Carrier mobilities or composition of nanostructures such as metal-oxide semiconductor field effect transistors (MOSFET) are tightly connected with local strain. Due to the uniqueness of Bragg's equation, nano-beam electron diffraction (NBED) is one of the most accurate tools for strain quantification with a precision in the $10^{-4}$ range. Strain analysis by NBED (SANBED) has recently improved drastically by using convergent STEM probes to yield sub-nm spatial resolution [1], and by precessing the STEM beam [2]. But still a major problem is the limited speed of contemporary, slow-scan CCDs with frame times around 100ms.

We introduce a scintillator-free, low-noise and radiation-hard pnCCD detector [3,4] with a detection quantum efficiency (DQE) close to 1, combined with an ultrafast readout-hardware working at 1kHz and above. We first investigated the In$_x$Ga$_{1-x}$NyAs$_{1-y}$/GaAs layers shown coloured in Fig.1a. The strain profile obtained from the 004 reflection recorded on a conventional Gatan CCD with 0.5s frame time is shown black. As depicted in Fig.1b, the pnCCD camera yields the same strain profile with equal precision of 0.07% at half the frame time of 0.2s. This is remarkable since each 300keV electron deposits its energy in up to 10 camera pixels, causing a large but isotropic point spread as shown in Fig.2. Next we used pnCCD frame times of 1ms only to obtain the profile in Fig.1c, agreeing with a-b while exhibiting a slightly lower precision of 0.13%, but speeding up the acquisition by a factor of 200. Fig.1d shows a strain profile calculated from the 008 reflection which is highly sensitive to strain but also very weak. The high DQE of the pnCCD allows for an improvement of strain precision to up to 0.04%.

Secondly 2D strain mapping was performed at a Ge$_x$Si$_{1-x}$/Si MOSFET shown in Fig.3. Parts a-b correspond to strain maps in the red region of the inset with 45x60=2700 scan pixels of the STEM beam and diffraction patterns recorded on a Gatan CCD with an overall acquisition time of 10min. Although sparsely sampled, the effect of the S/D-stressors is clearly observed with compressive lateral and tensile vertical strain of 2 and 3% below gate G, respectively. The high potential of the pnCCD camera is seen from Fig.3c-d, where we scanned over the yellow square in Fig.3a, sampled at 256x256=65536 pixels. With a frame time of 4ms for each diffraction pattern, the whole acquisition took only 4min while still resolving lateral and vertical strain maps with the GeSi/Si interface and a dislocation marked dashed in c-d. The precision achieved here was 0.1%, determined from a strain map in pure Si.

Fig. 1: (a) STEM HAADF image ( coloured) of InxGa1-xNyAs1-y/GaAs layers and strain profile along [001] measured from the 004 reflection by NBED using a Gatan UltraScan CCD. (b-c) Same as (a) but a scintillator-free pnCCD camera with (b) 200ms and (c) 1ms frame time was used. (d) As in (b) but strain was measured from the 008 reflection.

Fig. 2: Direct electron detection using the pnCCD camera at a primary energy of 300keV. At this relatively high energy, signal electrons are generated in traces of up to 10 pixels length. However, an FFT of a large number of single events shows the isotropy of this point spread, allowing a recognition of the 004 disc with high precision [1,3].

Fig. 3: (a-b) Strain map in the red region of the inset, showing a MOSFET with source/drain/gate S/D/G. The 333 reflection was recorded on a Gatan UltraScan CCD at 45x60 scan positions rastered in 10min. (c-d) Strain map in the yellow region. Here, 222 was recorded on a pnCCD with the STEM beam scanning over 256x256 pixels in 4min. Dashed: dislocation.