Observation of Radiation from Channeled Positrons

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(Received 7 February 1979)

Radiation from 56-MeV positrons ($\gamma = 111$) channeled between the major planes or along the $\langle 110 \rangle$ axis of an 18-μm-thick silicon crystal has been observed. The energies of the measured planar-channeling spectral peaks agree well with theoretical predictions.

Relativistic charged particles channeled in a crystal have a periodicity to their motion which should result in the emission of forward-directed electromagnetic radiation of relatively narrow linewidth. We report, for the first time, the observation of the emission of such channeling radiation. The observed spectral peaks, in the energy range of 30 to 50 keV, correspond well to those predicted for channeling of 56-MeV positrons along (110), (111), and (100) planes in a silicon crystal.

The properties of channeled charged particles have received considerable theoretical and experimental consideration in the literature.[1,2] Building upon this earlier work, predictions have been made, using both classical and quantum-mechanical viewpoints, which describe the expected radiation from these particles.[3-7] Until now there have not been any experimental observations of any of these effects, although it is likely that the low-energy enhancement of the bremsstrahlung spectrum observed by Walker, Berman, and Bloom[8] is attributable, at least in part, to channeling radiation.

The radiation from planar-channeled positrons is predicted[5-7] to arise from transitions between states bound in a symmetric planar potential.[2] In the classical harmonic approximation[5] the transition frequency $\omega_0 = (k_0/m_0)^{1/2}$ is determined by the force constant k_0 of the planar potential and the rest mass m_0. Since $m = \gamma m_0$, the frequency in the laboratory frame $\omega_{\rm lab} = \omega_0 \gamma^{-1/2}$ and the emitted radiation is Doppler shifted to give a maximum frequency (in the forward direction) $\omega_{\max} \simeq 2\gamma^{3/2}\omega_0$. This means that the photon energy can be varied by changing the incident-particle energy. The resultant radiation is predicted to be highly directional (half-angle $= 1/\gamma$); linearly polarized; and considerably more intense than ordinary bremsstrahlung on a per-unit-solid-angle, per-unit-frequency-interval basis. For 50-MeV positrons channeled in (110) silicon, the expected enhancement over bremsstrahlung is a factor of 14 for a beam divergence of 1 mrad [full width at half maximum (FWHM)]. [The capture angle for planar channeling under these conditions is $\simeq 1.3$ mrad (FWHM).[7]]

The positron beam for the present experiment was produced at the Lawrence Livermore Laboratory Electron-Positron Linear Accelerator Facility.[8,9] The positrons were energy analyzed to $\delta p/p = 0.01$, transported to the experimental area, and allowed to impinge on a thin (18-μm, measured by the α-particle energy-loss technique) single crystal of silicon, cut parallel to a (110) plane. A 56-MeV ($\gamma = 111$) positron beam was focused to achieve a beam divergence at the crystal of approximately 3 mrad (vertical) by 9 mrad (horizontal). After passing through the crystal the beam was swept 90° by a magnet into a dump hole.

In order to align the silicon crystal, a 0.5-cm-diam plastic-scintillator detector was placed 5.5 m downstream from the crystal. With the sweeping magnet turned off and degaussed, the intensity of the transmitted positron beam was observed with this detector while the crystal, which was mounted on a two-axis goniometer, was scanned through various spatial orientations in 0.32-mrad steps (see Ref. 8). Figure 1 shows the transmitted-positron counting rate as a function of crystal orientation; each peak in this figure results from a planar-channeling condition. Several such scans resulted in a map of the crystal and enabled precise alignment of the crystal with respect to the positron beam direction.

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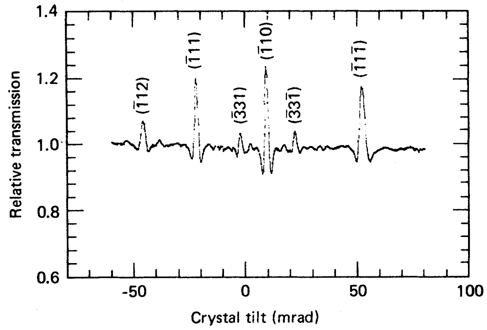

FIG. 1. Forward positron transmission as a function of crystal orientation about the horizontal goniometer axis. The orientation about the orthogonal axis was fixed at 47.4 mrad from the ⟨110⟩ axis for this scan.

An instrinsic-germanium photon detector (9 mm^2 by 7 mm thick), mounted on a two-dimensional positioner, was placed 8 m downstream from the silicon crystal in order to measure the forward-directed radiation (with the sweeping magnet energized). Its location was fixed by maximizing the integrated photon-beam intensity when the ⟨110⟩ axis of the silicon crystal was aligned along the positron-beam direction. The field of view of the silicon crystal seen by the detector was limited to a circle $\simeq 4$ mm in diameter by a copper collimator 2 m downstream from the crystal. The combined angular acceptance of the detector plus collimator was 1.6 mrad FWHM. The energy resolution of the combined detector and electronics was measured with the 60-keV ^{241}Am line to be 2 keV FWHM.

Figure 2 shows the measured photon spectra for a variety of crystal orientations. A spectrum for the "random" direction, illustrated in Fig. 2(a), was obtained by summing the nearly identical spectra taken at several different orientations away from major channeling planes. Figures 2(b), 2(c), and 2(d) show the spectra observed from crystal orientations maximizing (110), (111), and (110) planar channeling, respectively. The spectral peaks in the range 30–50 keV in Figs. 2(b)–2(d) are the channeling radiation. Figure 2(e) shows the spectrum observed with the positron beam parallel to the ⟨110⟩ axis.

Figure 3 shows the ratio of each channeling spectrum to a smoothed representation of the "random" spectrum, with the spectra first normalized to equal positron-beam flux. For the planar cases [Figs. 3(a)–3(c)] this normalization is known to $\simeq 3\%$, while in the axial case [Fig. 3(d)] the vertical scale is somewhat uncertain

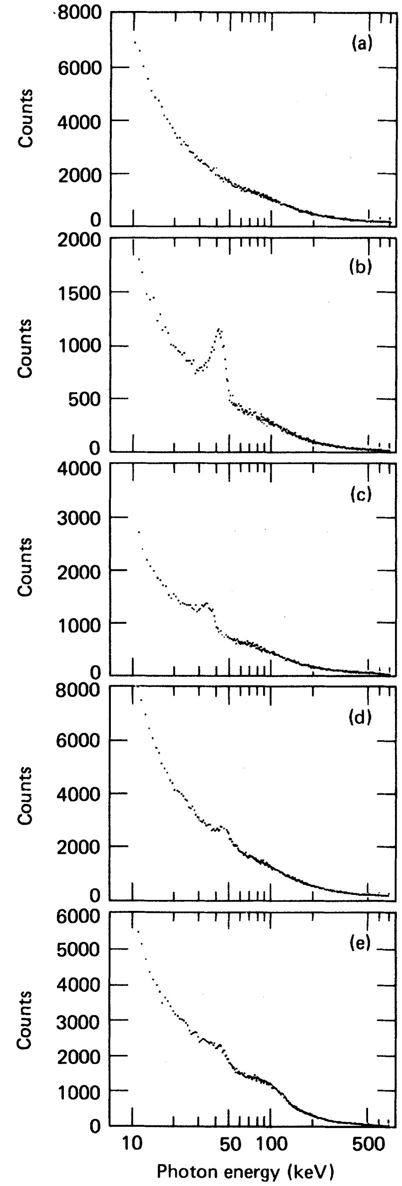

FIG. 2. Photon spectra measured with the germanium detector for the following crystal orientations: (a) "random" orientation, as described in the text; (b) (110) planar channeling; (c) (110) planar channeling; (d) (100) planar channeling; (e) ⟨110⟩ axial channeling. The ADC (analog-to-digital converter) channel width is 0.785 keV/channel. Channels 13–128 (10–100 keV) are plotted directly, while 2-, 4-, and 8- point averages are plotted for channels 129–256, 257–512, and 513–896, respectively.

since it was necessary to reduce the positron beam intensity (possibly affecting beam optics) before taking data. (From the earlier Livermore work of Walker, Berman, and Bloom,[8] we expect that the ratio plotted in Fig. 3(d) should decrease

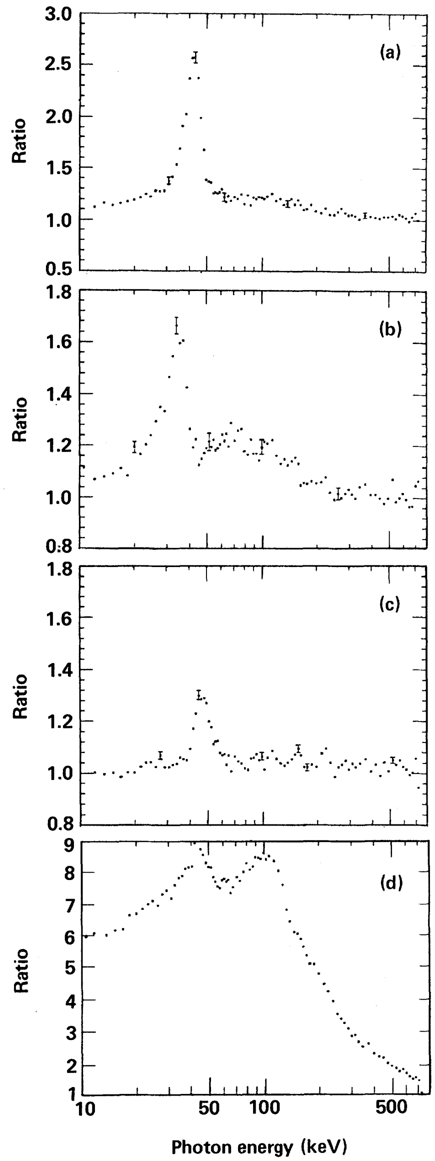

FIG. 3. Ratios of the channeling spectra of Fig. 2 to a smoothed version of the "random" spectrum: (a) (110) planar/random; (b) (111) planar/random; (c) (100) planar/random; (d) ⟨110⟩ axial/random. The use of a logarithmatic energy scale here distorts the line shape somewhat, as does the ratio method of data reduction. However, the skewed line shapes for the (110) and (111) cases are not an artifact of this procedure.

monotonically to a value of 1 if extended to somewhat higher energy.) These ratios bring the channeling radiation into sharp relief and are insensitive to uncertainties in normalization of the separate spectra. Table I gives a comparison of the energies of the peaks in the photon spectra of Fig. 3 with the range of frequencies calculated

TABLE I. Spectral features of channeling radiation.

Plane	γ	E_γ(calc)[a] (keV)	E_γ(expt) (keV)	Linewidth (%)
(110)	99	33–38	36.5 ± 1.0	$\simeq 20$
(110)	111	38–44	42.5 ± 0.5	24
(111)	111	29–35	35.3 ± 0.5	26
(100)	111	46–51	46.7 ± 0.5	18

[a]See Ref. 7.

from an anharmonic-oscillator model based upon a planar-averaged static Moliere potential. It is seen from Table I that the measured peaks lie within the calculated ranges.

Table I also gives the measured linewidths. The calculated linewidth for (110) planar channeling for a beam divergence of 1 mrad is 13%.[7] Both the skewed line shape and the somewhat larger linewidth for (110) and (111) planar channeling (see Fig. 3) probably result from Doppler broadening caused by the relatively large [$\simeq 7$ mrad (FWHM)] beam divergence parallel to these planes. The beam divergence parallel to the (100) plane was $\simeq 4$ mrad (FWHM), which accounts for both the narrower linewidth and the more symmetric line shape for this case.

An additional measurement of (110) planar-channeling radiation made at a positron energy of 50 MeV ($\gamma = 99$) verified the $\gamma^{3/2}$ photon-energy variation predicted by the model. The ratio of measured peak photon energies is 1.16 ± 0.03, in agreement with the predicted ratio of 1.19.

For the measured beam divergence perpendicular to the (110) plane [$\simeq 4$ mrad (FWHM)] and a 24% linewidth, the calculated enhancement of (110) planar-channeling radiation over bremsstrahlung[7] is in the ratio of 3.7 to 1, whereas the measured enhancement is in the ratio of 1.5 to 1. Factors which could contribute to this discrepency are (a) dechanneling, which would result in more bremsstrahlung relative to channeling radiation, and (b) surface effects, which might reduce the initial channeling fraction.

For the case of ⟨110⟩ axial channeling, shown in Figs. 2(e) and 3(d), a feature can be seen in the energy range where planar-channeling radiation was observed. This feature probably results from positrons which were scattered out of the axial channel and into the planar channels. Additional theoretical and experimental work is needed to understand other aspects of the axial spectrum and in particular the broad enhancement that appears in the vicinity of 100 keV.

We gratefully acknowledge the efforts of Phil Barth and Jacques Beaudouin of the Stanford Integrated Circuits Laboratory in the preparation of thin crystals and the support of the technical staff of the Lawrence Livermore Laboratory Linear Accelerator Laboratory. This work was supported by the U. S. Department of Energy under Contracts No. EY-76-S-0326, No. W-7405-ENG-48, and No. W-7405-ENG-26.

[1]D. S. Gemmell, Rev. Mod. Phys. 46, 129 (1974), and references therein.

[2]S. Datz, B. R. Appleton, and C. D. Moak, in *Channeling*, edited by D. V. Morgan (Wiley, New York, 1973).

[3]A. A. Vorobiev, V. V. Kaplin, and S. A. Vorobiev, Nucl. Instrum. Methods 127, 265 (1975).

[4]R. W. Terhune and R. H. Pantell, Appl. Phys. Lett. 30, 265 (1977).

[5]M. A. Kumakhov, Phys. Status Solidi (b) 84, 41 (1977).

[6]M. A. Kumakhov and R. Wedell, Phys. Status Solidi (b) 84, 581 (1977).

[7]R. H. Pantell and M. J. Alguard, J. Appl. Phys. 50, 798 (1979).

[8]R. L. Walker, B. L. Berman, and S. D. Bloom, Phys. Rev. A 11, 736 (1975).

[9]B. L. Berman and S. C. Fultz, Lawrence Livermore Laboratory Report No. UCRL-75383, 1974 (unpublished).

Structure of Amorphous $(\mathrm{Ge,Si})_{1-x}Y_x$ Alloys

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(Received 25 January 1979)

I propose kinetically determined topological models of lightly doped ($x \lesssim 0.05$) amorphous $(\mathrm{Ge,Si})_{1-x}Y_x$ alloys (Y = H, F, B, P, ...). Without adjustable parameters the model relates the lowest concentration x_H^0 of hydrogen atoms required to quench paramagnetic dangling bonds to the concentration c_0 of unpaired spins at $x=0$. Also discussed are the structural differences between freshly evaporated a-(Ge, Si) and various stages of ion-bombarded ("amorphized") crystalline material.

In the absence of definitive structural characterization by three-dimensional diffraction data, the most popular structural model for a-(Ge, Si) has been the infinite continuous covalent network with coordination number $N_\mathrm{cn}=4$. However, I have recently shown[1] that such networks, characterized by valence force field interactions, are strain free only for $\bar{N}_\mathrm{cn} \lesssim 6^{1/2}$, and that with $N_\mathrm{cn}=4$ in order to be strain free such a network would have to be embedded in an $N_d = 8$ (eight-dimensional) space. In the past it has been assumed that large excess strain energy (which renders the material amorphous rather than glassy) is accommodated entirely locally by equally admixing a fraction γ of five- and seven-membered rings into the six-membered rings of the crystal.[2] The present model assumes that such diversification of the ring population exists but is insufficient to prevent the accumulation of strain energy of order $\alpha\gamma^2\lambda^2$, where α is a bond-stretching force constant such that bonds are broken intrinsically at characteristic spacings λ of order 20–40 Å. In the present topological model, I do not calculate γ or λ from known interatomic forces and bond-breaking energies. However, I do obtain new relations between defect densities and I do predict novel kinetic effects in a material which is initially crystalline and is disordered systematically by ion bombardment.

Convincing evidence that internal surfaces exist and are intrinsic to a-(Ge, Si) has appeared slowly.[3-7] To describe this evidence I adopt the following conventions. A broken bond is one which can be saturated by a monovalent element Y_1 = H or F; the concentration of such bonds is $x = x_\mathrm{H} + x_\mathrm{F}$, and an atom with one (two) broken bonds is represented by Si* (Si**). The minimal concentrations in a fully disordered sample of surface, edge, and kink sites are represented, respectively, by x_s, x_e, and x_k. The contamination-free concentration of paramagnetic dangling bonds in similar samples is denoted by c_0 and its accepted value[3,4] is $c_0 = (1 \pm 0.5)\times 10^{-3}$. The minimal concentration of hydrogen required to quench these spins is denoted by x_H^0. Ordinarily heavy hydro-

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