Observation of phonon focusing with pulsed laser excitation of surface acoustic waves in silicon

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We have observed phonon focusing of surface acoustic waves in the (100) and (111) planes of silicon. The channeling directions were visualized by shaking off micron-size particles deposited on the surface. Quantitative measurements were performed by means of a laser probe.

The concentration of acoustic energy flux in certain directions under the action of a point source in an anisotropic crystal is called phonon focusing. This effect was first observed with high-frequency (terahertz) ballistic phonons excited by a pulsed heat source in the volume of a crystal cooled to low temperatures.[1,2] Phonon focusing (the term "channeling of acoustic waves" is also employed) is one of the general properties of the propagation of waves in an anisotropic medium; it also occurs for surface acoustic waves (SAWs). As far as we know, however, phonon focusing of SAWs has never been observed directly. The related phenomenon of diffraction-free propagation of a wide-aperture beam of monochromatic SAWs in specially selected directions of a crystal has been studied.[3]

We have investigated phonon focusing accompanying the propagation of SAW pulses with spectral width ~50 MHz, which were excited by laser radiation in silicon samples. Phonon focusing of ultrasonic bulk waves under conditions of laser excitation was recently studied in Ref. 4.

The samples were 100 mm in diameter and 0.5 mm thick slices of single-crystalline silicon. Radiation from a Nd:YAG laser, operating in the giant pulse mode ($\lambda = 1.06\,\mu$m, $\tau = 15$ *ns*, $E = 10$ mJ, TEM_{00} mode), was focused on the surface of the slices. The $1/e$ radius of the focusing spot was equal to 7 μm.

Application of the laser pulses on the silicon surface caused an optical breakdown and generated a powerful SAW Rayleigh pulses with a characteristic wavelength $\lambda \sim 100\,\mu$m corresponding to the duration of the laser pulse. The method of deflection of a probe beam[5] was used to record the SAW pulses. A beam from a continuous-wave helium–neon laser (12 mW, $\lambda = 0.63\,\mu$m) was directed obliquely on the surface and focused into a spot with a radius of 15 μm. After reflection it was recorded using a fast two-sector photodiode, whose signal was proportional to the angle of deflection of the beam. Thus the laser probe recorded the angle of inclination of the surface in the SAW, proportional to the normal component of the oscillatory velocity of the surface. The temporal resolution was 10 ns.

Before the probe measurements the phonon focusing pattern was investigated qualitatively by using the following method of visualization. The surface of silicon was dusted with 1–2 μm Al_2O_3 particles. Mechanical detachment of the microparticles from the surface accompanying the passage of an intense SAW was employed.[6] The action of the SAW causes the surface to move with acceleration, and an inertial force acts on a particle at rest in the coordinate system of the surface. If the acceleration of the surface is directed into the sample, and if $w_\perp > F_{\rm ad}/m$, where $w_\perp$ is the normal component of the acceleration, m is the mass of a particle, and $F_{\rm ad}$ is the force of adhesion of the particle to the surface, then the particle will detach itself from the surface (in order that the detached particle not settle back on the surface, in our experiments the silicon wafers were positioned vertically). Thus the degree of removal of microparticles from the surface is characterized by the amplitude of the SAW. In our experiments the accelerations in the SAW reached high values, $w_\perp \sim 10^8$ m/s^2, which corresponds exactly to detachment of micron-size particles.

Figure 1a shows a photograph of the dusted (111) surface of silicon. The dark regions in the photograph are sections from which microparticles have been removed as a result of the passage of a SAW. The diverging dark tracks represent the direction of maximum phonon focusing (direction of channeling). The symmetry of the observed pattern is determined by the fact that the normal to the surface is a threefold axis of the acoustic properties of silicon and there is a symmetry relative to the center and the $[1\bar{1}0]$ axis. The direction of maximum acoustic energy concentration makes an angle $\phi = 30°$ with the $[1\bar{1}0]$ axis and is also the direction of maximum phase velocity of SAWs. Figure 1b shows the angular dependence of the amplitude of the oscillatory velocity in a SAW, recorded with a laser probe at a distance $r = 10$ mm from the point of laser action. We see that the sharp spike lies near $\varphi = 30°$, which corresponds exactly to the direction of channeling recorded in Fig. 1a.

The observed picture of phonon focusing agrees qualitatively with the theory.[7] The anisotropy of the acoustic energy flux in the crystal is characterized by the enhancement factor

$$A = \left|\frac{d\varphi}{d\theta}\right|^{-1} = \left|1 + \frac{d\Phi}{d\theta}\right|^{-1}, \qquad \Phi = \tan^{-1}\frac{\partial c/\partial\theta}{c},$$

where $\Phi = \varphi - \theta$ is the difference between the angle φ characterizing the direction of the energy flux and the angle of the wave normal θ, and $c(\theta)$ is the angular dependence of the phase velocity of the SAW. From the dependence $\Phi(\theta)$, calculated for a SAW in the (111) plane of silicon and presented in Ref. 8, it follows that $A(\theta)$ reaches a maximum value at $\varphi = \theta = 30°$, which agrees with the results of our experiment.

Figure 2 shows analogous results for the (100) face of silicon. The normal to the surface in this case is a fourfold axis; there is additional symmetry relative to the [010] axis. The channeling directions form a doublet near the direction of maximum phase velocity of SAW and make with the [010] axis the angles $\varphi_1 = 21.5°$ and $\varphi_2 = 25°$ (the angles were measured within 0.5°); the degree of energy concentration is significantly higher in the direction $\varphi = \varphi_2$. The existence of a doublet of channeling directions apparently stems from the existence of two inflection points on the slowness curve near the direction of maximum phase velocity. However, a quantitative comparison with the theory requires additional analysis.

We have thus directly observed phonon focusing produced as a result of the propagation of SAWs from a point source in the (111) and (100) faces of silicon. Our

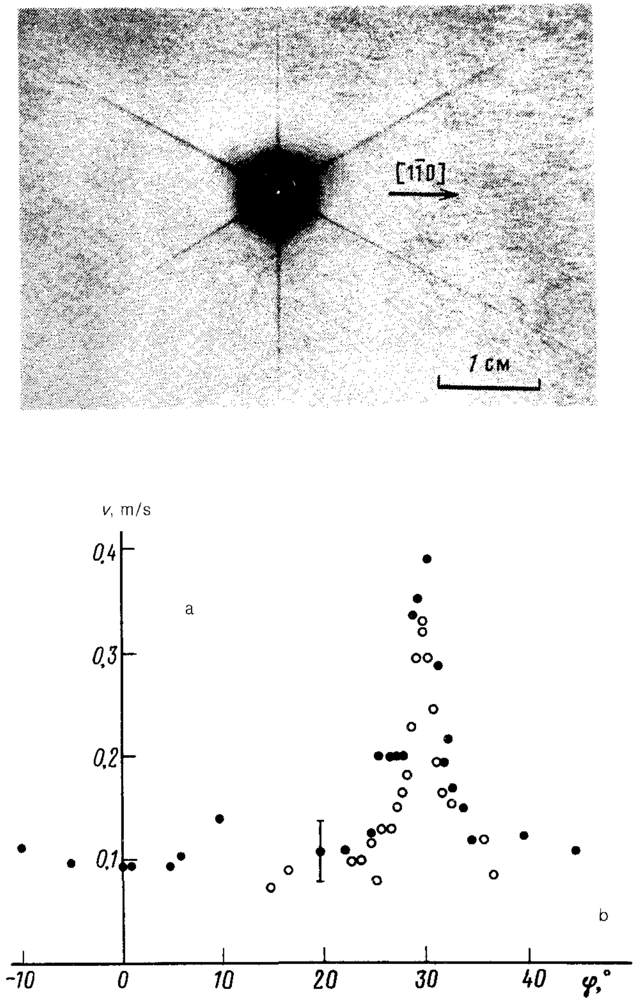

FIG. 1. Phonon focusing of SAWs in the (111) plane of silicon. (a) Photograph of the dusted surface after laser-acoustic action; (b) the angular dependence (obtained with the help of a laser probe) of the amplitude of the normal component of the oscillatory velocity of the surface in a SAW pulse. The black and white circles refer to different series of measurements.

simple method of visualization makes it possible to obtain two-dimensional pictures of phonon focusing of SAWs and the use of a laser probe makes it possible to perform contact-free quantitative investigations of phonon focusing for the faces of any single crystals whose dimensions are much larger than the characteristic wavelength of the acoustic wave. The results of such investigations could find application in acoustoelectronics, since the diffraction accompanying propagation of wide-aperture SAW beams is suppressed in the direction of phonon focusing.[3] This method of visualization can also be employed to obtain images of bulk phonon focusing in the ultrasonic frequency range. In particular, comparison of the angular distributions obtained by this method for comparatively low-frequency phonons with the corresponding distributions of

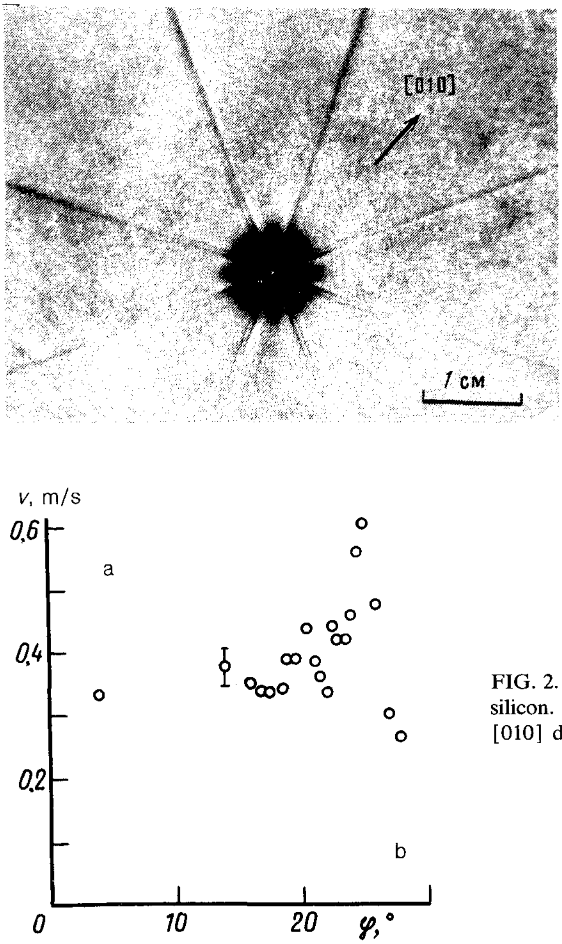

FIG. 2. The same as Fig. 1, but for the (100) face of silicon. In Fig. 2b the angle φ is measured from the [010] direction.

high-frequency phonons[9,10] would make it possible to determine the effect of the dispersion on phonon focusing.

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