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Active Pixel Sensors for Direct Imaging Of Electrons From 10 keV Up To Several MeV With Large Dynamic Range for TEM Applications

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In the past years the direct detection of electrons in position resolving silicon detectors has made substantial progress. CMOS active pixel sensors and fully depleted (sensitive) pnCCDs have recently been developed as electron imaging detectors in (S)TEMs. We will report on the progress made in electron detection and imaging with the high speed, radiation hard **De**pleted **p**-channel **MOS** (DePMOS) detectors with single electron resolution down to energies of 10 keV. A proposal for a new device will be presented being able to detect, record and more than 2.000.000 signal charges per pixel corresponding to 400 detected electrons from a TEM in a single pixel in one readout frame. The detector is thinned down to suppress the deterioration of the point spread function through multiple scattering processes. It is the aim of the present project to improve the modulation transfer function (MTF) and get close to the physical limits, to increase the dynamic range for high flux measurements and still maintain the single electron sensitivity [1]. A monolithic detector of 1k · 1k pixels of 40 µm size, leads to a system with a spatial resolution of the single STEM electrons of less than 10 µm. The system allows for a frame rate of up to 1.000 frames per second (fps). Last not least, the choice of technology and the mode of operation have to guarantee the long term stability of the detector and the system.

DePFET detectors have been developed as fast and low noise active pixel sensors for applications in X-ray astronomy with photon energies from 100 eV up to 20 keV. They have currently been qualified for ESAs BepiColombo mission for its way to Mercury (see Fig. 1). In the case of electron detection originating from e.g. a STEM, the number of generated electron-hole pairs in the silicon varies from 200 e-h pairs per µm for 100 keV STEM electrons down to 90 e-h pairs for 400 keV incident electron energy, approaching the minimum ionizing rate of 80 e-h pairs per µm track length. The total track length is about 110 µm for the 100 keV electrons, the projected track length about 50 µm. Centroiding of the signal charge cloud along the electron track allows for a sub-pixel spatial resolution. The very good noise performance of the DePFET below 20 e^- (rms) at room temperature and 5 e^- at -30 ^oC allows exploiting the charge sharing among neighboring pixels.

The proposed DePFET structure (see Fig. 2) is a detector and an amplifier at the same time, located on fully depleted, i.e. fully sensitive silicon with a thickness between 50 µm (see Fig. 3) and 500 µm depending on the application [2]. Signal charges, generated in the bulk of the silicon are drifted with the help of adequate electrical fields to the internal gate of the DePFET, inducing a positive mirror charge in the transistor channel and thus increasing the current between source and drain. Upon command the charge can be removed from the internal gate with the help of a positive voltage on the n^+ clear contact. The collection of the charge in the internal gate occurs within 10 ns, the removal of the charge takes about 50 ns. In case the device is thinned down to approximately 50 µm, the number of signal charges per hitting electron from the TEM is above 7.000 for TEM electron energies above 30 keV; the electronic noise of the DePFET system is below 20 electrons (rms) at room temperature yielding a very good signal-to-noise ratio of 350:1. The built-in non-linear amplification of the integrated amplifier allows the storage and processing for every frame of more than 2.500.000 electrons, generated in the silicon (see Fig. 4). This enables to record diffraction patterns without blooming pixels for up to 400.000 TEM electrons per pixel and per second.

If more than one electron from the TEM hits the DePFET pixel structure within one readout time (e.g. 1 ms), the centroiding of individual, single TEM electrons cannot be applied, but of course the centroiding of the integral of all scattered electrons in the diffraction peak reaching the DePFET pixels is still possible.

The high frame rate (1.000 fps), the excellent position resolution (10 µm), the very high dynamic range (400 STEM electrons per 1 ms) and the low noise operation at room temperature (ENC < 20 e^-) have stimulated the proposed approach for direct electron detection with the new DePFET devices for TEM imaging applications. More measured and simulated results and the potential for future implementations in TEMs will be presented.

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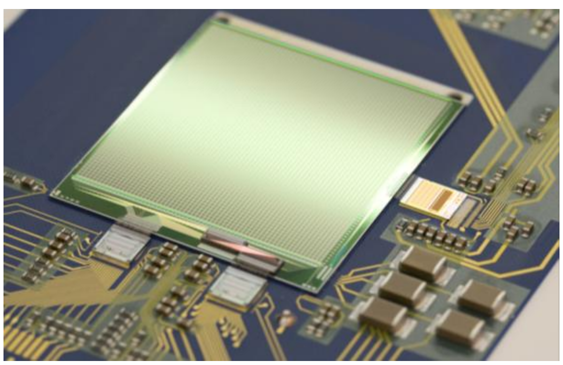

Fig. 1: Photograph of a DePFET detector mounted on a ceramic board including the signal processing ASIC (right) and the control ASICs (lower left).

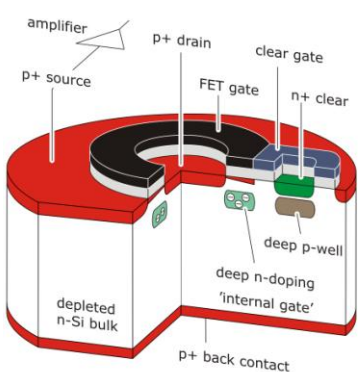

Fig. 2: Schematics of a DePFET detector-amplifier structure on a fully sensitive Si bulk. Pixel sizes of 20x20µm^2 to 1x1mm^2 can be realized.

Fig. 3: High purity silicon detector thinned down to a thickness of 50 µm. The detector properties remain unchanged [3].

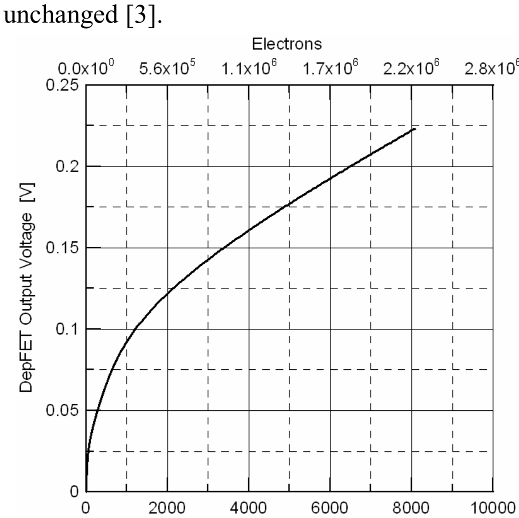

Fig. 4: Non-linear response of DePFET active pixel sensors as a function of signal charges in the internal gate. For small signals the gain is high and decreases with an increasing number of electrons in the internal gate.

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