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History, Status and Prospects of producing Silicon Sensors for HEP Experiments at Infineon Technologies

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Abstract

Within this project we are developing single-sided AC-coupled silicon strip sensors and DC-coupled hexagonal pad sensors for applications in High Energy Physics (HEP) experiments. The project started with a feasibility study to re-produce the state-of-the art of silicon sensors of that time, which were based on high-resistivity n-type float-zone 6-inch silicon wafers. Later, the first silicon strip sensors on 8-inch p-type wafers were produced within this project. This influenced the decision of another project to build a silicon sensor based sampling calorimeter. This paper presents the history, current status, and prospects of this sensor development project, jointly conducted by the Institute for High Energy Physics (HEPHY) of the Austrian Academy of Sciences and Infineon Technologies AG.

Keywords: Silicon Sensors, 8-inch, Silicon Strip Sensors, AC-coupled, hexagonal, Pad Sensors

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1. HEP Landscape

Back in the 1980s, the NA11 experiment at CERN was the very first high energy physics experiment that used planar silicon strip sensors for measurements of the charm quark lifetime [1]. About one decade later, the LEP experiments ALEPH [2], DELPHI [3], L3 [4] and OPAL [5] developed the first vertex detectors made of Silicon strip sensors. From there on, silicon strip sensors were used as tracking detectors in a variety of high energy physics experiments, continuously replacing the prevalent gaseous tracking detectors.

The great success of silicon sensors is influenced by the industrialisation of semiconductor processing. Initially, only small specialised companies and academic institutions fabricated silicon sensors for high energy physics applications. The small scale production and the associated high costs per sensor limited the achievable detector size. The industrialisation in sensor production enabled the construction of the silicon tracking detectors of today's large-scale experiments like CMS and ATLAS. The biggest device so far is the CMS Tracker utilising 24,244 individual silicon sensors [6]. Each sensor is approximately $10 \times 10 \text{ cm}^2$ in size and was manufactured on individual 6-inch n-type float-zone (FZ) wafers. The success of silicon sensors in high energy physics is still continuing. New fields of application, like for the end cap calorimeter of CMS, are foreseen (see below).

2. The project

In 2009, the Institute of High Energy Physics (HEPHY) started a collaboration with Infineon Technologies Austria AG (Infineon or IFX) on the development of planar silicon strip sensors for HEP experiments. The collaboration was initiated by physicists and engineers on both sides in a bottom-up approach and was established as a formal R&D project later on.

2.1. Infineon Technologies

Infineon Technologies operates a large semiconductor production site in Villach (Austria), where 6-inch, 8-inch and 12-inch wafers are processed. The large wafer throughput makes Infineon a suitable candidate for a future high volume supplier of silicon strip sensors. Furthermore, Infineon is one of the world's market leaders in power electronics, which have similar requirements for production as silicon particle sensors.

2.2. Collaborative Procedures

The work within the project is shared between Infineon and HEPHY such that HEPHY is providing the sensor design. The layout is created using Ruby scripts in the open source GDS editor KLayout [7]. Then, the sensors are produced at Infineon by a custom made workflow optimised for the special needs of fully depleted silicon particle detectors. Subsequently, the sensors are tested by electrical characterisation at HEPHY, which is also responsible for the irradiation of the sensors and to perform beam tests. Finally, the results of all these steps are fed back to Infineon to optimise the production process.

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2.3. Achievements

Several production runs of silicon sensors which are summarised in table 1 have been performed within the project. Each production consists of several different batches. One batch usually contains around 15-25 wafers. Within each batch, several parameters have been varied on purpose to see their influence on the detector performance. These parameter variations are referred to as split groups.

Figure 1: Produced wafers within this project and year of production. Compare to table 1 for details.

The first production aimed to re-produce the state-of-the art of silicon sensors of that time, which were based on n-type float-zone 6-inch Silicon wafers [8]. The wafer layout is shown in figure 1 a). Promising results were obtained from the first batch. Four further batches were produced addressing different aspects and issues. The performance of these sensors was demonstrated in various beam tests [9, 10]. The main problems of this production were identified as charge-up effects [11]. The 6-inch run, with a production of 50 wafers in total, was completed in 2015.

Similar to the trend in the chip industries to move to larger silicon wafers, the project went into a next phase with the production of the first AC-coupled silicon strip sensors on 8-inch wafers [12], with an example shown in figure 1 b). Most of the results presented in the subsequent sections are from this production.

The availability of 8-inch production technology for particle sensors facilitated the development of new detector concepts like the planned CMS High Granularity Calorimeter (HGCAL) which greatly profits from the large wafer size [13]. For this project, the available wafer area on the 8-inch sensors will be optimally used by placing hexagonal sensors on the wafers, as illustrated in Fig. 1 c).

To facilitate the production of sensors that are optimised towards 6" wafer sizes, a production process compatible with 6" p-type substrate technology was developed. A first production of AC-coupled strip sensors with this technology was performed very recently (wafer layout shown in 1 d).

3. Silicon Strip Sensors

A silicon strip sensor can be compared to a standard planar diode, where the implantation at the top is segmented into strips. Thereby, each segment represents an individual p-n junction. The design allows reconstruction of the position of traversing particles in one dimension. In the case of the n-in-p sensor developed within this project from 2015 onwards, the strips consist of highly doped n-type areas, abbreviated n^{++} , embedded into lowly p-type doped float-zone silicon substrate.

The substrate (bulk) resistivity is in the range of 3 – 8 kΩcm. To maintain a high inter-strip isolation resistance, a dedicated isolation structure is needed. It is either called p-stop, if the p^+ implantation is arranged in a way that it is surrounding each strip implant, or p-spray if it is homogeneous. Sensors built in this configuration are known to be more radiation-hard than the ones utilising n-substrate [14, 15, 16]. Figure 2 shows the basic features of a sensor in a schematic three-dimensional cross section.

Figure 2: Sketch showing the basic features of an AC-coupled n-on-p silicon strip sensor with p-stop strip isolation structures, poly-silicon biasing resistors and a periphery consisting of bias, guard and edge rings.

3.1. Electrical Characterisation

A semi-automated probe station at HEPHY is used for the electrical characterisation of the sensors [17]. It is used to determine global parameters like dark current at certain bias voltages, breakdown voltage, full depletion voltage, and some derived parameters from these measurements like the resistivity of the silicon bulk. These measurements are complemented by a set of tests performed on each strip, comprising the single strip currents, resistances of the poly-silicon resistors, coupling capacitances, and the currents through its dielectric.

The very first production batch of Si sensors on 8-inch wafers was summarised in [12]. Detailed measurements performed later revealed an issue with premature voltage breakdowns. Figure 3 (left) shows IV curves of the mini-sensors¹ from the first batch of 8-inch sensors. While the sensor design was optimised for high voltage operation up to 1 kV, the sensors showed early breakdowns between 50 and 950 Volts for the different wafers. The fact that a few sensors withstand 1000 V reveals that there is no systematic problem in the sensor layout that causes breakdown. It was found that this effect scales with sensor size, as smaller sensors (area $\approx 2 \text{ cm}^2$) were easily stable up to 1 kV (see fig. 3, right), while the largest sensors of the wafers with an

¹Mini-sensors are small replicas of the main devices with fewer and shorter strips but otherwise same properties.

Figure 3: Leakage current as a function of bias voltage of the mini sensors (left) and smaller so-called "center-bias" sensors (right) of the first batch of 8-inch wafers.

area of $15 \times 10 \text{ cm}^2$ (see table 1) suffer from early breakdowns on almost all tested wafers. Although several mitigation measures have been introduced in the second and the third batch, the problem is currently still present.

Another issue found in the first batch of the 8-inch strip sensor run was a frequency and amplitude dependence of the coupling capacitance as seen in figure 4 (left). This effect was tracked down to a too low strip implantation dose creating Schottky-contact behaviour with the metal and causing the observed measurement results. A mitigation measure was implemented for the second batch by increasing the doping concentration of the strip implant in general and underneath the contact holes in the coupling dielectric in particular. This solved the issue, and the capacitance measurement is now stable as shown in figure 4 (right).

Figure 4: Frequency scan of the coupling capacitance of an arbitrary strip from batch 1 (left) and 2 (right), respectively.

The poly-silicon resistor values target to $(1.5 \pm 0.5) \text{ M}\Omega$, but differed from these values for the first batch. Several implantation doses were used in order to calibrate the dose required for the target resistance in later batches [18].

As the dielectric layer responsible for the AC-coupling consists of a sandwich of silicon oxide and nitride, the dielectric is very stable and HV resistant. The measured currents through the dielectric layer are in general very low and usually only show the isolation resistance of the setup. Only two strips out of more than 30,000 measured strips gave values above 1 nA that indicate potential pinholes.

Different strip isolation options were tested by using various implantation profiles for the p-stop and a homogeneous p-spray implantation. The resistance between adjacent strips was determined and found to be around 30 G Ω cm for shallow p-stop implants and 100 G Ω cm for deep ones, respectively, and 56 G Ω cm for p-spray.

Much more detailed results from electrical characterisations are shown in [19].

3.2. Irradiations

Irradiation studies were performed in order to understand if the sensors behave according to theory [20]. Samples of the first batch were irradiated with protons at Los Alamos (US) and KIT (Germany), whereas samples of the second batch were exposed to neutrons at the Triga Mark reactor of JSI Ljubljana (Slovenia). In addition, gamma irradiations of test structures were performed. The results are presented in [21].

Sensors and diodes from the first two batches have been irradiated to fluences² from 1×10^{14} to $1 \times 10^{16} \text{ n}_{eq} \text{ cm}^{-2}$. Irradiation changes the effective doping concentration inside the silicon bulk thus shifting the full depletion voltage to higher voltages. Figure 5 shows this behaviour in a $1/C^2$ -over-voltage plot. It can be observed that no saturation of the capacitance was found for the highest fluence of $10^{16} \text{ n}_{eq} \text{ cm}^{-2}$. This indicates that the full depletion voltage is above 1000 V in this case.

Figure 5: Inverse squared capacitance vs. Voltage behaviour for different neutron fluences. The increase of the full depletion voltage (voltage where the capacitance stabilizes) with fluence is clearly visible. The AC voltage of the LCR meter to perform these measurements was 500 mV at a frequency of 1 kHz.

The defects introduced to the silicon lattice during irradiation are not stable but undergo diffusion effects. Particularly, two effects happen which have different time constants. One is called beneficial annealing and describes a decrease of the effective doping concentration that leads to a decrease in full depletion voltage. This effect is characterised by a short time constant compared to the slower reverse annealing, which works in the opposite direction.

Two of the proton irradiated mini sensors were used for an annealing study where the sensors were exposed to temperatures of 60 °C for certain times to accelerate both the beneficial and reverse annealing. The full depletion voltage was determined repeatedly by CV-scans during short breaks of these temperature exposures. Figure 6 shows the result of this study where the decrease of the full depletion voltage is clearly visible before it starts to rise again. The first region corresponds to the region where the beneficial annealing prevails, while later the reverse annealing dominates. The minimum was found at 80

²normalised to 1 MeV neutrons equivalent according to the NIEL hypothesis

minutes at 60 °C, which is fully compatible with literature [20].²¹⁵

Figure 6: Full depletion voltage as function of annealing time for two samples irradiated to different fluences.

Irradiation-induced defects located close to the center of the band gap act as additional generation-recombination centres that cause an increase in leakage current of irradiated sensors. The increase in leakage current is described by [20]:

$$\Delta I = \alpha \Phi_{eq} V \quad (1)$$

with $\Delta I = I_{irrad} - I_{initial}$ as the difference in leakage current after and before irradiation, V as the volume of the sample and the proportionality factor α as the current related damage rate or simply alpha factor.

IV curves measured at -20 °C after an annealing of 10 min at 60 °C of samples irradiated to different fluences were used to calculate the current related damage rate α . The data is plotted in figure 7, and from a linear fit α was determined to be $(5.27 \pm 0.23) \times 10^{-17} \text{ A/cm}$. This value is fully consistent with the parameterisations of prior measurements [20].

Figure 7: Difference in current before and after irradiation divided by the active volume. The resulting slope corresponds to the α factor.

3.3. Beam tests

Beam tests complement the electrical characterisation and irradiation studies and represent an essential part of the performance tests of silicon sensors. Within the scope of this project, different beam tests have been performed so far. They are listed in table 2. Initially, APV-based readout electronics developed at HEPHY for the electronics of the Belle-II experiment at

KEK [22] was used. Later on, the sensors were coupled to CBC2 (CMS Binary Chip version 2) prototype readout chips developed for the Phase-II Upgrade of the CMS tracker [23]. Finally, it was concluded that the binary CBC2 chip does not allow to study the sensors in the necessary detail. The well established ALiBaVa readout system [24] was used for the latest beam tests for that reason.

At the beam tests at DESY in April and October 2017, two detector modules were exposed to an electron beam with an energy of 3 – 6 GeV. Both modules consist of an ALiBaVa daughter board as front-end and mini sensors from the very same wafer of the second batch. This ensures comparability of results gained from both modules, as one sensor was unirradiated, while the second was irradiated with neutrons to $3.5 \times 10^{14} \text{ n}_{eq} \text{ cm}^{-2}$. Obviously, the module with the irradiated sensor had to be built in a way to allow cooling during operation, transport, and storage.

Prior to runs with beam, calibration and pedestal runs were recorded. Calibration runs were carried out to relate the ADC values measured by the ALiBaVa system to actual charge measured in electrons. From the pedestal runs the noise was determined to be between 1000 and 2000 electrons.

The signal distribution for beam particles traversing both sensors is shown in figure 8. The histograms were fitted by a Landau convoluted with a Gaussian PDF. The Most Probable Value (MPV) of the signal corresponds to a value of 23,660 electrons for the unirradiated sensor (figure 8 left) and 20,150 electrons for the irradiated one (right). This corresponds to a signal-to-

Figure 8: Signal distribution using the ALiBaVa readout system. Left: unirradiated mini sensor; Right: same sensor irradiated to $3.5 \times 10^{14} \text{ n}_{eq} \text{ cm}^{-2}$.

noise distribution with a MPV between 16.5 and 18.1 for both, the irradiated and the non-irradiated module³. This is caused by the fact that the unirradiated module suffers from a higher intrinsic noise than the irradiated one. The exact reason for this behaviour is still to be investigated.

Finally, the signal of the irradiated sensor can be plotted as a function of the applied bias voltage and normalised to the signal in the unirradiated case. This measurement is shown in figure 9, where the signal saturates at 85% compared to the unirradiated sensor at a bias voltage of approximately 400 V. This corresponds to the full depletion voltage expected at the respective fluence this sensor observed.

³Only clusters consisting of two strips were considered

Figure 9: Charge Collection Efficiency (CCE) as a function of bias voltage of the sensor irradiated with neutrons to $3.5 \times 10^{14} \text{ n}_{eq}\text{cm}^{-2}$ and normalised to the unirradiated case.

4. Hexagonal Pad Sensors

In addition to the AC-coupled silicon strip sensors for tracking applications, DC-coupled pad sensors were developed within the project from 2016 onwards. These sensors are aimed to be used as active elements in sampling calorimeters like the planned High Granularity Calorimeter (HGCAL) of the CMS experiment [25] or an experiment at the future International Linear Collider (ILC) [26, 27].

The sensors are of a hexagonal shape housing 235 individual diodes, each again of hexagonal shape (except some corner cells) [28]. The reason is to utilise the available space on the round wafer most efficiently. Moving to larger wafer sizes also simplifies the detector construction as the number of required modules is reduced. As a consequence, 8-inch wafers are used for this project as a baseline after we showed that such sensors are feasible. The sensors are kept as simple as possible, omitting any biasing circuit on the sensor. Thus, the sensors are DC-coupled and the leakage current of each hexagonal cell has to be compensated by the readout chip. However, this complicates testing of the sensors as there is no single biasing connection, but all channels have to be connected in parallel to obtain the same electric configuration as when the sensor is wire-bonded to the readout electronics on the module level. For this purpose, a sophisticated probe-card with internal switching was developed [29], which was used to test the sensors at HEPHY.

Figure 10 shows the results of such a measurement, where the dark current of each cell is plotted in its actual layout to make geometric effects visible. The measurement was performed at a bias voltage of 150 V, which is well above the full depletion voltage of 70 V. It can be seen that a couple of individual cells suffer from high dark currents in the range of μA .

5. Summary & Outlook

In the scope of widening the market for large-area silicon strip sensors, we initiated a development for the commercial production of those sensors. The project started by producing AC-coupled p-on-n strip sensors on 6-inch float-zone wafers with high resistivity. First promising results encouraged us to continue this project with constantly improving quality. Eventually, more than 100 sensors in five batches were produced.

Figure 10: Current map of an 8-inch hexagonal pad sensor at a bias voltage of 150 V. The color code refers to the cell current, while the imprinted numbers corresponds to the cell numbering.

Then, we followed the trend to move to p-type substrate material and even used 8-inch wafers. Up to now, three batches were produced in this technology, again continuously improving the quality. Now, all single strip parameters are under control and understood. The only remaining problem is the premature IV breakdowns. The breakdown probability scales with sensor size. At the moment, huge efforts are made to tackle this problem.

As CMS moved to sensors compatible with a 6-inch production for the Phase-II upgrade of the tracker, we followed this development this year with the production of a first batch of those sensors just finished. Since the application of silicon sensors in HEP is now widened also to calorimetry, we built first hexagonal pad sensors on 8-inch wafers for this purpose in 2016. This was a first demonstrator that helped the CMS HGCAL collaboration to define 8-inch sensors for the baseline in its Technical Design Report [25].

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Table 1: Summary of the sensor runs produced within this project.

Production year	Wafer size	Bulk Polarity	Layout	Size of main device	Thicknesses [μm]	produced batches
2012	6"	n	AC strips	$10 \times 7 \text{ cm}^2$	200, 300	5
2015	8"	p	AC strips	$15 \times 10 \text{ cm}^2$	200, 300	3
2016	8"	p	DC pads	$18 \times 16 \text{ cm}^2$ (hexagonal)	140, 200, 300, 350	1 (so far)
2017	6"	p	AC strips	$5 \times 10 \text{ cm}^2$	240, 500	1 (so far)

Table 2: List of beam tests performed with sensors developed in the scope of this project.

date	facility	particles	readout	sensors	comment
Oct. 2012	SPS	120 GeV hadrons	APVDAQ	6" n-type	including ^{60}Co γ Irradiation [9]
Nov. 2014	DESY	electrons	CBC2	6" n-type	published in [10]
Jan. 2014	DESY	4 GeV electrons	APVDAQ & CBC2	6" n-type	
Nov. 2014	SPS	120 GeV hadrons	APVDAQ	6" n-type	
Nov. 2015	SPS	120 GeV hadrons	CBC2	8" p-type	Prototype CMS Phase-II readout chip with irradiated module first test at MedAustron center-bias investigations
Apr. 2017	DESY	4 GeV electrons	ALiBaVa	8" p-type	
Jul. 2017	medAustron	50-250 MeV protons	ALiBaVa	8" p-type	
Oct. 2017	DESY	4 GeV electrons	ALiBaVa	8" p-type	
Dec. 2017	medAustron	50-250 MeV protons	ALiBaVa	8" p-type	