Journal of Computer-Assisted Microscopy, Vol. 10. No. I, 1998

Detection of the Angular Distribution of the Signal Electrons in VLESEM

Miroslav Horáček[1]

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 microscopy (VLESEM), using an electron-bombarded CCD sensor (EBCCD). We concentrate upon two problems-the design of appropriate electronics and determination of an appropriate energy of the signal electrons for the CCD sensor.

KEY WORDS: Very low energy scanning electron microscopy; angular distribution; immersion objective lens; cathode lens; electron bombarded CCD sensor.

SUMMARY OF THE CURRENT STATE OF THE LOW ENERGY MICROSCOPE

Considerable attention has been paid in the last ten years to the development of low voltage scanning electron microscopy (LVSEM) in order to reduce the radiation damage of some sensitive specimens (e.g., some biological or semiconductor structures) and possibly also to reduce the local charging of a semi-insulating specimen. A radical change in LVSEM has been made by the use of very low energy electrons, with energy below 10 keV.

The essential element of a low energy electron microscope that makes it different from the classical microscope (TEM) is the cathode lens. The advantages of the immersion objective (magnetic lens plus cathode lens) were fully recognized only recently (Lenc, 1992). So far, experiments demonstrating capabilities of very low energy scanning electron microscopy (VLESEM) have been realized in IS1 Brno (Müllerová and Lenc, 1992). These experiments showed that classical detectors are inferior at low energies. Secondary and backscattered electrons are reaccelerated in the cathode lens and their trajectories are similar to those of the primary beam electrons. There was many attempts to collect the signal electrons by using a nonstandard arrangement of the modified detectors in the microscope chamber. Unfortunately, the main (central) part of the signal electron beam is not detected in all these cases. A solution is to separate the signal and the primary electron beams, and to detect the signal beam with its most useful part of electrons. The Wien filter is suitable for the separation of the primary and the signal electron beams. The main benefits of the use of this separator is that the trajectories of the primary beam remain the same as without the separator.

SEPARATION AND DETECTION OF THE SIGNAL ELECTRONS IN VLESEM

A schematic arrangement of the optics with an immersion objective, Wien separator and electron bombarded Charged-coupled Device (CCD) detector is shown in Fig. 1. The primary electron beam (up to 10 keV) from the source of electrons passes through the Wien filters, which are balanced so that the axial ray with the nominal energy is not affected. Next, the primary beam passes through the deflection system, is

[1] Institute of Scientific Instruments, Academy of Sciences of the Czech Republic, Královopolská 147, CZ 612 64-Brno, Czech Republic. http://www.isibrno.cz; e-mail: mih@isibrno.cz

1040-7286/98/0300-0023$15.00/0

focused by the magnetic lens, decelerated to the desired energy by the cathode lens, and scanned over the specimen. The beam of signal electrons accelerated by the cathode lens, approximate to the primary energy, passes through the immersion objective lens, and it is deflected by the Wien filter to the region of the electrostatic transport optics shielded from the primary beam. The transport optics directs the signal beam to a suitable detector.

The arrangement employing the Wien filter makes the angle and energy-selective detection of signal electrons possible and gives rise to the corresponding sort of contrast, if the signal is properly collected. The use of CCD technology is very suitable for this purpose. The planar CCD sensor converts the angular distribution of electrons of the signal beam into the electrical signal that can be further processed, which makes it possible to form the image corresponding to the signal electrons from the selected areas of the CCD sensor.

The focused primary beam probe is scanned by the deflection system over the specimen in the scanning matrix of m-lines by n-columns. The signal beam is always directed by the Wien filter and transport optics to the CCD sensor. The electrons of the beam cover o-lines by p-columns of the CCD sensor. The probe stays in every point of the scanning pattern m by **n**” for the time needed for generating an optimum number of electrons in the potential wells of CCD. The image created in the CCD corresponds to the angular distribution of the signal electrons of one point of the specimen. We read this “o by **p**” image from the CCD and then we convert, process, and put it in the memory. This procedure is repeated for every point of the “ by **n**” pattern of the specimen. After one scanning of the specimen we obtain and process m∗ n ∗ o ∗ **p**” data.

We can process this data in many ways. The usual way is to define on the area “o by **p**” of the CCD two or more geometric **patterns—circles, annulin,**

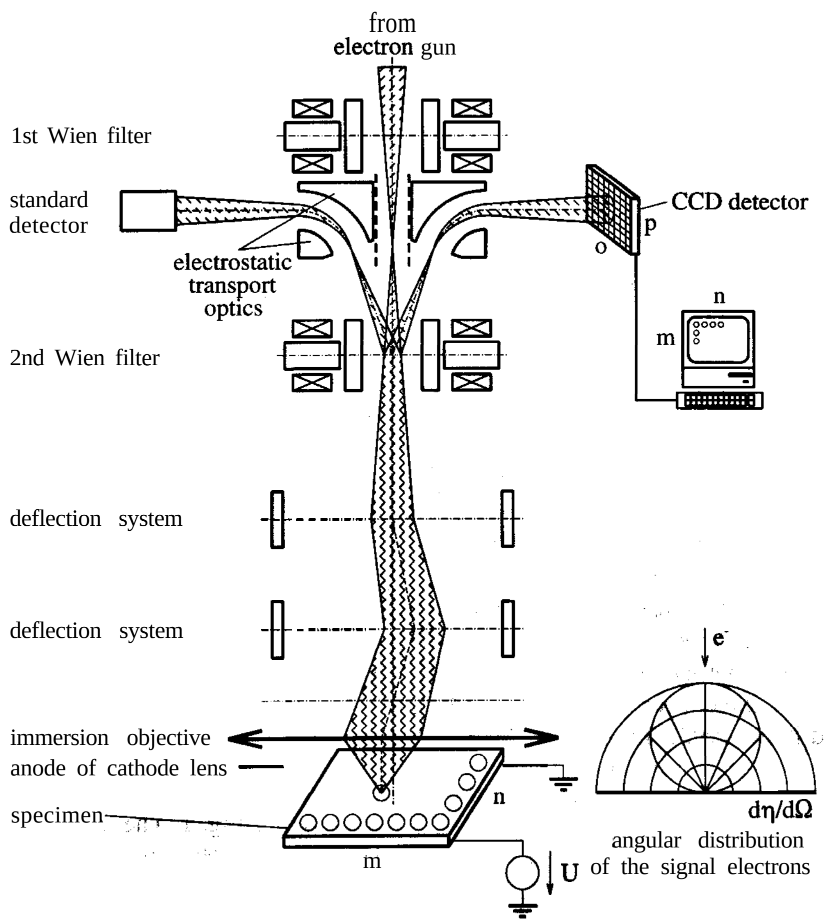


Fig. **1.** VLESEM with EBCCD detector.

quadrants, sectors, half-planes, etc. The data from all pixels belong to the geometric pattern we process in a suitable way; for example, we calculate an average signal for the given pattern. In this way, we obtain from every image of the CCD (for every point of the scanning matrix m byn") data for each geometric pattern we defined. We will use this data to create the image of the specimen with the scanning matrix m by n" on the monitor to whose every point we assign the combination of the signals from the geometric patterns on CCD. In the simplest case, we assign to every point only the signal from one pattern, usually, we assign the sum or difference of signals from two patterns. Let us recall that the shape of the geometric patterns is unchangeable through the scanning over the specimen and that we assign to every point the same combination of the signals from the geometric patterns on CCD.

Besides the.electron-bombarded CCD (EBCCD) detector, we need a standard detector (Everhart-Thornley), as shown on the left side of Fig. 1, working in the TV scanning mode to adjust the microscope before using the EBCCD detector, because the processing of the signal through the CCD sensor will be considerably slower than in the TV mode. The signal electrons are directed to the standard detector by a simple change of the orientation of the fields in the Wien filter.

DIRECT DETECTION OF ELECTRONS BY CCD SENSOR

In VLESEM we consider using the CCD sensor in the direct electron-bombarded mode. That is because we must process a very high amount of data in a short time at low energies of the electron beam (discussed more in detail below). The CCD systems with electron-photon conversion are designed for very high energies (TEM) or are using a very high integration and process time (slow-scan CCD cameras).

When one electron impinges on the silicon element, it creates signal electron-hole pairs through the electron bombarded semiconductor (EBS) cascading process, which exhibits two major features. First, 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):

$$G = E/(3.65\ \text{eV}) \tag{1}$$

Second, the multiplication process exhibits fluctuations: the variance is

$$\sigma = (F \cdot G)^{1/2} \tag{2}$$

where F, the Fano factor, is 0.12 in silicon van Roosbroeck, 1965; Fiebiger and Muller, 1972).

However, this ideal performance can only be obtained if the following conditions are fulfilled: (a) the incident energy is actually dissipated in the active material (not, for example, in the gate layer), (b) no incident electron is lost (for example, reflected back from the surface), (c) the signal electrons produced in the substrate are properly collected (no electrons are lost in the depth of the substrate), and (d) the electron bombardment does not disturb the CCD behavior (no radiation damage) (Richard and Vittot, 1992). 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,

$$G = \frac{N_w}{N_b} = \frac{E}{3.65\ \text{eV}} \cdot \varepsilon(E) \tag{3}$$

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 upward, 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, that 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.

USING EBCCD AS AREA-SELECTIVE DETECTOR OF ELECTRONS

In practice, for the specimen, i.e., m byn," we require a minimum resolution of 128 x 128 points, and the resolution 512 x 512 is considered as fully sufficient. For the CCD detector of area "o by p," the minimum resolution is 8 x 8 points, and the resolution 64 x 64 points is considered to be sufficient. The total time to scan one image of the specimen and to process the signal from the CCD for all points of the scanning matrix should be less than, say, 10 min. We assume VLESEM will work with a primary electron beam energy (i.e., the energy before deceleration) of about 5 keV (less than 10 keV) and a current of 10^{-9}–10^{-10} A. The signal electron beam current will be of the same order. A minimum dynamic range of the angular distribution of the signal electrons is expected to be 10^4.

For the first experiments we 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, 19943; that is why we now use the front side bombardment mode. The main benefits of the virtual phase technology as follows: (a) only one half of each pixel is covered with a gate structure, leaving the other half bare except for a thin layer of oxide. Electrons do not have to penetrate through the gate structure, and the detection efficiency is reduced only by this 0.5 μm thick protective coating, (b) Only single-phase clocking for horizontal and vertical transfer of the charge is used. This simplifies very much the hardware and software to operate the sensor, and makes a quick operation of the sensor possible (Hynecek, 198 1). From the above-mentioned basic parameters of CCD TC211, it follows that the resolution in the output signal corresponds to 150 electrons in the image-area potential well. To make the most of the dynamic range of CCD, one impinging electron must generate just 150 electrons in the potential well, i.e., G = 150. From Eq. (3) we can calculate the detection efficiency for the incident electron energy E = 5 keV and G = 150 to make the most of the dynamic range of the CCD: $\varepsilon(5\,\mathrm{keV}) \approx 0.1$.

The detection efficiency-incident electron energy dependence is characteristic of the CCD chip, and we cannot change it. For the optimum performance it is desirable to match the energy of the signal electrons beam to the CCD sensor.

THE EBCCD ELECTRONICS

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 Fig. 2. DSP generates clock signals to operate image-area and 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 the CCD are buffered and level shifted by parallel and serial clock drivers and outputs to the image sensor. The analog output signal from the 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 the program runs in DSP, which can work in two modes: (a) Image-mode in which the focused primary beam stays at some point of the specimen and we can observe the angular distribution at this point. This mode is useful to adjust the microscope and to prepare it for work in the detector mode. This mode is also used to debug electronics and in experiments to measure detection efficiency, dark current etc. (b) Detector-mode in which the microscope works in a way we described in the section entitled Separation and Detection of the Signal Electrons in VLESEM and shown in Fig. 1. In this mode, the microscope forms the image of the specimen corresponding to the angular distribution of the signal electrons over the specimen. The program running in the DSP communicates with another program working in the personal computer (PC) through an RS232 serial line. The program in the PC has two main tasks: (a) to start the CCD sensor (EBCCD detector) in Image or Detector mode by sending the appropriate data (integration time-in both modes, resolution m by n," definition of the geometric patterns on the area "o by p" of the CCD–in Detector mode) to the DSP; (b) to read data from the DSP and to display the image (or images) of the specimen on the computer monitor (save, retreive to/from the disk). The program can save the image in the MATLAB format to retreive and process this data in MATLAB used to compute the detection efficiency and dark current and to show the 3D profile of the images.

The kernel of the hardware is the Analog Devices EZ-KIT Lite Development Board with the ADSP-2181 digital signal processor to shorten the development time before the first experiment. The RS-232 serial operates at 38400 bps. The board with parallel and serial clock drivers, image sensor, A/D converter, and buffer to the processor data bus is connected directly to the EZ-KIT development board by using its expansion connectors. For experiments with light (debugging), the sensor is situated on the board; for experiments using the electron beam the sensor and

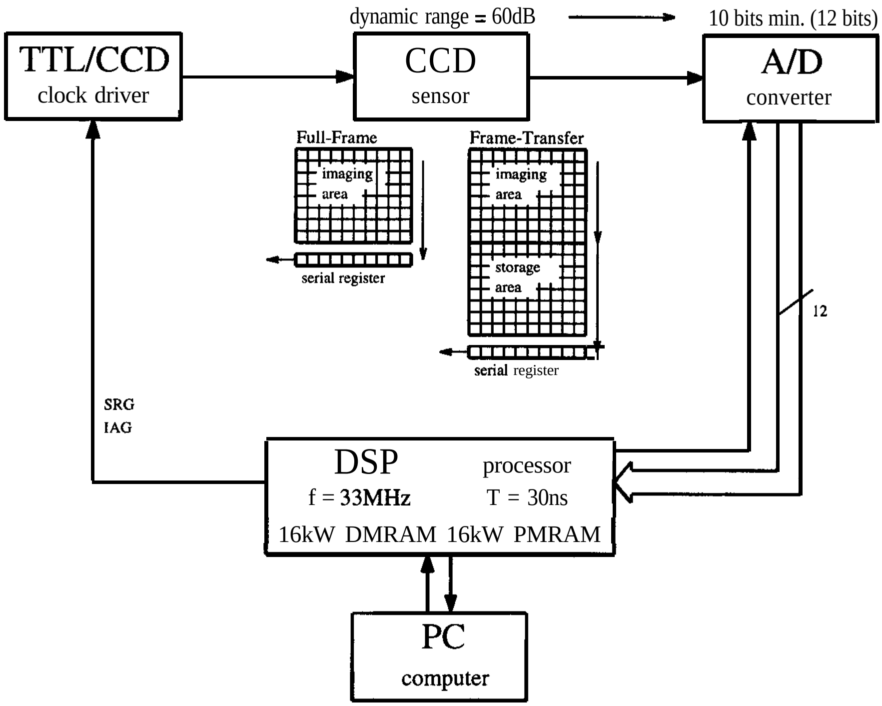


Fig. 2. Electronics of the EBCCD.

nearest transistor are situated on the vacuum suitable board and connected with other electronics by twisted cables.

The software for the DSP is written in assembler of the ADSP-2100 family, the software for the PC is written in the Borland C + + language.

THE EBCCD AREA AND TIMING

There are many ways for describing the distribution of the area of the CCD sensor on the desired geometric patterns. Ideally, for every pixel of the sensor, data describing its assignment to one of the geometric patterns can be individually assigned (i.e., 192x 165 = 31680 data for TC211, 1 bit-2 patterns, 2 bits ~ 4 patterns,...). Or we can divide the area of the sensor into groups of 2 x 2 pixels or 2 x 3 pixels, and create the patterns from these groups as basic elements. The advantage is the reduction in the data needed to describe the geometric patterns over the area of the sensor. We can achieve the same by focusing the signal beam only on the center of the sensor—for example on the circle of the relative diameter of 64 pixels. In this case, we work only with this reduced number of pixels, i.e., we form the geometric patterns only over this circle and we process the signal from the pixels of this circle. By this reduction of pixels we reduce the time needed to process one image of the angular distribution from the CCD in addition to the reduction of the data needed to describe the distribution of the CCD.

For reasons of timing, programming, and memory capacity on the chip of DSP, we decided to form the geometric patterns from groups-cells 2(H) x 3(V) pixels. A schematic arrangement of the area of the TC211 sensor divided into two patterns (circle, annulus, and others) is shown in Fig. 3. We cancel the first horizontal line and the area of the sensor is created from 64 x 82 cells (64 x 82 = 5248 data). To reach a maximum processing speed from the programming point of view, we reduced the period of the clock signal of the serial-register to 6 instruction cycles of the DSP (i.e., 6 x 30 ns = 180 ns ~ 5.5 MHz). In this 6-instruction cycles period we can distinguish only two geometric patterns by switching the primary and the secondary register set (bank) of the computational units of the DSP. To distinguish more patterns we would need more instructions and more time. To switch the register set we must change the corresponding bit in one of the control/status registers of the DSP. For this reason we describe the assignment of the cells to the geometric patterns by the data of this control/status register, so we send the definition of the

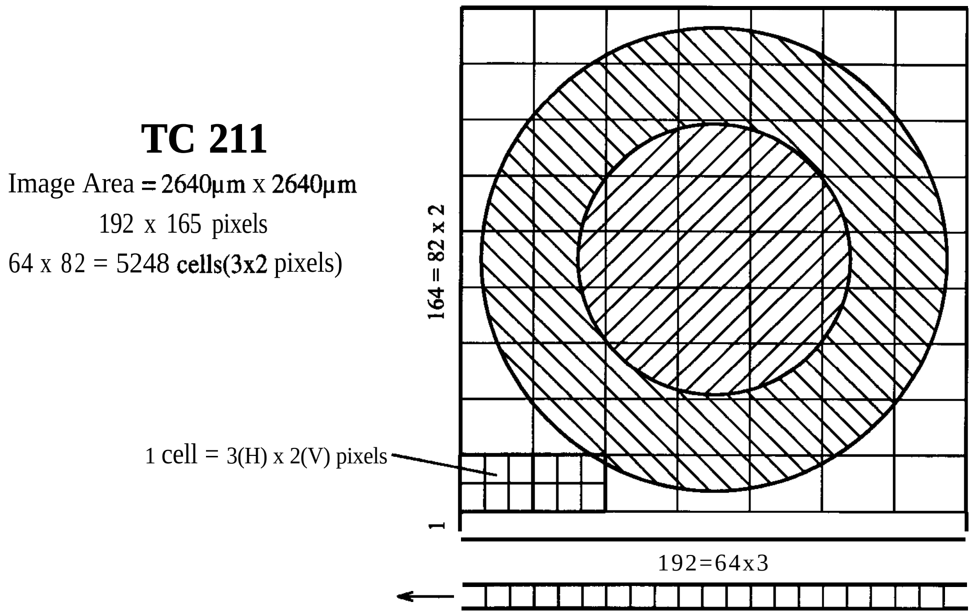


Fig. 3. Area of the EBCCD chip.

geometric patterns on the area "o by p of the CCD from PC to the DSP as a set of 8-bit words (i.e., 5248 Byte). To read this data in one instruction cycle during the program flow we must put them in the Data Memory RAM on the chip of the DSP, consisting of 16352 user-accessible locations. That is why we cannot describe each of 3 1680 pixels separately.

During one period of the clock signal of the serial register (i.e., moving the charge packet out of the serial register to the charge detection node of the amplifier, converting and summing), we change the clock signal for the serial register and converter, and at the same instruction cycle we sum the signal from the previous pixel (4 back);next, we test if the next pixel belongs to some pattern, we change the bank of registers, change the clock signal for the serial register and converter, and finally read (with 1 wait state) the data from the converter for the previous pixel (4 back)-in total 6 instruction cycles. Thanks to the timing of the electronic design, the clock signals of the serial-register gates and for the 12-bit analog-to-digital converter are the same. The timing for one period of the serial-register gates is shown in Fig. 4.

OPERATION OF THE DETECTOR

Now having designed the hardware and software solution for the EBCCD detector and the knowledge of conditions of an optimal interaction of the signal electron beam with the CCD sensor, we can calculate the total time to scan one image of the specimen and to process the signal from the CCD for every point of the scanning matrix 5 12 x 5 12 pixels.

We will process the signal electron beam carrying angular distribution by a sensor with a dynamic range of only 60 dB ideally. This value is typical for every standard CCD sensor. A higher dynamic range, up to

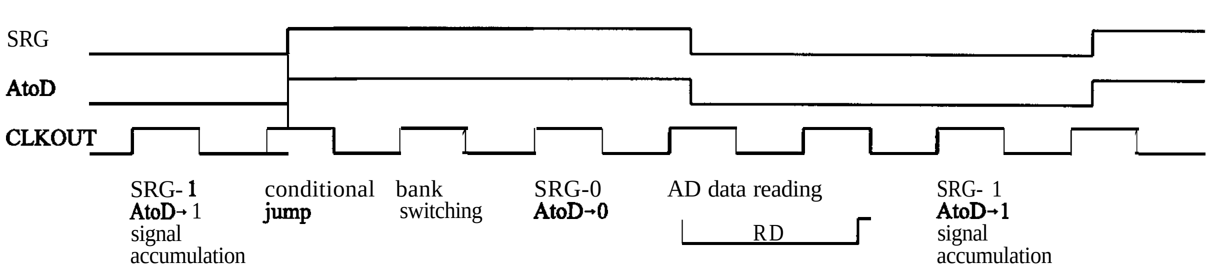


Fig. 4. Timing of the EBCCD.

100 dB, can be achieved by cooling the chip. For observing the image of the specimen with the naked eye on the monitor, the dynamic range of the standard CCD is fully sufficient. So now we develop an EBCCD detector with a sensor at room temperature.

The total time for scanning one image of the substrate will be calculated for two assumed beam currents, 10^{-9} and 10^{-10} A. The results are in Table I. We assume cosine angular distribution of the signal beam, i.e., after the generation of an optimal number of electrons in the potential wells of CCD to create in the sensor the image corresponding to the angular distribution of the signal electrons of one point of the specimen, only some pixels are saturated (150×10^3 electrons in the well). The ratio of the total number of the electrons in all bombarded wells in the case of a cosine distribution to the cased uniform distribution is $2/\pi$. For simplicity, we assume that the signal beam is focused on the circle of a relative diameter of 164 pixels (~ 21000 bombarded pixels) or 64 pixels (~ 3200 bombarded pixels). The beam current 10^{-9} A means 6.25. 10^9 electrons/sec. For example, for a circle of a diameter of 164 pixels the total number of the signal electrons to be generated in all potential wells is $N_w = 150 \cdot 10^3 \cdot 21000 \cdot 2/\pi = 2 \cdot 10^9$ electrons. To generate such an amount of electrons we need, from Eq. (3), $N_b = 2 \cdot 10^9/150 = 13 \cdot 10^6$ electrons in the beam, and for a beam current of 10^{-9} A we need an integration time of 2.1 ms. This time is needed to accumulate in the sensor the charge for one image of the angular distribution. For the transfer of the charge packets and for the processing of the data, we need 6.4 ms (for a circle of a diameter of 64 pixels this is 2.6 ms). In total, for the accumulation of the charge and for the processing of the data of an image of 512 x 512 points we need $(2.1 \cdot 10^{-3} + 6.4.\ 10^{-3}) \cdot$ 512.5 12 = 2228 sec ~ 37 min.

To the accumulation and process time we must add the time for the transfer of the data from the DSP to create the image of the specimen on the PC monitor; which is 2 x 12-bit word for two geometric patterns, that is 273 s for an image of 512 x 512 points and the serial line of 38400 Baud. This time is independent of the beam current and size of the bombarded area. This time is comparable with the accumulation plus process time (especially for a high current and low size of the area) and increases the total scanning time. We can write the data during the scanning to the external memory and transfer the data to the PC after scanning. But in view of the fact that the total scanning time is more than 10 min it is better to create the image on the monitor continuously. The solution is to use the built-in synchronous serial port in DSP and so to increase the serial line frequency up to the order of MHz.

Because the accumulation and process times are comparable, we must use a blanking system to blank the electron beam during processing or we can use a frame-transfer CCD sensor with a separate image area and screened storage area of pixels.

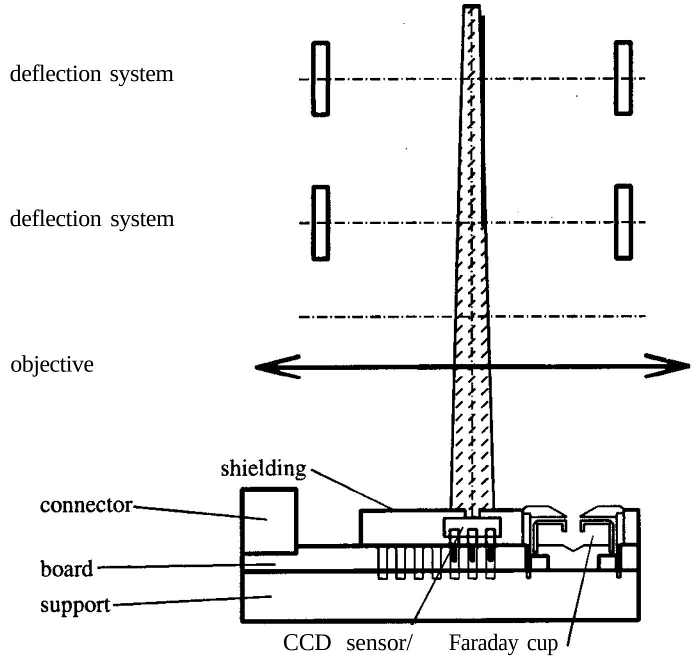
Table I

Beam Current	10^{-9} A	10^{-10} A
	Accumulation time (msec)	
Φ164 Pixels	2.1	21
Φ64 Pixels	0.3	3.3
	Total time (512 x 512 pixels; min)	
Φ1 64 Pixels	37	121
Φ64 Pixels	13	26

EXPERIMENTS AND RESULTS

The first experiments when the chip was bombarded by the electron beam, after debugging of electronics, were performed in the low energy scanning electron microscope developed in our Institute of Scientific Instruments (accelerating voltage O-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 a 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 also switched off. We moved the Faraday cup with a hole of a diameter of 2 mm under such an electron beam (with a diameter more than 2 mm) and measured the beam current I_b and current density J_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. The experimental configuration can be seen in Fig. 5.

The responses for 3-5 keV are presented in Fig. 6. 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



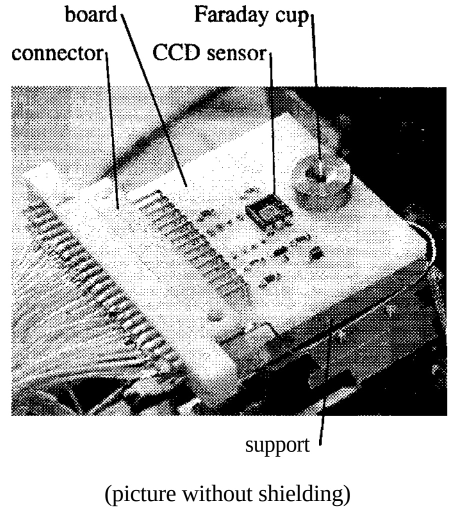


Fig. 5. Experimental configuration.

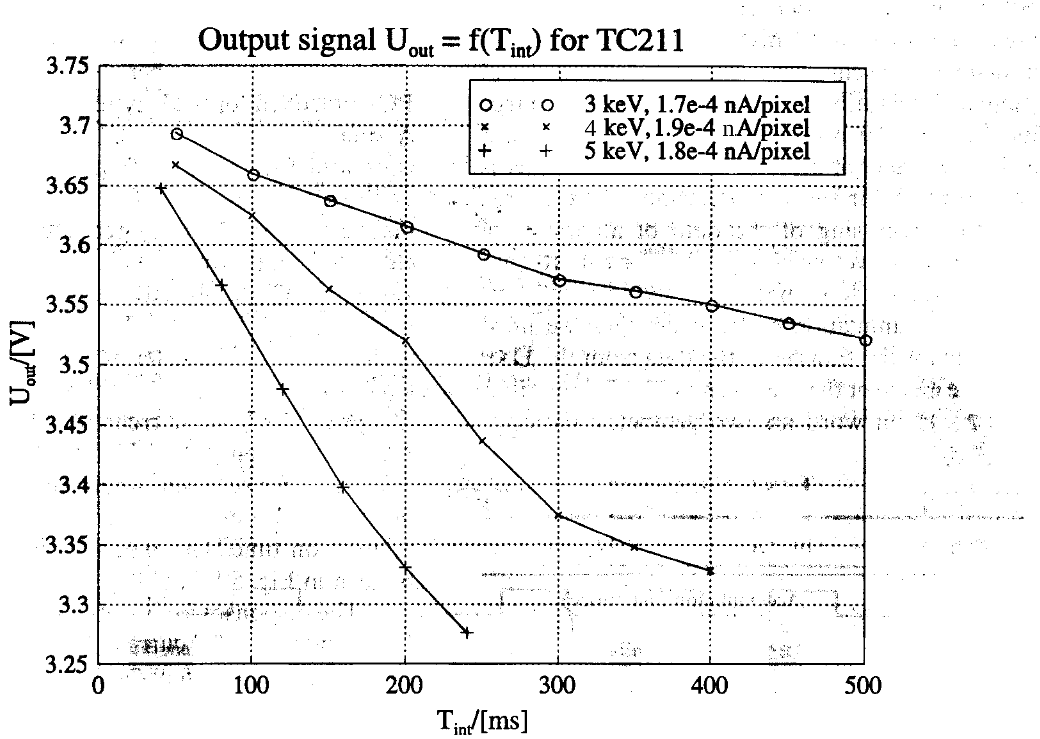


Fig. 6. The output signal measured.

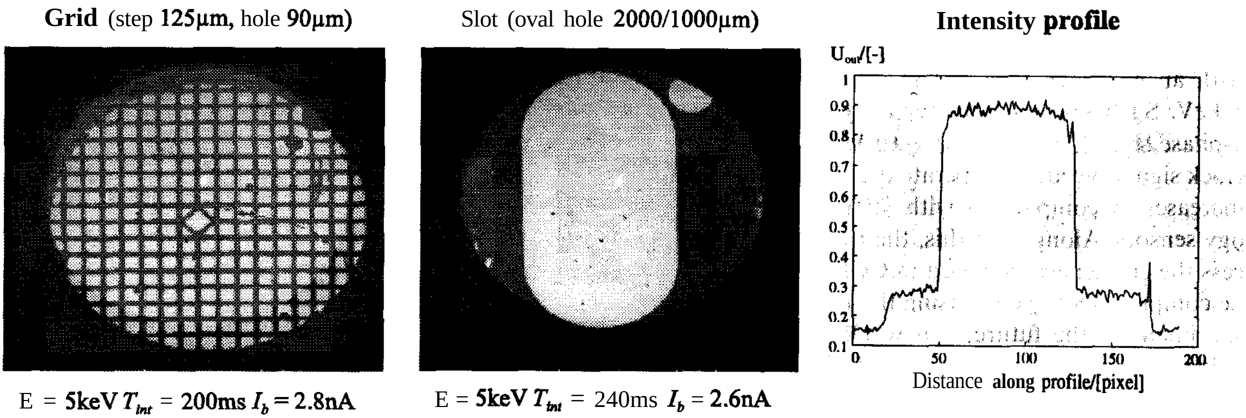


Fig. 7. E-beams images of grid and slot.

energy are G = (0.13, 0.23, 0.44) and $\varepsilon = (1.6 \cdot 10^{-4}, 2.1 \cdot 10^{-4}, 3.2 . 10^{-4})$.

Immediately after every measurement of the sensor when the chip was bombarded by the electron beam, the dark current was measured. It was subtracted from the output signal to calculate the correct value of the gain and detection efficiency. 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 to 19.0 nA/cm^2 with 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 $2 \cdot 10^{10}$ electrons/pixel during 10 hr. More 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 Fig. 7). 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 also shows the intensity profile along a horizontal line in an image of a slot to demonstrate the dynamic range. For a long integration time (above 10–20 ms), the dark signal and dark signal nonuniformity have the main influence on the attainment of the dynamic range. For a small integration time, the dark signal and noise signal are the main influence. Our image of the slot has a dynamic range of 31 dB, for the integration time under 10 ms it increases above 50 dB.

DISCUSSION

The electronics for the detector of the angle and energy-selective detection of signal electrons in VLESEM based on the directly electron-bombarded CCD sensor was designed, and the detection efficiency of the TC211 sensor was measured. The electronics based on the digital signal processor ADSP-2 181 can operate the TC211 sensor at a frequency of 5.5 MHz and scan one image of a specimen in 13 min. But the detection efficiency and EBS gain for an energy of up to 5 keV are small, the impinging electrons do not generate a sufficient number of electrons in the potential wells, and so we cannot fully exploit the speed of the electronics.

A possible solution is to increase the energy of the primary beam and so the energy of the electrons of the signal beam up to a maximum of 10 keV, with respect to the other components of the VLESEM. This increase does not influence the observation of the specimens because, thanks to the cathode lens, we can adjust the energy of the electrons of the scanning probe to the desired value. We want to continue this way and to measure the detection efficiency of the TC211 sensor for a higher energy of electrons. This can bring problems with an increase in the dark current due to the bombardment of the sensor by higher energy electrons as discussed in the section Experiments and Results above.

A second solution can be to replace the sensor by a low resolution thinned back-side illuminated CCD with an efficiency higher than 0.1 at energies below 5 keV. Such sensors have typically 3-phase parallel, 3-phase serial transfer architecture, so the number of clock signals needed to operate the sensor significantly increases in comparison with virtual-phase technology sensors. Along with this, the time needed to process the charge accumulated in CCD increases. It can be compensated by decreasing the resolution over the specimen. In the future, a new DSP could possibly help us reach the required resolution of 5 12 x 5 12 points. Or we can separate the clock generating and processing, thereby increasing the speed.

ACKNOWLEDGMENTS

I thank Michal Lenc from the Masaryk University in Brno for the main idea of the detector for the angle and energy-selective detection of signal electrons in very low energy scanning electron microscopy and for his continuous support during my work on this topic, and I thank Miroslav Kasal from the Institute of Scientific Instruments in Brno for supervision of my work, especially as regards, problems of electronics.

This work was carried out at the laboratories of the Institute of Scientific Instruments, Brno, Czech Republic, and was supported by an internal grant.

The work described in this paper is the kernel of the author s Ph.D. thesis at the Faculty of Electrical Engineering and Computer Sciences at the Technical University in Brno, Czech Republic.

REFERENCES

Fiebiger, J. R., and Muller, R. S. (1972). Pair-Production Energies in silicon and Germanium bombarded with low-energy electrons. ***J. Appl. Phys. 43: 3202.***

Hynecek, J. (1981). Virtual phase technology: A new approach to fabrication of large-area CCD's. ***IEEE Trans. El. Dev.***, Vol. ed-***28, No.*** 5.

Lenc, M. (1992). Immersion objective lenses in electron optics. Ph.D. Thesis, Delft University of Technology, The Netherlands.

Müllerová, I., and Lenc, M. (1992). The scanning very low energy electron microscope (SVLEEM). *Microchimica Acta* (Suppl.) 12: 173-177.

Opal, Ch. B., and Carruthers, G. R. (1989). Evaluation of large format electron bombarded virtual phase CCDs as ultraviolet imaging detector. ***SPIE Vol. 1158 Ultraviolet*** Technology ***III,*** pp. 96103.

Richard, J. C., and Vittot, M. (1992). Recent developments and applications on electron-bombarded CCDs in image intensifier tubes. *Nucl.* Instr. ***Meth. Phvs. Res.*** **A315**:368–374.

van Roosbroeck, W. (1965). Theory of the yield and Fano Factor of electron-hole pairs generated in semiconductor by high-energy particles. *Phvs.* ***Rev.*** **139**:A1702–A1716.

Stearns, D. G., and Wiedwald, J. D. (1989). Response of charge-coupled devices to direct electron bombardment. ***Rev.*** *Sci. Instrum.* **604**:1095–1 ***103.***

Texas Instruments. (1994). TC211 192- x 165-PIXEL CCD IMAGE SENSOR. ***Area Array Image Sensor Products Data Book,*** pp. 2-15.