Virtual phase CCD x-ray detectors

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A two-dimensional charge-coupled device (CCD) detector, based on the Texas Instruments "virtual phase" CCD, has been developed at the University of Michigan for synchrotron radiation applications. A series of performance tests were carried out at the LURE synchrotron facility, and the results show that the detector is ideally suited to measurements in dispersive absorption spectroscopy, high-resolution diffuse scattering, and small-angle scattering. The characteristics of the detector also show great promise for time-resolved experiments.

INTRODUCTION

The construction of a new generation of ultrahigh-brilliance sources, such as Argonne National Laboratory's 7 GeV Advanced Photon Source (APS) and the European Synchrotron Radiation Facility (ESRF), with undulator beams that are many orders of magnitude more intense than existing sources, will place stringent demands on detector technology. Charge-coupled devices (CCDs) are emerging as a very promising technology for x-ray detectors where large dynamic range, high spatial resolution, and fast data acquisition are called for.[1] These are among the most important requirements for experiments utilizing future sources such as APS and ESRF. In addition, CCDs possess certain desirable features that make them interesting for studies of time-dependent structural phenomena.[2] The way in which a CCD detector is read out, by a combination of parallel row transfers ($\sim 50\ \mu$s/row) and serial pixel-to-pixel transfers ($\sim 6\ \mu$s/pixel), allows for a versatility of operation that is unmatched by any other detector design. For example, two-dimensional full-frame (580×390 pixels) diffraction images can be integrated and read out in about a second. Alternately, the CCD can be used in a "streak camera" mode to record a sequence of time-resolved one-dimensional data sets on submillisecond time scales.

In this paper we describe a two-dimensional CCD x-ray detector system recently developed at the University of Michigan. The "virtual phase" architecture of the CCD chip employed by the detector offers several advantages for synchrotron radiation experiments, including low dark current, efficient front-side illumination, and radiation hardness.

I. THE VIRTUAL PHASE CCD

In an alternate approach to the standard three-phase readout method, Texas Instruments has introduced the so-called "virtual phase" CCD chip architecture.[3] The asymmetric well structure in this type of CCD is achieved by deep ion implants so that only a single level of external clocking electrodes is required. This results in higher device yields, significantly reducing the cost of manufacture. Also, this type of CCD is generally more efficient in front-side illumination because less of the incident energy is absorbed by the gate–electrode structure.

In addition to simpler readout electronics as a result of the single-phase operation, the virtual phase concept has distinct advantages relevant to its application for x-ray area detection. In particular, the buried channel implant electrodes promote low dark current and radiation hardness,[4] the latter feature being of importance when the CCD is used for direct imaging of x rays.[5]

The CCD used in the present detector is the TI4849 chip,[6] consisting of 584 rows of pixels arranged in 390 columns. Each pixel is 22.4 μm^2 with a depletion depth of 12 μm; the relatively large depletion depth is well matched to direct exposure by x rays in the energy range of 5–7 keV.

II. DETECTOR CONTROL ELECTRONICS

A detailed account of the readout and control electronics will appear in a separate publication.[7] Here we summarize the overall method of operation of the detector system. Figure 1 is a block diagram of the main components of the detector electronics, consisting of readout waveform generators, analog–digital converter (ADC), buffer memory, clock-synchronization modules, and local fast LSI-11-based microprocessor control. Global control is handled by a Microvax II computer. Each of the local control functions is supported by CAMAC modules connected by a common bus and is fully programmable.

The output from the on-chip amplifier is sent through a low-noise preamplifier, is processed in a correlated double-sampling circuit which significantly reduces noise associated with the periodic reset signal for the on-chip amplifier, then is digitized by a 12-bit ADC operating at 156 kHz. The overall gain of the system is 1000. The choice of a 12-bit ADC module is a compromise between resolution (4096 ADU) and speed; the ADC is a limiting factor in readout time for the CCD. Finally, the digitized CCD readout signal is stored in a 1 Mbyte buffer memory.

The LSI-11 microprocessor initiates fast-clear, integration, and readout operations of the CCD. The integration

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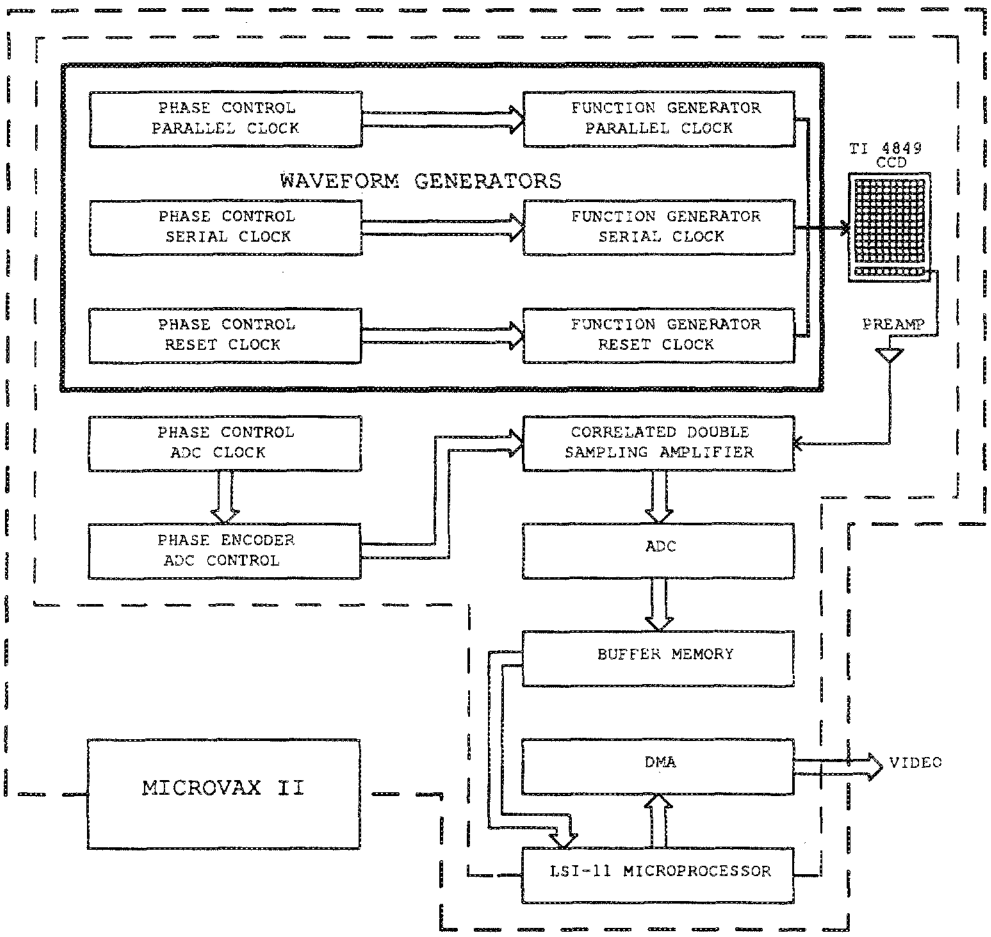

FIG. 1. Block diagram of CCD control and readout system.

time can be set on-line from a few microseconds to more than 10 s using a programmable delay-gate generator. The microprocessor is also provided with a direct memory-access (DMA) channel to a high-resolution color monitor where a pixel map of the CCD chip can be displayed. Intensity profiles through any desired row, and pulse-height histograms, are also possible using the graphics software. To be able to preview the data on-line before they are stored on disk is very important for diagnostic purposes. The question of data handling for a system that acquires data at rates in excess of 1 Mbyte s^{-1} is an important aspect of the overall detector design. The current design has addressed this issue by permitting new macro programs to be downloaded into the LSI-11 CAMAC module; every aspect of the detector control elec-

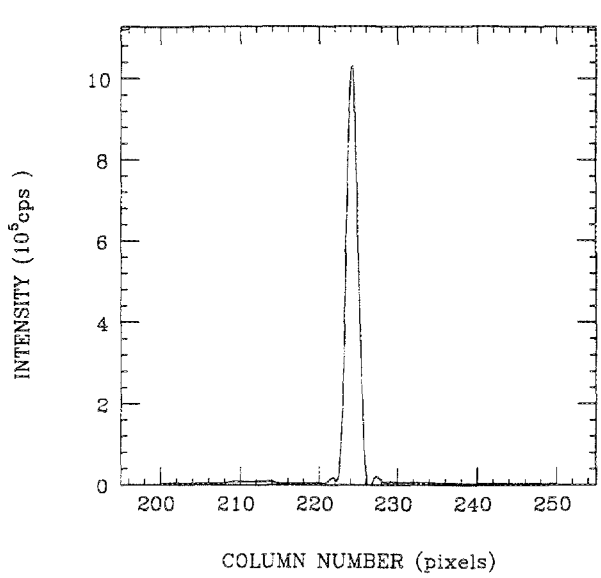

FIG. 2. CCD column readout of spatial-resolution test.

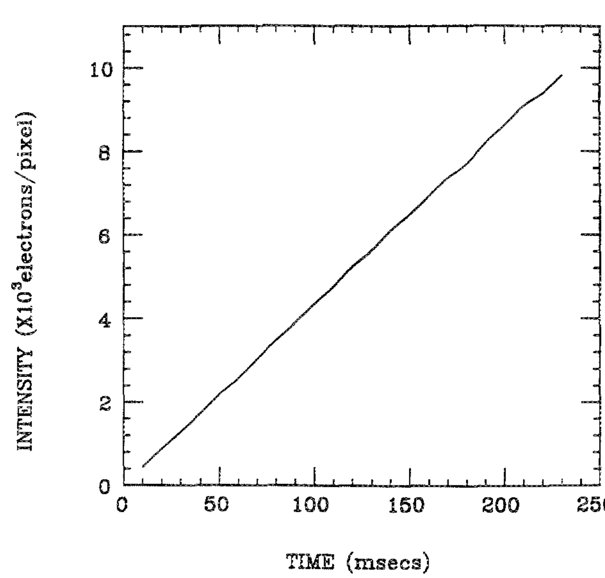

FIG. 3. Detector-linearity test using optical illumination.

TABLE I. Performance characteristics of the virtual phase CCD detector.

CCD chip	TI4849
Readout electronics	CAMAC
Frame size (pixels)	584×390
Readout noise	20 e^-/pixel
Operating temperature	−50 °C
Quantum efficiency	0.5
Charge-transfer efficiency	0.999 996
Pixel well depth	200 000e^-
Linearity (low light levels)	<0.5%
Sensitivity (with phosphor screen and lens coupling)	0.5 e^-/Xph
Spatial resolution	2 pixels
Dynamic range (with 12-bit ADC)	4×10^3
Readout time	6 μs/pixel
Row parallel transfer time	50 μs
Full frame readout	1 s

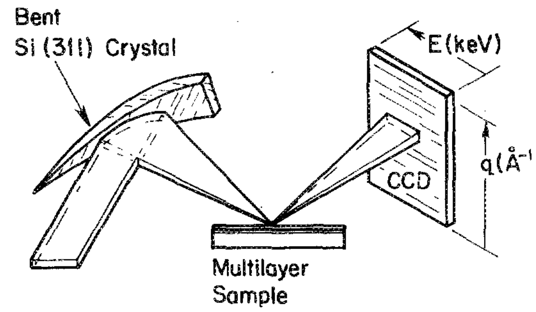

FIG. 4. X-ray optical arrangement for energy-dispersive measurements.

tronics is accessible from menu-driven routines selected from the Microvax master terminal.

III. PERFORMANCE OF THE DETECTOR

A variety of resolution and linearity tests were performed on the detector. For these tests an LED (light-emitting diode) was used as the source, triggered from the delay gate during integration mode.

Figure 2 shows a CCD image of a 150-μm-wide slit illuminated by the LED with the phosphor screen removed. The observed image size of 2 pixels (45 μm) full-width half-maximum is consistent with the expected width of 37.5 μm, given the 4:1 reduction in image size provided by a lens coupler.[7] A similar series of tests was conducted using x rays incident on a pinhole with a 40-mm-diam phosphor screen[8] in place, in order to check that there was no additional spreading of the image at the phosphor for x-ray exposures of size comparable to or larger than the thickness of the phosphor (~80 μm); no spreading of the image was observed.

The linearity of the detector at relatively modest levels of illumination (~5% of saturation) was determined by measuring the ADC output signal at different integration times ranging from 10 to 240 ms with the LED source. The results shown in Fig. 3 indicate that the system response is linear to within 0.5% over this operating range of the CCD. A summary of the detector performance parameters is given in Table I. When the detector is used in conjunction with a phosphor screen, losses in optical coupling, interface reflectivity, and absorption account for a reduction of $\sim 10^2$ in sensitivity. Deckman and Gruner[9] have discussed fiber optic tapers as a means to reduce significantly these coupling losses.

Finally, we describe some preliminary results on glancing-incidence diffraction from a Pt–carbon multilayer sample using the CCD detector to record simultaneously diffraction and near-edge absorption spectra[10] (see Fig. 4). Figure 5 shows a two-dimensional intensity map of the CCD chip revealing an $l=1$ diffraction peak together with a portion of the unscattered beam. The Pt L_{III} absorption edge (11.563 keV) is clearly visible on the energy-dispersed profile of the diffracted beam. The energy resolution in these data is ~2 eV and the wave-vector resolution is 1.5×10^{-3} Å^{-1} FWHM. A near-edge Pt L_{III} spectrum recorded using the CCD detector is shown in Fig. 6.

IV. CONCLUSIONS

We have described a CCD area detector for x-ray synchrotron radiation applications. The detector is based on the "virtual phase" CCD concept, which we find to be ideally

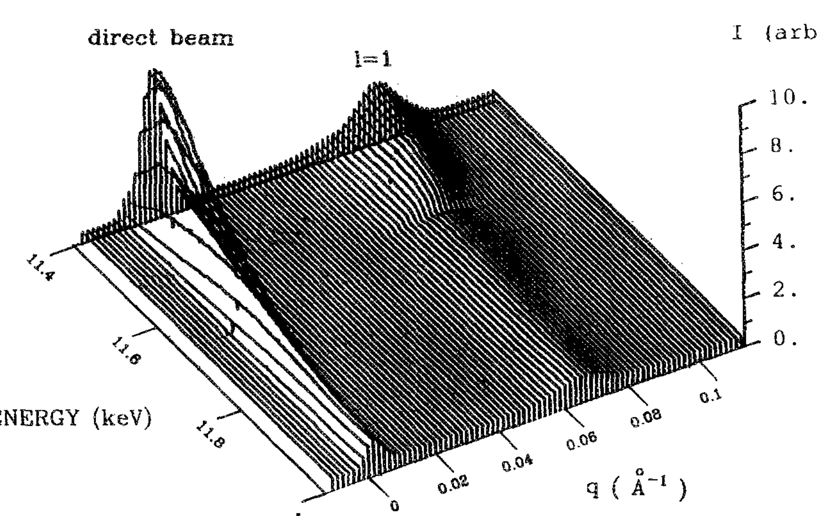

FIG. 5. CCD intensity map showing energy distribution across the Pt L_{III} absorption edge (sharp edge at ~11.6 keV on the $l=1$ diffraction peak).

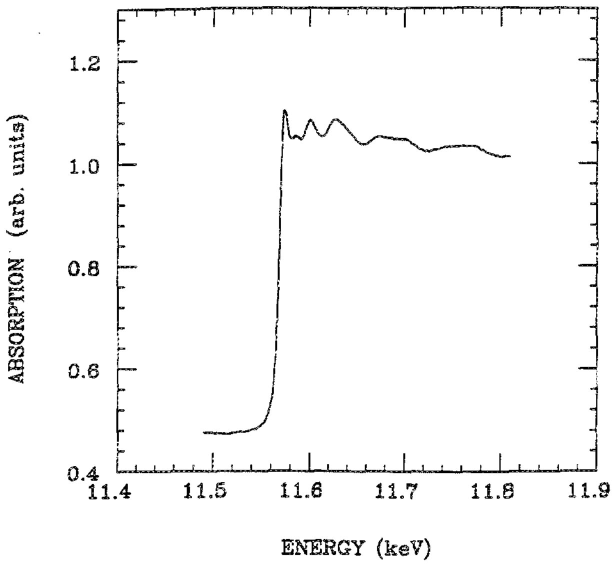

FIG. 6. Pt near-edge x-ray absorption spectrum measured using the CCD detector.

suited to experiments where large dynamic range, low noise, and fast readout are required. The detector can be used either in a direct-illumination mode or in conjunction with a phosphor screen and appropriate optical coupling. The optical coupling employed at present, a double-lens system, is found to be inefficient for many purposes and is to be replaced by a fiber optic taper.

We have demonstrated the recording of excellent high-resolution near-edge spectroscopic and diffraction data using energy-dispersive synchrotron radiation. The detector has characteristics that are attracive for time-resolved measurements, and we intend to exploit these aspects of the detector design in forthcoming experiments.

Full software control of all readout waveforms, data acquisition, and storage makes the detector easy to upgrade as new CCD chips and readout modules are introduced in this fast-developing technology.

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