Impulsive fracture of fused quartz and silicon crystals by nonlinear surface acoustic waves

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During nonlinear evolution of laser-generated surface acoustic wave (SAW) pulses, the stress increases with distance of propagation, and causes fracturing of brittle materials. This effect was used to evaluate the strength of isotropic fused quartz and anisotropic crystalline silicon with respect to impulsive loading in the nanosecond range and spontaneous cracking without using seed cracks. Crack nucleation and propagation along the surface was studied by optical microscopy and into the depth of the bulk by the focused ion beam technique and confocal microscopy. In fused quartz, fracturing produced characteristic regular patterns at the surface with cracks extending into the bulk at an angle of 30°–35° to the surface in the direction of SAW propagation. On Si(111) surfaces cracks extended at the surface in the ⟨110⟩ direction and propagated along the weak {11̅1} cleavage plane into the bulk. Other crack planes were observed in only a few cases, e.g., at a larger depth and on the Si(100) surfaces. The observed fracture behavior was rationalized by the complex displacement and stress tensor fields induced by elliptically polarized SAWs. © 2003 American Institute of Physics. [DOI: 10.1063/1.1594275]

I. INTRODUCTION

An important property of amorphous and crystalline materials that determines their potential applicability as a structural material is their mechanical strength. Our understanding of strength-determining factors is still rather poor and mechanical strength is therefore usually determined experimentally. However, in the case of brittle materials, two important strength-determining issues are obvious: (1) the ultimate mechanical strength is limited by brittle fracture and (2) the strength-determining step is the nucleation of the crack. Crack nucleation, unfortunately, is almost impossible to observe experimentally. Cracks usually start from preexisting defects and the macroscopically measured mechanical strength is therefore determined by the size of the largest flaw. In contrast, fundamental theoretical studies often deal with the ideal defect-free material and can only give an upper estimate of the strength or study the propagation of an already existing large crack.

Recently, it was discovered that dynamic crack nucleation can be initiated not only by loading macroscopic specimens with a constant force but also by applying a transient shock, generated by a strongly nonlinear surface acoustic wave (SAW) pulse.1 These two techniques, the well-developed constant force technique and the impulsive cracking technique, provide partially complementary information about crack nucleation and fracture. While static loading allows the fracture toughness, preferred cleavage planes, and crack propagation issues to be determined, the impulsive cracking technique gives access to the nucleation phase. A single SAW pulse can generate tens of crack nuclei during propagation and it leads directly to spontaneous cracking along the preferred cleavage planes, while any seed crack will only provide information on crack propagation.

Dynamic brittle fracture under static loading conditions has been studied extensively for glass and silicon single crystals.2–6 These experiments have revealed the {111} planes as the primary cleavage planes in silicon single crystals.2 Under certain conditions, the cracks can, however, also make use of {110} planes5,6 or higher-indexed planes5,7 as cleavage planes. Fracture toughness and the occurrence of {110} cracks can both be explained theoretically but require atomistic analysis.8,9 The dynamics of existing cracks can be well analyzed using continuum elasticity theory.10 While cracks in glass appear to propagate at velocities of only 0.3–0.5 of the Rayleigh wave velocity, in silicon, fracture experiments give velocities between 2300 and 3800 m/s, which corresponds to 0.5–0.85 of the Rayleigh wave velocity.3–9 The Rayleigh wave velocity is the upper limiting speed that tensile cracks cannot exceed according to continuum elasticity theory.10

With nonlinear SAW pulses it is possible to generate steep shocks with transient tensile stresses that exceed the mechanical strength of most brittle materials, for example, fused quartz and silicon crystals.11,12 This leads to spontaneous fracture without precrack or notch. In an anisotropic crystal the cracking plane realized depends on the strength of the particular cleavage plane and the nature of the stress field applied. The influence of a rapidly rising strain pulse of very short duration on the dynamics of fracture is not yet understood. In the work reported here we used strongly nonlinear
SAW pulses with shocks to study spontaneous crack nucleation and propagation in isotropic fused quartz and anisotropic silicon crystals in the surface region. These elastic pulses with finite amplitudes were excited by means of pulsed laser radiation and detected by a probe-beam deflection (PBD) setup at a distance of millimeters to centimeters from the line source. The SAW pulses gain steep shock fronts during propagation due to nonlocal elastic nonlinearity, and generate a series of similar crack patterns at certain distances from the source. The characteristic features of these nonlinear surface pulses are investigated with respect to their ability to fracture materials. The nature of the cracks at the surface can be studied by scanning force microscopy (SFM) and optical microscopy. Their propagation into the bulk of the material was studied in this work by the focused ion beam (FIB) technique and confocal microscopy.

II. EXPERIMENT

In the present fracture experiments fused quartz samples (Herasil I) with a size of $30 \times 20 \times 3$ mm$^3$ and silicon single crystals with $(111)$, $(110)$, and $(100)$ surface orientation and a size of $40 \times 40 \times 3$ mm$^3$ were investigated. Prior to the measurements the silicon samples were thermally oxidized, resulting in an oxide layer of 100–200 nm thickness. Wet chemical processing was employed to remove these thick oxide layers and to obtain essentially atomically flat H-terminated Si(111) surfaces. The ultrathin native oxide layer growing after the preparation in the normal atmosphere had a negligible influence on the measurements. For the Si$(110)$ and Si$(100)$ surfaces this preparation process provides less ideal surfaces with a roughness in the range of several angstroms. However, the influence of the residual damage introduced by the polishing and lapping processes was reduced substantially with this procedure. The surface of the fused quartz samples was mechanically polished to high optical quality and used as received.

Nonlinear SAW pulses were excited using Nd:YAG laser radiation (wavelength 1.06 μm, duration 8 ns, pulse energy up to 150 mJ). The laser beam was focused into a strip of length ~8 mm and width ~10 μm. In the region of the excitation line the sample surface was covered with a thin strongly absorbing carbon layer in the form of an aqueous suspension. Irradiation of such a suspension with short laser pulses leads to overheating and explosive evaporation of this liquid film. This results in a strong transient normal force acting on the surface, which generates SAW pulses with high amplitudes. These SAW pulses can develop spikes or shock fronts with tensile stress growing with the propagation distance, and induce cracks when the fracture strength of the material is reached.

The transient SAW pulses were detected with a PBD setup using a stabilized diode pumped continuous wave (cw) Nd:YAG laser (wavelength 532 nm, power 100 mW). The cw laser beam was divided into two parts of approximately the same intensity. Each probe beam was sharply focused by a gradient-index lens into a spot of approximately 4 μm diameter on the sample surface, forming two probe spots along the SAW path. The deflection of the probe beam due to the transient SAW pulse was monitored with a position-sensitive detector. The bandwidth of the entire detection setup was limited by the finite probe size to about 500 MHz. The deflection signal, which is proportional to the surface slope of the transient SAW pulse was amplified and recorded by a Tektronix TDS 680 B oscilloscope with 1 GHz bandwidth.

With the two-point detection setup the shape of the SAW pulses was measured at a small distance of about 2 mm and at a larger distance of 17 mm from the excitation line. The PBD technique provided a signal proportional to the mean slope of the displaced surface within the probe spot in the direction of wave propagation. Within the approximation of geometric optics, neglecting the finite size of the probe spot, the output of the PBD setup can be estimated by

$$i_d = \frac{8}{\pi \eta W} \cdot \frac{u_{3,1}}{\theta},$$

where $i_d$ is the differential photocurrent output, $\eta$ denotes the quantum efficiency of the photodiodes, $W$ is the total power of the probe beam reflected from the surface, $u_{3,1} = \partial u_3/\partial x_1$ is the surface slope along the $x_1$ axis, and $\theta$ denotes the convergence angle of the probe beam due to focusing. The accuracy of Eq. (1) is mainly determined by the uncertainty of $\eta$, and the geometrical approximation applied. In this work we used Eq. (1) as a first approximation for the calibration of the PBD setup. For further improvements we made use of the fact that in certain materials the nonlinear evolution of the short SAW pulses leads to a substantial pulse lengthening and formation of a U-shaped pulse with two narrow spikes, or an N-shaped profile with very narrow shock fronts. In both cases the duration of the pulse is a well-defined quantity. The nonlinear lengthening of the SAW pulse is determined by its magnitude, and this fact was employed for the calibration of the PBD setup.

The SAW pulse profile measured at the first probe spot location multiplied by a calibration factor was expanded into a Fourier series and substituted into an evolution equation of the following form:

$$i \frac{\partial}{\partial \tau} B_n = nq_0 \sum_{0<n'<n} F(n'/n) B_{n'} B_{n-n'} + 2 \sum_{n''>n} (n''/n') F^*(n/n') B_{n''} B_{n''-n''},$$

where $B_n$ stands for the spectral amplitudes, $\tau$ is the “stretched” coordinate along the direction of wave propagation, $q_0 = 2\pi/\Lambda$ is the fundamental wave number, and the kernel $F$ depends on the second- and third-order elastic constants, and thus describes the elastic nonlinearity of the medium.

The pulse shape at the remote probe location is simulated by means of Eq. (2). By varying the calibration factor the duration of the simulated pulse was fitted to the experimentally measured wave form. This method provides precise calibration in fused quartz, where the nonlinear evolution transforms the initial pulse into a U-shaped profile. It also provides a good estimate for SAW propagation in the [112]
III. EVALUATION OF STRESS IN SAW PULSES

Contrary to nonlinear elastic distortions in fluids, those in SAWs may result in an increase of stress with propagation distance. This growth of stress is limited by the frequency-dependent damping process, which we assume to be proportional to the frequency squared. If the characteristic shock formation length is sufficiently small in comparison to the attenuation length, the stress accumulated after a certain propagation distance can reach the mechanical strength of the material, causing failure of the solid.

In isotropic fused quartz the nonlinear distortions in the propagating SAW pulse result in the formation of a U-shaped $u_{3,1}$ profile. The experimentally measured pulse shapes are shown in Fig. 1 in comparison with the theoretical simulation based on Eq. (2). The comparison at the remote probe location indicates a substantially extended frequency range, which cannot be resolved experimentally due to the finite size of the probe spot. Therefore the predicted wave form has larger spikes than the experimental wave form, as shown in Fig. 1. We cannot exclude similar deviations at the first probe spot. The reasonable agreement between experiment and the theoretical prediction seems to confirm the correctness of the theoretical model and the applied calibration technique.

In isotropic media there is no a priori preferred orientation for crack growth. In order to determine the optimal conditions for fracture, the angular dependence of the peak longitudinal “opening” stress was calculated for the experimentally measured wave forms. The measured profiles of $u_{3,1}$, such as those shown in Fig. 1, determine uniquely the wave field at every instance and at any depth in the sample. For the evaluation of this field we used the exact solution for the conventional linear surface wave problem. This provides the complete set of eigenvalues: the phase velocity, the depth distribution, and the polarization vectors for all partial waves. The $u_{3,1}$ profile is extended into a Fourier series, and the wave field $u_{1}(x_{1},x_{3})$ is calculated as a superposition of the wave fields of all spectral components. The next step is to calculate the stress tensor field: $\sigma_{ij} = C_{ijkl}u_{k,j}$, where $C_{ijkl}$ designates the second-order elastic stiffness tensor. Finally we transform the stress tensor to the new coordinate system tilted into the specimen by an angle $\phi$. In this new coordinate system the stress component $\sigma_{11}$ represents the “opening” stress, directed normal to the conjectural cracking plane. Applying the linear elasticity approximation here assumes the smallness of all the values $u_{ij}$. This condition holds well in the SAW pulses considered here, since the displacement gradients are naturally limited to the order of $10^{-2}$ due to materials strength.

The result is presented in Fig. 2, indicating that the stress attains its maximum in the direction of wave propagation with $\varphi = 0$. Thus the crack is expected to grow perpendicularly to the surface if the opening mode (mode I) [17-18] cracking behavior prevails. In correlation with the traction-free boundary condition at the surface, the stress vanishes for $\varphi = 90^\circ$. The spatial-temporal distribution of $\sigma_{11} (\varphi = 0)$ for the experimental SAW pulse shown in Fig. 1 by the solid line is presented in Fig. 3. The stress distribution has a sharp peak at the surface, therefore the onset of fracture is expected to occur in the vicinity of the surface.

In anisotropic materials the character of nonlinear evolution depends on the crystal plane and propagation direction. Consequently the character of the stress field generated in a nonlinear wave varies with the plane orientation and the
wave propagation direction. As examples, we consider the propagation of a finite-amplitude SAW pulse along the Si(111) surface in the (112) directions. The crystal is not mirror symmetric with respect to the (112) plane. This results in opposite signs of the shock fronts generated and different stress distributions observed in the evolutions of nonlinear SAW pulses along the [112] and the [112] directions. The N-type pulse propagating in the [112] direction exhibits two short compression peaks, while the SAW pulse traveling in the opposite direction has only one strong tensile peak normal to the (111) cleavage plane. Therefore the latter is expected to induce fracture more easily by the opening mode of fracture. The good agreement achieved between the experimental results and theoretical simulations clearly demonstrates the applicability of the approach also to anisotropic materials such as silicon crystals.

IV. RESULTS

A. Fused quartz surfaces

Fused quartz (Herasil I) was studied as an example of a nonlinear isotropic material. Of special interest is the strain distribution at the spot located close to the first probe location because cracks were observed in that area. Obviously the nonlinearity of the SAW pulse developed at this point was sufficient to fracture the samples. Note that the peak intensity of the real wave form may be higher than measured due to bandwidth limitations. Since the isotropic amorphous material has no preferred cleavage planes, unlike silicon, fracture is expected to occur perpendicular to the direction of highest tensile stress or strain for the simplest case of mode I cracking behavior.

Figure 4 shows an optical micrograph of a series of symmetric patterns generated by a plane SAW pulse. The cracks are clearly visible at the surface and appear at a distance of several hundred micrometers to a few millimeters from the laser excitation line. After nucleation, occurring essentially perpendicular to the SAW propagation direction and the sample surface, the cracks bend forward, symmetrically on both sides, in the direction of SAW propagation, extending into different angles and branches.

The propagation of the cracks into the bulk material was investigated by probing different depths with the focus of a confocal laser microscope. The intensity of the backscattered light was used to track the orientation of a crack into the bulk, as is shown in Fig. 5. Within the inherently large error involved in determining the angle of propagation into the bulk material, the measurements indicate that the cracks penetrate at approximately 30°–35° to the surface in the direction of SAW propagation. The results are consistent with the aforementioned scenario that the cracks nucleate at the surface, first propagate a short distance perpendicular to the surface, and then change direction towards the direction of SAW propagation.

![Image of calculated spatial-temporal distribution of the opening stress σ_{11} at φ=0 for the simulated SAW pulse shown in Fig. 1.](image1)

![Image of optical microscope picture of the characteristic crack features at about 1 to 2 mm from the SAW excitation line in fused quartz. The arrow indicates the SAW propagation direction.](image2)

![Image of penetration of a crack into the bulk of fused quartz probed by confocal laser microscopy.](image3)
B. Silicon (111) surfaces

Figure 6 presents the SAW excitation line and the main area of cracks as obtained by optical microscopy. The first cracks were observed at a distance of about 400 μm from the source for the present conditions. The direction of crack extension on the surface is parallel to the SAW wave front, and therefore oriented along the $\langle 110 \rangle$ direction. The typical crack length was of the order of several hundred micrometers.

In Fig. 7 a FIB image of crack extension into the bulk of silicon is presented. The SAW pulse propagated from left to right in the $\langle 1 \bar{1} 2 \rangle$ direction, generating strong tensile loading. For this FIB measurement an individual crack located at a distance of about 800 μm from the source was selected from the cracks shown in Fig. 6. The interior surface shown in this and all other FIB figures, which was opened by the FIB cut, is always normal to the sample surface. The crack presented in Fig. 7 extends into the sample at an angle of $\sim 71^\circ$ to the surface direction of the incoming SAW pulse. Within the accuracy of the measurement of $\pm 3^\circ$ this is the angle between the Si(111) surface plane and the Si[$1\bar{1}1$] plane. Around a depth of 3.5–4 μm the crack suddenly changes direction. Beyond a depth of about 4 μm it continues perpendicular to the surface into the solid. This direction corresponds approximately to a $\{112\}$ plane. Further extension of this crack into the bulk could not be resolved because it was not possible to cut deeper into the solid with the FIB technique. It is important to note that the crack tip propagated backwards with respect to the direction of the traveling SAW pulse.

Figure 8 shows a crack that was initiated by a SAW pulse propagating along the Si(111) plane in the opposite direction, $\langle 1 \bar{1} 2 \rangle$, where compressional loading dominates, and therefore it is more difficult to fracture silicon. Nevertheless a similar failure behavior was found. From the surface the crack first extends into the solid along the $\{11\}$ cleavage plane up to a depth of about 4 μm, where it changes direction irregularly until a $\{112\}$ plane is reached at a depth of about 6–10 μm. Interestingly, near the surface the cleavage plane extends into the bulk in the direction of SAW propagation.

These SAW experiments reveal a significant difference in the conditions needed for crack induction in opposite directions. In the $\langle 1 \bar{1} 2 \rangle$ propagation direction cracks were observed only for laser pulse energies exceeding 120 mJ, whereas in the opposite, $\langle 1 \bar{1} 2 \rangle$, direction the threshold was as low as 30 mJ. Thus under suitable conditions cracks ap-
peared on only one side of the source, namely in the \([\bar{1}1\bar{2}]\) direction, while the wave propagating in the \([1\bar{1}2]\) direction did not cause failure, and therefore could be used to calibrate the SAW amplitude. This was realized by gradually increasing the laser pulse energy until fracture was observed in the \([\bar{1}1\bar{2}]\) direction. In this way the SAW amplitude at the cracking threshold could be evaluated, yielding the critical tensile stress for the weakest cleavage plane. From the spatial-temporal distribution of the stress at the cracking threshold, a critical tensile stress of about 1.6 GPa was extracted for the particular silicon sample.

C. Silicon (100) and (110) surfaces

Nonlinear SAW pulses on the (100) plane were excited in both the \(\langle 100 \rangle\) and \(\langle 110 \rangle\) directions. In either case the cracks extended along the \(\langle 110 \rangle\) direction. Since the angle between the \(\langle 100 \rangle\) and \(\langle 110 \rangle\) directions is 45°, a SAW pulse propagating in the \(\langle 100 \rangle\) direction generated a V-shaped crack on the surface, whereas the pulses traveling along the \(\langle 110 \rangle\) direction generated cracks parallel to the excitation line. From the FIB images it could be calculated (with an accuracy of \(\pm 5°\)) that in most cases the fracture plane extending into the bulk was the \(\{111\}\) plane at an angle of 54.7° to the Si(100) surface. Occasionally cracks were observed to run in other directions. These failures could be related to \(\{110\}\) planes, except for two cases, where the angle coincided with a \(\{113\}\) crack plane.

Figure 9 displays such a V-shaped crack on the Si(100) surface, with the SAW pulse propagating from the top of the image to the bottom in the \(\langle 00\bar{1} \rangle\) direction. Underneath the surface the two different \(\{111\}\) crack planes intersect smoothly. For a crack generated by a SAW pulse that propagated along the \(\langle 011 \rangle\) direction on the Si(100) surface the crack plane changed several times between different \(\{111\}\) and \(\{011\}\) planes. At a depth of approximately 8-10 \(\mu m\) underneath the surface the contrast of the crack faded out.

An interesting observation was made in a surface area in which nearly symmetric V-shaped cracks were initially generated by a SAW pulse propagating in the \(\langle 100 \rangle\) direction. A second nonlinear SAW pulse passing through this area in the \(\langle 110 \rangle\) direction caused an increase of the lengths of the cracks perpendicular to the propagation direction of the second SAW, whereas the cracks parallel to the propagation direction did not appear to be affected much by this second pulse.

On the (110) surface SAW pulses propagating in the low-index \([1\bar{1}0]\) direction produced V-shaped cracks. The angle between the two forward and the two backward running crack branches was about 109°. Figure 10 shows a top view onto the surface of these cracks. The SAW pulse propagating in the \(\langle 001 \rangle\) direction (perpendicular to the \([1\bar{1}0]\) direction presented in Fig. 10) also generated V-shaped cracks with an angle of 71° between the two forward running branches. Figure 11 displays the FIB cut of the right branch for illustration. As can be seen the crack runs perpendicular to the surface into the bulk, coinciding with a \(\{\bar{1}1\bar{1}\}\) cleavage plane.

V. DISCUSSION

The essential question to be discussed here is whether the observed fracture behavior nucleated by nonlinear SAW pulses can be correlated with the known fracture characteristics of fused quartz and silicon, and whether the crack patterns can be rationalized by means of the calculated nonlinear SAW profiles.

The SAW pulses have a duration in the nanosecond range. During nonlinear evolution, frequency-up conversion processes take place, which are responsible for the generation of shock fronts and spikes with subnanosecond duration. Note that due to the bandwidth limitation of the present setup shock fronts or spikes shorter than 1 ns could not be resolved experimentally. It is assumed that especially these features are responsible for the crack initiation process. Besides these shortening effects also frequency-down conversion processes
are observed, which lead to lengthening of the SAW pulses. It can be expected that the latter effects are less important for fracture. However, a full theoretical description of impulsive fracture processes taking into account the time dependence of the distortions generated by a transient strongly nonlinear SAW pulse is still lacking.

The displacement and stress field of a nonlinear SAW is characterized by a strong decay (essentially exponential) from the surface into the bulk of the material. Crack nucleation is therefore expected to occur only at the surface. Usually nucleation is expected to occur at the strongest defects at the surface, which could be surface steps, etch pits, voids, or other surface disturbances. However, on the chemically etched surfaces used here for silicon such disturbances may be rather small and nucleation occurs only at relatively high stresses. Were these stresses applied constantly to the specimens, the cracks would be heavily overloaded and penetrate through the entire specimens at a velocity close to the Rayleigh wave speed. However, the width of the spikes of the SAW pulses is only of the order of nanoseconds (see Fig. 1). Since the SAW pulses propagate along the surface with Rayleigh wave velocity, this is also the time during which reasonably high stresses are applied to the region of the crack nucleus. Assuming that the cracks quickly accelerate to a reasonable fraction of the Rayleigh wave velocity, they can travel distances of several micrometers during this time.

In fused quartz and silicon the observed cracks always developed symmetrically from the nucleation point at the surface. However, the size of this initial nucleus could not be determined. After nucleation the crack embryos simultaneously grow both into the bulk and along the surface. For the growth along the surface the cracks can make use of the full strength of the stress field of the SAW. The growth into the bulk is influenced by the displacement field of the SAW, which strongly decays with depth. This suggests that the crack extension should be much longer along the surface than into the bulk.

In isotropic fused quartz the cracks, which originally nucleate perpendicular to the SAW propagation direction, change their direction during growth along the surface in a distinctive way by turning partially towards the SAW propagation direction, forming characteristic “forward-bending” patterns. The simulation yields the highest tensile opening stress or strain, as calculated from the measured SAW pulse profiles, normal to the propagation direction. This indicates, at least at the first stage, a mode of crack propagation that corresponds to a normal separation of the crack faces, namely the expected opening-mode crack perpendicular to the free quartz surface. On the other hand, after several micrometers of normal growth these cracks propagate further into the depth of the amorphous material at an angle of 30°–35°. The change in the depth dependence, the characteristic surface contours, and the sideways propagation of the cracks are difficult to explain. For example, the stress gradient in the wake of the SAW pulse could effectively turn the crack towards the direction of SAW propagation.

In anisotropic silicon crystals the observations are much richer and must be analyzed in detail. The anisotropy makes SAW pulse shapes propagating in the opposite directions [1 1 2] and [1 1 2] along the Si(111) surface different. The resulting and somewhat surprising asymmetry in the fracture behavior, namely that the pulse for which the appropriate {1 1 1} cleavage plane extends into the bulk in the direction of SAW propagation is much less likely to lead to fracture than the pulse in the opposite direction, where the corresponding {1 1 1} plane extends in the backwards direction, can be explained by an analysis of the stress fields of the SAW pulses. They tend to put the front of the pulse in compression and therefore lead to much higher tensile stress normal to the backward-oriented {1 1 1} cleavage plane for the nonlinear SAW pulse propagating in the [1 1 2] direction. This indicates first that crack nucleation occurs preferentially under mode I conditions. Second, it suggests that the {1 1 1} cleavage plane is apparently the only one on which crack nucleation can occur. Analyzing all the different cracks obtained on silicon surfaces it is apparent that nucleation on the {1 1 1} planes must be very strongly preferred over nucleation on other planes. This is in contrast to the cases of crack propagation, where other crack planes such as {1 1 0} 1,3,5,8 and even {2 1 1} 5,7,8 have been observed to be able to propagate in certain directions. In the few cases in which other crack planes were observed in this work [only for the (100) surface], these other planes could well have been created during sideways growth and not during nucleation.

The fact that only [1 1 1] crack planes appear to nucleate is particularly striking for the SAW pulses on the (110) surface extending in the [1 1 0] direction. In this case the secondary cleavage plane, the {1 1 0} plane, is oriented normal to the SAW pulse, such that crack propagation into the bulk could proceed along the easy propagation direction for this plane; 5,8,9 nevertheless it did not make use of this but generated exclusively {1 1 1} cracks.

Given the preferred nucleation on the {1 1 1} planes, then the observed crack extension along these planes, the extension along the surface, and also the estimated lengths of the cracks of several tens to hundreds of micrometers appear to be logical consequences of the observed SAW pulse duration. However, the often irregular extension into the bulk and
the abrupt change of the fracture plane and direction of propagation at a distance of 4–6 μm beneath the surface (see Figs. 6 and 7) still remains to be explained. To rationalize this, it is important to consider not only the mode I tensile loading component, but also mode II contributions from shear components, and changes in the stress field as the pulse passes a particular spot. While the sideways extension of the crack simply ceases to continue when the tensile stress on the cleavage plane drops below a certain value, the crack in the depth of the material then experiences a drastic increase in the sliding mode loading. Such sliding mode loading tends to drive the cracks off the cleavage plane, which is exactly what was observed here.

The results presented here are typical examples representative of a large number of cracks that were selected from a particular crack field, as shown in Fig. 4 for fused quartz and in Fig. 6 for silicon, and crack fields that were generated in independent fracture experiments. Within the limitations of the nonlinear SAW technique applied, reproducible fracture behavior was observed.

VI. CONCLUSIONS

Nonlinear SAW pulses provide a new approach to fracture mechanics. In contrast to bulk waves they possess their largest displacements at the surface, where crack nucleation is expected to start. Another very important property of SAWs is that they are elliptically polarized and have both a longitudinal and a shear component. These features lead to a more complicated dynamic cracking behavior than found in constant force experiments, as the present experimental results clearly indicate. Consequently, the theoretical analysis of the induced fracture effects is more complicated for SAWs.

A second important feature of broadband nonlinear SAW pulses is the development of shock fronts during propagation. Due to the nonlocal nonlinearity of surface waves with finite amplitudes, the wave front steepens steadily during propagation, whereas in a bulk wave the amplitude always decreases. The resulting strong nonlinearity allows the detailed investigation of crack nucleation processes. In fact, the strain or Mach number that can be realized in a nonlinear SAW, launched by the absorption layer method, is limited only by the fracture strength of the material employed. Thus, using plane SAWs the dependence of fracture on the crystallographic plane and SAW propagation direction on this plane can be studied systematically.

The key result of this study is that crack nucleation in silicon occurred only on {111} cleavage planes, while crack propagation can make use of {110} and higher index planes, even under impulsive loading conditions. The stresses at which cracks are nucleated on Si{111} planes intersecting a surface are estimated to be of the order of 1 GPa, which is somewhat too low to be associated with homogeneous crack nucleation but could not be linked a posteriori to any particular defect at the surface.

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