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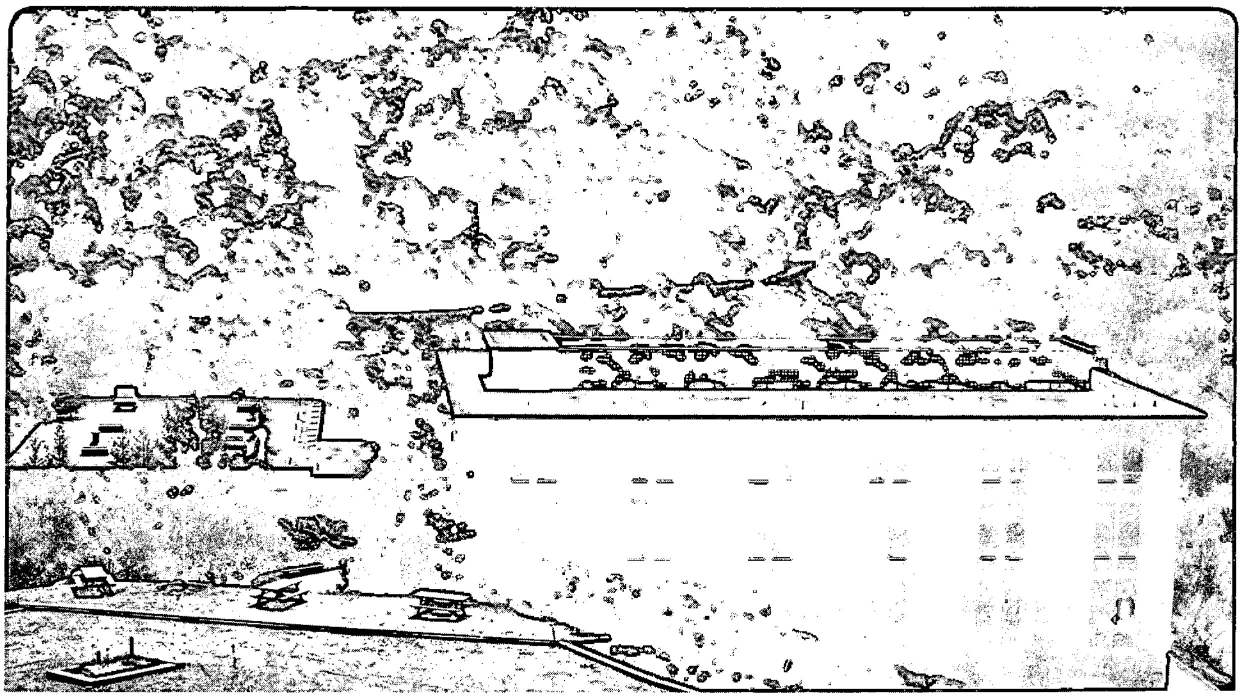
January 1994



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T. Wilhein,[1] D. Rothwieler,[2] A. Tusche,[2] F. Scholze,[3]
and W. Meyer-Ilse[4]

[1]Forschungseinrichtung Röntgenphysik
Georg-August-Universiät Göttingen
Geiststrasse 11
D-37073 Göttingen
Germany

[2]Lehrstulh fur Lasertechnik
RWTH Aachen
Steinbachstrasse 15
52074 Aachen
Germany

[3]Physikalisch Technische Bundesanstalt
Abbestrasse 10
10587 Berlin
Germany

[4]Center for X-ray Optics
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720 USA

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T. Wilhein[1], D. Rothweiler[2], A. Tusche[2], F. Scholze[3], W. Meyer-Ilse[4]

[1]Georg-August-Universität Göttingen, Forschungseinrichtung Röntgenphysik, Geiststraße 11, 37073 Göttingen, Germany

[2]Lehrstuhl für Lasertechnik, RWTH Aachen, Steinbachstraße 15, 52074 Aachen, Germany

[3]Physikalisch Technische Bundesanstalt, Abbestraße 10, 10587 Berlin, Germany

[4]Center for X-ray Optics, Lawrence Berkeley Laboratory, University of California, One Cyclotron Road, Berkeley, CA 94720, USA

1 Introduction

The selection of an image detection system for x-ray microscopy is oriented at the following criteria:

- high sensitivity combined with low system noise
- high dynamic range
- good linearity and known quantum efficiency (for radiometric measurements)
- spatial resolution and image field matched to a given x-ray microscope
- radiation hardness
- practicability (e.g. on-line data acquisition, display and processing)

Thinned, back illuminated CCD cameras promise to meet most of these requirements. We installed such a CCD camera at the Göttingen x-ray microscope, which is operating at the electron storage ring BESSY in Berlin [1]. From the first results we concluded that this thinned, back illuminated CCD seems to be an ideal detector for x-ray microscopy [2]. Subsequently we installed a similar system at the Göttingen x-ray microscope, which uses a pulsed plasma source [3,7].

2 The CCD Camera System

The CCD camera is a commercially build camera that has been mechanically adapted to the x-ray microscope. Normally the CCD sensor is covered with an antireflective coating. This coating was omitted from the CCDs used for x-ray microscopy. The CCD camera system consists of the following parts:

- Photometrics slow scan CCD camera AT200L
  Readout 16Bit ADC, 40kHz
  Peltier cooling to -45^0C
- Tektronix TK1024AB thinned, back illuminated CCD chip
  1024 x 1024 pixel, each $24\mu m$ x $24\mu m$
  full well capacity $\approx 5 \cdot 10^5 e^-$, limited to $S_{max} \approx 4 \cdot 10^5 e^-$ by ADC
- Host computer (80486) for camera controlling and data acquisition

The slow scan readout reduces the readout noise to a few electrons at the cost of an increased data acquisition time ($\approx 26s$ for 1024^2 Pixel). Cooling the CCD chip reduces the dark current.

3 Characterization of the CCD Camera

3.1 Quantum Yield

We measured the quantum yield of the CCD camera system, defined as the ratio of detected quanta (here: electrons stored in the potential well) per incident quanta (x-ray photons) using the SX-700 radiometric beamline of the PTB-lab at BESSY [4] in the photon energy range from $60eV - 800eV$. Fig. 1a represents the data.

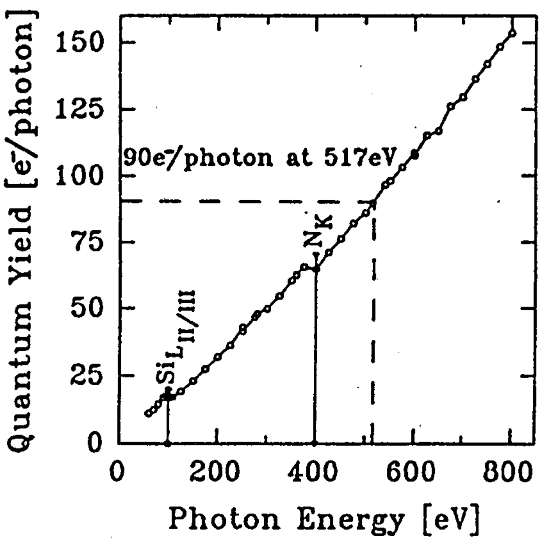

Fig.1a: Quantum yield of the thinned, back illuminated CCD. At $\lambda = 2.4nm$, the value for the QY is $90e^-/photon$

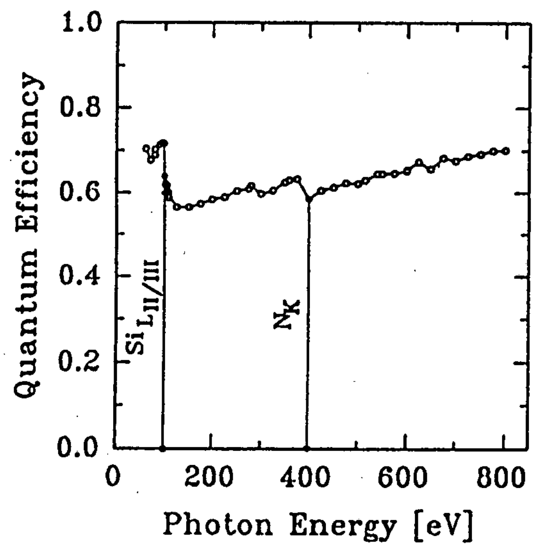

Fig.1b: Quantum efficiency of the thinned, back illuminated CCD. The $Si_{L_{II/III}}$-edge and the N_K-edge can easily be seen.

A linear function of the qantum yield can be observed, interrupted at the $Si_{L_{II/III}}$-absorption edge at $99eV$ and at the N_K-edge at $400eV$. The quantum yield is

$90e^-/photon$ at $2.4nm(517eV)$, the wavelength the Göttingen x-ray microscopes are working with. The average energy necessary for creating an electron-hole pair is $3.7eV$ [5]. The average number of electrons per photon detected in an *ideal* detector is therefore $n_{max} = h \cdot \nu / 3.7eV$. It is now useful to define an energy related quantum efficiency as the number of detected electrons per incident photon n_d divided by the maximum number n_{max}:

$$QE = \frac{n_d}{n_{max}} = \frac{n_d \cdot 3.7eV}{h \cdot \nu}$$

Fig. 1b shows the results for the quantum efficiency QE of the CCD as a function of the photon energy $h \cdot \nu$ in the range from $60eV$ to $800eV$. In this energy range, the QE is between 0.56 and 0.72. The accuracy of the measurement is $\approx$ 10%, determined mainly by the stability of the low intensity photon beam used for our measurements.

3.2 Readout Noise and Dark Current Noise

The readout noise of the CCD can be measured by acquiring a dark image with exposure time $0s$. When the exposure time of the dark image is increased to finite values, the CCD collects electrons thermally created by the dark current, giving an exposure time dependent contribution to the total signal and also to the total system noise of the CCD camera. The average dark signal itself can be measured and subtracted from the image data in order to obtain only the photon induced signal. The dark current is a function of the temperature. At -45^0C the dark current was found to be $2.9e^-/(pixel \cdot s)$. Fig. 2 represents the system noise without irradation as a function of exposure time. For integration times less then $30s$, the readout noise of $10e^-$ dominates the total noise of the CCD camera. The signal generated by one photon of $517eV$ is also indicated in fig. 2, showing that for exposure times up to $250s$ the camera noise is less than the signal from one photon. Exposure times in the Göttingen x-ray microscope are a few seconds, so that the camera noise can be neglected in this application.

3.3 Linearity and Dynamic Range

The linearity was measured at $\lambda = 2.4nm$ $(517eV)$; the CCD camera was used in its standard configuration in the x-ray microscope at BESSY without specimen. Fig. 3 shows the quantum yield as a function of the exposure in $photons/pixel$. Exposures were varied using a shutter and attenuation filters. The absolute value was taken from the measurements at the SX-700. The accuracy of the measurement is 2%, given by the slight move of the BESSY source during the measurements. From the plot the CCD response is linear within these limits until the ADC comes to saturation at an exposure of $\approx 4400 photons/pixel$. At very low exposures, the stochastic character of the photon absorption leads to an increased deviation from the mean.

According to the high quantum yield of the CCD it is convenient to define the dynamic range as the maximum detectable number of x-ray photons:

$$DR_{photon} = \frac{S_{max}}{QY} = \frac{4 \cdot 10^5 e^-}{90 e^-} = 4.4 \cdot 10^3 \qquad (\lambda = 2.4nm)$$

This is a good value for a dynamic range.

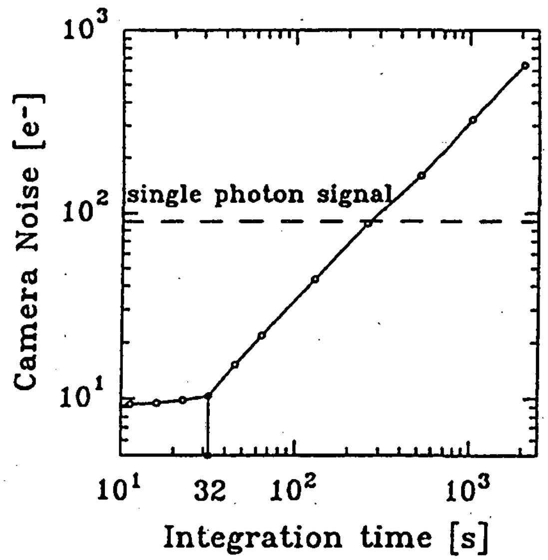

Fig.2: CCD system noise without irradiation at $T = -45^0C$.

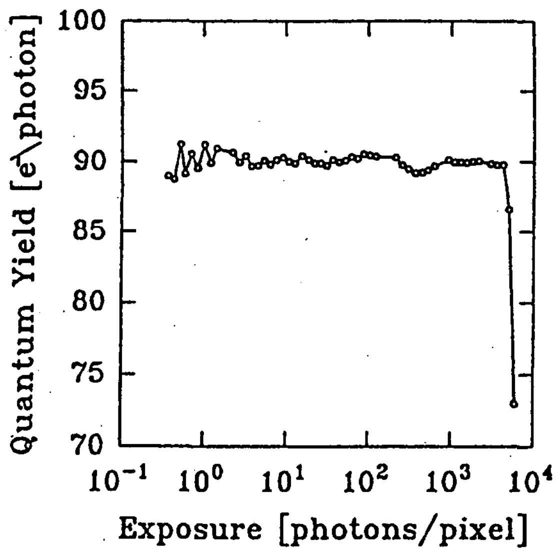

Fig.3: Linearity of the thinned, back illuminated CCD at $\lambda = 2.4nm$.

3.4 Radiation Damage

The effect of radiation damage can be observed as an increased dark current (and slightly decreased full well capacity). After $\approx$ 2400 x-ray microscope images and nearly the same amount of test images taken with the CCD operating at BESSY (the total number of absorbed x-ray photons in the CCD up to now is $\approx 10^{12}$), the dark current was found to be

$I_{du} = 2.9e^-/(pixel \cdot s)$ unexposed pixels (chip corner)
$I_{de} = 4.0e^-/(pixel \cdot s)$ after 2400 x-ray exposures (central region)

No influence of the radiation damage on the x-ray microscope images could be observed, and even if the dark noise increases further with the same rate, the CCD will be usable without a remarkable effect on the image quality for several years.

4 Conclusions

The thinned, back illuminated CCD chip in combination with a cooled slow scan CCD camera seems to be the best suited image detector for x-ray microscopy with soft x-radiation available today. It offers high sensitivity, the possibility of making radiometric measurements and the advantages of digital detection systems like on-line image acquisition, display and processing. Especially the investigation of wet biological specimen in the Göttingen x-ray microscope at BESSY [6] benefits from the advantages of the thinned, back illuminated CCD. With the Göttingen x-ray microscope with the pulsed plasma source, images exposed with only one pulse are now possible [7].

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720