A Multi-Channel Solid-State Detector

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Abstract
A five-channel solid-state detector of Si(Li) type has been made together with the necessary data-collecting system. Its characteristics and a preliminary application on the intensity measurements and on the anomalous scattering near the Ga K edge of GaP as a function of X-ray energy are described.

Introduction
A solid-state detector (SSD) is better, in energy resolution, than a scintillation counter or a proportional counter by a factor of about ten. Because of this merit, Giessen & Gordon (1968) carried out energy-dispersive diffractometry on a powder sample. This method can be carried out on a relatively simple optical system with a fixed diffraction angle. This system, called an SSD diffractometer, has rapidly become popular, particularly in diffraction under extreme conditions such as very high pressure and/or low temperature. Another feature is the feasible use of white X-rays even from an ordinary tube: thus both studies on and applications of anomalous scattering have been rapidly developed (Hosoya & Fukamachi, 1973; Fukamachi & Hosoya, 1975; Hosoya, 1975; Fukamachi, Hosoya & Okunuki, 1976a, b; Fukamachi, Hosoya, Kawamura & Okunuki, 1977, 1979; Sakamaki, Hosoya & Fukamachi, 1980a, b).

Another merit of an SSD is its high detecting efficiency over a wide range of energy. Therefore, if a one- or two-dimensional (1D or 2D) SSD is available, the versatility of the SSD becomes wider. For instance, such a position-sensitive SSD (PS-SSD) will make it feasible to carry out dynamic diffraction studies even with an X-ray tube, and more advanced experiments will be carried out by synchrotron radiation (SR). Another application may be non-diffraction uses such as highly efficient pure Ge area detectors (Gerber, Miller, Schlosser, Steidley & Deutchman, 1977; Miller, Schlosser, Deutchman, Steidley, Hunter, Gerber, Profant, Yocum & Hyland, 1979). Recently, Buras, Staun Olsen & Gerward (1980) have discussed some possible applications of a multi-element SSD.

For the use of low-energy X-rays for diffraction work, at least, it is necessary to keep the detector at liquid-N$_2$ temperature in order to realize high energy resolution. Therefore, there is severe spatial limitation and also technical difficulties in constructing a PS-SSD. That is why even a one-dimensional PS-SSD has not been manufactured for X-ray work so far.

The present paper reports on such a PS-SSD or MC (multi-channel)-SSD with five electrodes: its application for intensity measurements, including the anomalous scattering from Ga atoms in a (111) GaP crystal plate with the energy near the Ga K absorption edge, is reported. If this MC-SSD is manufactured with ca 100 channels or electrodes, then it will be used as a 1D-PS-SSD. This can be a kind of 2D detector, because the energy axis can be considered as the second dimension.

Structure of MC-SSD
The shape and size of the present MC-SSD are shown in Fig. 1. The Si disk shown in Fig. 1 is 4 mm thick and 16 mm in diameter: it has a thick region of intrinsic semiconductor with Li atoms drifted. After this drifting, the intrinsic semiconductive surface has been exposed by etching on the side of a positive electrode. Au has been evaporated as shown in Fig. 1, where the necessary dimension is shown in the figure caption.
Since the widths of both electrodes and the spaces between them are all 0.4 mm, the spatial resolution is not narrower than 0.8 mm, while the electrodes are 5 mm in length. These electrodes are attached to a cryostat (Fig. 2) to be kept at liquid-N\textsubscript{2} temperature. The cooled field-effect transistor (FET) was used at the first stage of the preamplifier and then the signal was taken from the SSD to keep the electronic noise low in the resistance feedback form.

Data-acquisition system

The present system of measurements and data processing is shown in Fig. 3, where a MC-SSD is used with the bias of -600 V supplied by the relevant circuit (NAIG, E503). This voltage is a standard value for a normal SSD; this value is neither too high to cause dark current or break down, nor too low to make the energy resolution low. Each output channel of the preamplifiers is connected to a respective linear amplifier (NAIG, E511) and then to an ADC (analog digital converter: NAIG, E551, 50 MHz, 1024 channels). The output from each ADC is divided into an interrupt signal (EOC: end of conversion) and a data bus line (converted value), and then both are connected to a small computer (AICOM C6 with 128 kbyte memory) through an interface. Therefore, its CPU receives positional information through interrupt signals, and receives energy information through a data bus line. In addition, the CPU is connected to an outside memory of floppy disks (1 Mbyte x 2), to a console (Tektronix 4006-1) with a graphic display, to a printer (Texas Instr. 810) and to an X-Y plotter (Watanabe WX4671).

Test of performance

(i) Positional resolution

In the optical system shown in Fig. 3, a slit 50 μm in width has been used for slit 2. A narrow X-ray beam ca 250 μm in width has then been obtained at the position of the MC-SSD. The white X-rays from a sealed-off tube with a Cu target have been diffracted by a single-crystal plate of Si. This narrow white X-ray beam has been changed only in the direction of a reflection, with the relative angular position between the tube and a monochromator kept constant. During this motion, the X-ray beam scans the MC-SSD from the first to the fifth electrode in steps of ca 100 μm. The results obtained by this scanning are shown in Fig. 4. Three peaks detected correspond to \( hh0 \) reflections with \( h = 2, 4 \) and 6 as shown in Fig. 4. These peaks correspond to the X-rays with about 10, 20 and 30 keV.

In Fig. 4, the peaks obtained in the third and the fifth channels are of lower intensity than the peaks in the other channels. This is mainly because the relevant channels are about 750 eV in resolution, being worse.
than other channels. Therefore, the differences in peak height do not directly correspond to the detecting efficiency, as is mentioned later.

From these data, the total number of photons for each peak of 220, 440 and 660 has been plotted in Fig. 5(a), (b) and (c). These results show the uniformity in detecting efficiency and positional resolution. The three sets of data shown in Figs. 5(a), (b) and (c) show that the third and fifth channels are a little lower in detection efficiency than the others. The main reason for this, as was shown in Fig. 4, is because the tail parts on the low-energy side of the peaks are not duly integrated because the energy resolution is worse than in the other channels. In Fig. 5, the detection efficiency fluctuates by about 5% from channel to channel.

As for the positional resolution, the following values are obtained from Fig. 5: 0.75 mm at 10 keV, 0.83 mm at 20 keV and 0.91 mm at 30 keV; i.e. the resolution has a tendency to become somewhat worse as the energy becomes higher.

(ii) Lowering of energy resolution due to X-rays falling between electrodes

The behavior of the first channel in Fig. 4 is reproduced in Fig. 6 so that the tail part on the low-energy side of the first channel can be better displayed. If the X-ray beam is perfectly inside the width of a p-type electrode, the foot part of the peak is low. However, the foot of the peak is fairly high even at the position outside the electrode. Moreover, an additional peak is found on the foot (lower-energy side) of the 220 reflection.

Fig. 7(a) shows the $hh0$ spectrum obtained by the $\theta-2\theta$ scan, where thin X-ray beams 250 $\mu$m wide may fall on the center of each electrode. Fig. 7(b) shows the result obtained with slit 2 wide enough to accommodate all beams from the first to the fifth channel, as shown in Fig. 3. This is the usual set-up of MC-SSD and gives the results where the background is high on the low-energy side in comparison with the result (a), as will be understood from Fig. 6.

Therefore, in order to obtain a good quality spectrum as shown in Fig. 7(a), it is recommended that the spaces between electrodes should be made narrow or a mask should be placed so that X-rays do not fall between electrodes in front of the MC-SSD, though this may be technically difficult. However, in the latter case, the detecting efficiency decreases, because X-rays are partly masked. In the present work, such a mask was not used.

Detection of the anomalous scattering

The diffraction spectra have been measured for the condition that the $333$ and $333$ reflections have energy near the Ga K absorption edge, by choosing a suitable
value of the Bragg angle. The polarity has been chosen so that Ga is at 0,0,0 and P at $\frac{1}{4}, \frac{1}{4}, \frac{1}{4}$. The result shown in Fig. 8 has been obtained by subtracting the fluorescence X-rays measured by the off-Bragg condition (Hosoya & Fukamachi, 1973). In the present case, the spatial intensity distribution of the X-rays incident on the sample could not be made uniform, and therefore the absolute intensities cannot be compared with each other among the channels shown in Fig. 8. However, as will be shown below, it is possible to measure qualitatively the intensity variation of the 333 and 333 reflections due to the anomalous scattering by normalizing the intensity values channel by channel. The reflections other than 333 and 333 are well away from the absorption edge, and therefore the change in the anomalous scattering is small enough in the energy range, being due to a small change in angle. Therefore these reflection intensities have been normalized for plus and minus reflections independently. The plus and minus reflections were then normalized by using the intensities of reflections with even indices, because they are to be equal to each other. The results on the intensity changes of the 333 and 333 reflections around the Ga K absorption edge are shown in Fig. 9.

Possible applications

As was shown theoretically in the paper by Herzenberg & Lau (1967), and later demonstrated by a laboratory X-ray source (Sakamaki, Hosoya & Fukamachi, 1980a), X-rays with at least three different energy values give the phase-angle values, in principle, as was demonstrated on hemimorphite. If the present MC-SSD is used, sufficient (in principle) intensity values are obtained at one time to determine phase-angle values. Naturally, more redundant measurements are desirable in general by using an SSD with more channels. Such applications are not possible if use is made of other kinds of detectors with much worse energy resolution.

The present system is also very useful because Bragg-reflected white X-rays usually include higher harmonics; they are well resolved by an SSD in most cases. Moreover, such a system will also be very effective for studies of absorption spectroscopy, Compton scattering, electron states, resonance Raman scattering, X-ray plasmon scattering, chemical shifts etc. If an SSD with more channels could be prepared, then the multi-wire proportional counter would be replaced by a MC-SSD in many fields. Thus, MC-SSD or PS-SSD will be used more widely than PS-MWPC, because the former is far better in both $s-n$ ratio and detecting efficiency and gives two-dimensional data in reciprocal space.

Conclusion and discussion

The MC-SSD reported here has only five channels. However, it is already very useful for the determi-
nation of phase-angle values. It will also be useful in related fields, such as the work by Cole & Stemple (1962), the determination of the polarity sense or the study of crystal imperfection. More recently, the present MC-SSD has been used for measuring the temperature change of the diffraction intensity near the absorption edge (Fukamachi, Kawamura, Hayakawa, Nakano & Koh, 1981).

The energy resolution of the present MC-SSD is about 600 eV for 10 keV. This value is fairly bad in comparison with the 200 eV of the usual SSD. This is not because of a problem in each Si(Li) element of the MC-SSD, but because of the characteristics of a FET amplifier. Therefore, the resolution of ca 200 eV will be attained by improving the FET.

The present SSD is a linear type with a one-dimensional electrode. In this sense, detectors described previously (Gerber et al., 1977; Miller et al., 1979) are of two-dimensional type, which are to be used as a camera with the space resolution of a few mm. In the present work, the authors are interested in crystallographic applications and, therefore, the spatial resolution should be higher. The present resolution could be made 0.8 mm, and it is possible to attain a better value, possibly several tens of μm. This may not be possible when the evaporation method is used for making electrodes. However, it is probably promising to use the ion-injection technique.

At the moment, the present authors are trying to prepare a large PS-SSD with 32 channels, an average energy resolution of 200 eV, and a positional resolution of 0.4 mm (the width of each electrode is 0.3 mm and the space between neighboring electrodes is 0.1 mm). This will be used in due course for the several kinds of above-mentioned studies.

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