Acoustic emission from fast heavy-ion irradiation on solids

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Abstract

Ultrasonic signals of near-MHz frequencies were observed when solid targets of Al_2O_3, KCl and metallic aluminum were irradiated with fast heavy-ions. The projectile beam of 26 MeV/u Xe ions were chopped to pulses shorter than 1 μs. Two piezoelectric sensors detected the acoustic signals at the both ends of the target. The signals were analyzed by Fourier transform and several peaks were observed in the frequency range from several hundred kHz. Amplitudes of the frequency components were nearly proportional to the number of the ions in the pulse. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

When a fast heavy-ion (above MeV/u) passes through a solid material, the kinetic energy is deposited first to the electronic system of the material through ionization and excitation processes resulting in a high-density excitation along the trajectory. The energy is then transferred to the lattice system and finally results in heat, lattice vibration, or formation of permanent change of structure along the ion path. The formation of permanent tracks is characteristic to the heavy-ions, and depends on the material, the ion velocity and species.

Intensive experimental studies have been performed to determine the size and characteristics of the tracks, employing methods of scanning microscopy, measurements of the electromagnetic properties or X-ray diffraction [1].

On the other hand, the lattice vibrations by ion impact should reflect the dynamical aspects of the energy transfer processes from the electrons to the lattice system in the material. Lattice vibrations at low-frequency (around MHz) by electron and microwave are described as transient surface heating [2] but those by heavy-ion irradiation may be due to the microscopic stress by formation of permanent defects or possibly of temporary defects.

A few works have been reported on the subject. Adliene et al. [3,4] observed by piezoelectric

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transducers two types, continuous and burst, of acoustic-emission (AE) signals during implantation of 50–150 keV H–Ar ions. They suggested that the continuous AE was related to microstrain events like breakaway of dislocation from pinning points initiated by ions, whereas the burst AE was related to the formations of cracks. Teichert et al. [5] observed acoustic emission from Al sample irradiated by a 35 keV Ga-ion beam with spot size of 300 nm. These studies employed low-velocity ions where nuclear stopping was dominant.

Here we report the observation of acoustic emission up to a few MHz from solid materials by high-energy heavy-ion beam. Acoustic signals were observed from samples of metal, oxide and alkali-halide irradiated by short pulses of 26 MeV/u Xe ions. A motivation of this work was to study in real time the transient deformation caused by fast heavy-ions, which deposit the kinetic energy to the material by electronic stopping.

2. Experiments

The experiments have been performed at the accelerator research facility of RIKEN. A Xe ion-beam was produced by an ECR ion source and was chopped to short pulses by a pulse-operated electric deflector and a sub-harmonic RF buncher. The width of the pulse was chosen shorter than 1 μs and the interval about 10–30 ms so that it was longer than the decay time of the elastic vibrations. The beam was then accelerated by a linear accelerator (RILAC) and a ring cyclotron (RRC) up to 26 MeV/u and was guided to an experimental beam line. The shortest pulse which we obtained consisted nearly of a single bunch with a length of 3 ns as shown in Fig. 1.

The experimental setup is schematically shown in Fig. 2. Before the target, the ions passed through two secondary-electron monitors; one for the microscopic time structure of the pulse (fast monitor) and the other for the measurements of ion intensity in the pulse (slow monitor). In the fast monitor, the ions passed through an Al foil and the secondary electrons were collected by an electrostatic field and amplified by a micro-channel plate (MCP). Because of the time focusing of the electrons by the
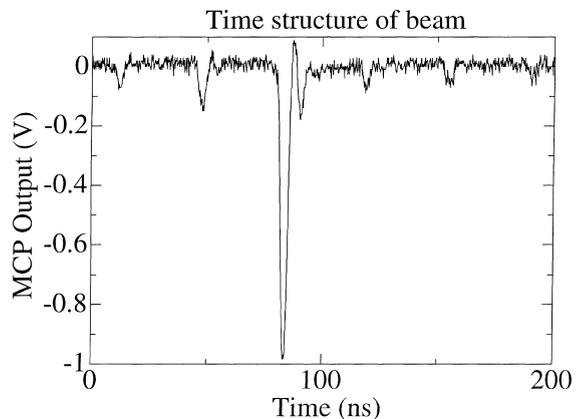

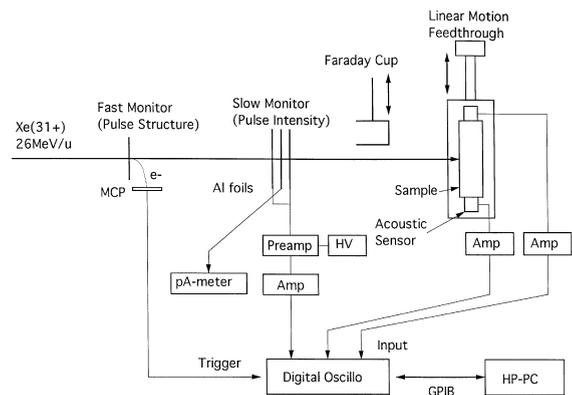Fig. 1. Time structure of the ion-beam pulse measured by the fast monitor.

Fig. 2. Experimental setup.

collecting field and a fast rise time of the MCP, the time resolution of the system was about 1 ns, which was fast enough to resolve the microstructure of the beam bunch with a frequency of 28 MHz. The beam pulse structure in Fig. 1 was measured by the fast monitor. The highest peak has a width of about 3 ns. The additional periodical peaks with an interval of about 35 ns are microbunches which were not collected by the sub-harmonic buncher. In the slow monitor, the beam passed through three Al foils where the first and the third were biased to a positive voltage. A slow amplifier (with a shaping time of 6 μs) was connected to the secondary-electron current pulse from the biased foils so that the output pulse height was proportional to the

number of the ions in the beam pulse. The middle foil was connected to a picoammeter. The pulse height was calibrated from the secondary electron current of the middle foil and the secondary electron current was compared with the ion-beam current at a Faraday cup downstream of the slow monitor. In the present measurements, the number of the ions in a pulse was estimated to be 10^4–10^5 depending on the pulse width.

The beam was then guided to a vacuum chamber where the irradiated sample was mounted. The beam spot size on the sample was about 4 mm × 4 mm. The sample materials were single crystals of Al_2O_3, and KCl, and metallic polycrystalline Al with a common dimension; 40 mm-long, 10 mm-wide and 5 mm-thick. The ion-beam was incident to the sample on the long and wide plane. According to calculations with TRIM code the range of the ions in the samples is shorter than the sample size; about 170 μm for Al_2O_3, 280 μm for Al and 380 μm for KCl. Therefore all the ions were stopped in the material near the incident surface.

For the detection of ultrasonic signals, we used AE detection, which is widely applied for non-destructive inspection of materials. We have used two piezoelectric ultrasonic sensors equipped with head amplifiers (Fuji Ceramics, M304A). The sensor [6] is highly sensitive to longitudinal waves up to about 2 MHz and has the highest sensitivity at about 300 kHz. The long axis of the sample was 90° to the beam and the sensors at the both ends of the sample detected the acoustic signals propagating perpendicular to the beam direction. The sample and the sensors were mounted on a frame at the end of linear motion feedthrough. Therefore the distances between the beam spot and the sensors could be adjusted by moving the frame perpendicular to the beam direction. A digital oscilloscope recorded the acoustic signals and the signal of the slow monitor for each pulse of the incident beam.

3. Results

Fig. 3 shows acoustic signals for samples of (a) metallic Al, (b) single crystal of Al_2O_3 and (c)
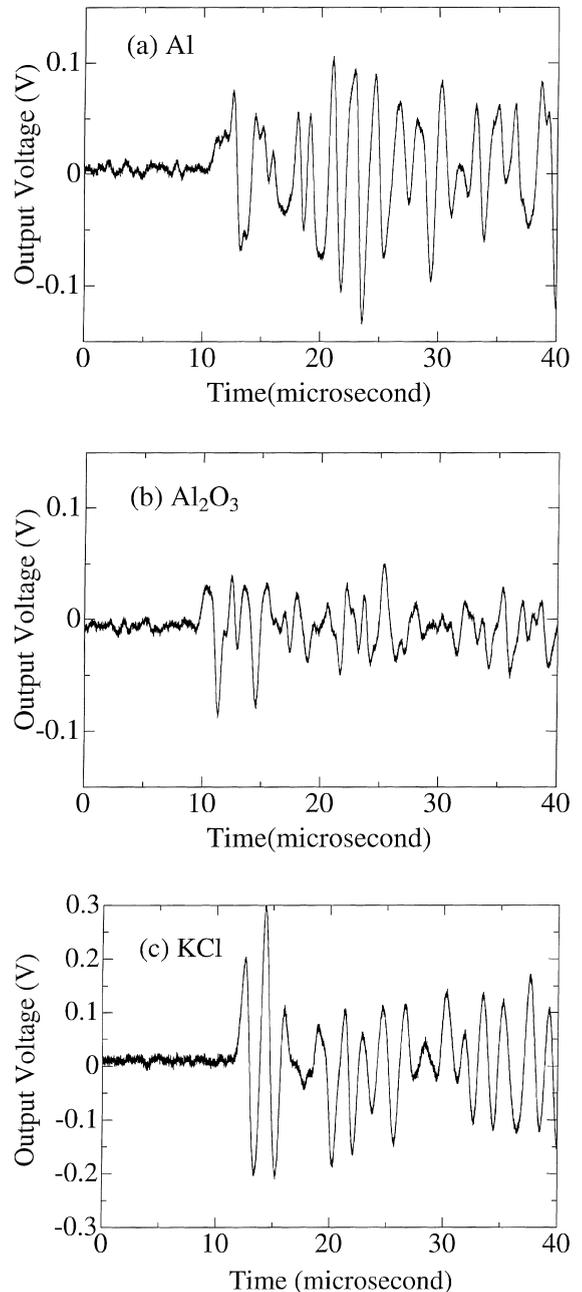

Fig. 3. Acoustic signals for (a) metallic Al, (b) single crystal Al_2O_3 and (c) single crystal KCl samples irradiated by a nearly single-bunch pulse of beam.

single crystal of KCl at almost the same ion-pulse intensity. The ion-beam consists of nearly a single bunch with pulse length of about 3 ns. The

acoustic signals have oscillatory structures with frequencies of hundreds of kHz. The frequency is dependent on the resonant vibration frequencies of the sample and the sensors. The acoustic signal for the Al_2O_3 shown in Fig. 3(b) has the lowest amplitude; lower than that for the metallic Al whereas that for KCl shown in Fig. 3(c) has highest amplitude. The first peak of the signals of the single crystals is steep without structures and the shape is not dependent on the source-sensor distance. For metallic Al, the rising part of the first peak (at around 10 μs) has an additional structure as shown in Fig. 3(a). This structure changes its shape and its amplitude decreases quickly as the distance between the sensor and the source increases.

To obtain the signal-propagation velocity in the sample, we measured the arrival time of signals between the two sensors as function of the irradiation position, changing the sample position perpendicular to the beam. The time difference between the signals from the KCl single crystal changed by 5.3 μs when the sample was moved by 12 mm. The signal-propagation velocity was estimated to be 4.5×10^3 m/s. This is in good agreement with the speed of longitudinal wave, 4470 m/s, estimated from the modulus of elasticity. The same is true for the similar measurement on Al_2O_3 single crystal where a propagation velocity of about 10^4 m/s was found.

We have studies the amplitude of the frequency components in the acoustic signal from the Al_2O_3 sample as function of the ion-pulse intensity. For the measurements, we set the width of the beam pulse to about 600 ns to achieve a higher ion-pulse intensity and a better signal-to-noise ratio. We also varied the ion-pulse intensity in a wide range by a beam attenuator at the RILAC. The acoustic signals are analyzed by Fourier transformation. The amplitude spectrum has peaks around 0.3, 0.4 and 0.6 MHz. In Fig. 4 the amplitude of the Fourier component is plotted as a function of the ion-pulse intensity. The amplitudes of the Fourier components are found to be nearly proportional to the ion-pulse intensity, indicating a linear increase with the total energy deposited in the material.
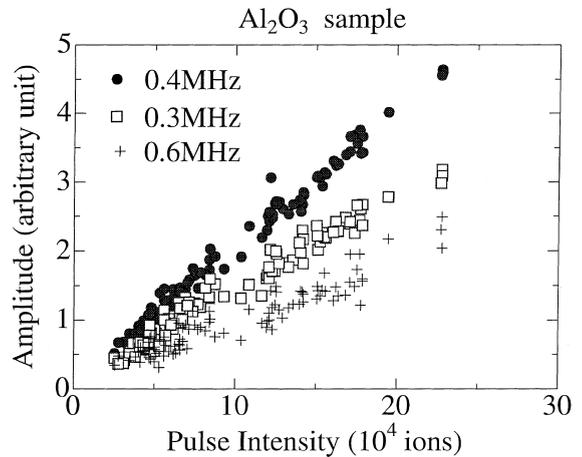

Fig. 4. Amplitudes of the Fourier components of acoustic signals observed for Al_2O_3 single crystal plotted vs the intensity of the ion-pulse.

4. Summary

Acoustic signals with frequencies between 100 kHz and 1 MHz are detected by irradiation of Al, KCl and Al_2O_3 by fast heavy-ions with pulse width between 3 and 600 ns. The waveform and amplitude is dependent on the material: The amplitude is higher for KCl single crystal followed by metallic Al and Al_2O_3 single crystal. It suggests that the amplitude is possibly correlated to the hardness of the material. The leading edge of the signal from metallic Al has a structure, whose shape changes and the amplitude decreases quickly with the source-sensor distance. This structure is considered to result from very high frequency ultrasonic waves. No such structures are found for KCl and Al_2O_3. A Fourier transform of the signals shows that the amplitude of the acoustic signal is nearly proportional to the energy deposited by the ions.

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