A Novel Position and Time Sensing APSs with Field Assisted Electron collection for Tracking of Charged Particles and Imaging Detectors for Electron Microscopy

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Abstract

A new type of Active Pixel Sensors (APSs) to track charged particles for particle physics experiments or to count number of electrons that cross any pixel at the focal plane of electron microscopes is described. The electric field of desirable shape is created inside the active volume of the pixel, introducing the drift component in movement of the signal electrons toward charge collecting electrodes. The electric field results from the flow of ~100mA/cm^2 hole currents within individual pixels of the sensor. The hole current does not recombine with the very small number of electrons created by the ionization. Sharing of the signal electrons between adjacent pixels by diffusion is strongly reduced with respect to classical APS devices. The proposed sensor is produced using a standard industrially available Complementary Metal Oxide Silicon (CMOS) process. It represents a large improvement of sensors for position detection. There is also a substantial improvement of the determination of the time of occurrence of charged particles crossing the sensors and of the quality of images produced by electron microscopes.

There are two main advantages of the proposed detectors when compared to the present (February 2005) state of the art, i.e. field free APS sensors. The first advantage is the reduction of the charge collection time thanks to the added transport mechanism (drift). The second advantage is the freedom to use both kinds of MOS transistors within each pixel of the sensor. Thus, the full functional power of CMOS circuits can be embedded in situ. As an example sixteen bit scalers will be implemented in each pixel of the sensor for electron microscopy. The reduced collection time combined with the state of the art electronics within each pixel provides the most complete information about the position and the timing of incident charged particles for particle physics experiments. Position resolution of new sensors was computationally simulated to be a few μm, that is, the same as the resolution of standard APSs. Moreover, the active depth of the sensor and the associate electronics is less than about $20\mu m$ and a thinned down sensor together with its beryllium backing can have a total thickness of less than

0.1% of one radiation length. The reduction of the thickness of the detector reduces the amount of multiple scattering within the detector. The determination of the momentum and of the origin of a particle can be improved in particle physics experiments and images from electron microscopes can be sharper. The proposed APSs should be radiation resistant.

1) Introduction

APSs for particle detection are closely related to CMOS image sensors that are rapidly developing. There are many publications about them and complete sessions at the major Integrate Circuit (IC) conferences are devoted to these devices. The efforts are driven by a possibility of low-cost single chip optical imaging systems solution. Another driving factor for an increased activity in CMOS image sensors is the continuous improvement in CMOS technology. Scaling down of the CMOS feature size is progressing faster than scaling of pixel size, which allows incorporation of more sophisticated electronics per pixel. APSs are arrays of pixels covering a certain area. Each pixel detects signals more or less independently from the signals in other pixels. Active Pixel Sensors include an active amplifier in each pixel. Pixels for imaging application thus serve a double purpose. Firstly they have to convert incoming photons into charge carriers (electrons) in silicon and secondly they have to read-out the signal charge. Photo-conversions take places in silicon just below the surface through which the light arrives. The sensor usually detects light in photon flux integrated mode. The photocurrent is integrated in the capacitance of a reverse biased p-n junction. N+ regions on p epi or p+ substrate form the junctions. The standard read-out electronics of a photodiode APS consists of 3 n-channel MOS transistors per pixel. An excellent description of light imagers based on APS can be found in [1].

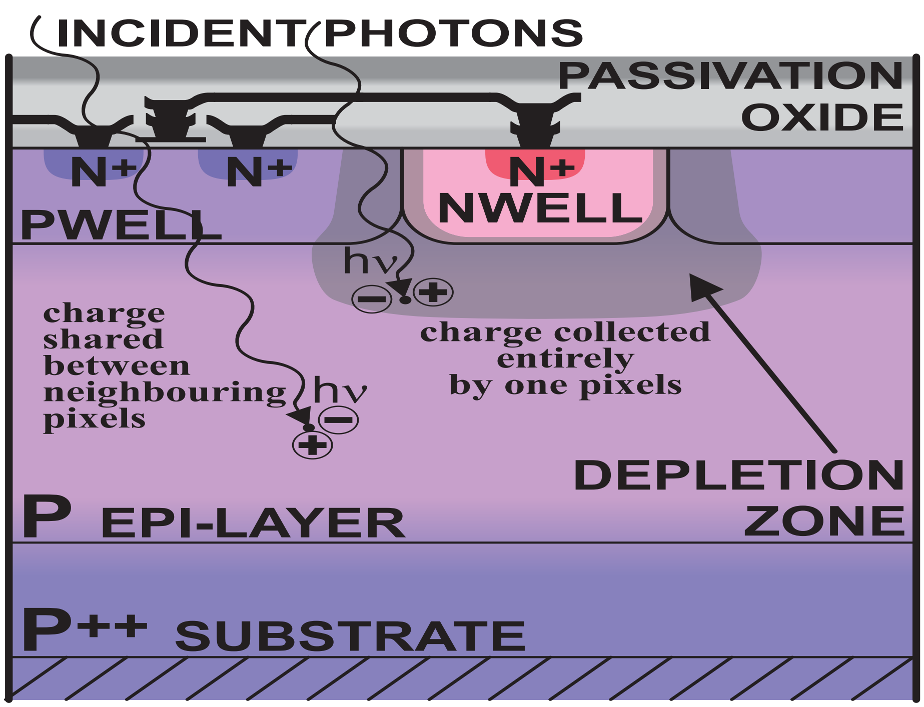

Fig1.   Section through a pixel of an APS as designed for position sensing of Minimum Ionizing Particles (MIP) [3]. The sensor is produced on a wafer having about 10μm thick high resistivity p epitaxial layer on the top of a heavily doped p^{++} substrate. The epitaxial layer is present on wafers to be processed by silicon foundries for production of CMOS circuits. N-channel (p-channel) MOS transistors are located in deep p^{+} (n^{+}) wells.

Particle detectors based on concept of APS were developed [2, 3] in the past several years. The design of these detectors is similar to the design of light imagers. The signal to be detected is produced by ionization of passing charged particles rather than by integration of a photocurrent within a pixel. Fig. 1 [3] shows processes in one pixel of an APS developed for particle detection.
The ionization produced by Minimum Ionizing Particles (MIPs) within the epitaxial layer is the signal charge. Most of the volume of the epitaxial layer is not depleted and is free of electric field. Signal electrons diffuse within this layer and are collected by the only n-well within the pixel that is functioning as an electron-collecting anode. There are no boundaries between adjacent pixels and the signal charge is shared among pixels according to the diffusion equation. The full charge is collected typically within a group of 3X3 pixels. The anode of each pixel is charged to the highest positive voltage at the beginning of the read-out cycle by a suitable bias of the gate of the reset transistor. The amplifier chain of each channel consists of 3 n-channel transistors and is described in detail in Ref.[3].

This three-transistor configuration is the optimal configuration for the light detection where the integrated light flux is the information of interest in the formation of an optical image. It is also widely adapted for the read-out of APSs intended for detection of charged particles. When the detected electrons are produced at the time of the passage of a charged particle through the epitaxial layer the three-transistor circuit may not be optimal. The time of particle crossing is lost and the only information about the time of occurrence of the event is given by the total integration time. The integration time has to be long enough to allow the read-out of all the pixels of the array. This time is several milliseconds for the simplest read-out with only a few principal read-out nodes per array. There is an active effort to reduce the read-out time and thus to improve the timing of individual events by paralleling read-outs to many principal read-out nodes and by decoupling the integration and read-out times. The last achievement in the read-out was an AC coupled amplifier with Correlated Double Sampling (CDS) and zero suppression, all implemented by n-channel MOS only [4, 5].

2) Principles of Proposed Sensor.

The proposed sensor is a radical departure from the standard architecture of the read-out of the present APSs. Let us start with the list of time scales present in detection of ionization produced by a fast charged particle crossing the epitaxial layer of silicon. Ionization electrons are produced promptly; the duration of this process is less than *1 ns*. The collection time due to the diffusion of electrons within the layer till the collection by the anode can be as long as *100 ns*. This collection time is still about 3-5 orders of magnitude shorter than the integration time of an APS imager. There is no reason to integrate the charge for such a long time when detecting charged particle. Traditional particle and X-ray detectors made on high resistivity silicon employ signal processing different from a simple time integration of APS imagers. The signal processing with its low-noise electronics is an important part of nuclear electronics developed into a mature state during the past 50 years [6, 7]. The processing can be optimized to obtain the best charge or timing information from the ionizing event. The processing time has its own optimal time scale independent of the integration time as requested by the read-out time of all pixels of an APS. The leakage current is continuously drained thus there is no need for a pulsed reset and no *kTC* (switching) noise is present. Here we describe sensors with a simplified low- noise preamplifier integrated within each pixel. The time information of the ionization event within the epitaxial layer can be recorded with a much better resolution than the integration time of the standard

APS. Also counting of particle passages can be performed for an imaging application. It can be recognized that the proposed APS should have the same functionality as the hybrid pixel sensors [8] proposed about 20 years ago. The main difference between the two is that the hybrid pixel sensors are composed of two chips of silicon; one containing an array of p-i-n diodes on high resistivity silicon and the other the electronics. Each diode is ball bonded to one preamplifier of the corresponding array of electronic channels produced on an electronic grade silicon. The presented APS combines the functions of these two arrays into a single array produced on standard electronic grade silicon in mass production in one of the silicon foundries. There are two reasons why 20 years ago physicists were thinking about hybrid structures rather than of a pure monolithic implementation. The first reason is an unprecedented development of CMOS electronics as illustrated in Fig. 2 [1].

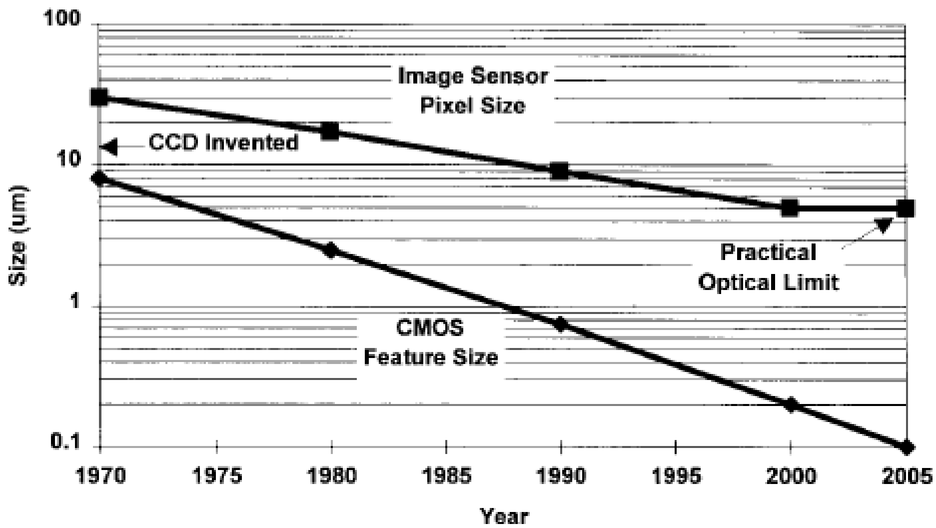

Fig. 2. Steady increasing ratio between the pixel size and the minimal CMOS feature size allows today an implementation of sophisticated circuitry within each pixel of APS. Pixel size refers to a size for optical imaging. The pixel size for particle detection depends on requirements of individual experiments. There are still hybrid pixel sensors introduced in experiment where the pixel size was frozen 15 years ago. Most likely the decrease of the pixel size for experiments in high-energy physics was even less rapid than the decrease of the size of optical pixels.

Fig. 2 shows that today we are able to implement many more transistors within the area of one pixel than physicists were able to do 15 years ago. The dimensions of hybrid pixel sensor for particle detection are about 50μmX400μm and there are hybrid pixels developed recently for X-ray applications with pixel size of 55μmX55μm. The decrease of the signal due to the decrease of the active silicon thickness, from about *300 μm* of the active silicon to only *10 μm* is not the main problem. The distribution of charge produced by a particle at the minimum of the ionization density (MIP) in *300 μm* of silicon peaks at the value of *24000 electrons* while the charge produced within *10 μm* has its peak only at *800 electrons.* To improve the position measurement of the fast charged particle by interpolation down to *10%* of the pixel size the Equivalent Noise Charge (ENC) of the read-out chain has to be less than about *30 electrons*. Several years ago the ENC of *10 electrons* was obtained in a full CMOS design [9]. The presence of electronics in each pixel of the proposed APS calls for a substantial reduction of dissipated power per read-out channel compared to the dissipation of the design of Ref. 8. We think that an ENC of *30 electrons* is possible when full attention is dedicated to the design. This statement should not imply that this design is easy.

The second reason monolithic APSs were not proposed a long time ago might be more important. To implement a full low-noise read-out chain, n-channel transistors as well as p-channel MOS transistors have to be present in each pixel of the sensor. P-channel transistors must be located in n-wells. The pixel of a standard APS has only one n-well that collects all electrons created in the epitaxial layer of the pixel region. An additional n-well within the pixel and biased to V_{DD}, that is, the most positive potential, would be in a direct competition with the anode to collect signal electrons within the pixel. Some fraction of signal electrons would be collected by the n-well instead of the anode and would be lost for detection. The proposed and discussed pixels have n-wells dedicated to p-channel transistors with a minimal loss of collection efficiency on the anode. Later we will see that the topology of n and p-wells as well as their bias voltage create a small drift field within the pixel. The presence of the drift field accelerates the process of collection of electrons on the anode and further improves the timing of ionization events.

To understand the main idea behind the design of the pixel with n-wells which do not collect signal charge we have to start with the basic equations describing electric field and transport of carriers in silicon [10]. The epitaxial layer is of p-type and the only electrons within this layer are signal electrons in such a small numbers that their charges can be neglected. It is sufficient to write the current density and the continuity equations for holes only. The important equations are:

$$-\Delta\varphi = \rho(x,y,z)/\varepsilon = q*(p(x,y,z)-N_A)/\varepsilon$$

$$\vec{J}_{hole} = q*\mu_{hole}\,p(x,y,z)*\vec{E} - q*D_{hole}\,\overrightarrow{grad}(p(x,y,z))$$

$$\partial p(x,y,z)/\partial t = -div(\vec{J}_{hole})/q$$

$$\Delta\varphi = 0$$

Where φ is the electric potential, ρ is the charge density, ε is the dielectric constant, $p(x,y,z)$ is the density of holes, N_A is the acceptor density, J_{hole} is the hole current density, E is the vector of the electric field, D_{hole} is the diffusion constant for holes, μ_{hole} is the hole mobility , q is the absolute value of the charge of an electron and the operator $\Delta = div(grad)$ which reduces into the sum of second derivatives relative to spatial coordinates in a Cartesian coordinate system.

The first equation is the Poisson equation the second equation is the current density equation for holes and the third equation is the continuity equation. These three equations are fundamental equations describing the device. The fourth equation is the combination of the second and the third equation valid only within the epitaxial layer where the hole density $p(x,y,z)$ is constant. The fourth equation also follows from the Poisson equation applied to an undepleted region of silicon, that is the region where $p(x,y,z) = N_A$. The agreement between the fourth equation and the first one in the region of non-depleted silicon explicitly proves the consistency of all 4 equations. Physically it means that the flow of current of holes through the epitaxial layer leaves the net charge density equal zero. The fourth equation can be recognized as the Laplace equation, the equation that governs many processes of physics. Here it describes the potential in the bulk of a uniform semiconductor through which some current is flowing. The Laplace equation does not contain parameters defining the scale of the solution. This scale is completely given by boundary conditions. The appearance of this equation encourages us to design the desired structure. The doping density N_A of the epitaxial layer is about $10^{15} cm^{-3}$ in standard technology. The depleted region in the proximity of the anode cannot extend more than $2\mu m$ when the maximal allowed voltage in CMOS circuits is applied, as can be seen on Fig.1. To fully deplete $10\ \mu m$ of the epitaxial layer is beyond the voltage limit. The extrinsic Debye length of the epitaxial layer is only about *0.13µm*, that is, too small to influence the entire volume of the epitaxial layer within a pixel. The design of the topology of n-wells has to be such that the potential in the epitaxial layer in the proximity of n-wells is lower than the potential farther away from the well in spite of a positive potential applied to the n-well. Being familiar with the Laplace equation we know that such a design is possible. The potential applied on the boundary of a region governed by the Laplace equation propagates into the depth of the region with an attenuation that depends very strongly on linear dimensions of the boundary segments. A potential applied to a shorter segment of the boundary penetrates much less into the depth of the region than a potential applied to a longer segment. The design has to have n-wells in areas having widths substantially shorter than the widths of p-wells. The need to implement a certain number of p-channel MOS transistors defines only the area of the n-well. There is complete freedom to select the shape of this area. The Laplace equation suggests that we should make n-well areas long and thin.

3) Topology and bias of wells and the anode

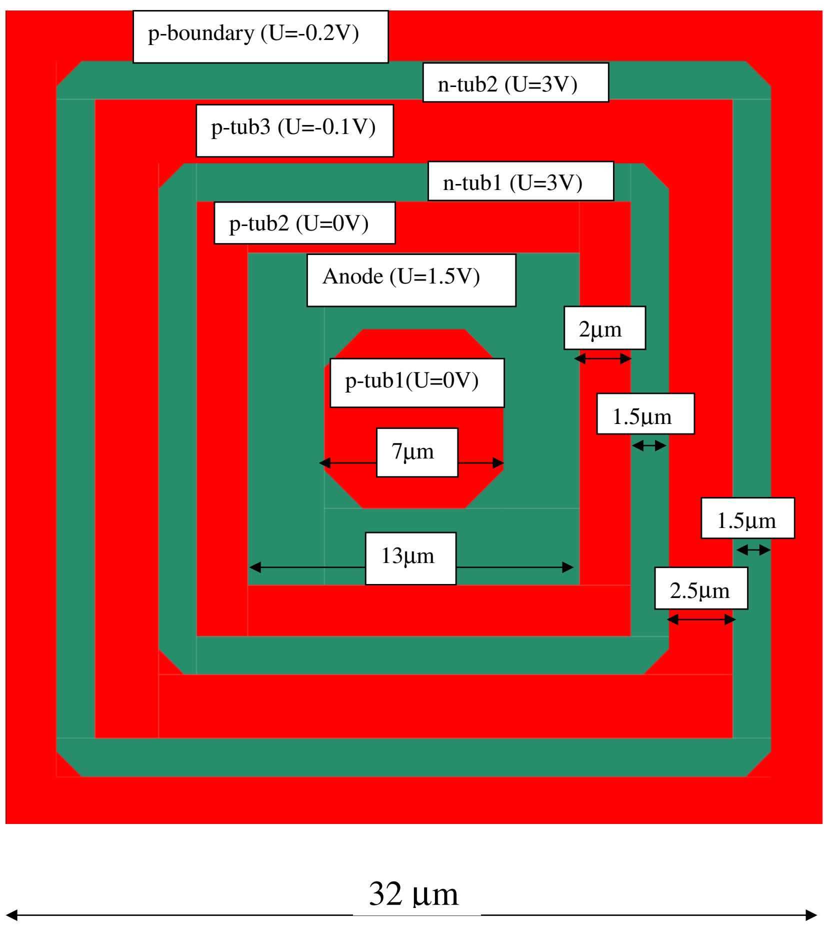

Fig. 3. Top view of a pixel. Red areas are p-wells where n-channel MOS are located, the green areas are n-wells. The wider green area closest to the center of the pixel is the anode, the two remaining ribbon-like areas are n-wells where p-channel MOS transistors are located.

Fig.3 shows the top view of one proposed pixel. The overall dimensions of a pixel are $32X32\mu m^2$. This dimension is just our first guess and should not be taken as something implicitly given by the design considerations. Different values of potential are applied onto individual n- and p-wells called sometimes n- and p-tubs. Later we will refer to the central p-area as p-tub1, the n-type area surrounding the p-tub1 is the anode, the next p-area is p-tub2, and the following n-area is n-tub1, then p-tub3, n-tub2 and finally p-boundary. Notice that the anode where electrons should be collected is considerably wider than the n-tub1 and n-tub2 areas where electrons should not be collected.

There are no transistors shown on Fig.3. The circuits are to be designed and the presence of transistors in wells should not interfere with the transport of electrons within the epitaxial layer. The circuits are completely different for tracking and for imaging applications.

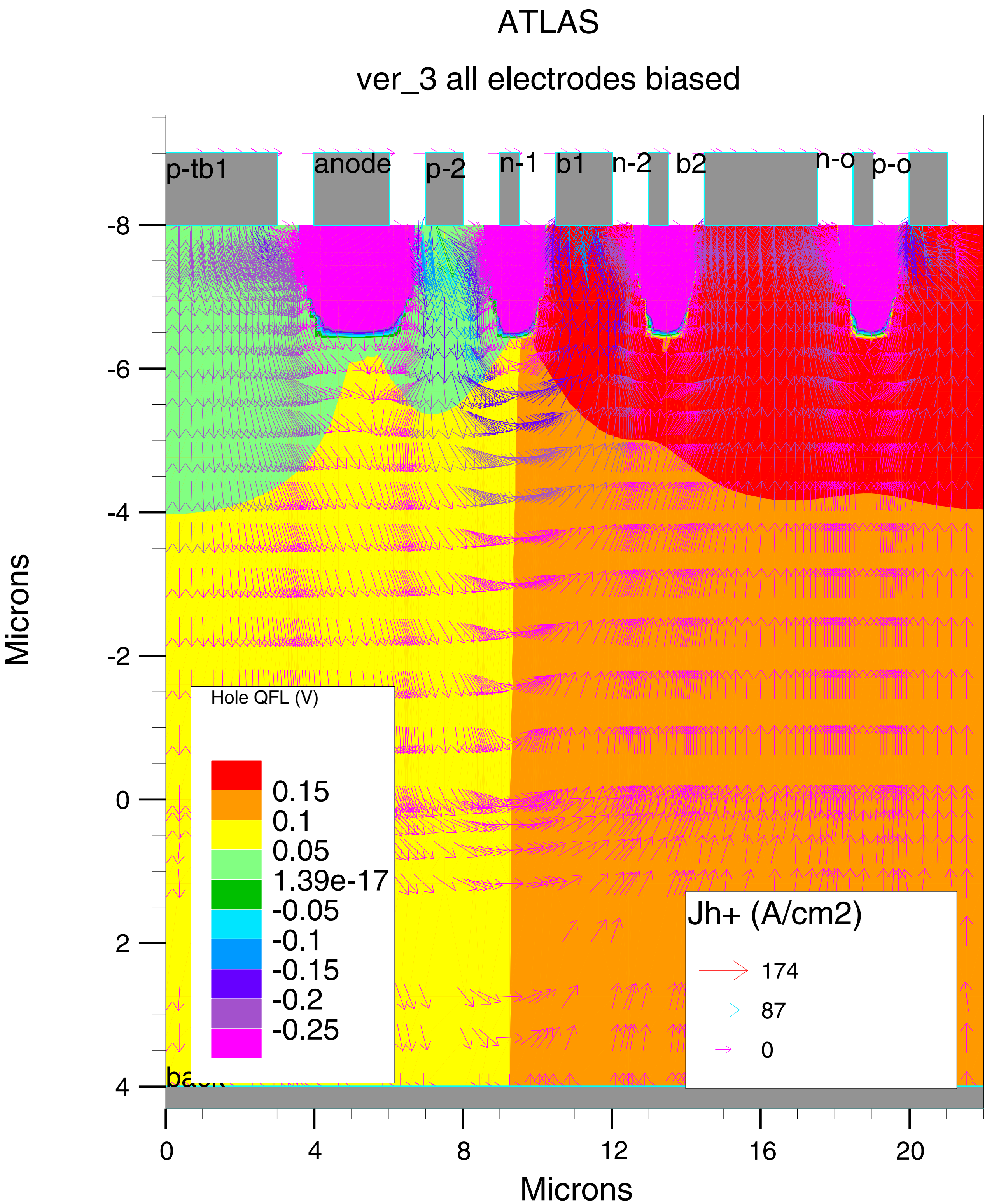

Fig. 4. Density of currents due to bias applied to all wells (tubs) of the pixel. The contour plot of quasi-Fermi levels for holes is also displayed.

The current density within the cross section of a pixel after bias applied on all wells (tubs) is shown on Fig.4. The following biases were applied: U on p-tub1 = *0V*, U on anode = *1.5V*, U on p-tub2 = *0V*, U

on n-tub1 = *3V*, U on p-tub3 = *-0.1V*, U on n-tub2 = *3V*, U on p-boundary = *-0.2V* and U on substrate (back) = *-0.1V*. Note that the potential on n-tubs is larger than the potential on the anode. This form of bias is required by the preamplifier and makes it harder to prevent electrons from being collected by n-tubs biased at *+3V* rather than anode at *+1.5V*. Hole currents shown on Fig.4 produce the desirable form of the potential within the epitaxial layer where only the anode should collect all signal electrons. We know that the relatively large density of hole current should not cause any recombination and disappearance of signal electrons.
Typical values of currents flowing into or sourcing from different p-type electrodes are about 1μA per pixel of 32μmX32μm. The total hole current flowing within a $2cm^2$ detector is a quarter of an Ampere leading to a density of power dissipation within the silicon of about $20\ mW/cm^2$.
The SILVACO ATLAS code [11] did not make the approximation that the electron current was negligible. To test the adequacy of this approximation and the lack of electron-hole recombination in the epitaxial layer the value of the leakage current flowing into the anode was simulated. Its typical value, below 1 *pA,* is in agreement with published [2] values of the leakage current of present APS.

The ratio of hole currents to the anode current is close to 9 orders of magnitude. We claim that the presence of a large bias current within a pixel of the sensor does not interfere with the collection of a signal of about *800 electrons.* The reported performance of standard APS [1-3] proves the point. Signal electrons were collected from the non-depleted bulk of silicon with the density of holes $10^{15}/cm^3$. The application of the described bias which results into the density of the hole current of $0.2A/cm^2$ changes the thermal velocity of holes by less than a few percent. Fig. 5 shows the negative potential in the epi-layer of a pixel when all p-electrodes are biased. The potential is the result of the flow of the hole current shown on Fig.4. All simulations were performed with the approximation of cylindrical symmetry in the pixel. The boundary between the epitaxial layer and the heavily doped substrate is located at a depth-coordinate equal to $8\ \mu m$ in Fig. 5. The drift of electrons in the negative potential of Fig.5 can be visualized as a movement of balls without inertia in the gravitational potential. The potential differences in most of the epilayer shown on Fig. 5 are only several thermal voltages ($kT/q=26mV$ at room temperature) and electrons suffer a substantial diffusion before they escape from the "box". The wall of this box is the result of the built-in potential at the transition between the epilayer doped at a density of $10^{15}cm^{-3}$ and the substrate or p-wells doped at densities of $10^{18}cm^{-3}$. Openings of the box at depth-coordinate equal to zero indicate the presence of an n-well. We can see from Fig. 4 that there are precipices at the left side of the openings. Electrons arriving to the proximity of the opening are collected by the anode or the n-well (tub). Fig. 6 shows the visualization of the negative potential within a pixel of a standard APS where there is only one n-well functioning as the anode. Signal electrons diffuse till an anode collects them. Most of the electrons are going to be collected on the anode of the pixel crossed by the ionizing particle; however, a certain fraction of electrons will be collected by anodes of neighbor pixels resulting in a complete absence of any boundaries among pixels within the epitaxial layer.

4) Simulations of transport of signal electrons

To study the transport of signal electrons within the epitaxial layer a Monte Carlo code was written. The code has a deterministic part responsible for the drift of electrons and a stochastic part that treats the diffusion. Fig. 7 shows the fractional sharing of charge due to the passage of a fast ionizing particle at different distances from the center of the pixel with the potential within the pixel as shown on Fig.5.

When a fast ionizing particle crosses the pixel closer than $5\mu m$ from the center the anode of the pixel it collects 90% of the signal charge. For distances larger than $5\mu m$ there is an approximately linear decrease of the charge collected by the central anode. The charge decreases to 27% when the ionizing particle crosses the epilayer right at the edge of the pixel ($r=16\mu m$). The loss of the collecting fraction is less due to the collection of the signal electrons on the anodes of the neighbor pixels and more due to the collection of electrons in n-tub1 of the same pixel. The collection on the anode of the next pixel would be desirable for the improvement of the position resolution due to interpolation. The collection on the n-tub indicates the problem of the present version and has to be corrected in a later version. Some studies showed that the fraction of the charge collected at n-tub1 (the fraction in the present design reaches 35% at $r=10\mu m$) could decrease to 25% just by different biasing of the pixel.

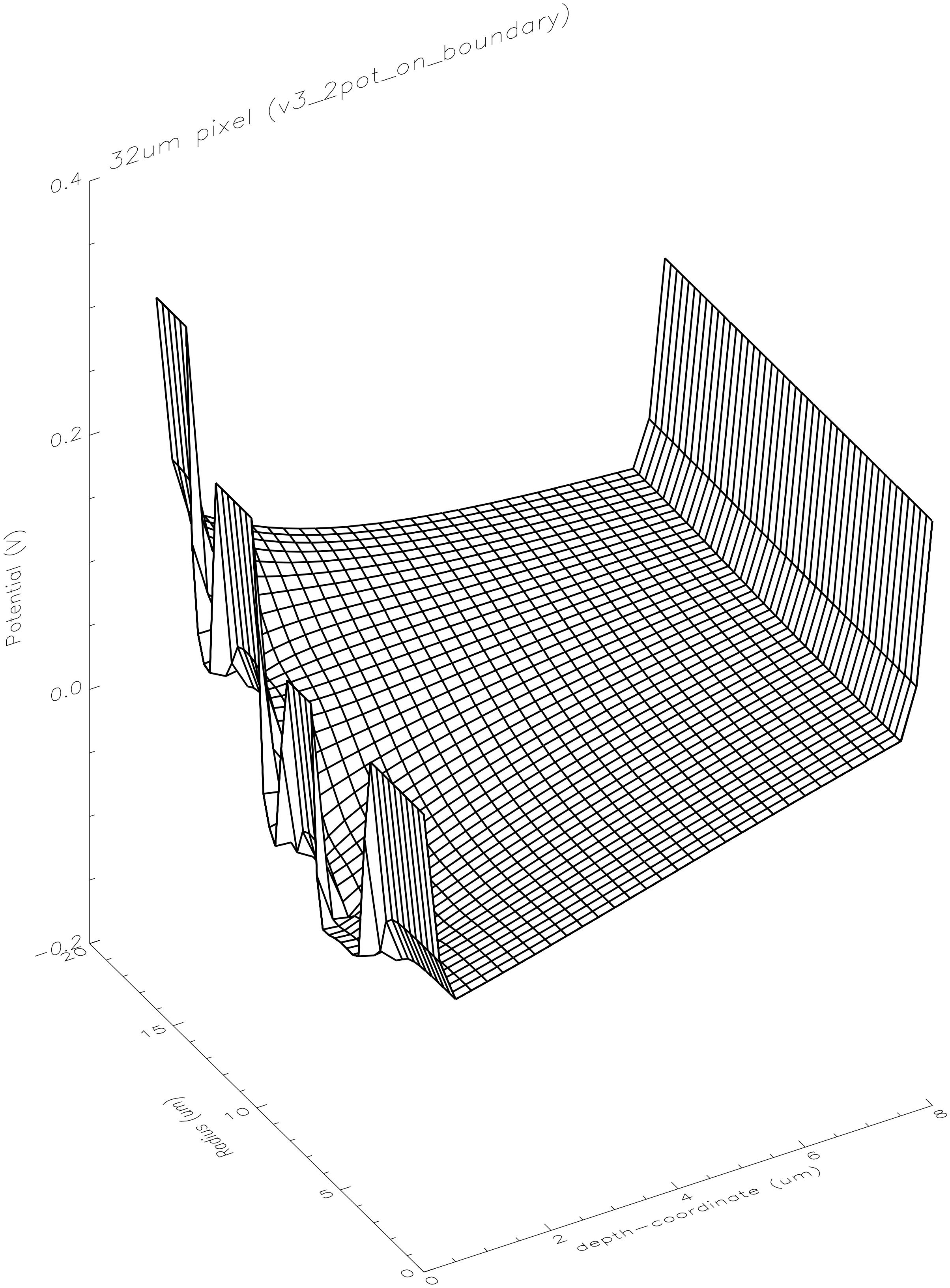

Fig. 5. Negative potential within the epitaxial layer.

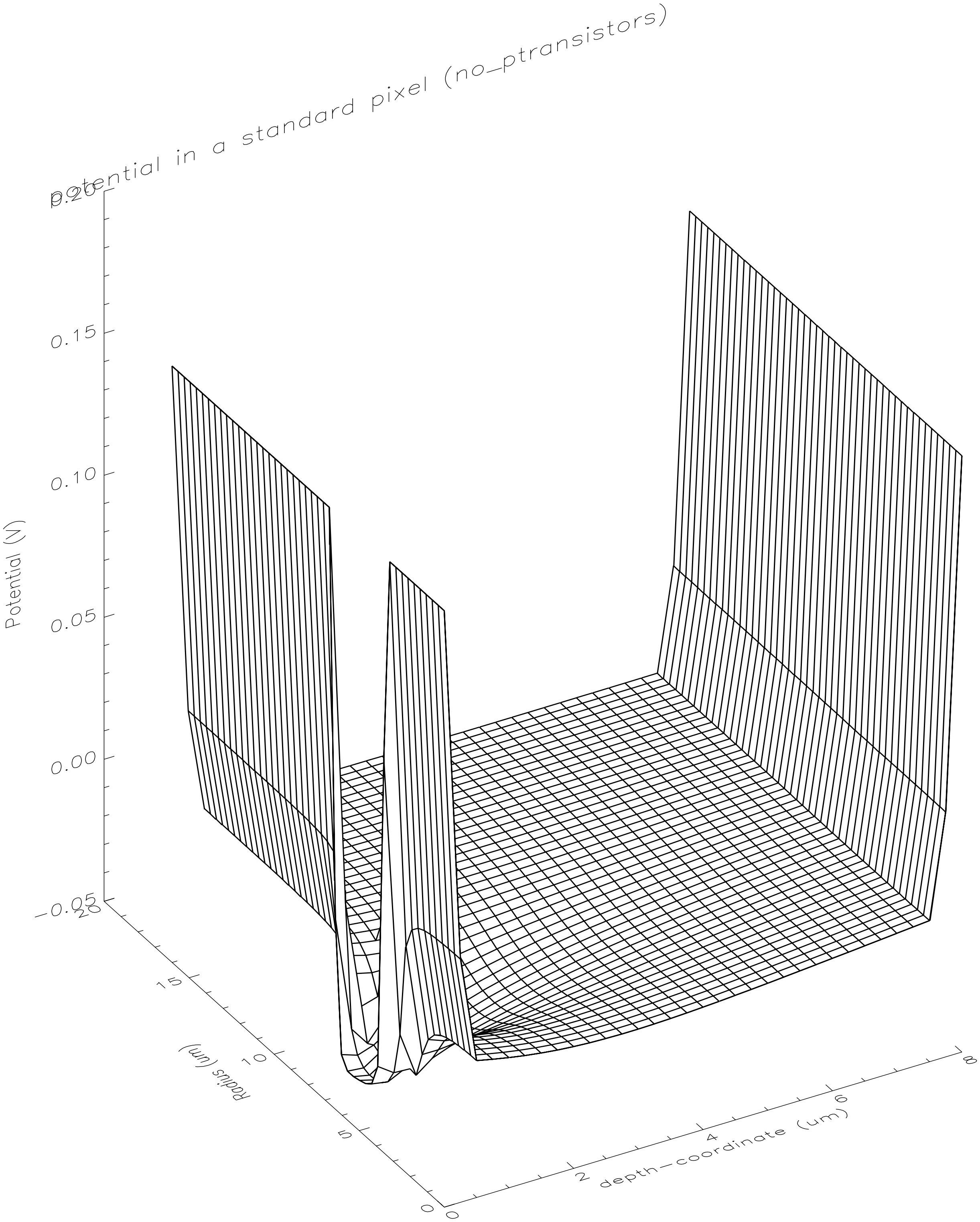

Fig. 6. Negative potential within one pixel of a standard APS.

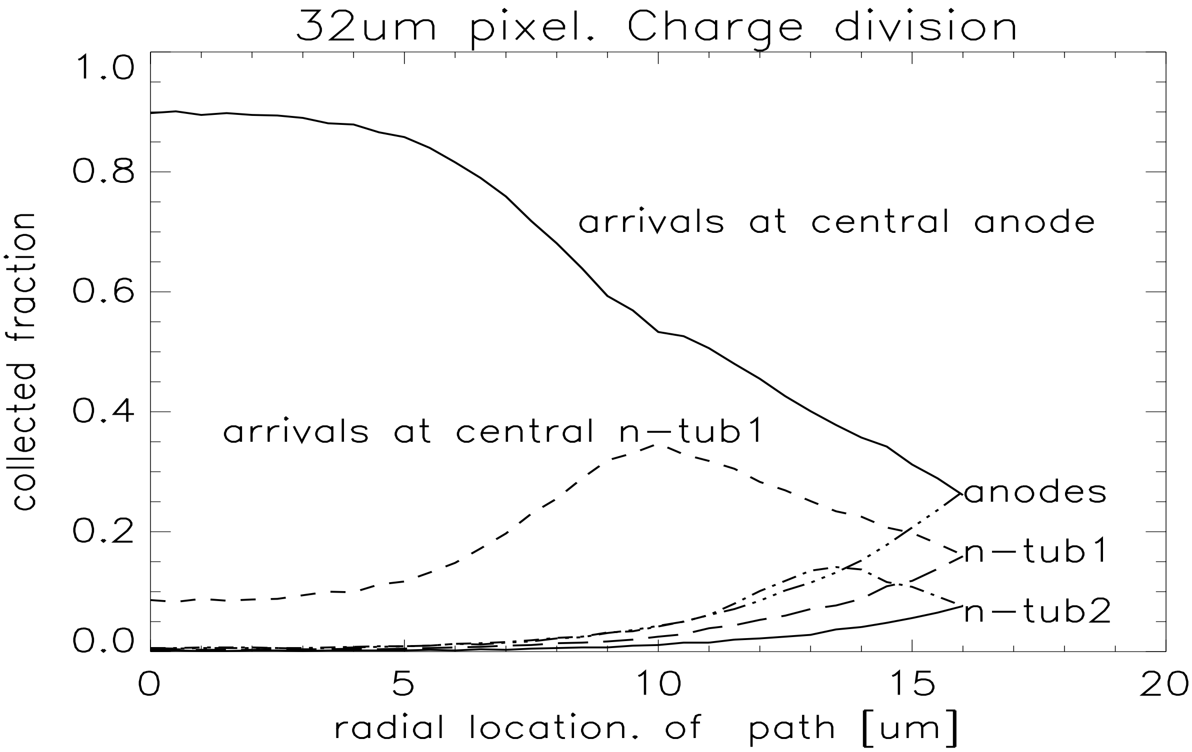

Fig. 7. Charge sharing among different anodes and n-tubs of the described APS.

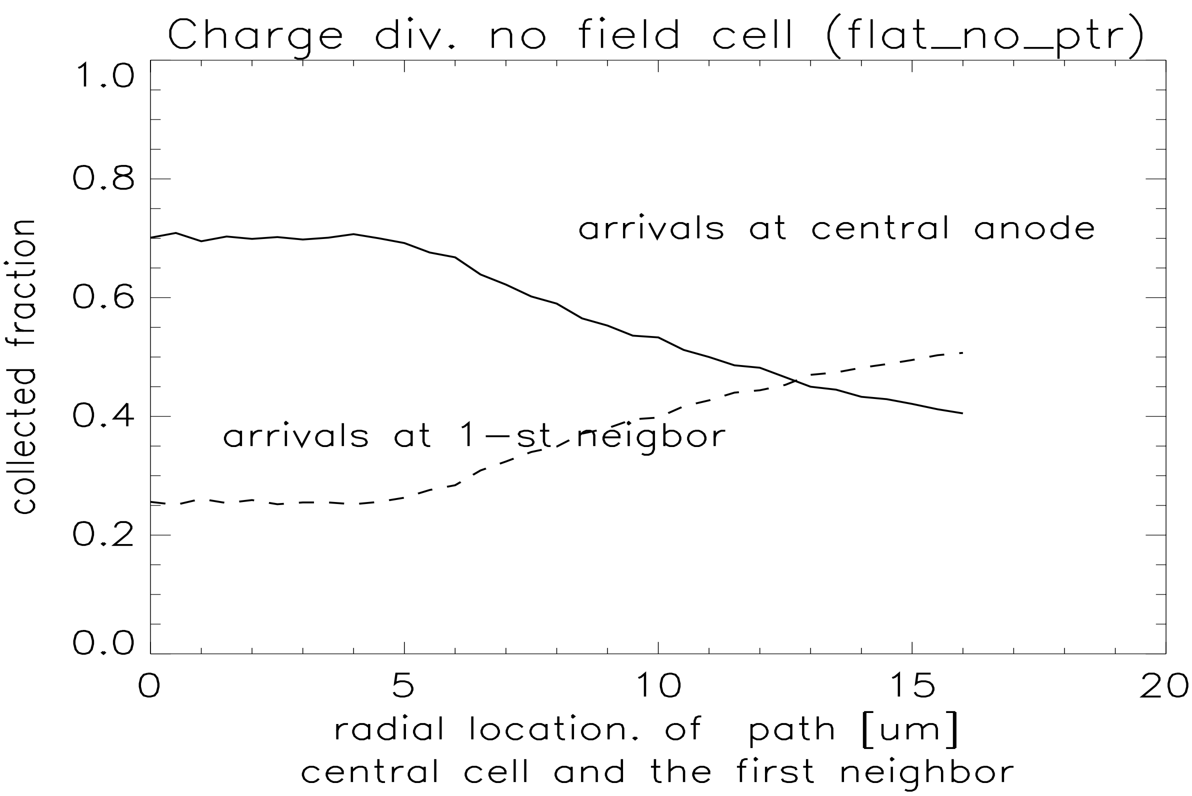

Fig. 8. Charge sharing between anode of the hit pixel and all first neighbor pixels of a standard pixel of APS shown on Fig. 6.

To obtain a larger improvement the geometry of the pixel has to be changed. The new geometry of the n-tub1 has to accommodate all p-channel MOS transistors of the linear part of the electronics and will be carried on during a later stage of the design. Then we will know the exact depth of n- and p- tubs and we will understand the percentage of loss in a realistic 3 dimensional simulation. There are also fractions of charge collected on the anode and the n-tubs in a neighbor pixel plotted on Fig.7. At the very boundary between two pixels, that is, at $r=16\mu m$ there is no difference between the central and the neighbor pixel and the two curves for each n-well pass through the same point. There is no charge diffused behind the first neighbor pixel (not shown). The amount of charge collected by the anode of the neighbor pixel for a particle crossing the central pixel at a distance smaller than about $r=10\mu m$ from the center may be too small for an effective position interpolation. This stresses again the fact that the present version of the design has to be improved. Fig. 8 shows collection fractions for standard APS pixels with the potential as shown on Fig. 6. Fractions of the total charge collected on the anode of the central pixel and on all anodes of first neighbors of the pixel as a function of the distance of the passage from the center of the pixel r are plotted. For $r<5\mu m$ both fractions are constant. About 70% of the charge is collected at the anode of the pixel and 25% on all anodes of neighbor pixels. The remaining 5% of charge diffuses and is collected beyond the anodes of the first neighbor pixels. When the particle crosses the pixel close to the pixel boundary at $r=16\mu m$, 40% of the charge is collected in that pixel while 50% of the charge is shared among all first neighbor pixels. The remaining 10% of the charge diffuses beyond the adjacent pixels.

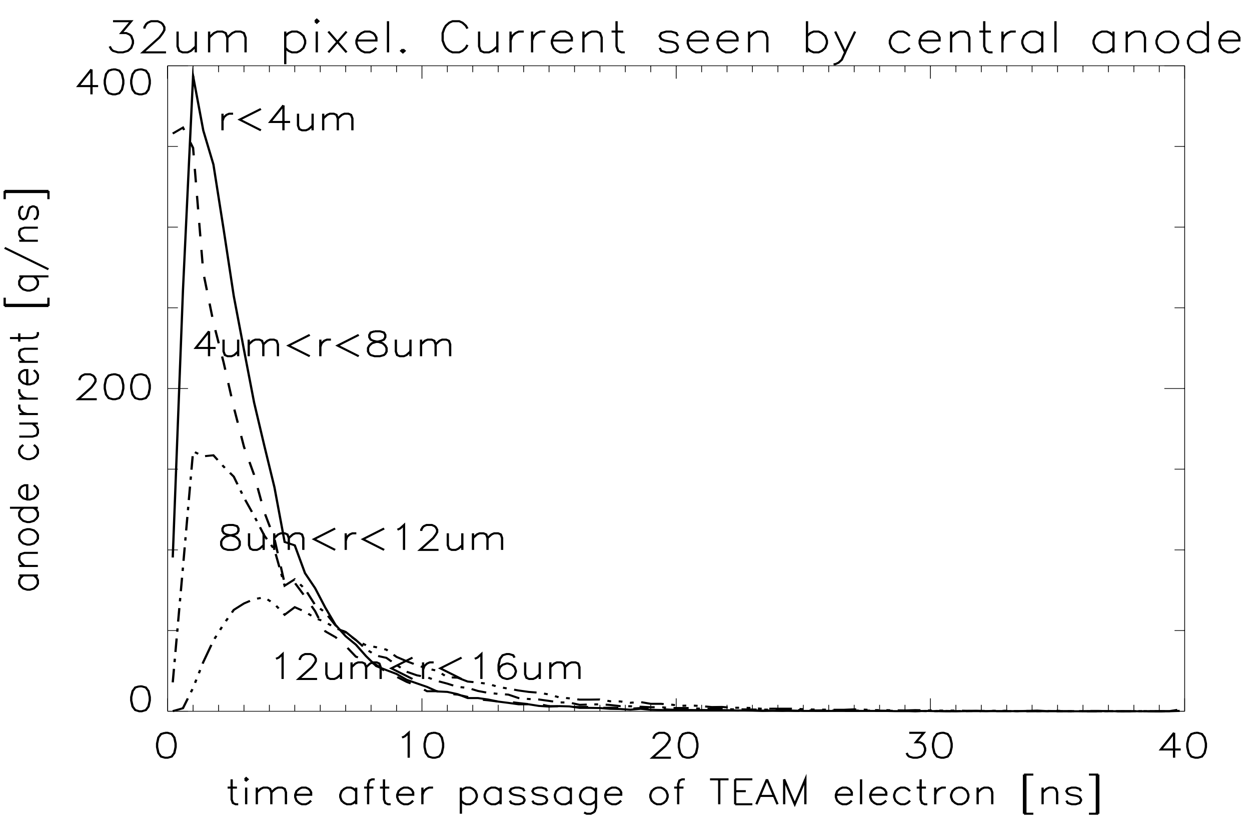

Fig.9. Waveforms of current collected on the anode by ionization of particles combined together according the distance from the center of the pixel.

Fig. 9 shows waveforms of current induced on the anode by the passage of a ionizing particle through the pixel. This particle is called "TEAM electron" for historical reasons. To keep the number of waveforms down to four, the locations of passage were grouped. The formation of current in an external circuit connected to the anode in this case of diffusion of electrons from conductive silicon is different from the formation of the signal from depleted silicon. The relaxation time constant in the epitaxial layer is only about *50 ps*. The layer perfectly screens electrons untill they arrive into the depleted region close to the anode. Waveforms of Fig. 9 indicate that more than 80% electrons are collected within *10ns* from the passage of a particle independently of their path.

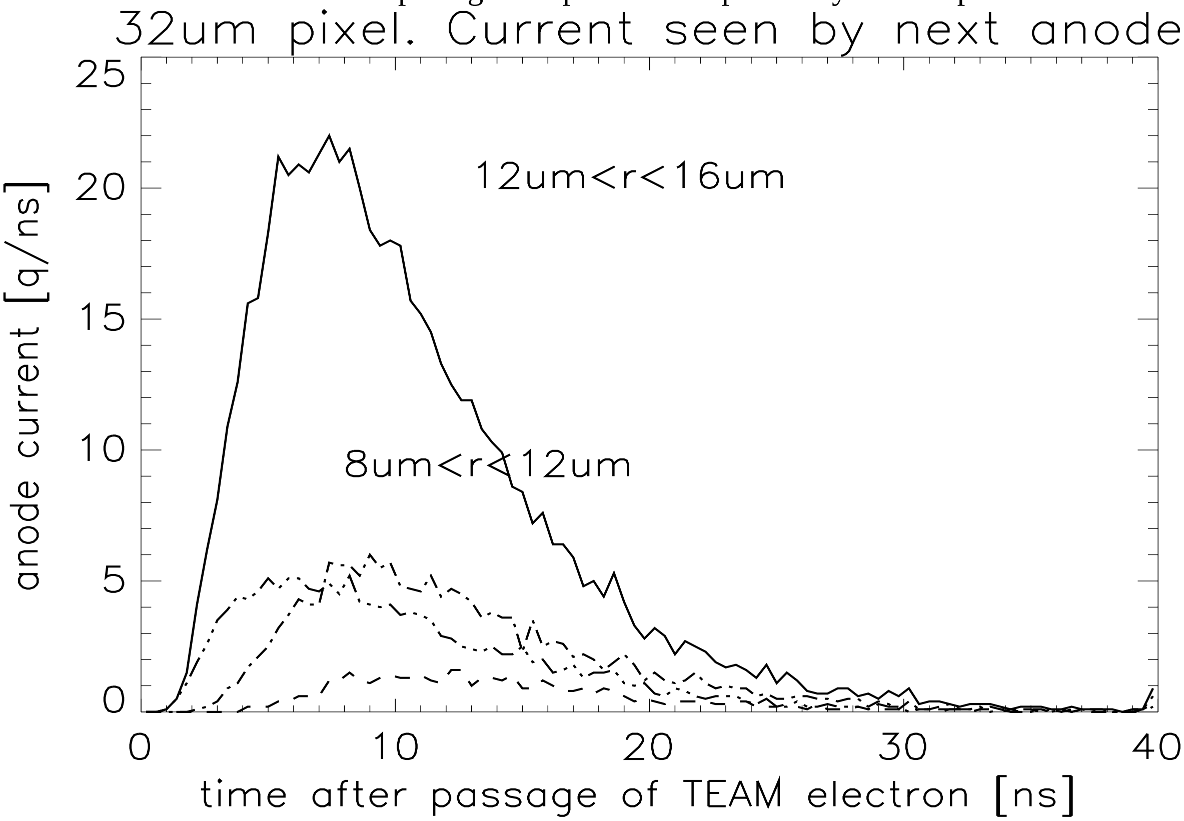

Fig. 10. Waveforms induced on the anode of the neighbor pixel

Fig. 10 shows the waveforms of current induced on the anode of the neighbor pixel. The waveforms are longer and the peak current smaller. The integral of the current gives the fraction plotted on Fig. 7.

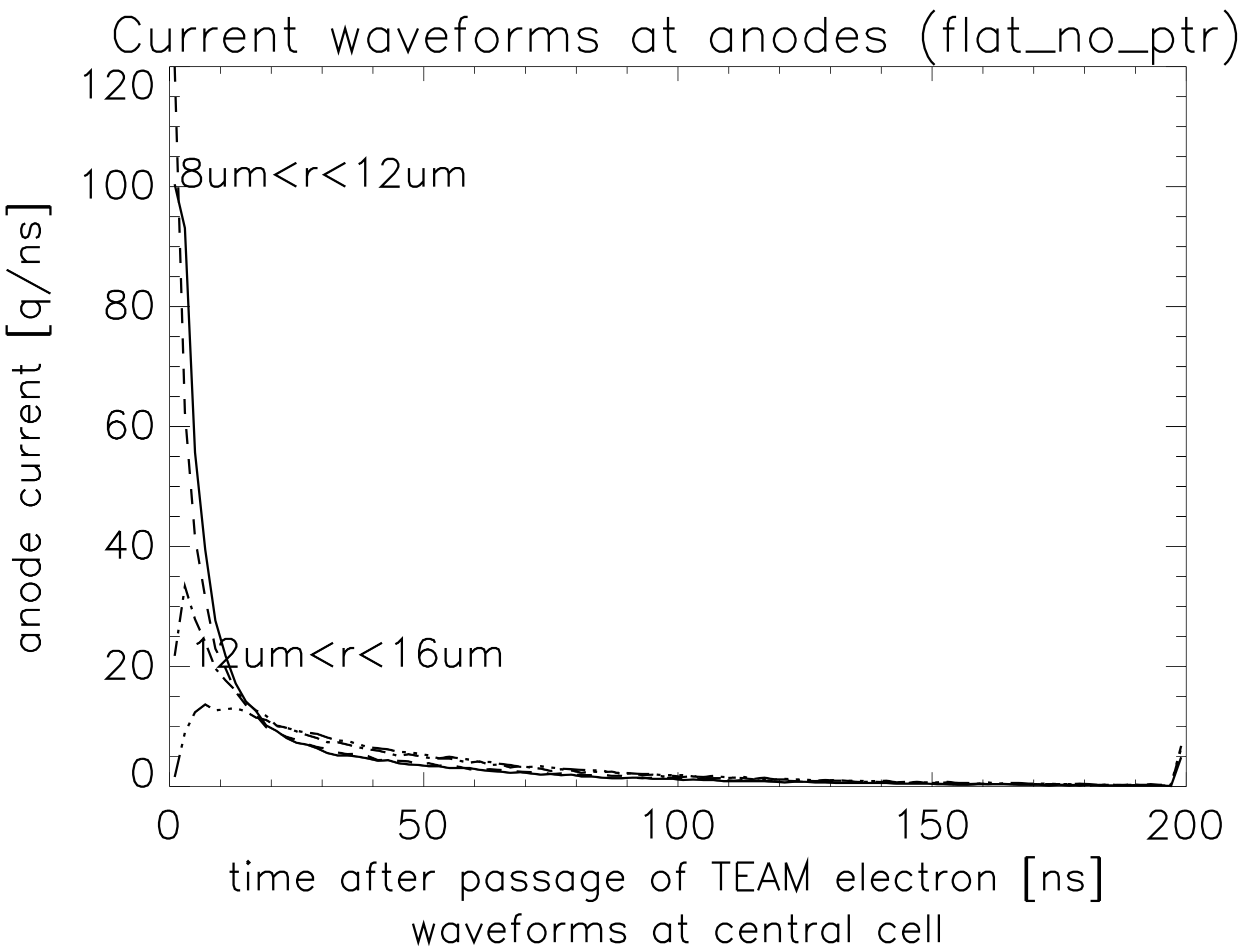

Fig.11. Waveforms of current induced in the central pixel of standard APS.

Fig. 11 shows waveforms induced on the central anode for a standard pixel of APS with the potential shown on Fig. 12. The forms are similar to those on Fig. 10, however the time axis of Fig. 11 is five times as long as the axis of Fig. 10. We see that the presence of the drift field accelerates the charge collection by about a factor of *5*.

5) Thinning of APSs.

The total thickness of the silicon sensitive layer and the wells where all transistors are located is only *10* to *20 μm*. The connection planes above the silicon add a thickness equivalent of about *10 μm* of silicon. The radiation length of silicon is *10 cm* and the necessary amount of material to detect the ionization produced by MIP is less than 0.03% of a radiation length. The remaining silicon on the wafer corresponds to an additional 0.5% of radiation length and once the processing of the wafer is finished it serves only as a mechanical support. In principle it is possible to remove most of the inactive layer of silicon. The thinning must stop at least 10 to 20 Debye lengths from the start of epitaxial layer to avoid any interaction of signal electrons with the imperfection of a newly formed interface. A conservative additional thickness should be *20 μm.* The additional silicon brings the minimum thickness of the active layer up to 0.05% of one radiation length. To mechanically support, keep flat and remove the heat from this very thin layer of remaining silicon we can use a *200 μm* thick flat sheet of beryllium. In terms of radiation length we are adding an additional 0.05% of radiation length bringing the total to 0.1%. This is a decrease of about a factor of 10 when compared to the thickness of hybrid pixel sensors. The thermal conductivity of beryllium is 3 times larger than the conductivity of silicon and for heat transport the $200\ \mu m$ thick layer of beryllium is equivalent to a $600\ \mu m$ thick layer of silicon. The final challenge would be the heat removal from a complete detector subsystem based on the proposed APS.

6) Radiation damage

Radiation damage may not be an important issue when the APS is used to detect electrons of energy below or at about *300keV*. No damage to silicon lattice can be inflicted by electrons at that energy. The oxide of the transistor gates is so thin in today's $0.25\ \mu m$ technology that the oxide charge created by the ionization tunnels away. The charge does not produce a shift of the threshold voltages. The sensor should be also less sensitive to damage by neutrons and other hadrons. The epitaxial layer is of p-type with the doping density of $10^{15} cm^{-3}$ and not depleted of mobile holes. The generation of the leakage current from the epilayer that represents most of the volume is proportional to the ratio of n_p / τ where n_p is the density of electrons in p-type silicon of the epitaxial layer and τ is the life time of the charged carriers. The generation of the leakage current in a fully depleted silicon is proportional to the ratio of n_i / τ where n_i is the density of carriers in an intrinsic silicon. n_p in the epilayer is 5 orders of magnitude smaller than n_i and a decrease of the carriers life time by this amount can be tolerated. The changes of the effective doping density due to the radiation damage at fluencies considered for hadron machines should not influence the performance of the proposed APS. Clearly, testing of the APSs for the radiation damage has to be performed as soon as the functional sensors are produced.

7) Conclusions

A new kind of APS was described and analyzed into all details possible at this stage of the development. The functioning of the proposed APS is based on the presence of relatively large hole currents within individual pixels of the sensors. These currents create the desirable shape of the potential within the pixel without recombining with the very small number of electrons corresponding to the signal. We believe that the presented sensors represent a large improvement of sensors for position detection and of the time of occurrence of charged particles crossing the sensors. The proposed sensors when developed will play an important function for tracking of charged particles for particle physics experiments and for producing images in electron microscopes.

8) References

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