structure is expected some hundreds of volts beyond the main edge. A comparative study for different directions of ejection should then be more rewarding.

It would appear that the structure for both of these ionic crystals is unaffected by the direction of photoelectron ejection within 15 volts of the main edge. No significant difference between 100 and 110 occurs for KCl throughout the entire structure range. One such difference does occur for the structure β in the Cl edge of NaCl. β is closer to the edge for 110 than 100 which, if β is caused by the same planes in each case, means that $\cos\theta_0$ is greater so that the angle with the plane is smaller. The question arises as to why there is a difference for NaCl at 18–20 volts from the edge and not for the features which are as much as 25 volts from the edge for KCl when both are ionic cubic crystals. This result implies greater symmetry of the Brillouin zones in the case of KCl. The probable explanation is that the ionic lattice for KCl contains identical numbers of scattering elements at every lattice point whereas that is not true for NaCl. Consequently KCl may be considered as a true simple cubic whereas NaCl represents an interlacing face-centered lattice network.

CONCLUSION

Pronounced structure has been observed close to the main absorption edge of chlorine using single-crystal absorbers of NaCl and KCl and polarized x-rays.

When the main direction of photoelectric ejection was changed from 100 to 110 there was a definite difference in shape and position of the feature β in NaCl. There were no significant differences for any absorption features in KCl. Thus greater symmetry of the Brillouin zones is implied for KCl, which condition may be attributed to its pure cubic structure.

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Direct Measurement of the Dielectric Constants of Silicon and Germanium

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Direct measurements of dielectric constants of silicon and germanium between 500 cps and 30 Mc/sec have been made. Small parallel-plate condensers were made from samples of these elements after doping with gold so as to produce high-resistivity material ($\rho \sim 10^7$ ohm cm for germanium at 77°K, $>10^{10}$ ohm cm for silicon). The dielectric constant of silicon (at 1 Mc/sec) was taken to be 11.7 ± 0.2, of germanium 15.8 ± 0.2. The dielectric constant of silicon is constant to ±1 percent over the range 500 cps–30 Mc/sec, whereas germanium, because of its lower resistivity, has a much greater apparent variation of dielectric constant with frequency.

RECENTLY it has been found possible to produce germanium and silicon having high resistivity (above 10^6 ohm cm) at reasonable temperatures[1,2] (77°K and above). The technique of doping with the proper amount of gold leads, in the case of germanium, to samples of resistivity at 77°K, as high as 50 meg cm; in the case of silicon, greater than 10^4 meg cm. This makes it possible to do experiments on these substances that have been difficult, either because of the high conductivity or the impracticability of doing the experiment at temperatures at which ordinary germanium and silicon would have suitably high resistivity (liquid helium or hydrogen temperatures).

A case in point is the measurement of the dielectric constants. Until recently the only available precision measurements were made at infrared frequencies. Briggs,[3] working with wavelengths of the order 1–2μ found values of index of refraction that extrapolate at zero frequency to dielectric constant values of 16.1 for germanium, 11.7 for silicon. Benedict and Shockley[4] have recently determined the dielectric constant of germanium by means of a wave guide method. Their value was 16.0 ± 0.5. An estimate of lesser precision has been recently made by Dacey.[5] He gives the value 16.0 ± 10 percent obtained by measurement of the "punch-through" voltage of a "unipolar" transistor.

Small parallel-plate condensers have been made of both silicon and germanium single crystals (some of the silicon wafers contained twin boundaries). A coating of aluminum-gallium paste was applied as electrodes. Fixed holders clamping the samples in a suitable position within a Dewar flask were used so that accurate correction for lead capacities would be obtained. Areas were calculated from the weight and thickness, using a density of 5.325 g/cm^3 for germanium at 25°C, 2.328 for silicon.[6]

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[1] W. C. Dunlap, Jr., Phys. Rev. **91**, 1282L (1953).
[2] E. A. Taft and F. H. Horn (to be published).
[3] H. B. Briggs, Phys. Rev. **77**, 287 (1950).
[4] T. S. Benedict and W. Shockley, Phys. Rev. **89**, 1152 (1953).
[5] G. C. Dacey, Phys. Rev. **90**, 759 (1953).
[6] M. E. Straumanis and E. J. Aka, J. Appl. Phys. **23**, 330 (1952).

The resistance between electrodes was sufficiently high for accurate capacity measurements to be made with ordinary precision-type capacity measuring equipment, such as the General Radio Twin-T circuit. Samples were also checked on several special laboratory equipments. Measurements were made in the frequency range 500 cps–30 Mc/sec. Generally there was an increase in apparent dielectric constant at the lower frequencies. The effect was much more pronounced for germanium than for silicon. It was also somewhat different for different samples. The effect is to be ascribed, we believe, to the inhomogeneity in resistivity that is almost unavoidable in these samples. The effects of inhomogeneity are negligible if the frequency is high enough for the capacitative admittance greatly to exceed the conductance for the most conducting region of the sample. Above this frequency, the apparent dielectric constant is found to be constant with increasing frequency. For the above reasons, dielectric constants are quoted for germanium at frequencies of 1 and 0.465 Mc/sec. For silicon the apparent dielectric constant changed, in most cases, by less than 1 percent over the entire frequency range.

Table I shows the results of measurements on a group of samples, made by a substitution method, using a parallel-connected resistance-capacity combination. A calibrated General Radio air condensor was the capacity reference. From these results the dielectric constant of germanium was taken to be 15.8 ± 0.2. The corresponding result for silicon was 11.7 ± 0.2.

The following remarks about the experimental method may be of interest.

(1) No corrections were made for edge effects, and no guard rings were used. It was felt that the dielectric constants were sufficiently high for fringing fields to affect capacity at most to the order of a few tenths of 1 percent. Detailed calculations bore out this prediction.

TABLE I. Experimental results of capacity measurements on three samples each of germanium and silicon containing traces of gold. The germanium samples were single crystalline whereas several of the silicon crystals contained a twin boundary. Measurements were made by comparison with a parallel-connected capacity-resistance combination.

Material	Sample	Area (cm^2)	Thickness cm	Freq. (Mc/sec)	Capacity ($\mu\mu$f)	d.c. Leakage (meg)	Dielectric constant
Germanium	DC-8	1.73	0.0695	1	36.31	0.25	16.0
	DC-6	1.89	0.1138	1	23.05	0.175	15.7
	DC-7	1.513	0.0475	0.465	44.98	2.0	15.8
Silicon	16	2.465	0.0696	0.465	36.88	>1000	11.68
	17	1.806	0.0539	0.465	34.09	>1000	11.76
	18	2.560	0.1181	0.465	22.43	>1000	11.70

(2) The amount of impurities present in both the silicon and germanium is so small that the dielectric constants are characteristic essentially of the pure materials. The gold content in both materials was of the order 10^{-5} percent.

(3) Since the silicon and germanium crystals were both photosensitive, measurements were made with samples in the dark. Illumination was found to have negligible effect on the dielectric constant for frequencies well below the resonant frequency of the circuit formed by leads, bridge, and capacity.

(4) The values, of course, apply strictly only at a temperature of 77°K. The error involved in their use for other temperatures is probably negligible.

The values obtained in the present work are in good agreement with others previously referred to. The data on germanium agree within experimental error with those of Benedict and Shockley and are within the expected order of agreement with Briggs' result, extrapolated to zero frequency. The value for silicon is in good agreement with Briggs' result.

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