Shaped silicon-crystal wafers obtained by plastic deformation and their application to silicon-crystal lenses

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Plastic deformation is an unlikely process by which to mould pristine silicon wafers into three-dimensional shapes owing to the inevitable detrimental impact that the resulting mechanically induced defects would have on their electrical properties. However, if one were to find a way of doing so without substantial degradation of these properties, a range of new applications might be opened up. Here we report on the successful plastic deformation of silicon crystal wafers for the preparation of wafers with various shapes. A silicon wafer was set between dies and pressed at high temperatures. One application of shaped wafers is as well-shaped concave silicon crystal lenses or mirrors. The lattice plane of such a crystal lens has a curvature exactly along the surface. A concave spheroidal X-ray lens, in the form of two-dimensional Johann[1,2] and Johansson's[2,3] monochromators, is proposed for an X-ray optical component system. We propose and demonstrate a new solar cell system with the concave silicon crystal mirror used as both a solar cell and a focused mirror. This system can make use of the reflected photons from solar cells.

It has been confirmed[4] by tensile tests at high temperatures of up to 1,380 °C that silicon crystals can be plastically deformed above 900 °C. The temperature dependence of the yield stress of silicon crystals has been reported mainly from the viewpoint of the dynamical behaviour of dislocations[4–8]. But there are no data on intentionally

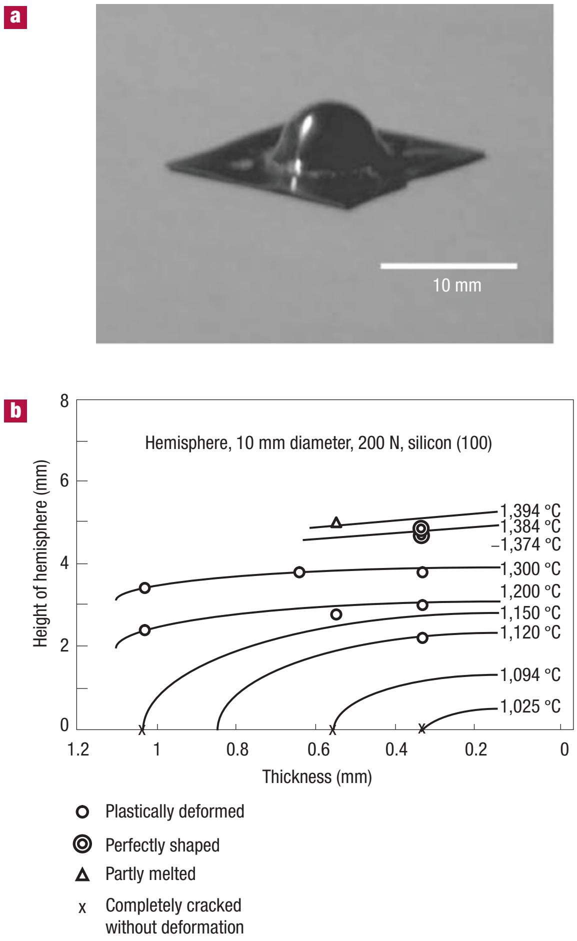

Figure 1 Hemispherical silicon-crystal wafer fabricated by plastic deformation, and the height of the hemispheres. a, A flat (100) silicon crystal wafer was pressed at 1,374 °C to obtain the shaped wafer. The diameter of the hemisphere is 10 mm. The thickness is 0.33 mm, and the wafer size is 18 × 18 mm^2. b, The height is governed by the temperature, thickness and overweight. An overweight of 200 N was used for the pressing process. Different symbols denote the heights of wafers that are perfectly shaped, plastically deformed, partly melted or completely cracked without deformation. The wafer thickness at which the wafers are completely cracked without any plastic deformation increases as the temperature increases. The depth of the hemisphere with diameter 10 mm is 5 mm, so the perfectly hemispherical silicon wafers have a height of 4.5–5 mm.

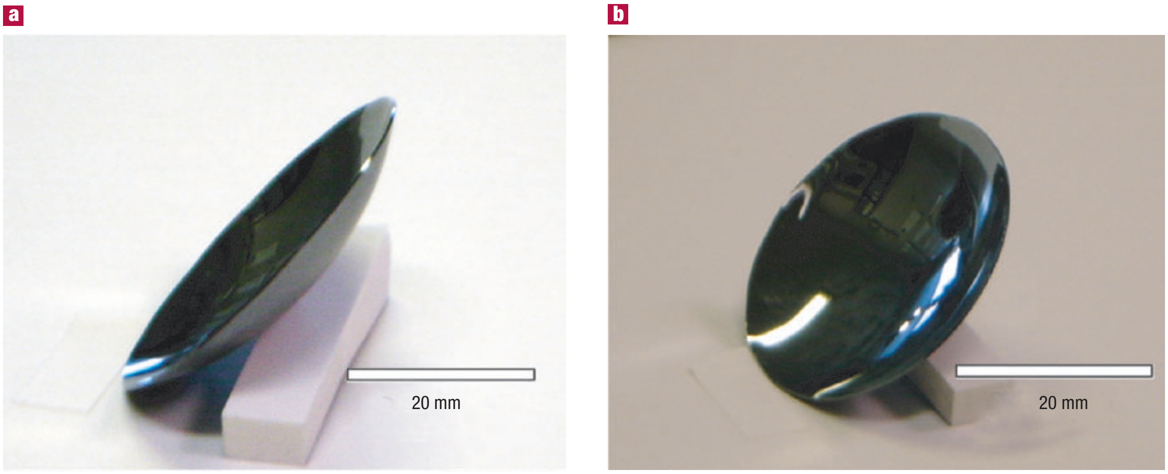

Figure 2 Concave silicon-crystal lens or mirror. The concave lens or mirror was prepared by pressing a (111) wafer with a thickness of 0.31 mm and a diameter of 38 mm at 1,300 °C. The focal distance is 30 mm.

obtaining shaped silicon crystal wafers by plastic deformation. The deformation region in which well-shaped wafers can be obtained is determined from the relationship between temperature, thickness, overweight and wafer orientation. We selected a hemisphere as a simple shape with which to obtain systematic data to elucidate the relationships among these parameters.

To obtain hemispherical silicon wafers, we used graphite dies. The diameter of the convex and concave hemispheres formed in the dies is 10 mm. A silicon wafer was set between the upper convex and lower concave dies, which were then heated to various temperatures below the melting point of silicon (1,414 °C) in hydrogen atmosphere while being pressed by an overweight of 200 N. The overpressure inside the hemisphere with diameter 10 mm is estimated to be 5 MPa for a wafer with thickness of 1 mm. Figure 1 shows an overview of a hemispherical (100) wafer with diameter of 10 mm (Fig. 1a), and the height of the hemisphere prepared by the pressing process (Fig. 1b). The height, which corresponds to the deformation strain, is determined by the temperature, thickness

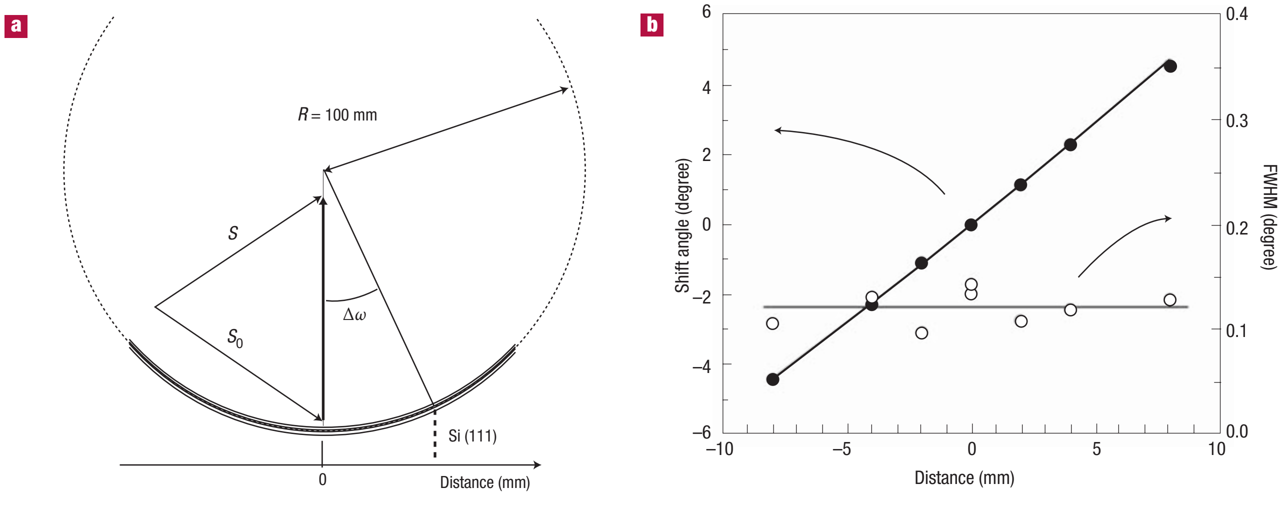

Figure 3 Curvature of (111) plane and the FWHM of the 333 Bragg peak of the deformed silicon wafer. a, Schematic illustration of (111) silicon (Si) wafer plastically deformed in a concave sphere with a radius of 100 mm. When the incident Cu Kα1 radiation illuminates a point from the centre of the crystal, the shift of the Bragg angle in an ω scan gives the curvature of the (111) crystallographic plane. S_0 and S are the wavenumber vectors of the incident and scattering X-ray, respectively. **b**, The 333 Bragg peak position for the wafer plastically deformed with a curvature of $R = 100$ mm, and the FWHM of the peak, measured by ω scan with Cu Kα1 radiation as a function of distance from the centre of the crystal. Solid circles are the shift of the Bragg peak position, giving the tilt of the (111) lattice plane. The solid line corresponds to the expected angle shift when the (111) lattice plane is bent at the same curvature as the crystal surface. Open circles indicate the distribution of FWHM of the peaks. It is clear that the (111) plane was uniformly deformed with a curvature of $R = 100$ mm, and the crystal quality is good over a large area. Even for this as-deformed crystal, the FWHM is better than those of undeformed lithium fluodite or graphite commonly used for bent monochromators.

and overweight. The height increases as the temperature increases and the thickness decreases or the stress increases. Perfectly shaped silicon wafers can be obtained by the pressing process near 1,380 °C using wafers with thicknesses of 0.3–0.4 mm. Plastically deformed wafers developed a very distinct slip-band system. The same slip system corresponding to slip on the {111} plane has been reported previously[4]. The dislocation density in the shaped wafers decreases considerably as the pressing temperature increases.

We prepared concave silicon-crystal lenses or mirrors with focal distances of 30, 40, 50 and 100 mm. A concave silicon crystal lens or mirror can be prepared using a (111) wafer (Fig. 2). A perfectly shaped crystal lens or mirror can be more easily obtained using a (111) silicon wafer than a (100) silicon wafer because of the crystallographic symmetry. The lattice plane of conventional crystals for a lens or monochromator prepared by the polishing or ion-milling process does not bend along the curvature of the surface, but that of the present crystal lens prepared by plastic deformation has a curvature exactly along the surface. Figure 3a gives a schematic illustration of the (111) silicon lens shown in Fig. 2 along with the Bragg geometry for X-ray diffraction (XRD). The curvature of the (111) lattice plane was measured from the shift of the 333 Bragg peak (Fig. 3b). The figure shows that the curvature of the (111) lattice plane agrees with that of the crystal surface. Such a well-defined curvature of the crystallographic plane is difficult to obtain by other methods.

As one of the applications of the shaped crystal lenses, we propose a concave spheroidal X-ray monochromator, consisting of two-dimensional Johann[1,2] and Johansson's[2,3] monochromators with a curvature of 100–300 mm for an X-ray optical component system, which can use X-ray photons from a generator efficiently without deteriorating angular resolution. The optics can be more easily prepared by combining the plastic deformation and polishing processes. Johan- and Johannson-type monochromator systems have long been known as high-resolution and high-efficiency X-ray optical components for conventional X-ray generators. However, there has not been a good solution for simultaneously realizing high efficiency in collecting X-ray photons and good spatial resolution, because the former requires deformability of the crystal, whereas the latter requires high crystal quality. The shaped single crystal can provide X-ray optics having good angular resolution with a very high angle of acceptance (Fig. 3b). For example, the expected receiving angle of about 4°, corresponding to a solid angle of 0.015 sr for the present crystal, would be about 2×10^3 times as large as that of 9×10^{-6} sr for a flat lithium fluoride monochromator having almost the same full-width at half-maximum (FWHM) of the Bragg peak.

We propose a new solar cell system as one of the applications of the silicon-crystal lens. In this system, the lens is used as a focused mirror. For a conventional solar-cell system, some number of photons is reflected from the surface of solar cells, and these photons have never been effectively used as an energy source. A plastic mirror, which does not generate solar energy by itself, is used to focus the solar beam to a small spot at which a high-efficiency solar cell is set to obtain electric energy[9]. Our new solar-cell system combines the conventional solar-cell system with the focused solar-cell system using the mirror. In this system, the concave silicon-crystal mirror

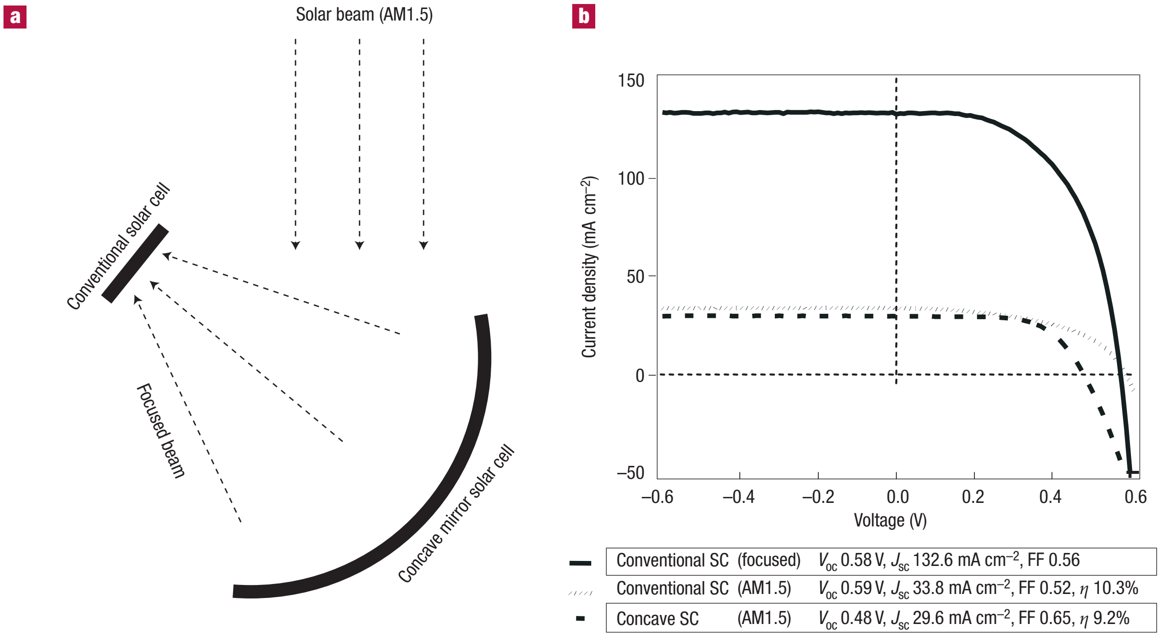

Figure 4 New solar cell system using a concave silicon-crystal mirror, and the characteristics of the solar cells used in the new system. a, The concave mirror solar cell can generate electronic energy, and the conventional small solar cell set at the focused spot can also generate energy from the reflected photons. **b**, The characteristics of solar cells were measured at 25 °C using a solar simulator system (YQ-250BX, JASCO Japan) with an irradiation beam light intensity of 100 mW cm^{-2} (AM1.5). The light-illuminated current density (mA cm^{-2}) is shown as a function of voltage (V) of the solar cells. To prepare a concave silicon crystal mirror with a focal distance of 100 mm, a (111) crystal wafer was deformed by pressing at 1,200 °C and then annealing at 1,210 °C for 30 min. The solid, broken and dotted lines are the current densities of the conventional solar cell set at the focused spot, the conventional solar cell irradiated by beam light and the concave mirror solar cell irradiated by beam light, respectively. The open-circuit voltage (V_{oc}), the short-circuit current (J_{sc}), the fill factor (FF) and the efficiency (η) are shown in the figure. By using the concave solar cell (Concave SC (AM1.5)) to focus light onto a conventional flat solar cell (conventional SC (AM1.5)), the intensity of the light falling on and therefore the current generated by this conventional cell can be increased by about a factor of four.

plays dual roles as a solar cell and a mirror to focus the solar beam onto another small solar cell (Fig. 4a). The crystal mirror can generate electric energy by itself, and the photons reflected from its surface can also be effectively used by the small solar cell set at the focal spot to generate electric energy. The focused solar beam from the silicon mirror solar cell obtains a current density of 132.6 mA cm^{-2} when the conventional small solar cell is set at the focused spot of 1 mm^2 (Fig. 4b). The effective total number of photons is the sum of photons from both the mirror solar cell and the small cell at the focal spot, and it determines the efficiency of the entire system.

The applicability of plastically shaped crystals holds high potential because our method can be used for other crystalline materials, and the shape, size, curvature, lattice structure, defect density and orientation can be used as variable parameters.

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Competing financial interests

The authors declare that they have no competing financial interests.