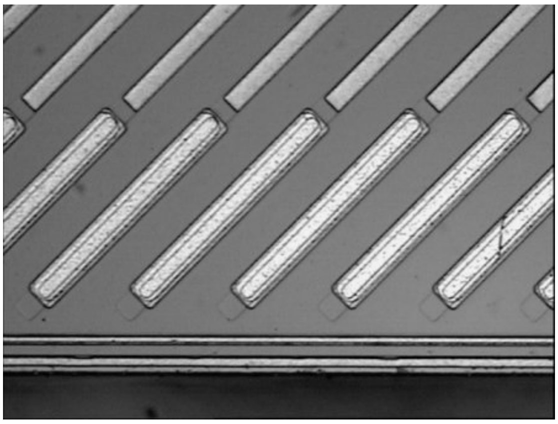

Figure 6. Cut edge of SED (distance between strips is 66 μm). [3]

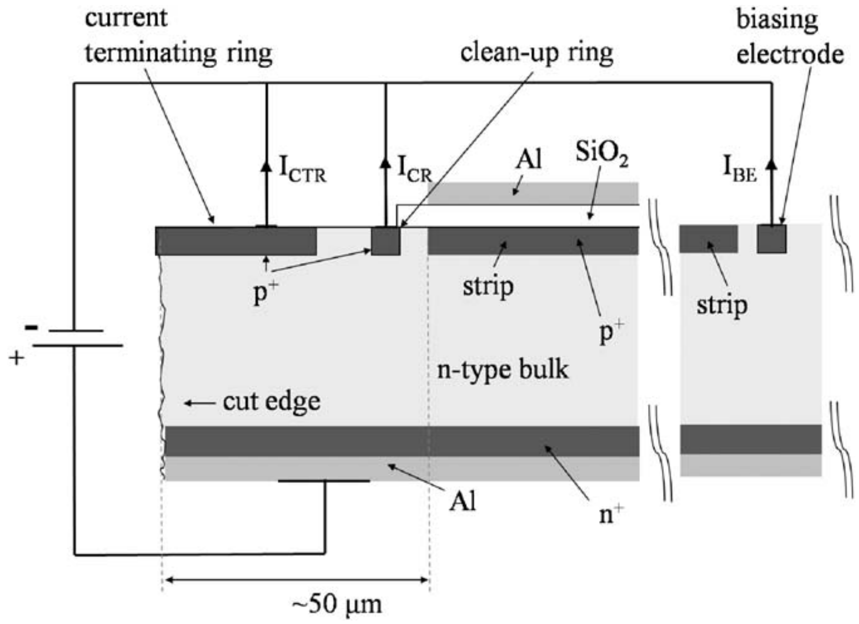

Figure 7. Cross-section of a silicon detector with a current terminating structure in the plane parallel to the strips and its biasing scheme. [3]

3. Scanning electron microscopy

Scanning electron microscope (SEM) was chosen as investigation tool for this work, so this chapter covers construction and working principles as well as some physical phenomena inside this device.

SEM is a complicated scientific device, whose main task is to investigate different materials at microscopic level by falling electron beam onto their surface. This investigation instrument is successfully applied in many fields of science and technology as well as in life science. The main requirements are that the specimen must be able to withstand the vacuum and the electron bombardment.

First electron microscope was constructed in 1932 by two German scientists Max Knoll and Ernst Ruska, and the first commercial microscope was offered by German company Siemens in 1939. Those days were long ago, but principles of SEM are the same till nowadays.

3.1 Construction of the SEM

A scanning electron microscope consists of an optical column, a vacuum system and an electronic unit (see Figure 8). There are scanning and display electronics in the SEM electronic system. All the components of the SEM are usually housed in one unit. On the left side of SEM installation there is the electron-optical column mounted on the top of specimen chamber. The specimen chamber is an element of the vacuum system. On the right side there are the monitor, the keyboard and the mouse which are used for control of the microscope and the video system. A SEM is equipped with two image monitors: one is for observation by the operator, and another, a high resolution monitor, which is equipped with an ordinary photo camera. [4, 5]

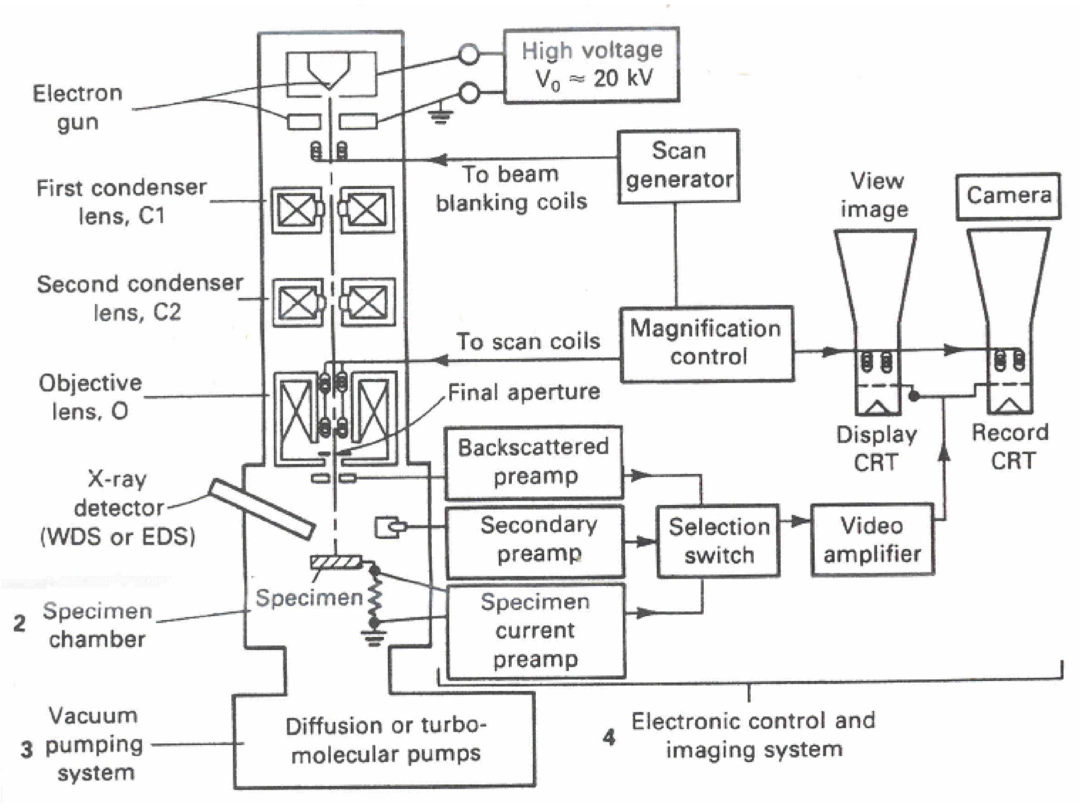

Figure 8. Typical scheme of SEM. [6]

3.1.1 Electron gun.

The electron gun at the top of the column (see Figure 9) produces an electron beam, which is focused into a small spot (less than 4 nm in diameter) on the specimen surface. Cathode of SEM is the heated tungsten hairpin. Electrons from cathode have acceleration on anode up to different energies, from 1 kV to 50 kV. A special condenser lenses are used for electron beam focusing. They should be sufficiently stable to provide the high resolution. The obtained strong focused electron beam scans the specimen from the left to right at a speed from 2 to 5 µm/s. While scanning, there exists a simple rule: the higher is resolution, the smaller beam current must be, so the time of scanning will be longer. The faster is scanning speed – the higher is the beam current.

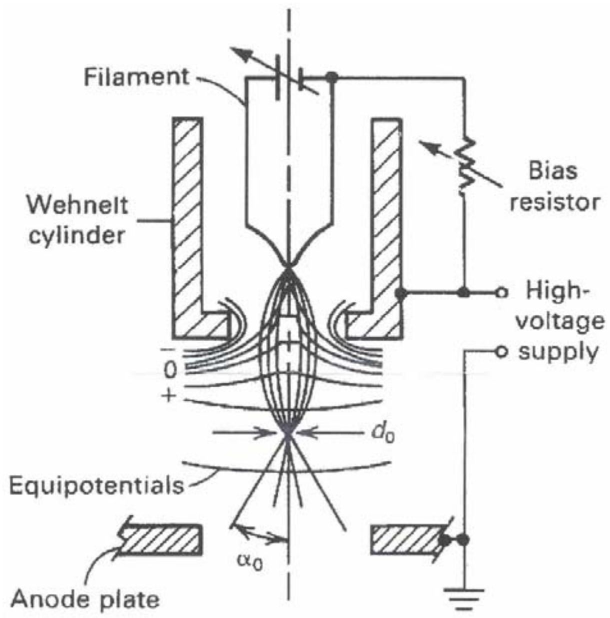

Figure 9. Scheme of electron gun. [6]

3.1.2 Vacuum

In order to avoid the backscattered and secondary electron scattering, the vacuum exists around the specimen. In general, a sufficiently low vacuum in SEM is produced by either an oil diffusion pump or turbomolecular pump, in each case backed by rotary pre-vacuum pump.

3.1.3 Secondary electron detector

When a beam of primary electrons fall onto surface of specimen, it produces a number of phenomena that could be the following (see Figure 10):

- Backscattered electrons – electrons of electron beam that had been elastically reflected from the surface of specimen;
- Secondary electrons – electrons from the surface, that had been extracted from it by hitting of primary electrons;
- Cathodoluminescence – emitting of photons of visible light from material of specimen;
- X-rays.

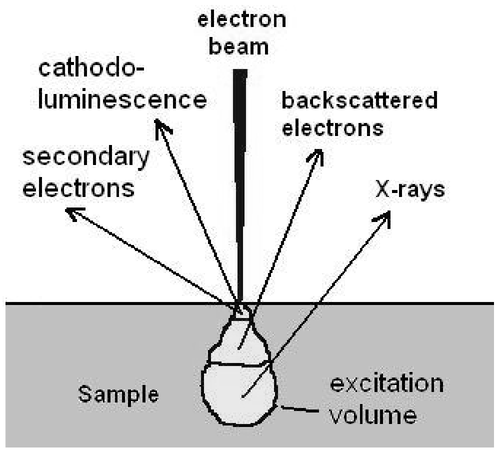

Figure 10. Effects, caused by inelastic interaction of electron beam with specimen.

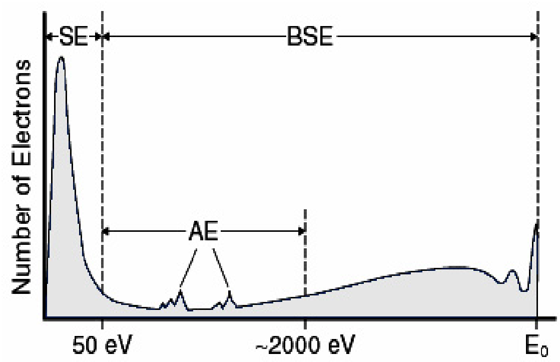

Figure 11. Electron energy spectrum versus number of electrons. [7] SE – secondary electrons, AE – Auger electrons, BSE – backscattered electrons.

In this work SEM uses secondary electrons for image construction. Physical device, that "catches" secondary electrons and separates them from other forms of knocked-on particles is called Everhart-Thornley detector (see Figure 12). When electrons with high energy (~15 keV) from beam hit the surface of specimen, they extract low-energy secondary electrons (~50 eV) (see Figure 11) from material, which are attracted by low positive voltage of Faraday cage. Backscattered electrons have much higher energy, in range up to 2 keV, so Faraday cage can not attract them because its potential is not enough.

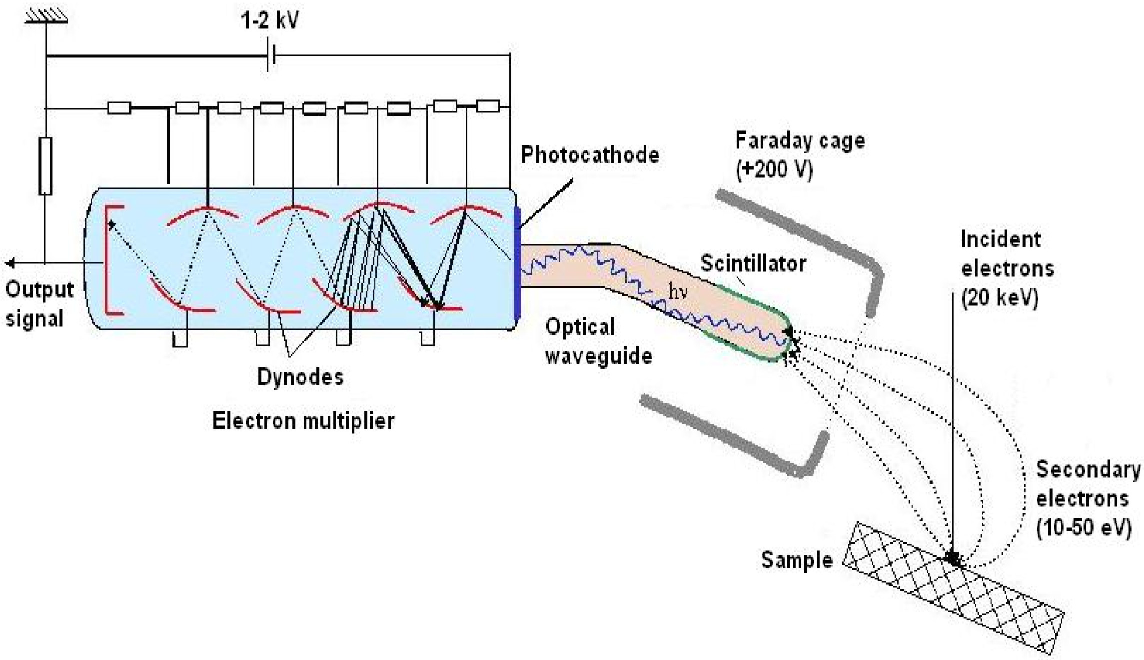

Figure 12. The construction of Everhart – Thornley detector.
(http://fr.wikipedia.org/wiki/Détecteur_Everhart-Thornley)

3.2 Specimen preparation for scanning

In general case specimens can be brought into chamber without any preparation. If the specimen contains any volatile elements such as water, these components need to be removed. Heavy elements like gold also give good yield of secondary electrons and thereby a good image quality. Non-conducting specimens will be charged up under the falling electron beam and they need to be coated with a special conducting layer. This conducting layer is quite thin (typically about 10 nm). However, sometimes it is impossible to cover the specimen by the conducting layer, because it completely changes the specimen surface and can make the sample inappropriate for further use. [5]

4. Installation for measurements of electric field

The main aim of this experiment is the investigation of electric field distribution in silicon edgeless detector. Below the scheme of installation is presented (see Figure13).

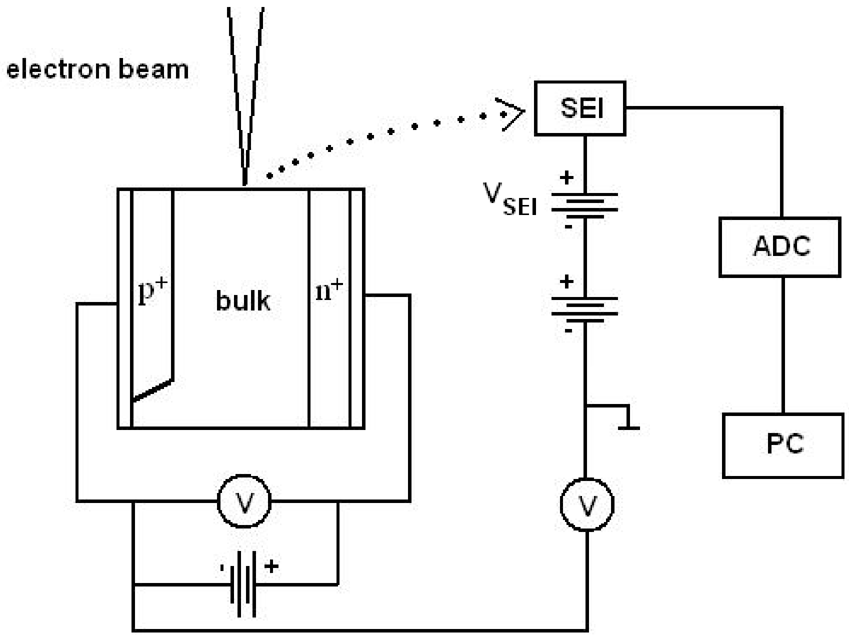

Figure 13. **Scheme of measurements.** SEI – secondary electron image, ADC – analogue-digital converter, PC – personal computer.

In this experiment an edgeless detector is placed into the vacuum chamber. The detector's bias is provided by external power supply Source meter 2410. This power supply source is further used for measurement of current flowing through the detector. The scanning electron beam of SEM with energy of 15 keV scans the detector surface. The penetration depth of primary electrons has a value of only few nanometers. The energy of secondary electrons going out the specimen is small, less than 50 eV. As a result, they are attracted to the secondary electron detector, which has positive potential of 500 V. When taking a measurement, SEM operates in voltage contrast mode. This is an investigation method that employs a voltage constant phenomenon, an effect that even a small voltage on the sample surface could considerably change the amount of secondary electrons arriving to the secondary electron detector. The electric signal collected by secondary electron detector, couldn't be processed by PC directly. That's why such a signal should be amplified and then converted from analog to digital form before the PC processing.

The next equipment was used for the measurements:

1. Scanning Electron Microscope JEOL JSM 5800;
2. SourceMeter 2410, manufactured by Keithley Instruments;
3. PC with special software installed.

Let us consider in more details each of them.

4.1 SEM JEOL JSM 5800

Figure 14. Scanning electron microscope JSM 5800 manufactured by JEOL.

Distribution of electric field in silicon edgeless detector has been studied by the scanning electron microscope JEOL 5800 (see Figure 14). This model is a kind of quite sophisticated SEMs which operates in high vacuum mode. The diffusion and rotary pump are used to maintain the vacuum in the column and in the specimen chamber. A high vacuum level is strongly required for the column and gun. The JEOL 5800 SEM is equipped with detectors for imaging of secondary electrons (SE), backscattered electrons (BSE), X-rays and cathodoluminescence. SE detector is a highly efficient Everhart – Thornly detector which provides imaging at all the scan rates in high vacuum. The Everhart – Thornly detector couldn’t be used in the low vacuum level and its duties are carried out by the BSE detector in the low vacuum mode. CL detector is an independent optical device that must be inserted into the electron path at the specific height. It is important that only SE detector can be used when CL is inserted. [8]

4.2 Model 2410 Series SourceMeter

Figure 15. Front panel view of Model 2410 SourceMeter.

Keithley’s SourceMeter family is designed specifically for testing applications. Model 2410 Series SourceMeter is a compact, single-channel DC parametric tester (see Figure 15). The model provides precision voltage and current sourcing as well as measurement capabilities. The characteristics of this power source include low noise, precision and read back. This device can act as a voltage source, a current source, a voltage meter, a current meter and an ohmmeter. The characteristics of 2410 model are shown below.

- Source voltage from 5 µV to 1100 V; measure voltage from 1 µV to 1100 V.
- Source current from 50 pA to 1.05 A; measure current from 10 pA to 1.055 A.
- Measure resistance from 100 µΩ to 211 MΩ.
- Maximum source power is 22 W.

As the model 2410 has the high voltage source range, it is appropriate for resistors and voltage coefficient testing, testing the varistors and high voltage diodes, including switching, Zener diodes, RF diodes and rectifiers. [9]

4.3 Detector

In this work a silicon detector was used, where all contacts were connected together with conductive paint (see Figure 16), so this operation simplified connection of spring to the detector. The area of sample investigation was edge of detector with its width approximately 230 µm. This detector was placed in a special holder, where metallic spring pressed it to the contact square pad situated in the upper side of the detector (See Figure 17)

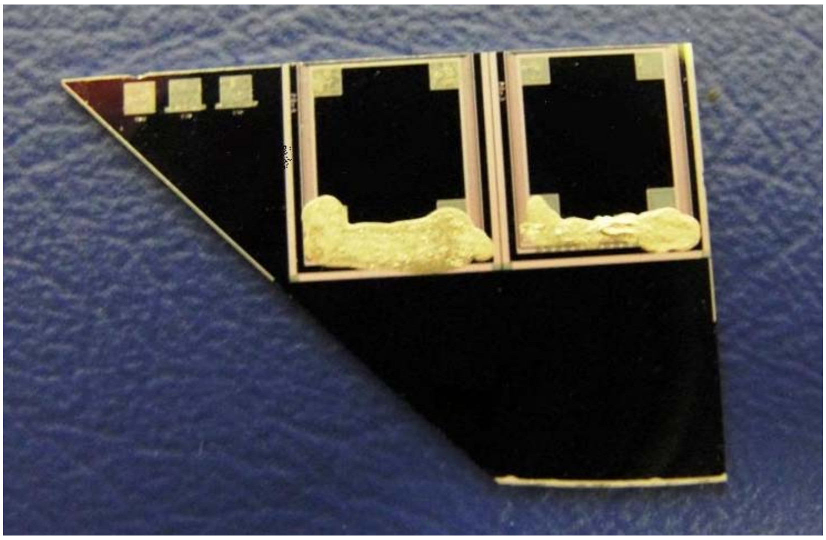

Figure 16. Silicon detector used in this work.

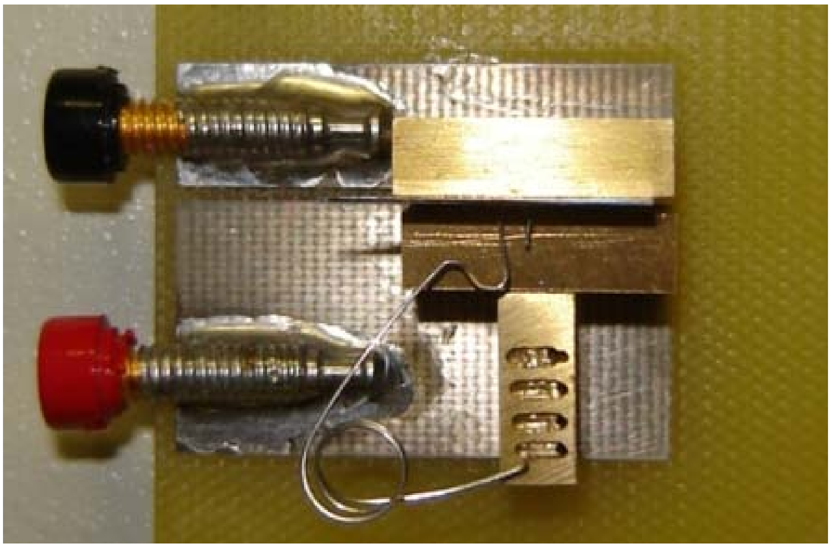

Figure 17. Detector installation in the measurement system (top view).

The sample holder is equipped with two connectors, through which detector was electrically connected with power supply and voltmeter. For making connection from vacuum camera to power supply, which was situated outside, a special flange was used (See Figure 18).

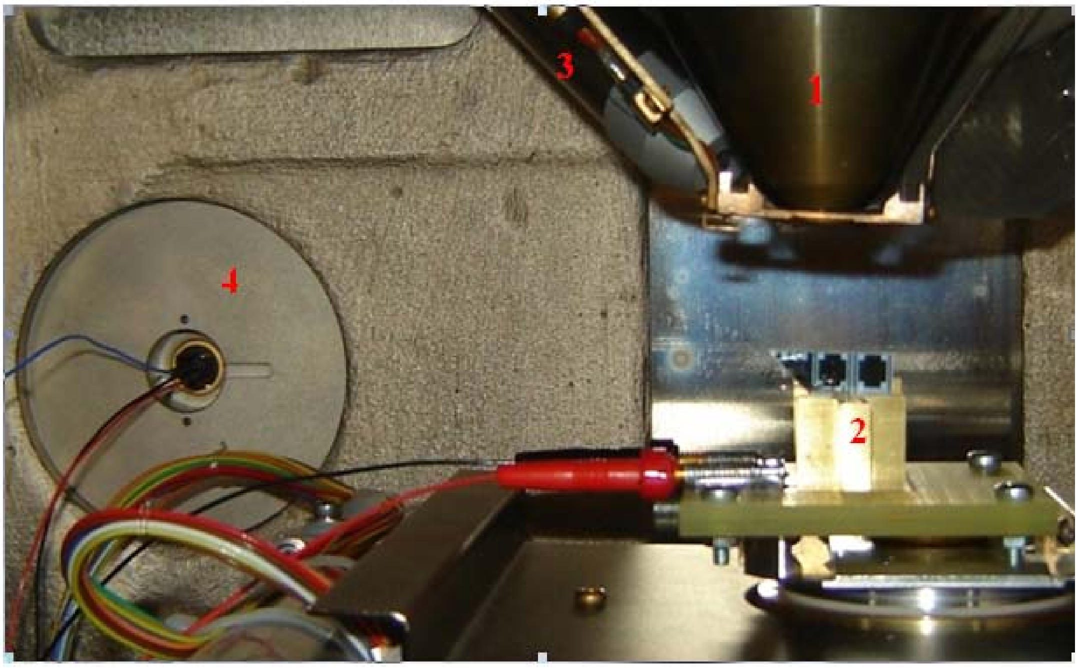

Figure 18. **Specimen inside SEM vacuum chamber.**1 – electron gun, 2 – specimen, 3- Everhart-Thornley detector, 4 – flange for connection with sourcemeter.

4.4 Software

Amplified and converted signal from secondary electron detector was further analyzed by PC. In order to work with images a special program Noran System Six (NSS) 2.1 was used. (See Figure 19)

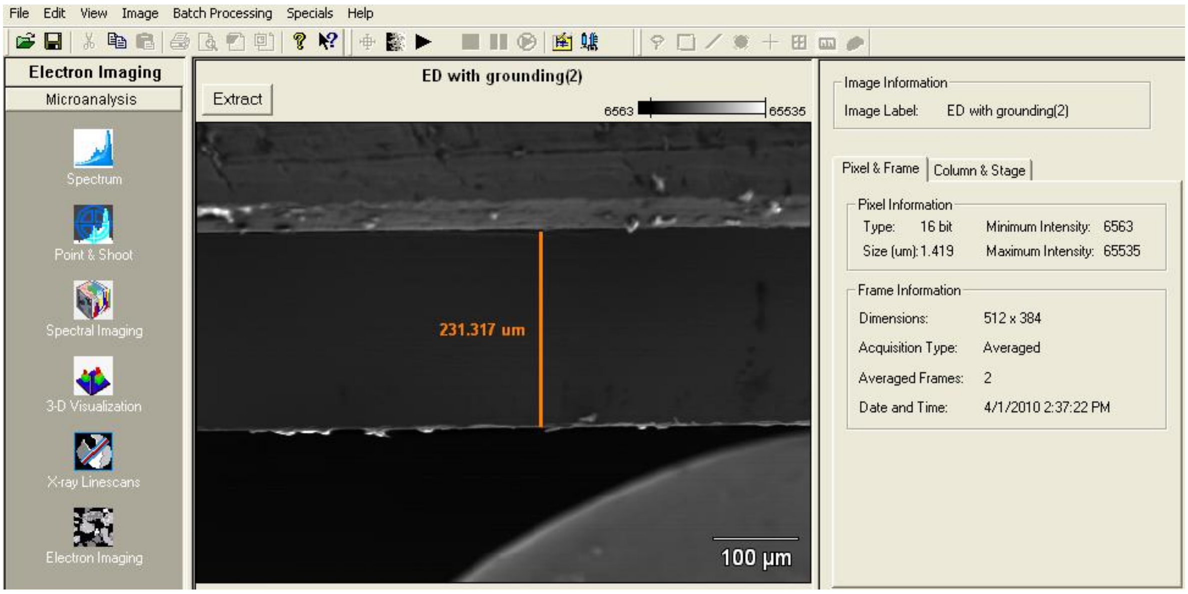

Figure 19. Interface of NSS software in Electron Imaging mode with “ruler” tool applied.

4.5 Measurements of electric field

Measurement of electric field was done at different biasing voltage from sourcemeter. Totally 11 Figures were obtained when potential difference varied from 0V to 100V with step 10V. These Figures are in gray scale, and the variation of white/black colors shows the electric field distribution. The darker is the area of the picture – the lower is the value of electric field in this point. The upper side of the Figure has zero potential (zero side) and the lower side of the Figure is under biasing voltage (potential side). There are some areas that differ from common Figure, which are considered as dirt or defects of the surface. Here are three pictures which show a condition of detector's surface in case when no bias is applied, when biasing is equal to 50 Volts and when the biasing is equal to 100 volts (See Figures 20, 21, 22).

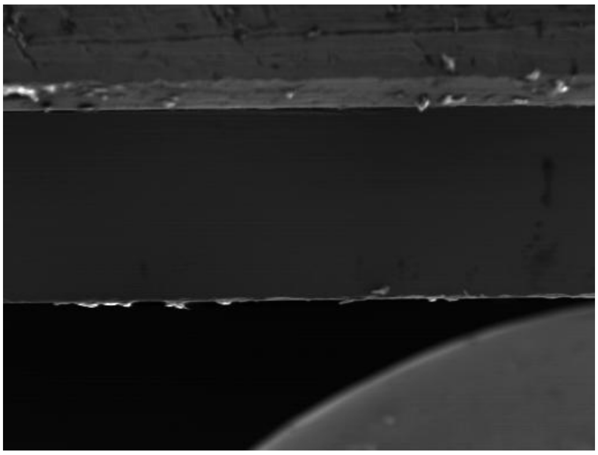

Figure 20. SEM scan of edge of detector when no voltage is applied.

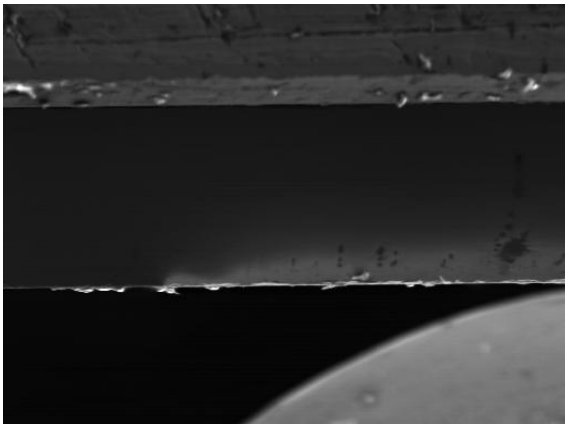

Figure 22. SEM scan when biasing voltage is 50V.

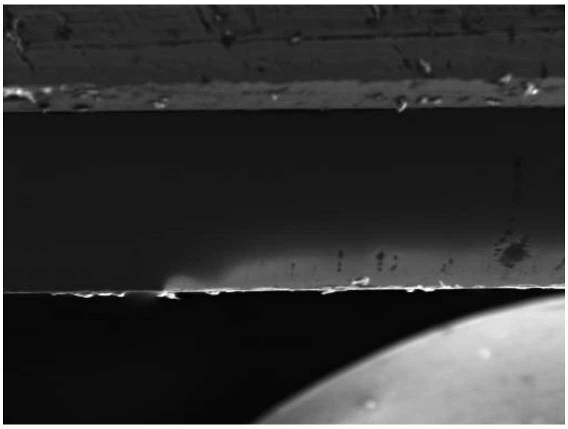

Figure 23. SEM scan when biasing voltage is 100V.

5. Calculation of electric field distribution

5.1. Data obtained from NSS software

All data from the NSS computer program was obtained as graphic files in TIFF format that were converted to CSV-files (comma separated values). Graphic files had resolution 512 * 384 pixels, so in CSV-file every pixel was presented as value of color intensity in range from 15 to 65535. In this work a 16-bit format of data was used, so it allowed getting more precise results in comparison to the earlier measurements. The CSV-files represents tables, where data from one string is written in one cell, so there only one column exists in one table. These tables were opened in Excel program, where they were divided with the help of "rows by columns" option. The next task was to separate values, corresponded to the detector area from the other values. This was made visually, based on that fact that the electric field at the edge of detector is higher than in its volume (See figure 24).

area of the detector	16001	15895	15795	15791	15751
	15943	15871	15745	15563	15599
	15691	15581	15623	15485	15459
	16027	15913	15911	15917	15911
	15433	15437	15547	15557	15341
	15657	15407	15513	15559	15751
	15333	15385	15465	15577	15629
edge of the detector	18987	19545	20967	22759	23487
	29613	30267	30027	29389	29237
	27093	28559	27323	25921	26997
	41539	40521	39233	38037	37693
	33247	32651	31999	31151	31951
some space outside	8441	8327	8151	8085	8905
	8443	8641	8813	8977	9319
	9531	9739	10087	10339	10713
	11205	11485	11761	12161	12513
	12811	13121	13441	13669	13927
	14697	15057	15303	15669	16183

Figure 24. Example of excel-table with the values corresponding to the edge of detector.

The width of the detector is 300 µm, and from NSS program data, width of one pixel at applied magnification is 1,9 µm, so for analysis of whole cut edge of detector it is necessary to obtain data from table from 300 µm / 1,9 µm = 158 cells. That's why it is not possible to present this table in the text.

5.2 The correction of zero shifts

The numerical values of brightness/distance dependence obtained from NSS software are not very correct because of noises that influence on scanning process, so we need to do some corrections to get more precise data. For this task a curve was selected, which shows brightness/distance dependence when no bias is applied. Then a trend line of this curve was created showing us its equation: **Y = 22,286 * X + 13596**, where X represents distance from zero side and Y – relative brightness(See figure 25).

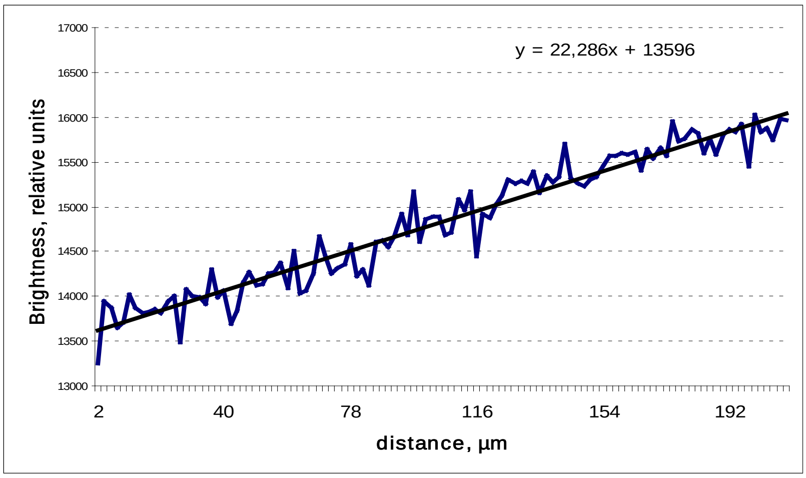

Figure 25. Uncorrected curve with trend line.

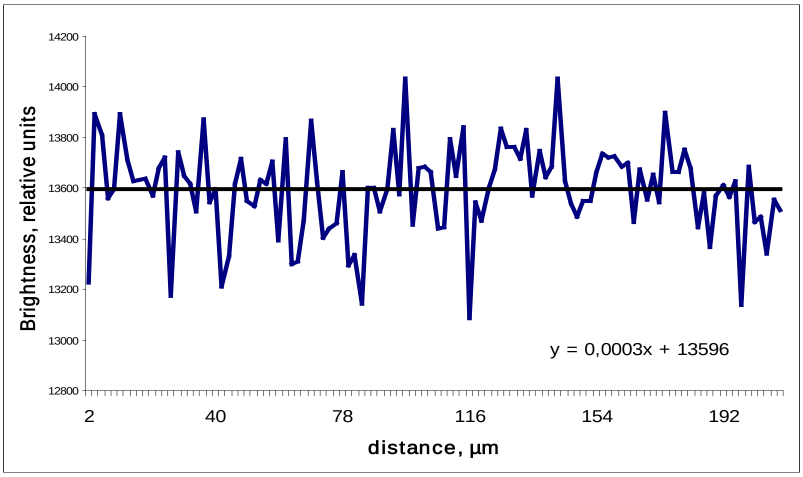

Figure 26. Curve after correction, the trend line lies now in parallel with X axis.

The correction was done in following way: in order to calculate the change in brightness occurs with the certain distance caused by the zero shift we need to multiply **22,286** by the distance from zero side (X) and then to subtract this value from measured brightness value. Such a calculation should be applied to all brightness values and as a result we get clean brightness numerical values that depend only on the applied biasing voltage (See figure 26).

The graph below represents dependence of brightness of each point as a function of a distance from zero side (See Figure 25). Five columns were taken from the values, represented as the area of detector, then averaging of values took place in each string.

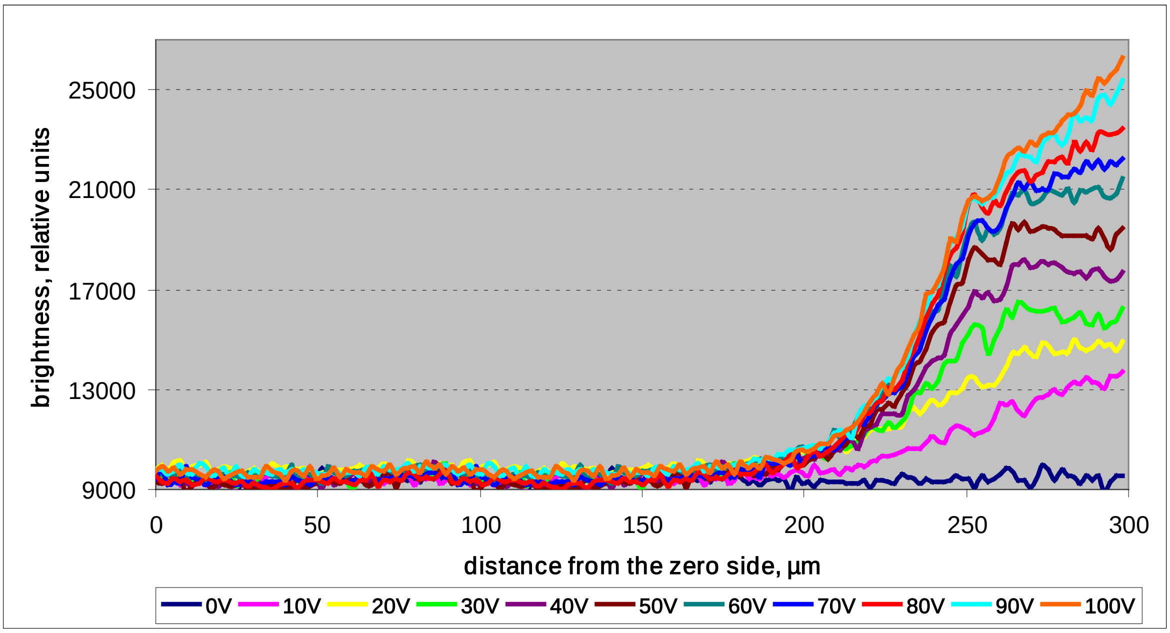

Figure 25. Brightness change with distance for different biasing voltage applied.

From this graph is seen that electric field starts to become apparent somewhere near the point of 210 μm from the zero side, and increasing of bias voltage almost doesn't influence on the distribution of electric field farther from that point.

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5.3 Connection between brightness and biasing voltage.

The next step in calculations was to connect brightness in relative units and biasing voltage. For this purpose a graph was constructed, on the X axis is the difference in brightness between upper and lower point of detector, on the Y axis – biasing voltage. The polynomial approximation was chosen as the best for purpose to find brightness/voltage dependence (See figure 26). With the equation of trend line it is easy to find value of voltage if we know value of brightness: **$Y = -0{,}838 \cdot X^2 + 224 \cdot X + 10246$.**

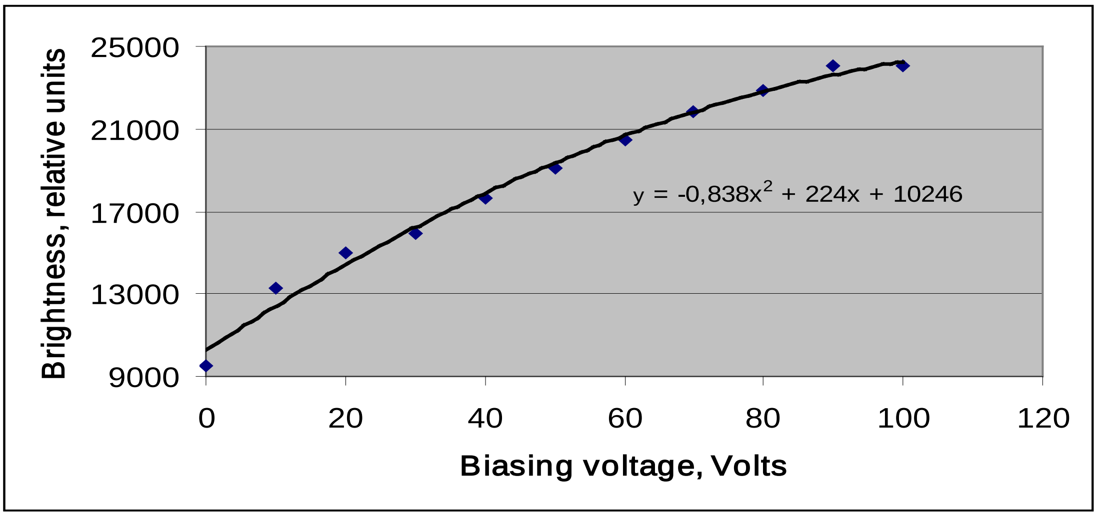

Figure 26. Dependence voltage versus brightness.

After this calibration another graph was constructed to show the voltage/distance dependence (See figure 27).

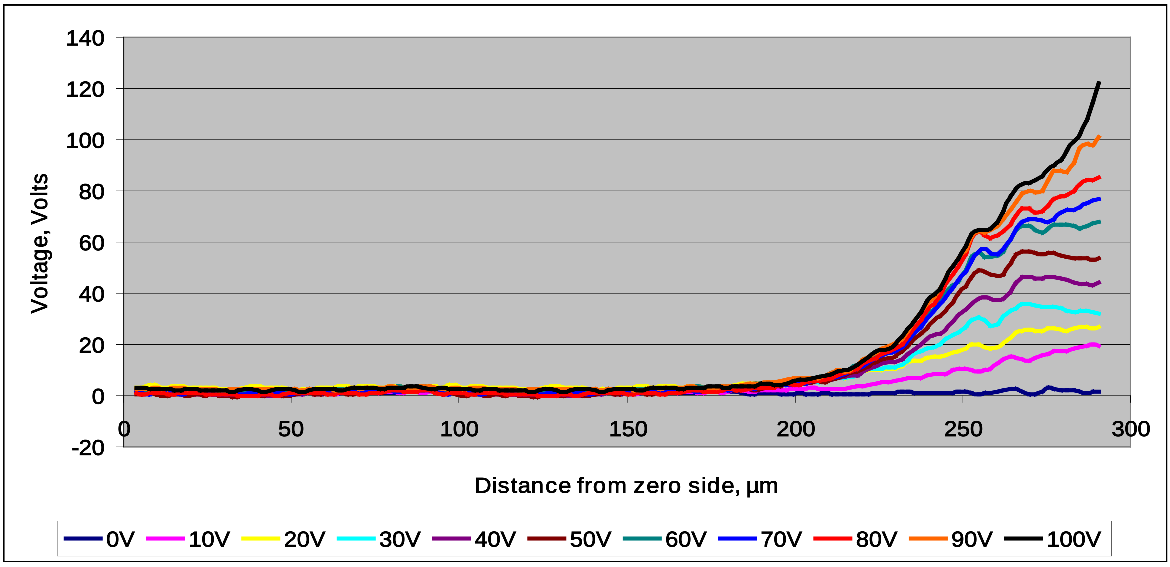

Figure 27. Voltage dependence on distance from zero side.

5.4 Distribution of the electric field

Finally now it is possible to make a graph of electric field distribution on silicon edgeless detector. For this purpose formula **E = ΔU / ΔX** was used. The calculation was done in following way: difference between current value of potential and previous value of potential was divided by distance between current point and previous point.

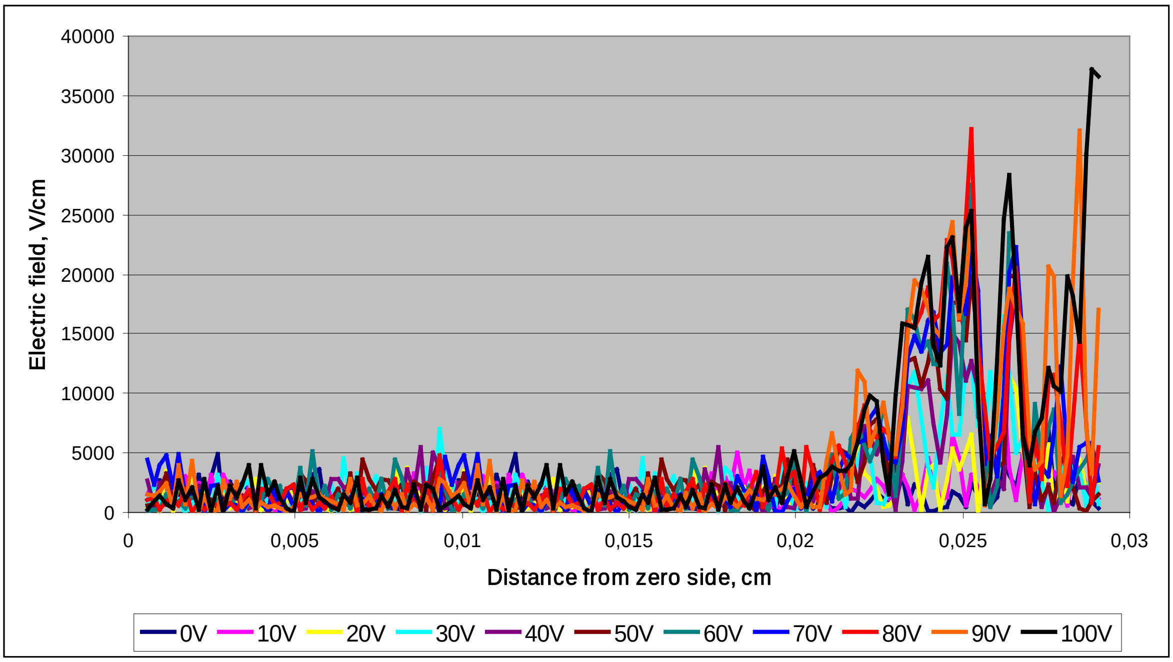

Figure 28. The electric field distribution at the surface of edgeless detector with the different biasing voltage applied.

The electric field increases up to 32 kV/cm when biasing voltage is 80-90 Volts (See figure 28). As you can see, the electric field starts its growth fast between X = 230 μm and X = 250 μm, this is because of fact, that silicon edgeless detector behaves as semiconductor diode in this area. Also, there exist some inaccuracies with two upper curves; this is because the curves of distribution of the potential (See Figure 27) have different shape from the distribution of potential in semiconductor diode.

6. Conclusion

In this work electric field measurements in the silicon edgeless detector were done, which allowed to get information about electric field distribution. The main aim – measurement of the electric field distribution at different biasing voltages – was achieved. The numerical values of obtained data from electron microscope scans were improved in comparison to previous studies of that problem (data in 16-bit format). It was found that electric field doesn’t influence onto whole area but appears near the object that had initiated it at the distance of 90 μm (a metallic spring). Also it was found that electric field has values of 32 kV/cm in the area of junction. All this obtained things can help in the following studies of edgeless detectors.

7. References

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