Direct detection of electrons by area array CCD

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Abstract

The topic of this work is the study of direct detection of electrons by Charge-Coupled-Devices (CCD). The aim is to design a detector for the angle and energy-selective detection of signal electrons in very low energy scanning electron microscope (VLESEM), based on the directly electron-bombarded CCD sensor (EBCCD). The planar CCD sensor is very suitable to convert the area information carrying by impinging electrons of the beam into the electrical signal that can be further processed. We concentrate upon two problems - the design of appropriate electronics and determination of an appropriate energy of the bombarded electrons for the CCD sensor.

Direct detection of electrons by CCD sensor

In VLESEM we consider to use the CCD sensor in the direct electron-bombarded mode. That is because the EBCCD-detector must process a very high amount of data in a short time at low energies of the electron beam. It is assumed VLESEM will work with an impinging electron beam energy of about 5 keV (less than 10 keV) and a current of 10^{-9} - 10^{-10} A.

When one electron impinges on the silicon element, it creates signal electron - hole pairs through the electron bombarded semiconductor (EBS) cascading process. The average EBS gain *G* (number of signal electrons in the potential well generated by one incident electron) is related to the incident particle energy *E* (electron beam) (assuming that the generation of one signal electron in silicon requires 3.65 eV) (Fiebiger and Muller, 1972)

$$G = E/(3.65\ \text{eV}) \quad [\text{-}] \tag{1}$$

In the case of the real CCD sensor we must calculate the EBS gain *G* directly as the ratio of the number of the signal electrons generated in the potentional well, N_w, to the number of the impinging electrons in the electron beam, N_b

$$G = \frac{N_w}{N_b} = \frac{E}{3.65\ \text{eV}} \cdot \varepsilon(E) \quad [\text{-}] \tag{2}$$

where $\varepsilon(E)$ is the detection efficiency of the CCD. The detection efficiency is defined as the ratio of the detected energy E_w to the energy incident on the surface of the CCD, E_b, and it is a function of the incident electron energy *E* (Stearns and Wiedwald, 1989). In practice, the front-side illuminated CCD shows a reasonable efficiency ($\varepsilon > 0.1$) at an energy from 8 - 12 keV upwards, depending on type of the sensor (Opal and Carruthers, 1989; Stearns and Wiedwald, 1989). The efficiency generally decreases rapidly with decreasing electron energy. The available thinned back-side illuminated CCDs have an efficiency higher than 0.1 at energies below 5 keV. Of course, the integration time, i. e. the time we need to illuminate the sensor to generate and accumulate an optimal amount of electrons in the potential wells of CCD, is longer owing to a worse efficiency.

The EBCCD electronics

For the first experiments were used the easily available low resolution sensor suitable for direct detection of electrons - Virtual phase CCD TC211 made by Texas Instruments (192 pixels (H) by 165 pixels (V), well capacity 150 x 10^3 electrons, ideal dynamic range 60 dB, clock frequency (serial register) 10 MHz) (Texas Instruments, 1994), that is why we now use the front side bombardment mode. The main benefits of the virtual phase technology are: i) only one half of each pixel is covered with a gate structure, ii) Only single-phase clocking for horizontal and vertical transfer of the charge is used (Hynecek, 1981).

The electronics to control the CCD sensor and to process the signal data is based on the digital signal processor (DSP) from Analog Devices ADSP-2181. The block diagram of the electronics is shown in Figure 1. DSP generates clock signals to operate image-area and

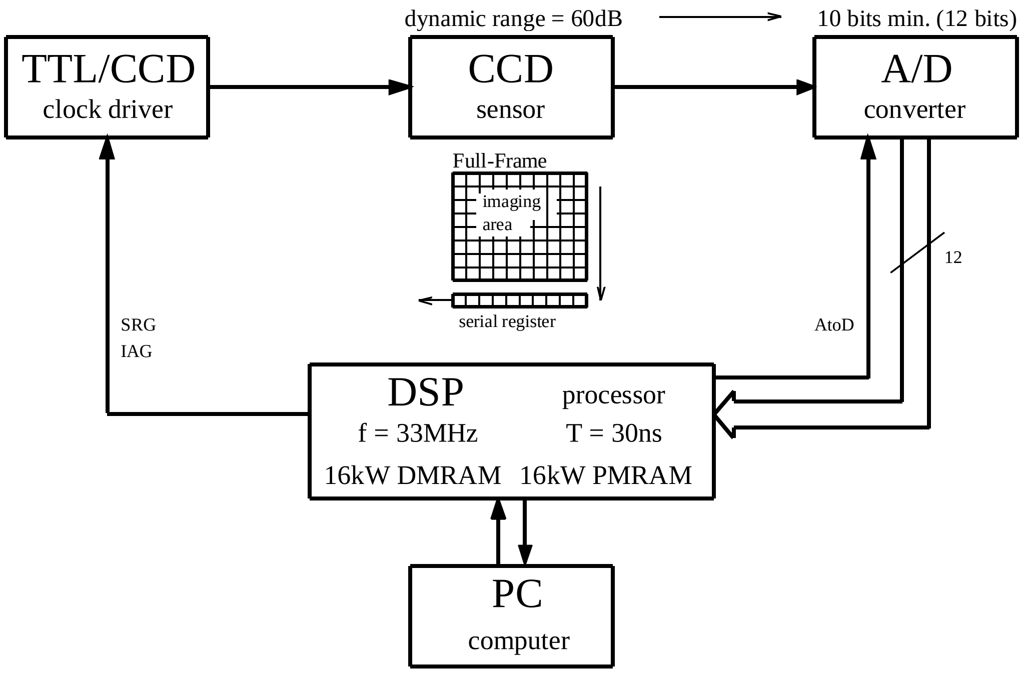


Figure 1. Electronics of the EBCCD.

serial-register gates of the full-frame operation CCD image sensor TC211 and a synchronous clock signal for the 12-bit analog-to-digital converter. Clock pulses for CCD are buffered and level-shifted by parallel and serial clock drivers and outputs to the image sensor. The analog output signal from CCD is synchronously converted by the 12-bit AD9220 A/D converter, buffered by the line driver to the processor data bus, read and processed. All these functions ensure program runs in DSP. The program working in DSP communicates with another program working in the personal computer (PC) through the serial line RS-232.

Experiments and results

The first experiments were performed in the low energy scanning electron microscope (accelerating voltage 0 - 5 keV, clean vacuum (chamber 10^{-5} Pa, gun 10^{-7} Pa), PC-controlled optical system and specimen stage). A small board with the CCD sensor, nearest transistor and Faraday cup of picoammeter was attached to the x-y translation stage inside the chamber. The main electronics was situated outside the vacuum. The electron beam from the electron gun was defocused by switching-off the objective lens. The deflection system was switched-off too.

We moved the Faraday cup with a hole of a diameter of 2 mm under such an electron beam and measured the beam current I_b. Next we moved the shielded CCD sensor with a hole of a diameter of 2 mm under the electron beam and measured the detected signal as a function of the integration time.

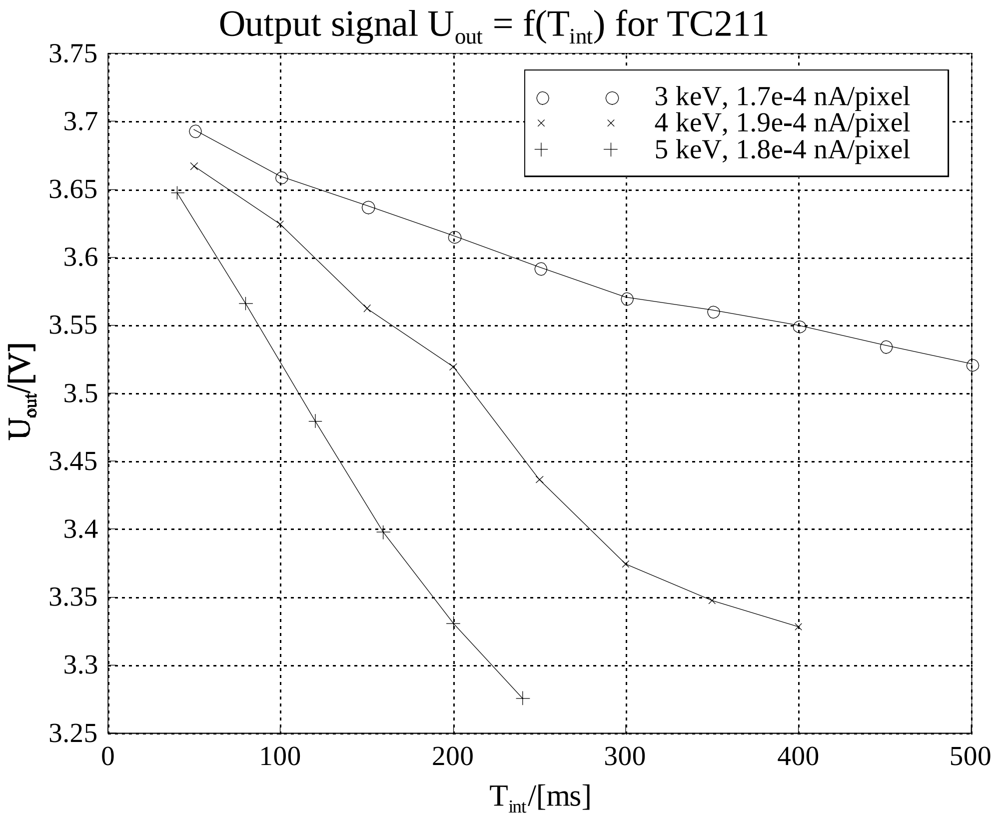


Figure 2. The output signal measured.

The responses for 3, 4 and 5 keV are presented in Figure 2. From the measured current I_b, output signal from the sensor U_{out} and integration time T_{int} we calculated the gain G and detection efficiency ε as a function of the incident electron energy E. The values of the gain and detection efficiency corresponding to the electron energy are in Table I. The needed accumulation time was calculated from the measured gain values.

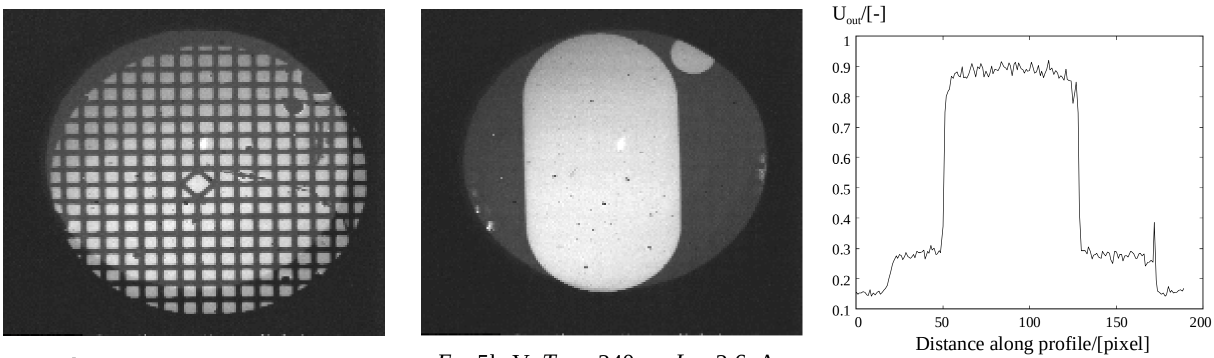
Table I.

E [keV]	3	4	5
G [-]	0.13	0.23	0.44
ε [-]	$1.6\cdot10^{-4}$	$2.1\cdot10^{-4}$	$3.2\cdot10^{-4}$
Accumulation time ($I_b = 10^{-9}$ A)			
Φ 2.64 mm (~25880 pixels)	3.0 s	1.7 s	900 ms
Φ 1 mm (~3740 pixels)	440 ms	250 ms	130 ms

The dark current was measured as an output signal without any illumination and electron bombardment. The first measurement of the dark current was made before the experiments with the electron beam - a current density of 2.4 nA/cm^2 was measured (at room temperature 22°C). The measured values during the experiments fluctuated from 5.0 nA/cm^2 to 19.0 nA/cm^2 in the dependence on the temperature and electron energy. The dose during one measurement was of the order of 10^9 electrons/pixel. The total dose was approximately $2\cdot10^{10}$ electrons/pixel during 10 hours. A larger radiation damage was noticed after exposure by a higher energy electron beam (E > 10 keV), after a long time from the last exposure (days-month) and after exposing the chip to air. In all cases it was helpful to scan the chip by using an electron beam of a low energy (5 keV) in the TV mode, and the dark current rapidly and significantly decreased to a value of about 10 nA/cm^2.

For illustration, images of the grid and slot were scanned, see Figure 3. The specimen of a diameter of 3 mm in the holder of a diameter of 2 mm which worked as a shield was placed approximately 1 mm above the chip. The figure shows also the intensity profile along a horizontal line in an image of a slot to demonstrate the dynamic range. Our image of the slot has a dynamic range of 31 dB.

Grid (step 125µm, hole 90µm) **Slot** (oval hole 2000/1000µm) **Intensity profile**



E = 5keV T_{int} = 200ms I_b = 2.8nA E = 5keV T_{int} = 240ms I_b = 2.6nA

Figure 3. E-beam images of grid and slot.

Discussion

The electronics based on the digital signal processor ADSP-2181 can operate the TC211 sensor at a frequency of 5.5 MHz, i. e. it can process the image signal from the full image area in 6.7 ms. But the detection efficiency and gain for an energy of up to 5 keV are low, the impinging electrons do not generate a sufficient amount of electrons in the potential wells and the integration time would have to be 900 ms so we cannot fully exploit the speed of the electronics. A possible solution is to increase the energy of the electron beam in VLESEM and so the energy of the bombarded electrons or to replace the sensor by a low resolution thinned back-side illuminated CCD with a higher efficiency at energies below 5 keV.

References

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