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## Positron lifetime studies in some crystals

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**Abstract.** Positron lifetime measurements in some single crystals have been made with 0.200 ns (fwhm) prompt time resolution and  $4 \times 10^4 : 1$  peak-to-background ratio. In general, the decay spectra displayed essentially a single exponential. The intensity  $I_2$  of the long component was found to be less than or equal to 1% in practically all cases and was assigned to source sample effects. No difference in lifetime was observed between n type and p type crystals. Measurements on X ray irradiated samples do not show any change in the  $\tau_1$  lifetime values.

### 1. Introduction

Positron lifetime measurements in semiconductor crystals have been made by quite a few workers (Weisberg and Berko 1967, Fabri *et al.* 1966, Fieschi *et al.* 1968). In these crystals the decay feature is quite simple, exhibiting a very short component  $\tau_1 \sim 0.2$  to  $0.4$  ns. which occupies the major contribution of the positron decay, and a long component  $\tau_2 \sim 0.5$  to  $2.0$  ns. of very low intensity. This decay feature in crystals is very similar to that of metals. The data obtained from the angular correlation experiments (Stewart 1957, Lang and DeBenedetti 1957, Colombino *et al.* 1964, Hantojarvi and Jauko 1967) of the two 0.510 MeV annihilation gamma rays in Ge and Si crystals display an inverted parabola shape, thereby inferring that positrons decay without forming any bound state and that annihilations take place with the free electrons.

A very brief account of the different workers concerned with positron lifetime studies in crystals is worth mentioning. Weisberg and Berko (1967), using a very fast timing set up (fwhm  $\sim 0.30$  ns), observed no difference in lifetime between intrinsic and heavily n type Ge and Si crystals. In the measurement of neutron irradiated samples, Fabri *et al.* (1966) observed that both the short and the long components in Ge, Si and GaAs are sensitive to the radiation-damage or lattice defects. The later authors came to the conclusion that the short component  $\tau_1$  arises due to the positron annihilation with the valence electrons. Fieschi *et al.* (1968) assigned the origin of the low intensity component  $\tau_2$  to spurious effects. In their measurement on Ge and Si powders, very high intensity of the  $\tau_2$  component was observed: Ge  $\sim (46$  to  $66)\%$  and Si  $\sim (21$  to  $37)\%$ , and they have assigned the origin of this large abundance to unclear extrinsic processes, in spite of the fact that they took the measurements under vacuum.

The aim of this work is firstly to make systematic positron lifetime measurements in some single crystals, using an extremely fast timing set-up, thereby resolving the discrepancies between the different lifetime results observed by various workers, and secondly to discover the origin of the weak  $\tau_2$  component and whether or not it is a true effect of positron decay in a pure crystal.

### 2. Experimental technique

Positron lifetime measurements were made by the conventional two-detector arrangement using a time-to-amplitude converter and a multichannel analyzer.

Two (1 in  $\times$  1 in) pilot B phosphors with XP 1021 photomultipliers have been used. An energy compensator and a differential time-to-amplitude converter have been employed in the timing set up. The lifetime measurements were made with the system having a prompt resolution of approximately 200 ps (fwhm) with slopes of approximately 35 ps. The prompt resolution curve was obtained with a  $^{60}\text{Co}$  source using the same settings of the energy windows as with  $^{22}\text{Na}$  source. Details of the performance of the complete timing set up have recently been published (Sen and Patro 1970).

A very highly diluted positron source  $^{22}\text{Na}$ , deposited and sandwiched between two 0.1 mil thick nickel foils, was used in these studies. While making the weak positron source, use of insulin, which might contribute to the weak  $\tau_2$  component, was avoided. Under typical experimental conditions the peak-to-background ratio was  $4 \times 10^4 : 1$ . This peak-to-background ratio is better by a factor of 4 than that of Weisberg and Berko (1967).

All the samples on which positron lifetime measurements were made were single crystals of high purity. The lifetimes were obtained by a standard least-squares-fit method and the intensity of the long component  $\tau_2$  was obtained by using the method of Green and Bell (1957). The long component  $\tau_2$  was subtracted from the total curve to get the shorter  $\tau_1$  component.

### 3. Results and discussions

Positron lifetime measurements were made on the following samples: Si n type, 5.8  $\Omega$  cm resistivity, and Si p type, 5.6  $\Omega$  cm resistivity (single crystals from Dow Corning Corp. Michigan), Ge p type, 20  $\Omega$  cm resistivity (single crystal from General Diode Corp. Mass.), anthracene (single crystal from Isomet Corp., N.J.), diphenyl acetylene (single crystal from National Radiac, N.J.) and CsI (Tl) (single crystal from Harshaw, USA).

The results of the time distribution measurements on the above samples have been collected in table 1. In general, the time distribution spectra display a short

**Table 1. The results of lifetime measurements on single-crystal samples**

Samples	$\tau_1$ (ns)	$\tau_2$ (ns)	$I_2$ (%)
Si n type	$0.210 \pm 0.005$	$0.75 \pm 0.10$	$0.7 \pm 0.3$
Si p type	$0.210 \pm 0.005$	$1.14 \pm 0.23$	$0.6 \pm 0.4$
Ge p type	$0.220 \pm 0.004$	$0.84 \pm 0.07$	$0.7 \pm 0.2$
Anthracene	$0.250 \pm 0.005$	$0.79 \pm 0.16$	$0.7 \pm 0.3$
Diphenyl acetylene	$0.300 \pm 0.006$	$0.93 \pm 0.10$	$4.7 \pm 1.1$
CsI(Tl)	$0.260 \pm 0.006$	$0.98 \pm 0.18$	$0.7 \pm 0.3$
CsI(Tl), X ray irradiated	$0.260 \pm 0.006$	$1.20 \pm 0.20$	$0.5 \pm 0.4$

component (major contribution from positron decay) and a long component of quite low intensity ( $\leq 1\%$ ), excepting the case of diphenyl acetylene. Typical lifetime distribution spectra in two cases are shown in figure 1 (for Ge) and figure 2 (for diphenyl acetylene). Figure 1 also contains the prompt spectrum taken with  $^{60}\text{Co}$  gamma rays without disturbing the side channel settings.

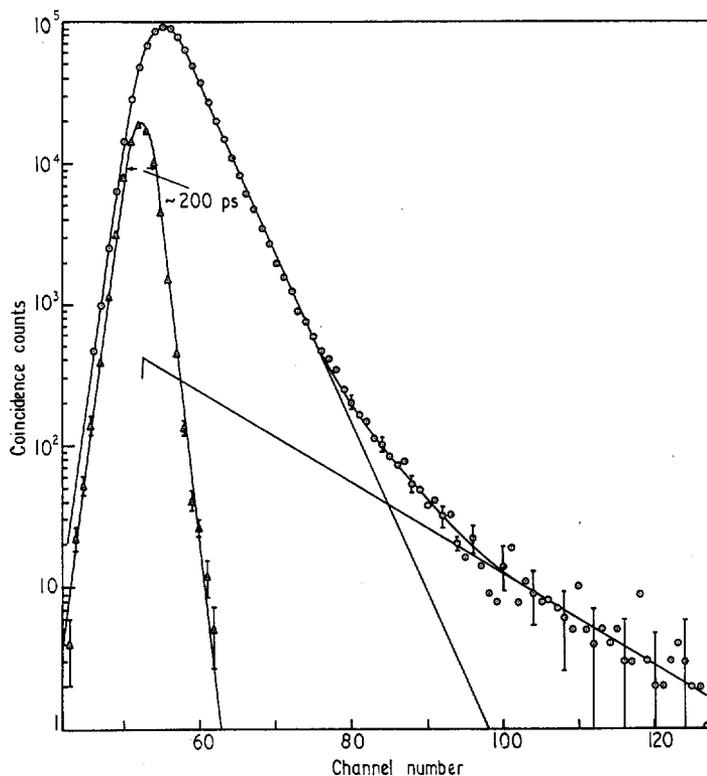


Figure 1. Time distribution spectrum obtained with Ge crystal sample ( $\odot$ ). The prompt curve is taken with a  $^{60}\text{Co}$  source ( $\triangle$ ). 1 channel =  $0.59 \times 10^{-10}$  s.

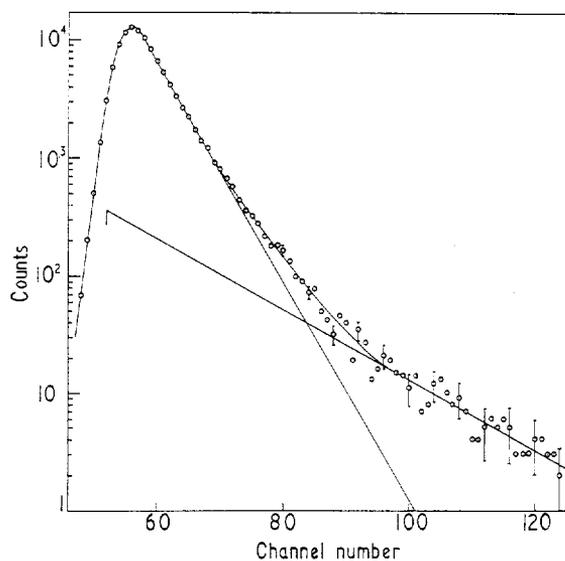


Figure 2. Time distribution spectrum obtained with diphenyl acetylene crystal sample. 1 channel =  $0.66 \times 10^{-10}$  s.

Considering first the  $\tau_2$  component and leaving aside the case of diphenyl acetylene—which we shall take up at a later stage—it is clear that, with such a good peak-to-background ratio as 40 000 : 1, and a high-order resolution set-up, the observance of  $I_2 \leq 1\%$  in all the crystals leads to the possibility that the  $\tau_2$  component might be purely a source sample component and not one from any kind of bound state formation, and therefore suggests that the previous attempts at finding any correlation between this long component and any other parameter of the crystal were not justified.

The case of diphenyl acetylene is quite anomalous compared with other crystals. No data are available for comparison purposes. The only thing that can be said about this sample, giving  $I_2 \sim 5\%$  (figure 2), is that there might be some kind of bound-state formation of an unknown nature.

Now, coming to the short component  $\tau_1$ , the values given in table 1 for Si and Ge are quite close to the values already available from the literature. Since there is no difference in the values obtained for n type Si and p type Si it is probable that doping has little effect on the positron decay mode and, since doping decides the conduction electron concentration, it follows that positron annihilation does not take place with the conduction electrons but with the valence electrons—confirming the observations of the previous workers. The value of  $\tau_1 \sim 0.250 \pm 0.005$  ns in anthracene is quite close to that of Hatcher *et al.* (1958)— $0.23 \pm 0.04$  ns—but lower than that of Cottini *et al.* (1960)— $0.37 \pm 0.02$  ns. This last value should not be taken very seriously since the data were obtained with a poor-resolution set-up. The case of diphenyl acetylene is again different in showing a high  $\tau_1$  ( $\sim 0.300 \pm 0.006$  ns).

No difference was observed between the data of irradiated and non-irradiated samples of CsI(Tl) crystal. The irradiation was made by 23 krad X rays for about 40 min. The fact that there was no difference in the  $\tau_1$  values of  $0.260 \pm 0.006$  ns for the two samples is quite similar to the observation of Cottini *et al.* (1960), within errors, on the non-irradiated and irradiated anthracene sample. Therefore the supposition of Fabri *et al.* (1966), based on their data on neutron-damaged samples, that the short component  $\tau_1$  does not come only from free annihilations, is doubtful. However, the damage introduced by X rays and neutrons may be different.

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