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Development of a high gain and high MTF CMOS electron detector for transmission electron microscope (TEM)

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Last advanced TEM techniques are dedicated to the observation of sensitive materials which can be damaged with the electron dose, such as biological specimen. In this situation it is mandatory to use a low dose and conventional beam energies (200keV). Consequently, electron detectors need to have a gain as high as possible while maintaining high spatial resolution performances. Nowadays, camera providers propose CMOS image sensors for the direct detection of electrons with optimizations focused on the improvement of spatial resolution, only demonstrated at 300kV [McMullan2009]. Indeed, one big issue with TEM detectors is the large spread of the electron distribution in the silicon substrate, greater than the pixel size, which induces a bad spatial resolution. Thus, one solution chosen by camera providers is to back-thin the substrate. However, the drawback is a strong reduction of the gain. One other big issue is the strong ionizing dose imposed by the experiment, which require to use specific hardening by design pixels, based on 3T (3 transistors) architectures.

In this study, Technology Computed Aided Design (TCAD) simulations are used to determine the best substrate characteristics (thickness, doping concentration) leading to a high detector gain and a high detector spatial resolution estimated by means of the MTF, for beam energies equal or lower to 200keV. Actually, state of the art cameras have a gain in the range of 50. The goal is therefore to develop a detector with a gain higher than 100 while keeping similar MTF performances compared to state of the art detectors.

TCAD simulations are performed with the Synopsys software with a special method based on two optical illuminations demonstrated in a previous work [Marcelot2023] (see the Fig.1). Then, several substrates are used and the gain is simulated in 3 dimensions (3D), while the MTF is extracted from a 2D simulation of the line spread function acquired on 11 pixels. Substrates are defined by:
- doping concentration ranging from 10^12B/cm2 to 10^15B/cm3
- epitaxy thicknesses ranging from 7µm to 30µm on un-thinned substrates and back-thinned substrates.

With un-thinned substrates, the simulations are showing a gain 3 times higher compared to state of the art camera for most of the substrate doping concentration. The drawback is a weak MTF, but it is shown that it can be improved by using low doped 7µm epitaxies, because of a better lateral collection of electrons induced by a larger depleted region. Therefore, at 200kV, a higher gain and MTF is demonstrated compared to state of the art cameras.
With back-thinned substrates, the gain is strongly reduced due a the reduction of the sensitive volume. In addition, and in contrary to a previous study performed at 300kV [McMullan2009], it is shown that the MTF is degraded with 200kV and 150kV electron beams. This unexpected result is due to the fact that a lower beam energy induces much more electrons in the epitaxy and the reduced volume of silicon cannot efficiently recombined the electron excess which diffuses to adjacent pixels and reduce the MTF.

Auteur principal: Dr MARCELOT, olivier (ISAE-SUPAERO)

Co-auteur: Dr MARCELOT, Cécile (CEMES-CNRS)

Orateur: Dr MARCELOT, olivier (ISAE-SUPAERO)

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