STABILITY OF THIN SILICON TARGETS EXPOSED TO A HIGH-FLUX BEAM OF RELATIVISTIC ELECTRONS

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In the study of the penetration of relativistic electrons through a silicon single crystal it was first observed that the orientation effect is affected by target heating. This is due to nonuniform thermal expansion and resultant stresses which increase with the electron current and cause the crystal to lose its flat shape. We propose a simple model which describes well the measurement results. This establishes a limit for the current in orientation-effect applications.

We investigated the penetration of relativistic electrons through single silicon crystals, using 64 mm disks of 350-380 μm thickness with a chemically etched central part 56 μm in diameter. The etched areas were 10 or 50 μm deep. The crystal target, mounted in a goniometer rotating in two mutually perpendicular planes, was placed in the beam of a pulsed high-flux electron accelerator (mean current 200 μA); the electron energy was 30-50 MeV, and the energy spread $\Delta E/E \sim 10\%$.

The experimental arrangement is shown in Fig. 1. The electrons pass through a 20-mm collimator 1 and hit the silicon crystal 2, generating gamma rays; the cross-sectional area of the electron beam at the target is 1-3 cm^2, and the back of the target is coated with pitch. The electron beam is deflected by a magnet 3 into a collector 4 with an electrical output registering the current through the crystal. The gamma rays pass through a 10 mm collimator 5 set in a shield 6 and hit a detector 7.

The detector is a thin (1.3-1.4 mm) CsJ scintillator crystal 40 mm in diameter, whose emission is recorded by a PMT; the collimation angle of the photons produced in the target is $\sim\gamma^{-1}$ (γ is the relativistic factor). The energy E_{abs} absorbed in the scintillator as a function of the incident gamma energy E_γ was calculated on a computer by the Monte Carlo method. The results, plotted in Fig. 2, show that the detector is efficient at photon energies up to 100 keV, corresponding to the energies characteristic of electron channeling radiation and coherent bremsstrahlung of above barrier electrons of $E_{e^-} \sim 50$ MeV moving along a crystallographic axis.

The recording equipment subtracts the background from the signal and normalizes it to the current through the target [1], and the normalized signal is then used to orient the crystal. The orientation procedure is as follows (see [2]): a voltage proportional to the goniometric displacement is fed to one plotter input, and the normalized detector signal is fed to the other input; the angular coordinate is varied continuously by a stepper motor and the plotter traces out a curve which has peaks at the angular coordinates at which the electron beam is directed along a crystallographic plane or axis. The target can be oriented in two ways: 1) One of the angular coordinates is scanned until the orientation curve shows the peaks of two or three planes; the second angular coordinate is then varied by an amount equal to half the inter-peak distance, for instance, and the first coordinate is scanned again. A two-dimensional coordinate grid is used to plot the points corresponding to the resultant plane peaks, and straight lines are drawn through pairs of matching points; the coordinates of the intersection point of the lines represent the target position at which the electron beam is directed along a crystallographic axis (see [2]). The graphically obtained coordinates are used to adjust the crystal position near the axial peak. 2) Only one adjustment is made near the axial peak. This is easy to do, since the crystal holder is initially set so that the crystal surface is perpendicular to the beam, and the <100> axis of the crystals then coincides with the normal to the surface to within 0.5°.

The above method was used to position the crystal at an axial orientation peak. One of its angular coordinates was then shifted by about 0.5° (the Lindhard angle for the axial potential of silicon and an energy of 50 MeV is ~2 mrad). The orientation curves near the

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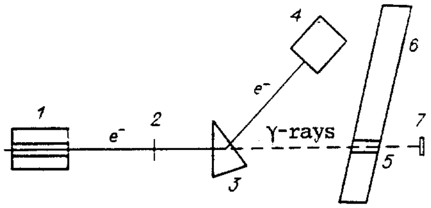

Fig. 1

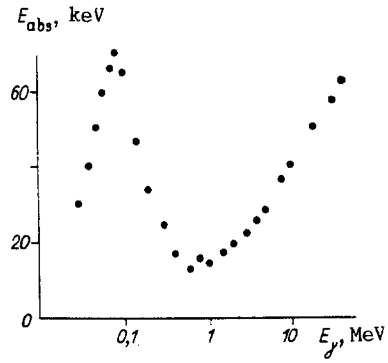

Fig. 2

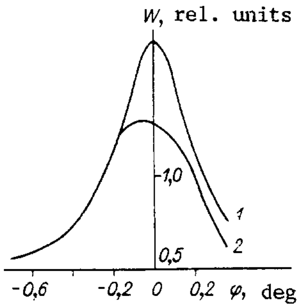

Fig. 3

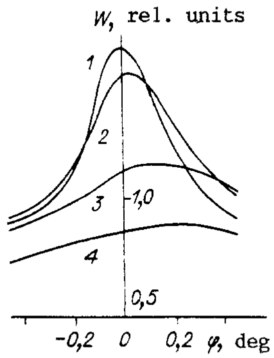

Fig. 4

axial peak were plotted for different mean electron currents through the crystal. The mean current was controlled by the accelerator pulse repetition rate.

Figures 3 and 4 show the radiation intensity W as a function of the disorientation angle φ between the crystal axis and electron beam for targets of 10 um (Fig. 3) and 50 μm (Fig. 4). Curves 1 and 2 in Fig. 3 are for currents i = 5 and 10 μA, curve 1 in Fig. 4 is for i = 4 and 8.5 μA, and curves 2-4 in Fig. 4 are for i = 16, 31, and 65 μA. It is seen that when the current increases beyond a certain point the orientation curve becomes broader and the peak intensity decreases. This is due to the crystal heating up and bending.

In fact, a fraction of the electron beam energy is deposited in the crystal by ionization losses, producing an axisymmetric temperature distribution which leads to radial stresses caused by nonuniform expansion. At a certain current the radial stresses exceed a critical value and the flatness of the target disk becomes unstable.

The stability can be described by the following model. The target is considered as a thin circular disk of thickness h (10 or 50 μm) and radius ρ_t = 28 mm conforming to the etched region; the boundary conditions of the equilibrium equation are defined by the thick (unetched) 4-mm-wide annular part of the crystal, and the disk edge is therefore assumed enclosed [3]. The stability problem for a circular disk of radius R with a force p uniformly distributed over its edge has the solution (see [4]) $p_c = KD/R^2$, for the critical stress, where K = 14.68 for an enclosed edge and D is the cylindrical rigidity, i.e., $D = Eh^3/[12(1-\mu^2)]$ (E is Young's modulus and μ is Poisson's ratio). In our case the elongation of a disk element at a distance ρ from the center is $\delta(d\rho)/d\rho = \alpha d\rho \partial T/\partial\rho$ (α is the coefficient of linear expansion). Accordingly, the radial stress increment $d\sigma_{\rho\rho} = dp/h = E\delta(d\rho)/d\rho$ or $dp = -\alpha E h d\rho \partial T/\partial\rho$ ($\sigma_{\rho\rho}$ is the stress tensor component). The minus sign in the last expression denotes stresses towards the disk center (compressive), produced when $\partial T/\partial\rho < 0$. The disk stability is thus defined by

$$I = \int_0^{\rho_t} dp/p_c(\rho) = -\frac{\alpha E h}{KD}\int_0^{\rho_t} \rho^2 \frac{\partial T}{\partial \rho} d\rho = -\frac{12\alpha(1-\mu^2)}{Kh^2}\int_0^{\rho_t} \rho^2 \frac{\partial T}{\partial \rho} d\rho.$$

If I < 1, the target flatness is stable.

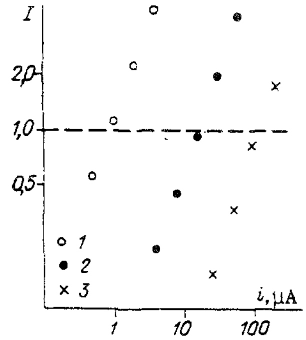

Fig. 5

The temperature distribution is calculated under the following assumptions: the heat source (the crystal region crossed by the electron beam) lies uniformly about the origin and is bounded by the radius ρ_b; the crystal emits only from its soot-coated side (temperature measurements on the uncoated edge showed that the integral blackness of silicon $\varepsilon \ll 1$ in the $290 < T < 370$ K range). Since the integral blackness of soot is ~0.95 at $366 < T < 533$ K [5], its temperature brightness is assumed the same as for a blackbody. The power deposited in the target by interaction with the electron beam is calculated from the formula for ionization losses in [6].* The steady-state temperature distribution and gradient are given by the solution of the one-dimensional equation

$$\begin{aligned}\frac{\partial^2 T}{\partial\rho^2} &= -\frac{1}{\rho}\frac{\partial T}{\partial\rho} - \frac{1}{\varkappa}\frac{\partial\varkappa}{\partial T}\left(\frac{\partial T}{\partial\rho}\right)^2 + \frac{\sigma}{\varkappa T}\left(T^4 - T_0^4\right) - \frac{W}{\pi\rho_b^2\varkappa h}, \quad \rho < \rho_b,\\ \frac{\partial^2 T}{\partial\rho^2} &= -\frac{1}{\rho}\frac{\partial T}{\partial\rho} - \frac{1}{\varkappa}\frac{\partial\varkappa}{\partial T}\left(\frac{\partial T}{\partial\rho}\right)^2 + \frac{\sigma}{\varkappa T}\left(T^4 - T_0^4\right), \quad \rho_b < \rho < \rho_t\end{aligned} \tag{1}$$

with the boundary conditions $\partial T/\partial\rho(0) = \partial T/\partial\rho(\rho_t) = 0$,† where $\varkappa = \varkappa(T)$ is the thermal conductivity of silicon, W is the power deposited in the crystal,‡ σ is Boltzmann's constant, and T_0 is the room temperature. In the numerical solution of Eq. (1) we replaced $\partial T/\partial\rho(\rho_t) = 0$ with the equivalent condition

$$2\pi\sigma\int_0^{\rho_t}\rho\left(T^4 - T_0^4\right)d\rho = W, \tag{2}$$

which is more convenient in the algorithm we used. The calculations consist of specifying T and $\partial T/\partial\rho$ at $\rho = 0$, solving Eq. (1) and verifying condition (2), then changing T(0) and solving (1) again; this is repeated until (2) holds to a given precision.

The calculated values of I for h = 10, 50, and 170 μm (points 1-3) and different currents are plotted in Fig. 5; thus I = 1 at i ≈ 1 and 16 μA for h = 10 and 50 μm, respectively. The calculation and measurement results (Figs. 3, 4) show good agreement for the h = 50 μm crystal. A heat sink at the junction of the target with the holder apparently upsets the temperature gradient at the edge and alters somewhat the current at which stability loss occurs. In a 10 μm crystal (Fig. 3) bending becomes noticeable at currents several times higher than the critical, because at $i_c \approx 1$ μA (Fig. 5) the elongations produced by heating are small, i.e., the typical bending angles are less than the measurement resolution defined by the angular scale of the orientation curve. Figure 5 also shows the values calculated for a 170 μm target, in which $i_c \approx 100$ μA.

*The radiation losses can be neglected, although at the electron energy involved they are comparable to the ionization losses. The point is that even in a thicker (50 um) target the absorbed fraction of radiation is only 0.01, which is much less than the calculation precision.

†This is due to the fact that there are virtually no heat sinks, since in all orientation measurements the crystal is attached at a single point (i.e., its contact with the holder is far smaller than the disk circumference).

‡The deposited power is given by $W = ih\partial^2 W/\partial h\partial i$, where $\partial^2 W/\partial h\partial i = 4.8\cdot10^{-4}$ W/(μm·μA).

These results provide an estimate for the currents at which practical difficulties arise in orientation-effect applications. This is based on the following considerations: silicon has the smallest thermal expansion coefficient and Z number (lowest ionization losses) of the crystals used in orientation-effects physics; the ionization losses of relativistic particles vary little with their energy; reducing the target diameter or increasing its thickness must appreciably raise the temperature, which can reach ~300°C at the center for $i = 100$ µA and $h = 170$ µm. Thus, given beam and target sizes of 0.3 cm $< \rho_b$ and $\rho_t < 3$ cm and a ratio $\rho_b/\rho_t \sim 0.3$-0.5, a mean current $i = 0.3$-1 mA should be the maximum in orientation-effect applications, without special cooling of the crystal.

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