FIRST TESTS WITH FULLY DEPLETED PN-CCD'S

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Abstract

We have fabricated 280 μm thick fully depletable pn CCD's on high resistivity silicon ($\rho \approx 2.5 \text{ k}\Omega\text{cm}$). Its operation is based on the semiconductor drift chamber principle proposed by Gatti and Rehak. They are designed as energy and position sensitive radiation detectors for (minimum) ionizing particles and X-ray imaging. Two dimensional semiconductor device modeling demonstrates the basic charge transfer mechanisms. Prototypes of the detectors have been tested in static and dynamic conditions. A preliminary charge transfer inefficiency was determined to $6 \cdot 10^{-3}$. The charge loss during the transfer is discussed and as a consequence we have developed an improved design for a second fabrication iteration which is now being produced.

Introduction

The implementation of commercially available buried channel charge coupled devices (BCCD's) in the NA32 fixed target experiment at the SPS at CERN has lead to a significant improvement of vertex reconstruction needed for the precise lifetime measurement of charmed particles [2]. The advantages of the CCD's have been a good two track resolution of 40 μm allowing to install them close to the interaction region and the good two dimensional position accuracy of 5 μm in both dimensions rejecting a large fraction of the combinatorial background from the one dimensional position information of the silicon strip vertex detector.

But the use of the new components has also pointed to some limitations of standard MOS CCD's. Due to the shallow depletion depth of approximately 8 μm only 1000 to 1500 electrons are collected in the pixels by drift and diffusion from the depleted and adjacent undepleted silicon. In order to reduce all thermal noise contributions the detector and the front end electronics had to be cooled to 180 K. The second major disadvantage for their use in high energy physics experiments arises directly from the device performance: Because the signal charges are transferred only 1 μm from the SiO_2 -Si interface the system is very sensitive to radiation damage. Every 10^4 Rad integrated dose of particles the voltage at the transfer gates has to be increased about 1 V to compensate the additionally created fixed space charge in the silicon oxide.

The new concept of the presented CCD overcomes these

restrictions by increasing the sensitive depth of the sensor to 280 μm resulting in a total of 20.000 to 30.000 signal electrons and in avoiding MOS structures. Because the entire semiconductor is drained of mobile charge carriers we call the device fully depleted CCD and because all the potentials in the semiconductor are steered and defined by pn junctions instead of MOS structures we call it according to its topology pn CCD. In addition to the above mentioned properties the pn CCD will have a fast clear mechanism [3] by forward biasing the p^+ electrodes storing the signal charges. By thermionic emission processes we inject holes from the electrodes in a controlled way which recombine with the signal charges.

For the measurement of low momentum tracks multiple scattering in the silicon of the particles under study represents a serious limitation. A fully depleted detector, thus fully sensitive over the entire volume represents the optimum performance (best signal to noise ratio for a given detector thickness) with regard to the position uncertainty due to multiple scattering.

We first present the basic ideas of the fully depleted pn CCD's derived from the semiconductor drift chamber principle presented by Gatti and Rehak [1]. Two dimensional device simulations give a clear idea of the electrical behaviour dependent of the physical, geometrical and technological input data.

The presentation of the tests will be introduced by current-voltage measurements to determine the semiconductor properties of the devices. The test of the dynamic behaviour of the pn CCD's under typical operating conditions proves the function principles of the devices of the first fabrication iteration. Limitations resulting from the non optimum first design will be discussed.

Fully Depleted pn CCD's

In 1983 Gatti and Rehak proposed a new detector scheme based on the idea that a large semiconductor wafer of e.g. high resistivity n-type silicon can be depleted from a small n^+ ohmic contact positively biased with respect to the planar p^+ contacts covering both surfaces of the wafer. The depletion zone will expand from both rectifying junctions simultaneously as long as the ohmic access from the n^+ anode to the entire bulk is not interrupted. At a given voltage the depleted regions touch each other. Under this condition the former conductive electron chan-

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nel symmetrically located in the middle of the substrate between the large p^+ implants will abruptly disappear. At this moment the depletion is completed at a voltage which is four times lower than the voltage needed to deplete a simple diode of the same thickness. The above described removal of mobile charge carriers is called sideward depletion. In this case the electron potential energy in a cut perpendicular to the wafer surface has a parabolic shape, with an electron potential minimum in the middle of the wafer. The electron potential can be moved out of the center towards either surface by applying non equal voltages to the two p^+ contacts.

Fig. 1: Basic configuration of CCD topology

The advantages of the technique are evident: Independently of the size of the depletion region the capacitance of the n^+ anode can be kept extremely small - necessary condition for good noise performance - and the position of the potential minimum can be controlled by external means. This scheme is adapted for the operation of fully depleted pn CCD's. The basic topology is shown in Fig. 1. The p^+ back contact is negatively biased with respect to the shift electrodes on the top side thereby shifting the electron potential minimum close top surface. By an appropriate choice of the voltages at the p^+ transfer registers φ_1 , φ_2 , and φ_3 it is possible to create local potential minima for electrons and an adequate change with time in these voltages allows a discrete shift of the signal charges towards the readout anode.

Fig. 2: Schematic view of the linear CCD geometry with implantation topologies including channel stop mechanism

The more complex three dimensional arrangement of a linear CCD structure including the readout region with the p^+ guard ring is shown in Fig. 2. A deep n^- implantation below the p^+ transfer registers and below the SiO_2 is introduced a) to prevent large thermally injected currents (reach through currents) between p^+ junctions at different potentials and b) to form a guiding channel for signal charges. The lateral spread of the charges is prevented by the gap of the deep n^- implant between neighboring guiding channels. The absence of the positive space charge in the vicinity of a channel guide creates a negative potential for electrons with respect to the depleted deep n^- doped region, thus acting as a potential barrier for the signal charges, confining them to the channel guide area [3].

Device Modeling

We use device modeling as a powerful tool for feasibility studies of new semiconductor devices and for establishing design criteria for the mask layout. The interpretation of the potential and charge carrier distributions allows a detailed understanding of the electrical behaviour and a first estimation of the expected properties. In addition to it the related process simulation yields process parameters for the fabrication as implantation doses and -energies and diffusion- and annealing times.

The non-equilibrium potential distribution of one picture cell was calculated by solving the Poisson equation with a Fast Fourier Transform program. The influence of the fixed SiO_2 -Si interface charges and the inhomogenous doping close to the pixel structure are taken into account.

The steady state behaviour was studied with a two dimensional program solving Poisson-, Transport- and Continuity equation simultaneously by iterative means, describing the operation conditions of the CCD, when all pixels are completely filled up with signal charges.

Fig. 3: Schematically drawn geometry for the device simulation corresponding to "cut 2" in Fig. 2

Fig. 3 shows the geometrical arrangement and the implantation topology for the non equilibrium simulation.

The potential energy distribution of a three phase CCD pixel under typical operation conditions is plotted in Fig. 4. The potential applied at the 1. electrode is -10 V (φ_1), at the 2. electrode -7 V (φ_2) and at the 3. electrode -4 V (φ_3). The 4. electrode corresponding to φ_1 once more is set to -10 V. The voltage at the backside - in this calculation located at a depth of 100 μm - is equivalent to the real operation voltage of -70 V in the 230 μm thick fully depleted device.

As can be seen from the related equipotential plot in Fig. 5 the individual pixels are electrically separated from each other, electrons accumulated under the SiO_2 do not interfere with the signal charges and the potential minimum for electrons is located at a distance of approximately 35 μm from the surface having the pixel structure.

Fig. 4: Potential energy distribution of one pixel under non equilibrium conditions

Fig. 5: Equipotential of a CCD pixel under non equilibrium conditions

First Tests of a Linear Fully Depleted CCD

The CCD measurements presented below refer to a linear array of 33 pixels with a pixel size of $150 \times 100 \mu\text{m}^2$.

Fig. 6: Sketch of the device under test

A scheme of the device seen from the top is drawn in Fig. 6. Only the p^+ shift register and the n^+ readout anode area have the previously introduced deep n^- implantation as channel guide for the signal charges. The p^+ guard structures prevent the contamination of the signals from thermally generated charge carriers from the outer part of the chip. An appropriate negative voltage at these p^+ junctions also focuses the signal charges towards the sensitive channel guide while drifting and diffusing across the wafer.

Static measurements

Numerous current-voltage (I/V) and capacity-voltage (C/V) measurements have been performed to provide informations about the fabrication process, the device characteristics and the criteria for device selection such as confirmation of the expected depletion characteristics, low leakage currents at full depletion and long term stability.

Three examples are shown in Fig. 7 - 9.

Fig. 7: Leakage current arising from bulk depletion

Fig. 8: Leakage current collected at the n^+ anode as function of the voltage of the p^+ electrodes on the top side. Complete depletion from the backside with a constant potential at -100 V

Depleting the CCD from the p^+ backside the current collected at the anode is mainly due to generation and recombination in the bulk and to injection of minority carriers from the p^+ junction (Fig. 7). Note that the deep n -implantation under the p^+ transfer register and the volume directly under the SiO_2 is not yet depleted.

In order to measure the entire leakage current contribution limiting the resolution of the CCD output signal the bulk is depleted with a constant bias at the back contact of -100 V. The a^+ anode is reverse biased with respect to all p^+ contacts on

Fig. 9: Reach through current characteristic of a $p^+n^-p^+$ structure formed by the p^+ guard rings and the p^+ back-contact and the high resistivity n -type bulk

the top side leading to the I/V characteristic shown in Fig. 8 displaying the overall current collected at the readout node.

Fig. 9 gives the hole current thermionically injected from the p^+ guard structures from the top side through the n^- bulk into the p^+ back contact. The p^+ guard structures have no underlying deep n implant.

From this type of measurements suitable operation conditions can be extracted.

$$\begin{aligned} V_{back} &= -70 \text{ V} \\ V_{anode} &= +10 \text{ V} \\ V_{shift} &= +3 \text{ V} \rightarrow -3 \text{ V} \\ V_{guard} &= -25 \text{ V} \end{aligned}$$

C/V measurements confirm full depletion under these conditions.

Dynamic measurements

In our experimental setup the signal of ionizing particles is simulated with a pulsed infrared laser illuminated from the backside ($\lambda = 904 \text{ nm}$) with an average penetration depth of about $20 \mu\text{m}$. Each light pulse creates 250,000 electron hole pairs simulating 10 minimum ionizing particles in a $280 \mu\text{m}$ thick wafer. The repetition rate was 1500 Hz. The laser system also supplies a trigger signal for the readout while the CCD is running continuously under the above described operation conditions. The three shift registers are clocked with square waves at 1/6 MHz.

Fig. 10: Experimental setup

Fig. 11: Mounting of the chip on the printed circuit board

The CCD response was online monitored on a digitizing oscilloscope. The experimental setup and the mounting of the chip is shown in Fig. 10 - 11. The four consecutive plots (Fig. 12 - 15) display the transfer of the injected signal charges to the anode: The variation of the position of the laser spot causes a correlated delay of the electron signal response reaching the readout anode at different times.

As the clock frequency is 167 kHz the transfer time for one pixel is $6 \mu\text{s}$. With a pixel width of $150 \mu\text{m}$ the distance of 1.5 mm (≈ 10 pixels) from the anode to the laser spot corresponds to a time delay of $60 \mu\text{s}$ on the oscilloscope in Fig. 13. The significantly higher signal in Fig. 12 where the anode region is

Fig. 12: Laser spot injected from the back side in the anode region

Fig. 13: Laser spot injected from the back side 10 pixels far from the anode

Fig. 14: Laser spot injected from the back side 17 pixels far from the anode

Fig. 15: Laser spot injected from the back side 24 pixels far from the anode

directly illuminated is due to the effective larger sensitive area around the n^+ readout contact completely containing the light spot. The width of the output pulse is mainly caused by the spot size of the laser (about $500\text{ }\mu\text{m}$) and the shaping of the preamplifier signal. The decrease of the slope of the trailing edge in Fig. 13-15 can be attributed to a backward flow loss of signal charges. From the decreasing pulse height in Fig. 13-15 a preliminary transfer efficiency of 0.994 per pixel was determined.

Discussion and outlook

The loss of signal charges can be mainly attributed to the weak electrical control of the SiO_2 regions within the pixel structure. They seem to be short circuited due to the presence of the electron accumulation layer at the SiO_2 - Si interface. In order to reduce the mixture of signal charges with the accumulated electrons we have to displace the charge transfer deep in the bulk. But the control of the potentials at that distance becomes very ineffective resulting in small fringing fields for signal transport giving rise to increased backward flow losses.

An improved transfer efficiency is expected with a more suitable transfer gate structure which allows signal charge shifting closer to the surface. A new charge is being produced taking into account the experiences of the first tests. The integration of the preamplifier on the CCD for better noise performance is actually under study [4]. A first version of the circuit is realized on the same chip.

The confirmation of the function principles of fully depleted pn CCD's has lead to an extended feasibility analysis for X-ray detection in the XMM satellite experiment.

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