Positron absorption in silicon

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A mass absorption coefficient $\mu^+ = 39$ cm^2/g has been found through measurements of the penetration profile of positrons from a Na^{22} source in a single-crystal silicon absorber of finite thickness. No anomalous transmission of positrons in the silicon was observed.

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Most of the fast positrons which enter matter annihilate after they reach epithermal energies.[1] Since the diffusion length of positrons is relatively short,[2] a penetration profile of positrons in a bulk sample can be found by measuring the dependence of the number of annihilation events in a thin layer on the distance from this layer to the surface. Brandt and Paulin[3] have measured these profiles and have found the absorption coefficients for positrons from a Cu^{64} source in a wide range of materials. Corresponding studies for sources with a different β^+ spectral boundary have confirmed[4] that dependence of the absorption coefficient on the atomic number of the particular element which had been observed previously by a positron transmission method.[5,6] Mourino *et al.*[4] showed that a more suitable parameter of the positron spectrum than the spectral boundary $E_{\max}$ is a certain average energy $\bar{E}$, which depends, in particular, on the source substrate material.

Dekhtyar *et al.*[7,9] have reported annihilation experiments and have interpreted the results as a consequence of an anomalous transmission of Na^{22} positrons through single-crystal silicon wafers. In Ref. 7, for example, it was reported that the positron flux measured behind a wafer with a thickness of a few hundred microns is almost an order of magnitude higher than the value calculated from the absorption coefficients found in Refs. 3 and 4. Furthermore, the positron absorption coefficient in silicon found indirectly in Ref. 8 turns out to be roughly half the values given in Refs. 3 and 4. In Ref. 9, Dekhtyar *et al.* analyzed measurements of the positron flux density detected behind silicon wafers of various thicknesses. These results proved inconsistent with the conventional exponential law for positron transmission, although these investigators had used this law to analyze data in a previous study.[8]

Under the circumstances, we felt it was worthwhile to measure the penetration profile of Na^{22} positrons in single-crystal silicon wafers of finite thickness.

The penetration profile was measured by a method similar to that of Refs. 3 and 4. The experimental apparatus is shown in Fig. 1. The thickness of the shielding and of the collimator walls is chosen to keep the random-coincidence count rate well below the background level. The background coincidence count rate (measured in the absence of a sample) was less than 1% of the maximum count rate corresponding to the coincidences of annihilation γ rays. The time resolution of the coincidence

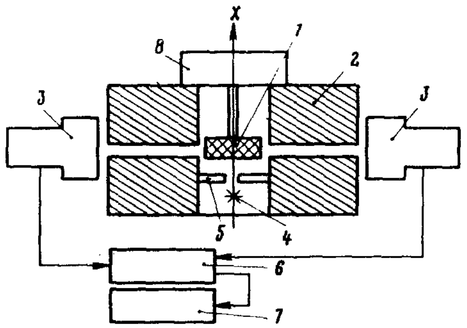

FIG. 1. Apparatus used to measure the positron penetration profiles. 1–Sample; 2–lead collimator; 3–scintillation detectors; 4–positron source; 5–beam diaphragm;; 6–coincidence circuit; 7–scaler; 8–sample manipulator.

circuit was ~150 ns. We used plane-parallel collimators with slit widths of 25, 50, and 100 μm. The sample was a dislocation-free single cyrstal of p-type silicon. A wafer of square cross section with a side of 2 cm and a thickness of 400μm was cut out parallel to the (111) face. The surface layer with the structural damage resulting from the mechanical processing was removed with a chemical etchant and polish.

Points 1 in Fig. 2 show the experimental positron penetration profile obtained with a collimating-slit width of 50 μm. These results are actually the dependence of the count rate of coincidences corresponding to annihilation γ rays, $N(x)$, on the positron of the sample with respect to the (fixed) collimators. The absorption law is seen to be exponential over nearly the entire thickness of the sample. The more rapid decrease in $N(x)$ near X_{S2} corresponds to the rear surface of the sample (as seen from the positron source). The increase in $N(x)$ near X_{S1} becomes faster as the width of the collimating slits is reduced.

By analogy with Refs. 3 and 4, we can approximate the experimental profile

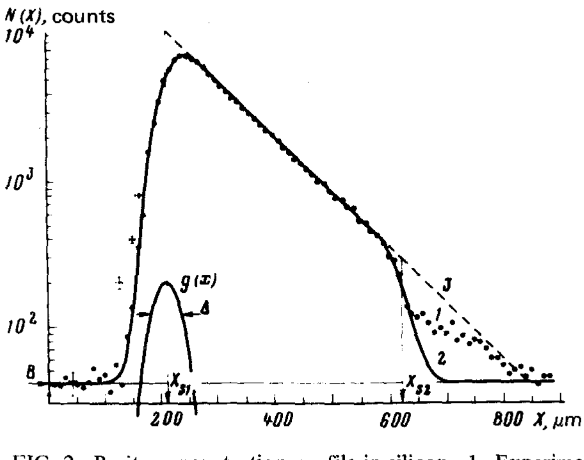

FIG. 2. Positron penetration profile in silicon. 1–Experimental profile for a slit width of 50 μm; 2–fitting curve [Eq. (3)]; 3–asymptotic extrapolation of the data with a slope $a^+ = 91$ cm^{-1}; $g(x)$–resolution function; B–background level; X_{S_1} –coordinate of the sample's front surface (the surface nearer the positron source); X_{S2}–coordinate of the sample's rear surface.

$N(x)$ for a sample of finite thickness by a convolution of an exponential function with the resolution function $g(x' - x)$:

$$N(x) = B + C \int_{X_{S1}}^{X_{S2}} e^{-a^+ x'} g(x' - x)\, dx', \quad (1)$$

where a^+ is the linear positron absorption coefficient, B is the background, and C is a constant.

If we adopt a Gaussian curve for the resolution function,

$$g(x' - x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x' - x)^2/2\sigma^2}, \quad (2)$$

the result of the convolution in (1) is

$$N(x) = B + C e^{-a^+ x} \left[\Phi\left(\frac{x - X_{S1}}{\sigma} - a^+\sigma\right) - \Phi\left(\frac{x - X_{S2}}{\sigma} - a^+\sigma\right) \right], \quad (3)$$

where $\Phi(z) = 1/\sqrt{2\pi} \int_0^z e^{-t^2/2} dt$ is the probability integral, $2\sigma = \Delta$, and Δ is the slit width.

Solid curve 2 in Fig. 2, which was calculated from Eq. (3), is the result of convolution (1) for $a^+ = 91$ cm^{-1} and $B = 40$ (at the maximum there were more than 8000 counts). There is a good agreement between calculation and experiment over nearly the entire range of x studied. At $x > X_{S2}$, the experimental points lie above the calculated curve; this effect represents a contribution of positrons which annihilate in the sample holder.

The position indicated in Fig. 2 for the front surface of the sample, X_{S1}, was determined through the natural assumption that the area under the experimental curve (after subtraction of the background) would be the same as that under the extrapolation of this experimental curve to an "ideal" geometric resolution (the triangular figure, 3, in Fig. 2). The difference $X_{S2} - X_{S1}$ agrees well with the wafer thickness. We believe that this method for determining the position of the front surface of the sample is better than the methods described in Refs. 3 and 4.

Measurements of the penetration profile for collimator slit widths of 25, 50, and 100 μm yield the following values of a^+: 91.5 ± 1, 91.0 ± 0.7, and 93.3 ± 0.6 cm^{-1}. The values of a^+ agree well for the two narrowest slits; the slight increase in a^+ for the widest slit is attributed to the limited applicability in the region $\Delta < 1/a^+ < |X_{S2} - X_{S1}|$ of the approximation which we used above. Adopting $a^+ = 91$ cm^{-1}, we find a mass absorption coefficient $\mu^+ = a^+/p = 39$ cm^2/g. This value agrees with the results of earlier measurements by both the transmission method and the profile-measurement method. Our measurements thus do not reveal the anomalous transmission of positrons through single-crystal silicon wafers which was reported by Dekhtyar *et al.* Furthermore, the experimental points reported in their most recent paper[9] demonstrate a constant "background" which may be caused, for example, by the scattering of positrons by edges of the sample. When we correct the data of Ref. 9 for this "background," we find the usual exponential dependence of the transmission coefficient on the thickness of the sample, which leads to a normal positron absorption coefficient in silicon.

We conclude that at present there is no adequate justification for discussing mechanisms for the anomalous positron transmission reported in Refs. 7 and 9-11.

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